MAGNETISM *and* MAGNETIC MATERIALS

HOTEL NEW YORKER, NEW YORK
NOVEMBER 14–17, 1960

MAGNETICS AND MAGNETIC MATERIALS EXHIBIT

NORTH BALLROOM AND FOYER

NEW YORKER HOTEL

A Magnetics and Magnetic Materials exhibit has been arranged with some of the nation's outstanding firms engaged in research, manufacture, and application of magnetic materials, components, and equipment. The exhibits will be open each day of the Conference. The hours are 0900-1730.

	Booth
The Arnold Engineering Company, Marengo, Ill. Permanent Magnets of Alnico and Ceramic; Silectron transformer cores; High Permeability tape wound cores of Deltamax, Permalloy, Supermalloy, Supermendur, as well as Bobbin cores; Powder cores of Molybdenum, Permalloy Carbonyl Iron and Sendust; Barium Titanate Transducers; Special magnetic materials.	26 & 27
Bell Telephone Laboratories, Inc., Murray Hill, N. J. Research in Magnetism.	3
Columbian Carbon Company, New York, N. Y. Iron Oxides for Ferrites and Recording Pigments.	15
Crucible Steel Company of America, Pittsburgh, Pa. Permanent Magnets.	7
Dynacor, Inc., Rockville, Md. Magnetic Cores.	17
GRH Halltest Company, Valparaiso, Ind. Siemens Hall Generators, Gaussmeters, Fluxmeters, Automatic Magnet Test Equipment, Coercimeters.	24
General Electric Research Laboratory and **Magnetic Materials Section,** Schenectady, N. Y. and Edmore, Mich. Magnetic Materials and Phenomena.	21 & 22
Hamilton Watch Company,- Precision Metals Division, Lancaster, Pa. Soft Magnetic Alloys and Permanent Magnets.	20
Harvey-Wells Electronics, Inc., East Natick, Mass. Electromagnets and Accessories.	28-31
IBM Research Laboratory, Yorktown Heights, N. Y. Research and Development Activities in Magnetics.	13 & 14
Indiana General Corporation, Valparaiso, Ind. Permanent Magnets, Ferrites and Memory Products.	10 & 11
Leyman Corporation,- Magnetics Division, Cincinnati, Ohio Plastiform Magnets.	25
Magnetic Metals Company, Camden, N. J. Electromagnetic Cores and Shields.	1
Magnetic Shield Division - Perfection Mica Company, Chicago, Ill. Magnetic Shielding Alloys and Products.	2
Microwave Chemicals Laboratory, Inc., New York, N. Y. Single Crystal and Polycrystalline Ferrimagnetic Materials and Applications.	12
Radio Frequency Laboratories, Inc., Boonton, N. J. Magnet Chargers, Magnetreater, Gaussmeters and Accessories.	9
Rese Engineering, Inc., Philadelphia, Pa. Magnetic Core Testing Equipment, Millimicrosecond Current Pulse Generators.	23
U. S. Naval Ordnance Laboratory, Silver Spring, Md. Ferrotracer.	16
Varian Associates, - Instrument Division, Palo Alto, Calif. Electromagnet Systems and NMR Fluxmeters.	5 & 6
C. K. Williams & Company, East St. Louis, Ill. Magnetic Iron Oxides and Iron Oxided for Ferrites.	19

This Sixth Annual Conference on Magnetism and Magnetic Materials is the first held under the joint sponsorship of the American Institute of Electrical Engineers and the American Institute of Physics. As before, the Institute of Radio Engineers, the Metallurgical Society of the A.I.M.E. and the Office of Naval Research are cooperating with the sponsors.

It is intended that this conference will bring together in a stimulating environment those individuals who are interested in basic and applied work in magnetism.

This program contains abstracts of the invited and contributed papers. Discussion will be invited following the presentation of each of the papers.

The Conference is to be held November 14-17, 1960 in the Hotel New Yorker, New York City.

Inquiries should be directed to L. R. Bickford, Jr., Local Chairman, IBM Research Center, Box 218, Yorktown Heights, New York.

SUMMARY OF ACTIVITIES

Time	*Session*	*Title*	*Locations**
Monday			
0800-1600		Registration	M
0930-	A	Ordered Spin Systems	GB
1400-	B	Computer Devices	GB
1400-	C	Spin Configurations	TR
0900-1730		Magnetics Exhibit	NBF
Tuesday			
0900-	D	Metallic Films	GB
0900-	E	Nuclear Hyperfine Fields	TR
1400-	F	Ferromagnetic Resonance	GB
1400-	G	High Coercive Materials	TR
0900-1730		Magnetics Exhibit	NBF
Wednesday			
0900-	H	Exchange Interactions and Nonlinear Microwave Processes	GB
0900-	I	Magnetization Processes and Fine Particles	TR
1400-	J	Anisotropy	GB
1400-	K	Domain Walls and Domain Wall Motion	TR
0900-1730		Magnetics Exhibit	NBF
1730-		Cocktail Hour and Banquet	TR
Thursday			
0900-	L	Microwave Devices	GB
0900-	M	Metals and Alloys	TR
1400-	N	Soft Magnetic Metals	GB
1400-	O	Oxides	TR
0900-1700		Magnetics Exhibit	NBF

* GB - Grand Ballroom
TR - Terrace Room
NBF - North Ballroom and Foyer

Preregistration

A preregistration form accompanies this program. Everyone is urged to preregister to save time and to aid the Conference Committee in its planning. Make checks payable to the Conference on Magnetism, and mail to F. G. Brockman, Phillips Laboratories, Irvington - On - Hudson, New York. Since the address given on this form will be used in mailing your Conference Proceedings, be sure to give an accurate and sufficient address.

Registration and Proceedings

The registration desk will be located on the mezzanine of the Hotel New Yorker. It will be open from 0800 to 1600 on Monday, November 14, and from 0830 to 1630 on the other days of the Conference.

The registration fee will be $10. Each registrant will receive a copy of the Proceedings which will appear as a separate issue of the Journal of Applied Physics, to be issued in the Spring of 1961. The Proceedings will be published later in book form by the McGraw-Hill Book Company.

Hotel Reservations

A large block of rooms has been reserved at the Hotel New Yorker. Please utilize the enclosed form or mention the Conference when requesting reservations. If difficulties develop, please contact the Local Chairman or E. L. Boyd, IBM Watson Laboratories, 612 West 115th Street, New York 27, New York, Telephone: MO 6-9600.

Cultural and Recreational Activities

After considering the great diversity of cultural and recreational possibilities in New York, the Local Committee decided not to schedule any events other than the Banquet on Wednesday evening. A large number of leaflets containing information on New York City and its many attractions will be available at the registration desk. Those desiring theater tickets should write to the appropriate box office immediately. Though some tickets will be available during the meeting, the selection of plays and prices will be relatively limited.

Banquet

The social highlight of the Conference will be a banquet on Wednesday evening in the Terrace Room of the New Yorker. This banquet will be preceded by a cocktail hour starting at 1730 hours.

The principal speaker at the banquet will be T. Keith Glennan, Administrator of the National Aeronautics and Space Administration who will discuss problems faced in making space systems successful. Mr. Glennan heads all non-military effort directed towards the exploration and exploitation of space. As director of NASA, he is in a position as no other person to know the problems and future of space research.

Since the number of banquet attendees is limited, it is strongly recommended that you place your order with the preregistration form.

Questionnaire

The present form of the Conference and the method of publishing its proceedings are a result of a gradual evolution greatly aided by suggestions offered by conference participants. In order to determine whether the best possible compromise of the various interests participating in the Conference is achieved, the committee has prepared a questionnaire which will be available at the registration desk. Please cooperate by filling out and turning in this questionnaire before you leave the Conference.

Reportorial Session

The session on ferromagnetic resonance (Tuesday afternoon) will be conducted according to the reportorial system which has been successfully used in other technical conferences. George T. Rado will report on recent developments in the field as represented by the contributed papers accepted by the Conference Program Committee. An extended discussion period will follow this talk. The individual papers will appear with the other conference papers in the Journal of Applied Physics.

Information for Speakers

The sessions of this meeting will be held in the Terrace Room and the Grand Ballroom of the Hotel New Yorker, both very large rooms which will be familiar to those who have attended recent New York meetings of the American Physical Society. Slide projectors ($3\frac{1}{4}$" by 4" and 2" by 2") and Vu-Graphs will be provided. There will be a

small lighted blackboard. If you require any other equipment, please write directly to the Chairman of the Local Committee.

The Program Committee strongly urges the use of lantern slides for the display of data as well as of mathematics. A less desirable alternative is the use of prepared Vu-Graph transparencies. The grease pencil approach to the Vu-Graph or any use of the blackboard is strongly discouraged for the presentation of papers. Experience has shown that these procedures slow the presentation of papers and often fail to be effective with the audience. These two visual aids, however, will be available for use during the discussion periods.

CONFERENCE ON MAGNETISM AND MAGNETIC MATERIALS

NEW YORK, NOVEMBER 14-17, 1960

HOTEL NEW YORKER

Technical Program

MONDAY, NOVEMBER 14, 1960

0930 Hours

Session A Grand Ballroom

ORDERED SPIN SYSTEMS

A. M. Clogston, Presiding

1. ELEMENTARY THEORY OF SPIN WAVE INTERACTIONS (Invited)
   Frederic Keffer,
   University of Pittsburgh.
2. MAGNETIC ORDERING IN THE FERROMAGNETIC RARE EARTH METALS (Invited)
   K. Yosida and H. Miwa,
   University of Tokyo.
3. CLASSICAL THEORY OF THE GROUND SPIN-STATE IN SPINELS (Invited)
   T. A. Kaplan, K. Dwight, D. Lyons, and N. Menyuk,
   Massachusetts Institute of Technology.
4. NEUTRON DIFFRACTION BY HELICAL SPIN STRUCTURES (Invited)
   W. C. Koehler,
   Oak Ridge National Laboratory.
5. MAGNETIZATION PROCESS OF A HELICAL SPIN CONFIGURATION (Invited)
   U. Enz,
   Philips Research Laboratories.

1400 Hours

Session B Grand Ballroom

COMPUTER DEVICES

C. J. Kriessman, Presiding

6. THE POSSIBILITIES OF ALL-MAGNETIC LOGIC CIRCUITRY (Invited)
   U. F. Gianola,
   Bell Telephone Laboratories.
7. SUBMICROSECOND MAGNETIC MEMORIES (Invited)
   W. Lee Shevel, Jr.,
   IBM Research Center.
8. MAGNETIC FILM DEVICES USING PASSIVE LOADING
   J. M. Daughton, T. A. Smay, A. A. Read and A. V. Pohm,
   Iowa State University of Science and Technology.
9. DEMAGNETIZATION OF TWISTOR BITS
   W. A. Barrett,
   Bell Telephone Laboratories.
10. FLUX DISTRIBUTION IN FERRITE CORES UNDER VARIOUS MODES OF PARTIAL SWITCHING
    R. H. James, W. W. Overn and C. W. Lundberg,
    Remington Rand Univac.
11. IMPULSE SELECTION FOR CORE LOGIC
    Roger H. Tancrell,
    Lincoln Laboratory, M.I.T.
12. 50 MC AC DRIVE AND PARTIAL SWITCHING TECHNIQUES
    Robert E. McMahon,
    Lincoln Laboratory, M.I.T.
13. RECORDING AND REPRODUCTION OF NRZI SIGNALS
    R. S. Schools,
    IBM Data Systems Division.
14. PREPARATION AND PROPERTIES OF THIN FERRITE FILMS
    E. Banks, N. H. Riederman, H. W. Schleuning and L. M. Silber,
    Polytechnic Institute of Brooklyn.
15. FERRITE THIN FILMS
    H. P. LeMaire and W. J. Croft,
    RCA Semiconductor and Materials Division.

MONDAY, NOVEMBER 14, 1960

1400 Hours

Session C Terrace Room

SPIN CONFIGURATIONS

J. B. Goodenough, Presiding

16. NEUTRON DIFFRACTION INVESTIGATION OF MAGNETIC ORDERING IN DYSPROSIUM
    M. K. Wilkinson, W. C. Koehler, E. O. Wollan and J. W. Cable,
    Oak Ridge National Laboratory.
17. A NEUTRON DIFFRACTION STUDY OF METALLIC ERBIUM
    J. W. Cable, E. O. Wollan, W. C. Koehler and M. K. Wilkinson,
    Oak Ridge National Laboratory.
18. ANTIFERROMAGNETIC DOMAINS IN α-MANGANESE AND ITS ALLOYS
    A. Arrott and B. R. Coles,
    Scientific Laboratory, Ford Motor Company.
19. REMARKS ON THE MAGNETIC PROPERTIES OF Au-Mn SYSTEM
    H. Sato,
    Scientific Laboratory, Ford Motor Company.
20. EXCHANGE INVERSION IN $Mn_{2-x}Cr_xSb$
    W. H. Cloud, T. A. Bither and T. J. Swoboda,
    E. I. duPont de Nemours and Company.
21. ELECTRICAL RESISTIVITY AND MAGNETIC ANISOTROPY IN EXCHANGE INVERSION COMPOUNDS
    H. S. Jarrett, P. E. Bierstedt, F. J. Darnell and M. S. Sparks, E. I. duPont de Nemours and Company.
22. TRIANGULAR MOMENT ARRANGEMENTS IN MANGANESE SPINELS
    V. L. Moruzzi,
    IBM Research Center.
23. SPIN-FLOPPING IN MnF_2 BY HIGH MAGNETIC FIELDS
    I. S. Jacobs,
    General Electric Research Laboratory.
24. ANTIFERROMAGNETIC RESONANCE IN $(Cr_2O_3)_{1-x} \cdot (Al_2O_3)_x$ SINGLE CRYSTALS
    S. Foner,
    Lincoln Laboratory, M.I.T.
25. INFRARED ANTIFERROMAGNETIC RESONANCE IN MnO
    F. Keffer, A. J. Sievers III and M. Tinkham,
    University of California.
26. THE MAGNETIC SUSCEPTIBILITY OF $FeCl_2 \cdot 4H_2O$ AT LOW TEMPERATURES
    R. D. Pierce and S. A. Friedberg,
    Carnegie Institute of Technology.
27. THE STRUCTURE OF NICKEL CHROMITE
    E. Prince,
    U. S. Naval Research Laboratory.

0900 Hours

Session D Grand Ballroom

METALLIC FILMS

A. H. Eschenfelder, Presiding

28. ANISOTROPY IN IRON-NICKEL FILMS (Invited)
    D. O. Smith,
    Lincoln Laboratory, M.I.T.
29. EPITAXIAL GROWTH AND MAGNETIC ANISOTROPY OF SINGLE CRYSTAL FILMS OF IRON, NICKEL AND PERMALLOY
    S. Chikazumi,
    IBM Research Center
30. MAGNETIC ANISOTROPIES OF Ni FILMS EVAPORATED AND MEASURED AT 10^{-8} mm Hg AND BELOW
    C. D. Graham, Jr. and J. M. Lommel,
    General Electric Research Laboratory.
31. ANNEALING OF OBLIQUE-INCIDENCE PERMALLOY FILMS
    G. P. Weiss and D. O. Smith,
    Lincoln Laboratory, M.I.T.
32. PERMALLOY FILMS EVAPORATED AT GRAZING INCIDENCE
    M. S. Cohen,
    Lincoln Laboratory, M.I.T.
33. TEMPERATURE DEPENDENCE OF MAGNETIC PROPERTIES OF THIN PERMALLOY FILMS
    A. Segmueller,
    IBM Research Laboratory, Zurich.
34. ROTATABLE ANISOTROPY IN THIN PERMALLOY FILMS
    R. J. Prosen, J. O. Holmen and B. E. Gran,
    Minneapolis-Honeywell.
35. ANISOTROPY ROTATION IN THIN PERMALLOY FILMS AT ROOM TEMPERATURE
    T. Matcovich, E. Korostoff, A. Schmeckenbecher,
    Remington Rand Univac.
36. FREE OSCILLATIONS OF THE MAGNETIZATION IN THIN PERMALLOY FILMS
    P. Wolf,
    IBM, Research Laboratory, Zurich.
37. SOME PROPERTIES OF UNIAXIAL PERMALLOY FILMS PREPARED BY CATHODIC SPUTTERING
    M. H. Francombe and A. J. Noreika,
    Philco Corporation.
38. MAGNETIC THIN FILMS BY IMPACT EVAPORATION
    E. Kay,
    IBM, San Jose, California.
39. PREPARATION AND PROPERTIES OF AMORPHOUS NICKEL FILMS
    R. F. Adamsky and A. F. Sears,
    Laboratory for Electronics.

TUESDAY, NOVEMBER 15, 1960

0900 Hours

Session E Terrace Room

NUCLEAR HYPERFINE FIELDS

J. S. Smart, Presiding

40. NUCLEAR MAGNETIC RESONANCE IN RARE EARTH INTERMETALLIC COMPOUNDS (Invited)
    V. Jaccarino,
    Bell Telephone Laboratories.
41. NUCLEAR RESONANCE IN FERROMAGNETIC AND ANTIFERROMAGNETIC SOLIDS UNDER HYDROSTATIC PRESSURE (Invited)
    G. Benedek,
    Division of Engineering and Applied Physics,
    Harvard University.
42. THE MOSSBAUER EFFECT: APPLICATIONS TO MAGNETIC MATERIALS (Invited)
    G. K. Wertheim,
    Bell Telephone Laboratories.
43. ON THE CONTRIBUTION OF THE FERMI CONTACT TERM TO THE MAGNETIC FIELD AT A NUCLEUS
    R. E. Watson,
    AVCO R.A.D.,
    Solid-State and Molecular Theory Group, M.I.T. and
    A. J. Freeman,
    Ordnance Materials Research Office,
    Solid-State and Molecular Theory Group, M.I.T.
44. NUCLEAR MAGNETIC RESONANCE OF Fe^{57} IN UNENRICHED Fe
    J. I. Budnick, L. J. Bruner, R. J. Blume, and E. L. Boyd,
    IBM Watson Laboratory.
45. NUCLEAR RESONANCES IN CUBIC, HEXAGONAL, AND MIXED PHASE COBALT POWDERS AND THIN FILMS
    Wilton A. Hardy,
    International Business Machines Laboratory.
46. TRANSIENT EXCITATION OF NUCLEI IN FERROMAGNETIC METALS
    M. Weger, E. L. Hahn, and A. M. Portis,
    University of California.
47. NUCLEAR MAGNETIC RESONANCE IN NiF_2 DOMAIN WALLS
    R. G. Shulman,
    Bell Telephone Laboratories.

1400 Hours

Session F Grand Ballroom

FERROMAGNETIC RESONANCE

R. C. Fletcher, Presiding

Reportorial Session
George T. Rado, Reporter

48. FERRIMAGNETIC RESONANCE IN SINGLE CRYSTALS OF COBALT SUBSTITUTED MANGANESE FERRITE
R. W. Teale and M. J. Hight,
Mullard Research Laboratories.

49. MICROWAVE RESONANCE IN TETRAGONAL MANGANESE-IRON SPINEL
James Overmeyer,
IBM Research Center.

50. FERROMAGNETIC RESONANCE IN PIEZOELECTRIC $Ga_{2-x}Fe_xO_3$
A. Dymanus,
Gordon McKay Laboratory
Harvard University, and
I. P. Kaminow,
Bell Telephone Laboratories.

51. FERROMAGNETIC RESONANCE DUE TO MAGNETIC FIELDS GENERATED BY DISPLACEMENT CURRENTS IN FERRITES
Isidore Bady and Gilbert S. McCall, Jr.,
United States Army Signal Research and Development Laboratory.

52. EXCITATION AND BOUNDARY EFFECTS IN SPIN WAVE RESONANCE
R. F. Soohoo,
Lincoln Laboratory, M.I.T.

53. MAGNETIC RESONANCE IN CANTED FERRIMAGNETICS
Perry Miles,
Laboratory for Insulation Research
Massachusetts Institute of Technology.

54. FERRIMAGNETIC RESONANCE IN YTTERBIUM IRON GARNET
R. W. Teale, R. F. Pearson and M. J. Hight,
Mullard Research Laboratories.

55. ANISOTROPY OF THE SPIN WAVE SPECTRUM
Marcel Muller and Charles Buffler,
Varian Associates.

56. FERRIMAGNETIC RESONANCE IN A SINGLE CRYSTAL DISC OF YTTRIUM IRON GARNET
Archibald W. Smith and Akira Watanabe,
Defence Research Telecommunications Establishment.

57. FERROMAGNETIC RESONANCE LINE WIDTH IN COBALT-SUBSTITUTED FERRITES
C. Warren Haas and Herbert B. Callen,
Department of Physics,
University of Pennsylvania.

(Continued on next page)

58. A NEW CHARACTERISTIC IN THE TEMPERATURE DEPENDENCE OF FERRIMAGNETIC RESONANCE LINE WIDTH IN SOME RARE EARTH DOPED YTTRIUM IRON GARNET
J. F. Dillon, Jr.,
Bell Telephone Laboratories.

59. THE NATURE OF THE LOW TEMPERATURE LINE WIDTH MAXIMUM IN YTTRIUM IRON GARNET
E. G. Spencer and R. C. LeCraw and E. H. Turner,
Bell Telephone Laboratories.

60. PEAK POWER CHARACTERISTICS OF LOW MAGNETIZATION GARNETS
J. H. Saunders and J. J. Green,
Research Division,
Raytheon Company.

61. METHOD FOR THE DETERMINATION OF FUNDAMENTAL TRANSITION PROBABILITIES IN FERRIMAGNETIC RESONANCE BY THE USE OF ELLIPSOIDAL SAMPLES
T. J. Matcovich, Henry S. Belson, and N. Goldberg,
Remington Rand Univac,
Division of Sperry Rand Corporation.

62. METHOD FOR THE DETERMINATION OF THE TRANSITION PROBABILITIES OF SPIN WAVES IN FERRIMAGNETIC RESONANCE WITH THE AID OF MAGNETOSTATIC MODES
Henry S. Belson and N. Goldberg,
Remington Rand Univac,
Division of Sperry Rand Corporation.

63. INSTABILITY OF MAGNETOSTATIC MODES IN A MICROWAVE MAGNETIC FIELD APPLIED PARALLEL TO THE DC FIELD
E. Schlömann and R. I. Joseph,
Raytheon Company.

64. TEMPERATURE DEPENDENCE OF THE SPIN WAVE SPECTRUM OF YTTRIUM IRON GARNET
R. C. LeCraw and L. R. Walker,
Bell Telephone Laboratories.

65. FERROMAGNETIC RELAXATION AT LOW MICROWAVE FREQUENCIES
J. J. Green and E. Schlömann,
Raytheon Company.

1400 Hours

Session G Terrace Room

HIGH COERCIVE MATERIALS

C. D. Graham, Presiding

66. THE DEVELOPMENT OF FINE PARTICLE MAGNETS (Invited)
Fred E. Luborsky,
General Electric Research Laboratory.

67. MAGNETIC PROPERTIES OF SINGLE DOMAIN IRON AND IRON-COBALT PARTICLES PREPARED BY BOROHYDRIDE REDUCTION
A. L. Oppegard, F. J. Darnell and H. C. Miller,
Central Research Department,
Experimental Station,
E. I. duPont de Nemours and Company.

68. EXCHANGE ANISOTROPY IN OXIDIZED IRON-COBALT PARTICLES
F. J. Darnell,
Central Research Department,
Experimental Station,
E. I. duPont de Nemours and Company.

69. UNIDIRECTIONAL PROPERTIES IN THE IRON-IRON SULFIDE SYSTEM
J. H. Greiner, I. M. Croll and M. Sulich,
International Business Machines Corporation,
Federal Systems Division.

70. A NEW LIGHT WEIGHT MATERIAL FOR PERMANENT MAGNETS
R. B. Falk and G. D. Hooper,
Metallurgical Products Department,
General Electric Company.

71. STRUCTURE OF ALNICO V
Robert B. Campbell and Carl A. Julien,
Crucible Steel Company of America.

72. MAGNETIC ANNEALING OF "TICONAL" G MAGNET STEEL
H. Zijlstra,
Metallurgical Laboratory, N. V. Phillips' Gloeilampenfabrieken.

73. CRYSTAL LATTICE INVESTIGATION OF THE PERMANENT MAGNET PRECIPITATE IN VARIOUS ALNICO MATERIALS
K. J. Kronenberg,
The Indiana General Corporation.

74. SOME INVESTIGATIONS ON IRON-COBALT PERMANENT MAGNET ALLOYS OF THE VICALLOY II TYPE
W. Baran, W. Breuer, H. Fahlenbrach, and K. Janssen,
Fried Krupp Widia-Fabrik.

75. TEMPERATURE DEPENDENCE OF MAGNETOSTRICTION AND ANISOTROPY IN MnBi
P. A. Albert and W. J. Carr, Jr.,
Westinghouse Research Laboratories.

76. STUDIES OF A HIGH COERCIVITY ELECTRODEPOSIT HAVING A LAMELLAR STRUCTURE
J. S. Sallo and K. H. Olsen,
Minneapolis-Honeywell,
Research Center.

0900 Hours

Session H Grand Ballroom

EXCHANGE INTERACTIONS AND NONLINEAR MICROWAVE PROCESSES

E. Schlömann, Presiding

77. OPTICAL AND INFRARED SPECTRA OF THE FERRITES AND GARNETS (Invited)
K. A. Wickersheim,
Hughes Research Laboratory.

78. ELECTRON SPIN RESONANCE MEASUREMENTS OF EXCHANGE INTERACTIONS (Invited)
J. Owen,
Clarendon Laboratory,
Oxford University.

79. CHROMIUM ION PAIR INTERACTIONS IN THE PARAMAGNETIC SPECTRUM OF RUBY
H. Statz, L. Rimai, M. J. Weber and G. A. deMars,
Research Division,
Raytheon Company, and
G. F. Koster
Massachusetts Institute of Technology.

80. MAGNETIZATION AT ULTRA-HIGH PRESSURES
W. G. Field, E. R. Czerlinsky and R. A. MacMillan,
Air Force Cambridge Research Laboratory.

81. ANISOTROPIC CURIE TEMPERATURE
Earl R. Callen,
U.S. Naval Ordnance Laboratory.

82. INTERACTION OF SPIN WAVES AND PHONONS IN YIG (Invited)
E. H. Turner,
Bell Telephone Laboratories.

83. LINE SHAPE OF SUBSIDIARY RESONANCE IN YIG
T. S. Hartwick, E. R. Peressini and M. T. Weiss,
Hughes Aircraft Company.

84. PARAMETRIC EFFECTS IN MAGNETOACOUSTIC RESONANCE
R. L. Comstock and B. A. Auld,
W. W. Hansen Laboratories of Physics,
Stanford University, and
G. Wade,
Raytheon Manufacturing Company.

85. NONLINEAR RESPONSE OF YIG
Robert M. Hill and Robert S. Bergman,
Palo Alto Laboratories,
General Telephone & Electronics Laboratories, Inc.

WEDNESDAY, NOVEMBER 16, 1960

0900 Hours

Session I Terrace Room

MAGNETIZATION PROCESSES AND FINE PARTICLES

D. S. Rodbell, Presiding

86. THE TEMPERATURE DEPENDENCE OF SPONTANEOUS MAGNETIZATION IN SUPERPARAMAGNETIC NICKEL
Carlos R. Abeledo and P. W. Selwood,
Department of Chemistry,
Northwestern University.

87. THE MAGNETIC PROPERTIES OF ANGSTROM DIAMETER IRON PARTICLES
Fred E. Luborsky,
General Electric Research Laboratory.

88. BEHAVIOR OF FERRO OR FERRIMAGNETIC VERY FINE PARTICLES
C. J. Lin,
The Franklin Institute Laboratories.

89. PREPARATION, GROWTH AND STUDY OF ULTRA FINE FERRITE PARTICLES
William J. Schuele and V. D. Deetscreek,
The Franklin Institute Laboratories.

90. FINE PARTICLE FERRITES . I . NICKEL FERRITE
W. W. Malinofsky and R. W. Babbitt,
U. S. Army Signal Research and Development Laboratory.

91. THE ANGULAR VARIATION OF THE MAGNETIC PROPERTIES OF PARTIALLY ALIGNED γ-Fe_2O_3 PARTICLES
G. Bate,
International Business Machines Corporation.

92. COHERENT AND INCOHERENT MAGNETIZATION PROCESSES IN POWDERS
S. Shtrikman and E. P. Wohlfarth,
Imperial College,
London, England.

93. THEORETICAL MAGNETIZATION CURVES FOR PARTICLES WITH CUBIC ANISOTROPY
Clark E. Johnson, Jr.,
Minnesota Mining and Manufacturing Company, and
William Fuller Brown, Jr.,
Department of Electrical Engineering,
University of Minnesota.

94. ON ADDITIVITY OF IMPERFECTIONS AS MEANS FOR DOMAIN NUCLEATION
A. Aharoni,
The Weizmann Institute of Science,
Rehovoth, Israel.

95. QUANTITATIVE DETERMINATION OF THE INTERACTION FIELDS IN AGGREGATES OF SINGLE DOMAIN PARTICLES
Donald F. Eldridge,
Ampex Corporation.

96. GENERAL SUPERPARAMAGNETIC BEHAVIOR OF AN ALIGNED ASSEMBLY OF UNIAXIALLY ANISOTROPIC PARTICLES
Forrest G. West,
Texas Instruments Incorporated.

97. AN ANALYTIC HYSTERESIS FUNCTION
F. H. Middleton,
University of Rhode Island.

1400 Hours

Session J Grand Ballroom

ANISOTROPY

R. L. White, Presiding

98. ANISOTROPY AND MAGNETOSTRICTION IN MAGNETIC OXIDES (Invited)
J. C. Slonczewski,
IBM Research Center.

99. ANISOTROPY OF YIG CALCULATED FROM CRYSTAL FIELD PARAMETERS OF Fe^{3+} IN YTTRIUM GALLIUM GARNET
S. Geschwind,
Bell Telephone Laboratories.

100. THE MAGNETIC ANISOTROPY OF YTTRIUM IRON GARNET AT 0 °K
L. R. Walker,
Bell Telephone Laboratories.

101. CALCULATION OF UNIAXIAL SPIN HAMILTONIAN CONSTANTS IN YIG
J. J. Pearson,
Department of Physics,
University of Pittsburgh.

102. TORQUE MEASUREMENTS ON DOPED YTTRIUM IRON GARNET
R. F. Pearson and R. W. Cooper,
Mullard Research Laboratories.

103. LOW TEMPERATURE MAGNETIC PROPERTIES OF SOME RARE EARTH GARNET COMPOUNDS
M. Ball, G. Garton, M. J. M. Leask, D. Ryan and W. P. Wolf,
Clarendon Laboratory,
Oxford University, England.

104. UNIAXIAL ANISOTROPY IN POLYCRYSTALLINE GARNETS
D. J. Epstein, B. Frackiewicz and R. P. Hunt,
Laboratory for Insulation Research, M.I.T.

105. MAGNETIC PROPERTIES OF THE LOW-TEMPERATURE FORM OF MAGNETITE
D. B. Bonstrom, A. H. Morrish and L. A. K. Watt,
University of Minnesota.

106. EXCHANGE ANISOTROPY IN MIXED MANGANITES WITH THE HAUSMANNITE STRUCTURE
I. S. Jacobs and J. S. Kouvel,
General Electric Research Laboratory.

107. EXCHANGE ANISOTROPY IN STAINLESS STEEL
W. H. Meiklejohn,
General Electric Research Laboratory.

108. THE MAGNETOCRYSTALLINE ANISOTROPY OF FERROMAGNETIC CRYSTALS UNDER HYDROSTATIC PRESSURE
J. S. Kouvel and R. H. Wilson,
General Electric Research Laboratory.

WEDNESDAY, NOVEMBER 16, 1960

1400 Hours

Session K Terrace Room

DOMAIN WALLS AND DOMAIN WALL MOTION

L. R. Bickford, Jr., Presiding

109. DOMAINS AND EXTREME-VALUE STATISTICS
William Fuller Brown, Jr.,
University of Minnesota.

110. THE FREQUENCY DEPENDENCE OF ULTRASONIC WAVE ATTENUATION IN ARMCO IRON AND LOW CARBON STEEL
U. M. Martius and W. J. Bratina,
Ontario Research Foundation.

111. DOMAIN WALL MOBILITY IN SINGLE CRYSTAL YTTRIUM IRON GARNET (YIG)
F. B. Hagedorn and E. M. Gyorgy,
Bell Telephone Laboratories.

112. MEASUREMENTS OF DOMAIN WALL AREA DURING SLOW FLUX REVERSALS
R. M. Brownell and R. C. Barker,
Yale University.

113. REVERSIBLE FLUX CHANGES IN 50% NICKEL-IRON ALLOYS
F. J. Friedlaender and L. L. Ogborn,
Purdue University.

114. SPIRAL WALLS IN THIN MAGNETIC FILMS
Harrison W. Fuller, Harvey Rubinstein and Donald L. Sullivan,
Computer Products Division,
Laboratory for Electronics.

115. THIN FILM SWITCHING IN THE HARD DIRECTION BY WALL MOTION
Robert J. Spain and Harvey Rubinstein,
Computer Products Division,
Laboratory for Electronics.

116. MAGNETORESISTIVE MEASUREMENTS ON DOMAIN ROTATION AND WALL DEVELOPMENT IN Ni-Fe ALLOY FILMS
Forrest G. West,
Central Research Laboratories,
Texas Instruments.

117. MAGNETRORESISTANCE AND MAGNETIC SWITCHING IN PERMALLOY FILMS
R. L. Coren and H. J. Juretschke,
Polytechnic Institute of Brooklyn.

118. NUCLEATION PROCESSES IN THIN PERMALLOY FILMS
S. Methfessel, S. Middelhoek and H. Thomas,
IBM Research Laboratory, Zurich.

119. DOMAIN STRUCTURES IN IRON WHISKERS AS OBSERVED BY THE KERR METHOD
C. A. Fowler, Jr., E. M. Fryer and D. Treves,
Department of Physics,
Pomona College.

120. DETERMINATION OF THE DIRECTIONS OF MAGNETISATION IN POLYCRYSTALLINE FERRITES
D. R. Callaby,
Standard Telecommunication Laboratories, England.

121. HALL PROBE RESOLUTION
Heinz Koehler and Bohdan Kostyshyn,
IBM General Products Division Development Laboratory.

0900 Hours

Session L Grand Ballroom

MICROWAVE DEVICES

P. H. Vartanian, Presiding

122. THEORETICAL AND EXPERIMENTAL CHARACTERISTICS OF A FERROMAGNETIC AMPLIFIER USING LONGITUDINAL PUMPING (Invited)
R. T. Denton,
Bell Telephone Laboratories.

123. ANTIFERROMAGNETIC MATERIALS FOR MILLIMETER AND SUBMILLIMETER DEVICES (Invited)
G. S. Heller, J. J. Stickler and J. B. Thaxter,
Massachusetts Institute of Technology.

124. THE GENERATION OF MICROWAVE ELECTROMAGNETIC RADIATION IN MAGNETIC MATERIALS
J. H. Rowen and F. G. Eggers,
Bell Telephone Laboratories.

125. FINE WIRE FERRITE LIMITERS
Ernest Stern,
General Electric Company.

126. TRAVELING WAVE FREQUENCY DOUBLING IN FERRITES
B. A. Auld, H. J. Shaw and D. K. Winslow,
Stanford University.

127. SATURATION EFFECTS IN FERRITE FREQUENCY DOUBLERS OPERATING IN THE UNIFORM PRECESSION MODE
B. A. Auld,
Stanford University.

128. SUBHARMONIC GENERATION IN FERRIMAGNETIC ELLIPSOIDS
Glenn E. Bennett,
Air Force Cambridge Research Laboratories.

129. PERFORMANCE OF TETRAHEDRAL JUNCTION WAVEGUIDE SWITCHES
Dwight A. Caswell,
Caswell Electronics Corporation.

130. A COMPACT UHF ISOLATOR
D. Bruce Swartz,
Sperry Microwave Electronics Company.

131. PHASE SHIFT STUDIES IN FERRITE-DIELECTRIC LOADED COAXIAL LINES AT 2200 MC
J. J. Rowley,
Lockheed Aircraft Corporation.

132. PERTURBATION TECHNIQUES FOR MINIATURIZED COAXIAL Y-JUNCTION CIRCULATORS
J. Clark,
Sperry Microwave Electronics Company.

THURSDAY, NOVEMBER 16, 1960

0900 Hours

Session M Terrace Room

METALS AND ALLOYS

A. Arrott, Presiding

133. ON THE NATURE OF THE MAGNETIC COUPLINGS IN TRANSITIONAL METALS (Invited)
J. Friedel, G. Leman and S. Olszewski,
University of Paris.

134. EXPERIMENTAL g' AND g VALUES OF SOME METALS AND ALLOYS (Invited)
G. Asch and A. J. P. Meyer,
Institut de Physique,
Strasbourg, France.

135. PYROMAGNETIC MEASUREMENTS ON NICKEL
E. W. Pugh and B. E. Argyle,
IBM Research Center.

136. PARAMAGNETISM OF POLYCRYSTALLINE GADOLINIUM, TERBIUM, AND DYSPROSIUM METALS
Sigurds Arajs and R. V. Colvin,
United States Steel Corporation

137. PARAMAGNETIC RESONANCE OF ^{8} S STATE IONS IN METALS
M. Peter,
Bell Telephone Laboratories.

138. MAGNETIC CHARACTERISTICS OF SOME AMn_5 INTERMETALLIC COMPOUNDS
L. V. Cherry and W. E. Wallace,
University of Pittsburgh.

139. MAGNETIC MOMENTS OF COMPOUNDS OF COBALT WITH RARE EARTH ELEMENTS HAVING A Cu_5Ca STRUCTURE
E. A. Nesbitt, H. J. Williams, J. H. Wernick and R. C. Sherwood,
Bell Telephone Laboratories.

140. PRECIPITATION IN GOLD NICKEL SINGLE CRYSTALS
P. J. Flanders and F. R. L. Schoning,
The Franklin Institute Laboratories.

141. THE FERROMAGNETIC PHASE OF Mn-Al
Robert B. Campbell and Carl A. Julien,
Crucible Steel Company of America.

142. REVERSIBLE SOLID-STATE TRANSFORMATION IN IRON-NICKEL ALLOYS IN THE INVAR COMPOSITION-RANGE
N. I. Ananthanrayanan and R. J. Peavler,
University of Kansas.

1400 Hours

Session N Grand Ballroom

SOFT MAGNETIC METALS

R. M. Bozorth, Presiding

143. METALLURGY AND MAGNETIC PROPERTIES OF A Fe-Co-V ALLOY (Invited)
C. W. Chen,
Westinghouse Research Laboratories.

144. IMPROVED MAGNETIC PROPERTIES OF HIGH PURITY IRON-COBALT ALLOYS CONTAINING 27 TO 43 PER CENT COBALT
Daniel S. Shull, Jr.,
Westinghouse Electric Corporation.

145. CUBE TEXTURE IN ULTRA-THIN MOLYBDENUM PERMALLOY TAPE
P. K. Koh,
Allegheny Ludlum Steel Corporation.

146. DIFFUSION REACTION IN THE AGING OF 4-79 MOLYBDENUM PERMALLOY
E. M. Tolman,
Bell Telephone Laboratories.

147. INDUCED MAGNETIC ANISTROPY CREATED BY MAGNETIC AND STRESS ANNEALING OF IRON-ALUMINUM ALLOYS
H. J. Birkenbeil and R. W. Cahn,
University of Birmingham,
England.

148. HIGH TEMPERATURE LAG IN IRON NICKEL ALLOYS
Dieter Gerstner and Eckart Kneller,
Max Planck Institut fur Metallforschung,
Stuttgart, Germany.

149. SOME EFFECTS OF DIRECTIONAL ORDERING IN ZONE MELTED Fe
R. E. Maringer,
Battelle Memorial Institute.

150. LOSSES IN SILICON IRON AT VERY LOW FREQUENCIES AND HIGH FLUX DENSITIES
Daniel A. Wycklendt and Robert M. Kay,
Allis-Chalmers Manufacturing Company.

151. MAGNETIC CORE LOSSES RESULTING FROM A ROTATING FLUX
A. Kaplan,
General Electric Company.

152. HIGH TEMPERATURE STABILITY OF MAGNETIC MATERIALS
Norman Pavlik,
Westinghouse Electric Corporation.

THURSDAY, NOVEMBER 16, 1960

1400 Hours

Session O Terrace Room

OXIDES

J. F. Dillon, Jr., Presiding

153. MAGNETIC PROPERTIES OF SOME FLUOSILICATES AT LOW TEMPERATURES (Invited)
E. Kanda,
Tōhoku University.

154. SYNTHESIS AND PROPERTIES OF FERROMAGNETIC CHROMIUM OXIDE
Paul Arthur, N. L. Cox, J. N. Ingraham, A. L. Oppegard, T. J. Swoboda and M. S. Sadler,
E. I. DuPont De Nemours & Company.

155. GROWTH OF YTTRIUM IRON GARNET SINGLE CRYSTALS BY THE FLOATING ZONE TECHNIQUE
L. L. Abernethy, T. H. Ramsey, Jr., and J. W. Ross,
Texas Instruments.

156. EQUILIBRIUM ATMOSPHERE SCHEDULES FOR THE COOLING OF FERRITES
John M. Blank,
General Electric Company.

157. REINTERPRETATION OF THE REACTION KINETICS OF NICKEL FERRITE
R. C. Turnbull,
International Business Machines Laboratories.

158. PREPARATION AND PROPERTIES OF LOW LOSS FERRITES
Aaron P. Greifer, Yoshinao Nakada, and Howard Lessoff,
Radio Corporation of America.

159. EFFECT OF COBALT OXIDE IN POROUS NICKEL FERRITES AT VHF
H. F. Remde,
Indiana General Corporation.

160. INITIAL PERMEABILITY CHARACTERISTICS OF VANADIUM DOPED MANGANESE ZINC FERRITES
Yūzō Shichijō,
Nippon Telegraph and Telephone Public Corporation,
Noboru Tsuya,
Tōhoku University, and
Kōki Suzuki,
Tōhoku Metal Industries.

161. EFFECT OF INDIUM SUBSTITUTION IN YTTRIUM IRON GARNET: HIGH PERMEABILITY GARNETS
J. Richard Cunningham, Jr., and Elmer E. Anderson,
U.S. Naval Ordnance Laboratory.

162. A FERRITE SYSTEM FOR APPLICATION AT LOWER MICROWAVE FREQUENCIES
C. F. Jefferson and R. G. West,
Solid State Electronics Department, Motorola.

163. CATION DISTRIBUTIONS IN MAGNESIUM-NICKEL FERRITES
C. J. Kriessman,
Remington Rand Univac,
Division of Sperry Rand, and
S. E. Harrison,
R.C.A. Laboratories.

164. THE REMANENT MAGNETIZATION OF A SYNTHETIC HEMATITE SINGLE CRYSTAL
S. T. Lin,
Massachusetts Institute of Technology

SESSION A

ORDERED SPIN SYSTEMS

A. M. CLOGSTON, Presiding

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1. ELEMENTARY THEORY OF SPIN WAVE INTERACTIONS* (Invited)

FREDERIC KEFFER
Department of Physics,
University of Pittsburgh,
Pittsburgh, Pennsylvania

As the temperature of a ferromagnet is raised from 0°K, the excitation of spin waves causes the average angle Φ_E between the directions of adjacent spin vectors gradually to open up. The exchange energy is $-JNzS^2\cos\Phi_E$; and the difference between this energy and its minimum value $-JNzS^2$ is equal to the energy in the spin waves. Alternatively the exchange energy equals $-JNz\bar{S}^2$ with $\bar{S}\approx S-\frac{1}{2}\epsilon$, where $JNz\,\epsilon$ is the energy in the spin waves. This energy, by the simple Bloch theory, is proportional to $T^{5/2}$. The presence of spin waves thus causes the effective value of S, and hence the effective exchange field, to decrease by a term in $T^{5/2}$. When this decrease is incorporated into any formula of simple spin wave theory, the first-order effect of spin wave exchange interactions is thereby expressed. In particular, when this decrease is fed into the coefficient of Bloch's $T^{3/2}$ law for the magnetization, it gives rise to a term in $T^{5/2}\cdot T^{3/2}=T^4$ which is precisely Dyson's[1] correction. Similar simple arguments yield the thermodynamic effects of spin wave interaction in ferromagnets in applied fields, in anisotropic ferromagnets, and in antiferromagnets and ferrimagnets.

The random-phase approximation (RPA) modifies the effective exchange field by a term involving the drop in magnetization and hence $T^{3/2}$. This gives rise to a $T^{3/2}\cdot T^{3/2}=T^3$ correction to Bloch's law[2]. However, at low temperatures (long wavelength spin wave region) the effective exchange coupling decreases as the average angle Φ_E between adjacent spins, not as the average angle Φ_M between each spin and the direction of bulk magnetization. As long as $\Phi_E \ll \Phi_M$ the RPA "overdoes" the spin wave interactions and is therefore incorrect. At temperatures above roughly one-half the Curie temperature, however, where Φ_E becomes comparable to Φ_M, the spin wave picture breaks down; and the RPA, inheriting the chaos, comes into its own.

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*This work was performed while the author was Visiting Professor at the University of California, Berkeley, and was supported there by the Union Carbide Corporation. Portions of the work were done in collaboration with Dr. R. Loudon.

[1]F. J. Dyson, Phys. Rev. 102, 1217 and 1230 (1956).
[2]R. Brout and H. Haken, Bull. Am. Phys. Soc. 5, 148 (1960); F. Englert, Phys. Rev. Letters 5, 102 (1960).

2. MAGNETIC ORDERING IN THE FERROMAGNETIC RARE EARTH METALS (Invited)

K. YOSIDA and H. MIWA
Institute for Solid State Physics
University of Tokyo
Tokyo, Japan

It is known that the ferromagnetic rare earth metals with a more-than-half filled 4f shell undergo a transition from the ferromagnetic state to the antiferromagnetic state with temperature. The occurrence of this type of magnetic transition could be understood on the basis of the spin wave theory, as Kasuya and Yanase, and Liu have shown. The antiferromagnetic state which appears at higher temperatures easily changes to the ferromagnetic state by an external field. This means that the energy difference between these two states is small compared with that between the ferro-state and the para-state, as is the case for the CuMn alloy. Such a situation may be possible if there are acting several kinds of exchange interaction.

Assuming a suitably chosen Fourier transform of the exchange integral a possibility of the magnetic transition of ferro- to antiferro and ferro to screw structure is investigated by comparing the free energies of the two states obtained by the spin wave approximation. In the case where the easy direction is in the c-plane, the ferro-screw transition can occur with an uniaxial anisotropy energy, but in order that the ferro-antiferro transition may take place a large anisotropy energy in the c-plane is needed. Therefore, it seems that the ferro-screw transition more likely occurs. This seems to be consistent with the recent neutron diffraction results.

The temperature variation of the pitch of the screw is calculated, and it is shown that the change of the pitch with temperatures is proportional to the thermal energy of the spin waves which shows a T^4-dependence. This result is quite similar to that for the thermal expansion of the lattice.

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3. CLASSICAL THEORY OF THE GROUND SPIN-STATE IN SPINELS (Invited)

T. A. KAPLAN, K. DWIGHT, D. LYONS, and N. MENYUK
Lincoln Laboratory*
Massachusetts Institute of Technology
Lexington, Massachusetts

An investigation of the ground state of the classical Heisenberg exchange energy in spinels has led to several new results. By means of a recent generalization of the method of Luttinger and Tisza, we have rigorously obtained the ground state in part of the exchange parameter space defined by nearest neighbor AB and BB interactions for tetragonally distorted spinels. The regions in this space where the Néel and Yafet-Kittel configurations minimize the energy are much smaller than predicted by the Yafet-Kittel theory. Outside of these regions, there exists a domain where the ground state is an antiferromagnetic spiral similar to those recently introduced in the literature. In still other regions, the ground state is a new type of spiral which is ferrimagnetic.

An investigation of a parameter region including cubic spinels shows such a ferrimagnetic spiral to yield an appreciably lower energy than that given by the Yafet-Kittel model, and the lowest energy over a much larger class of spin configurations. However, the modified Luttinger-Tisza method indicates that this ferrimagnetic spiral is not the ground state throughout this region.

*Operated with support from the U. S. Army, Navy and Air Force.

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4. NEUTRON DIFFRACTION BY HELICAL SPIN STRUCTURES (Invited)

W. C. KOEHLER
Oak Ridge National Laboratory
Oak Ridge, Tennessee

In this talk is given a brief review of the application of neutron diffraction methods to the determination of magnetic structures in solids with particular reference to the helical spin structure, and to structure types closely related to it. Illustrations drawn from results of recent investigations of manganese compounds, and of rare earth metals will be presented.

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5. MAGNETIZATION PROCESS OF A HELICAL SPIN CONFIGURATION (Invited)

U. ENZ
Philips Research Laboratories
Eindhoven, Netherlands

The behavior of a helical spin configuration of a hexagonal crystal in an applied field is discussed for the case where the axis of the helix is identical with the hexagonal c-axis and the magnetization vactor in each layer is parallel to the basal plane. In a small field applied parallel to the basal plane a slight deformation of the helix occurs resulting in a small increase in overall magnetization. If the field surpasses a certain critical value, the helix changes abruptly into a state with high resulting magnetization. In this state the spin-directions are oscillating about the direction of the applied field, the magnetization being about 85% of the saturation value. In still higher fields, saturation is reached completely. A helical spin configuration has been found in $MnAu_2$ by Herpin, Meriel and Villain. We have investigated the properties of the hexagonal oxide $(BaSr)_2Zn_2Fe_{12}O_{22}$ which is of the Y-type. The Ba-rich composition is ferrimagnetic and has a preferential plane for the magnetization at all temperatures. The Sr-rich composition has no spontaneous magnetization, but a magnetization equal to the one in the Ba-case can easily be induced by an applied field. This behaviour can be explained by the assumption of a helical spin configuration. As an other example, we show that the magnetic properties of Dysprosium as investigated by Behrendt, Legvold and Spedding can be explained by assuming a helical spin configuration between 85°K and 178°K. The angle α between two neighbouring layers is equal to zero at 78°K, the ferromag-

netic Curie temperature, and increases at higher temperatures. The magnetization process mentioned above is modified slightly in Dysprosium by the presence of a strong magnetic anisotropy in the plane. In the presence of this anisotropy the transition between the ferromagnetic state and the helical state turns out to be a first order transition, which explains the observed specific heat.

SESSION B

COMPUTER DEVICES

C. J. KRIESSMAN, Presiding

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6. THE POSSIBILITIES OF ALL-MAGNETIC LOGIC CIRCUITRY (Invited)

U. F. GIANOLA
Bell Telephone Laboratories
Murray Hill, New Jersey

As a result of the success of magnetic memory devices, considerable effort has been directed towards using similar components in the complementary logic circuitry. A number of suitable devices have been developed for combinational logic, i.e. translating and access circuits, but for sequential logic the tendency has been to use semiconductor-core circuit combinations. There are certain difficulties associated with such combinations. For example, because of the different impedance levels of the two types of components, the core must normally have multiturn windings in order to achieve maximum power transfer. In general, there is a loss of the potential economy and reliability offered by the magnetic device itself. For this reason a number of circuits based upon the use of magnetic devices exclusively have been proposed recently.

Sequential logic circuits must have provision for memory, combinational logic, unidirectionality and power gain. Memory, without the need for standby power, is made possible by the remanent character of the magnetization. Combinational logic is possible through flux steering or inhibition. Unidirectionality and power gain are made possible by the bistable nature of the remanent magnetization. Suitable devices and circuits will be examined, and the present state of their development discussed. It is concluded that feasibility has been proven, that certain approaches are practicable, but that there is a common speed-power limitation. Experimental circuits will be described.

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7. SUBMICROSECOND MAGNETIC MEMORIES (Invited)

W. LEE SHEVEL, JR.
IBM Research Center
Yorktown Heights, New York

The status of submicrosecond storage by magnetic elements is examined by respect to the speed, capacity, and cost of systems employing these elements. The factors allowing significant advances in the capabilities of magnetic storage will be discussed. Devices characterized by switching coefficients as low as .01oe-μsec allow fast switching at low excess fields. Techniques of partial switching permit nanosecond writing and reading times for core arrays as well. Load-sharing magnetic switches for easing driver requirements, diode matrices to reduce driver count, and new fast transistors and diodes allowing rapid decoding have resulted in improved associated circuits. The influence of element size on storage characteristics

will be discussed. Finally, some estimates are made of memory performance expected from new developments in the above areas throughout the computer industry.

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8. MAGNETIC FILM DEVICES USING PASSIVE LOADING*

J. M. DAUGHTON, T. A. SMAY, A. A. READ and A. V. POHM
Electrical Engineering Department and Engineering Experiment Station
Iowa State University of Science and Technology
Ames, Iowa

Computer solution of the equations developed elsewhere by Read[1] indicated that if an inductor, constructed from a uniaxial single magnetic domain thin film, were coupled to the changes of the magnetization in the easy direction through the proper RLC network, randomly spaced pulsed fields applied in the hard direction could toggle the magnetization alternately from one of its rest directions to the other. In order to verify these analytical results several magnetic film inductors were constructed. The pulsed fields were applied by passing pulses of current through a drive winding having its axis parallel to the hard direction. The changes of the magnetization in the easy direction were coupled to the RLC network by a load winding perpendicular to the drive winding. Various waveforms and the effects of varying the circuit parameters were examined experimentally and compared with the mathematical predictions. The experimental devices operated successfully with drive pulses having periods in the order of 0.1 microsecond, amplitudes greater than 5 oersteds, and recovery times of above 0.5 microsecond. Signal voltages observed across the load winding were typically several volts in amplitude.

The above analysis indicates that R-L loading on a magnetic-film inductor can be used to preserve either of the two remanent states in the presence of large pulsed transverse fields which are larger in magnitude than the anisotropy field (H_k). This loading, however, increases the switching time, or, for a digital computer memory application, the "write" time. A magnetic-film inductor was constructed with such loading and large NDRO outputs were obtained, as predicted. Pulsed transverse fields greater than 1.5 times the anisotropy field H_k were applied without destroying the stored information. With no loading the information was destroyed for transverse fields less than H_k. A technique for embodying this principle in a film memory with enhanced output signal amplitude and stability, and lending itself to total fabrication by evaporation techniques, is described.

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*This work was partially supported by the National Science Foundation.

[1] A. A. Read, "A dynamical analysis of single domain magnetic films in parametric inductors." To be presented to the Proceeding of the Institute of Radio Engineers, Inc.

9. DEMAGNETIZATION OF TWISTOR BITS

W. A. BARRETT
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

As a consequence of the open flux structure of the twistor, large demagnetizing fields act upon each magnetized region used to store a binary digit (bit). These fields establish a practical maximum bit density and modify the writing and reading characteristics of the wire. An analytical evaluation of the magnetization of a bit is difficult. Therefore, in order to provide a better understanding of the effects of the demagnetizing field, the magnetization distribution in the bit region has been measured. The magnetization was measured by means of a small search coil (one turn, 0.006" diameter) around the twistor wire. The twistor bit region was magnetized by means of short current pulses through a solenoid winding or through the twistor wire itself. The actual magnetization was measured for different locations within the bit region by moving the search coil.

In the experiments, the following procedure was used. (1) The entire wire was magnetized in one direction by means of a large wire current. (2) Coincident current reversal pulses of various amplitudes were applied to the wire and the solenoid. (3) A read current pulse was applied to the solenoid alone. (4) The magnetization was measured. In the first experiment, step (3) was omitted, to determine the shape of the bit region in the absence of disturb fields. The effects of varying the solenoid and wire currents in step (2) were determined for a particular solenoid. It was found that an increase in either tended to broaden the bit region. In the second experiment, step (3) was included. It was found that for nonzero wire current in step (2) short regions of partial magnetization remained at either end of the bit following step (3). Their presence is believed to be due to wall propagation under the influence of wire current in step (2). The implication of this result will be discussed. In particular, this experiment helps explain the difficulties encountered in applying coincident current writing techniques.

The twistor wire used in these experiments was a ribbon of rectangular-loop Mo-permalloy 0.9×10^{-6} in^2 in cross-section wrapped at 45° around a 0.003" diameter copper wire. The twistor coercive field was 4 oe. Each solenoid was 0.15" wide. Three adjacent solenoids were used, each separated from its neighbor by 0.15", in order to study the behavior of the region between bits.

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10. FLUX DISTRIBUTION IN FERRITE CORES UNDER VARIOUS MODES OF PARTIAL SWITCHING

R. H. JAMES, W. M. OVERN, and C. W. LUNDBERG
Remington Rand Univac
St. Paul, Minnesota

Two different distributions of flux are suggested by an investigation of partial switching using current pulses of amplitude insufficient to produce saturation (amplitude limiting) and by current pulses of sufficient amplitude to produce saturation but of insufficient duration (time limiting).

The distribution of flux under amplitude limiting is determined by the inverse relationship of the field to the radius[1]. This is demonstrated by sensing different areas of a core in a radial direction. It was found that with amplitude limiting the inside of the core can be switched to saturation while the outside of the core is switched very little.

The flux switched under time-limited conditions is distributed throughout the core[1]. This is also demonstrated by again sensing different areas of the core in a radial direction. Here it was found that while there was slightly more flux switched in the inside area a considerable amount of switching also takes place at the outer edge of the core.

Experiments described in this paper have generated additional evidence that a ferrite core does not have the same flux distribution when it has been switched by different methods to states possessing the same value of residual induction. Three methods were used to reach the same flux density: (1) by amplitude limiting, (2) by time limiting, and (3) by applying a fixed pattern of alternate polarity pulses with diminishing amplitude. From this point a characteristic curve, similar to a normal magnetization curve was taken in each case. The difference between the three curves are discussed. In the third case as the number of pulses in the pattern increases, the curve approached that of the time limited case. The shapes of the curves in the third case indicate that there are concentric rings of alternately directed flux. It also appears that there are domains of closure formed in between the areas of oppositely directed flux, because it is more difficult to reach saturation from both the time limited and the alternately directed flux states.

It is postulated from an analysis of the curves taken that the flux distribution with time-limiting consists of a very large number of alternately directed areas of flux with domains of closure in between these areas, while with amplitude limiting only two oppositely directed areas of flux have been observed.

[1]R. H. Tancrell and R. E. McMahon, J. Appl. Phys. 31, 762, (1960)

11. IMPULSE SELECTION FOR CORE LOGIC

ROGER H. TANCRELL
Lincoln Laboratory*
Massachusetts Institute of Technology
Cambridge, Massachusetts

In order to perform logic functions in digital computers with magnetic elements several factors are required. Among these requirements is a threshold property which the magnetic element must have in order to allow selectivity of elements in a system. Another consideration requires 'flux gain' which is necessary in order to overcome losses which occur between elements and also to allow 'fan-out'. And still a further requirement is that the direction of information flow must be controlled.

A new magnetic phenomenon on low coercive force ferrite cores has been observed which shows promise of meeting these requirements for logic. Basically this magnetic property utilizes two thresholds of the magnetic material. One of the thresholds is time dependent, being a function of the width of an applied current pulse. The other threshold is related to the d. c. coercive force of the saturated core. This coercive force can be changed electrically. With these properties, circuit possibilities can be achieved which in previous magnetic devices were performed by means of turns ratios on cores or by geometry configurations.

Selection of a core is achieved by applying to the core an impulse of high current which lowers its coercive force. A low amplitude current, which is otherwise below the d. c. coercive force, can then continue the switching process. In a logic scheme, the switching output of one core can be used directly to supply the current pulse to initiate switching in a receiver core. Most of the energy required to switch the receiver is supplied by a low amplitude current from an external generator. By this means 'flux gain' is achieved. Control of the information flow can be obtained by connecting cores in the proper configuration with single turn windings.

*Operated with support from the U.S. Army, Navy, and Air Force.

12. 50 MC AC DRIVE AND PARTIAL SWITCHING TECHNIQUES

ROBERT E. McMAHON
Lincoln Laboratory M.I.T.
Lexington, Mass.

The application of a high frequency (5-50 MC) sine wave drive to ferrite cores combined with partial switching (impulse switching) provides information concerning wall area characteristics during the switching process and leads to useful memory and logic methods.

The AC drive based on the experiment of J. J. Becker[1] develops an AC output voltage that is proportional to the existing wall area at any time during switching. By partially switching the ferrite cores various conditions of flux reversal are achieved that in effect allow a continuous observation of the AC modulation for these various states.

From this technique it is possible to obtain information about wall mass, threshold field Ho, an apparent coercivity for domains at inclusions and other related characteristics.

Although the paper will emphasize the information obtained concerning the magnetic properties and characteristics of ferrites, a brief discussion of the application of the AC and partial switching to 1) a 50 MC non distructive readout, 1 μs cycle time memory, 2) a fixed memory, and an analogue learning type memory will be included.

[1]J. J. Becker, Journal Appl. Phys. 30, 387 (1959)

13. RECORDING AND REPRODUCTION OF NRZI SIGNALS

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The method of NRZI recording and reproduction, a process widely used in computer tape systems, is described, as completely as possible theoretically, within this report. The dependence of tape magnetization and of output signal pulse width and magnitude on the major system parameters has been investigated and determined. These parameters are the magnetic field distribution of the recording head, write current rise time and magnitude, tape thickness and hysteresis characteristics, head to tape spacing, head gap length and bit density.

The investigation into the non-linear recording process is centered about the magnetization transition in the storage layer and the influence of the applicable system parameters on this transition. The nature of this sudden change in magnetization is significant since it is the critical factor determining the output signal pulse width. Results from this study show the importance of using high head field gradients, high tape hysteresis squareness, and thin tape thicknesses to reduce the magnetic transition in the tape, thereby decreasing the signal pulse width and effects of recording demagnetization. They also show the transition to be relatively insensitive to write current rise time and magnitude changes, at least within the range used here. This method is now being extended so that the recording process can be simulated by an IBM 704 Computer. Any combination of write current, recording head or tape hysteresis characteristics can be accounted for in this program.

NRZI reproduction is a non-sinusoidal process. However, under the assumption of linearity, this process is described by the method of harmonic analysis. The magnetization is represented by a Fourier series and the output signal is computed for each harmonic. The sum of these terms is the resultant output for NRZI magnetization. The results of computations using two tape magnetization functions, one a simple trapezoidal function, and the other, a function representing the calculated magnetization actually in tape, are given along with the results of experimental data. These results show how the signal output pulse width and magnitude depend on gap length, tape thickness, head to tape spacing and bit density. In addition, the field distribution above the magnetized tape, showing the influence of the presence of the reproducing head, is included.

Although periodic write current functions are used in this report, the methods developed herein can be used for arbitrary input current waveforms for studying the recording and reproduction of coded information.

14. PREPARATION AND PROPERTIES OF THIN FERRITE FILMS*

E. BANKS, N. H. RIEDERMAN, H. W. SCHLEUNING, and L. M. SILBER
Polytechnic Institute of Brooklyn

Thin films of ferrites, of the order of 1000 Angstroms thickness, have been prepared by vacuum evaporation of the metals, and subsequent high temperature oxidation. Films of iron, nickel, cobalt, magnesium, and copper ferrites, mixed ferrittes and mixed ferrite-aluminates, as well as yttrium iron garnet, have been prepared. X-ray powder diffractometry indicates that the ferrite films are single phase spinels, while the garnet shows the garnet structure.

In many respects, the properties of the films are the same as those of bulk ferrites of similar composition. The resistivity of the films can be controlled by proper oxidizing procedures. X-band magnetic resonance measurements indicate that the saturation magnetizations of the films are comparable to those of the corresponding bulk ferrites, though the films show larger resonance linewidths. It has been possible to prepare magnesium ferrite films with magnetizations from 2200 gauss to less than 500 gauss by proper annealing and quenching. The possible advantages of thin films are that they allow optical studies of the material by transmission, and should permit determination of magnetic exchange constants through observation of spin wave resonance.

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*This research was supported by the U.S. Army, Signal Corps Engineering Lab under contract DA 36 039sc78107

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15. FERRITE THIN FILMS

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Thin films of ferrites of various compositions have been prepared. Two methods have been developed, both involving a spray technique using hot suspensions of hydroxides directed onto a heated substrate. The ferrite films are formed essentially through a coprecipitation mechanism. The films have been identified as having a cubic spinel structure by x-ray diffraction. Various compositions have been attained - magnetite, nickel ferrite, a magnetite-zinc ferrite series, and other mixed ferrites.

Hysteresis loops for the films were obtained on a 1000 cycle loop tracer and indicate a high squareness ratio. The films as prepared are magnetically isotropic.

Film thicknesses can be varied from a few hundred angstroms to about 1 micron. Thicknesses of some films were measured by interferometry and are compared to relative thicknesses estimated using a spectrophotometric technique. Coercive force measurements are related to thickness in a set of nickel ferrite films and to composition variations in a series of films of differing composition in magnetite-zinc ferrite series.

SESSION C

SPIN CONFIGURATIONS

J. B. GOODENOUGH, Presiding

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16. NEUTRON DIFFRACTION INVESTIGATION OF MAGNETIC ORDERING IN DYSPROSIUM

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Neutron diffraction experiments have been performed on single crystals of dysprosium in an attempt to understand the nature of the magnetic ordering that occurs in this metal at low temperatures. Previous magnetic measurements[1] have shown that dysprosium has two magnetic ordering transitions: at 179°K, there is a transition from the paramagnetic state to an antiferromagnetic arrangement of the moments, while at 85°K, there is a transition from antiferromagnetism to ferromagnetism.

The neutron diffraction results indicate that the magnetic structure in the antiferromagnetic region is a helical-type arrangement of the moments similar to that observed in holmium.[2] In this arrangement, the moments within a hexagonal layer are aligned parallel with the moment direction perpendicular to the c-axis of the crystal. However, between adjacent layers the moment direction within the layer changes by a specific angle, and the value of this angle is dependent on the temperature of the sample. At the ferromagnetic transition there appears to be a sudden change from this helical-type structure to the normal type of ferromagnet, and the moment direction remains perpendicular to the c-axis.

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[1] Behrendt, Legvold, and Spedding, Phys. Rev. **109**, 1544 (1958).

[2] Koehler, Wollan, Wilkinson, and Cable, Proceedings of Neutron Diffraction Conference, April, 1960.

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17. A NEUTRON DIFFRACTION STUDY OF METALLIC ERBIUM

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Neutron diffraction measurements were made on erbium single crystals in the temperature range from 298° to 4.2°K. The material is antiferromagnetic below 80° K and ferromagnetic below 20°K. In the antiferromagnetic region the magnetic scattering consists of satellite reflections corresponding to a modulation of the magnetic scattering amplitude along the c-axis. The spacing and intensity distribution of these satellites show two distinct sub-regions of antiferromagnetism. In the upper region, between 80° and 53.5°K, the data suggest a sinusoidal modulation of the magnitude of the c-axis component of magnetic moment with a period of 3.5 c_o. Between 53.5° and 20°K the wavelength of the modulation varies continuously from 3.5 c_o to 4.0 c_o. In addition there is a squaring up of the modulation and a simultaneous ordering of the component of the moment normal to the c-axis. Below 20° K the material is basically ferromagnetic with a moment of 7.3 μ_B directed parallel to the c-axis.

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18. ANTIFERROMAGNETIC DOMAINS IN α-MANGANESE AND ITS ALLOYS

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Under certain conditions it has been shown that hysteresis appears below 50°K in the magnetic isotherms of α-Mn.[1] The coercive forces attain the order of kilooersteds. This is also observed for alloys of Mn with Fe and Cr prepared in the α-phase. Field cooling can give a permanent magnetic moment which may or may not be accompanied by hysteresis. An interpretion in terms of domains is possible. The driving force for domain formation can arise from disorder as a result of alloying or from imperfections induced by preparation. It is also noted that the powder pattern neutron diffraction results of Kasper and Roberts[2] can be reinterpreted as giving evidence for spin arrangements with a periodicity incommensurate with the lattice periodicity. This incommensurateness could also lead to domain formation in the way described by Overhauser[3] in discussing Cu-Mn and Cr.

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[1] Arrott, Coles, and Goldman, Phys. Rev. 98 1864 (1955) Cooper, Arrott, and Paxton, Bull. Am. Phys. Soc. 2 117 (1957)

[2] J. S. Kasper and B. W. Roberts, Phys. Rev. 101 537 (1956)

[3] A. W. Overhauser, Jour. Phys. Chem. Solids 13 71 (1960); also to be published; A. W. Overhauser and A. Arrott, Phys. Rev. Letters 4 226 (1960)

*Permanent address: Imperial College of Science and Technology, London, United Kingdom

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19. REMARKS ON THE MAGNETIC PROPERTIES OF Au-Mn SYSTEM

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Au-Mn alloys show magnetic behavior which depends upon the various types of superlattice existing in this system. The analysis of magnetic properties of these compounds revealed the possibility that the magnetic dipole interaction is responsible for the cooperative spin alignment in some compounds of the system. For example, in both Au_4Mn and Au_2Mn, the Mn atoms form body-centered tetragonal lattice with c/a ratio of 0.62 and 2.60 respectively. Although the first- and second-neighbor distance between Mn atoms for these two compounds are practically the same, the former is ferromagnetic but the latter is

antiferromagnetic (metamagnetic). The first-neighbor distance corresponds to the ferromagnetic interaction range of Mn atoms, but geometrically this alone cannot cause any cooperative alignment of spins. The second-neighbor distance, on the other hand, is too long to expect any appreciable interaction. It is questionable, on the above grounds, to adopt a conventional model to describe the screw type spin structure of Au_2Mn by competing localized exchange interactions. However, it is proved that the existence of a minor interaction between the second neighbors is sufficient to produce the expected cooperative phenomena. The magnitude of such an interaction is found to be of the same order as the magnetic dipole interaction. Furthermore, such magnetic dipole interactions can explain the difference of the magnetic behavior of Au_2Mn and Au_4Mn.

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20. EXCHANGE INVERSION IN $Mn_{2-x}Cr_xSb$

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The first example of a ferrimagnetic to antiferromagnetic first order phase transition with decreasing temperature has been found in $Mn_{2-x}Cr_xSb$ for $0.02 \leq x \leq 0.2$[1]. These compounds exhibit normal Curie point behavior with a Curie temperature only slightly lower than Mn_2Sb. The magnetization increases with decreasing temperature in a manner similar to Mn_2Sb but at a critical temperature decreases to zero over about a 10° interval. The temperature T_S at which this transition takes place increases with increasing chromium content. The tetragonal crystal structure of this material is the same as that of Mn_2Sb and does not change on passing through the phase transition. Neutron diffraction studies[2] have shown that for $T > T_S$ the magnetic structure is the ferrimagnetic structure of Mn_2Sb[3], but for $T < T_S$ both the Mn(I) and the Mn(II) sublattices are antiferromagnetically ordered along the tetragonal axis. The three adjacent Mn(II)-Mn(I)-Mn(II) layers remain ferrimagnetically ordered at all temperatures. Above T_S, this set of three atomic layers is ferromagnetically coupled to adjacent sets, but below T_S, it is antiferromagnetically coupled to adjacent sets. Kittel[4] has proposed recently that ferromagnetic-antiferromagnetic transitions can arise if the sign of the molecular fields is dependent on a critical lattice dimension. This theory suggests there should be a discontinuous change in lattice dimension at T_S and that the magnitude of this change should increase as the square of the sublattice magnetization. These conclusions are in agreement with our observations. A ferromagnetic to antiferromagnetic transition with increasing temperature has been suggested to explain the magnetic behavior of MnAs[5] and dysprosium[6], but in these cases the antiferromagnetic ordering has not been established.

[1] T. J. Swoboda, W. H. Cloud, T. A. Bither, M. S. Sadler, H. S. Jarrett, Phys. Rev. Letters 4, 509 (1960).
[2] W. H. Cloud, H. S. Jarrett, A. E. Austin, E. Adelson - submitted to Phys. Rev. Letters.
[3] M. K. Wilkinson, N. S. Gingrich, C. G. Shull, J. Phys. Chem. Solids 2, 289 (1957).
[4] C. Kittel, Phys. Rev. - to be published.
[5] D. S. Rodbell, P. E. Lawrence, J. Appl. Phys. 31, 275S (1960).
[6] D. R. Behrendt, S. Legvold, F. H. Spedding, Phys. Rev. 109, 1544 (1958).

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21. ELECTRICAL RESISTIVITY AND MAGNETIC ANISOTROPY IN EXCHANGE INVERSION COMPOUNDS

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Exchange inversion compounds[1] are excellent systems for study of spin interactions, since they provide a crystal lattice in which both structure and composition are very nearly preserved while enabling either ferrimagnetic or antiferromagnetic spin ordering to be obtained. Measurements of the electrical resistivity of Mn_2Sb have been extended over a wider temperature range than first reported by Guillaud[2]. In agreement with this work we find a monotonically decreasing resistivity with temperature and no unusual change either at the Curie point or at -27°C., the temperature at which the magnetocrystalline anisotropy changes sign, although there is a change by a factor of 2 in the slope of the resistivity at this temperature. Exchange inversion compounds exhibit the same resistivity as Mn_2Sb above the ferrimagnetic/antiferromagnetic (F/AF) transition temperature T_S, but at T_S the resistivity rises sharply to a higher value and decreases with decreasing temperature at about the same rate. The sharp rise in electrical resistivity at the F/AF transition suggests that s-d exchange contributes strongly to the resistivity either through spin wave scattering or by altering the energy distribution of conduction electrons.

Lack of any abrupt change in resistivity of Mn_2Sb when the anisotropy changes sign indicates that the magnetic scattering centers must be nearly symmetrical. Such a situation could occur if the two types of manganese possessed half-filled shells, for example, a half-filled d shell of Mn^{+2} and a half-filled $d\epsilon$ shell of $Mn^0(3d^7)$ in a strong crystal field. This assignment of spin moments is in agreement with susceptibility data[3] but at variance with neutron diffraction results[4]. The axial magnetrocrystalline anisotropy is expected therefore to arise from dipole-dipole interaction, but explicit calculation of the dipole contribution is not in agreement with measurements, indicating other mechanisms are operative. The magnetocrystalline anisotropy of the exchange inversion compounds exhibits a temperature dependence similar to Mn_2Sb, but the temperature at which the anisotropy changes sign decreases with increasing chromium content.

[1] T. J. Swoboda, W. H. Cloud, T. A. Bither, M. S. Sadler, H. S. Jarrett, Phys. Rev. Letters 4, 509 (1960).
[2] C. Guillaud, R. Bertand, Comp. Rend. 221, 493 (1945).
[3] A. Serres, J. Phys. Rad. (8) 8, 146 (1947).
[4] M. K. Wilkinson, N. S. Gingrich, C. G. Shull, J. Phys. Chem. Solids 2, 289 (1957).

22. TRIANGULAR MOMENT ARRANGEMENTS IN MANGANESE SPINELS

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Low temperature magnetization measurements at pulsed fields of 75 kilo-oersted for selected single crystal members of the spinel series $Mn_xFe_{3-x}O_4$ are discussed in terms of Yafet-Kittel-Lotgering triangular moment arrangements. For $x < 1$, it was found that, within experimental error, no high field susceptibility exists. For $1 \leq x \leq 3$, high field susceptibilities ranging from 1.0×10^{-4} to 3.3×4^{-4} gauss/oersted were observed. The results for $MnFe_2O_4$ and for Mn_3O_4 are in essential agreement with previously reported polycrystalline measurements[1,2]. For Mn_3O_4, the magnetization curves at 4.2°K depend upon orientation. Extrapolation of these curves results in an anisotropy field of approximately 150 kilo-oersted.

The anomalously low spontaneous magnetization and the observed high field susceptibility values for $1 \leq x \leq 3$ are best explained by a noncollinear moment arrangement in which the B lattice moments are subdivided into two groups. The angles between the B lattice moments are determined from assumed ionic distributions and observed magnetic moments at 4.2°K. From these values and the high field susceptibility measurements, values of n (the AB Weiss constant) and of β (the ratio of the BB to the AB Weiss constants) are calculated. In addition, Curie temperature measurements are used to obtain estimates of values of α (ratio of the AA to the AB Weiss constants). $\alpha\ \beta$ diagrams which qualitatively explain observed anomalies in magnetization vs. temperature curves are constructed. From the $\alpha\ \beta$ diagram for Mn_3O_4 it is expected that the vanishing of the spontaneous magnetization at 43° K represents a transition from a triangular moment arrangement to one in which the A lattice is paramagnetic and the B lattice is antiferromagnetic. Torque measurements on Mn_3O_4 crystals, grown in this laboratory, provide evidence for the existence of this antiferromagnetic state. At 77°K, a uniaxial torque is observed which is proportional to the square of the applied field. The amplitude of this torque decreases rapidly with increasing temperature and vanishes in the neighborhood of 100°K.

[1] I. S. Jacobs, J. Phys. Chem. Solids, II 1, (1959).
[2] I. S. Jacobs, J. Phys. Chem. Solids, (to be published).

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23. SPIN-FLOPPING IN MnF_2 BY HIGH MAGNETIC FIELDS*

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Néel, in 1936, predicted the magnetic field conditions under which an antiferromagnet would show a rather abrupt decoupling between the direction of antiferromagnetism and the easy axis of the crystal. He later extended this to metamagnetic behavior in which an antiferromagnet rather abruptly transforms to a ferromagnet. Interest in both phenomena has been considerable, especially when the interaction energies can be reconciled with theoretical treatment on an atomic level. At temperatures well below the Néel point, the critical magnetic field for the decoupling of axes if approximately given by $(2H_EH_A)^{1/2}$, where H_E is the Weiss exchange field and H_A is the effective anisotropy field. The several previous observations of this effect have been confined either to antiferromagnets with rather low Néel temperatures, or to those with low anisotropy energies such that the decoupling is tantamount to a domain rotation. This paper reports the observation in MnF_2 of the decoupling of axes or "spin-flopping" at 4.2°K and 20°K by measurements of magnetization along the c-axis of a single crystal** in pulsed fields to 140 koe. The critical field for decoupling is found to be 92 ± 2 koe. This is in good agreement with the values found by microwave resonance in the work of Foner and of Johnson and Nethercot. This example demonstrates that magnetization measurements in high magnetic fields can be used as an alternative tool to explore the critical interaction energies in antiferromagnets.

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*This work was supported by Wright Air Development Division, Air Research and Development Command, U.S.A.F.
**The crystal was made available through the courtesy of Dr. J. W. Nielsen of the Bell Telephone Laboratories.

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24. ANTIFERROMAGNETIC RESONANCE IN $(Cr_2O_3)_{1-x} \cdot (Al_2O_3)_x$ SINGLE CRYSTALS

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Pulsed magnetic fields and 36 and 70 kMcps radiation were employed previously for observations of antiferromagnetic resonance (AFMR) in Cr_2O_3.[1,2,3] The results were unusual in two respects: 1) the quantity $(2\lambda K)^{1/2}$, where λ is the exchange constant and K is the anisotropy energy, was found to be almost independent of temperature[4] from T = 4.2 to $\approx$ 200°K, and 2) the AFMR line width was also constant over a wide range of temperature.[5] The magnitude and temperature dependence of $(2\lambda K)^{1/2}$ could be explained if one assumed that the crystalline field contribution to K was opposite in sign to that of the dipolar contribution, but then this crystalline field contribution was about 1/10 of that observed for dilute Cr^{3+} in Al_2O_3 and of opposite sign. Preliminary experiments[3] with single crystals of $(Cr_2O_3)_{0.9}(Al_2O_3)_{0.1}$ showed an increase of $(2\lambda K)_c^{1/2}$ to about 80 kilogauss from the Cr_2O_3 value of $(2\lambda K)_0^{1/2}$ of about 60 kilogauss.[6] In order to examine this variation of $(2\lambda K)^{1/2}$ we have studied AFMR in crystals of $(Cr_2O_3)_{1-x} \cdot (Al_2O_3)_x$ with x - 0.006, 0.008, 0.06, 0.1 and 0.9 to date.[7] Although the detailed results are best described by graphical means, the general features can briefly be summarized as follows: 1) $(2\lambda K)_0^{1/2}$ is about 80 kilogauss for both x = 0.06 and x = 0.1 thus indicating a very marked change of $(2\lambda K)_0^{1/2}$ for only small changes in x; the Néel temperature decreases rapidly with increasing x; 3) the crystalline field contribution to K, calculated assuming reasonable changes of λ and the dipolar anisotropy, reverses in sign between

x = 0.008 and x = 0.06; 4) for x = 0.06 and x = 0.1, the temperature dependence of $(2\lambda K)^{1/2}$ approximates a modified Brillouin function for S = 3/2, in agreement with the above interpretation of a reversal in sign of the crystalline field contribution to K. The detailed dependence of the AFMR as a function of frequency, temperature, field, and x, and some limitations of this method of measuring the crystalline field in concentrated spin systems will be discussed. The possibility of inhomogeneous line broadening caused by crystalline field variations in Cr_2O_3 will also be discussed and compared with line width measurements as a function of impurity concentrations.

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*Operated with support from the U.S. Army, Navy, and Air Force.

[1] S. Foner, Bull. Am. Phys. Soc. Ser. II, 3, 193 (1958).

[2] Foner, Jour. Phys. et le Rad. 20, 336 (1959).

[3] S. Foner, Bull. Am. Phys. Soc. Ser. II, 4, 142 (1959).

[4] The Néel point is approximately 308°K for Cr_2O_3.

[5] Similar results have been obtained by G. S. Heller and J. J. Stickler with 2 mm wavelength experiments - private communication.

[6] The value of $(2\lambda K)^{1/2}$ extrapolated to T = O°K is given by $(2\lambda K)_0^{1/2}$.

[7] These crystals were grown at Rutgers University, Dept. of Ceramics, New Brunswick, N.J., under a subcontract with Lincoln Laboratory.

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25. INFRARED ANTIFERROMAGNETIC RESONANCE IN MnO*

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Antiferromagnetic resonance has been observed in powdered MnO at 364 microns at 1.5° K. The resonance frequency at higher temperatures falls roughly as the square-root of the Brillouin function of spin 5/2. Fields of the order of 10^4 oersteds have no observable effect on the line at 1.5°K. All of these results give quantitative confirmation of a model in which the sublattice magnetizations are constrained to a [111] plane by magnetic dipolar interactions and are held to a preferred direction within the plane by a much weaker anisotropy.[1] In MnO the [111] axis is thus the hard direction. Simple macroscopic theory shows that this type of anisotropy decreases with temperature as the first power of the magnetization, thereby accounting for the temperature dependence of the resonance. In this resonance mode there exists no net magnetic moment, and therefore external fields can shift the resonance frequency only by small displacements quadratic in the field strength.

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*Supported in part by the A. P. Sloan Foundation, the National Science Foundation, the Office of Naval Research, and the National Carbon Research Laboratories.

**On leave from the University of Pittsburgh.

[1] F. Keffer and W. O'Sullivan, Phys. Rev. 108, 637 (1957).

26. THE MAGNETIC SUSCEPTABILITY OF $FeCl_2 \cdot 4H_2O$ AT LOW TEMPERATURES*

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The magnetic susceptibility of $FeCl_2 \cdot 4H_2O$ has been measured in the liquid helium and hydrogen ranges by an a.d. mutual inductance method. Between 14° and 20° K the molar powder susceptibility is described by the Curie-Weiss law $\chi_p = 3.4/(T + 2.0)$. The Curie constant found here is the same as that observed above 90° K by Ishiwara. At 1.6° K, χ_p exhibits a maximum apparently associated with a paramagnetic-antiferromagnetic transition. This transition will be compared with the one occurring in $MnCl_2 \cdot 4H_2O$ at very nearly the same temperature, as well as with those found in $NiCl_2 \cdot 6H_2O$ and $CoCl_2 \cdot 6H_2O$ at somewhat higher temperatures. As in the two latter substances, each metal ion in $FeCl_2 \cdot 4H_2O$ is octahedrally coordinated with four water molecules and two Cl^- ions which are situated at opposite vertices of the octahedron. Single crystal measurements are in progress and will be described.

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*Work supported by the Office of Naval Research, the National Science Foundation, and the Alfred P. Sloan Foundation.

27. THE STRUCTURE OF NICKEL CHROMITE

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Nickel chromite is a normal spinel whose structure has a tetragonal distortion below about 30°C. The structure parameters have been determined by neutron diffraction at 77°K, at which temperature the c/a ratio of a face-centered unit cell is 1.04. The space group is $I4_1/amd$ with four Ni ions in positions 4 (a), eight Cr ions in positions 8 (d), and sixteen oxygen ions in positions 16 (b) with x = .261, z = .142. The two independent Cr-O distances are 1.98 Å and 1.99 Å, indicating that the octahedron is not greatly distorted. The tetrahedron around the nickel is elongated by nearly 14% parallel to the C axis. Below a Curie temperature of about 65°K nickel chromite has a small ferromagnetic moment. The neutron diffraction pattern at 4.2°K shows extra peaks which can be indexed on the basis of a primitive cell having the same dimensions as the body-centered chemical cell. The intensities of these peaks cannot be accounted for by any simple model for the magnetic structure. In fact a systematic search of possible structures belonging to magnetic space groups with symmetries as low as classes m' m' 2 and m m' 2' has failed to turn up any structure which is consistent with the diffraction data.

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*Portions of this work were done at Brookhaven National Laboratory while the author was a member of the technical staff of Bell Telephone Laboratories, Inc.

SESSION D

METALLIC FILMS

A. H. ESCHENFELDER, Presiding

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28. ANISOTROPY IN IRON-NICKEL FILMS (Invited)

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Anisotropy is induced in vacuum-evaporated iron-nickel polycrystalline films if the depositing vapor is incident at an oblique angle to the substrate normal; in the case of normal incidence, anisotropy is induced by the magnetization M itself, the direction of which can be controlled by an external field applied during deposition. These anisotropies are designated as oblique-incidence and M-induced, respectively. Oblique-incidence anisotropy is caused by a geometric process of "self-shadowing" which causes chains of crystallites to form perpendicularly to the incident beam. These chains are in tensile strain ($\sim 10^{-3}$ for 200°C substrate) along their long axes as the result of the opposing demands of surface tension, which would be lowered by the chains contracting into a sphere, and bonds to the substrate, which try to keep the chains extended. The observed magnetic anisotropy is due to the combined effects of chain-shape anisotropy and magnetoelastic coupling to the strain. Annealing can increase the strain by an order of magnitude (to several percent) as further evolution toward spherical shape takes place; in favorable cases four-fold magnetic anisotropy is observed due to higher-order magnetoelastic effects becoming important at such large strain. Isotropic tensile strain will be generated in normal-incidence films by similar action of surface tension between randomly located crystallites; for compositions with negative magnetostriction this results in "mottled films" possessing a unique set of properties.

A remarkable feature of normal-incidence M-induced anisotropy is the presence of regions of negative anisotropy in a film of predominately positive anisotropy, i.e., certain regions have their easy axis perpendicular to the field applied during deposition. The existence of negative-anisotropy regions is established by Bitter-pattern studies of the remanent state after hard-axis saturation; localized 90° domains appear and are assumed to be associated with individual negative-anisotropy regions. Simple qualitative models to explain the following effects follow directly from the presence of negative-anisotropy regions: 1) locking in inverted films, 2) intermediate-speed switching, and 3) anomalous internal fields observed in resonance experiments. As a function of composition, the M-induced anisotropy is found to have a minimum at about 90 percent nickel.

A strain-pair model for M-induced anisotropy postulates a slight crystallite elongation in the direction of M during deposition. Surface tension will cause such an elongated crystallite to be in compression along the long axis; consequently, if the magnetostriction is positive, the anisotropy will be negative, and conversely. The effective shape anisotropy is assumed to be small due to surface-pole interaction between closely packed crystallites. A positive contribution to the anisotropy is assumed to arise from directed pairs of iron atoms. By combining the effects of strain and pairs the observed compositional dependence of the average anisotropy and the negative-anisotropy regions can be qualitatively explained. A specific mechanism for crystallite elongation is suggested, based on the assumption of anisotropic diffusion which depends on the direction of M and the fact that the surface energy of crystals is anisotropic. Direct support for anisotropic diffusion comes from experimental results regarding the dependence of oblique-incidence chains on the orientation of M during deposition.

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*Operated with support from the U.S. Army, Navy, and Air Force.

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29. EPITAXIAL GROWTH AND MAGNETIC ANISOTROPY OF SINGLE CRYSTAL FILMS OF IRON, NICKEL, AND PERMALLOY

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A number of single crystal films have been made epitaxially by vapor deposition onto (001) surfaces of NaCl and MgO crystals. The substrate is normally annealed for about one hour at 500° C before cooling to the temperature at which the film is evaporated. The orientation of crystallites is almost perfect for Ni on NaCl, Ni on MgO, Fe on MgO, and permalloy on NaCl when the substrate is held above some critical temperature during the deposition. In contrast, the orientation of Fe films on NaCl is poor over the entire temperature range from 20° C to 500°C. An automatic recording torque balance is used to measure the crystalline anisotropy in the plane of the film and also the perpendicular anisotropy (a uniaxial anisotropy measured by rotating the magnetization out of the plane of the film). By using the value of thickness obtained from the later measurement the crystalline anisotropy energy per unit volume can be determined exactly.

The fourth order anisotropy constant K_1 is found to be anomalously large for Ni films on NaCl and on MgO, and the temperature dependence of K_1 is found to be reversible from 20° C to -196° C. After removal of the film from the substrate, the anomaly in K_1 disappears. If the large value of K_1 is assumed to originate in epitaxial tension in the film, the tension is calculated to be 15 kg/mm^2 by using the h_4 term in the magnetostriction equation. No anomaly is observed for Fe on MgO, where the [110] direction of iron is always parallel to the [100] direction of NaCl, yielding a lattice misfit of only 5%.

The value of the perpendicular anisotropy for Ni on NaCl is also anomalously large and dropped to the normal value after removal from the substrate. The stress required to explain the large perpendicular anisotropy is an order of magnitude larger than, and of the opposite sign from that used to explain the anomalous value of crystalline anisotropy.

Magnetic annealing permalloy films has been found to induce uniaxial anisotropies of the same order of magnitude as in similar bulk samples. Magnetic annealing of pure Ni

films results in changes in the residual uniaxial anisotropy but the direction of these changes appears to be independent of field direction during annealing.

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30. MAGNETIC ANISOTROPIES OF Ni FILMS EVAPORATED AND MEASURED AT 10^{-8} mm Hg AND BELOW

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Thin films of Ni, about 700A thick, have been vapor deposited on glass substrates at normal incidence at room temperature in vacua of about 5×10^{-9} mm Hg, and their magnetic properties measured with a torque magnetometer in the vacuum system.

At fields below about 50 oe, the films show a $\sin \theta$ torque curve with the magnitude of the peak torque proportional to field. In this range, the films behave like permanent magnetic dipoles. From 50 to about 500 oe, the torque curve is irregular in form, and the rotational hysteresis is large. Above about 500 oe, the torque is very nearly $\sin 2\theta$ and is independent of field. The magnitude of the uniaxial anisotropy is about 2000 ergs/cc. The direction of the remanent magnetization of the films may be changed at will by saturating the film in a high field; the uniaxial anisotropy measured at high fields is not reflected in the properties measured in low fields.

The films show magnetic annealing at room temperature, i.e., a film placed in a saturating field at room temperature gradually forgets its original anisotropy and acquires a new anisotropy parallel to the applied field. The time dependence of the anisotropy is given by exp. $(-bt^{1/3})$ at room temperature.

Exposing the films to air causes only slight changes in the magnetic properties.

One single crystal Ni film has been prepared by sublimation onto a rock salt crystal. Normal magnetic annealing effects were not present in this case.

31. ANNEALING OF OBLIQUE-INCIDENCE PERMALLOY FILMS

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The anisotropy of oblique-incidence Permalloy films made at a substrate temperature of 200°C has been studied after anneal for several hours at 300°C. Before the anneal the usual twofold magnetic axis with the easy direction perpendicular to the incident depositing beam is present.[1] After anneal films with positive magnetostriction have the same general magnetic symmetry, while those with negative magnetostriction may have either twofold or fourfold anisotropy but with the original easy direction now a hard direction. Application of a large magnetic field in any direction during anneal does not influence the final magnetic anisotropy. Electron diffraction shows no crystallographic texture before or after anneal.

The anisotropy was measured by means of ferromagnetic resonance. A coaxial bridge permits measurement over the frequency range 50 Mc to 2100 Mc. The film is placed in a rectangular coaxial cavity which can be heated up to 500° C in a vacuum of 10^{-6} mm Hg; continuous angular orientation of the film is possible with a resolution of ±0.5°. Bridge balance is good enough to permit samples of less than 500 Å thickness to be measured.

[1] D. O. Smith, M. S. Cohen, G. P. Weiss, J. Appl. Phys. (October, 1960).

*Operated with support from the U.S. Army, Navy, and Air Force.

32. PERMALLOY FILMS EVAPORATED AT GRAZING INCIDENCE

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The results of an investigation of oblique-incidence evaporated Permalloy films have been reported previously.[1] This investigation showed that "chains" of crystallites form in the film perpendicular to the direction of the vapor beam because of a "self-shadowing" effect. The geometric anisotropy of these chains causes the films to be dichroic with the axis of greatest optical absorption parallel to the chains; the magnetic easy axis is also parallel to the chains because of the geometric anisotropy. Most of these films were made at incidence angles which were less than about 60°. The present study showed new effects for angles greater than 65°: Electron micrographs demonstrate that the crystallites become elongated in the direction of the vapor-beam for such high angles, although the chains are still present. The cause of this elongation is simply a geometric phenomenon; At very high incidence angles the vapor deposits more rapidly on the front face of a crystallite than on its top; the effect becomes more pronounced as the incidence angle increases. For angles greater than about 75° the axis of greatest optical absorption is parallel to the vapor beam, i.e. the crystallite shape anisotropy outweighs the anisotropy due to chains. Anomalous magnetic characteristics are also observed for such films.

[1] D. O. Smith, M. S. Cohen, G. P. Weiss, J. Appl. Phys. 31, October, 1960.

*Operated with support from the U.S. Army, Navy, and Air Force.

33. TEMPERATURE DEFENDENCE OF MAGNETIC PROPERTIES OF THIN PERMALLOY FILMS

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Thin films of permalloy (≈80% Ni-Fe) were evaporated in a vacuum of 10^{-5} mm Hg on to heated substrates in a d.c. magnetic field. After the evaporation, the films were put into a bakable vacuum annealing apparatus. The films were heated by irradiation of a projection lamp from outside of the vacuum. During the heating, the BH loop could be measured in all directions in the plane of the film by means of a very sensitive 1000 cps BH loop tracer. All measurements and annealing treatments were performed in a vacuum better than 10^{-6}mm Hg.

Below 350° C the coercive force, measured in the easy direction of magnetisation, is little dependent on temperature ($H_c \approx 1$ to 2 Oe). Once heated above 400° C the film now has a much higher coercive force ($H_c \approx 4$ to 6 Oe at room temperature) strongly dependent on temperature. The BH loop in the hard direction, formerly rather closed, is now quite open.

Annealing with a magnetic field in the hard direction changes the uniaxial anisotropy already at temperatures below 350° C very fast, in agreement with observations of other authors. These changes are strongly dependent on whether or not a magnetic field is applied in the hard direction during cooling to room temperature. After once heating above 400° C this low temperature annealing behaviour disappears. Now the uniaxial anisotropy changes in the range from 400 to 500° C with relaxation times in the same order of magnitude as observed by other authors on bulk permalloy. Moreover, some films have an additional anisotropy which cannot be changed in this range.

This annealing behaviour suggests that three modes of uniaxial anisotropy are important in thin films:

1) One which can be changed at low temperatures with short relaxation times dependent on evaporation conditions, and which is probably due to imperfections and impurities, and which disappears after some annealing.
2) One which can be changed at higher temperatures, and which is probably due to the Néel-Taniguchi model of short range order.
3) One which cannot be changed at temperatures below the Curie point, and which is probably due to crystal shape or texture.

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34. ROTATABLE ANISOTROPY IN THIN PERMALLOY FILMS

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Vapor deposited permalloy films have been prepared which possess a new property, which we call "rotatable" anisotropy, in which the direction of easy magnetization is aligned by a suitable magnetic field. The threshold value of this field, which we denote by H_A, has the following properties:

1) It is of the order of 30 oersteds and is greater than the coercive force;
2) It is isotropic in the plane of the film;
3) It is independent of temperature from 345°K to at least 78°K;

The hysteresis curves are identical for any established easy axis. This easy direction loop has a remanence, which is approximately one-half of the saturation value for all thicknesses studied while the hard direction loop has the low loss characteristics typical of anisotropic thin films.

The time necessary to establish a new easy direction of magnetization with a given field is independent of temperature for the range 78° to 345°K. Therefore, we conclude that a diffusion process is not involved in establishing the new easy axis.

The rotatable anisotropy can be irreversibly destroyed by heating the films to temperatures above 650° K. Following this treatment the films exhibit a lower coercive force and show a rectangular, isotropic hysteresis loop for all drive fields in the plane of the films.

By employing partial etch techniques, we find that when the surface layer, which is less than 150A thick, is removed, the rotatable anisotropy disappears; the film then shows a hysteresis loop identical to those obtained by heating above 650°K. This is strong evidence that the origin of rotatable anisotropy lies in a thin surface layer.

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35. ANISOTROPY ROTATION IN THIN PERMALLOY FILMS AT ROOM TEMPERATURE

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It has been observed that the magnetic anisotropy direction of certain thin permalloy films prepared by the thermal decomposition of nickel and iron carbonyls can be rotated through 90 degrees at room temperature by fields less than 10 oersteds. The experimental conditions under which these films were prepared suggest that this phenomenon is due to the presence of carbon. Minor hysteresis loop properties were observed on a conventional 60 cycle hysteresis loop tester. The induction in the hard direction was substantially less than the induction in the easy direction. The application of a high field (approximately 9 oersteds) of short duration in the hard direction results in an increase of the minor loop induction. The repeated application of this high field causes the minor loop induction to increase to the value obtained in the original easy direction. At the same time the induction in the original easy direction is substantially reduced. The relaxation time for the rotation of the anisotropy axis was calculated from the time dependence of the induction and found to be 10 milliseconds. The activation energy calculated from this relaxation time is 5000 cal/mole which is substantially less than the values obtained for carbon diffusion in bulk metallic systems.

A simple model has been developed which relates the anisotropy rotation to specific domain wall configurations

and to the establishment of a "directional order" among interstitial carbon atoms. Although the method of preparation suggests that the presence of carbon is essential to the anisotropy rotation, the low activation energy suggests either that the carbon diffusion is substantially easier in thin films than in bulk material or that another phenomenon is responsible for the observed effects.

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36. FREE OSCILLATIONS OF THE MAGNETIZATION IN THIN PERMALLOY FILMS

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Free oscillations of the magnetization, the counterpart of the well-known forced oscillations of ferromagnetic resonance, were excited in magnetic uniaxial permalloy films (80/20 Ni-Fe, 1000 - 3000 Å thick). With a magnetic d.c. field up to 20 Oe in the plane of the film, the magnetization was aligned in the field direction. A sharp-rising step pulse field with a relatively small amplitude of 0.3 Oe and a rise time of less than 0.35 ns was applied in the plane of the film perpendicular to the d.c. field. The magnetization vector then rotated away from its initial equilibrium position and effected damped oscillations around its new equilibrium position. These oscillations were detected by means of a sampling oscilloscope with a time resolution of 0.35 ns. The oscillations, the frequency of which depended on the d.c. field and its orientation to the easy axis, were investigated in the range from 500 mc/s to 1200 mc/s. The decay time of the oscillations increased from about 0.5 ns to 1 ns with increasing oscillation frequency.

For comparison, ferromagnetic resonance experiments were performed on the same films in the same frequency range. The resonance frequency of ferromagnetic resonance and the frequency of free oscillations showed reasonable agreement. The damping constant λ evaluated from the line width of ferromagnetic resonance and from the decay time of free oscillations, was in the range from 100 mc/s to 200 mc/s and decreased with increasing frequency for both experiments.

These results were compared with theory based on the Landau-Lifshitz equation.

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37. SOME PROPERTIES OF UNIAXIAL PERMALLOY FILMS PREPARED BY CATHODIC SPUTTERING

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Much of the research to date on magnetic films has been based on films prepared by evaporation or electrodeposition. Evaporation has been found to yield films showing significant variations in magnetic anisotropy, which render them unsuitable for use as memory storage elements. The geometrical effects, to which these variations have largely been attributed, can be eliminated by using the method of electrodeposition, which results in greatly improved reproducibility of magnetic characteristics.

The present paper describes a preliminary evaluation of an alternative preparative approach, in which the films are deposited by cathodic sputtering. Films of the non-magnetostrictive Ni:Fe::81:19 composition have been prepared by sputtering either from solid alloy cathodes or from copper cathodes which had been previously electroplated with permalloy.

Studies have been made of the conditions of sputtering in order to control thickness and magnetic anisotropy of the films. Sputtering in argon at a pressure of 100 microns, with the electrode potential 3500 V and discharge current 150 ma. produces deposition at a rate of about 15 Å/sec.

The film-thickness distribution, which is shown to be a function of electrode separation, can be made very uniform within areas extending over about one-half the surface of the anode. Films deposited in an applied field of 20 oersted display uniaxial anisotropy with $H_c \approx 2.5$ oersted and $H_k/H_c \approx 1.4$. An evaluation of the reproducibility of thickness, coercive force and alignment of the magnetic preferred axis indicates that films prepared by this method would be suitable for use in planar memory matrices.

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38. MAGNETIC THIN FILMS BY IMPACT EVAPORATION

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Impact evaporation has long been used for the preparation of thin films of elements and compounds for optical and electrical applications; however relatively little work has been done on magnetic thin films prepared in this way. Data will be presented indicating that a controlled glow discharge system can be compatible with contemporary demands in thin film technology. Reproducible thin films of iron have been prepared whose structural and magnetic properties depend on the location of the substrate within the discharge. Very uniform iron films 1,000 Å thick having coercivities up to 250 oersted and Br/Bs ratio very nearly equal to unity have been prepared with unusually high remanence values. These results differ considerably from iron films of equal thickness prepared by thermal evaporation under high vacuum conditions at similar substrate temperatures.[1,2] Films prepared by impact evaporation showed no evidence of either preferred crystallographic orientation or preferred direction of magnetization.

In sharp contrast to findings by several authors, ferromagnetic nickel films can be deposited by impact evaporation.[3,4] Results to date indicate that transport of alloys by impact evaporation holds considerable promise.

Sixty-cycle B.H. loop characteristics, electron microscopy and diffraction, and microchemical analysis were used for film evaluation.

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[4] L. R. Ingesoll and Y. D. Hanawalt, Phys. Rev., 34, 972 (1929)

39. PREPARATION AND PROPERTIES OF AMORPHOUS NICKEL FILMS

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Films evaporated from high purity nickel onto glass substrates held at ambient temperatures are often found to be amorphous over a wide range of evaporation conditions. Evaporation was carried out from tungsten boats and alumina crucibles at rates ranging from 10 to 50 Å/sec with pressures below 10^{-5}mm Hg and with film thicknesses from 200 to 3000 Å. The nickel films were examined by reflection electron diffraction, and X-ray diffraction using a Seemann-Bohlin camera, and instead of the normal f.c.c. pattern there is obtained only a single diffuse maxima with a spacing of 1.97 Å.

The films generally exhibit no ferromagnetism up to drive fields of about 200 oe although some of the films are very slightly magnetic, and occasional films are similar to films deposited on heated substrates. With very thick films (>1500 Å) the normal f.c.c. pattern appears weakly in the diffraction patterns, indicating that part of the film exists in the usual Ni structure. The continued absence of ferromagnetism at large thicknesses indicates that the percentage of cubic nickel is slight, and that it is dispersed in the amorphous film.

Upon heating the amorphous films at temperatures of 100-200°C the diffuse maxima shifts toward spacings closer to that of the (111) plane of Ni (2.03 Å) and heating the film for 30 minutes at 450°C results in the formation of the cubic structure. The crystallinity of the film depends on substrate material, and films evaporated onto formvar or carbon usually show the normal structure.

The nickel films are easily removed from the glass substrate, however, the magnetic properties of the films remain unchanged.

The amorphous nickel films are apparently in a highly disordered state resulting from negligible diffusion of nickel atoms within the film during formation. The diffusion process is probably hindered by impurity atoms or molecules (e.g. nitrogen) trapped in the film as it grows, as well as by the loss of thermal energy into the substrate. No evidence of a hexagonal modification of nickel was observed in this work, however, no effort was made to study extremely thin films where possibly such a structure is stable.

SESSION E

NUCLEAR HYPERFINE FIELDS

J. S. SMART, Presiding

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40. NUCLEAR MAGNETIC RESONANCE IN RARE EARTH INTERMETALLIC COMPOUNDS (Invited)

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The magnitude and sign of the conduction electron polarization in rare earth intermetallic compounds has been determined using NMR techniques. Large, temperature dependent, Knight shifts of the Al^{27} NMR in XAl_2 (X ≡ rare earth ion) were found. These observations may be explained by assuming a *negative* exchange interaction of ~0.1 ev to exist between the localized f electrons of the rare earth ion and the conduction electrons. A variation in the magnitude of the exchange interaction and its anisotropy as a function of number of 4f electron was also found. An investigation of other rare earth aluminum intermetallic compounds suggests that the negative sign of exchange interaction is not unique to the cubic Laves structure.

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41. NUCLEAR RESONANCE IN FERROMAGNETIC AND ANTIFERROMAGNETIC SOLIDS UNDER HYDROSTATIC PRESSURE (Invited)

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The pressure dependence of the nuclear resonance frequency (ν) of the Fe^{57} nucleus in enriched iron has been measured over the range 1 to 10,000 kg/cm^2 at -77°C, 0°C, and 84.2°C. ν is observed to be a linear function of the pressure at each temperature with $(d\nu/dP)_T$ given respectively by $-(7.4 \pm .5) \times 10^{-3}$ kc/(kg/cm^2); $-(7.49 \pm .04) \times 10^{-3}$ kc/(kg/cm^2); $-(7.0 \pm .3) \times 10^{-3}$ kc/(kg/cm^2). These results show that $(1/\nu)\,(d\nu/dP)$ is independent of the temperature and therefore arises solely out of the effect of pressure on the hyperfine coupling constant A and on the saturation moment per atom at absolute zero ($\sigma(T=0)$). Disagreement between different published measurements[1] of $d\sigma(0)/dP$ make it impossible to accurately separate these two effects. However, one may use the existing data on $d\sigma(0)/dP$ to correct for the effect of thermal expansion on the temperature dependence of $\sigma(T)$[2] and $\nu(T)$[3]. It is found, outside the uncertainty in $(\alpha\sigma(0)/dP)$, that A in the fundamental relation $\nu(T) = A\sigma(T)$ is an appreciable explicit function of the temperature at constant volume. Possible mechanisms for this temperature dependence of A will be presented.

The nuclear magnetic resonance frequency of the F^{19} nucleus in antiferromagnetic MnF_2, in zero external field, has been measured as a function of pressure at 4.2°K, 20.4°K, and 35.7°K using a new type very high frequency variable frequency spectrometer. From these measure-

ments we have deduced the pressure dependence of the hyperfine coupling constant (A) between the manganese electrons and the fluorine nucleus and the pressure dependence of the Néel temperature. This deduction gives $(1/A)(dA/dP) = +(1.9 \pm 0.1) \times 10^{-6}/(kg/cm^2)$ and $(1/T_N)(dT_N/dP) = +(4.4 \pm 0.3) \times 10^{-6}/(kg/cm^2)$. We have also measured the compressibility of MnF_2. The magnitude and pressure dependence of A is explained using the theories of Mukherji and Das, and Marshall and Stuart, which permit a calculation of the dependence of A on the interatomic distances, starting with the Hartree-Fock self-consistent field wave functions for Mn^{2+} and F^- with the Mn^{2+} wave functions properly adjusted to bring it into agreement with neutron scattering form factor measurements. The theory is in very good agreement with the experimental results.[4]

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42. THE MÖSSBAUER EFFECT: APPLICATIONS TO MAGNETIC MATERIALS (Invited)

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The Mössbauer effect, the resonant absorption of nuclear gamma rays in solids, may be used to obtain the hyperfine structure of Fe^{57} in magnetic materials. Experiments are performed by observing the absorption by *stable* Fe^{57} of the 14.4 kev gamma ray coming from a source which contains *radioactive* Fe^{57} produced by the decay of Co^{57}. The experiments are not limited to naturally iron-bearing materials; other substances can be studied provided only that small amounts of cobalt can be introduced into lattice sites of interest. The magnetic moments of the ground and first excited states of Fe^{57} are known and make possible direct determination of the field at the iron nucleus once the hyperfine structure has been measured. The magnetic field at iron nuclei has been determined in the ferromagnetic transition metals (Fe 333 koe, Co 310 koe, Ni 265 koe at 300°K) but no hyperfine structure has so far been observed in the antiferromagnetic transition metals, Mn and Cr. Other materials under investigation are the transition metal oxides and some ferrites, where, for trivalent iron, fields in the vicinity of 500 koe have been generally found. In the case of yttrium-iron-garnet the hyperfine structures associated with the tetrahedral and octahedral sites have been separately observed. The most complete analysis so far has been made in FeF_2 where the magnetic field in the antiferromagnetic state ($H_{T=0}$ = 340 koe) and the quadrupole coupling in the paramagnetic state (31.2 mc/sec) have been obtained.

43. ON THE CONTRIBUTION OF THE FERMI CONTACT TERM TO THE MAGNETIC FIELD AT A NUCLEUS

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The effective magnetic field at a nucleus in ferromagnetic materials has now been studied by nuclear magnetic resonance[1] and Mössbauer[2] techniques. These important experiments have revealed a large (-333 koe) but quite unexpectedly[3] *negative*[2] effective field for Fe^{57}.

Since an important source of this effective field is the Fermi contact term, i.e., the field due to the ion's net s electron spin density at the nucleus, we have investigated this contribution with several spin-polarized Hartree-Fock calculations (calculations where one-electron orbitals of differing m_s are allowed differing radial dependence) for iron series ions.[4] Calculations have been done for the free Ni^{+2} and Mn^{+2} ions and for a Ni^{+2} ion inserted in a *crude* crystalline environment represented by a point charge cubic field. The 1s and 2s shells contribute to a magnetic field of one direction whereas the 3s contribution is smaller and of opposite direction. The free ion results are of the right sign and are approximately 30% larger than the common value (-3 a.u.) reported by Abragam, Horowitz and Pryce[5] for iron series ions in hydrated salts. The cubic field Ni^{+2} results differ appreciably from the free ion results and are in better agreement with experiment. This difference is primarily due to the 3s shell contribution which is sensitive to 3d electron behavior and thus in turn to the cubic field which perturbs the 3d electrons. This 3s sensitivity is quite consistent with the findings of Abragam, Horowitz and Pryce[5] who pointed out that the total contact term is sensitive to the type of salt and of Marshall[6] who assumes a widely varying 3s contribution in order to interpret experimental results for metals. The relation of these contributions to the measures[1,2] effective field in metals will also be discussed.

*Work of this author was supported in part by Ordnance Materials Research Office, Watertown, Massachusetts.

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44. NUCLEAR MAGNETIC RESONANCE OF Fe^5 IN UNENRICHED Fe

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The nuclear magnetic resonance of Fe^{57} has been observed in specimens in the form of powders of various sizes, foils, and whiskers. Our results are consistent with previously reported work of Gossard, Portis and Sandle[1] on enriched iron, and with the work of Robert and Winter[2] on natural iron. We find that the resonant frequency varies slightly among nominally pure iron specimens taken from different sources suggesting that it is somewhat sensitive to impurity content. Prestrain of the specimen has a marked effect, the resonance in cold rolled foil being very broad and weak compared to that observed in annealed foils. Observations of nuclear magnetic resonance in iron whiskers oriented both axially and transversely in the RF coil offers interesting conformation of the domain wall enhancement mechanism put forth by Gossard and Portis[3]; the amplitude of the resonance is significantly reduced in the transverse case. The application of a small external dc field suppresses the resonance completely in whisker samples. The temperature dependence of the Fe^{57} resonance has been investigated and results of the measurements to 200°C will be presented.

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45. NUCLEAR RESONANCES IN CUBIC, HEXAGONAL, AND MIXED PHASE COBALT POWDERS AND THIN FILMS

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The Co^{59} nuclear magnetic resonance in ferromagnetic cobalt was first observed by Portis and Gossard in cubic phase cobalt powders, and their work clarified the nature of the interaction of the nuclear hyperfine field with local magnetization fields in the metal; in particular, frequency shifts in applied magnetic fields indicated that the hyperfine field was oppositely oriented to the bulk magnetization due to anti-ferromagnetic interactions between the core and conduction electrons. Thus, in cubic cobalt, the internal magnetic field is measured as -211,000 oe. at room temperature, and -214,740 oe. at 77°K.

Experiments on a number of cobalt samples in these laboratories have shown four additional resonances with larger hyperfine fields than in the cubic phase. The shifts are attributed to non-vanishing dipolar internal fields and, in oersteds, these are:

Line / Temperature	A	B	H	C
295°K	-2,390	-5,300	- 7,800	-10,090
77°K	-2,960	-6,390	-10,140	-11,850

External magnetic field studies to 10,000 oe. decrease the resonance frequencies, as in the cubic phase, justifying the use of the negative sign. All the cobalt resonances show a pronounced intensity dependence and an approximate 10^{-4} frequency dependence on the previous magnetic history of the sample. Following Portis and Gossard, we take a dispersion shaped rf absorption signal to indicate domain wall excitation and a normal rf absorption to indicate domain rotation. Mixtures of these phases are present in all the lines, and in large externally applied fields domain rotation dominates. Only line H, however, has been observed mainly as absorption and only for electroplated film samples--indicating single domain polycrystalline structure. Finally, at 4.2°K the new resonances reported here saturate easily among themselves, but show little coupling to the cubic line.

These resonances are identified as originating in hexagonal phase material and in fault structure of different symmetries. Studies in a number of samples have shown line H to be connected with the hexagonal phase detected by X-ray analysis and this assignment is confirmed by annealing studies in which lines A, B, and C are diminished with respect to line H. Some sample preparation techniques are selective with respect to the type of fault detected in the material.

46. TRANSIENT EXCITATION OF NUCLEI IN FERROMAGNETIC METALS*

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Free precession signals and spin echoes have been observed from Co^{59} and Fe^{57} nuclei in finely divided multidomain cobalt and iron, respectively. Spin-spin coupling has been thoroughly investigated in cobalt. The apparent spin-spin time varies between 20 and 30 microseconds at room temperature depending on power level, increasing to 90 microseconds at 4.2°K. Spin diffusion through the frequency spectrum of cobalt has been investigated at low temperatures by the stimulated-echo technique. The results are consistent with a theory of one-dimensional diffusion with exchange rate and exchange distance of the order of $1/T_2$. Spin-lattice relaxation times have been measured in cobalt from 2.9°K up to 600°K. The relaxation time is inversely proportional to the temperature suggesting that the dominant relaxation mechanism is a coupling to the conduction electrons. Spin-spin coupling is very much weaker in iron because of the smaller magnetic moment of Fe^{57}. The spin-lattice time does not appear to follow the $1/T$ law expected for conduction electron relaxation. The spin echo technique has also been used in both metals to study the effect of wall motion. A dc pulse, which displaces the domain walls by a controllable amount, is interposed

between the first rf pulse and the echo. These experiments confirm that the induction signals arise from nuclei in the domain walls and also permit a study of the connection between the line broadening and domain wall processes. Free precession signals have been observed and are consistent with the over-all resonance line width. A weak precession signal, arising from domain rotation, has been observed from cobalt in high magnetic fields. The sign of the precession has been measured directly, confirming that the hyperfine field is directed opposite to the magnetization.

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47. NUCLEAR MAGNETIC RESONANCE IN NiF_2 DOMAIN WALLS

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Nuclear Magnetic Resonances of the F^{19} nucleus in single crystals of NiF_2 have been observed[1] and have helped to explain the weakly ferromagnetic ordering.[2,3] In addition to these resonances, which were consistent with a single domain model, we have recently observed, in the ordered state, two other resonances from the F^{19} nuclei. At 4.2°K these new resonances are observed in zero magnetic field at $\nu = 26.6$ Mc/sec and $\nu = -51.2$ Mc/sec. For $S \parallel [110]$ and $[1\bar{1}0]$ we calculate[1] frequencies of +19 Mc/sec and -54 Mc/sec. With $H_0 \parallel [110]$ they shift with g-factors of +4.00 kc/sec and -4.00 kc/sec. respectively. Both resonances are broad, asymmetric and easily saturated with an apparent value of $T_1 \sim 8$ seconds at 20.3°K. These features in conjunction with the resonances' dependence upon the directions of H_1, H_0 and H_{mod} lead us to the conclusion that the resonances arise from F^{19} nuclei in 90° domain walls.[4]

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SESSION F

FERROMAGNETIC RESONANCE

R. C. FLETCHER, Presiding
Georget Rado, Reporter

48. FERRIMAGNETIC RESONANCE IN SINGLE CRYSTALS OF COBALT SUBSTITUTED MANGANESE FERRITE

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The results of microwave resonance measurements of g-factor and first and second order magnetic anisotropy constants, K_1/M and K_2/M, will be discussed for crystals with the nominal composition $Co_xMn_{1-x}Fe_2O_4$ where x = 0, 0.001, 0.01, 0.02, 0.04, 0.06, 0.08, 0.10 and 0.25. The greater the value of x the smaller the temperature range covered. For x = 0 and 0.001 $300°K > T > 4.2°K$; for x = 0.25 $300°K > T > 250°K$. Precise chemical analyses of the crystals are available.

In the temperature range 77°K to 300°K measurements were made at 9,400 Mc/s and at 17,000 Mc/s.

A harmonic analysis of the values of static applied resonant field, H_r, as a function of crystallographic direction showed that H_r can be described satisfactorily using K_1/M and K_2/M; higher harmonics with much smaller amplitudes may be present at the lower temperatures. Values of K_1/M and K_2/M deduced from measurements at the two frequencies do not differ significantly.

The conclusions concerning K_1/M are in agreement, for $x \leqslant 0.10$, with those reached by Pearson[1] from torque measurements, though accurate comparison of the present K_1/M values with static values is limited by the available data on M. A difference for x = 0.25 has already been reported.[2]

The substitution of cobalt for manganese results in a negative K_2/M which increases linearly with x up to $x \approx 0.08$. K_2/M increases rapidly in magnitude as the temperature is reduced and becomes much greater than the cobalt contribution to K_1/M. The substitution of cobalt into $MnFe_2O_4$ has an effect upon K_2/M several times smaller than the same substitution into Fe_3O_4,[3] but the effect in the former composition increases more rapidly with reducing temperature.

The g-values are isotropic and they increase linearly with x up to x = 0.10 in the room temperature region. For a given x the g-factor increases slightly with reducing temperature. The cobalt ion g-factor deduced is 2.46, in agreement with the value deduced from the saturation moment of cobalt ferrite at 0°K.

It is shown that the reduction in the negative value of K_1/M between 20°K and 4.2°K and the 1.5% increase in g-value in the range 100°K to 20°K which occur for x = 0 are intrinsic properties of manganese ferrite and not the result of small cobalt impurities.

The paper adds to the evidence which shows that the differences in the environment of the cobalt ion in $MnFe_2O_4$ and Fe_3O_4 are important.

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49. MICROWAVE RESONANCE IN TETRAGONAL MANGANESE-IRON SPINEL

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An interesting feature of the system $Mn_xFe_{3-x}O_4$ is that while the anisotropy for $0 < x < 1.8$ exhibits cubic symmetry, compositions with $x > 1.8$ have tetragonal symmetry due to the distortion induced in the lattice by Mn^{3+} ions.[1] In this paper we report on microwave resonance experiments on a single crystal of composition $Mn_{1.85}Fe_{1.15}O_4$. The data are analyzed in terms of an anisotropy energy of the form:

$$E_A = K_1\alpha_3^2 + K_2\alpha_3^4 + K_3(\alpha_1^4 + \alpha_2^4)$$

wherein α_1 and α_2 are direction cosines of the magnetization referred to the tetragonal a axes, and α_3 is the direction cosine of the magnetization referred to the c axis. The c axis is found to be the hard direction and the tetragonal a axis (corresponding to the [110] direction in the undistorted cubic structure) is easy. Although the crystallographic distortion from cubic symmetry is small, the axial anisotropy K_1/M is approximately 3000 gauss at room temperature, K_1/M increases rather slowly as the temperature is lowered to approximately 160°K and more rapidly below this temperature. This temperature also coincides with a break in the M vs $T^{3/2}$ curve, which may be associated with the formation of a triangular moment arrangement. The anisotropy K_2/M is insignificant at room temperature, but must be included to obtain a detailed fit to the data at low temperatures. The quantity K_3/M, which measures the anisotropy in the basal plane, is about -25 gauss at room temperature and increases to several hundred gauss at 77°K. The effective g value was obtained by varying the microwave frequency with the external field along the c axis to eliminate errors due to the large axial anisotropy. Values thus obtained were nearly equal to 2 and substantially independent of temperature. Further measurements on samples containing greater manganese concentrations are in progress.

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50. FERROMAGNETIC RESONANCE IN PIEZOELECTRIC $Ga_{2-x}Fe_xO_3$*

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The growth of single crystal ferromagnetic, piezoelectric insulators with the composition $Ga_{2-x}Fe_xO_3$ ($0.7 < x < 1.4$) has been reported recently by Remeika.[1] Mrs. Wood[2] finds the unit cell to be orthorhombic, with $c < a < b$ and a twofold axis along b (C_{2v}). Microwave resonance measurements have been made at 24, 34 and 55 kmc sec at room temperature ($x > 1$) with single crystal spheres which are rotated about each of the three principal directions. The field for resonance curves exhibit the orthorhombic symmetry with stationary points in the three principal directions. The hard direction is along the b axis, the intermediate direction along a, and the easy direction along the c axis. The anisotropy fields are in excess of 10,000 oersteds. Measurements of anisotropy, g-value and line shape are reported for several samples and the origins of the large anisotropy are discussed.

*That portion of work performed by A. Dymanus supported by Air Force contract.

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51. FERROMAGNETIC RESONANCE DUE TO MAGNETIC FIELDS GENERATED BY DISPLACEMENT CURRENTS IN FERRITES

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A novel mode of excitation of ferromagnetic resonance has been observed, wherein the rf magnetic field causing the resonance is generated by a displacement current in the ferrite. When a ferrite rod is placed in the center of a rectangular waveguide parallel to the E field, a relatively large displacement current may be set up due to the relatively large dielectric constant of the ferrite (typically 9 to 13). This displacement current generates a magnetic field which is circumferential with the rod. The ratio of this magnetic field to the transverse magnetic field due to normal waveguide modes in an empty waveguide is proportional to the dielectric constant and the ratio of rod diameter to free space wavelength. For a rod with a dielectric constant of eleven and a diameter of 1/8 inch, the above ratio is approximately 1:2 at 3000 megacycles. The formula for the magnetic biasing field required to produce resonance is shown to be $H(H + 4\pi Ms) = (\omega/\gamma)^2$. An experiment is described wherein a ferrite rod is placed in a short circuited waveguide, first at a magnetic field maximum and then at an electric field maximum. The ratio of energy absorbed at ferromagnetic resonance at the two locations was measured and checked well with theoretical calculations. This phenomenon explains why ferrites with relatively high saturation magnetizations (eg, $4\pi Ms > 1500$ gauss) appear to have very large dielectric losses when measured at S band, whereas they had very low dielectric losses when measured at X band.

52. EXCITATION AND BOUNDARY EFFECTS IN SPIN WAVE RESONANCE

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Using the general exchange boundary condition[1] and the general spin wave dispersion relations,[2] a calculation of the line shapes of spin wave resonances in metallic films is made by assuming various excitation conditions at the surfaces of the films. For a given set of excitation conditions, the results of the calculation shows that whereas the static magnetic field spacings between the various spin wave resonance peaks are determined mainly by the exchange constant A, the relative intensities of the various resonances are strongly dependent upon the surface anisotropy energy density K_{surf}. Conversely, the surface energy density K_{surf}, which does not seem to have been actually measured so far can be inferred from the observed intensities in a thin film spin wave resonance experiment at microwave frequencies.

Rado and Weertman,[1] in a recent publication, derived the general exchange boundary condition at the surface of a ferromagnet to be $(2A/M_S)\ \vec{i}_z \times \frac{\partial \vec{m}}{\partial n} + T_{surf} = 0$ where A is the exchange constant, M_S and $\vec{m}$ are respectively the static and r-f magnetizations and $\vec{n}$ is a unit vector normal to the surface of the ferromagnet. T_{surf} is the sum of all the surface torque densities which arise from forces other than ferromagnetic exchange. In our calculation, we assumed that the anisotropy axis is parallel to $\vec{i}_z$. This assumption seems to be a plausible one for the case where the static magnetic field is applied in the direction of the film normal. With this assumption, the aforementioned exchange boundary condition reduces simply to $2A\ \partial\vec{m}/\partial n - K_{surf}\ \vec{m} = 0$. Utilizing this relation and the ordinary electromagnetic boundary conditions at the surfaces of the film to determine the unknown amplitudes of the various plane spin waves, we arrived at the spin wave resonance spectrum of a metallic film. The results of such a calculation show that whereas the location of the z-directed spin wave resonance peaks are dependent upon the surface anisotropy energy density K_{surf}, the spacings of the various peaks on the static field scale are determined mainly by the exchange constant A obeying the approximate relation $A \simeq (H_{oi} - H_{oj})\ Ms\ t^2/2\pi^2\ (n_j^2 - n_i^2)$ where $H_{oi} - H_{oj}$ represents the difference between the static magnetic field values at resonance peaks i and j and n_i and n_j are odd integers. This result is consistent with the conclusions of previous workers. On the other hand, the intensities of the various peaks are strongly dependent upon the ratio $K_{surf}\ \vec{m}/(2A\ \partial m/\partial n)$ as well as upon the electromagnetic field at the surfaces of the film. Thus, to make our results as general as possible, we have included in our calculation the effects of different exciting electromagnetic field values at the surfaces of film as well as the effects of different values of K_{surf} upon the line shape of spin wave resonances.

The results of our calculation show that the observed relative intensities of the spin wave resonance peaks in a Permalloy film could be used to determine the surface anisotropy energy density K_{surf}.

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53. MAGNETIC RESONANCE IN CANTED FERRIMAGNETICS*

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The classical theory of the uniform modes (k = 0) of a four sublattice canted ferrimagnetic is developed. An equilibrium configuration is assumed wherein sublattices A_1, A_2 are collinear, and antiparallel to the resultant of the canted sublattices B_1, B_2. Three of the four possible modes may be excited by uniform r.f. fields. Of these, one is the analogue of the familiar microwave resonance in two-sublattice collinear ferrimagnetics, another the analogue of the corresponding infrared mode. This result is comparable with the previous work of Eskowitz and Wangsness.[1]

Of particular interest is a new intermediate frequency mode corresponding to a symmetric, out of phase, precession of the canted sublattices B_1, B_2 while the sublattices A_1, A_2 remain stationary. In a manner analogous to the degenerate case of resonances in antiferromagnetics, its frequency may be determined by a combination of an exchange torque alternating in time with an anisotropy torque as

$$\omega = -\gamma_B \mu_o \sqrt{H_{exch} \cdot H_{anis}} \qquad (1)$$

This "Y-mode" is excited by an r.f. magnetic field parallel to the net magnetization vector, and may be expected to have, in a typical case, an intensity of the order of 1 of the normal microwave resonance.

The dependence of the Y-mode frequency on applied fields and temperature is considered on the basis of Lotgering's[2] development of the Yafet-Kittel canted lattice theory[3]. These effects, together with the characteristic property of longitudinal excitation, should permit the detection and analysis of canted ferrimagnetic structures with less ambiguity than is now possible.

*The work reported in this paper is supported jointly by the Army, Navy and Air Force under contracts with the Mass. Institute of Technology. NONR 1841 (10) and AF 19 (604) - 5482

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54. FERRIMAGNETIC RESONANCE IN YTTERBIUM IRON GARNET

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The paper will report the anomalous microwave resonance properties of ytterbium iron garnet. The resonance field applied in a [100] direction, H_r [100], increases slowly

as the temperature is reduced from 300°K to 100°K whereas H_r [111] falls rapidly with temperature in the range 220°K to 100°K. There is a greater fall in H_r [111] in measurements at 17,000 Mc/s than at 9400 Mc/s. H_r for other crystallographic directions shows intermediate behaviour.

According to the normal interpretation of microwave resonance which has been used by Rodrigue and coworkers[1] to deduce parameters for ytterbium iron garnet, the anisotropy in H_r arises from magnetocrystalline energy. This leads to the relationship $\omega = \gamma(H_r + H_K)$ where $H_K = 2K_1/M$ for H_r in the [100] direction and $-\frac{4}{3}\frac{K_1}{M}$ for H_r in the [111]. Hence γ and K_1/M can be determined from H_r [100] and H_r [111] at a single frequency.

It is evident that this is not valid for ytterbium iron garnet between 220°K and the lowest temperature of measurement because:

(1) The K_1/M and γ values deduced in this way from the 17,000 Mc/s results differ widely from those deduced from the 9,400 Mc/s measurements.

(2) K_1/M deduced from static measurements is much smaller in magnitude than the values deduced from resonance.

It is also observed that the magnetic resonance line-width becomes increasingly anisotropic as the temperature is reduced below 300°K with ΔH [111] and ΔH [110] $\gg \Delta H$ [100].

γ and K_1/M can be deduced from the relationship $\omega = \gamma(H_r + H_K)$ using measurements at two frequencies in a single crystallographic direction. Using H_r [100] the g-factor deduced ($\gamma = ge/2$ mc) is 1.87 ± 0.02 with no significant variation between 300°K and 100°K and the values of K_1/M are in reasonable agreement with values determined statically. Using H_r [111] no such agreement is obtained. Hence the observations cannot be explained by postulating an anisotropic g-factor.

It seems that the behaviour of H_r [100] follows the normal pattern (with a slight divergence between 150°K and 77°K) but in passing from the [100] to [111] a range of behaviour is observed in which an anomalous reduction in H_r grows in magnitude. The linewidth data suggest that the anomaly is associated with the highly damped motion of the rare earth sublattice. Kittel[2] has suggested that the effect of such damping is to increase H_r.

Below about 130°K the resonance line becomes too broad for measurement in the [111] direction. Observations will therefore be reported on a specimen with 1.9% Yb in $Y_3Fe_5O_{12}$ in the temperature range 4.2°K to 300°K. For this crystal excessive line broadening is absent but the anomaly in H_r is present.

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55. ANISOTROPY OF THE SPIN WAVE SPECTRUM

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The frequency of a spinwave depends on its propagation vector and on the effective internal field, H_i, in which it propagates. In an isotropic medium this implies that all the spinwaves on a θ_K cone about H_i are degenerate. If anisotropy is taken into account, this degeneracy is removed in those directions in which the minimum of the energy surface is not axially symmetric; thus, for example, if H_i is along (110) in a cubic crystal, certain spinwaves are shifted in frequency relative to one another and in particular, relative to the uniform precession. This effect should be observable experimentally because the top of the spinwave spectrum then depends on crystalline direction; thus the discontinuity in linewidth which occurs in roughed yttrium garnet when the uniform precession passes through the edge of the spectrum should occur at different values of frequency (or temperature) in different directions. Experimental verification of this effect is in progress and will be reported.

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56. FERRIMAGNETIC RESONANCE IN A SINGLE CRYSTAL DISC OF YTTRIUM IRON GARNET

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The use of discs instead of spheres for ferrimagnetic resonance investigations will be discussed briefly. Discs have the advantage that the line width is insensitive to the surface roughness. In addition, discs can be cut close to the (110) growth faces of garnet crystals, which is usually the location of the best material, and can easily be examined for internal imperfections with an optical or infra-red microscope.

Resonance measurements have been carried out on a single crystal disc of yttrium iron garnet placed in a shorted coaxial line. The d.c. magnetic field was perpendicular to the plane of the disc and the frequency was 1980 mc/s. The disc was 0.157 cm in diameter and 0.0085 cm thick, and had a (110) growth face on one side.

The lowpower linewidth was $\Delta H = 0.70$ oe. The relative susceptibility was determined as a function of r.f. magnetic field at the sample. The critical field for saturation was found to be $h = 9.7 \times 10^{-3}$ oe. by extrapolation of the $1/h_{rf}$ portion of the saturation curve. The resultant value of ΔH_K, the line width of the unstable z-directed spin wave, is 0.34 oe. These results will be compared with those for spheres.

57. FERROMAGNETIC RESONANCE LINE WIDTH IN COBALT-SUBSTITUTED FERRITES*

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It has been observed that even small concentrations of substitutional cobalt ions produce large increases in the resonance line widths of ferrites. To investigate the source of this line width we have computed the magnon scattering due to the variation from ion-to-ion of the spin-orbit interaction.[1] The effect of the spin-orbit coupling is particularly large in the cobalt ion because it has a degenerate orbital ground state when situated in a crystalline field of trigonal symmetry; this degeneracy is also responsible for the large change in anisotropy caused by the substitution of small amounts of cobalt in ferrites.[2] The resultant line width is found to be of the order of 20-30 oersteds for each percent of cobalt introduced into a normal (non-inversed) spinel or into disordered ferrous ferrite. For other ferrites the effect of the cobalt ions is diminished because the non-equivalence of all B-sites destroys the trigonal symmetry of the local crystalline field and lifts the orbital ground-state degeneracy. Equal fractions of A and B ions distributed at random over the octahedral sites of the host ferrite would reduce the line-width contribution of the cobalt ions by a factor of .16. The line width is found to be isotropic, in contrast to the spin-orbit scattering of ions with non-degenerate ground states.[1] The line width is temperature-independent, except possibly at very low temperatures. Finally, the resultant g-factor is found to be insensitive to the scattering. The latter two predictions are in contrast to the results found by Kittel[3] and by de Gennes, Kittel and Portis[4] for the effect of substitutional ions which couple the uniform mode strongly to the lattice, rather than to the other spin-wave modes as in our model. On this basis it would appear that although direct relaxation to the lattice is dominant in the rare earth garnets, scattering among the spin wave modes is the dominant loss mechanism in the ferrites.

The most relevant quantitative experimental data is that of Schlömann, Green and Milano[5] who have measured the line width of the z-directed spin waves degenerate with the uniform mode, using the method of power saturation of the primary resonance. Because this mode is of long wavelength ($\cong$ 200 interatomic distances) its scattering should be roughly comparable to that of the uniform precessional mode. For a nickel ferrite host crystal they found an increase in line width of 6.8 oersteds for each percent of substitutional cobalt. With plausible estimates of the spin-orbit parameters of the cobalt ion, theory gives approximately 3 oersteds for each percent of cobalt.

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*Supported by ONR

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58. A NEW CHARACTERISTIC IN THE TEMPERATURE DEPENDENCE OF FERRIMAGNETIC RESONANCE LINE WIDTH IN SOME RARE EARTH DOPED YTTRIUM IRON GARNET

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Measurements have been made of the ferrimagnetic resonance line width of YIG doped with each of the rare earths. These results will be presented in full elsewhere. For the most part there is a peak in the $\Delta H(T)$ curve at some temperature between about 20° and 150°K. The position of this peak varies with the impurity, the frequency, and the crystal direction of the steady field. However, several cases have been observed in which the line width increases very rapidly with decreasing temperature down to the lowest temperature reached, about 1.5°K. This behavior occurs over a very narrow angular range. For ytterbium doped YIG, it is associated with a very mild peak in the field for resonance. For the case of europium there appears to be no anomaly in H_{res}, though a plot of line width against angle shows an increase of about fifteen fold with a half width of perhaps 1.5°. It is suggested that this anomalous linewidth versus angle and temperature as well as the more generally encountered peak in $\Delta H(T)$ represent the excitation of transitions between sublevels of the rare earth multiplet which approach within an energy comparable with that of a photon of the exciting radiation. The temperature variation is related to the transition probability of the transitions involved, to the simple difference in population resulting from the Boltzmann distribution, and to the breadth and separation of the levels.

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59. THE NATURE OF THE LOW TEMPERATURE LINE WIDTH MAXIMUM IN YTTRIUM IRON GARNET

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Two types of experiments have been performed in order to understand the origin of the residual low temperature ferromagnetic resonance line width maximum in high purity single crystal yttrium iron garnet.[1] The measured values of $\Delta H(T)$ have the general characteristics which would be shown either by (a) the presence of paramagnetic and other impurity ions which replace yttrium ions to set up a fast relaxing paramagnetic sublattice coupled to the net ferric lattice or (b) the presence of divalent ferrous ions caused by the presence of certain impurity ions or by oxygen defects.

The first experiment is a measurement of the k independent line width, ΔH_{ko}, as functions of frequency and temperature through the line width maximum. At 9300 mcs the line width maximum is at 40°K and is approximately equal to the room temperature value of 150 millioersteds. The maximum appears as a single curve. At 16,500 mcs

there is evidence that several curves are present which are not resolved at the lower frequency. For one sample ΔH_{ko} has two maxima, one at 35°K and one at 45°K. In a second sample there are at least four maxima. The shape of the curve and reduction in height are those which would be expected for resolved structure.

The second experiment was designed to introduce the divalent ion mechanism in a single crystal sphere of high purity YIG which had previously been measured. By heat treating the sphere at greatly reduced pressures the oxygen ions were driven off causing some of the Fe^{+++} ions to become Fe^{++}. If no phase transitions occur then it is probable that the divalent ions, being larger, are located on octahedral sites. The processing was carefully done so that the intrinsic line width increased by a factor of only 1.5 or room temperature. At the low temperature line width maximum, however, the increase was 40 times. ΔH was measured through the line width maximum as both 9300 and 16,500 mcs. Results of these experiments will be discussed in relation to the nature of the residual line width maximum.

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60. PEAK POWER CHARACTERISTICS OF LOW MAGNETIZATION GARNETS*

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The magnetization of YIG can be lowered by substituting small amounts (less than 30%) of either aluminum or gallium for iron without a substantial change in the room temperature linewidth. The ferromagnetic resonance absorption of these polycrystalline garnets has been studied as a function of power level, frequency, temperature, and sample shape. The critical field and the spin wave linewidth, ΔH_k, of the unstable spin waves has been determined from the saturation of the main resonance. Measurements on spheres indicate that decreasing the magnetization results in a smaller ΔH_k. In YIG with a magnetization of 1750, ΔH_k is about 4.5 oe. while in YAlIG with a 500 oe., magnetization ΔH_k is about 3 oe. In both cases ΔH is about 45 oe. In some disks ΔH_k has been found to be five times smaller than it is in a sphere of the same composition. This is in qualitative agreement with recent theories of spin wave relaxation.[1,2] To study frequency dependence, saturation measurements were performed at 1.3, 5.5 and 9.3 kMc. ΔH_k has been found to increase with frequency due to the presence of rare earth impurities. Samples with small dopings of holmium emphatically demonstrate the presence of a contribution to the relaxation process which is proportional to frequency. By increasing the temperature, it is possible to reduce the rare earth contribution to the relaxation processes. In the samples which have a substantial rare earth doping both ΔH and ΔH_k show a temperature dependence in agreement with the theoretical work of Kittel and co-workers.[3] In both the doped and undoped samples ΔH, ΔH_k and h_{crit} decrease as the temperature is increased and reach a minimum value just below the Curie temperature.

*Support in part by the United States Army Signal Research and Development Laboratory and by the Air Research and Development Command U.S.A.F.

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61. METHOD FOR THE DETERMINATION OF FUNDAMENTAL TRANSITION PROBABILITIES IN FERRIMAGNETIC RESONANCE BY THE USE OF ELLIPSOIDAL SAMPLES

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Callen[1] has shown that the three fundamental transition probabilities of spin waves are related to the line width and relaxation times in ferrimagnetic resonance. Fletcher, LeCraw and Spencer[2] have measured these transition probabilities using a modulated rf power technique. An alternate method using ellipsoidal samples has been developed. The transition probabilities are related to the line width in the resonance experiments by

$$\gamma\Delta H = \frac{\lambda_{o\sigma}\lambda_{ok} + \lambda_{o\sigma}\lambda_{k\sigma} + \lambda_{ok}\lambda_{k\sigma}}{\lambda_{ok} + \lambda_{k\sigma}} \qquad (1)$$

where $\lambda_{o\sigma}$ is the probability of a transition from a $k = 0$ magnon to a phonon, λ_{ok} is the probability of a transition from a $k = 0$ magnon to a $k \neq 0$ magnon and $\lambda_{k\sigma}$ is the probability of a transition from a $k \neq 0$ magnon to a phonon. The transitions from $k \neq 0$ back to $k = 0$ magnons have been taken into account in deriving this expression as suggested by Seiden.[33]

The general expression for the resonant frequency of an ellipsoidal sample is

$$\omega = \gamma\left[H_o + (2\pi - \frac{3}{2}N_z)M_z\right] \qquad (2)$$

For a sphere the demagnetization factor $N_z = \frac{4}{3}\pi$, and the coefficient of the M_z term is zero. For an ellipsoid $N_z \neq 4/3\ \pi$ and M_z may be determined by measuring ω and the external field H_o. The z component of the magnetization is related to the rf power by

$$M_o - M_z = \frac{2M_o h^2\gamma}{\Delta H}\,\frac{\lambda_{k\sigma} + 2\lambda_{ok}}{\lambda_{k\sigma}\lambda_{ok} + \lambda_{k\sigma}\lambda_{o\sigma} + \lambda_{o\sigma}\lambda_{ok}}$$

where h is the amplitude of the linearly polarized rf field.

A single measurement of ΔH and M_z is not sufficient to determine the transition probabilities. However, if the experiment is repeated with the sample ground to a different eccentricity, the transition probabilities may be determined provided the relaxation to the lattice is not affected by the

change in eccentricity. This is a reasonable assumption if both experiments are performed at the same frequency.

Measurements were made on an oblate ellipsoidal sample of single crystal YIG. The sample, which was 25 mils in diameter with an eccentricity of 4.7, had its rotation axis in a [100] direction. The polished surface had one ten micron pit with no other flaws greater than one micron. The transition probabilities $\lambda_{k\sigma}$, $\lambda_{0\sigma}$, and λ_{0k} were determined from our data based on the assumption that the transition probabilities to the lattice are equal. These values are compared to those obtained by Fletcher, LeCraw and Spencer[2] using the modulation technique.

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62. METHOD FOR THE DETERMINATION OF THE TRANSITION PROBABILITIES OF SPIN WAVES IN FERRIMAGNETIC RESONANCE WITH THE AID OF MAGNETOSTATIC MODES

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The determination of the steady state value of the z component of the magnetization during a ferrimagnetic resonance experiment and the line width of the resonance can yield information about the transition probabilities of spin waves.[1] A procedure to determine the z component of the magnetization requiring the excitation of a magnetostatic mode has been developed. In this procedure power from two klystrons is incident on the sample simultaneously. The sample is positioned in a specially designed section of waveguide in such a way that the sample is in the uniform rf magnetic field of the klystron which is exciting the uniform precessional mode (k = 0) and in the rf field of the other klystron which is appropriate for exciting the 210 magnetostatic mode. The resonant frequency of the 210 mode is

$$f_{210} = f_0 - \frac{4}{15}\gamma M_Z$$

where f_0 is the resonant frequency of the k = 0 mode.[2] The difference in frequency of these two modes is directly proportional to M_Z. Increasing the rf power which is exciting the k = 0 mode increases the precessional angle of the spin system and diminishes M_Z. Although this power has been restricted to levels below that necessary for the onset of non-linearities, it still heats the sample resulting in a temperature dependent change in M_Z. Problems associated with detecting the weak signal from the magnetostatic mode in the presence of the much larger signal from the uniform precessional mode and with keeping the sample at constant temperature independent of the power incident on the sample have been solved and will be described.

Measurements have been made on a spherical sample of yttrium iron garnet. The frequency difference of two modes was measured as a function of power exciting the k = 0 resonance. These results, coupled with the measured line width, determine $\frac{n'}{n_0}$, where n' = number of $k \neq 0$ magnons and n_0 = number of k = 0 magnons, $\lambda_{0k}/\lambda_{k\sigma}$, and $\lambda_{k\sigma}/\lambda_{0\sigma}$. Values of these parameters will be presented.

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63. INSTABILITY OF MAGNETOSTATIC MODES IN A MICROWAVE MAGNETIC FIELD APPLIED PARALLEL TO THE DC FIELD*

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We have examined the stability criterion of the magnetostatic modes of a long circular cylinder magnetized along its axis assuming that a microwave magnetic field of sufficiently large amplitude is applied parallel to the dc field. Previous calculations of the instability threshold[1,2] have been based on a plane-wave analysis which is strictly applicable only in an infinite medium. According to the plane-wave analysis the rf field couples spin waves of equal and opposite wave number (momentum conservation). As a consequence the frequency of the unstable spin waves equals half the pump frequency. For samples of finite size the boundary conditions at the surface of the sample modify the selection rules. The rf field now couples many more mode pairs. Instability can occur if the frequencies of two such modes add up to the pump frequency. In addition the mode pair must satisfy two strict selection rules: The mode numbers corresponding to variation of the magnetostatic potential along the axis of the cylinder and also those corresponding to the angular variation (m) must be opposite and equal. The third selection rule (corresponding to the radial variation of the potential) is not generally applicable and becomes valid only if the sample diameter is much larger than the radial wavelength. The following results have been derived:

1. The surface modes[3] (with frequencies higher than the extrapolated spin-wave spectrum) are not subject to instability in this geometry.

2. For m = 0 the instability threshold is lowest if the mode frequencies equal one half of the pump frequency.

3. Instability at half the pump frequency can occur only for m = 0. The instability criterion for these modes is identical to that deduced on the basis of the plane-wave analysis, except that the frequencies now have to satisfy the characteristic equation derived from the boundary conditions.

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**Permanent address: Harvard University, Cambridge, Massachusetts.

[1] E. Schlömann, J. J. Green, and U. Milano, J. Appl. Phys. 31, 386 S (1960).
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64. TEMPERATURE DEPENDENCE OF THE SPIN WAVE SPECTRUM OF YTTRIUM IRON GARNET

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Growing pairs of spin waves of equal and opposite momentum, $\pm \vec{k}$, may be excited when an rf field of sufficient magnitude is applied parallel to the dc magnetic field.[1] The threshold is lowest for pairs with $\vec{k}$ transverse to the applied field. For such pairs one has

$$\left(\frac{\omega_p}{2\gamma}\right)^2 = \left(H_i + \frac{D}{\gamma\hbar} k^2\right)\left(H_i + 4\pi M_0 + \frac{D}{\gamma\hbar} k^2\right)$$

where ω_p is the angular frequency of the pump, γ the gyromagnetic ratio, H_i the internal dc magnetic field, M_0 the saturation magnetization and D_a constant. As shown by Turner,[2] if the excited spin waves have a velocity equal to $\frac{1}{\hbar}$ the phonon velocity the instability threshold is abruptly raised. If the phonon velocity is v, the break in the threshold appears at $k = \frac{\omega_p}{2v}$ or at a dc field given by

$$H_i\left(k = \frac{\omega_p}{2v}\right) - H_i\ (k = 0) = -D\left(\frac{\omega_p}{2v}\right)^2 \frac{1}{\gamma\hbar}$$

The displacement of the break from the field corresponding to k = 0 is thus directly proportional to D as long as v is unchanged.

In the present experiments this displacement has been measured as a function of temperature from 4°K to 450°K in very pure YIG at a pump frequency of 11.38 kMc. The results show that D increases by about 5% from 4°K to 100°K, remains essentially unaltered from 100°K to 325°K and then starts to fall at higher temperatures. It drops about 20% between 325°K and 450°K.

One may possibly account for this behavior by taking into account the ferrimagnetic character of YIG. If there is a temperature range in which the random phase approximation holds, one may assume that the spins S_A and S_B, which appear in the usual two sublattice theory, are proportional, at a finite temperature, to the sublattice magnetizations. Then the familiar theory of antiferromagnetic spin waves gives for YIG

$$D \propto \frac{-8\, J_{aa}\, M_a^2 + 3\, J_{dd} M_d^2 + 5\, J_{ad}\, M_a\, M_d}{3\, M_d - 2\, M_a}$$

where $M_{a,d}$ are the sublattice magnetizations and the J's Pauthenet's molecular field constants. In the absence of any other information one may use the molecular field values for $M_{a,d}$; the calculated variation of D now agrees excellently with the observations. The prediction of the correct qualitative behavior is more significant than the good numerical fit. It can be seen that the shape of the D vs. J curve will, in general, depend sensitively on the relative sizes of J_{ad} and $J_{aa,dd}$.

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65. FERROMAGNETIC RELAXATION AT LOW MICROWAVE FREQUENCIES*

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The observation of spin-wave instability in a microwave magnetic field applied parallel to the dc field[1] can be used to determine the magnitude of the spin-wave relaxation rate as well as its variation with wave number. This experiment is not subject to the low frequency limitations of conventional ferromagnetic resonance experiments in spherical samples since the frequency of the unstable spin waves approaches zero as the internal dc magnetic field approaches zero. The experiments indicate that the spin-wave relaxation rate varies linearly with the wave number (k). For pure yttrium iron garnet at frequencies below approximately 5 kMc the k-independent part of the relaxation rate appears to be largely due to the "splitting process"[2] in which the relaxing magnon imparts its energy and momentum to two daughter magnons. The splitting process can occur only if the pump frequency is less than $4/3\ \gamma\ 4\pi M$ (γ = gyromagnetic ratio, M = saturation magnetization). The k-dependent part of the relaxation rate is largely due to the "confluence process."[3,2] This contribution to the relaxation rate varies as the inverse second power of the frequency at low frequencies.

*Supported in part by the United States Army Signal Research and Development Laboratory and by the Air Research and Development Command U.S.A.F.

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SESSION G

HIGH COERCIVE MATERIALS

C. D. GRAHAM, Presiding

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66. THE DEVELOPMENT OF FINE PARTICLE MAGNETS (Invited)

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The development of permanent magnet materials is briefly reviewed. The present status of fine particle magnets is discussed from the viewpoint of our present understanding and lack of understanding of their behavior. The present method of preparation and the various theoretical descriptions of the properties of elongated particles are reviewed.

Recent advances in our fundamental understanding of the mechanisms responsible for the formation of elongated particles prepared by electrodeposition into mercury has resulted in the laboratory preparation of elongated iron particle magnets with energies up to 4.2 million gauss-oersteds and iron-cobalt particle magnets with energies above 6 million gauss-oersteds. The properties of these magnets will be discussed. New work is also presented relating the parameters of preparation to the resulting diameter of the elongated particles. Thus by controlled electrolysis into mercury, the diameters of elongated iron-cobalt particles were varied from about 100 to 350 Å without changing their relative structure or elongation. Rotational hysteresis, coercive force, and coercive force as a function of orientation were studied and found to be relatively invariant over this change in diameters. This observed behavior is compared to various theoretical descriptions and found to correspond to a non-coherent magnetization reversal mechanism most similar to the "chain of spheres" model rather than the "curling", "buckling" or "coherent rotation" models.

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67. MAGNETIC PROPERTIES OF SINGLE DOMAIN IRON AND IRON-COBALT PARTICLES PREPARED BY BOROHYDRIVE REDUCTION (Invited)

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Single domain iron and iron/cobalt particles with length-to-width ratios up to 20 : 1 have been prepared by the reduction in 500-1000 gauss magnetic fields of aqueous solutions of the metal salts with sodium borohydride. In the absence of a magnetic field shorter particles with lower coercivities are obtained. The bulky, air-stable particles .02-.10μ wide and up to 2μ long resemble strings of beads. The powders can be cold pressed into compacts of about 50% theoretical density. Saturation magnetizations (σ_s) of 120-170 emu, energy products up to 10^6 gauss-oersteds and total metal contents of about 90% indicate the presence of nonmagnetic components which are probably metal oxides.

Bulk coercivities of randomly oriented compacts are in the range of 500-700 oersteds for iron and 800-1200 oersteds for iron/cobalt and the packing dependence of coercivity is close to (1-p). Interpretation of the temperature dependence of coercivity in terms of the equation

$$H_C = A \times I_S + B \times K/I_S$$

shows contributions from both shape and crystalline anisotropy, with the former dominant. Particle aggregation is also indicated. Rotational hysteresis measurements furnish additional evidence that the iron and iron/cobalt particles have magnetic properties expected for long chains of small particles in approximate agreement with predictions based on the Jacobs-Bean "chain-of-spheres" model.[1]

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[1] I. S. Jacobs and C. P. Bean, Phys. Rev. 100, 1060-67 (1955).

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68. EXCHANGE ANISOTROPY IN OXIDIZED IRON-COBALT PARTICLES

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Compacts of single domain particles of iron-cobalt, prepared by borohydride reduction[1] and heated in air for several hours at temperatures of 400° C., showed increase in weight and decrease in specific magnetization corresponding to oxidation of ~ 30% of the ferromagnetic phase originally present. After oxidation three forms of evidence were found for the presence of exchange anisotropy upon cooling from room temperature to -196° C. (1) Cooling in a field of 4,000 oe. gave a large sin θ torque not present at room temperature and not present if cooled in zero field. (2) Cooling in a magnetic field caused a shift in the normal hysteresis loop along both the magnetization and field axes. It was deduced that for the fields used in tracing the loop (4,000 oe. maximum) there exists a "fixed" magnetization. This fixed magnetization was usually ~ 15% of the total magnetization and was in the direction of the field applied during cooling. Application of fields of the order 15,000 oers. at -196° reoriented a large part of the fixed magnetization. (3) Rotational hysteresis at high fields was present at low temperatures whether cooled in a field or in zero field. This hysteresis was in addition to the low field peak present at all temperatures due to the internal shape and crystalline anisotropy fields. The high field hysteresis rose rapidly up to 15,000 oe., and from the field dependence of hysteresis and sin θ torque it was concluded that anisotropy fields of ~ 30,000 oe. were present.

The basic mechanism believed effective here is that originally proposed by Meiklejohn and Bean[2] for the exchange interaction in Co-CoO. The ferromagnetic phase is believed to be the iron-cobalt cores of the individual particles and the antiferromagnetic phase a surface layer of CoO or CoO-FeO solid solution. The effective of T_N of the

antiferromagnetic phase was determined to be ~ -60° C. The weight increase upon oxidation would give monoxide coating on each particle of ~ 3 lattice spacings thick. Three possible sources for the fixed magnetization are (1) an unbalance of spins in the antiferromagnetic shell, as might occur for exactly three layers; (2) the outermost spins of the ferromagnetic core held aligned by exchange with the surface and (3) a ferrimagnetic phase arising from ordering in a CoO-FeO solid solution.

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[2]W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956).

69. UNDIRECTIONAL PROPERTIES IN THE IRON-IRON SULFIDE SYSTEM

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The presence of unidirectional properties has been observed in the iron-iron sulfide system.[1] Iron particles, formed by decomposition of the formate, were reacted with H_2S at 350° C. Compacts of the powder, when cooled in a magnetic field, displayed sin θ variation of the torque and a nonvanishing rotational hysteresis for applied magnetic fields $> 2K/I_s$.

Subsequent investigations have been made on the temperature dependence of the sin θ term, maximum torque, and rotational hysteresis as a function of increasing field. Torque curves were measured for applied fields up to 7,000 oe. at temperatures between 140° and -196° C. Maximum torques of 10^6 to 10^7 dyne-cm/cm^3 of Fe were measured at -196° C and 7,000 oe. For a 6,000 oe. measuring field, the rotational hysteresis increased from -196° C to a maximum of 10^6 to 10^7 ergs/cm^3 of Fe/cycle at -75° C. The Néel temperature of iron sulfide is ~ 340° C, however, there is a reordering temperature reported[2] at ~ 130° C. At 6,000 oe the rotational hysteresis approached zero at the reordering temperature rather than at the Néel temperature. No increase in maximum torque was found when cooling in a field from temperatures greater than 150° C. Repeated cooling from temperatures near the Néel temperature resulted in a decrease in torque possible due to desulfiding and/or sintering.

Two particularly interesting effects occur at the higher temperatures with high fields (1) the sin θ term disappears with a large rotational hysteresis remaining, and (2) the unidirectional axis, obtained by cooling in a magnetic field, can be rotated from its original direction. The observed behavior may be explained by assuming that the antiferromagnetic spins near the interface are irreversible realigned when the iron spins are rotated in a strong magnetic field. This would be expected to occur if exchange interaction[3] between the spins of the ferromagnetic iron and the antiferromagnetic iron sulfide were sufficiently strong

[1]J. H. Greiner, I. M. Croll, and M. Sulich, to be published.
[2]T. Nagamiya J. Phys. Radium **20**, 70 (1959)
[3]W. H. Meiklejohn and C. P. Bean, Phys. Rev. **105**, 904 (1957)

70. A NEW, LIGHT WEIGHT MATERIAL FOR PERMANENT MAGNETS

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An investigation of the system cobalt, iron, and oxygen has led to the preparation of a highly anisotropic structure having a composition in the region 28% Co, 57% Fe, and the balance oxygen. By suitably controlling the amount of oxygen present, high intrinsic coercive forces, typical of ferrite structures, as well as high saturation magnetizations can be achieved. Permanent magnets, having a physical density of 3.7 grams/ccm. were prepared from this material and had the following properties:

B_r	= 6000 G
B_{is}	= 6850 G
H_{ci}	= 1750 Oe
H_c	= 1600 Oe
$(BH)_{max}$	= 4.0 x 10^6 G.Oe

Coercive force measurements, electron photomicrographs, and demagnetization curves are shown as a function of Co, Fe, and oxygen composition.

71. STRUCTURE OF ALNICO V

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The microstructure and crystal structure characteristics of Alnico V in various conditions of heat treatment have been determined by electron transmission microscopy and by electron and X-ray diffraction. Single crystal X-ray data confirms the presence of order in this system.

The a_o values of the different cubic phases have been determined from the electron diffraction data by using a MgO smoke film as an "internal" standard.

In the water-quenched condition this material is a single phase; b.c.c. with $a_o = 2.84 \pm 0.03$ Å.

Transmission electron micrographs of the material in the magnetic field cooled condition show a structure appearing to be comprised of a matrix phase and a well-developed, oriented rod-like precipitate phase. Transmission diffraction patterns of the micrographed regions reveal the presence of two phases a_o values are found to be 2.84 ± 0.03 Å and 2.62 ± 0.03.

In the fully heat-treated (i.e., field cooled plus coercive-aged) condition the same microstructural appearance and lattice parameters, within experimental error, prevail. The change in magnetic properties with coercive aging appears to be due to phenomena not determinable by these means.

Magnetic test data also show that anisotropy is developed by field cooling alone.

72. MAGNETIC ANNEALING OF "TICONAL" G MAGNET STEEL

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A study was made of anisotropy and interparticle distance in "Ticonal" G, a dispersion-hardening permanent magnet alloy, when subjected to heat treatment in a magnetic field.

From simultaneous measurements of the saturation magnetization after isothermal heat treatment it was observed that decomposition of the homogeneous alloy into two phases was complete after the first few minutes of heat treatment and that the occurrence of anisotropy and the growth of the particles during the rest of the heat treatment must be entirely due to the change in particle shape and volume respectively, the total volume and composition of each phase remaining constant.

The experimental results support the correctness of a theoretical diffusion model in which the amount of material transported by diffusion per unit time is made proportional to the decrease in free energy corresponding to the amount transported.

It is concluded that the response to thermomagnetic treatment depends on the ratio between the magnetostatic energy of the dipolar field of the particles and the interfacial free energy between the phases. An estimate of these two energies is made from the experiments.

73. CRYSTAL LATTICE INVESTIGATION OF THE PERMANENT MAGNET PRECIPITATE IN VARIOUS ALNICO MATERIALS*

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Transmission electron diffraction has been applied to study the crystal lattices of various Alnico materials. The method seems to be accurate enough to determine quantitatively the differences in the lattice parameters of different Alnico materials in the as-cast state. During the technical heat treatment a phase precipitates which has a lattice parameter of 2.88 Å. Within the limits of error we found this parameter uniform for all investigated Alnico alloys in spite of their different original composition.

The different magnetic properties of different Alnico magnets are correlated to the mosaic structure and the degree of ordering achieved by this precipitated phase. These factors vary considerably for the different Alnico materials as electron diffraction reveals. In Alnico V particularly in the grade with columnar crystal growth (energy product above $7 \cdot 10^6$ gauss oersted) the precipitate appears to have developed into a network extending continuously throughout the magnet body displaying single crystal order.

*Work was sponsored by the Wright Air Development Division of the Air Research and Development Command of the United States Air Force.

74. SOME INVESTIGATIONS ON IRON-COBALT PERMANENT MAGNET ALLOYS OF THE VICALOY II TYPE

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A permanent magnet alloy composed of 52% Co, 8% V, 4% Cr, balance Fe was subjected to severe cold working by drawing or rolling to produce a reduction in cross-sectional area of over 90%, and to subsequent heat treatments at temperatures varying between 20 and 700 deg C, after which the following properties were measured: magnetic saturation as a function of temperature in the range from - 200 to + 700 deg C; coercive force as a function of temperature in the range from - 200 to + 400 deg C; remanence torque in the magnetic field and anisotropic energy; and longitudinal magnetostriction as a function of temperature in the range from + 20 to + 400 deg C. Vickers hardness, ultimate tensile strength, Young's modulus, and coefficient of expansion were also in some cases determined and electron photomicrographs of the structure taken. The permanent magnet alloy tested consists of a fine two-phase structure of which only the body-centered cubic α-phase is ferromagnetic above room temperature, while the second phase becomes ferromagnetic only at temperatures below room temperature. Magnetizing and demagnetizing of this alloy is brought about chiefly by domain rotation. Basically, permanent magnet characteristics are not produced by crystal anisotropy or anisotropy of directional order but by a single-axis anisotropy which may be either a shape or a tension anisotropy. The measured magnetic properties can be more easily explained by an anisotropy of internal stresses, which in one model concept, is produced by the process of α-γ transformation because of the clear-cut textures of both components. There are also indications that the mutual transformation of the two structure components coincides with noticeable shifts in chemical composition or in order, particularly in the γ-phase.

75. TEMPERATURE DEPENDENCE OF MAGNETOSTRICTION AND ANISOTROPY IN MnBI*

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Measurements were made of the magnetostriction and anisotropy in oriented polycrystals of MnBi at various temperatures between 77 and 300° K. The magnetostriction constants in a four constant expression have been evaluated as a function of temperature, and the first three anisotropy constants also have been estimated. At least at the lower temperatures it is found that all three constants are necessary to fit the anisotropy data.

*This work was supported by the Aeronautical Research Laboratory at WADC, Air Force Contract No. AF33 (616)-5555.

76. STUDIES OF A HIGH COERCIVITY ELECTRODEPOSIT HAVING A LAMELLAR STRUCTURE

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A cobalt-nickel-phosphorous electrodeposit having a 60-cycle coercive force of 1000 oersteds has been prepared. Electron micrographs of the surface of the deposit indicate that a lamellar type of structure is present. The lamellae appear to be about 500Å wide, to 1000Å wide, grow with their thinnest dimension perpendicular to the base metal, and occur in oriented clusters. The coercivity is independent of deposit thickness, as would be expected from the lamellar structure.

X-ray diffraction studies show the material to be hexagonal with its main (c) axis in the plane of the film. The uniaxial easy direction of magnetization is also in the plane of the film. The film is isotropic, probably due to the random orientation of lamellae clusters.

Since individual lamellae are in the order of 1000Å thick and clusters are about one micron across, domain studies were undertaken utilizing the high resolving power of the electron microscope. The method of Craik[1], which results in a dry film suspension of magnetite suitable for viewing in the electron microscope, was utilized. The surface of a demagnetized sample shows a magnetite pattern, at 4000X, which implies that poles exist only at cluster boundaries. The surface of a magnetized sample shows no magnetite pattern.

In order to verify these conclusions, an extension of the technique was developed. The dry film containing the magnetite is pulled from the sample and a film of carbon is shadow cast upon it. Since the carbon film forms a replica of the surface, the domain structure and the surface topography of the deposit can be seen simultaneously. With the use of this method it becomes clear that the demagnetized surface has poles only at the boundaries of lamella clusters and that the magnetized surface has no poles which are not in the plane of the film.

It is suggested that each lamella is a single domained particle. This explains the unusually high coercive force and accounts for the absence of domain walls between lamella. The magnetite collections on the demagnetized surface are attributed to closure fields, rather than to domain walls. In the case of the magnetized surface, internal closure is possible because all lamellae have a magnetic component in the direction of the previously applied field.

[1]D. J. Craik and P. M. Griffiths, Brit. J. Appl. Phys. (9), 279 (1958).

SESSION H

EXCHANGE INTERACTIONS AND NONLINEAR MICROWAVE PROCESSES

E. SCHLÖMANN, Presiding

77. OPTICAL AND INFRARED SPECTRA OF THE FERRITES AND GARNETS (Invited)

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Although the ferrimagnetic spinels and garnets are normally opaque to the eye, appropriate sample preparation techniques allow the observation of the absorption spectra of many of these crystals from the far infrared to the visible. Furthermore, transparent analogue crystals (e.g., magnesium gallium spinel and yttrium gallium garnet) exist, and these analogues may be studied by infrared or Raman techniques or they may act as hosts for the study of pertinent paramagnetic ions on sites similar to those on which they occur in the ferrites and iron garnets. The phenomena subject to examination by spectroscopic techniques include (among others) the excitation of crystal vibrations, the excitation of electrons of transition metal and rare earth ions, composite transitions involving both of the above types of excitation and in some instances the excitation of localized vibrations of complex ion impurities. All of the above types of spectra occur in the ferrites and garnets and information obtained therefrom can have bearing, either directly or indirectly, on the magnetic properties of the materials.

This paper will consist for the most part of a discussion of these various types of spectra and the light they can shed on the magnetic behavior of the corresponding materials. Existing data will be cited, and areas where further work is to be desired will be discussed.

The final few minutes of the talk will be reserved for a discussion of a highly specialized example of a spectroscopic study of the garnets intimately related to magnetic properties—the study of the rare earth-iron exchange interaction by optical techniques. The data which will be presented allow direct calculation of exchange fields and a direct test of the isotropic exchange model as well as calculation and (independent) measurement of gross magnetic anisotropies. Problems encountered or anticipated in the study of the various rare earth iron garnets will be discussed.

78. ELECTRON SPIN RESONANCE MEASUREMENTS OF EXCHANGE INTERACTIONS (Invited)

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Oxford, England

A brief survey is given of some electron spin reso-

nance experiments on exchange coupled pairs of paramagnetic ions and magnetically dilute crystals. Some examples are discussed, particularly pairs of Mn^{2+} ions in MgO where the exchange is expected to be similar to that responsible for the antiferromagnetism of MnO. It is found[1] that the isotropic exchange interaction, $J\,\underline{S}^i \cdot \underline{S}^j$, is approximately the same for nearest neighbours (Mn-Mn) as for next nearest neighbours (Mn-O-Mn), the value of J being about 20 cm^{-1}. The anisotropic part of the interaction is found to be mainly due to the expected dipole-dipole coupling, though for nearest neighbours there are also other contributions.

[1]B. A. Coles, J. W. Orton and J. Owen, Phys. Rev. Letters, 4, 116 (1960)

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79. CHROMIUM ION PAIR INTERACTIONS IN THE PARAMAGNETIC SPECTRUM OF RUBY

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Raytheon Company
G. F. KOSTER
Massachusetts Institute of Technology

In crystals of Al_2O_3 with concentrations of 0.05 atomic percent and higher of Cr_2O_3 one can readily detect besides the normal lines due to isolated Cr^{3+} ions, an additional weak spectrum which is attributable to Cr^{3+} pairs interacting through exchange and dipolar forces. We have extended earlier measurements [Phys. Rev. Letters 4, 125 (1960)] and have attempted to explain the main features of the spectrum. Paramagnetic resonance measurements were made on samples with concentrations of Cr_2O_3 of 0.05, 0.15, and 0.5 atomic percent. The temperature range covered was 700° K to 1.2° K. The magnetic field ranged from a few hundred gauss to about 8.4 kgauss and it was chosen to lie along the c-axis of the crystal.

Theoretical analysis predicts and experimental measurements confirm that relatively distant neighbors with negligible exchange interactions give rise to lines which cluster around the transitions due to isolated Cr^{3+} ions with a spread of a few hundred gauss. The separations from the main line are due to dipolar interactions. The intensity of these lines follows 1/T where T is the absolute temperature. Pairs coupled through exchange forces which are strong as compared to the Zeeman and crystalline field energies give rise to lines that cluster around certain magnetic field values which in general are different from those of the isolated chromium transitions. According to perturbation theory the various clusters should be simply related to each other, a prediction which checks approximately with experiment. Exact calculations on the I.B.M. 704 computer have been used to assign certain lines in a cluster to certain neighbors. It appears that up to the 8th neighbor shell the exchange interaction is strong enough to have the corresponding pairs contribute to the clusters. The variation of line intensity with temperature is used to determine the exchange forces between the various neighbors.

Other lines corresponding to pairs in which the exchange interaction is comparable to the Zeeman and crystalline field energies depend for their position on the exact magnitude of the exchange interaction. Because of the strong dependence of the exchange interaction on the lattice constant these lines shift very rapidly with temperature. It is also observed that these lines have a much shorter spin lattice relaxation time which indicates that the exchange interaction is of importance in the coupling of the spins to the lattice. Measurements of the type described are believed to be very useful in studying the details of exchange interactions in solids.

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80. MAGNETIZATION AT ULTRA-HIGH PRESSURES

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Laurence G. Hanscom Field
Bedford, Massachusetts

Recent developments in the field of ultra-high pressure research have resulted in the development of equipment and associated techniques capable of reaching pressures of 150,000 bars at temperatures in excess of 3,000° C. One such facility, a 600-ton tetrahedral-anvil press, has been utilized to examine selected properties of ferrimagnetic and ferromagnetic materials. This press has a maximum sample cavity size of approximately 3/8 inch by 1/2 inch. A special cell, which fits into this cavity, has been designed which permits the determination of several of magnetic properties. The sample is in the form of a small toroid. The heater, producing the temperature, also provides magnetization for the core. A metallic cup, holding the core, provides a one turn pick up loop and at the same time acts as one thermocouple lead. This method of operation requires the minimum number of leads be brought out of the high pressure cavity. The type of measurements that can be performed in this type cell include determination of the existence of ferrimagnetism or ferromagnetism, the measurement of Curie temperature, and a reasonable indication of saturation flux density and magnetizating force. Curie temperature as a function of pressure has been investigated in several materials. The maximum pressure utilized was 100,000 bars at temperatures sufficient to determine the Curie temperature. The effects of pressure on Curie temperature have been studied in terms of existing theories, structure of the material, and exchange forces present.

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81. ANISOTROPIC CURIE TEMPERATURE

EARL R. CALLEN
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In previous work[1] we have discussed from a perturbation theory viewpoint the variation of the magnitude of the magnetization as it is rotated with respect to the crystal axes in an anisotropic material. However, when perturbation theory is employed, the Curie temperature is inde-

pendent of the orientation of the magnetization. We now consider a case in which the anisotropy energy can be comparable with the exchange. Our model is a quantum-mechanical internal field Hamiltonian with a one-ion uniaxial anisotropic term, which we treat exactly. We calculate the variation of the magnetization with orientation at fixed temperature, its variation with temperature at fixed orientation, as well as the dependence of the Curie temperature on the orientation of the magnetization. The magnetization satisfies an equation which reduces to a Brillouin function only in a particular intermediate direction. In easier directions the Curie temperature is higher, because the anisotropic forces help to hold the spins together. In harder directions, the Curie temperature drops very quickly to 0°K with increasing anisotropy. When the ratio of anisotropy to exchange energy exceeds a particular value, the magnetization curves take a very peculiar form; the magnetization falls off with increasing temperature, down to a critical size, and then drops discontinuously to zero at the Curie temperature. Comparison will be made with experiments[2,3] which we believe have shown some of these effects.

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[1]Earl R. Callen and Herbert B. Callen. "Anisotropic Magnetization." To be published in J. Phys. Chem. Solids. A short discussion appears in J. Appl. Phys. Supplement 31, 149S (1960).

[2]Kirby Dwight and Norman Menyuk. "Magnetic Properties of Mn_3O_4 and the Canted Spin Problem." Lincoln Laboratory Report 53-34, Feb. 2, 1960.

[3]Behrendt, Legvold and Spedding, Phys. Rev. 109, 1544 (1958).

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82. INTERACTION OF SPIN WAVES AND PHONONS IN YIG (Invited)

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Pairs of spin waves of a known direction and wavelength can be generated by means of a microwave magnetic field applied parallel to a steady biasing field. The relaxation time of these spin waves can be measured by determining the magnitude of the microwave field required to generate them. In the course of making such a determination of relaxation times it was found that at certain values of biasing field more power was required to initiate growth of spin waves, indicating that these spin waves were damped more heavily. The frequency dependence of these anomalies indicates they are due to direct interaction of spin waves and phonons.

The experimental methods used in making the observations will be described. Measurements have been made over a range of temperatures and the results of these measurements will be discussed.

83. LINE SHAPE OF SUBSIDIARY RESONANCE IN YIG

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The real and imaginary components of susceptibility at subsidiary resonance have been measured for a polished YIG sphere. These measurements were made as a function of d.c. magnetic field and power level for both h_{rf} parallel and perpendicular to the applied magnetic field.

The results for h_{rf} parallel to the applied field are as follows: For h_{rf} just above the critical value ($\frac{h_{rf}}{h_{crit}} = 1.12$) the "resonance" linewidth is approximately 40 oersteds. As h_{rf} is increased χ'' increases and the linewidth broadens. Large amplitude relaxation oscillations are also observed on the high field side of the absorption curve similar to those previously reported[1] for the main resonance. For still larger h_{rf} ($\frac{h_{rf}}{h_{crit}} = 1.78$) the absorption broadens rapidly to low d.c. field values with the line becoming highly asymmetric and several broad sets of low amplitude relaxation oscillations are observed on both sides of the absorption peak. As the power is increased further, χ'' declines as expected. The χ' is always quite small throughout the range of powers and is of the order of .01 while χ'' is of the order of 0.1.

The line shape and variation of χ'' for h_{rf} oriented perpendicular to H_{DC} is in qualitative agreement with theory. For the χ' variation a detailed theory is not yet available to afford a check on the experiment. In addition for perpendicular orientation strong relaxation oscillations are again observed.

The relation of these results to spin wave theory and to parametric amplifier design will be indicated.

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[1]M. T. Weiss, Phys. Rev. Letters, 1, 239, October 1, 1958.

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84. PARAMETRIC EFFECTS IN MAGNETOACOUSTIC RESONANCE

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Stanford, California
G. WADE
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Burlington, Massachusetts

E. G. Spencer and R. C. LeCraw observed acoustic vibrations of a Y.I.G. sphere excited by microwave power[1] and have proposed that the oscillations are due to the parametric excitation of a magnetostatic-acoustic mode pair. This paper discusses verification of this proposal along with new results concerning the behavior of the system for microwave pump powers less than that necessary to excite the acoustic vibrations.

An analysis extending Kittel's field—theoretical treat-

ment of the interaction between the magnetization of a ferrite sample and the elastic strain[2] has predicted the acoustic excitation. A nonlinear magnetostrictive coupling is shown to exist between the uniform precession and the acoustic modes. When driven by microwave fields of sufficient amplitude, this nonlinear coupling can result in parametric excitation of the acoustic modes. This analysis also predicts the threshold microwave power necessary for acoustic excitation in terms of, among other things, the acoustic Q.

In order to check the above prediction of threshold pump power, experiments were devised to measure the acoustic Q. A technique was used which involved pulsing the oscillations on with a pulse modulated pump and then observing the decay in oscillation amplitude with the pump switched off. The acoustic Q was found to be between 30 and 40,000. Measurements at liquid nitrogen temperature show little change in this value. The measured value of acoustic Q leads to a calculated threshold pump power which is in reasonably close agreement with experiment.

Since the uniform precession-acoustic mode system can be parametrically excited into oscillation, we have been led to investigate its behavior for pump powers less than the oscillation threshold. Using a microwave signal as a probe of the shape of the uniform precession resonance while another signal was used as the pump, we have observed negative resistance effects reflected into the uniform precession mode. The d.c. magnetic field was swept across the uniform precession absorption while both signals were present, the pump being filtered out before detection of the line shape. The observed absorption line first becomes narrow and then broadens out and eventually disappears as the pump power approaches the oscillation threshold. This is consistent with the behavior of an equivalent circuit model derived from the analysis.

[1]E. G. Spencer and R. C. LeCraw, Phys. Rev. Letters 1, 241 (1958)
[2]C. Kittel, Phys. Rev. 110, 836 (1958).

85. NON-LINEAR RESPONSE OF YIG*

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A study of the small, and not so small signal, second harmonic output of a single crystal YIG sphere has been made. The significant results, to date, are:

1. The crystalline magnetic anisotropy appears to be primarily responsible for the observed second harmonic.
2. At signal levels significantly above the first saturation threshold large scale (up to 20 db), coherent amplitude modulation appears on the second harmonic.

The 0.020'' sphere is mounted on a dielectric rod in the center of a non-resonant, matched, dielectric loaded, rectangular waveguide, to suppress the excitation of higher magneto-static modes and to avoid confusion with circuit effects. The second harmonic is observed in a superheterodyne receiver. The fundamental is supplied by a pulsed, 100 watt, X-band magnetron with a pulse width of >20 microseconds. The crystal is X-ray oriented within 0.2° and may be rotated about a [100] axis.

A second order solution to the torque equation, including anisotropy, has been obtained which shows a term in $\dot{m}_z$ at the second harmonic which depends on K_1/M_s $(1 - \cos 4\theta)$ where θ is the angle between H_z and a [100] crystal axis. The data has an 8 θ dependence with minima along both [100] and [110] directions. The peak to valley ratio of second harmonic output is more than 20 db.

Second harmonic is first observed at about 1 milliwatt peak power for favorable orientations. As the fundamental is increased, saturation begins at 10 - 100 milliwatt level. When 1 watt peak power is reached amplitude modulations begin to appear. These are coherent within a pulse and repeat from pulse to pulse. The frequencies of these modulations may be anywhere from 100 Kc to several megacycles, and may be varied by both power and magnetic field. Attempts to observe correlated variations in the absorption of the fundamental are inconclusive. However, a small one loop coil around the ferrite does detect correlated variations in M.

*This work was performed under Contract No. AF 19(604)-5512 with Air Force Research Division.

SESSION I

MAGNETIZATION PROCESSES AND FINE PARTICLES

D. S. RODBELL, Presiding

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86. THE TEMPERATURE DEPENDENCE OF SPONTANEOUS MAGNETIZATION IN SUPERPARAMAGNETIC NICKEL

CARLOS R. ABELEDO and P. W. SELWOOD
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The possibility of an anomalous temperature dependence of the spontaneous magnetization of superparamagnetic particles has been the subject of several investigations. Knappwost and Illenberger[1] found the spontaneous magnetization of 14 A. cobalt particles to be independent of temperature up to 573° K.; Cahn, Jacobs and Lawrence[2] found no temperature dependence for 16 A. cobalt particles between 4.2° K. and 300° K. but Kneller[3] reported a Curie temperature of 270°K. in 23 A. Ni_3Mn particles as contrasted with the normal Curie temperature of 740°K. Henning and Vogt[4] have also reported an anomalous temperature dependence of the spontaneous magnetization of iron amalgams. The problem is one of some importance in the interpretation of magnetization-volume isotherms used to determine the mechanism of chemisorption as of hydrogen on nickel surfaces.

We have investigated nickel particles in the 30-150 A. diameter range. These were prepared on silica gel supports in the manner familiar in contact catalysis. The magnetizations were measured as described by Dietz and Selwood.[5]

The initial slope of the magnetization curve is proportional to the square of the spontaneous magnetization $I_S(T)$. From the determination of these slopes at several temperatures between 298° K. and 500° K. we have calculated $I_S(T)/I_S$ (298); these values may be compared with the accepted values for bulk nickel[6]. Results on the four separate preparations thus far investigated, containing nickel particles in the 30 A. to 150 A. range show a normal temperature dependence of the spontaneous magnetization. The maximum probable experimental error was estimated as 10%.

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[1]Knappwost and Illenberger: Naturwissenshaften **45**, 238 (1958).

[2]Cahn, Jacobs and Lawrence: as quoted by Bean and Livingston, J. Appl. Phys. Supplement **30**, 120S (1959).

[3]Kneller: Z. Physik, **152**,574 (1958).

[4]Henning and Vogt: J. Phys. Rad., **20**, 277 (1959).

[5]Dietz and Selwood: J. Appl. Phys. Supplement, **30**, 101S (1959).

[6]Weiss and Forrer: Ann Physique, **5**, 210 (1926).

87. THE MAGNETIC PROPERTIES OF ANGSTROM DIAMETER IRON PARTICLES

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Spherical iron particles were prepared by electrodeposition into mercury and heat aged to produce samples of increasing average particle size. The complete magnetization curves in fields from 0 to 150,000 oersteds were obtained as a function of temperature from 4° to 300° K. Particle size and size distributions were calculated from the magnetization curve at sufficiently high temperatures so that the samples were completely superparamagnetic by means of the Langevin function. These results were compared to the particle sizes calculated from the temperature dependence of the remanence to saturation ratio. The two methods show substantial agreement and are consistent with the properties and sizes of larger particles previously determined by direct electron microscope examination. The mean particle diameters thus determined were from about 15Å for the freshly deposited samples to about 60Å for the aged samples. Beyond this range the onset of stable magnetic behavior in a large fraction of the particles made the particle size calculation by these methods unsuitable. The shape of the magnetization curve of the initially prepared samples is independent of concentration from 0.2 to 4% iron by volume. The smallest particle size samples required fields of the order of 50,000 oersteds or more to unambiguously determine their saturation magnetization. The saturation magnetization remained constant even down to the 15 Å particle sizes and corresponded to the total iron present.

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88. BEHAVIOR OF FERRI- OR FERROMAGNETIC VERY FINE PARTICLES*

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Very fine particles refer here to single domain particles of such a size that the thermal effect is significant. The relative importance of thermal energy and anisotropy energy determines whether the particles fall in or out of the superparamagnetic region. This classification of superparamagnetism differs from the strict paramagnetic requirement of Bean and Jacobs[1] and Néel's[2] relaxation time criterion.

Within the superparamagnetic region a phenomenological calculation, including anisotropy terms for the uniaxial, cubic and hexagonal symmetries, yields the initial susceptibility as rapidly convergent sums of complete beta functions. Outside the superparamagnetic region the distribution of particle moments is localized on several solid angular sectors which require separate calculations. Good approximations can be obtained in terms of complete and incomplete beta functions. Within these regions which are connected by relaxation processes, Néel's[3] or Brown's[4] expressions for transitions are valid.

At various temperatures measurements of initial susceptibility of ferrite particles[5] of various types and several sizes are made by a 60 cycle loop tracer. Samples falling in or out of the so defined superparamagnetic region are clearly indicated. Size effects in saturation magnetization are clearly evident.

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*Supported by grant from American Iron and Steel Institute

[1]Bean, C. P. and Jacobs, J. D., J.A.P. 30, 120S, 1959

[2]Néel, L., Ann. Geophys. 5, 99, 1949

[3]Néel, L., loc. cit.

[4]Brown, W. F., J.A.P. 30, 130S, 1959

[5]All the ferrite particles were prepared by Dr. W. J. Schuele of the Franklin Institute Laboratories

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89. PREPARATION, GROWTH AND STUDY OF ULTRA FINE FERRITE PARTICLES*

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Ultra fine ferrite particles were prepared by a chemical precipitation process below 100° C in an aqueous medium. Variations in the initial preparation resulted in materials with different magnetic and physical properties. The resulting materials were grown hydrothermally at moderate temperatures for extended periods of time. Samples were removed at various times during the growing process and their magnetic and physical properties determined. Coercive forces varied from zero for some truly superparamagnetic samples to ca. 800 oersteds at room temperature for some hydrothermally grown cobalt ferrites. At liquid nitrogen temperature coercive forces to 10,000 oersteds were measured. Crystallite size measurements were made by x-ray line broadening and the particle size was determined by electron microscopy. An apparatus to measure hysteresis loops in pulsed fields was constructed and used for measuring magnetic properties of samples difficult to saturate, i.e. cobalt ferrite samples at -196° C. Good agreement was obtained between pulsed fields and d.c. measurements where samples could be measured by both systems.

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90. FINE-PARTICLE FERRITES . I . NICKEL FERRITE

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The objective of this investigation was the development of a process for preparing dense nickel ferrite bodies composed of grains small enough to remain single domain, and determining the magnetic and crystallographic properties thereof. This was accomplished by combining two techniques, flame-spraying and hot-pressing, and investigating the effect of varying the parameters in each of these. Powders as fine as 0.02 micron were prepared of single phase ferrites of various Ni/Fe ratios, and these were subsequently densified by hot-pressing while maintaining the crystallite size at 0.06 micron (below the critical size for single-domains). The effect on μ' and μ'' as a ferrite is annealed through the critical size for single-domains will be shown. Magnetic measurements include μ' and μ'' (to 1000 mc/s), B_S, B_r, H_c, and incremental μ, as well as the temperature dependence of some of these properties. Of practical interest was an improvement in the temperature coefficient of initial permeability over conventionally prepared ferrite. X-ray diffraction determinations of crystalline phases and crystallite sizes will be presented, along with measurements of apparent density. Some theoretical considerations will be discussed.

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91. THE ANGULAR VARIATION OF THE MAGNETIC PROPERTIES OF PARTIALLY ALIGNED γ-Fe_2O_3 PARTICLES

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Using a torsion balance magnetometer, measurements have been made on oriented particles of γ-Fe_2O_3 covering a range of packing densities. Microscopic examination revealed that the specimens consisted essentially of long chains of particles, parallel to the orientating field, with varying degrees of cross linkages. Measurements were made as a function of the angle between the direction of the orientating field and the direction of the measuring field. The graphs of H_c (the coercivity) versus angle showed a characteristic peak at 50-60°, while H_r (the remanence coercivity) has its highest value at 90° to the chains and decreases with decreasing angle. Thus, the samples showed their lowest value of H_c and highest value of H_r at 90° to the chains. Results will also be presented of torque curves and rotational hysteresis measurements made on the samples.

Finally, agreement between these results and those predicted by current models of fine particle behavior will be discussed.

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92. COHERENT AND INCOHERENT MAGNETIZATION PROCESSES IN POWDERS

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The magnetic properties of a random assembly of uniaxial non-interacting particles are considered on the basis of two extreme mechanisms of magnetization reversals:

(a) coherent reversals, (b) completely incoherent reversals for which only the field component parallel to the easy direction of each particle is effective. Mechanism (b) corresponds, in a way, to pure 180° wall motion. The bulk properties are determined for each mechanism as weighted averages, the weighting factor $f(H_0)$ corresponding to the variations of the critical field H_0 for irreversible magnetization changes. Special integral expressions involving the bulk properties are, however, shown to be independent of $f(H_0)$, and may thus be used, in principle, to differentiate between the mechanisms (a) and (b). As examples the following properties are considered: (1) Static remanence curve, (2) remanence acquired after the application of a field H and its rotation through 180°, measured in a direction perpendicular to H in the plane of rotation, (3) alternating and (4) rotational hysteresis loss (a particular case involving (4) is the rotational hysteresis integral). Methods are also suggested for determining $f(H_0)$ from the field dependence of these properties.

The effects on this analyses of 'interactions' are briefly considered and an approximate criterion for their neglect is suggested.

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*On leave of absence from Weizmann Institute of Science, Rehovoth, Israel; at present at Franklin Institute, Philadelphia, Pennsylvania.

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93. THEORETICAL MAGNETIZATION CURVES FOR PARTICLES WITH CUBIC ANISOTROPY

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Saint Paul 6, Minnesota
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Theoretical hysteresis loops have been calculated for a single crystal ferromagnetic particle with only cubic magnetocrystalline anisotropy. These calculations have been carried out for various crystal orientations with the applied field. The method of computation consists of determining the magnetostatic energy over the unit sphere and then searching for minima.

The curves appear similar to those so resulting from shape anisotropy (Stoner-Wohlfarth) except that with certain orientations, states of stable magnetization appear which are inaccessible by traversing hysteresis loops. Averaging of the coercive force over all orientations for both positive and negative anisotropy has been carried out in that range of fields where no jumps occur.

A complication which causes some uncertainty is the existence, with certain particle orientations, of several stable states at which a jump might terminate. It is impossible to decide for our static energy calculation which path the magnetization follows during reversal.

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*Now with Leyghton-Paige Corporation, Spring Park, Minnesota.

94. ON ADDITIVITY OF IMPERFECTIONS AS MEANS FOR DOMAIN NUCLEATION

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One of the possible a priori ways to resolve the Brown Paradox[1] is to assume[2] that the magnetocrystalline anisotropy is zero in a certain region. A one dimensional study of this possibility[3] showed, however, that one cannot reduce the theoretical field by more than one order of magnitude[4] for reasonable sizes of the "defective" region in which K=O. There still remained the possibility that several "defects" of similar type will further reduce the nucleation field.

To settle this point, two one dimensional cases are studied here. In the first case two such defective regions equal in length are assumed. It is found that the nucleation field is smaller the closer these regions are to each other. However, even when this distance is 0.1 the width of each region, the nucleation field is somewhat larger than when only one such region is present. The second case is a periodic array of such "defects" over the whole (infinite) material and it is found that the nucleation field becomes even larger than in the case of two "defective" regions.

The model is therefore insufficient to resolve the Brown Paradox.

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[1]W. F. Brown, Jr., Revs. Modern Phys. 17, 15 (1945)
[2]Rathenau, Smit and Stuyts, Z. Physik, 133, 250 (1952)
[3]A. Aharoni, J. Appl. Phys. 30, 70 S (1959)
[4]A. Aharoni, Phys. Rev., July 1st issue (1960)

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95. QUANTITATIVE DETERMINATION OF THE INTERACTION FIELDS IN AGGREGATES OF SINGLE DOMAIN PARTICLES

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The distribution of interaction fields in a substance composed of single domain particles may be determined from the anhysteretic magnetization characteristic of the bulk material. This characteristic as used here is the remanent induction versus applied field when, during application of the field, an alternating field decreasing slowly from well above the coercive force to zero is applied. It may be seen that when such a process is applied to an isolated single domain particle, the resulting magnetization will always be of the same sense as the applied D. C. field, even for almost negligible values of applied field. It follows that any group of independent single domain particles will also act in the same way even though there may be a distribution of coercive forces within the group; that is, for any applied D. C. field all the particles will be magnetized in one direction or the other after the application of the decreasing alternating bias field. This would imply an

anhysteretic characteristic rising with infinite slope at the origin. A finite slope does not result if one merely adds a demagnetizing field, since this will only subtract from the applied field and any applied field would produce saturation.

The finite slope of the anhysteretic characteristic may be explained only by including the effects of the interaction fields. The interaction field acting on any particle is the sum of the fields from all the other particles and is determined by the geometrical arrangement of the particles independently of the applied field. Now the total D. C. field applied to any particle will be the sum of its interaction field and the external D. C. field. For any value of applied external field, all particles with interaction fields smaller than the applied external field will be magnetized in the same sense as the applied field after the application of the alternating bias field. The total net magnetization of a group of particles will therefore by the cumulative distribution function of the interaction fields be independent of the coercive force. The actual distribution of amplitudes of the interaction fields may therefore by readily measured.

An expression is derived for the standard deviation of the interaction field at any point in an infinite aggregate of single domain particles. This expression states that the average interaction field may be determined from the volumetric packing factor of the particles and their remanent induction. The experimentally measured distribution of interaction fields for an aggregate material in the form of magnetic recording tape is in close agreement with a calculated random distribution.

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96. GENERAL SUPERPARAMAGNETIC BEHAVIOR OF AN ALIGNED ASSEMBLY OF UNIAXIALLY ANISOTROPIC PARTICLES

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Several special cases of superparamagnetic behavior of assemblies of ferromagnetic particles have been considered by Bean and coworkers[1]. In particular, the cases of low particle anisotropy energy and low applied field have been treated.

Recent work by the author[2] on a Boltzmann distribution of Stoner-Wohlfarth particles has shown the usefulness of the tabulated function[3]

$$y(x) = \exp(-x^2) \int_0^x \exp(t^2)\, dt$$

for obtaining averages over a partition function of the form

$$Z = 2\pi \int_0^{\pi} \sin\theta \exp(-a \sin^2\theta)\, d\theta,$$

where $A = KV/kT$; θ is the angle between the spontaneous magnetization and the anisotropy axis of the particle of volume V, having anisotropy energy density K; k is the Boltzmann factor; and T is the absolute temperature. The same function can also be used to obtain averages over a partition function of the form

$$Z = 2\pi \int_0^{\pi} \sin\theta \exp(-a \sin^2\theta + b \cos\theta)\, d\theta.$$

If $b = \mu H/kT$, where H is the magnetic field applied along the particle anisotropy axis, and μ is the particle magnetic moment, then Z determines the general behavior of an aligned assembly of particles the magnetic moments of which are in thermal equilibrium at temperature T.

The fractional magnetization $m_{\|}$ along the field direction has been calculated for a = 0.01, 0.1, 1, 2, 5, 10, 100, ∞, and $0.01 \leq b \leq 100$. Curves of $m_{\|}$ vs. b with a as a parameter are presented. For $a < 25$ the curves are the magnetization curves for superparamagnetism. For a = 1 the maximum deviation from the Langevin function is about 30%. As $a \to \infty$, $b/2a \ll 1$, and $m_{\|} \to \tanh b$. For a = 10 the latter approximation is fairly good. The dependence on a shows that superposition of magnetization curves when H is normalized to b is allowable only for $a \ll 1$ and $a \gg 1$. Thus, the use of such superposition to demonstrate properties of superparamagnetic particles in samples in which there is any particle alignment is questionable when a is not known.

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[1] C. P. Bean and J. D. Livingston, J. Appl. Phys. 30, 120S-129S also 318S-319S (1959).
[2] F. G. West, Bull. Am. Phys. Soc. 5, 148 (1960).
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97. AN ANALYTIC HYSTERESIS FUNCTION*

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An analytic function is developed in a parametric form which displays the character of an adjustable hysteresis loop. The type of function used was suggested by the phase-frequency characteristic of a conventional passive phase shift network. There are two parameters in the analytic function, one of which controls the width of the loop and the other, the steepness of the sides of the loop. These two parameters are related to the conventional magnetic parameters such as coercivity, residual induction, etc., so that one may construct a synthetic loop corresponding to a given experimental loop.

Thus, one may completely characterize a given loop or family of loops in terms of only two analytic function parameters.

By means of the analytic function, one can find expressions for the Fourier series coefficients of B and H corresponding to a given experimental loop. A similar expression is obtained for the hysteresis loss associated with a given loop. Both of these results are given in terms of the parameters of the analytic function. The experimental worker is employed to show an application of these equations.

An analog computer schematic is given as well as a set of CRO pictures of a family of synthesized hysteresis loops. Plots of two quite different experimental loops are given along with their corresponding synthetic loops for the

purpose of demonstrating the matching accuracy to be expected.

The suitability of the analytic function to the representation of the wide range of experimental hysteresis loop shapes is discussed.

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*This work was done at the Johns Hopkins University under the sponsorship of the United States Steel Corporation.

SESSION J

ANISOTROPY

R. L. WHITE, Presiding

98. ANISOTROPY AND MAGNETOSTRICTION IN MAGNETIC OXIDES (Invited)

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Considerable progress has been made recently in crystal-field theories of magnetocrystalline anisotropy and magnetostriction of ferrimagnetic oxides. These phenomena are particularly interesting when orbital momentum is not quenched completely by the crystal field, for then the effects are very large and explicit calculations are practical. An extreme example is that of divalent cobalt in the spinel lattice. The orbital moment of the ground state is coupled strongly to the trigonal axis of the crystal field and very large anisotropy and magnetostriction result. The theory is found to account for many of the effects of cobalt in ferrites, particularly in cobalt-iron ferrite and cobalt-manganese ferrite.

A less extreme but still striking example is that of divalent iron in the spinel lattice. Here the orbital moment is more nearly quenched but the spin is still rather strongly coupled to the trigonal axis. The coupling gives rise to a cubic anisotropy term in second order approximation. This term appears to account for the large compositional dependence of anisotropy of manganese-rich manganese-iron ferrite. Crystal field theory of the ferrous ion leads also to interesting conclusions about the orthorhombic distortion and magnetic anisotropy of the low-temperature form of magnetite.

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99. ANISOTROPY OF YIG CALCULATED FROM CRYSTAL FIELD PARAMETERS Fe^{3+} IN YTTRIUM GALLIUM GARNET

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It was recently recognized[1] that the measured anisotropy of cubic ferrimagnets with S state ions was comparable to the ground state crystal field splitting of Fe^{3+} as familiarly observed in paramagnetic resonance. This led to the proposal of the "single ion" theory of anisotropy in which the anisotropy is pictured as arising from the local electric crystal field anisotropy of each ion appropriately averaged in the Weiss field.

The crystal field parameters of a small Fe^{3+} impurity in the diamagnetic yttrium gallium garnet, YGaG, (which is isostructural with YIG) have been previously measured by paramagnetic resonance.[2] Under the assumption that these parameters do not change significantly from YGaG to YIG one can predict the anisotropy of YIG by suitably averaging the local Fe^{3+} crystal field anisotropy over the different orientation of all the tetrahedral (d) and octahedral (a) sites.

While this geometrical average has been previously performed[3], there appear to have been some discrepancies which arose mainly from the selection of the local cubic crystal field axes for the *distorted* octahedra. We review here the calculation and give an explicit expression for the anisotropy.

It is convenient to express the anisotropy in terms of the angles α and β which measure the angles through which the local cubic crystal field axes of the octahedra and tetrahedra are rotated respectively about the <111> and <100> unit cell directions away from coincidence with the unit cell edges. In terms of these angles the cubic crystal field parameters $\underline{a}_a$ and a_d of the (a) and (d) sites, and the axial field parameters F_a and F_d, the anisotropy per unit cell is given by

$$K_1 = [\underline{a}_d\,(14 + 10\cos 4\beta) + \frac{28}{3} F_d] r_d(y) + [\underline{a}_a \frac{16}{27}(7 + 20\cos 3\alpha) - \frac{112}{27} F_a] r_a(y)$$

Here $r_a(y)$ and $r_d(y)$ are temperature factors. According to the molecular field theory as applied by Wolf[1] and Yosida and Tachiki,[1] $r(y) \to -5/2$ for $T \to 0$. The angles α and β are given in terms of the oxygen parameters x, y and z of the lattice by

$$\tan\alpha = \sqrt{\frac{3}{2}}\,\frac{(y-x)}{[z - \frac{(x+y)}{2}]}$$

$$\text{and } \tan(\frac{\pi}{4} - \beta) = \frac{y}{\frac{1}{4} - z}$$

Using the oxygen parameters given by Geller[4] and Gilleo for YIG, one finds at $T = 0°K$ the anisotropy per unit cell K_1 to be $K_1 = -0.385\ cm^{-1}$ compared to the experimental value $K_1 = -0.241\ cm^{-1}$. Several possible sources for this discrepancy of 50% are discussed.

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100. THE MAGNETIC ANISOTROPY OF YTTRIUM IRON GARNET AT 0°K

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Geschwind has recently measured the paramagnetic resonance of Fe^{3+} ions in the tetrahedral and octahedral sites of yttrium gallium garnet. His results yield the fourth order terms in the crystalline spin Hamiltonian; from these using the molecular field averaging procedure of Yosida and Tachiki and of Wolf, one may predict the dc anisotropy constant, K_1, of YIG as a function of temperature. The agreement with Dillon's rf measurements is poor even at 0° K.

The latter discrepancy may be attributed to the neglect in previous theories of the character of the ferrimagnetic ground state. In a spin wave description, the zero point motion of the spin waves in the ground state may be expected to lower the expectation value of the anisotropy energy, just as it depresses the sublattice magnetization, M. If we recall that the thermal excitation of spin waves is known to produce 10 times as rapid a change in K_1 as in M, we would expect a large zero point effect on K_1 and a rough calculation confirms this estimate.

We may calculate the latter with reasonable accuracy by using second order perturbation theory on the aligned state, with the transverse terms in the exchange Hamiltonian as the perturbation, to evaluate the ground state energy. The expectation value of the anisotropy energy may then be found by differentiation with respect to the strength of the anisotropy. This yields for the relative decrease, $\frac{\Delta K_1}{K_{10}}$, in K_1

$$\frac{\Delta K_1}{K_{10}} = \frac{K_a + K_d}{N_a K_a + N_d K_d} \cdot \frac{10S(N_a Z_{ad})}{\left[S(Z_{ad} + Z_{da} - \frac{Z_{aa}J_{aa} + Z_{dd}J_{dd}}{J_{ad}}) - 1\right]^2}$$

K_{10} is the value of K_1 in the aligned state, $K_{a,d}$ are the magnitudes of the relevant fourth order terms for a and d sites (suitably averaged over inequivalent sites); $N_{a,d}$ are the numbers of a and d sites; Z_{ad} means the number of a and d sites; Z_{ad} means the number of d sites adjacent to an a site and so forth; S is the spin and the J's are exchange constants in Pauthenet's notation.

This expression depends sensitively on the relative sizes of J_{ad} and J_{aa}, J_{dd}; if Pauthenet's values for the J's are used one obtains a reduction of 80% rather than the observed 30%; if J_{aa} and J_{dd} are ignored the reduction is 20%. A more refined calculation would provide a useful means of estimating the relative size of J_{aa}, J_{dd}.

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101. CALCULATION OF UNIAXIAL SPIN HAMILTONIAN CONSTANTS IN YIG*

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The uniaxial spin Hamiltonian constants in YIG are calculated by a method originated by Kondo and generalized by the author. The method considers the distortion of the spherical charge cloud surrounding a magnetic ion by its non-magnetic nearest neighbors, and averages the individual electron spin-orbit and spin-spin interaction over the distorted charge distribution. In YIG there are two types of Fe^{+++} sites, one surrounded by an octahedron of 0^{--} ions and the other by a tetrahedron, each trigonally distorted from the regular figures. The constants D in a spin Hamiltonian term of the form DS_z^2 have been measured experimentally by Geschwind, and found to have the values:

$D_{octahedral} = -.14\ cm^{-1}$ and $D_{tetrahedral} = -.093\ cm^{-1}$. The present calculation yields values: $D_{octahedral} = -.11\ cm^{-1}$ and $D_{tetrahedral} = -.090\ cm^{-1}$. Although the excellent agreement is certainly fortuitous because of the rough estimates of overlap and transfer integrals used, the calculation shows that the effect considered does produce anisotropy of the observed order of magnitude.

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†This work was done during the tenure of a Westinghouse Electric Corporation Fellowship.

102. TORQUE MEASUREMENTS ON DOPED YTTRIUM IRON GARNET

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This paper describes torque measurements made at 20° K, and 4.2° K and 1.5° K on yttrium iron garnet crystals containing small rare earth dopings, kindly supplied by Dr. J. F. Dillon and Dr. J. W. Nielson of the Bell Telephone Laboratories. Resonance measurements by Dillon[1] showed that the giant anisotropy peaks observed in yttrium iron garnet at 4.2° K were due to the presence of rare earth ion impurities and since then his results on samples containing known impurities have been interpreted by Kittel[2], in terms of energy level 'crossovers' of the rare earth ion in the combined crystal field and exchange field. In the present work torque measurements have been made on several crystals with different rare earth ion impurities, but results here are confined to crystals doped with terbium (Tb 0.19%), holmium (Ho 0.19%) and dysprosium (Dy 1.0%). The crystal containing dysprosium was grown by J. L. Page in our laboratories. The torque curves were measured in a (110) plane (also in a (100) plane for the Tb sample) in a magnetic field of 15,000 oersteds and the maximum torques were in the range 20 - 200 dyne cm. For the three crystals the energy surface deduced from the torque curves is consistent with the resonance field behavior observed by Dillon[1]. The torque curve of the Tb crystal had more pronounced discontinuities than any other samples and variation in the applied field between 7,000 and 15,000 oersteds did not alter the angle at which they occurred whereas shifts of up to 5° had been predicted using the Kittel model. So far attempts to correlate the position of the discontinuities in the (110) and (100) planes which showed fewer discontinuities have proved unsuccessful using the above model. At 20° K the torque curve can be analysed in the standard way giving values of K_1 and K_2 of + 88,000 and - 460,000 ergs/cc respectively. The torque curve for Ho sample at 4.2° K was steepest at the [110] and [100] directions, in agreement with the position of the resonance peaks reported by Dillon[1]. However, for the Dy crystal no sharp discontinuities are observed and the torque curve shows a large $\sin 8\theta$ component. On reducing the temperature from 4.2° K to 1.5° K, no change in the curve was observed.

The curves for Ho and Dy were found to be quite reversible in the fields of 15,000 oersteds.

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103. LOW TEMPERATURE MAGNETIC PROPERTIES OF SOME RARE EARTH GARNET COMPOUNDS*

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Low temperature magnetic susceptibility measurements have been carried out on single crystals of $Dy_3Al_5O_{12}$, $Dy_3Ga_5O_{12}$, $Er_3Al_5O_{12}$, $Er_3Ga_5O_{12}$, and diamagnetic $Y_3Al_5O_{12}$ and $Y_3Ga_5O_{12}$ containing nominally 1% Dy and Er. The dilute samples have also been investigated by paramagnetic resonance (9 KMc at 4.2° K), and with the exception of Dy in $Y_3Al_5O_{12}$ for which no resonance was found, the g-tensors of the ground state doublets have been determined in each case. In contrast to the previously reported experiments on Yb garnets[1,2,3] considerable differences have been found in the magnetic behavior of the Al and Ga compound. Thus in the resonance experiments on the 'dilute' Er samples g-values differing by factors of the order of 2 were found, while in the concentrated Er compounds susceptibility measurements indicated similar differences both between the Curie constants and the Er-Er interactions (Weiss constants). In the case of Dy^{3+} an abrupt change in the susceptibility versus temperature curve indicated that $Dy_3Al_5O_{12}$ undergoes an antiferromagnetic transition at 2.55° K, in contrast to $Dy_3Ga_5O_{12}$ which showed purely paramagnetic behavior over the whole range of measurement (1.3° to 20.4° K). Susceptibility measurements on the dilute samples showed further (a) that the crystal field energy of the first excited state also differs in the Al and Ga compounds; (b) that the magnitude of the splittings is less than about 50 cm^{-1}, an order of magnitude smaller than that found for Yb^{3+} [3]; and (c) that, even neglecting magnetic interactions, the properties of the rare earth ions may depend on rare earth concentration.

These results show that the magnetic properties of Dy and Er garnets are sensitive to very slight changes in the crystal structure. This and also the small crystal field splittings are readily explained[4] if the main cubic part of the crystal field is such that the lowest states belong to a degenerate Γ_8 quartet, which is split into two doublets by the relatively weak orthorhombic deviations from cubic symmetry. (For Yb^{3+} the cubic field leads to a twofold degenerate Γ_7 Kramers doublet which is not very sensitive to small distortions.)

As in the case of the previous measurements on Yb garnets these experiments were originally undertaken to provide data for the interpretation of the properties of the corresponding rare-earth iron garnets. However, our results now show that in the cases of Dy and Er considerable care must be exercised in applying paramagnetic data from one garnet compound to another, and only general conclu-

sions can be drawn until there is considerably more detailed information on the properties of these particular compounds.

*Supported in part by the U. S. Air Force Cambridge Research Center through E.O.A.R.D.C.

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104. UNIAXIAL ANISOTROPY IN POLYCRYSTALLINE GARNETS*

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In samples of polycrystalline yttrium-iron garnet which exhibit domain-wall relaxation effects[1], it is possible to establish a field induced uniaxial anisotropy at low temperatures. This magnetic anneal is responsible for the development of rectangular hysteresis loops in these materials[2].

The anneal is attributed to the directional ordering of defects (presumably electronic) induced within the garnet lattice by an applied magnetic field. Correlation between annealing and the defect state is suggested by studies on a series of garnets having prefired compositions $(3-x)\,Y_2O_3 \cdot (5+x)\,Fe_2O_3$ with $-0.4 \leq x \leq +0.4$. On the basis of magnetic, x-ray, and metallographic analysis, we find that the off stoichiometric compositions (x=0) are characterized by the development of a secondary phase. However, evidence obtained from the anneal studies indicates that the coexisting primary garnet phase contains a defect structure, for we find that the anneal tends to be absent in the stoichiometric garnet (x=0), but is present in the other compositions.

In a typical experiment we cool a non-stoichiometric polycrystalline garnet disc from room temperature to liquid nitrogen in a 6 kilogauss field and establish a uniaxial anisotropy of 3000 ergs/cc. With the temperature held fixed, at -190° C, we can shift the direction of the induced axis by altering the orientation of the applied field. The shift in axis to the new field direction occurs with a finite time constant (order of thirty seconds). If torque measurements are made before the axis shift has fully occurred, the disc is found to have a multi-axial anisotropy.

Similar effects have been observed in lutetium-iron garnet.

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105. MAGNETIC PROPERTIES OF THE LOW-TEMPERATURE FORM OF MAGNETITE*

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Magnetite (Fe_3O_4) undergoes a phase transition at a temperature of about 119° K, depending on the sample purity and stoichiometry. Above this temperature the crystal structure is cubic (spinel); below it is orthorhombic. We have studied some of the magnetic properties of magnetite from 2° to the transition temperature T_c both by ferromagnetic resonance measurements on single crystals and by coercive force measurements on fine particle powders.

A steady magnetic field applied to a single crystal of magnetite as it is cooled through the transition temperature selects the edge nearest the field as the orthorhombic c-axis. However, there are two possible orientations for the a,b axis, and in general, the crystal will be "twinned." The resonance spectrum then consists of two lines. Under certain conditions, this twinning can be removed; then only one resonance line is observed. The ferromagnetic resonance technique has proved to be a powerful one for the study of twinning in orthorhombic magnetite.

The anisotropy energy may be described to second order by

$$E_k = K_1\alpha_1^2 + K_2\alpha_2^2 + K_{11}\alpha_1^4 + K_{12}\alpha_1^2\alpha_1^2 + K_{22}\alpha_2^4$$

where α_1 and α_2 are the direction cosines relative to the hard and intermediate axes, respectively. The values of these anistropy constants have been determined at three temperatures below 80° K; they are of the order of 10^6 ergs/cm^3.

This large crystalline anisotropy may be expected to be the main origin of the coercive force of single-domain particles, even when considerable shape anisotropy is present. Experiment confirms this, since it is found that the coercive force of single-domain particles with a mean axial ratio of 6.5/1 increases from about 265 to 800 oe on cooling through the transition temperature. The variation of the coercive force of single-domain and multidomain particles with temperature has been determined down to 2° K; the results are consistent with the resonance measurements of the anisotropy.

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106. EXCHANGE ANISOTROPY IN MIXED MANGANITES WITH THE HAUSMANNITE STRUCTURE

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Magnetic properties are reported of powder compounds isomorphous to hausmannite, but containing partial to nearly complete substitution of diamagnetic Zn^{2+} or Mg^{2+} ions in the tetrahedral sites of Mn_3O_4. X-ray diffraction of these compounds reveals a single phase, whose

structure corresponds to a tetragonally distorted spinel. Unidirectional anisotropy is present and is detected by the observation of hysteresis loops displaced along the field axis when the materials are cooled to low temperatures in magnetic fields of several kilo-oersteds. The unidirectional behavior is stable to reverse field pulses of 140 kilo-oersteds. An exchange anisotropy model is proposed involving interactions between ferrimagnetic and nearly antiferromagnetic regions brought about by the random distribution of the diamagnetic ions among the tetrahedral sites and the consequent magnetic inhomogeneity. This model is similar to that proposed for disordered alloy systems. Magnetic viscosity effects are observed which correspond in part to ordinary magnetic viscosity, but which also are connected to the unidirectional anisotropy. However, the identity of this anisotropy is not impaired by the presence of the viscosity effects. The viscosity phenomena in these materials include observation of differences in the hysteresis loops measured dynamically and quasi-statically.

107. EXCHANGE ANISOTROPY IN STAINLESS STEEL

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"Non-magnetic" stainless steel is a paramagnetic material at room temperature with a face-centered cubic lattice structure. It has been shown by Kondorsky and Sedov[1] that the susceptibility has an anomaly at 40° K which is quite characteristic of an antiferromagnetic transition. This result suggested to us that cold working such a material to transform part of the material to the ferromagnetic body-centered cubic structure might yield a shifted hysteresis loop; if the b.c.c. structure is in exchange contact with the f.c.c. material.

A cold worked (swaged) type 347 stainless steel did develop a shifted hysteresis loop when cooled in a magnetic field from room temperature to 4.2° K, while the hysteresis loop was symmetrical when the material was cooled in a zero magnetic field.

We also measured the shift of the hysteresis as a function of temperature and found that the shift disappeared at 40° K, which is in agreement with the susceptibility measurements of Kondorsky and Sedov.

[1]E. I. Kondorsky and V. L. Sedov JETP, 35, 6 p. 1104.

108. THE MAGNETOCRYSTALLINE ANISOTROPY OF FERROMAGNETIC CRYSTALS UNDER HYDROSTATIC PRESSURE

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Room temperature magnetization measurements were made on single crystals of an iron-silicon alloy (6.0 atomic percent Si) and of pure nickel under a hydrostatic pressure of about 5000 atm. and at atmospheric pressure. From the change in the magnetization curve measured along a <110> direction of the Fe-Si crystal, a value was obtained for the pressure dependence of K_1, the primary magnetocrystalline anisotropy coefficient, which may be expressed as $K_1^{-1}(\partial K_1/\partial p) = -(60 \pm 5) \times 10^{-7}\ \text{atm}^{-1}$. This value for $K_1^{-1}(\partial K_1/\partial p)$ was confirmed by similar measurements along a <111> direction from which it was also found that $K_2^{-1}(\partial K_2/\partial p) = (0 \pm 60) \times 10^{-7}\ \text{atm}^{-1}$. These experiments also gave $K_1 = +(46 \pm 4) \times 10^3$ erg/gm and $K_2 = +(7 \pm 3) \times 10^3$ erg/gm, which are in very good agreement with recent torque measurements on this Fe-Si alloy.[1] From similar measurements along an easy (or <100>) direction, the pressure dependence of the saturation moment, σ_S, of this Fe-Si crystal was determined; the same result, $\sigma_S^{-1}(\partial \sigma_S/\partial p) = -(5.5 \pm 0.2) \times 10^{-7}\ \text{atm.}^{-1}$, where $\sigma_S = 204$ emu, was also obtained from data taken at high fields along the harder <110> and <111> directions. Following Carr's arguments[2] these values for $K_1^{-1}(\partial K_1/\partial p)$ and $\sigma_S^{-1}(\partial \sigma_S/\partial p)$ can be used to explain most of the apparent experimental deviation from the theoretical expression, $K_1(T)/K_1(O) = (\sigma_S/\sigma_O)^{10}$, which relates the temperature dependence of K_1 and σ_S (normalized to their values at 0°K).

The measurements along a hard (or <100>) direction of the nickel crystal gave magnetization curves whose shapes were not in very good accord with theory (whereas for the Fe-Si crystal there was excellent agreement). Nevertheless, when the assumption that both K_2 and $\partial K_2/\partial p = 0$ was made, the following values for nickel could be extracted from these measurements: $K_1^{-1}(\partial K_1/\partial p) \simeq -26 \times 10^{-7}\ \text{atm}^{-1}$ and $K_1 \simeq -7 \times 10^{-3}$ erg/gm. From data taken at high fields along this hard direction (and, also along an easy <111> direction), it was found that $\sigma_S^{-1}(\partial \sigma_S/\partial p) = -(2.5 \pm 0.5) \times 10^{-7}\ \text{atm}^{-1}$, where $\sigma_S = 55$ emu. In this case, the $K_1^{-1}(\partial K_1/\partial p)$ value has the wrong sign for alleviating the discrepancy between experiment and the theoretical 10th-power relation between $K_1(T)/K_1(O)$ and σ_S/σ_O.

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SESSION K

DOMAIN WALLS AND DOMAIN WALL MOTION

L. R. BICKFORD, JR., Presiding

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109. DOMAINS AND EXTREME-VALUE STATISTICS

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A "statistical" theory of ferromagnetic domains was developed in the 1930's, fell into disuse in the 1940's, and was revived in the 1950's.[1] Let p_j be the probability that a point chosen at random is in a domain of type j (j = 1, 2, . . . , n; n = 2, 6, 8 for cobalt, iron, and nickel crystals, respectively, at room temperature). Then according to this old theory, $p_j = e^{-\beta E_j}/\Sigma_i e^{-\beta E_i}$ (a); E_i is the free-energy density, not including contributions from random forces such as internal stresses, in a domain of type i, and β is a constant whose reciprocal is a measure of the free-energy density associated with the random forces. No satisfactory derivation of (2) was ever given, and it must be regarded as a guess based on an analogy to statistical mechanics. Now postulate, instead, that at each point the actual orientation i is that of smallest $E_i + \epsilon_i$, where ϵ_i is the contribution of the random forces; and that at each point $\epsilon_1, \epsilon_2, \ldots \epsilon_n$ are mutually independent random variables with a common distribution function F(x) and probability density F'(x). Then, rigorously, $p_j = \int_{-\infty}^{\infty} \{\Pi_{i \neq j} [1 - F(x - E_i)]\} F'(x - E_j)\, dx$ (b). When $E_1 = E_2 = \ldots = 0$, the integrand in (b) is 1/n times the probability density $\psi_n'(x)$ of the smallest value among the n ϵ_i's. It is known that under certain conditions the distribution function of the smallest value, $\psi_n(x)$, reduces asymptotically, for large n, to $1 - \exp[-e^{\alpha_n(x-u_n)}]$, where $F(u_n) = 1/n$ and $\alpha_n = nF'(u_n)$.[2] Under the same conditions (b) reduces asymptotically to (a), with $\beta = \alpha_n$. When F(x) is Gaussian, the approach of $\psi_n(x)$ to its asymptotic form is rather slow; the asymptotic approximation (2) must therefore be expected to be poor when n = 2, 6, or 8. The old theory was in fact not very successful in fitting data. Future calculations might better be based, instead, on (b), with reasonable assumptions about F(x).

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110. THE FREQUENCY DEPENDENCE OF ULTRASONIC WAVE ATTENUATION IN ARMCO IRON AND LOW CARBON STEEL

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Ultrasonic wave attenuation in annealed Armco iron and low carbon steel was measured as a function of external magnetic field strengths (0 - 400 Oe) at frequencies between 1 and 10 Mcps and under the conditions of carefully closed magnetic flux. At a given field strength the magnetic component of the attenuation increases with increasing frequency. No magnetic relaxation was observed. The structure sensitivity of the underlying basic magnetic loss mechanisms was studied by changing the dislocation density of the material. Discrepancies were found between the experimental results and the predictions of theory. These may indicate the existence of processes which would involve losses within the stationary domain walls. The possibility of such processes is examined.

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111. DOMAIN WALL MOBILITY IN SINGLE CRYSTAL YTTRIUM IRON GARNET (YIG)

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Reasonable agreement between the damping constant inferred from rf resonance line widths and that obtained from the domain wall mobility has been found for ferrites previously[1,2,3]. However, the recent line widths reported for YIG by Spencer, LeCraw and Clogston[4] are substantially narrower than those for ferrites. Using this narrow line width to calculate the YIG wall mobility, one finds that a specimen 1mm wide would reverse in less than 100 millimicro-seconds by a single wall moving in a field of one oersted above threshold. We have measured the reversal time as a function of applied field at 77°K and at room temperature in a single crystal YIG specimen cut so as to be capable of supporting a single domain wall. The usual linear relationship between the reciprocal switching time and the applied field is observed with only a slight temperature dependence. Although the existence of a single wall has not been demonstrated conclusively, it is possible to place an upper limit on the wall mobility in single crystal YIG. At room temperature this upper limit is more than 100 times smaller than the mobility calculated from the line width measurements, implying that the damping constant inferred from wall mobility measurement is more than 100 times larger than the line width damping constant. A similar discrepancy in nickel-iron ferrite at 77°K has been reported by Galt[1] and by Yager, Galt and Merritt.[2] Since single crystal YIG would be expected to contain much less divalent iron than nickel-iron ferrite, the particular loss mechanism described by Galt should not be important in YIG.

Assuming that the damping constant is not a function of frequency, we can obtain some understanding of this discrepancy in YIG from a study of the equation of motion for a domain wall. It appears likely that a single moving domain wall may excite spin waves if the damping constant is sufficiently small. The damping constants implied by the reported narrow line widths[4] are probably small enough to make this effect important. These spin waves could then lead to a much larger apparent damping constant in a way similar to that by which spin waves broaden the resonance line width. Consequently, correlation of wall mobility measurements with resonance line width measurements may be complicated by this added phenomenon.

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112. MEASUREMENTS OF DOMAIN-WALL AREA DURING SLOW FLUX REVERSALS

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In previous papers,[1,2] it has been shown that slow, constant-voltage hysteresis loops on polycrystalline tape cores have irregularly varying sides. The concept of flux change by an outward-moving transition region has been introduced. The equation $e_c = K(H - H_T)$ has been used to describe the core, where e_c is the induced voltage-per-turn, and H is the field applied to the transition region. It has been argued that the variations on the loop sides show variations in H_T, and that K can be measured by modulating e_c and observing the resulting change in H. This modulation technique, which is similar in principle to Becker's,[3] has been used for the measurements reported in this paper. Following Becker, it is argued that variations in K show variations in the area of active domain wall. These variations have been measured in detail during slow flux reversals, and study of the results has led to a more detailed model of the transition region.

The measurements to be presented were made on a Magnetics, Inc. 50041-2A Orthonol core for which slow-speed hysteresis loops have been previously published.[2] The standard saturation level is $H_{sat} = 10\ H_c$, where H_c is the nominal coercive force of the core. The standard transition region velocity is 10 centimeters per second. Under these conditions, the mean value of K averaged over the entire loop side, $\overline{K}$, is about 1.5×10^{-5} volts per ampere-turn per meter. The corresponding area of active domain wall is difficult to determine, because the configuration of walls is unknown. If a multiple-wedge configuration[4] exactly one wrap long is assumed, and the relation between applied field and wall velocity found by Williams *et al*[5] is used, then the average wall area is of the order of $3\ell_{Fe}d$, where ℓ_{Fe} is the mean path length of the core, and d is the tape thickness. As the transition region velocity is increased by a factor of 10, $\overline{K}$ increases, nonlinearly by more than a factor of 10. When the saturation level is reduced below $2\ H_c$, $\overline{K}$ more than doubles.

During the course of a standard reversal, K varies over a range greater than 5/1. These variations show some correlation with the variations of H_T: K and H_T tend to vary together, indicating that the wall area is least when the reversal is proceeding easily, and greatest where the reversal is difficult. A physical model of the transition region which appears qualitatively to predict this behavior will be described if space permits.

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113. REVERSIBLE FLUX CHANGES IN 50% NICKEL-IRON ALLOYS

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It has been shown previously[1,2] that a domain wall model consisting of semi-cylindrical domains at the surface of the material can be used to describe irreversible flux changes in grain oriented 50% nickel-iron alloys of these flux changes are produced by pulses of magneto-motive force. It is useful to adapt this model to certain reversible flux change problems as far as possible.

The equation

$$\alpha r - \eta/r = H,$$

where r is the radius of the domain and α and η are constants, is developed as a description of the static model for the semi-cylindrical domain wall. From the observed variation of B, the magnetic flux density, as a function of H, the magnetic field intensity in the saturation region, the constants α and η are evaluated. Good agreement is found between the value of the initial radius (for $H = 0$) and that predicted by previous investigators.[1,2] Using the values of spin relaxation damping and eddy current damping determined by Leliakov,[2] it is possible to predict the behavior of the small signal differential permeability in the saturation region as a function of a d-c biasing field. It is also possible to predict the behavior of the real and imaginary parts of the differential permeability as a function of frequency. Experimental results give good agreement with the theory.

If a small a-c signal is superimposed on a step of magneto-motive force applied to the material, information about the domain wall velocity and available domain wall area is obtained. The ideas advanced recently by Becker[3] are discussed and it is shown that in the case of a planar domain wall, the incremental induced voltage due to the superimposed a-c signal is proportional to the average induced voltage caused by the step of magneto-motive force even though the domain wall area remains constant.

It is therefore possible to describe the switching characteristics and the small signal behavior of grain oriented 50% nickel-iron through the use of one model.

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114. SPIRAL WALLS IN THIN MAGNETIC FILMS*

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Dense concentrations of walls were previously observed[1,2] to appear in very thin magnetic films with the application of an AC field. Some observations showed roughly circular concentric walls around barely discernible imperfections.

Particularly clear powder patterns of such walls are presented that were obtained on the thin end of a permalloy film of tapered thickness. The patterns allow the deduction of the detailed magnetization distribution which takes the form of a pair of antiparallel domains that spiral in toward the central imperfection.

A mechanism for the formation of spiral walls is presented, together with confirming experimental evidence. The experiments establish the nature of the central imperfection as a region of abnormally high uniaxial anisotropy where the magnetization is constrained to lie in one direction along the easy axis while the magnetization of the surrounding regions of the film can be rotated with an applied field.

*This work was supported in part by contract with the Electronics Research Directorate of the Air Force Cambridge Research Center.

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115. THIN FILM SWITCHING IN THE HARD DIRECTION BY WALL MOTION*

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Hysteresis loops in thin films observed with the driving field applied perpendicular to the easy axis often exhibit appreciable square-ness of the loop suggesting the existence of another easy axis along what is presumed to be the hard direction. Measurement of the anisotropy in such films indicates a uniaxial anisotropy with the hard axis along the direction in which the second square loop is found.

Observing magnetization reversal in these specimens by Kerr effect one notices wall motion which is again characteristic of a second easy axis perpendicular to the first. The use of Bitter powder patterns shows this wall activity with sufficient detail to support the theory that the occurrence of an apparent second easy axis can be normal behavior in a film with uniaxial anisotropy.

If the characteristics of the film are such as to cause the magnetization to return to a multi-domain state when a saturating field is applied along a hard direction and then removed, this direction can be expected to exhibit properties normally associated with an easy axis. The directions which seem to define the hardest axes are then found at angles slightly greater and less than 90° from the real easy axis.

It is the purpose of this paper to describe the theory behind such behavior and the experimental observations which it explains.

*This work was supported in part by contract with Information Systems Branch, Office of Naval Research.

116. MAGNETORESISTIVE MEASUREMENTS ON DOMAIN ROTATION AND WALL DEVELOPMENT IN Ni-Fe ALLOY FILMS

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The magnetoresistive effect in a polycrystalline ferromagnet is given by $\Delta\rho/\rho = \Delta\rho_0/\rho \cos^2\theta$, where $\Delta\rho_0$ is the resistivity change measured when the electric current is oriented first normal then parallel to the magnetic induction, and θ is the angle between the current and induction at which $\Delta\rho$ is measured. This expression has been verified for nickel films by Rappeneau.[1] Other investigators have measured the dependence of coercive force in ferromagnetic films on various parameters by D.C. bridge magnetoresistance measurements in static fields. Hellenthal,[2] using a dynamic method, has measured the frequency dependence of coercive force in evaporated nickel films.

This paper shows that the measurements obtained by the magnetoresistive method can be correlated with those of the inductive method to give additional information about the magnetization processes in 80-20 Ni-Fe films. It is shown that both domain wall motion and domain rotation can be detected and that, as with inductive method, the uniaxial anisotropy energy can be determined from the magnetoresistive hysteresis curve obtained when a film is magnetized normal to the anisotropy axis (transverse hysteresis). The simplicity of the method makes remote measurements; e.g., at low temperature, in vacuum, particularly easy. The lack of dependence on frequency makes the method useful at low magnetizing frequencies where the usual inductive method is difficult to apply in films. Furthermore, the sensitivity of the technique is essentially independent of film thickness down to at least 100 Å.

Some interesting conclusions have been drawn from these measurements. First, it has been found that the transverse hysteresis in 80-20 Ni-Fe films is predominantly rotational hysteresis with the percentage of flux rotating to saturation[3] greater than 90%. Second, this rotational

hysteresis is associated with the formation of 180° domains (parallel to the anisotropy axis) within which the magnetization rotates to saturation in the transverse direction. Third, the magnetization process parallel to the anisotropy axis consists of a partial rotation with subsequent domain wall motion. The latter can be observed as magnetoresistive Barkhausen discontinuities.

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117. MAGNETORESISTANCE AND MAGNETIC SWITCHING IN PERMALLOY FILMS

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Magnetoresistance measurements have been used to study the magnetic properties of permalloy films. Resistivities parallel and transverse to the current were measured simultaneously as the applied magnetic field was varied in magnitude or direction in the film plane. The results are discussed in terms of a new representation in which the resistivity components are regarded as Cartesian coordinates. This representation is independent of the current direction relative to any magnetically preferred orientations in the film. The statistical, domain wall, switching model of Conger and Essig[1] is extended to include the situation in which the field and easy magnetic axis are not parallel and a switching profile is constructed which gives a unified representation of the domain wall and coherent rotational switching response of a uniaxial film to an applied field. The incidence of moving domain walls under certain field conditions is discussed with the help of this profile and it is shown that the magnetoresistance curves may be understood in terms of the magnetic changes.

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118. NUCLEATION PROCESSES IN THIN PERMALLOY FILMS

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Thin permalloy films with uniaxial anisotropy subjected to a magnetic field parallel to the easy direction, reverse their magnetization by wall motion. Normally, this wall motion starts from nuclei of reversed magnetization at the edges of the film, which are created by the demagnetizing field. Nucleation processes inside the film are rarely observed, since the driving field for wall motion, H_W, is generally smaller than the field for the nucleation of a reversed domain, H_N, inside the film.

Several methods are described to suppress this edge effect, thus allowing investigation of the nucleation processes within the film. In this case, two different hysteresis loops can be observed depending on the amplitude of the a.c. driving field. With a large field amplitude, magnetization reversal must start with a nucleation process, and the coercive force is equal to H_N. With a field amplitude equal to H_W, two possibilities exist. When the film is initially in a single domain state, it remains in this state. When, however, a wall is already present, it is moved to and fro by the field, thus giving rise to a minor loop with a coercive force equal to H_W. The transition from one state to the other can be effected by an additional d.c. field.

If artificial imperfections, such as scratches or holes are introduced, the nucleation field, H_N, can be decreased, and if the perturbations are strong enough, it becomes smaller than H_W. In this case, wall motion is not restrained and the coercive force is equal to H_W for all amplitudes.

The dependence of the nucleation field, H_N, on H_K, H_C and the type of imperfection is discussed.

119. DOMAIN STRUCTURES IN IRON WHISKERS AS OBSERVED BY THE KERR METHOD*

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An improved apparatus has made possible the microscopic observation of domain configurations with the longitudinal Kerr magneto-optic technique, a method that has customarily been used only for the low-power examination of large scale configurations. With a high intensity source and refined optical components, domain structures have been readily observed visually or photographically at magnifications of 100X or more and with optical resolution of a few microns. By utilizing the light amplification of a closed circuit TV system it has been possible to take motion pictures of the dynamical domain behavior of magnetic specimens. The apparatus is also readily adaptable to the observation of domain structure in transparent specimens by transmission, utilizing the Faraday effect.

Employing this improved instrument, we have studied the magnetization process in iron whiskers under high magnetic fields.[1] In all of the whiskers studied, a domain structure could be observed near the whisker tip up to about 6000 oe for the axially directed field. Above approximately 2000 oe, this structure at the tip consists of domains magnetized perpendicular to the axis of the whisker and in the same sense around all of its lateral faces. Beyond 6000 oe these domains became too small to be resolved by the instrument, but reappeared as the field was reduced.

A detailed study of the effect of metallic reflection in the Kerr method shows that the available contrast at high power microscopic observation is practically independent of angle of incidence of the illuminating beam.[2]

*Supported by the Office of Naval Research.
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***On leave from the Weizmann Institute of Science, Rehovot, Israel and now at the Bell Telephone Laboratories, Murray Hill, New Jersey.

[1] C. A. Fowler, Jr., E. M. Fryer and D. Treves, J. Appl. Phys. To be published.
[2] D. Treves, to be published.

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120. DETERMINATION OF THE DIRECTIONS OF MAGNETIZATION IN POLYCRYSTALLINE FERRITES

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To explain the switching properties of 'square loop' ferrites, assumptions have had to be made as to the detailed configuration of the magnetisation because of the lack of experimental evidence. This paper presents a method for determining directly the directions of magnetisation from grain to grain across the surface of a ferrite toroid subject to an alternating magnetic field. The method uses the Kerr transverse magneto-optic effect which arises from a change in reflection coefficient r_p and is a maximum when the magnetisation is normal to the plane of incidence.

An area of the ferrite surface 200 microns square is illuminated from a tungsten filament source and the intensity of the reflected beam measured with a germanium photodiode. When the ferrite is magnetised to saturation with an alternating field of 1100 c/s a modulation of this same frequency appears in the output of the photodiode, the depth of modulation being approximately 0.01% of the dc output. If the peak value of the magnetic field is made equal to the coercive force of the ferrite the modulation is smaller and changes markedly as the light probe is traversed across the ferrite. This is due to the different angles of the magnetisation in the separate grains and, by choosing a sample with large grains (500 - 300 microns), it is possible to examine the light reflected from an individual grain. By rotating the grain about the light probe and recording the variation in size of the modulation with angle the disposition of the magnetic field in the grain as it reverses with the applied field can be determined.

Results obtained from large grained toroids of magnesium-manganese ferrite are presented and discussed.

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121. HALL PROBE RESOLUTION

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The resolution problem using the Hall probe to map the magnetic field has been studied. It is established that the output from the probe is an average of the Hall voltage due to the magnetic field across the effective area of the probe, therefore the output is dependent both on the size of the probe and the field itself. A theoretical expression has been developed which can be used to correct for the effect due to the size of the probe from the actual data obtained in mapping. To a first order approximation, one can define the resolution of the probe (R) as proportional to the ratio of the length of the probe (h) and the radius of curvature of the magnetic field (ρ).

$$R = C \frac{h}{\rho}$$

SESSION L

MICROWAVE DEVICES

P. H. VARTANIAN, Presiding

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122. THEORETICAL AND EXPERIMENTAL CHARACTERISTICS OF A FERROMAGNETIC AMPLIFIER USING LONGITUDINAL PUMPING (Invited)

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A ferromagnetic parametric amplifier requiring fractional watts of pump power has been developed and investigated experimentally. The amplifier employs magnetostatic modes as resonances which are parametrically pumped by a longitudinal r. f. magnetic field.

A theoretical discussion of the characteristics of longitudinal parametric pumping on the magnetostatic modes is presented including selection rules for determining which pairs of modes can be pumped and an expression for the threshold pump field required for pumping the modes to oscillation.

A model of the amplifier has been built which utilizes X-band pump power and amplifies at C-band frequencies. The signal circuit is a coaxial line with a loop connected from the center conductor around a sphere of yttrium iron garnet providing coupling to the magnetostatic mode at the signal frequency. Results are presented of measurements on the amplifier at room and liquid nitrogen temperatures and compared with the results of a theoretical analysis. In addition speculation is included on the sources of noise in this amplifier.

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123. ANTIFERROMAGNETIC MATERIALS FOR MILLIMETER AND SUB-MILLIMETER DEVICES* (Invited)

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The high internal fields in antiferromagnetics causes them to have natural resonant frequencies in the millimeter and sub-millimeter regions of the spectrum. These resonances may be tuned by an applied magnetic field and are polarization sensitive. Devices similar to the usual ferrite devices are therefore possible. The important physical quantities which characterize an antiferromagnetic are briefly discussed. Figures of merit for various devices are given and experimental data showing nonreciprocal resonant absorption at 77°K in chromic oxide at 140 kMcps will be presented.

*The work reported in this paper was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology with the joint support of the U. S. Army, Navy, and Air Force.

124. THE GENERATION OF MICROWAVE ELECTROMAGNETIC RADIATION IN MAGNETIC MATERIALS

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Microwave electromagnetic energy has been generated in a single crystal YIG by direct conversion of low frequency input signals. Through a novel means of excitation one achieves an effective driving field at the harmonic frequency whose amplitude is determined by the magnitude of the anisotropy energy so that the amplitude of even the high order harmonics is still quite large. On the basis of quite conservative assumptions we are able to show that the amount of power radiated at the harmonic frequency is ultimately limited by the level of the spin wave breakdown and that power outputs of the order of several watts or more per cubic centimeter are theoretically possible.

In the experimental verification of this principle a spherical sample 0.035" in diameter was excited by a driving frequency of 9.2 mc, and output signals in the S-band range were observed. For convenience the input 9.2 mc signal was applied in bursts about 2 microseconds long and clearly identifiable output pulses were passed through a waveguide section to eliminate low frequency components and were detected by a superheterodyne system, having a sensitivity of 10^{-12} watts. The output signals exhibited the proper dependence on static magnetic field and were estimated to be approximately 10^{-8} watts in amplitude. While this amplitude is far below the level predicted above, it is still quite large enough to provide unmistakable verification of the principle and to suggest that further experimental refinements may result in significant output.

In order to generate signals in the millimeter range one must employ materials having higher anisotropy, and it is suggested that ultimately antiferromagnetic resonance excited by an analogous technique can be employed.

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125. FINE WIRE FERRITE LIMITERS

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The subsidiary resonance observed in ferrite at high microwave magnetic field intensities is suitable for limiting purposes. The limiter threshold power, therefore, is related to the oersteds of magnetic field intensity produced in the ferrite per watt of power input. The circumferential field about a wire is directly proportional to the current and inversely proportional to the wire diameter. Thus a fine wire imbedded in ferrite will produce intense microwave fields at low microwave power levels provided that the wire is properly matched to the microwave structure. The response of a ferrite limiter to a microwave pulse characteristically exhibits a leakage spike whose duration is inversely proportional to ΔH_K, the spin linewidth, and a plateau whose power level is proportional to ΔH_K^2. Thus, low threshold power levels normally can be achieved at the expense of long spike duration.

This paper analyzes the fine wire technique for limiter applications and shows that threshold power levels less than a watt can be achieved in ferrite with wide spin linewidths. A particular structure was designed, built and evaluated. It was found that a threshold power level less than one watt was achieved with material producing spike duration times of less than 20 nanoseconds. In addition, the experimental results show that the spike decreases rapidly with increasing power. This effect is thought to be related to the excitation of spin waves of progressively broader linewidths with increasing input power.

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126. TRAVELING WAVE FREQUENCY DOUBLING IN FERRITES

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Correlation has been obtained between experimental results and second order theory for a traveling wave frequency doubler using a ferrite slabloaded rectangular waveguide.

Past experimental work in various laboratories has demonstrated the importance of ferrite frequency doublers in producing high power output and high conversion efficiency. This work was empirical and led to physical parameters for the system which made correlation with theory virtually impossible. It is felt that correlation of theory and experiment for devices of this kind, to define the role of the various parameters, is important to the further development of ferrite doublers.

It is possible to design frequency doublers as traveling wave devices, in which a cumulative traveling wave interaction exists between the second harmonic magnetization sources in the ferrite and the second harmonic fields in a waveguide. This system has the important features that its detailed behavior can be analyzed theoretically while at the same time using large ferrite samples. The importance of large samples for obtaining high power output and conversion efficiency have been demonstrated in past experimental work.

There are two objectives in the present study. One was to obtain a correlation between experiment and the predictions of the second order theory. This included an evaluation of the accuracy of the theory in predicting the effects of changing such device parameters as relative phase velocities of fundamental and second harmonic waves, wave impedance, ferrite line width, and ferrite slab dimensions. The second objective was to investigate the optimum power output and conversion efficiency obtainable with the device operating in the saturation region.

Theoretical analysis has been made of propagation in ferrite loaded waveguides. A perturbation theory is used which satisfies the differential equations of waveguide propagation together with the various boundary conditions on the waveguide and at the ferrite. Numerical calculations have been made using the results of this theory. These calculations give quantitative predictions for second harmonic power output as a function of various parameters. The values and ranges chosen for these various parameters are the same as used in experiments which were performed to check the theory.

The geometry used consisted of a rectangular X-band waveguide loaded with uniform strips of ferrite of dimensions .010 x .080 x 5.5 inches. The agreement obtained between the calculated and experimental values is good. Qualitative features of the curves of second harmonic power output normalized to the square of the input power as functions of both the dc magnetic field and the waveguide width (which controls phase velocity synchronization between the fundamental and second harmonic waves) correlate well. Quantitative agreements are within three db. The theory predicts that operation at gyromagnetic resonance is a more critical requirement than operation with phase synchronism. This is confirmed in the experiments.

It was found that the above waveguides could not readily provide the proper impedance at the second harmonic frequency for optimum extraction of power from the ferrite. An approach for overcoming this problem is presented.

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127. SATURATION EFFECTS IN FERRITE FREQUENCY DOUBLERS OPERATING IN THE UNIFORM PRECESSION MODE*

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It is possible to distinguish three distinct saturation mechanisms which occur in ferrite frequency doublers. These are (1) the non-linear reaction of the second harmonic field on the motion of magnetization, (2) the "sticking" of the precession angle due to transverse pumping of spin waves, and (3) the non-linear damping of the second harmonic due to parallel pumping of spin waves.

Saturation due to the reaction of the second harmonic field is analyzed for the case of a ferrite disc or slab biased in the plane of the sample and operating in the uniform precession mode. It is assumed that the sample is placed in a cavity which supports modes at frequency ω and 2ω only, the r-f fields being linearly polarized in the plane of the disc, with the fundamental and second harmonic fields normal and parallel respectively to the D.C. field. An approximate non-linear equation of motion for this system is obtained by retaining only the second order non-linear terms and the one third order term which involves the second harmonic reaction field. The latter term dominates all other third order terms when the second harmonic cavity Q is high. If the reaction field is expressed in terms of magnetization by means of a "circuit" relation, there results a non-linear equation for the magnetization, containing a cubic reaction damping term. In the case of a strongly elliptical precession, this equation may be solved to give a simple conversion relation between P_2 and P_1. Conversion is found to be square-law at small signal levels, saturating to a linear law as the reaction damping dominates the intrinsic damping and the conversion efficiency approaches 100 per cent. The influence of ferrite and circuit parameters on the conversion law is discussed, and an expression is obtained for the input reflection coefficient at the fundamental frequency as a function of input power.

Before 100 per cent conversion is reached, the above analysis is invalidated by the onset of spin wave saturation effects. Expressions are obtained for the critical values of second harmonic power at which the thresholds for transverse and parallel saturation are reached. The influence of system parameters on these critical power levels is discussed, and expressions are given for the critical conversion efficiencies reached at the thresholds for transverse- and parallel-pumped spin waves.

*The research reported in this document was supported jointly by the U. S. Army Signal Corps, the U. S. Air Force, and the U. S. Navy (Office of Naval Reserve).

128. SUBHARMONIC GENERATION IN FERRIMAGNETIC ELLIPSOIDS

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The existence of nonlinear resonances in ferrimagnetic materials has been well established. The application of a longitudinal microwave magnetic field to an excited ferrimagnet produces transverse side-band frequencies, these directions defined with respect to the internal dc biasing field. If this biasing field is adjusted for resonance at one of the side-band frequencies, a resonant state will be established in which the principal response is not at the transverse driving frequency.

Morgenthaler[1] has pointed out that this type of process can occur without external longitudinal pumping. In an excited ferrimagnetic ellipsoid magnetized in a direction other than along a principal axis, there exists a longitudinal demagnetizing field varying at the precession frequency and proportional in amplitude to the precession cone angle. Using this internal pumping field, a nonlinear resonance may be established in which a single transverse microwave driving field excites a half frequency response. The subharmonic so generated is maximized for thin disc samples magnetized internally at 45° to the plane of the disc.

This effect has been observed in a cavity mounted, single crystal YIG disc. Driven at 3 kmc., 1.5 kmc. oscillations are detected when the sample is magnetized for 1.5 kmc resonance. The interesting power dependence of this process and the dependence on magnetization direction will be given together with a comparison with Morgenthaler's analysis.

[1]Morgenthaler, F. R., Ph.D. Thesis, MIT, June, 1960.

129. PERFORMANCE OF TETRAHEDRAL JUNCTION WAVEGUIDE SWITCHES

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Tetrahedral junction switches have been designed in both S-and X-band and with unusually good microwave characteristics. This switch consists of two waveguides with a common axis butted together with their E planes oriented at 90°. A ferrite pencil is located at the junction. When the switch is not energized the microwave energy is concentrated in the ferrite pencil, transmitted through the junction and reflected back from the far end of the ferrite pencil because the second waveguide cannot propagate the cross-polarized energy. When a longitudinal magnetic field is applied, the plane of polarization is rotated 90° in the ferrite pencil so the plane of polarization is no longer crossed and the energy is transmitted. Measurements of the VSWR and attenuation indicate that the energy is passed through the ferrite pencil and reflected from the far end rather than from the junction of the two waveguides. It will be observed that in the normal frequency range of a waveguide, energy will not be transmitted into the secondary waveguide unless the ferrite is energized. This means the switch will also serve as a shutter.

In X-band, with the switch in the "off" position, the attenuation has been measured in excess of 45 db, while in the "on" position the insertion loss is less than 0.2 db. Similar results have been obtained in S-band though an insertion loss of 0.4-0.6 db is more typical. In the transmit condition the match can be made less than 1.05:1 while in the "off" position the VSWR exceeds 100:1.

Because of the high isolation in the "off" position and the low insertion loss in the "on" position, this switch appears as a possible replacement for a TR tube in duplexing applications. In the past, ferrite switches have seldom been wholly satisfactory because the insertion loss is equal to or higher than a gas tube and the isolation is appreciably lower. With further design and the choice of low hysteresis ferrite, it appears that switches with even greater isolation can be achieved. Comparatively low driving power is required. The S-band switch required 350 milliamperes operating into 30 millihenries. Improved efficiency of magnetic circuit could substantially reduce the drive power.

Another possible application of this switch is for lobing antennas. Instead of firing a gas tube in front of a short to move the effective short position, the tetrahedral junction switch may be used. The variation in apparent short position of the switch in the reflect condition and the mechanical short position in the transmit condition has been measured with encouraging results.

A third application is for a selective switch between several ports. Using a single circulator in conjunction with three tetrahedral switches a selection can be made between any one of three ports. If two circulators are used and six junction switches are used the selection can be made between any one of six ports. Due to losses in the circulators and the switches it is probably not practical to gang further switches for most applications. The maximum loss in a three output switch would be about 1.2 db in X-band.

Experiments have been made to measure the effects of variation of frequency, temperature, driving current, high peak power, loading, and hysteresis.

130. A COMPACT UHF ISOLATOR

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The realization of a solid state isolator at frequencies below 1000 megacycles has presented a formidable problem in TEM mode transmission lines. Conventional coaxial isolators for frequencies below 500 megacycles are large and relatively heavy. This paper reports a strip transmission line structure which yields excellent isolator characteristics over a broad bandwidth to frequencies as low as 300 megacycles while its dimensions are less than $1\frac{1}{2}$" x $2\frac{1}{4}$" x $6\frac{1}{2}$".

In contrast to conventional isolators in which a region of circulator polarization of the h-vector is created by use of a dielectric loading technique, this stripline structure utilizes only a ferromagnetic material and this material, by virtue of its asymmetrical placement on the center conductor, produces the mode distortion and other effects necessary for nonreciprocal wave propagation.

Important parameters such as fundamental ferromagnetic material characteristics (including saturation magnetization, linewidth, material size and shape, applied magnetic field), as well as the degree of asymmetrical placement of the material in the device were investigated to obtain optimized operation. Design information useful to obtain high isolation at any operating frequency between 300 and 1300 megacycles was obtained from devices operated at low power levels.

Typical electrical performance as well as the above information is given for several frequency ranges with yttrium iron garnet as the ferromagnetic material. In general, it is possible to achieve a 15 db to 1 db reverse to forward wave attenuation over a 20% bandwidth. For single frequency operation, maximum ratios of 40 db to .5 db were obtained with peaks of 35 db to 1 db being observed at frequencies as low as 375 megacycles.

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131. PHASE SHIFT STUDIES IN FERRITE-DIELECTRIC LOADED COAXIAL LINES AT 2200 MC

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Results are presented of an experimental study which was undertaken to determine the parameters which affect total and differential phase shift associated with a ferrite-dielectric loaded coaxial line. The dependence of phase shift per unit length on the parameters of dielectric angle, ferrite cross sectional area, and the dielectric constant of the dielectric mode distorter is shown for a $\frac{7}{8}$" diameter coaxial line. These experimental results are compared to those computed by Button[1,2] for a $1\frac{5}{8}$" diameter coaxial line and found to agree qualitatively. The cases corresponding to large differential phase shifts were then solved theoretically for the $\frac{7}{8}$" diameter coaxial line and when compared were found to be in excellent agreement. This study has shown experimentally that the theory developed for ferrite-dielectric loaded coaxial lines correctly predicts the differential and forward phase shifts. The magnitude of differential phase shifts was 60° per inch with a forward phase shift of 100° per inch for the best experimental results.

[1]K. J. Button, "Theory of Nonreciprocal Ferrite Phase Shifters in Dielectric-Loaded Coaxial Lines," TR No. 176, Lincoln Lab., M.I.T., Cambridge, Massachusetts; March 7, 1958.

[2]K. J. Button, "Theory of Nonreciprocal Ferrite Phase Shifters in Dielectric-Loaded Coaxial Lines," J.A.P., Vol. 29, No. 6, pp. 998-1000, June, 1958.

132. PERTURBATION TECHNIQUES FOR MINIATURIZED COAXIAL Y-JUNCTION CIRCULATORS

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Using Auld's[1] Synthesis procedure as a guide, systemized means were developed for constructing miniaturized coaxial Y-junction circulators at frequencies in C-band and X-band. Subsequent investigation revealed that the techniques developed were useful at all frequencies down to the UHF region. Maximum utilization of this synthesis procedure calls for techniques of symmetrical perturbation that will yield broad range adjustment of the junction scattering matrix eigenvalues. Such techniques, involving dielectric loading and systematic deformation of the junction, are described.

The device to be described, including permanent magnets, measures 1.5 inches in diameter, 0.75 inches in height, and weighs less than 4 ounces. Using the symmetrical perturbation techniques mentioned above, the device can easily be made to operate as a circulator at all frequencies from approximately 4 kmc to 10 kmc. Adjusted for use over the 5.4-5.9 kmc range, the circulator exhibits isolation greater than 20 db, insertion loss less than 0.5 db and VSWR less than 1.3. These characteristics are maintained over a temperature range from -55°C to 110°C. At 5.65 kmc the circulator was operated satisfactorily at peak powers above 25 kw and average power in excess of 25 watts.

[1]Auld, B. A. "The Synthesis of Symmetrical Waveguide Circulators," IRE Trans. on Microwave Theory and Technique, Vol. MTT-7, p. 238; April, 1959.

SESSION M

METALS AND ALLOYS

A. ARROTT, Presiding

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133. ON THE NATURE OF THE MAGNETIC COUPLINGS IN TRANSITIONAL METALS (Invited)

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This paper develops a simple model of magnetism for transitional metals, which is somewhat intermediary between Heisenberg's atomic model and Stoner's band model.

Starting with a paramagnetic d band, described in the tight binding approximation and with equal population of both spin directions, exchange interactions are introduced. They are shown to be able to produce localized magnetic moments, by attracting locally the (travelling) electrons of one spin direction at the expense of the others. A simple condition is obtained for such magnetic moments to appear spontaneously; it is shown to be fullfilled in many transitional metals.

Using general results obtained recently by the authors and by others, it is then shown that each of these magnetic moments, if produced alone, should extend over a certain region in space, and should be surrounded by "fringes" of spin polarization with an alternating sign. The size of the central region and the wave length of the fringes are related to an average wave length of the Fermi electrons, thus to the filling of the d band.

The sign and the strength of the coupling between magnetic moments centered on neighbouring atoms is deduced from the extend of their overlap. The magnetic coupling observed in the first transitional series are shown to be in fair agreement with this model. The conditions prevailing in the other series and in alloys are also discussed.

This model is compared to those put forward by Zener, Yoshida and Slater. It is emphasized that it leads to the equivalent to chemical exchange integrals between the moments of neighbouring atoms, without loosing the characteristic features of the d band, especially its high electronic specific heat and Pauli paramagnetism.

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134. EXPERIMENTAL g' AND g VALUES OF SOME METALS AND ALLOYS (Invited)

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Increased precision in measurements of g' by the Einstein-de Haas effect and of g by ferromagnetic resonance at 36 000 mc/s allowed for a test of the validity of Kittel-Van Vleck's relation $g-2 \simeq 2-g'$, more conveniently expressed as $(g-1)(g'-1) = 1$, when g is not very close to 2,0.

Precise experiments were made by the two methods using samples of high purity Iron and Nickel from the same stock material. The following results were obtained:

		g' measured	g' converted in g	g measured
Fe	Armco (99,9)	1,929±0,008	2,076±0,009	2,110±0,03
Ni	IG (99,9)	1,852±0,010	2,174±0,012	2,162±0,02
NI	JM_2 (99,99)	1,845±0,008	2,183±0,010	2,193±0,02

The results of the two experiments show a reasonable agreement when compared by means of the Kittel-Van Vleck relation. The g' values agree well with those of other authors, the means for all valid gyromagnetic experimental values lead to $g'_{Fe} = 1,929±0,004$, $g'_{Ni} = 1,841±0,008$, $g'_{Co} = 1,854±0,004$. The orbital moment contributions are therefore at room temperature for Fe : 0,081 μ_B, Ni : 0,053 μ_B, Co : 0,132 μ_B.

g was also measured in the alloy systems Fe-Ni, Fe-Co, Co-Ni where g' had already been measured. The comparison of g values with the converted g' values yields a good agreement especially for Fe-Ni and Co-Ni alloys: thus verifying again Kittel-Van Vleck's relation. The results on this alloys were also used to test the Wangsness-Tsuya formula which allows one to calculate the g value of an alloy starting from the g values and saturation moments of his components: the agreement between calculated and measured g values is fairly good in the case of Fe-Ni and Co-Ni.

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135. PYROMAGNETIC MEASUREMENTS ON NICKEL

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A new method is described for measuring the temperature dependence of magnetization at low temperatures. The technique is simple in principle yet it has already demonstrated a sensitivity and reproducibility 10 to 100 times greater than the best previous techniques. A spherical sample is placed within a sense coil in series with a flux integrator. The temperature of the sample is altered and the integrated flux change during the thermal pulse is recorded along with the change in temperature. Using this technique, the change in magnetization of a nickel single crystal pulsed by as little as 5° from 4.2°K can be detected with less than 10% error.

The magnetization of nickel has been found to decrease monotonically with increasing temperature from 4.2°K to 120°K without any anomalies as previously reported by Foner and Thompson[1]. The dominant term at the higher temperatures is a $T^{3/2}$ term as predicted by spin wave theory, however, a good fit to the whole curve cannot be achieved without terms of T in lower order as suggested by Charap[2].

The experimental technique will be described with particular emphasis on methods for circumventing problems relating to thermal equilibrium, thermoelectric effects, and thermal expansion within the system.

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[1] S. Foner and E. D. Thompson, J. Appl. Phys. 30, 229S (1959).
[2] S. H. Charap, Phys. Rev. (in press).

136. PARAMAGNETISM OF POLYCRYSTALLINE GADOLINIUM, TERBIUM, AND DYSPROSIUM METALS

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The paramagnetic behavior of polycrystalline gadolinium, terbium, and dysprosium metals has been studied from about 300°K to 1500°K by the Faraday method.

Gadolinium obeys the Curie-Weiss law only up to 740°K. The Bohr magneton number for this range is 8.07 ± 0.05, in satisfactory agreement with the theoretical value 7.94 for the state $^8S_{7/2}$. A slight anomaly in the plot of the inverse paramagnetic susceptibility vs. temperature is observed at about 750°K. The origin of this anomaly is not understood at the present time. It appears that the anomaly can be made more pronounced by increasing impurity content. Above 750°K small deviations from the Curie-Weiss law occurs resulting from the paramagnetism of d- and conduction-electrons.

Terbium metal follows the Curie-Weiss law up to 1500°K. The experimental Bohr magneton number is 9.62 ± 0.05, which compares favorably with the theoretical number 9.72 for the spectroscopic state $^7F_6$.

Dysprosium satisfies the Curie-Weiss law up to 700°K. The effective Bohr magneton for this range is 10.67 ± 0.05, which is in very good agreement with the theoretical value 10.64 for the ground state $^6H_{15/2}$. Above 700°K the inverse paramagnetic susceptibility vs. temperature curve has a downward curvature which can be described by an additional temperature independent paramagnetic susceptibility term having a value of 1.15×10^{-6} g^{-1} cm^3. This quantity is interpreted as resulting from the d-electron and conduction-electron contributions to the total paramagnetism in dysprosium metal.

The paramagnetic behavior of polycrystalline gadolinium, terbium, and dysprosium will be discussed in some detail using the localized f-electron model and the Van Vleck theory of paramagnetism.

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137. PARAMAGNETIC RESONANCE OF ^8S STATE IONS IN METALS

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Electron paramagnetic resonance (EPR) has been observed in Europium metal and several intermetallic compounds containing either Europium or Gadolinium.

The study of absorption intensity and its variation when La or Y were substituted for Gd and Eu showed conclusively that the observed resonances were due to Gd and Eu. Care was needed to avoid interference from free radicals generated at the surface of the reactive metals. From the relatively long spin-lattice relaxation times at room temperature and the g factor of nearly two it was concluded that the resonances were caused by the two ^8S state ions Gd^{+++} and Eu^{++}.

These ions show very nearly the free ionic g value in their paramagnetic spectra in ionic crystals, indicating that only small admixtures of higher states to the free ionic ground state are caused by the crystalline perturbation. In metals there is, however, a contribution to the ionic g factor which can be attributed to the exchange interaction between the magnetic core and the conduction electrons. We have measured this contribution in $GdAl_2$. The effect was small and could only be identified after careful analysis of the observed line shapes and a correction for the magnetization of the samples.

The magnitude of this exchange interaction has previously been estimated by experiments on superconductivity and on ferromagnetism, but the sign has been determined only by the present measurements and by NMR measurements by Jaccarino.

The sign of the exchange interaction is found to be negative, whereas such interactions are always positive in free ions.

The interaction gives also rise to an indirect coupling with the other magnetic ions. The resonance lines are therefore exchange narrowed and of the Lorentz type. If other rare earths are substituted for some of the Gadolinium, then an additional broadening is observed from which the s-f interaction for all rare earths can be estimated.

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138. MAGNETIC CHARACTERISTICS OF SOME AMn_5 INTERMETALLIC COMPOUNDS

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This work is part of a continuing series of investigations which has been in progress for several years dealing with magnetic and structural properties of intermetallic compounds between the lanthanides and the transition metals of the First Long Period.[1,2] In the present study the thermomagnetic behavior and field dependence of the moments have been investigated for a series of alloys of stoichiometry represented by the formula AMn_5, in which A represent Y or one of the following lanthanides: Nd, Gd, Tb, Dy, Ho or Er. All of these materials except $NdMn_5$ exhibit cooperative magnetic effects between 80°K and the following observed Curie temperatures:

Material:	YMN_5	$GdMn_5$	$TbMn_5$	$DyMn_5$	$HoMn_5$	$ErMn_5$
Curie Temp., °K:	489	465	443	430	425	415

$NdMn_5$ does not exhibit a Curie point when subjected to thermomagnetic analysis (TMA) at 2500oe., the field strength used for the other six materials. However, when it is examined at 7000oe. a break in the TMA curve begins to occur, suggestive of a Curie temperature at about 80°K.

Saturation moments per unit cell (one AMn_5 unit) measured at room temperature are as follows:

Material:	YMn_5	$GdMn_5$	$TbMn_5$	$DyMn_5$	$HoMn_5$	$ErMn_5$
μ_S (Bohr Magnetons):	1.3	2.9	2.7	2.5	2.0	1.6

The measured susceptibility of $NdMn_5$ is field dependent and shows saturation effects suggesting that this material may be a weakly ferromagnetic or ferrimagnetic material.

Lattice parameters for four of the AMn_5 compounds—YMn_5, $GdMn_5$, $DyMn_5$ and $HoMn_5$—have been reported earlier by Nassau, Cherry and Wallace.[1] They appear to be isomorphous, possessing an orthorhombic structure with the parameters a, b and c having values approximately 7.2, 4.4 and 3.1 Å, respectively. Analysis of the X-ray data has not progressed to the point of establishing the space group and locating the particles within the unit cell.

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[1] K. Nassau, L. V. Cherry and W. E. Wallace, I, J. Phys. Chem. Solids, in press.

[2] K. Nassau, L. V. Cherry and W. E. Wallace, II, ibid, in press.

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139. MAGNETIC MOMENTS OF COMPOUNDS OF COBALT WITH RARE EARTH ELEMENTS HAVING A Cu_5Ca STRUCTURE

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Recently, the compound Co_5Gd was shown to have antiferromagnetic coupling. The present work is on compounds of this type in which most of the rare earth elements have been substituted for gadolinium and copper has been substituted for some of the cobalt. The rare earth elements which have a high magnetic moment (Gd, Tb, Dy, Ho, Er, Tm) have an effect on the magnetization versus temperature curve which is startling. The moment is greatly reduced in the vicinity of 0°K by the presence of one of these elements in contrast to the high moment obtained when yttrium or a low moment rare earth element (Ce, Pr, Nd, Sm) is present. As a result of these measurements, we may think of the magnetic structure of most of the compounds of cobalt with a rare earth element as consisting of a sublattice of the rare earth whose magnetic moment is in opposition to that of sublattice of the cobalt atoms. All of the compounds conform to this picture with reasonable accuracy except those which contain Pr and Nd. In these two cases the moment of the compounds is actually increased but the reason for this behavior has not been determined. The presence of compensation points in the magnetization of some of these materials has been demonstrated experimentally.

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140. PRECIPITATION IN GOLD NICKEL SINGLE CRYSTALS*

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Magnetic and x-ray diffraction measurements have been made on single crystal discs of a Au-Ni alloy containing 24.8 atom percent nickel. The crystals were annealed at 860°C, quenched and reannealed at 400°C for varying lengths of time. The heterogeneous decomposition into an Au-rich and Ni-rich phase, reported in the literature, was confirmed. The distribution of the ferro-magnetic Ni-rich phase in the specimen was determined by etching-off successive surface layers and observing the magnetic and structural properties of the remaining material. It was found that the degree of decomposition was a function of the time of annealing and of the depth in the crystal.

New results with regard to the shape, size and orientation of the Ni-rich particles and the texture of the Au-rich phase were obtained. The magnetic torque curves measured at room temperature could be interpreted by assuming that the Ni-rich particles were in the form of prolate spheroids pointing in the <111> directions. The demagnetization factor, which had a value of 2.6 if all the particles were oriented, gave an average length to width ratio of 1.8. The same demagnetization factor was obtained independently from rotational hysteresis measurements at room temperature. The presence of appreciable rotational hysteresis at room temperature indicated that the shape of the Ni-rich particles was that of a prolate spheroid and not that of an oblate spheroid.

The magnetic torque observed at 77°K was mainly due to the crystalline anisotropy of the oriented Ni-rich phase. Using the anisotropy constant of nickel (-550×10^3 erg/cm^3) it was estimated that the rotational hysteresis would have its maximum value at 950 gauss. The observed maxima fell between 800 and 1000 gauss.

The Curie temperature of the Ni-rich phase was 328°C ± 3°C, 30°C below that of pure nickel, indicating that some gold was dissolved in the ferromagnetic phase.

Most of the Ni-rich particles were in the single domain range as indicated by the rotational hysteresis data.

Torque measurements at 77°K showed that the fraction of Ni-rich particles which were oriented with respect to the original single crystal increased with increasing time of annealing, reaching 16% after 22,800 minutes.

X-ray diffraction observations supported the magnetic result that only a fraction of the Ni-rich phase was oriented with respect to the original crystal. A substantially greater portion of the Au-rich phase was found to be crystallographically oriented. An oriented crystallite of the Au-rich phase had one of its {100} planes parallel with a (100) plane of the original crystal.

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141. THE FERROMAGNETIC PHASE OF Mn-Al

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Following the work of Kono[1] and Koch et al[2], we have investigated the structural properties of Mn-Al from 50-65 atomic % Mn. Our X-ray data confirms the crystallographic data as given by the above investigators. The ferromagnetic tetragonal phase has been obtained both by a controlled cooling, and also by an isothermal annealing procedure (also reported by Köster and Wachtel[3]).

Transmission electron micrographs of specimens of the ferromagnetic tetragonal phase as formed by isothermal transformation of the parent hexagonal close packed phase (bulk $_{I}H_{C}$ = 1130 oe) show striations of light (transmitting) and dark (non-transmitting) material. From diffraction data on the above specimens it is concluded that the intersection of the striations with the specimen surface coincides with a projection of the c-axis. The striations are presumed to arise due to unavoidable stresses induced by the specific volume change on transformation and possibly also cooling stresses.

Comparative data on the equi-atomic Co-Pt[3,4] alloy and possible mechanisms for the magnetic behavior of the Mn-Al alloy are discussed.

[1] H. Kono, J. Phys. Soc. Japan, 13 1444-51, 1958.
[2] A. J. J. Koch, et al, J. Appl. Phys 315, #5, 755-775, 1960.
[3] W. Köster & E. Wachtel, Z. Metallkunde, 51 #5, 271-80, 1960.
[4] D. L. Martin, Trans. AIME, Vol. 212, 478-85, 1958.

142. REVERSIBLE SOLID-STATE TRANSFORMATION IN IRON-NICKEL ALLOYS IN THE INVAR COMPOSITION-RANGE

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High-temperature X-ray diffraction study of fine-particle iron-nickel alloys containing 25 to 45 atom per cent nickel has revealed the existence of a new reversible transformation in the iron-nickel system. When the alloys are quenched to room temperature from the gamma-state, broad diffraction lines appear and have been found to be due to the presence of two gamma phases of slightly different lattice constants. Upon heating the quenched alloys, the two gamma phases coalesce to form a single gamma phase. The transformation has been found to be *reversible*, the two gamma phases reappearing readily when the temperature is lowered. The transformation temperatures are dependent on the alloy composition and lie in the range of 150° - 250°C.

Considering the general sluggishness of solid-state transformations in the iron-nickel system, the reversibility at the low temperatures of 150° - 250°C at which the transformation appears, is indeed very striking.

Temperature-variation of the magnetic properties of these alloys suggests that the two co-existing gamma phases may be due to a ferromagnetic anti-ferromagnetic transformation of the gamma phase in the iron-nickel system. Such a transformation may serve as the key to the proper understanding of the anomalous behavior of the thermal expansion and other physical properties for which these alloys are noted.

SESSION N

SOFT MAGNETIC MATERIALS

R. M. BOZORTH, Presiding

143. METALLURGY AND MAGNETIC PROPERTIES OF A Fe-Co-V ALLOY (Invited)

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A comprehensive study of the famous Fe-49% Co-2%V has revealed many new aspects of the metallography of the alloy and led to a better understanding of its mechanical and magnetic properties. Results of the study necessitate revision of previous reports on the metallography by Greiner and Ellis (1951) and Köster and Schmid (1955). In addition to the well-known phase transformation of γ(f.c.c.) to α(b.c.c.) and the ordering of the α phase, a martensitic transformation has been established. Rapid cooling may hinder the $\gamma \rightarrow \alpha$ transformation and converts the γ phase through a diffusionless process to a b.c.c. structure of the martensitic type. The metallography is further complicated by a variety of polyphase microstructure produced at various temperatures and the formation of subgrain structure accompanying the ordering of the α phase. X-ray diffraction, dilatometric, and metallographic studies have not, however, confirmed the decomposition of the ordered α phase suggested by Greiner and Ellis.

The problem of brittleness has been broadly investigated. Cleavage fracture is a major cause of brittleness. Other causes include the gaseous (hydrogen and oxygen) embrittlement at grain boundaries and the cracking at the incoherent interface between the α phase and the martensite. Unless specially treated, all b.c.c. constituents including disordered α are inherently susceptible to cleavage fracture. The effect of quenching in the attainment of ductility has been elucidated in terms of current theories of fracture and lattice imperfections. We believe that the main purpose of quenching is to introduce excess vacancies or immobile dislocations so as to inhibit cleavage fracture, not to suppress ordering, as has been customarily postulated. Only when a ductile matrix has been prepared, can ordering exert a pronounced adverse effect on the ductility of the alloy. The martensitic transformation also plays a prominent role in the brittle-to-ductile transition.

Measurements of the saturation magnetic moment at elevated temperatures discloses a 2% increase owing to ordering. Room temperature magnetization curves are compared for different microstructures. The electron configuration outside the argon core is discussed in relation to the composition-variation of the magnetic moment and electrical resistivity.

144. IMPROVED MAGNETIC PROPERTIES OF HIGH PURITY IRON-COBALT ALLOYS CONTAINING 27 TO 43 PERCENT COBALT

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Iron-cobalt alloys have been of interest to electrical equipment designers for many years because of their high saturation induction. The use of these alloys on a large scale has been prevented by five major factors: poor physical properties, low resistivity, relatively high hysteresis loss, manufacturing problems, and high cost. The first four items can be corrected to a great extent by special melting and fabricating techniques. Not much can be done to reduce the cost, since its minimum value is set by the relatively high price of cobalt and by the special processing required. However, by obtaining improved properties, alloys of lower cobalt content which require less complicated processing (and hence cost less) can be used in applications where alloys of higher cobalt content would otherwise be needed.

The development of Supermendur several years ago by Gould and Wenny of the Bell Telephone Laboratories revived considerable interest in iron-cobalt alloys. This interest is based on several outstanding properties that make the alloys very attractive for aircraft and military applications. These properties are: (1) the high saturation induction, which would allow up to 30% reduction in size and weight of cores in transformers, rotating machines, and other magnetic devices, (2) a rectangular hysteresis loop when magnetically annealed, which makes the material suitable for pulse transformers, power magnetic amplifiers, and other saturable core devices, and (3) high Curie temperatures, which make the alloys potentially useful in space age applications.

The outstanding improvement in the magnetic properties of Supermendur (49 Fe - 49 Co - 2 V) over its less pure predecessor, Vanadium Permendur, indicated that a complete reappraisal of other alloys in the iron-cobalt system was desirable. Similar improvements in alloys of lower cobalt content would result in materials with several advantages over Supermendur: (1) better physical properties for some compositions, due to decrease in or absence of ordering, (2) less complicated annealing cycles, for the same reason, (3) better dynamic properties, because of higher electrical resistivity, and (4) lower cost, due to lower cobalt content and less complicated processing.

This paper describes the preparation of high purity iron-cobalt alloys containing 27% to 43% cobalt, and the d-c and 400 cps core loss properties which were obtained. The investigation included binary ingots, and ternary ingots with chromium and vanadium. The ingots were vacuum melted from high purity (electrolytic grade) ingredients, and throughout subsequent processing care was taken to maintain this purity. Material from all of the ingots was successfully cold rolled, although some difficulty was experienced with two of the binary compositions. The four mil tape obtained after final cold rolling was wound into toroidal cores which were annealed in a magnetic field. The d-c coercive forces of the various alloys ranged from 0.22 to 0.60 oersteds, which is about one-fourth that of present lower-purity commercially-produced material of corresponding compositions.

145. CUBE TEXTURE IN ULTRA-THIN MOLYBDENUM PERMALLOY TAPE

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With identical annealing heat treatment the role of major annealed texture component seems to depend primarily upon the degree of cold reduction. Cube texture was evident on annealing all three thicknesses of tape, 1/2 mil, 1/4 mil and 1/8 mil, at 760°C. On raising the annealing temperature to 927°C there was no trace of cube texture in tape cold reduced 96.9% before annealing. But cube texture still remained as the strongest annealing texture component in tapes similarly treated at 927°C but cold reduced only to 93.8% and 87.5% respectively before annealing. The present results agree to some extent, although not entirely, with previous investigators on the transitional nature of cube texture in similar but not the same materials as the present tape.

The switching coefficient, S_w, increases with increasing cube pole concentration in the order of increasing thickness of tapes annealed at 760° and 927°C. Therefore, 1/2 mil tape with the highest value of S_w would have the longest switching time in microseconds under a constant applied field.

The squareness ratio of the hysteresis loop, B_r/B_m, at the applied field of 1/2 oersted decreases with the increasing cube pole concentration in the order of increasing thickness of tapes annealed at 760°C and 927°C.

No correlation could be found between cube pole concentration in annealed tapes and observed coercive force.

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146. DIFFUSION REACTION IN THE AGING OF 4-79 MOLYBDENUM PERMALLOY

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A series of accelerated aging experiments at elevated temperatures was undertaken to estimate the useful life of 4-79 molybdenum permalloy twistor wire at the operating temperature of a memory. This work was initiated because of observed aging effects of nickel-iron alloys of a composition comparable to that of the 4-79 alloy. Twistor wire samples representing varying degrees of stress relief anneal were further annealed over a temperature range from 120 to 190°C until stability in the coercive force was reached. This required heating periods up to 2000 hours. Regardless of the annealing temperatures used, the coercive force, which decreased exponentially, was found to reach a value which was constant for a particular casting of the alloy.

The transformations attending these decreases in coercive force are believed to result from the relief of intracrystalline microstresses with a rearrangement of dislocations in the crystal structure into a lower energy state. The later stages, in particular, of this approach to an equilibrium as measured above can be approximated by the use of a diffusion equation similar to that applied to a

monomolecular reaction. Reaction velocity constants and an energy of activation have been calculated in accordance with the classical equations.

147. INDUCED MAGNETIC ANISOTROPY CREATED BY MAGNETIC AND STRESS ANNEALING OF IRON-ALUMINUM ALLOYS

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Polycrystalline samples of five iron-aluminum solid solutions were subjected to various heat treatments (i) in a strong external magnetic field, or (ii) under an external stress. For (i) the samples were in the form of cylinders, while in case (ii) they were machined into this form after stress treatment. Torque-azimuth plots were subsequently obtained from each sample by means of a torque magnetometer; further heat treatments were then applied, followed by renewed magnetometer measurements, to permit elimination of the intrinsic anisotropy due to preferred orientation of grains.

The maximum value of stress-induced anisotropy arises at a composition near 20 at. percent aluminum, while the greatest field-induced anisotropy is found near 22 at. percent aluminum. Induced anisotropy constants up to 20,000 ergs/cm^3 were recorded. A variety of different heat treatments were used in an attempt to explore the inhibiting effect of spontaneous long- or short-range order on the development of induced anisotropy. This inhibiting effect is very pronounced, and in stoichiometric Fe_3Al it is possible to prevent almost completely the creation of physical anisotropy. The results are discussed in terms of the Néel-Taniguchi directional-order theory of field- and stress-induced anisotropy. There is a close relationship between the magnitude of the reduced anisotropy and the magnitude of the Zener internal friction.

148. HIGH TEMPERATURE LAG IN IRON NICKEL ALLOYS

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The kinetics of the permeability decrease (desaccomodation) occurring in quenched iron nickel alloys with 50 to 80 per cent nickel at temperatures between 300 and 500 degrees centigrade have been investigated. Two different processes could be separated, a short time and a long time process. The activation energy of the short time process is the same as that for diffusion of iron in iron nickel. Its time constant corresponds to the time for migration of iron atoms within the unit cell. This process thus shows the same kinetics as the formation of uniaxial anisotropy after measurements of Ferguson.[1] The permeability decrease due to the short time process can be suppressed by a rotating magnetic field. From these results it is concluded that the short time process is very likely to result from short range directional ordering according to the theory of Néel[2] and Taniguchi-Yamamoto.[3]

The long time process is not suppressable by a rotating field. The permeability decrease due to this process disappears at temperatures above the Ni_3Fe order-disorder transformation temperature. Furthermore the long time process shows similar kinetics as the formation of Ni_3Fe long range order and thus is possibly due to the formation of this order.

At the beginning of annealing the permeability decreases considerably faster in quenched specimens than in specimens slowly cooled in a rotating field. This effect can be explained by the presence of frozen in extra vacancies after quenching.

Finally it has been shown that molybdenum permalloy shows principally the same lag behaviour as permalloy without additions.

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[3] Taniguchi, S. and M. Yamamoto: Sci. Repts. Tohoku Univ. (Japan) A6, 330 (1954).

149. SOME EFFECTS OF DIRECTIONAL ORDERING IN ZONE MELTED Fe

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The directional ordering of C and N in Fe produces effects which can be observed by both magnetoelastic and magnetic methods. Low-frequency internal-friction experiments have been used to follow the magnetoelastic aftereffect of both carbon and nitrogen at low temperatures (below about -40 C). Relaxation times calculated from these experiments agree with relaxation times observed using the techniques of elastic aftereffect and the time decrease of magnetic permeability. At high temperatures (60 to 110 C) other effects of directional ordering were observed using a transformer-type device and studying the same specimens as were used for the internal-friction experiments. Relaxation times calculated from these experiments differed from the expected values by a factor of between two and three.

Other effects of directional ordering are observed in the temperature range of the Snoek peaks (20 to 40 C) in internal-friction experiments. Relaxation times can be estimated from these observations, and are found to differ appreciably from expected results. These results parallel in many ways those found in the FeAl system by D. B. Fischbach (to be published) who also used low-frequency internal-friction techniques. The mechanisms responsible for the various phenomena observed will be discussed.

This research was conducted under the sponsorship of the Office of Naval Research.

150. LOSSES IN SILICON IRON AT VERY LOW FREQUENCIES AND HIGH FLUX DENSITIES

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Past measurements of losses in soft magnetic materials magnetized to high flux densities have been largely confined to determination of a quasi-static hysteresis loss over a nondescript cycle of magnetization and losses with sinusoidal magnetization with frequencies greater than 15 cps. However, since the simple concept of a hysteresis loss combined with an eddy current loss in a homogeneous medium has become outmoded, measurements of losses resulting from sinusoidal magnetization over a frequency spectrum from near-zero to power frequencies is desirable.

This paper describes losses in (110) [001] textured silicon iron strips which were magnetized with sinusoidal induction of negligible distortion in the frequency range 0.02 to 100 cps. Flux density amplitudes of 10, 15, and 17 kilogauss were used. A direct-coupled amplifier with very large negative feedback and a low distortion oscillator were used to excite the specimens. Losses in the range 0.02 - 0.4 cps were obtained from loop measurements; bridge measurements were made in the range 0.4 - 100 cps.

The measurements reveal a sharp drop in the loss per cycle as the frequency is decreased from 1.5 to 0.02 cps. The downward concavity of the loss-frequency curve which has been observed previously for the power frequency range is therefore even more prominent at very low frequencies. The effect increases with the amplitude of the flux density.

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151. MAGNETIC CORE LOSSES RESULTING FROM A ROTATING FLUX

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Most work in the past for determining magnetic core losses has been based on the assumption of an alternating flux. However, in parts of many machines such as generators, the flux rotates rather than alternates. Because of this, it would be advantageous when calculating the losses in a machine if data on losses due to a rotating flux were available.

At the 1957 Conference on Magnetism, a paper was delivered in which the magnetic core loss comparator (also known as the magnetic probe) was described. Since that time, a procedure has been devised by means of which the magnetic core losses caused by a rotating flux can be determined using this instrument. One obtains a rotating flux by inserting the legs of a cross-shaped lamination into two sets of magnetizing coils, each set at right angles to the other. If the phases of the magnetizing currents going into each set of coils are adjusted so that the resulting fluxes are 90° out of phase (electrically) with one another, a rotating flux results in the lamination. Core loss readings are made every 30° (geometrically) about a point near the center of the lamination using the magnetic probe. The actual loss of the material can then be determined by adding the losses in any two mutually perpendicular directions.

Core loss measurements can be made under varying flux conditions ranging from a pure alternating flux (flux in only one direction) to a pure rotating flux (flux in two mutually perpendicular directions of equal magnitude). Intermediate to these two extremes, measurements can also be made with the flux densities in the two directions of unequal magnitude. This latter condition is that which is found in an actual generator.

Utilizing the above technique, the magnetic core losses caused by a rotating and an alternating flux were determined for an oriented and a non-oriented silicon iron.

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152. HIGH TEMPERATURE STABILITY OF MAGNETIC MATERIALS

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Magnetic materials able to perform in environmental extremes are a prerequisite to many military applications such as space vehicles, ballistic missiles and other advanced systems. Industry in cooperation with various government agencies is in constant search for better magnetic materials to meet these requirements.

Of the environments to be considered for these applications, temperature has the most deleterious effect on magnetic materials. Numerous investigations in the past have reported on high temperature properties which included silicon-irons, aluminum-irons, nickel-irons, and vanadium-cobalt-irons. Most of these materials were reported to show a significant irreversible change in magnetic properties as a result of exposure to 500°C and return to room temperature.

This paper will present a possible explanation to the cause of some of these changes especially in the high Curie point alloys. Our investigations showed that cobalt-iron alloys containing from 27 to 50% cobalt can be stable magnetically up to at least 600°C. However, this temperature stability is dependent upon several important considerations. One of these is the geometry of the test system. For example: a tape wound toroidal core tested at elevated temperatures in air becomes severely oxidized—this oxidation or the strains induced by it adversely affect the magnetic properties. However, when the same core is tested in a neutral atmosphere the strains due to oxidation are minimized and the magnetic properties remain stable.

Data will be presented comparing tests on toroids with and without neutral atmospheres, both oriented and non-oriented alloys containing 27, 35, 43, and 50% cobalt. Finally all results will be compared with square punchings relating the differences in high temperature stability of the magnetic properties due to geometric configurations.

SESSION O

OXIDES

J. F. DILLON, JR., Presiding

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153. MAGNETIC PROPERTIES OF SOME FLUOSILICATES AT LOW TEMPERATURES (Invited)

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154. SYNTHESIS AND PROPERTIES OF FERROMAGNETIC CHROMIUM OXIDE

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Ferromagnetic chromium oxides of high purity have been synthesized by thermal decomposition of chromium trioxide in the presence of water at elevated pressure. These materials consist entirely of a rutile-type crystalline phase with cell constants $a_o = 4.41 \pm 0.01$Å and $c_o = 2.91 \pm 0.01$Å and have compositions that are very close to the exact stoichiometry of the dioxide, CrO_2. Saturation specific magnetizations of these oxides are in the range of 98-100 emu/g. at room temperature and their Curie temperatures are about 126°C. By using different reaction conditions, it is possible to obtain either microcrystalline particles from 3-10μ in length and from 1-3μ in width or single crystals of fractional millimeter size that are suitable for physical studies. In addition, elongated single domain crystals only 0.5-1.5μ in length and with length-to-width ratios of 8:1 or higher can also be obtained merely by adding catalytic amounts of Sb_2O_3 and RuO_2 under hydrothermal synthesis conditions. While the coercivity of large single crystals is only approximately 12 oersteds, coercivities of up to several hundred oersteds are exhibited by powders composed of the small single domain crystals.

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155. GROWTH OF YTTRIUM IRON GARNET SINGLE CRYSTALS BY THE FLOATING ZONE TECHNIQUE

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Since YIG melts inconguently, single crystals must be grown from an iron-rich melt. A high oxygen pressure is necessary, during crystal growth, to maintain oxygen stoichiometry. Because of the high volume resistivity of YIG, it was not practical to use direct RF coupling, but an oxidation-resistant molybdenum disilicide ($MoSi_2$) susceptor was used successfully to melt and move an iron-rich zone through 1/4-3/8 inch polycrystalline bars. Usually, a small amount of iron oxide (αFe_2O_3) was added to the initial molten zone to shift the melt composition to the Fe_2O_3-rich side of the peritectic. However, since the formation of orthoferrite ($YFeO_3$) causes Fe_2O_3 enrichment of the melt by the reaction $3Y_2O_3 \cdot 5Fe_2O_3 \rightarrow 3(Y_2O_3 \cdot Fe_2O_3) + 2Fe_2O_3$, equivalent results were obtained by simply melting-in and moving a zone through stoichiometric YIG. Large YIG crystals, 1/4 inch diameter or larger, were obtained with the highest possible stable-zone temperature, a zoning rate of 0.10 inches/hr, and an oxygen pressure of 75 psig or higher. The presence of silicon contamination, crystalline imperfections, or non-equilibrium phases in YIG crystals effected a broadening of ferrimagnetic resonance line width, but values of two oersteds or less at x-band were obtained from highly polished test spheres. Dielectric constant, dissipation, and line width were minimal for high oxygen pressures. Volume resistivities of 10^9 and 10^{10} ohm-cms were calculated from 1000 cps measurements of capacitance and dissipation for oxygen pressures of 25 and 75 psig, respectively. Quantitative determinations of yttrium in float-zoned YIG crystals were within 0.1% of stoichiometry. A lattice constant of 12.378 Å and [110] growth direction were determined by x-ray diffraction. Properties of YIG single crystals are discussed in terms of phase equilibria and parameters of the floating zone technique.

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156. EQUILIBRIUM ATMOSPHERE SCHEDULES FOR THE COOLING OF FERRITES

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It has been recognized for many years that the chemical, physical, and magnetic properties of ferrites are not uniquely determined by the proportions of the initial ingredients. Instead, there is a continuum of compositions all spinel in structure which differ from one another by the amount of oxygen they contain and by the distribution of valences among their cations. Any particular composition in the continuum can be obtained at high temperature by the proper choice of oxygen content in the ambient atmosphere.

If a ferrite is cooled very quickly by removing it from the furnace directly to room temperature, a desired composition can often be maintained. But the thermal shock set up by the internal mechanical strains are undesirable and will fracture ferrite bodies of any reasonable size. Also, the distribution of cations among the spinel sites is different at high temperatures than at room temperature. It is, therefore, very desirable to have a means of cooling ferrites slowly from high temperature without altering the composition or introducing inhomogeneous layers.

If, as the temperature of the ferrite is lowered from the high temperature at which its composition was established, the oxygen content of the surrounding atmosphere is also decreased according to a proper schedule (the equilibrium atmosphere schedule) a condition can be maintained in which there is no net gain or loss of oxygen to the ferrite and consequently, no composition change. The specification of these equilibrium atmospheres is the subject of this paper.

A gas mixture, containing oxygen and argon or

hydrogen and carbon dioxide in measured proportions, were passed over the ferrite samples, maintained at one of a series of constant temperatures, until equilibrium was attained. The samples were then quenched and analyzed for ferrous ion content. The temperature ranged from about 1000°C to 1400°C, and the partial pressure of oxygen in the ambient atmosphere ranged from about 10^{-8} to 1 atmosphere.

Ferrous ion analyses and petrographic examinations were carried out on samples of two manganese-zinc-iron ferrites and two nickel-zinc-iron ferrites prepared in the manner described above. Fairly complete phase diagrams of the spinel field of each were obtained including contour lines of constant ferrous ion content. These latter contour lines are the desired equilibrium atmosphere lines.

A comparison of these new data with the Darken and Gurry[1,2] data on Fe_3O_4 led to the unexpected result that one family of contours specifies the equilibrium atmosphere schedules for all four ferrites and magnetite. In seeking an explanation, one recalls that these ferrites (and all technically useful ferrites for that matter) contain more iron than all other cations combined. These observations have led the author to propose the hypothesis that the subject equilibrium atmosphere diagram is a universal diagram, in the sense that it is good first approximation to the equilibrium atmosphere diagram for any ferrite whose cation population is dominated by iron. This generalization includes the garnets and the barium "ferrites" having hexagonal crystal structures.

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157. REINTERPRETATION OF THE REACTION KINETICS OF NICKEL FERRITE

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Recent work on the kinetics of formation of nickel ferrite has been analyzed in terms of an equation developed by Jander. He employed as a model, a sphere of one component surrounded by spheres of a second component and calculated the reaction as interdiffusion of the components assuming that diffusion through the product layer was the rate determining step and as such was inversely proportional to the layer thickness. When Jander's equation is applied to experimental data, a poor fit is found both in the initial and final stages of the reaction process.

Re-analysis of the $NiO-Fe_2O_3$ system indicates that the reaction closely fits the equation $C = A \log t + B$ where C is the percent reaction, t is time, and A and B are constants. The above equation can be derived from Fick's diffusion law by assuming that the concentration gradient is inversely proportional to time.

Measurements of the growth of saturation magnetization in the $NiO-Fe_2O_3$ system show a sharp break in the concentration time curve and indicate that two separate and distinct mechanisms occur. These are interpreted as (1) an initial surface diffusion of significance at temperatures in the 600° - 800°C range, and (2) bulk diffusion in temperature ranges above 700°C. Activation energies for the surface diffusion and bulk diffusion are 30 Kcal and 18 Kcal, respectively. Both reactions are very well fitted by the logarithmic time dependence given above. As is characteristic with solid state reactions, the lattice imperfections disappear with increasing time or at high temperature, and the reaction rate slows as the degree of perfection increases.

Both the low, for ferrite formation, activation energy for the bulk diffusion, and the high initial reaction rate at higher temperatures suggest that the reaction proceeds through an intermediate magnetic phase. Such a component has been prepared in the form of defect NiO and its presence accounts for the ease with which bulk diffusion takes place.

158. PREPARATION AND PROPERTIES OF LOW LOSS FERRITES

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Nickel zinc ferrites containing one to three mol percent of cobalt ferrite and small additions of molybdenum or vanadium oxides have been prepared with U_oQ products ranging from 49,000 at 500 kc. to 4,000 at 55 mc. The effect of stoichiometry, ferrous iron content, firing temperature and firing time on the initial permeability, U_o, and the magnetic quality factor, Q, is discussed. The nickel ferrite-zinc ferrite system is unique in its ability to yield materials with high U_oQ products in this frequency range. These properties are intimately related to the perminvar characteristics these compositions possess and are interpreted in terms of the Néel-Taniguchi approach. It is believed that a necessary condition for good high frequency response is the domination of the resonance phenomena by a spin rotation mechanism in preference to a domain wall process. This is achieved in properly constituted nickel-zinc ferrites by combining a high density, a low magnetocrystalline anisotropy and a very small grain size.

159. EFFECT OF COBALT OXIDE IN POROUS NICKEL FERRITES AT VHF

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Low-loss ferrites for vhf applications usually contain cobalt oxide and have high porosities (10-30%). The effect of cobalt oxide in improving Q is particularly striking. By addition of a small amount of cobalt oxide to plain nickel ferrite, the vhf loss maximum can be made to occur at higher frequency.[1] In an attempt to understand this action of cobalt oxide, complex permeability of a series of porous

ferrites ($NiO_{(1-x)}CoO_xFe_2O_3$) has been studied in the frequency range 1-600 Mc/s. The data are reviewed on 3-dimensional diagrams having cobalt oxide as a parameter and frequency and fraction of theoretical density as variables.

In almost all cases, a resonance-type dispersion appears in the vhf region. Evidence that this is not due to a rotation process is given by the following: The data do not satisfy Snoek's relation $\omega_r \chi_s = \frac{2}{3}\gamma M$ where ω_r is the angular frequency of the loss maximum and χ_s is the static initial (rotational) susceptibility, with the possible exception of the composition x = 0.02; the calculated rotational susceptibility is less than the measured value, again with the exception x = 0.02 to 0.04; earlier measurements on a series of dense cobalt-containing nickel ferrites have indicated[2] that rotational (spin) resonances occur at frequencies much higher than vhf, in good agreement with limits set forth by Polder and Smit.[3]

Evidence that the vhf dispersion is due to a wall resonance can be obtained in the following way. By assuming that the dispersion can be described by a single equation of the form $m\ddot{x} + \beta x + kx$ = driving force, one can, from the frequencies at which the inflection in permeability and the loss maximum occur, obtain numerical ratios for k/m and β/m in the above equation. No assumption is made as to how much of the permeability is contributed by rotation or by wall movement. When curves of k/m and β/m for porous nickel ferrite are plotted vs fraction of theoretical density, and extrapolated to a fractional density of 1.0, the values are consistent with k/m and β/m as determined on a nickel ferrite single crystal.[4] The suggestion is therefore made that in a porous nickel ferrite, the low-frequency portion of the loss corresponds to wall movement taking place in small, relatively perfect regions or grains. According to this picture a small addition of cobalt oxide increases k/m in these "single crystal" regions, causing the dispersion to occur at higher frequency.

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160. INITIAL PERMEABILITY CHARACTERISTICS OF VANADIUM DOPED MANGANESE ZINC FERRITES

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In this report we should like to mention the effects of doping of vanadium to reduce the core losses in polycrystalline manganese zinc ferrites and also of the simultaneous effects of both addition of small amounts of vanadium and calcium. The reason of selection of vanadium as a doping element is as follows. One of the present authors had considered[1] previously the magnetostriction in ferrites and found that the cobaltous ions in ^4F state in spinel lattice play an interesting part, and also the essential behaviors of this incomplete quenching of orbital moment in ^4F state were considered by Kanamori[2] and by Slonczewski.[3] Because the electronic charge distribution in V^{3+} is similar as that in Co^{2+} group-theoretically, it is reasonable to consider that something similar interactions such as magnetocrystalline and strictive ones between spin and lattice system owing to V^{3+} would be expected as for the case of Co^{2+}, and an adequate amount of doping of V^{3+} into manganese zinc ferrite may decrease core losses of it.

Toroidal specimens were prepared under the standard sintering techniques with final treating temperature ranging from 1200° to 1400°C. Manganese zinc ferrites, one of the basic composition represented as $(MnO)_{0.255}$ $(ZnO)_{0.220}$ $(Fe_2O_3)_{0.525}$ doped by small amount of vanadium in the form of V_2O_3 or V_2O_3, the concentration of which is less than 1 mol percent, and also by small amount of calcium in the form of $CaCO_3$ with the concentration less than 1 mol percent. Measurements have been performed, the one part of which is the core loss of these toroids represented as

$$\tan \delta_m = h_1\sqrt{L/V}\, i + e_1 f + C_1$$

where δ_m (radian) is loss angle, L (henry) the inductance, V(cm^3) the volume of the ferrite core, i (amp.) the measuring high frequency current, f (cycles/sec) the frequency used (3-100 kc/s) and h_1 corresponds to the hysteresis coefficient, e_1 (sec) to the eddy current loss coefficient, and C_1 to the residual loss term. The brief summary of the results is as follows. With the increasing concentration of vanadium in the ferrites the initial permeability μ increases rapidly and simultaneously tan δ_m decreases, and after certain doping stage tan δ_m/μ increases rather slowly. The hysteresis coefficient h_1 behaves similarly as tan δ_m/μ, the minimum value of which is less than one third of the undoped ones. These facts suggest that the adequate amount of vanadium reduces the magnetic energies which suppress the initial magnetization in the ferrites. The

addition of small amount of calcium reduces not only the specific conductivity of the ferrites as already emphasized by Guillaud,[4] but also reduces h_1, and it seems the both additive elements behave almost independently. The detailed experimental results will be discussed in terms of possible models.

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161. EFFECT OF INDIUM SUBSTITUTION IN YTTRIUM IRON GARNET: HIGH PERMEABILITY GARNETS

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Initial studies on the effect of small substitutions of indium for iron in polycrystalline yttrium iron garnet showed a substantial increase in the initial permeability.[1] Since previous substitution of other ions has produced either little change or a decrease in the permeability, we have prepared additional members in this series in order to study the effect of indium on the garnet structure in more detail. Although from the general formula, $3Y_2O_3 \cdot xIn_2O_3 \cdot (5 - x)Fe_2O_3$, it appears that x may take any value up to 5, the single-phased garnet structure is formed only for x values less than about one. This is due for the most part to the roughly 30% increase in ionic radii of In^{3+} over that of Fe^{3+}. X-ray determination of the lattice parameters for this series shows a linear increase from 12.376 ± .005A(x = 0) to 12.445 ± .005A(x = 0.6) for those samples in which no detectable second phase appears. For $x \geq 0.7$ a second phase ($YFeO_3$) is clearly evident indicating that the system becomes double phased somewhere between $0.6 < x < 0.7$.

The relative initial complex permeability, $\mu^* = \mu' - j\mu''$, was measured over a frequency range from 10^3 to 2×10^9 cps on high density, 96 ± 2% of the theoretical x-ray density, toroids with x varying from x = 0 to 0.7 in increments of 0.1. Increases in μ'_0, the low frequency value of μ', over that of YIG were found for all x values with the exception of x = 0.7. A plot of μ'_0 as a function of x shows an essentially linear increase from $\mu'_0 = 100$ for x = 0 (YIG) to $\mu'_0 = 620$ for x = 0.6.

As in the case of other substitutions for Fe^{3+} the substitution of In^{3+} resulted in a decided decrease in the Curie temperature from that of YIG (T_c = 290°C) to $T_c \sim 185$°C for x = 0.6. Magnetic moment measurements indicate that the low temperature moment is increased from 9.4 μ_B for x = 0 to approximately 13 μ_B for x = 0.6. The room temperature moment is only slightly higher than that of YIG. On the basis of comparison of their thermal magnetic properties it could be expected that Sc^{3+} substitution in small amounts would also produce a rise in μ'_0. Apparently the increase in μ'_0 is due to the lowering of the Curie temperature while the magnetic moment is held nearly constant or increased slightly. Measurements of μ'_0 as a function of temperature up to the Curie point for this series will be presented.

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162. A FERRITE SYSTEM FOR APPLICATION AT LOWER MICROWAVE FREQUENCIES*

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The ferrimagnetic system $(LiFe)_{1-\frac{a}{2}-\frac{x}{2}}Zn_xMn_{.02}Fe_{2a-y}Ti_{1-a}Al_yO_{4\pm}$ is found to possess properties compatible with the requirements of ferrites for utilization in nonresonant devices at lower microwave frequencies. The basic system consists of $(LiFe)_{1-\frac{a}{2}}Fe_{2a}Ti_{1-a}O_4$. For approximately $0.2 \leqslant a \leqslant 0.4$ the system exhibits a relatively high Curie temperature, a moderate saturation moment and low dielectric losses. The composition with a = 0.3 was selected for further investigation because it exhibits a saturation moment compatible with lower microwave frequency requirements.

The compositions $(LiFe)_{.85-\frac{x}{2}}Zn_xMn_{.02}Fe_{.6-y}Al_yTi_{.7}O_{4\pm}$, where $0 \leqslant x \leqslant 0.1$ and $0 \leqslant y \leqslant 0.15$ are found to possess intrinsic properties superior to the basic system. Small substitutions of Zn^{++} afford control of the saturation moment and line width in addition to that control obtained with variations of a. With increasing Zn^{++} substitution the saturation moment is increased and the line width is reduced. Al^{+++} substitutions provide a simultaneous decrease in line width and saturation moment. Since difficulty is encountered in preparing sound ceramic specimens with a concentration of Ti^{++++} greater than 0.7, Al^{+++} substitutions provide additional means of lowering the moment without destroying the physical properties of the material. Data on magnetic properties of this system are given, including S-band phase-shifting data of one of the members, and methods of controlling the magnitude of these properties through compositional variations. Results of investigations of the system $(LiFe)_{1-\frac{a}{2}}Fe_{2a}Sn_{1-a}O_4$ are also given. This system does not form a single-phase solid solution except possibly for values of a approaching 1.0.

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163. CATION DISTRIBUTIONS IN MAGNESIUM-NICKEL FERRITES

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The dependence of the non-thermal part of the internal energy (u_1) of mixed magnesium-nickel ferrites, $Mg_yNi_{1-y}Fe_2O_4$, on the cation distribution has been studied. The cation distribution, which is characterized by the parameters η (the fraction of Mg ions on tetrahedral sites) and ξ (the fraction of Ni ions on tetrahedral sites), is determined from measurements of the saturation magnetization of samples quenched from temperatures between 1400°C and 400°C.

As in the case of magnesium-manganese ferrites,[1] it is found that

$$u_1 = u_0 + R\,(\theta_0 - \tfrac{1}{2}\,\theta_1\,\eta^2).$$

This result is contrary to the original work[2] on the cation distribution of magnesium ferrite which reported a linear dependence of u_1 on η.

The parameters θ_0 and θ_1 are related to the energies necessary to transport Mg ions from octahedral (B) to tetrahedral (A) sites. The Madelung energy portion of θ_0 predicts a linear dependence of θ_0 on y and this is observed experimentally for values of y = 0.2, 0.4, 0.5, 0.6, 0.8, 0.9 and 1.0. It is also demonstrated that θ_0 is increased considerably by the substitution of Ni ions for Mn ions in the spinel lattice as dictated by the Madelung energy. The dependence of θ_1 on y can also be qualitatively explained.

It is shown that the magnetic moment data considered as a function of composition can give useful information about the degree of inversion in the spinel lattice despite the two degrees of inversional freedom (ξ and η). The variation of the maximum attainable value of η with composition depends critically on and the magnetic moment of the Ni ion. Values of ξ and the Ni ionic magnetic moment compatible with the observed data are discussed.

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[1] C. J. Kriessman and S. E. Harrison, Phys. Rev. **103**, 857 (1956).

[2] R. Pauthenet and L. Bochirol, J. Phys. Radium **12**, 249 (1951).

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164. THE REMANENT MAGNETIZATION OF A SYNTHETIC HEMATITE SINGLE CRYSTAL*

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The magnetic properties of a synthetic single crystal of hematite have been carefully studied by measuring the remanence of a virgin sample[1] along different directions through a temperature range from 77°K to 400°K. Some remarkable phenomena have been found.

1. There is no weak ferromagnetism along the [111] direction throughout the whole temperature range under investigation.

2. The weak ferromagnetism is strictly limited to the (111) plane above the Morin transition point and is sharply reduced to zero at 259°K. The thermal hysteresis of the remanence-temperature curve forms a perfect square loop in contrast with the natural crystal which shows a wide transition region about 100°K.[2]

3. If the sample is cooled below the transition point and warmed above it again in zero external magnetic field (the earth magnetic field must be completely compensated) there is no ferromagnetism along any direction in the crystal.

The last phenomena mentioned above immediately suggest that if the sample were warmed above the transition in zero external field, the weak ferromagnetic moments would be equally distributed along the easy directions in the basal plane and hence the resultant ferromagnetic moment would be zero. The phenomena also suggest that the usually observed weak ferromagnetism is probably due to the effect of the directive field from the earth magnetism when the material was formed or warmed through transition.

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*This work was carried out under contract with the U. S. Atomic Energy Commission.

[1] The author is deeply grateful to Dr. R. M. Bozorth and Dr. J. W. Nielsen for their kindness in supplying the sample.

[2] S. T. Lin, Phys. Rev. **116**, 1447 (1959); S. T. Lin, J. Appl. Phys. Supplement, **31**, 273S (1960).

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