AIEE

4th conference

magnetism and magnetic materials

Nov. 17-20, 1958

SHERATON HOTEL • PHILADELPHIA

MAGNETICS EXHIBIT

(Delaware Valley Suite; Connie Mack, Independence, and Constitution Rooms.)

A Magnetics Exhibit has been arranged on the third floor of the Hotel with some of the country's outstanding firms engaged in research, manufacture, and application of magnetic materials, components and equipment. Everyone is welcome. Open hours are 9 A.M. to 5:30 P.M. each day. Exhibiting companies include:

	BOOTH
The Arnold Engineering Co., Marengo, Ill. Alnico Permanent Magnets Cast and Sintered; Silectron "C" and "E" Cores; High Permeability Tape Wound Cores of Deltamax, Permalloy, Supermalloy, and Supermendur; Tape Wound Bobbin Cores; Powder Cores of Molybdenum Permalloy, Iron and Sendust; Special Magnetic Materials	21 and 22
Bell Telephone Laboratories, Inc., Murray Hill, N. J.	25
Columbian Carbon Co., New York, N. Y. Pure Synthetic Iron Oxides as Raw Materials for Ferrite Manufacture.	20
Crucible Steel Co. of America, Pittsburgh, Pa. Permanent Magnets and Magnetic Components	12
Encyclopaedia Brittanica, Philadelphia, Pa. The 1958 Edition	18
G-L Electronics Co., Inc., Camden, N. J. Tape Wound Magnetic Cores and Bobbin Cores.	26
General Electric Company, Research Laboratory, Schenectady, N. Y. and Metallurgical Products Division, Detroit, Mich. Demonstrations of Magnetism and Magnetic Resonance.	29 and 30
GRH Halltest Co., Valparaiso, Ind. Magnetic Precision Measuring Instruments Based on the Hall-Effect; Indium-Arsenide-Phosphide Hall-Gnerators.	23
Hamilton Watch Co., Lancaster, Pa. Ultra Thin Tape; Miniature Coils; Magnetic Materials.	19
The Indiana Steel Products Co., Valparaiso, Ind. Alnico and Indox Ceramic Permanent Magnets; Cunife Magnets; Hyflux "One Piece" Wound Cores.	13
Magnaflux Corp., Chicago, Ill. and Dr. Foerster Institute Electronic Eddy Current Nondestructive Testing Equipment; Magnetic Field Measuring Instruments.	11
Magnetic Metals Co., Camden, N. J. Electromagnetic Core Parts and Shields.	10
Magnetic Shield Division-Perfection Mica Co., Chicago, Ill. Magnetic Shielding Materials, Both Raw Materials and Fabricated Parts.	8
Nuclear Magnetics Corp., Norwalk, Conn. Precision Gaussmeter.	9
Radio Frequency Laboratories, Inc., Boonton, N. J. Magnet Charging, Treating, and Measuring Equipment.	14
Rese Engineering, Inc., Philadelphia, Pa. Flux-Reset Core Tester; Pulse Type Core Testers.	16
United States Steel, Pittsburgh, Pa. Electrical Steel Sheets.	27
Leyman Corporation, Magnetics Division, Cincinnati, Ohio Permanent Magnets.	24

The Fourth National Conference on Magnetism and Magnetic Materials, sponsored by the American Institute of Electrical Engineers in cooperation with the American Physical Society, The Metallurgical Society of A. I. M. E. And the Office of Naval Research will be held November 17-20, 1958 at the Sheraton Hotel, Philadelphia, Pa.

The Conference is arranged by the Magnetics Subcommittee of the Basic Science Committee of the AIEE.

The purpose of the Conference is to bring together those interested in basic and applied work in magnetism.

Any questions not answered in the following pages may be referred to C. J. Kriessman, Local Chairman, Remington Rand Univac, 1900 W. Allegheny Avenue, Philadelphia 29, Pa.

SUMMARY OF SESSIONS

Monday, November 17

8:00 A.M. - 4:30 P.M.	Registration
9:30 A.M. - 12:00 Noon	Session I - General Session with Opening Remarks and Invited Papers, Ballroom
2:00 P.M. - 5:00 P.M.	Session IIa - Ferrites, Ballroom
2:00 P.M. - 5:00 P.M.	Session IIb - Computer Components, Pennsylvania Room
9:00 A.M. - 5:30 P.M.	Magnetics Exhibit
5:00 P.M.	Crucible Quench Room, Pennsylvania Room.

Tuesday, November 18

9:00 A.M. - 12:00 Noon	Session IIIa - Micromagnetics, Domain Walls, Ballroom.
9:00 A.M. - 12:00 Noon	Session IIIb - Magnetic Properties of Metals and Alloys, Pennsylvania Room
2:00 P.M. - 5:00 P.M.	Session IVa - Fine Particles, Ballroom
2:00 P.M. - 5:00 P.M.	Session IVb - Amplifiers, Microwave Applications, Pennsylvania Room
9:00 A.M. - 5:30 P.M.	Magnetics Exhibit
5:00 P.M.	Crucible Quench Room, Pennsylvania Room

Wednesday, November 19

9:00 A.M. - 12:00 Noon	Session Va Resonance, Ballroom
9:00 A.M. - 12:00 Noon	Session Vb - Metallurgical Considerations, Pennsylvania Room
2:00 P.M. - 5:00 P.M.	Session VIa - Fundamental Interactions, Ballroom
2:00 P.M. - 5:00 P.M.	Session VIb - Instrumentation, Pennsylvania Room
9:00 A.M. - 5:30 P.M.	Magnetics Exhibit
5:00 P.M.	Reception, Magnetic Metals Co., Assembly Area of Ballroom
6:30 P.M.	Dinner, Ballroom

Thursday, November 20

9:30 A.M. - 12:00 Noon	Session VIIa — Thin Films, Ballroom
9:30 A.M. - 12:00 Noon	Session VIIb - Neutron Diffraction and Irradiation, Pennsylvania Room
2:00 P.M. - 5:00 P.M.	Session VIIIa - Garnets and Other Compounds, Ballroom
2:00 P.M. - 5:00 P.M.	Session VIIIb - Anisotropy, Other Than in Thin Films, Pennsylvania Room
9:00 A.M. - 5:30 P.M.	Magnetics Exhibit

Preregistration

A pregistration 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 R. B. Campbell, Franklin Institute, Philadelphia, Pa.

Registration and Proceedings

Registration will be at the Sheraton Hotel from 8:00 A.M. to 4:00 P.M. on Monday, November 17 and from 8:30 A. M. to 4:30 P. M. on the other days of the Conference.

The registration fee will be $9.00. Each registrant will receive a copy of the Proceedings which will appear as a separate issue of the Journal of Applied Physics, probably Part 2 of the March 1959 issue. Other copies will be available only from a publisher at about $10.00 a copy.

Social Gatherings

In order to encourage free flow of information and distillation of new ideas, the Crucible Steel Company is sponsoring two cocktail parties on the 17th and 18th of November at 5 P.M. in this years' Quench Room, The Pennsylvania Room of the Sheraton Hotel.

High School Science Day

The Magnetics Subcommittee in conjunction with the Public School System of Philadelphia is sponsoring a Science Day for gifted high school science students. The purpose of this meeting is to encourage these students to continue their science education. A number of prominent scientists will be present. A special exhibit of research science projects and demonstrations will be held on the fifth floor of the Sheraton Hotel.

Reception and Dinner

A special reception to which all registrants at the Conference are invited is being held in the Assembly Area of the Ballroom of the Sheraton Hotel at 5:30 P. M. on Wednesday, November 19th in honor of the foreign guests and invited speakers of the Conference. This reception is being sponsored by the Magnetic Metals Company.

Immediately after the reception a dinner will be held in the ballroom. The theme of this dinner will be the High School Science Day sponsored by the Conference and will pay honor to the many prominent people taking part in this program. It is believed that this general type of program will be of great value to the country and it is hoped that everyone will attend its inception.

The reception is open to all registrants without cost. Dinner tickets will be available at registration. A special effort is being made to guarantee an excellent meal.

Hotel Reservations

Accommodations have been guaranteed at the Conference Headquarters, The Sheraton Hotel. Please mention the Conference when writing for reservations. If any difficulties develop please contact the Local Chairman or R. B. Campbell, Franklin Institute, Philadelphia, Pa.

Program for Wives

Do not hesitate to bring your wife for fear she might be bored. The local committee has planned the following activities: a tour of historic Philadelphia (Independence Hall, Christ Church, etc.), a Philadelphia Orchestra concert, a fashion show, a night at the theatre, a tour of historic Valley Forge.

Information for Speakers

The meeting rooms will be provided with a standard slide projector for 3-1/4" x 4" slides, blackboard and a reading stand. Speakers must furnish completed manuscripts to the session chairman at the time papers are given. Papers are prepared for publication on the day following the meeting.

ORGANIZATION

General Chairman - J. E. Goldman

Program Committee Chairman - H.G. Callen

Local Committee Chairman - C. J. Kriessman

Program Committee - J. J. Becker, A. C. Beiler, L. R. Bickford, R. M. Bozorth, W. F. Brown, Jr., M. E. Caspari, J. E. Goldman, L. R. Maxwell, G. T. Rado, J. S. Smart, and M. T. Weiss.

Local Committee
- Printing and Program, A. E. Berkowitz, W. Flannery, E. Levinson
- Registration, R. B. Campbell
- Finance, J. Blades
- Exhibits, D. O. Schwennesen
- Meeting Rooms, K. Atkins
- High School Science Exhibit, H. Belson
- Foreign Visitors, H. Amar
- Publicity, J . Smith, J. Mather
- Dinner and Tours, T. Matcovich

Publications Committee Chairman - J. A. Osborn

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Society Representatives
American Institute of Electrical Engineers
R. S. Gardner

American Physical Society
J. E. Goldman

The Metallurgical Society of A. I. M. E.
J. J. Becker

American Institute of Radio Engineers
C. L. Hogan

Office of Naval Research
W. R. Gruner

CONFERENCE ON MAGNETISM AND MAGNETIC MATERIALS,

PHILADELPHIA, NOVEMBER 17-20, 1958
SHERATON HOTEL

TECHNICAL PROGRAM

Monday, November 17, 1958

Session I Ballroom

GENERAL SESSION
H. B. Callen, Presiding

Opening Remarks:

J. E. Goldman, Conference Chairman
C. J. Kriessman, Local Chairman
H. B. Callen, Program Chairman

Invited Papers:

1. TRAINAGE DE DIFFUSION ET ORDRE DIRECTIONNEL LES FERROMAGNETIQUES
   L. Neel, Institut Fourier, Grenoble, France
2. THE PHENOMENOLOGICAL TREATMENT IN THE QUANTUM THEORY OF FERRO- AND ANTI-FERRO-MAGNETICS
   S. V. Vonsozski, Academy of Sciences, U.S.S.R., Sverdlosk
3. SPIN WAVES
   C. Kittel, University of California
   Berkeley, California
4. PRINCIPLES OF FERRITE REACTANCE AMPLIFICATION
   A. Gardner Fox, Bell Telephone Laboratories, Holmdel, New Jersey.

2:00 P. M.

Session II-A Ballroom

FERRITES

L. R. Maxwell, Presiding

5. HEAT CONDUCTION IN SOME FERRIMAGNETIC CRYSTALS AT LOW TEMPERATURES (Invited Paper)
   S. A. Friedberg,
   Carnegie Insitute of Technology.
6. MAGNETIC PROPERTIES AND GRANULAR STRUCTURE OF Mn-Zn FERRITES
   W. Heister,
   Research Lab. of the Fried. Krupp Widia-Fabrik, Essen, Germany.
7. DISTRIBUTION OF CATIONS IN SPINELS
   Arthur Miller,
   RCA.
8. ON THE ORIGIN OF LOW MOMENTS IN CHROMIUM-CONTAINING SPINELS
   Philip K. Baltzer and Peter J. Wojtowicz,
   RCA.
9. THEORETICAL MODEL FOR CUBIC TO TETRAGONAL PHASE TRANSFORMATIONS IN TRANSITION METAL SPINELS
   Peter J. Wojtowicz,
   RCA.
10. MEASUREMENTS OF ROTATIONAL MAGNETIC LOSSES IN FERRITES AT VERY LOW FREQUENCIES
    Hermon M. Parker, B. W. Bullock and W. H. Dancy, Jr.,
    Ordnance Research Laboratory,
    University of Virginia.
11. REMAGNETIZATION EXPERIMENTS IN $Mn_{1+x}Fe_{2-x}O_4$
    T. J. Matcovich and C. J. Kriessman,
    Remington Rand Univac
12. LOW TEMPERATURE MAGNETIC PROPERTIES OF NICKEL-IRON FERRITE
    N. Menyuk and K. Dwight,
    Lincoln Laboratory, MIT.
13. THE MAGNETIC PROPERTIES OF SUBSTITUTED MANGANESE-TIN SPINELS
    M. A. Gilleo and D. W. Mitchell,
    Bell Telephone Laboratories.
14. SOME CRYSTALLOGRAPHIC AND MAGNETIC PROPERTIES OF SQUARE-LOOP MATERIALS IN FERRITE SYSTEMS CONTAINING COPPER
    Aaron P. Greifer and William J. Croft,
    RCA.
15. AN APPROACH TO A RATIONALE IN FERRITE SYNTHESIS: EVALUATION OF MAGNETIC MOMENTS
    Louis Gold,
    Edgerton, Germeshausen and Grier, Inc.

2:00 P. M.

Session II-B Penna. Room

COMPUTER COMPONENTS

A. C. Beiler, Presiding

16. RECENT ADVANCES IN MAGNETIC COMPUTER ELEMENTS (Invited Paper)
    D. H. Looney,
    Bell Telephone Laboratories.
17. A REVERSIBLE, DIODELESS, TWISTOR SHIFT REGISTER
    Andrew H. Bobeck and Robert F. Fischer,
    Bell Telephone Laboratories.
18. A MILLIMICROSECOND MAGNETIC SWITCHING AND STORAGE ELEMENT
    Donald A. Meier,
    National Cash Register Company.
19. MILLIMICROSECOND SWITCHING PROPERTIES OF FERRITE COMPUTER ELEMENTS
    W. Lee Shevel, Jr.,
    IBM.
20. AN EVALUATION OF A NEW HIGH SPEED MAGNETIC FERRITE SYSTEM FOR USE IN COMPUTER COMPONENTS
    Barlane R. Eichbaum,
    IBM.
21. A STUDY OF THE RESIDUAL STATES OF FERRITE CORES IN COMPUTER MEMORY OPERATION
    W. M. Overn and V. J. Korkowski
    Remington Rand Univac.
22. COINCIDENT-CURRENT NONDESTRUCTIVE READOUT FROM THIN MAGNETIC FILMS
    Lewis J. Oakland,
    Remington Rand Univac, and
    Thomas D. Rossing,
    St. Olaf College, Northfield, Minn.
23. THE REVERSIBLE COMPONENT OF MAGNETIZATION
    R. W. McKay,
    University of Toronto.
24. INHIBITED FLUX -- A NEW MODE OF OPERATION OF THE THREE-HOLE MEMORY CORE
    J. A. Baldwin, Jr. and J. L. Rogers,
    Bell Telephone Laboratories.
25. HIGH SPEED MAGNETIC CORE STORAGE
    Henning F. Harmuth,
    GE Advanced Electronics Center,
    Cornell University.
26. OPERATING CHARACTERISTICS OF A THIN FILM MEMORY
    Jack I. Raffel,
    Lincoln Laboratory, M.I.T.

TUESDAY, NOVEMBER 18, 1958

9:00 A. M.

Session III-A Ballroom

MICROMAGNETICS; DOMAIN WALLS
C. P. Bean, Presiding

27. MICROMAGNETICS, DOMAINS, AND RESONANCE (Invited Paper)
William Fuller Brown, Jr.,
University of Minnesota.
28. SOME RECENT DEVELOPMENTS IN MICROMAGNETICS AT THE WEIZMANN INSTITUTE OF SCIENCE (Invited Paper)
Amikam Aharoni,
The Weizmann Institute of Science, Israel.
29. THEORETICAL APPROACH TO THE ASYMETRICAL MAGNETIZATION CURVE
A. Aharoni, E. H. Frei and S. Shtrikman,
The Weizmann Institute of Science.
30. DOMAIN BOUNDARY CONFIGURATIONS DURING MAGNETIZATION REVERSALS
Joseph J. Becker,
General Electric.
31. INITIAL PERMEABILITY PROCESSES IN NICKEL-COBALT FERRITES OF VARIOUS DENSITIES
J. E. Pippin,
Sperry Microwave Electronics Company.
32. INTERNAL STRUCTURE OF CROSS-TIE WALLS IN THIN PERMALLOY FILMS THROUGH HIGH RESOLUTION BITTER TECHNIQUES
Ralph M. Moon,
Lincoln Laboratory, M.I.T.
33. OBSERVATIONS MADE ON DOMAIN WALLS IN THIN FILMS
Harrison W. Fuller and Harvey Rubenstein,
Laboratory for Electronics, Inc.,
Boston, Massachusetts.
34. CORRELATION OF ENERGY LOSSES WITH PERFECTION OF CRYSTAL ORIENTATION AND DOMAIN STRUCTURE
H. Hu and G. Wiener,
Westinghouse.
35. HYSTERESIS AND EDDY LOSSES IN SILICON IRON AS A FUNCTION OF SHEET THICKNESS
Peter W. Neurath,
General Electric.
36. ENERGY LOSSES RESULTING FROM DOMAIN WALL MOTION
W. J. Carr, Jr.,
Westinghouse.

9:00 A. M.

Session III-B Penna. Room

MAGNETIC PROPERTIES OF METALS AND ALLOYS
J. J. Becker, Presiding

37. MAGNETIC CONTRIBUTION TO THE ANOMALOUS Y-LOOP SHEAR OF Fe-Al ALLOYS
Ryoichi Kikuchi,
Wayne State University, and
Hiroshi Sato,
Ford Motor Company.
38. REMARKS ON MAGNETICALLY DILUTE SYSTEMS
H. Sato and A. Arrott,
Ford Motor Company, and
R. Kikuchi,
Wayne State University.
39. SATURATION MAGNETIZATION AND CURIE POINTS IN DILUTE ALLOYS OF Fe
A. Arrott and J. E. Noakes,
Ford Motor Company.
40. THE SATURATION MAGNETIZATION AND FERROMAGNETIC INTERACTION IN TERBIUM METAL
Warren E. Henry,
U. S. Naval Research Laboratory.
41. THE EFFECT OF CHEMISORBED HYDROGEN ON THE MAGNETIZATION OF NICKEL AT LOW TEMPERATURES
Robert E. Dietz and P. W. Selwood,
Northwestern University.
42. STRUCTURAL AND MAGNETIC PROPERTIES OF Mn-Co-C ALLOYS
A. H. Holtzman and G. P. Conard, II,
Lehigh University.
43. EFFECTS OF HIGH TEMPERATURE ON MAGNETIC PROPERTIES OF CORE MATERIALS
Michael Pasnak and Richard Lundsten,
U. S. Naval Ordnance Laboratory.
44. TEMPERATURE DEPENDENCE OF THE MAGNETIC PROPERTIES OF NICKEL-IRON ALLOYS
J. J. Clark and J. F. Fritz,
Westinghouse.
45. THE EFFECT OF MAGNETIC ANNEALING ON THE PROPERTIES OF (110) [001] ORIENTED 3-1/4 PER CENT SILICON-IRON STRIP
H. C. Fiedler and R. H. Pry,
General Electric.
46. PRECIPITATION IN A BETA BRASS-Fe ALLOY
A. E. Berkowitz and P. J. Flanders,
The Franklin Institute Laboratories.
47. THE EFFECT OF COMPOSITION AND PROCESSING ON THE ACTIVITY OF SOME MAGNETOSTRICTIVE MATERIALS
C. M. Davis, Jr. and S. F. Ferebee,
U. S. Naval Ordnance Laboratory.
48. THE INFLUENCE OF VARIOUS HEAT EXPOSURES ON ALNICO V MAGNETS
Rudolph K. Tenzer,
The Indiana Steel Products Company.

TUESDAY, NOVEMBER 18, 1958

2:00 P. M.

Session IV-A Ballroom

FINE PARTICLES
T. O. Paine, Presiding

49. THE ANGULAR VARIATION OF THE COERCIVITY OF PARTIALLY ALIGNED ORIENTED FERRO-MAGNETIC PARTICLES (Invited Paper)
    E. P. Wohlfarth,
    Imperial College,
    London, England.
50. SUPERPARAMAGNETISM (Invited Paper)
    C. P. Bean,
    General Electric.
51. ON THE MAGNETIC PROPERTIES OF MULTI-DOMAIN PARTICLES
    Henri Amar,
    The Franklin Institute Laboratories.
52. RECENT DEVELOPMENTS IN THE FIELD OF ELONGATED SINGLE-DOMAIN IRON AND IRON-COBALT PERMANENT MAGNETS
    R. B. Falk, G. D. Hooper, and R. J. Studders,
    General Electric.
53. MAGNETIC PROPERTIES OF SOME FERRITE MICROPOWDERS
    A. E. Berkowitz and W. J. Schuele,
    Franklin Institute Laboratories.
54. SHAPE DISTRIBUTION OF MAGNETIC POWDERS
    Clark E. Johnson, Jr.,
    Minnesota Mining and Manufacturing Co., and
    William Fuller Brown, Jr.,
    University of Minnesota.
55. RELAXATIONAL BEHAVIOR OF FINE MAGNETIC PARTICLES
    William Fuller Brown, Jr.,
    University of Minnesota.
56. MAGNETISM OF SUBMICROSCOPICAL IRON PARTICLES
    Klaus J. Kronenberg,
    The Indiana Steel Products Company.
57. A NOVEL LIGHT-WEIGHT MOLDABLE PERMANENT MAGNET MATERIAL
    R. S. Norman and L. I. Mendelsohn,
    General Electric.
58. STABILITY STUDIES OF MAGNETS COMPOSED OF ELONGATED SINGLE-DOMAIN IRON PARTICLES
    E. J. Yamartino, H. R. Broadley, Jr. and R. C. Lever,
    General Electric.

2:00 P. M.

Session IV-B Penna. Room

AMPLIFIERS, MICROWAVE APPLICATIONS
A. G. Fox, Presiding

59. MICROWAVE AND LOW FREQUENCY OSCILLATIONS DUE TO RESONANCE INSTABILITIES IN FERRITES
    M. T. Weiss,
    Bell Telephone Laboratories.
60. MAGNETO-ACOUSTIC RESONANCE IN YTTRIUM IRON GARNET
    E. G. Spencer and R. C. LeCraw
    Bell Telephone Laboratories.
61. EXPERIMENTAL STUDY OF THE MODIFIED SEMISTATIC FERRITE AMPLIFIER
    W. L. Whirry and F. B. Wang,
    Hughes Aircraft Company
62. LIMITATIONS OF ELEMENTARY MODE CONSIDERATIONS IN FERRITE LOADED WAVEGUIDE
    R. C. Fletcher and H. Seidel,
    Bell Telephone Laboratories.
63. A NEW Y-TYPE CIRCULATOR
    Herman N. Chait and Thorton R. Curry,
    U. S. Naval Research Laboratory.
64. THE REGGIA-SPENCER MICROWAVE PHASE SHIFTER
    Jerald A. Weiss,
    Bell Telephone Laboratories.
65. COMPACT PASSIVE NONRECIPROCAL STRUCTURES FOR UHF FREQUENCIES
    H. Seidel,
    Bell Telephone Laboratories.
66. LOW-LOSS GYROMAGNETIC COUPLING THROUGH SINGLE CRYSTAL GARNETS
    R. W. DeGrasse,
    Bell Telephone Laboratories.
67. HIGH POWER EFFECTS IN FERRITE SLABS AT X-BAND
    Ronald L. Martin,
    Bell Telephone Laboratories.
68. A STUDY OF MICROWAVE FERRIMAGNETIC MULTIPLE SIGNAL CONVERSION PROCESSES WITH APPLICATION TO MILLIMETER WAVE GENERATION AND FERRIMAGNETIC AMPLIFICATION
    E. N. Skomal and M. A. Medina,
    Sylvania Microwave Physics Laboratory.
69. HARMONIC GENERATION IN FERRIMAGNETIC ELLIPSOIDS
    Frederic R. Morgenthaler,
    Air Force Cambridge Research Center.

9:00 A. M.

Session V-A Ballroom

RESONANCE
M. T. Weiss, Presiding

70. FERRIMAGNETIC RESONANCE IN RARE EARTH IRON GARNETS NEAR THE COMPENSATION POINT (Invited Paper)
S. Geschwind and L. R. Walker,
Bell Telephone Laboratories.
71. FERROMAGNETIC RESONANCE NEAR THE UPPER LIMIT OF THE SPIN WAVE MANIFOLD
C. R. Buffler,
Gordon McKay Lab, Harvard University.
72. IONIC DISTRIBUTION AND FERRIMAGNETIC RESONANCE IN MAGNESIUM FERRITE
H. S. Belson and C. J. Kriessman,
Remington Rand Univac.
73. MICROWAVE RESONANCE IN HEXAGONAL FERRIMAGNETIC SINGLE CRYSTALS
H. S. Belson and C. J. Kriessman,
Remington Rand Univac.
74. FERROMAGNETIC RESONANCE IN POLYCRYSTALLINE FERRITES WITH HEXAGONAL CRYSTAL STRUCTURE
Ernst Schlomann,
Raytheon Manufacturing Company, and
R. V. Jones,
Gordon McKay Lab, Harvard University.
75. MEASUREMENT OF FERROMAGNETIC RELAXATION BY A MODULATION TECHNIQUE
Joseph I. Masters and Roy W. Roberts, Jr.,
Air Force Cambridge Research Center.
76. THE COUPLING OF MAGNETOSTATIC MODES
P. C. Fletcher and I. H. Solt, Jr.,
Hughes Research Laboratories.
77. OBSERVATIONS ON LINE WIDTH IN FERRIMAGNETIC RESONANCE
Robert L. White,
Hughes Research Laboratories.
78. FERROMAGNETIC RESONANCE g-VALUES TO ORDER $(kR_o)^2$
J. E. Mercereau,
Hughes Research Laboratories.
79. A SURFACE-INDEPENDENT RELAXATION IN FERROMAGNETIC RESONANCE OF YTTRIUM IRON GARNET
R. C. LeCraw and E. G. Spencer,
Bell Telephone Laboratories.
80. FERROMAGNETIC RESONANCE OF IRON WHISKER CRYSTALS
D. S. Rodbell,
General Electric.

9:00 A. M.

Session V-B Penna. Room

METALLURGICAL CONSIDERATIONS
J. A. Osborn, Presiding

81. THE INFLUENCE OF PLASTIC DEFORMATION ON THE TIME DECREASE OF PERMEABILITY IN TRANSFORMER STEEL (Invited Paper)
A. K. Smolinski,
Technical University of Warsaw, Poland.
82. THE DEVELOPMENT OF METALLURGICAL STRUCTURES AND MAGNETIC PROPERTIES IN IRON SILICON ALLOYS (Invited Paper)
R. H. Pry,
General Electric Company.
83. SOLUBILITY OF CARBON IN IRON AND SILICON IRON AS DETERMINED BY MAGNETIC AFTER-EFFECT
Joseph Singer and Eugene S. Anolick,
General Electric.
84. BRITTLENESS IN IRON-COBALT ALLOYS
C. W. Chen and G. Wiener,
Westinghouse.
85. ROOM-TEMPERATURE DECOMPOSITION OF AUSTENITE IN FIFTY PER CENT NICKEL - FIFTY PER CENT IRON MAGNETIC ALLOY TAPES
N. I. Aananthanarayanan and R. J. Peavler,
Westinghouse.
86. MERCURY PROCESS FOR MnBi PRODUCTION
A. Goldman and G. I. Post
Westinghouse.
87. INVESTIGATION OF A PRECIPITATION HARDENING ELINVAR
Fred Hawkes,
Raytheon Manufacturing Company.
88. VARIATION IN ORIENTATION TEXTURE OF ULTRA THIN MOLYBDENUM PERMALLOY TAPE
P. K. Koh,
Allegheny Ludlum Steel Corporation,
H. A. Lewis and H. F. Graff,
Arnold Engineering Company.
89. ON THE TEMPERATURE DEPENDENCE OF THE (110) [001] TEXTURE IN SILICON IRON
J. E. May and D. Turnbull,
General Electric.
90. PROGRESS IN ULTRATHIN MO-PERMALLOY TAPES WITH SQUARE HYSTERESIS LOOPS
Martin F. Littmann and Chester E. Ward,
Armco Steel Corporation.

WEDNESDAY,

2:00 P. M.

Session VI-A Ballroom

FUNDAMENTAL INTERACTIONS
G. T. Rado, Presiding

91. THE EXPERIMENTAL DETERMINATION OF THE HYPERFINE COUPLING IN FERROMAGNETIC METALS AND ALLOYS (Invited Paper)
N. Kurti,
Clarendon Laboratory,
Oxford, England.
92. THE ELECTRONIC STRUCTURE OF TRANSITION METALS (Invited Paper)
W. Marshall,
Harvard University and A.E.R.E.,
Harwell, England.
93. NUCLEAR MAGNETIC RESONANCE IN MAGNETIC MATERIALS (Invited Paper)
R. G. Shulman,
Bell Telephone Laboratories.
94. NUCLEATION OF FERROMAGNETIC DOMAINS IN IRON WHISKERS
R. W. DeBlois and C. P. Bean,
General Electric.
95. DIRECT OBSERVATION OF SPIN WAVE RESONANCE
M. H. Seavy, Jr. and P. E. Tannenwald,
Lincoln Laboratory, MIT.
96. TEST OF SPIN-WAVE THEORY WITH PRECISION MAGNETIZATION MEASUREMENTS
S. Foner and E. D. Thompson,
Lincoln Laboratory, MIT.
97. MAGNETIC CONTRIBUTIONS TO THE ELASTIC CONSTANTS OF Ni AND AN Fe-30% Ni ALLOY AT HIGH MAGNETIC FIELDS
G. A. Alers, J. R. Neighbours, and H. Sato,
Ford Motor Company.
98. SOME CONSIDERATIONS ON OBTAINING POLARIZED PHOTOELECTRONS FROM MAGNETIZED METALS.
E. S. Dayhoff,
U. S. Naval Ordnance Laboratory.
99. ANTIFERROMAGNETIC MAGNON DISPERSION LAW AND BLOCH WALL ENERGIES IN FERROMAGNETS AND ANTIFERROMAGNETS.
R. Orbach,
University of California, Berkely.

NOVEMBER 19, 1958

2:00 P. M.

Session VI-B Penna. Room

INSTRUMENTATION
E. Both, Presiding

100. STRONG EDDY-CURRENT APPLICATIONS OF PERMANENT MAGNETS
K. Tendeloo,
Phillips' Laboratories,
Eindhoven, Netherlands.
101. A THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE FERROMAGNETIC EXPLOSIVELY SHOCKED CURRENT PULSE GENERATOR
Jerome H. Johnson,
Sandia Corporation.
102. AN ELECTROMAGNETIC SUPPORT ARRANGEMENT WITH THREE DIMENSIONAL CONTROL — PART I — THEORETICAL
A. W. Jenkins and Hermon M. Parker,
Ordnance Research Laboratory,
University of Virginia.
103. AN ELECTROMAGNETIC SUPPORT ARRANGEMENT WITH THREE DIMENSIONAL CONTROL, — PART II — EXPERIMENTAL.
Hugh S. Fosque and Glenn Miller,
Ordnance Research Laboratory,
University of Virginia.
104. MAGNETIC RECORDING HEAD WITH D-C RESPONSE
Robert E. Fischell and S. J. Meenan,
Emerson Research Laboratories.
105. SHAPE ANISOTROPY IN A WIDE RANGE GAUSSMETER
F. E. Luborsky and L. I. Mendelsohn,
General Electric.
106. THE DESIGN OF AUTOMATIC RECORDING INSTRUMENTS FOR MAGNETIC MEASUREMENTS IN A HOT CELL
W. S. Byrnes, R. G. Crawford and R. C. Hall,
Westinghouse.
107. A FLUX INSTRUMENT FOR RAPID COMPARISON OF CRYSTAL ANISOTROPIES
R. W. Cole and C. R. Honeycutt,
Crucible Steel Company.
108. MAGNETIC DOMAIN MOTION OBSERVED BY ELECTRON MIRROR MICROSCOPY.
Ludwig Mayer,
General Mills.

9:30 A. M.

Session VII-A Ballroom

THIN FILMS
C. J. Kriessman, Presiding

109. PARTIAL SWITCHING OF THIN PERMALLOY FILMS
F. B. Hagedorn,
Bell Telephone Laboratories.
110. ROTATIONAL HYSTERESIS IN THIN FILMS
J. R. Mayfield,
IBM.
111. A STUDY OF SLOW WALL MOTION SWITCHING OF THIN VACUUM DEPOSITED IRON-NICKEL FILMS
R. W. Olmen and E. N. Mitchell,
Remington Rand Univac.
112. STRESS ANISOTROPY IN Ni-Fe THIN FILMS
John D. Blades,
Burroughs.
113. ANISOTROPY AND COERCIVITY IN THIN FILMS
C. J. Kriessman, H. S. Belson and F. H. Edelman,
Remington Rand Univac.
114. ANISOTROPY IN PERMALLOY FILMS
Donald O. Smith,
Lincoln Laboratory, MIT.
115. MAGNETIC EFFECTS OF ISOTROPIC STRESS IN PERMALLOY FILMS
Ernest E. Huber, Jr. and D. O. Smith,
Lincoln Laboratory, MIT.
116. ANISOTROPY FIELD MEASUREMENTS ON Ni-Fe THIN FILMS
Rexford C. Alexander,
Burroughs.
117. MAGNETO-OPTICAL STUDY OF THE BARKHAUSEN EFFECT IN EVAPORATED NICKEL-IRON FILMS
N. G. Ford, Jr. and E. W. Pugh,
IBM.
118. SOME OBSERVATIONS ON EVAPORATED PERMALLOY FILMS
William W. L. Chu, J. Edmond Wolfe and Bernard Wagner,
General Electric.
119. STRUCTURAL AND MAGNETIC PROPERTIES OF PERMALLOY FILMS
J. C. Lloyd and R. S. Smith
IBM.
120. THE INFLUENCES OF SUBSTRATE PROCESSING ON THE MAGNETIC PROPERTIES AND REPRODUCIBILITY OF EVAPORATED NICKEL-IRON FILMS
Klaus H. Behrndt and Fred S. Maddocks,
IBM.

9:30 A. M.

Session VII-B Penna. Room

NEUTRON DIFFRACTION AND IRRADIATION
J. S. Smart, Presiding

121. NEUTRON DIFFRACTION INVESTIGATIONS OF MAGNETIC PHENOMENA IN CRYSTALLINE COMPOUNDS (Invited Paper)
M. K. Wilkinson,
Oak Ridge National Laboratory.
122. SYMMETRY OF MAGNETIC STRUCTURES (Invited Paper)
L. M. Corliss and J. M. Hastings,
Brookhaven National Laboratory.
123. NEUTRON DIFFRACTION INVESTIGATION OF A POSSIBLE FERRO-ANTIFERROMAGNETIC PHASE TRANSITION IN $Mn_{0.2}Cr_{0.8}Sb$
S. J. Pickart,
U. S. Naval Ordnance Laboratory and Brookhaven National Laboratory, and
R. Nathans,
Pennsylvania State University and Brookhaven National Laboratory.
124. THE EFFECT OF NEUTRON IRRADIATION ON THE MAGNETIC PROPERTIES AND DEGREE OF ORDER OF MAGNETIC METAL ALLOYS
A. I. Schindler, E. I. Salkovitz and G. S. Ansell,
U. S. Naval Research Laboratory.
125. IN-PILE MEASUREMENTS OF RADIATION EFFECTS IN MAGNETIC MATERIALS
R. E. Alley, Jr.,
Bell Telephone Laboratories.
126. THE REDUCTION OF MAGNETIZATION OF γ Fe_2O_3 AND Fe_3O_4 BY PILE IRRADIATION
W. E. Henry and E. I. Salkovitz,
U. S. Naval Research Laboratory
127. RADIATION EFFECTS ON THE ANISOTROPY OF SINGLE CRYSTALS OF SEVERAL SOFT MAGNETIC MATERIALS INCLUDING ALLOYS OF NiFe, SiFe, AND AlFe
R. C. Hall, W. S. Byrnes, and R. G. Crawford,
Westinghouse.

THURSDAY, NOVEMBER 20, 1958

2:00 P. M.

Session VIII-A Ballroom

GARNETS AND OTHER COMPOUNDS
M.E. Caspari, Presiding

128. MAGNETIC PROPERTIES OF THE RARE EARTH GARNETS (Invited Paper)
R. Pauthenet,
Laboratoire d'Electrostatique et de Physique du Metal, Grenoble, France.

129. MAGNETIC ANNEALING OF YTTRIUM IRON GARNET
B. A. Calhoun,
IBM.

130. TEMPERATURE DEPENDENT LAG IN POLY-CRYSTALLINE YTTRIUM-IRON GARNET.
D. J. Epstein and B. Frackiewicz,
MIT.

131. MAGNETIC-ION INTERACTION IN $Gd_3Mn_2Ge_2GaO_{12}$ AND RELATED GARNETS
M. A. Gilleo and S. Geller,
Bell Telephone Laboratories.

132. SOME ELECTRICAL AND MAGNETIC PROPERTIES OF GARNETS
Elmer E. Anderson,
U. S. Naval Ordnance Laboratory.

133. EVIDENCE FOR TRIANGULAR MOMENT ARRANGEMENTS IN $MO{\cdot}Mn_2O_3$
I. S. Jacobs,
General Electric.

134. THERMOMAGNETIC BEHAVIOR OF NICKEL OXIDE
N. Perakis,
University of Strasbourg,
Strasbourg, France, and
G. Parravano,
University of Notre Dame.

135. DEFECTS IN THE CRYSTAL AND MAGNETIC STRUCTURES OF FERROUS OXIDE
W. L. Roth,
General Electric.

136. LOW TEMPERATURE MAGNETIC PROPERTIES OF THE CHROMIUM (III) HALIDES
Wilford N. Hansen,
Iowa State College.

137. SOME NEW MAGNETIC PHENOMENA OF HEMATITE SINGLE CRYSTALS
S. T. Lin,
MIT.

138. UNIFORM ROTATION IN FERRITE TOROIDS
E. M. Gyorgy and F. B. Hagedorn
Bell Telephone Laboratories.

2:00 P. M.

Session VIII-B Penna. Room

ANISOTROPY, OTHER THAN IN THIN FILMS
R. M. Bozorth, Presiding

139. THE EFFECT OF ORBITAL DEGENERACY ON ANISOTROPY AND MAGNETOSTRICTION
J. C. Slonczewski,
IBM.

140. EXCHANGE ANISOTROPY IN DISORDERED Ni-Mn ALLOYS
J. S. Kouvel and C. D. Graham, Jr.
General Electric.

141. EXCHANGE ANISOTROPY IN AN Fe-Al ALLOY AT VERY LOW TEMPERATURES
J. S. Kouvel,
General Electric.

142. ON THE MAGNETIC ANISOTROPY IN MANGANESE-IRON SPINELS
R. F. Penoyer and M. W. Shafer,
IBM.

143. THE ANISOTROPY CONSTANTS OF IRON AND 3% SILICON-IRON AT ROOM TEMPERATURE AND BELOW
C. D. Graham, Jr.,
General Electric.

144. ANISOTROPY OF SUPERPARAMAGNETIC COBALT PARTICLES AS MEASURED BY TORQUE AND RESONANCE
C. P. Bean, J. D. Livingston and D. S. Rodbell,
General Electric.

145. THE SYNTHESIS OF A (110) [001] TYPE TORQUE CURVE IN SILICON IRON
C. G. Dunn and J. L. Walter,
General Electric.

146. STONER-WOHLFARTH CALCULATIONS ON PARTICLE WITH BOTH MAGNETO-CRYSTALLINE AND SHAPE ANISOTROPY
Clarke E. Johnson,
Minnesota Mining and Manufacturing Co., and
William Fuller Brown, Jr.,
University of Minnesota.

SESSION I

INVITED PAPERS

1. TRAINAGE DE DIFFUSION ET ORDRE DIRECTIONNEL DANS LES FERROMAGNETIQUES

L. NEÉL
Institut Fourier
Grenoble, France

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2. THE PHENOMENOLOGICAL TREATMENT IN THE QUANTUM THEORY OF FERRO- AND ANTIFERRO-MAGNETS

S. Vonsozski
Academy of Sciences
U.S.S.R., Sverdlovsk

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3. SPIN WAVES

C. KITTEL
Department of Physics
University of California
Berkeley 4, California

This talk has been arranged as an explanatory pedagogical introduction to spin waves in ferromagnets, starting from a macroscopic viewpoint. Analogies with the problems of elastic waves in solids are drawn. It is suggested that from the existence of Bloch walls one is led almost inexorably to the concept of a spin wave. The experimental evidence is discussed, together with several possible new lines of attack.

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4. PRINCIPLES OF FERRITE REACTANCE AMPLIFICATION

A. GARDNER FOX
Bell Telephone Laboratories, Inc.
Holmdel Radio Laboratory
Holmdel, New Jersey

This paper will review the physical principles of ferrite amplification in non-mathematical terms, and with emphasis upon the spatial relations required between the several magnetic fields. Some of the experimental characteristics of such amplifiers will be mentioned.

SESSION II-A

FERRITES

L. R MAXWELL, Presiding

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5. HEAT CONDUCTION IN SOME FERRIMAGNETIC CRYSTALS AT LOW TEMPERATURES* (Invited Paper)

S. A. FRIEDBERG
Carnegie Institute of Technology
Pittsburgh 13, Pennsylvania

Heat conduction in many solids is adequately described in terms of energy transport via quasi free electrons and/or lattice vibrations with due allowance for the interaction of these "excitations" with one another and with impurities, imperfections, or crystal boundaries. Other types of elementary excitations are thought to occur, for example, in magnetic solids and it is of interest to consider the role which these play in heat transport in such substances. Some of the existing speculation on this topic will be reviewed. Recent measurements of the thermal conductivities of single crystals of several ferrites** will also be discussed. These observations were carried out between 1.5° and 25°K in zero external field and in applied fields of about 10 kilo oersted. In those materials having very low zero field thermal conductivity a positive longitudinal magnetoconductivity was found. It has been suggested that this effect results from the reduction in a field of the scattering of lattice vibrations by elementary magnetic excitations, i.e. spin waves.

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

**D. Douthett and S. A. Friedberg, Bull. Am. Phys. Soc., Ser II, 3, 226 (1958).

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6. MAGNETIC PROPERTIES and GRANULAR STRUCTURE OF Mn-Zn-FERRITES

W. HEISTER
Research Laboratory,
Fried. Krupp Widia-Fabrik,
Essen, Germany

Of all known ferrites, the manganese zinc ferrites are of the greatest technical importance in telecommunication and television engineering by virtue of the extremely low losses occurring at frequencies up to about 1 Mc/s and their relatively high saturation magnetization at elevated temperatures. Especially the hysteresis losses can be reduced by adding a small amount of Fe_3O_4 having a positive magnetostriction.

Now, it has been found that besides the composition, the contents of Fe_3O_4, and the impurities, the granular structure of the Mn-Zn-ferrites has a marked influence on the magnetic properties, particularly on the hysteresis losses. Electron microscopic examinations of the structural fracture in connection with magnetic measurements have shown that the magnetic loss values become extremely low in cases where these ferrites, after sintering, possess a granular structure consisting of well defined monocrystals of the same shape and size. With a crystallite size of 5 to 10 microns an initial permeability of 3000, and a Curie point of 180°C the following loss factors, according to Legg, are obtained: a hysteresis loss coefficient $a = 0.16 \cdot 10^{-6} \frac{cm}{A}$, an eddy current loss coefficient $e = 0.18 \cdot 10^{-9}$ sec, and a residual loss coefficient $c = 4 \cdot 10^{-6}$. Compared with a normal ferrite of the same composition or with a molybdenum permalloy powder core the hysteresis loss coefficient is smaller by a factor of 10 and the residual loss coefficient by a factor of 5.

The change of the magnetic properties and the granular structure with the sintering temperature has been studied and we have found that for this temperature there are optimum values for the losses and the permeability. The lowest losses were observed at a sintering temperature of 1270°C and a grain size of 5 to 10 microns, whereas the highest permeability of $\mu_i = 4000$ is at a sintering temperature of 1370°C and a grain size of about 20 microns. In either case we find a characteristic monocrystal structure the fracture of which is always intercrystalline.

The special magnetic properties can be explained by the low shape anisotropy of the pores having nearly the form of spheres and, therefore, the same demagnetization factor in all directions. This fact is due to the regular polyhedron shape and the size of the monocrystals. As a result, magnetization of the monocrystals by rotation is easily possible, especially when the crystal anisotropy and the magnetostriction are low as is the case with ferrites containing zinc and ferrous ferrite. In connection with a low magnetostriction this means low hysteresis losses for the magnetization of the single crystals. Furthermore, the regular granular structure produces a homogeneous flux distribution in the polycrystalline ferrite, a condition also necessary for obtaining low hysteresis losses. Any impurities present are contained in the grain boundaries and, therefore, do not influence the process of magnetization. Moreover, these ferrites show a higher specific resistance and thus a lower eddy current loss than the ordinary ferrites. From these investigations it has been found that in making low loss ferrites, efforts should be made to achieve the following:

1.) Formation of a ferrite crystal being as complete as possible and free from magnetic anisotropies (crystal and stress anisotropy) as well as from impurities, and
2.) A homogeneous granular structure of such uniform monocrystals the size of which does not exceed 10 microns, so that the pores between them have a very low shape anisotropy.

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7. DISTRIBUTION OF CATIONS IN SPINELS

ARTHUR MILLER
RCA Laboratories
Princeton, New Jersey

The concept of octahedral site preference energy in spinels,[1,2] set forth by McClure, has been extended to include Madelung and short ranged, as well as crystal field terms. A set of site preference energies has been formulated which can be used to predict the ionic distribution of spinels involving the non-transition, as well as the transition ions. The agreement between predicted and experimentally determined ionic distributions is surprisingly good, and a number of heretofore puzzling ionic distributions are explained.

It is found that other things being equal, the tendency for an ion to occupy the octahedral spinel sites increases with increasing charge, and decreases with increasing radius.

As a consequence of the model of interatomic forces assumed in this formulation, it is shown that the u parameter of a spinel depends solely on the average ionic charge on the tetrahedral sites. This relationship has previously been observed empirically by Romeijn[3].

1. McClure, D. S., J. Phys. Chem. Solids 3,311 (1957).
2. Dunitz, J. D., and Orgel, L. E., J. Phys. Chem. Solids 3, 318 (1957).
3. Romeijn, F. C., Philips Res. Rep. 8, 304 (1953).

8. ON THE ORIGIN OF LOW MOMENTS IN CHROMIUM-CONTAINING SPINELS

PHILIP K. BALTZER and PETER J. WOJTOWICZ
RCA Laboratories
Princeton, New Jersey

The outstanding problem in the physics of the chromium-containing spinels has been that of the origin of the anomalously low moments observed in many of these compounds. The most commonly offered interpretation of the moment measurements has relied on the existence of the Yafet and Kittel ordering scheme. The experimental evidence for angular ordering schemes on the B-lattice of spinels is, however, inconclusive and contradictory. Prince[1] and Edwards,[2] for instance, have obtained neutron diffraction data on $CuCr_2O_4$ and $MnCr_xAl_{2-x}O_4$, respectively, which is consistent with, but does not uniquely determine the Yafet-Kittel scheme. Pickart and Nathans[3,4] on the other hand have found no evidence of the angular scheme in data on $MnCr_xFe_{2-x}O_4$ and $NiFe_{2-x}Cr_xO_4$, although they did establish that the moment of the B-lattice was lower than expected on a simple Néel picture. In this report we wish to present a new approach to this problem which appears to lead to a reasonable, adequate, and consistent treatment of the moment data.

It is usually supposed that the spin of the Cr^{3+} ion in octahedral environment of the spinel B-site is 3/2 giving a moment of three Bohr magnetons. A consideration of the crystal field theory pertinent to Cr^{3+} shows, however, that if the B-site is given a sufficient tetragonal or trigonal distortion, the doublet state, having a spin of 1/2 and a moment of one Bohr magneton, becomes the ground state. It is known further that the B-sites can be distorted from regular octahedral symmetry by the presence of Jahn-Teller distortions in neighboring sites. For example,[5] Ni^{2+} and Cu^{2+} cause distortions when on A-sites, while Cu^{2+} and Mn^{3+} cause distortions when on the B-sites. The process by which the moment of an ion is reduced in this way is called "spin quenching."

We therefore propose that the origin of the low moments in the chromites is the spin quenching effect imposed on the Cr^{3+} ions by the appropriate Jahn-Teller distortions of of their neighbors. We also emphasize that a macroscopically distorted phase is not required for this effect. It is only necessary that a distribution of distorting neighbors be present, sufficient in number to alter the symmetry about (and hence spin quench) at least a fraction of the chromium ions. In compounds where no Jahn-Teller distortions exist, spin quenching does not occur, and the moment data is explicable in terms of the usual concepts.

With the aid of these hypotheses it has proven possible to explain the moment data for many chromites in a consistent way. Of particular interest are the recently studied systems, $CuFe_xCr_{2-x}O_4$ [6] and $NiFe_xCr_{2-x}O_4$ [7].

1. E. Prince, Acta. Cryst. 10, 554 (1957).
2. P. L. Edwards, Bull. Amer. Phys. Soc. II, 3, 43 (1958).
3. S. J. Pickart, Bull. Amer. Phys. Soc. II, 3, 42 (1958).
4. S. J. Pickart and R. Nathans, Bull. Amer. Phys. Soc. II, 3, 231 (1958).
5. J. D. Dunitz and L. E. Orgel, J. Phys. Chem. Solids, 3, 20 (1957).
6. S. Miyahara and H. Ohnishi, J. Phys. Soc. (Japan), 11, 1296 (1956).
7. T. R. McGuire and S. W. Greenwald, private communication.

9. THEORETICAL MODEL FOR CUBIC TO TETRAGONAL PHASE TRANSFORMATIONS IN TRANSITION METAL SPINELS

PETER J. WOJTOWICZ
RCA Laboratories
Princeton, New Jersey

The origins of the large tetragonal distortions which occur in a number of transition metal oxides having the spinel structure have been examined recently by Dunitz and Orgel[1] in terms of the general crystal field theory. According to these authors, the distortions arise as a consequence of a Jahn-Teller type distortion in the litigation of certain transition metal cations. Thus, cations having the electronic configurations, d^4 and d^9 cause large prolate tetragonal distortions in the oxygen octahedra about the B-sites; the tetrahedra of oxygens about the A-sites are distorted prolate or oblate tetragonally by the configurations d^3 and d^8, or d^4 and d^9, respectively. All the observed large distortions in spinels can be correlated with the results of the above mentioned treatment.

In this communication we wish to investigate the detailed properties of the transformations from tetragonal to cubic phases which are observed at elevated temperatures. By analogy with a previous investigation found to be successful in explaining the behavior of transition metal perovskites[2], we have constructed an approximate model for the spinel which explicitly takes into account the interactions between local Jahn-Teller distortions about neighboring transition metal cations. In this paper we are concerned with those spinels having distorting cations on B-sites only; certain general conclusions about the more general case will be made, however.

By the use of the usual methods of statistical mechanics it is possible to derive the thermodynamic behavior of this model, and hence to contribute to an understanding of the cooperative nature of these crystal transformations. In particular, the temperature and composition dependence of the free energy, entropy, internal energy, heat capacity, and lattice parameters is computed. The principal result of importance is the demonstration that the transformations from distorted to cubic spinel phases are thermodynamically of the first order. That is, a latent heat, a volume discontinuity, and a lambda anomaly in the heat capacity are to be observed at the transformation temperature. A comparison of the theoretical results with the experiments to which they apply is presented; the available evidence seems to support the conclusions drawn from our model.

1. J. D. Dunitz and L. E. Orgel, J. Phys. Chem. Solids 3, 20 (1957).
2. P. J. Wojtowicz, Phys. Rev., to be published.

10. MEASUREMENTS OF ROTATIONAL MAGNETIC LOSSES IN FERRITES AT VERY LOW FREQUENCIES

HERMON M. PARKER, B. W. BULLOCK and
W. H. DANCY, JR.
Ordnance Research Laboratory
University of Virginia

For some time this laboratory has been interested in the rotational magnetic losses in ferrites at low frequencies. Apparatus has been developed and successfully operated in which these losses are measured at frequencies of the order of 0.1 cps in fields up to about 5000 gauss and over a reasonably wide temperature range. It consists of a quartz fiber torsion pendulum (the fiber perpendicular to the field) operating in a vacuum and in a reasonably constant temperature enclosure. The principle involved is that of observing the decay of free oscillations of the system, and determining the torques due to the losses by comparison with an appropriate analysis of the damped oscillatory system. By a process developed in our laboratory the samples are ground into spheres to accuracies of the order of 0.1% which can be improved if desired.

In the absence of magnetic anisotropy of the sample, the method can in principal distinguish between coulomb or constant torque losses (customarily assumed for rotational hysteresis loss torque) and loss torques proportional to the angular velocity (viscous). However, for all samples so far measured the anisotropy has been sufficiently large to prevent the disentangling of the coulomb and viscous losses. (Qualitative indications of the anisotropy are obtained from the measurements and it is interesting that the losses and anisotropy seem to be proportional.) The procedure has been to assume the losses are of the constant torque type and determine them by making the best engineering fit with the decay curves.

Results of measurements will be presented. These include brief measurements on a large number of samples which were not interesting to us because of excessive losses and anisotropy. Rather complete data over field ranges of 1000-5000 gauss and at temperatures of 35, 55, and 75 C for Ferroxcube 3B samples will be presented. It is expected that loss data on some samples composed of single domain assemblages will be available to present.

11. REMAGNETIZATION EXPERIMENTS IN $Mn_{1-x}Fe_{2-x}O_4$

T. J. MATCOVICH and C. J. KRIESSMAN
Remington Rand Univac
Division of Sperry Rand Corporation
Philadelphia, Pennsylvania

Interest in the remagnetization process in ferrites has been regenerated by the rotational hypothesis of Gyorgy[1] which contradicts the original domain wall motion theory of Goodenough and Menyuk.[2] In order to investigate the relative merits of these two theories, the switching time, t, has been measured as a function of external field, H, for a series of manganese ferrites, $Mc_{1+x}Fe_{2-x}O_4$. The principal aim of this work was to correlate the switching constant S_W with various physical properties of the ferrites such as anisotropy and magnetization which vary with composition. The domain wall theory, when simplified with certain reasonable assumptions, implies that

$$S_W = \frac{\alpha}{\gamma} \frac{M_S d}{\langle M_{\cos\theta} \rangle} \left[\frac{a(K + \lambda_i \sigma)}{KT_C} \right]^{1/2}$$

whereas the rotational hypothesis of Gyorgy implies

$$S_W = \frac{1}{\alpha T}$$

Measurement of S_W as a function on Mn content (x) gives information about the dependence of S_W on the basic physical parameters. Comparison of S_W with quantitative experimental measurements of the loss parameter α, the saturation magnetization M_S, the magnetization reversed during the remagnetization experiments $\langle M\cos\theta \rangle$, the lattice parameter a, the grain size d, the anisotropy constant K, and the Curie temperature T_C as a function of the composition x tend to corroborate Goodenough's theory. Gyorgy's theory predicts no variation of S_W with composition and predicts S_W values several times larger than the experimental values.

1. Gyorgy, J. of Appl. Phys. 28, 1011-1015 (1957).
2. Goodenough and Menyuk, J. of Appl. Phys. 26, 8 (1955).

12. LOW TEMPERATURE MAGNETIC PROPERTIES OF NICKEL-IRON FERRITE*

N. MENYUK and K. DWIGHT
Staff Members
Lincoln Laboratory
Massachusetts Institute of Technology

The magnetic properties of a single crystal of nickel-iron ferrite with composition $Fe^{3+}_{1.00}\left[Ni^{2+}_{0.79}Fe^{2+}_{0.36}Fe^{3+}_{0.90}\right]O_4$ have been studied between 77°K and 4.2°K. From 77°K to 10°K the anisotropy energy has cubic symmetry; and the absolute value of the first order anidotropy constant, $|K_1|$, increases slowly with decreasing temperature. At 10°K there is an abrupt transition in the anisotropy characteristics. Below this temperature $|K_1|$ increases with decreasing temperature, and the anisotropy energy contains a uniaxial term in addition to the cubic terms. The Uniaxial term has the form $\sum \alpha_i^2 \beta_i^2$, where α_i

and β_i are the direction cosines of the magnetization at the measuring temperature and at the annealing temperature ($10^{o}K$) respectively.

The sample composition, as given above, indicates the existence of excess cations. If these cations are assumed to occupy normally vacant octahedral sites of the spinel lattice, the application of the theory of magnetic anneal introduced by Taniguchi and Yamamoto,[1,2,3] and independently by Néel,[4] yields results in accord with the behavior described above. The low annealing temperature is possible since an effective ionic mobility is achieved by electron interchange between Fe^{2+} and Fe^{3+} ions. In addition, this model is able to give a semi-quantitative explanation of the non-cubic anisotropy energy obtained upon cooling the sample through the transition temperature in the absence of an external annealing field.

1. S. Taniguchi and M. Yamamoto, Sci. Rep. Res. Inst. Tohoku Univ. A6, 330 (1954).
2. S. Taniguchi, Sci. Rep. Res. Inst. Tohoku Univ. A7, 269 (1955).
3. S. Taniguchi, Sci. Rep. Res. Inst. Tohoku Univ. A9, 196 (1957).
4. L. Neel, J. Phys. Radium 15, 225 (1954).

*The research in this document was supported by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

13. THE MAGNETIC PROPERTIES OF SUBSTITUTED MANGANESE-TIN SPINELS

M. A. GILLEO and D. W. MITCHELL
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

In a $M_2^{2+}Sn^{4+}O_4$ spinel, Sn^{4+} is known to occupy octahedral sites. Therefore manganese-tin spinel, Mn(MnSn)O4, would be antiferromagnetic because of the strong interaction between octahedral and tetrahedral ions characteristic of magnetic spinels. The magnetic exchange interaction in a Mn^{2+}-O^{2-}-Mn^{2+} linkage is of particular interest because it is known to be much weaker than is the case for Fe^{3+} with which Mn^{2+} is isoelectronic; magnetic measurements on Mn_2SnO_4 yield a Néel temperature of $58^{o}K$.

When the initial equality of the sublattice magnetizations of Mn^{2+} ions in octahedral and tetrahedral sites is upset by substitution of non-magnetic, divalent ions, Mg^{2+} and Zn^{2+}, for Mn^{2+}, spontaneous magnetization appears. The Néel temperature is decreased by these substitutions largely as a consequence of the smaller number of interactions between the reduced number of Mn^{2+} ions in the two different sites. For equal substitutions of Mg^{2+} and Zn^{2+} for Mn^{2+} in Mn_2SnO_4, the moment which results is larger in the case of Mg^{2+} than Zn^{2+}. The moment depends upon the size of the substituent ion because, in this case, the ions involved are spherical and of the same valence. The small size of the substituent ions suggests a predominance of occupation of the octahedral sites will occur as consequence of the effect on the Madelung potential. The sequence, Mg^{2+}, Zn^{2+}, Mn^{2+}, of increasing ionic sizes corresponds to that of increasing lattice constants, 8.60, 8.67, 8.86Å, of the respective tin spinels.

Similarly spontaneous magnetization arises with oxidation of Mn_2SnO_4 because the resultant oxidized manganese ions are of higher valence (presumably Mn^{3+}) and smaller size than Mn^{2+} and, therefore, probably also appear in octahedral sites.

Analogous two-four spinels of titanium have been prepared.

14. SOME CRYSTALLOGRAPHIC AND MAGNETIC PROPERTIES OF SQUARE LOOP MATERIALS IN FERRITE SYSTEMS CONTAINING COPPER

AARON P. GREIFER and WILLIAM J. CROFT
Radio Corporation of America
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Rectangular hysteresis loops have been found in ferrite systems containing copper. This occurrence is in accord with the theory expressed by Baltzer* that a zero value or near zero value of the effective magneto crystalline domain anisotropy is a necessary condition for loop squareness. Addition of copper ferrite to ferrites having negative magneto crystalline anisotropy such as lithium ferrite, nickel ferrite and magnesium ferrite causes the anisotropy to go through zero by imposing localized tetragonal distortions on the spinel lattice.

Data on loop squareness of polycrystalline bodies as a function of composition, firing conditions, magnetostrictive effects and crystallographic parameters are presented with particular emphasis on the system: Copper ferrite - magnesium ferrite. Polycrystalline samples have been prepared in this system at ten mole percent intervals and, in the region of high squareness, at five mole percent intervals. Crystallographic and magnetic properties have been investigated from room temperature to $78^{o}K$ on samples that have been quenched or cooled slowly from high temperatures. The entire system has cubic crystallographic symmetry when fired under conditions that give maximum squareness (>.8 for optimum composition). The relationship of magnetic properties such as coercive force and flux density at moderate fields has been investigaged. Microscopic observations have been made to study the effect of grain size on the switching coefficient.

*Baltzer, P. K., Technical Conference on Magnetism, Pittsburgh, June 1955.

15. AN APPROACH TO A RATIONALE IN FERRITE SYNTHESIS: EVALUATION OF MAGNETIC MOMENTS

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A systematic development of broad classes of composite ferrites is given in terms of MO or R_2O_3 addition to a mother spinel under three groupings I-I, N-N, I-N which refer to systems involving two inverse spinels, two normal and one of each. The behavior of the related magnetic moments is examined in terms of composition for certain idealized conditions in the light of antiferromagnetic coupling of spins at the tetrahedral and octahedral sites. The conditions under which the magnetic moment shifts in direction (referred to as a reversal effect already observed in the system

$$NiO \cdot [Fe_2O_3]_{1-x} \cdot [Al_2O_3]_x$$

are established so that predictions can be made as to its general occurrence. Certain departures between theoretical and experimental magnetic moment dependence on composition are pointed out, and in particular, the interesting case of

$$MgO \cdot [Fe_2O_3]_{1-x} \cdot [Al_2O_3]_x$$

is re-examined by allowance for incomplete inversion in $MgO \cdot Fe_2O_3$ itself — a procedure which still fails to reconcile theory with the reported observation.

SESSION II-B
COMPUTER COMPONENTS

A. C. BEILER, Presiding

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16. RECENT ADVANCES IN MAGNETIC COMPUTER ELEMENTS (Invited Paper)

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Murray Hill, N. J.

The ferrite core has been very successful as a storage element in digital computers. Consequently a number of magnetic devices have been investigated as replacements or improvements on the simple toroid. The present paper will review the field of such new devices. The general objectives of these developments will be discussed and illustrated by the characteristics of the new components, such as multi-aperature devices, ferrite sheets, evaporated films, and twistors.

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17. A REVERSIBLE, DIODELESS, TWISTOR SHIFT REGISTER

ANDREW H. BOBECK and ROBERT F. FISCHER
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

A twistor shift register has been built and operated successfully. The design utilizes interaction effects which exist between magnetized regions on a magnetic wire. Only a single magnetic wire is required for a complete register. The information is stored as magnetically polarized zones which can be moved along the wire by means of a five phase pulse source.

No diodes are required. Therefore, drive powers can be greatly decreased since the only threshold consideration is the magnetic material itself. Bi-directional operation is easily secured. The upper frequency limit has not been established; however, a several hundred kilocycle bit rate should be possible.

Physically, the register could be made of no more than magnetic and copper wire. This should make fabrication considerably cheaper than conventional shift registers.

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18. A MILLIMICROSECOND MAGNETIC SWITCHING AND STORAGE ELEMENT

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A Magnetic Rod element suitable for performing both the logical switching and storage functions of a digital computer has been developed. The element consists of a substrate of glass or metal upon which is electroplated an Fe-Ni alloy several thousand Angstroms thick. The Rod configuration makes a continuous fabrication and testing process practical.

A single magnetic element for a coincident-current memory requiring two inputs, an inhibit winding, and a sense winding, would consist of four separate single layer concentric solenoids over the Magnetic Rod. Memory matrices, each consisting of many solenoids, can be stacked and simultaneously threaded with the Rod. Eight to ten bit positions per linear inch along the Rod are practical without mutual interference. The switching speed of the element in a coincident-current mode is approximately 70 millimicroseconds. The output voltage generated across a ten-turn sense winding is 200 to 500 millivolts depending upon the Rod structure.

Machine winding of the solenoids appears to be practical and makes fabrication economically attractive. An experimental 64 bit transistor-driven array has been built and its operation will be described.

The Rod is also suitable as a multi-input switch for performing all the logical gating functions of a digital computer. When used as a gate in an inhibiting manner[1] a total of up to thirty separate inhibiting propositions have been demonstrated. Further, by a suitable choice of substrate resistivity an ideal one to zero ratio can be fabricated. Such an ideal Rod will be described. The operation of a two-megacycle counter using the Rod as the logical gate will also be described.

1. L. J. Andrews - "A Technique for using Cores as Logical Elements." Proc. of EJCC., Dec. 1956.

19. MILLIMICROSECOND SWITCHING PROPERTIES OF FERRITE COMPUTER ELEMENTS

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Flux Reversal in various ferrite materials has been studied in an attempt to correlate the observed switching properties with other material characteristics. Ferrites that were investigated have remanence to saturation flux ratios of from 0.6 to 0.95 and a switching threshold field as high as 3 oersteds.

Techniques are described for the accurate measurements of switching time when the material is subject to a fast-rise (1 m μ sec) square pulse of excitation. Fields up to 25 oersteds are employed and switching times are measured as fast at 10 m μ sec. The magnetization rate of change is observed by applying the signal directly to CRT deflection plates. In addition, measurements of switching time as a function of temperature are made from liquid nitrogen temperature to near the magnetic Curie temperature.

In the plot of inverse of switching time versus applied field, two linear portions are found for which the slopes differ by a factor of from two to five. The inverse slope known as the switching constant of the material has therefore two values. The field at which the discontinuity in slope occurs is described as a threshold field for rotational switching. Data for several ferrites is presented and correlation is made with other magnetic properties.

20. AN EVALUATION OF A NEW HIGH SPEED MAGNETIC FERRITE SYSTEM FOR USE IN COMPUTER COMPONENTS

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International Business Machines Corporation
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Present day computer speeds are limited by the magnetic components utilized in their construction. Such components have been fabricated from square loop ferrites of the MgO. MnO. Fe_2O_3 system. Since such materials limit the speeds at which the computers can operate a new ferrite system; namely, the CdO. MnO. Fe_2O_3 system was studied and has been proven feasible for many new high speed applications. Some of the compositions of this new system exhibiting square hysteresis loops have switching constants as low as 0.200 oersted microseconds. Such materials in comparison with those of the MgO. MnO. Fe_2O_3 system have a much lower coercive force, require lower driving currents and have a flux reversal or switching time which is five times as fast. These materials have been used in fast switching multipath elements and matrix switch cores.

21. A STUDY OF THE RESIDUAL STATES OF FERRITE CORES IN COMPUTER MEMORY OPERATION

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Division of Sperry Rand Corp.

When a ferrite memory core is subjected to the program of excitation that it receives in a conventional coincident-current storage system, two quasi-stable residual states of magnetic induction ($B_{1,0}$) result. These complimentary residual states, which are used to represent binary information, are not equally disposed about the zero residual state, but may differ in absolute value of flux-density by significatn amounts. By use of a pulse-pattern generator and voltage-integration techniques through which the value of flux-density can be accurately determined at every point between successive pulses in the cycle, this residual state asymmetry and other related phenomena have been studied.

The displacement of the operating minor hysteresis loop relative to the origin has been found to be a function of both the immediate past history of the core and the more remote history of fields larger in magnitude than are applied during normal operation of the system. The noise voltage induced by partial-select half-amplitude pulses was examined and found to be a multi-valued function of residual flux state depending on past history. The effect of immediate operating history (read and write-disturbed states) is well known, but effects of equal or greater magnitude caused by remote high-field history are obscured to casual observation by compensating effects of the minor-loop displacement described above. "Delta noise" (an unbalance in the partial-select noise from a pair of cores storing a "one" and "zero" respectively) has been found to be the sum of two effects of approximately equal magnitude. The sign of one of these effects may be changed by imposing a slight asymmetry between the read and write current pulses such that the total delta noise may be cancelled and thus completely eliminated in a memory plane of identical cores. The post-write-disturb pulse plays an important role in preventing errors in a memory that has inadvertently been subjected to a transient high-amplitude partial-select pulse or a low-amplitude full select pulse. If such a transient has occurred at any address in the memory plane, errors may thereafter appear repeatedly at any other address in the memory if the disturb pulse is not included in the excitation cycle.

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22. COINCIDENT-CURRENT NONDESTRUCTIVE READ-OUT FROM THIN MAGNETIC FILMS

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By using cores which consist of two vacuum-deposited ferromagnetic films it is possible to build memory arrays from which data can be read out nondestructively by use of coincident-current selection. It is thus possible to eliminate the external selection matrices commonly associated with nondestructive readout memories. This system promises to be inexpensive, reliable and fast, especially in a memory in which read operations occur more frequently than write operations.

Three different devices are described which fulfill the criterion of coincident-current non-destructive readout. Good signal to noise has been achieved with each of these.

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23. THE REVERSIBLE COMPONENT OF MAGNETIZATION

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In addition to the main component of magnetization which is characterized by a rectangular hysteresis loop, ferrite cores of the type used in computer storage devices display a smaller, reversible component of magnetization which is proportional to and practically in phase with the applied field. A method of non-destructive sensing for a high-speed memory, based on the variations of this reversible magnetization, has been suggested[1]. The work reported here is an experimental study of the dependence of this reversible magnetization on the state of the core, to provide data for the design of such a memory. Since disagreement still exists regarding the mechanism of the main component of magnetization in these ferrites[2,3] no attempt is made here to explain this additional property theoretically.

The reversible magnetization was studied by measuring the response of a core to a very short test pulse with a rise time of 20 mμ sec and a duration of less than 50 mμ sec. The state of the core was altered by means of constant current pulses of various amplitudes and durations from 0.2 to 1.6 μ sec. The state of magnetization was determined by measuring the flux change from the remanent point produced by the constant current pulses.

Using 0.2 μ sec pulses to alter the state of the core the response of cores of General Ceramic S4 and S5 ferrites was found to be approximately three times greater for demagnetized cores than for cores at the remanent points. When longer magnetizing pulses were used this effect appeared to be much smaller. It was shown that this was due to the fact that the cores were not thin walled, so that layers of differing radii were not equally magnetized. Using an empirical formula for rate of magnetization and assuming that the reversible magnetization was a function of the state of magnetization, curves were calculated for a core with finite wall thickness, which showed the same form as the experimental curves.

It was found that the short test pulses produced no permanent change in the state of the core even when their amplitude was much greater than the coercive force. This effect is being investigated further.

1. University of Illinois, Digital Computer Laboratory Report No. 80, p. 178.
2. Haynes, M. K., J. Ap. Phys., Vol. 29, p. 472, 1958.
3. Gyorgi, F. M., J. Ap. Phys., Vol. 29, p. 283, 1958.

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24. INHIBITED FLUX — A NEW MODE OF OPERATION OF THE THREE-HOLE MEMORY CORE

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A new method of operation of the three-hole memory core has been developed. As in the case with the coincident-flux scheme developed by IBM, read and write times may be made very short. However, by using single-line drive rather than coincident current, one need pass but one conductor through each hole. A description is given of a small memory array which uses this method.

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25. HIGH SPEED MAGNETIC CORE STORAGE

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Magnetic core storages are usually based on the coincident current principle, which allows a core to be set either to positive or to negative remanence and thus to store one bit of information. This storage principle utilizes the rectangularity of the hysteresis loop of certain materials. The reliability of such a storage system as well as the maximum size of the storage matrices, depends on the shape of the hysteresis loops. As a consequence, the magnetic material must be used either in the form of toroidal cores or as extremely thin film. The dependence on the hysteresis loop also limits the switching speed, because the magnetization of the selected core cannot be made larger than three times the coercitivity, unless additional - diagonal - wires are introduced.

One may overcome the dependence on the shape of the hysteresis loop by abandoning the coincident current principle and using for selection some nonlinearity other than the breaks of the hysteresis loop. From the economic point of view, the nonlinearity of glow lamps would be desirable, but the high voltage required to fire presently available glow lamps calls for a prohibitive large number of turns in the drive winding around the magnetic material. The nonlinearity of diodes is more practical and it allows to obtain an almost infinite current ratio between selected and unselected cores. As a consequence, the core matrices can be made much larger then in coincident current systems. Since the hysteresis loop does not need to be rectangular, there is no stringent need to use toroidal cores. The larger current permissible in a diode selection system also allows faster switching of the cores.

The big obstacle to the use of diode selection systems is the high price of diodes. This obstacle may be overcome by storing more than one bit of information per core, thus reducing the number of cores and diodes and the drive circuitry for a storage of given capacity.

The storage of more than one bit per core is achieved by feeding in a certain amount of flux rather than driving the cores with large currents to positive or negative saturation. The cores may then come to rest not only at positive or negative remanence, but also at intermediate levels of induction. This means that one core is not restricted to the storage of one binary digit, but can be used to store one trinary, one quarternary, or other digit. Since computers generally use the binary system, the storage of quarternary digits (=two binary digits) or octonary digits (=three binary digits) is much more easily accomplished, for example, than that of trinary or quintary digits.

The principle of flux storage offers two other advantages besides cost: a) Since for a given core and a given drive power it takes the same to read out (or in) a binary, a quarternary, or an octonary digit, the read-out rate in bits per second is double, triple, or even a higher multiple, of that for one-bit-per-core storage systems. b) A core storage must be designed for peak energy dissipation, which occurs if all digits that are read in are "ones". All the cores will then be set to positive remanence, and upon read out they will be reset to negative remanence. It is under this operating condition that the most energy will be drawn from the driving circuits, and dissipated as heat in the core matrix. Since a two-bits-per-core storage has only half as many cores as a one bit-per-core storage of equal capacity, the peak energy required and dissipated is halfed. For a three bits-per-core storage the peak energy is reduced to one-third, and so forth.

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26. OPERATING CHARACTERISTICS OF A THIN FILM MEMORY*

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Massachusetts Institute of Technology.

An experimental prototype memory with 32 ten bit words has been designed, built and tested. Circular spots 1/16 inch in diameter about 600 Angstroms thick are used. These are evaporated on two pieces of glass each comprising a 16 x 16 spot array. An operating cycle time of about one-half microsecond appears possible.

The circuitry for driving and sensing is transistorized and the memory used external register selection from a core-diode matrix. Word selection is provided by a transverse field and a digit winding conditions the information written by applying longitudinal field in the ONE or ZERO direction.

Fabrication of drive and sense lines in obtained by sticking conventional magnet wire to plexiglass plates. Films may be easily removed from the wire configuration and replaced with others for test purposes.

Extension to sizes of the order of 1000 words is planned using these techniques. The memory constructed here will soon be installed in the TX-2 computer for use in configuration control.

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* The research in this document was supported by the Army, Navy and Air Force under contract with the Massachusetts Institute of Technology.

SESSION III-A
MICROMAGNETICS; DOMAIN

C. P. BEAN, Presiding

27. MICROMAGNETICS, DOMAINS, AND RESONANCE
(Invited Paper)

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Ferromagnetic domains were originally postulated to provide a mechanism for demagnetization. Current theories of their behavior are based largely on the wall concept and on the 1935 paper of Landau and Lifshitz. That same paper contained the germ of another type of theory; in it the magnetic structure is examined on a smaller scale, and the basic concept is a spontaneous magnetization whose direction varies continuously with position. This alternative approach, micromagnetics, can in principle yield a complete, self-consistent theory, from which the domain and wall concepts--when valid--will emerge naturally, without having to be postulated. The present paper summarizes the history, accomplishments, and possibilities of such a theory.

In domain theory, one-dimensional micromagnetics is used to find the thickness and energy of a wall. Early calculations of Bitter and of Shirobokov[1] were also one-dimensional. The general three-dimensional problem was explored by Elmore and by Brown; it proved tractable only at high fields, where the partial differential equations could be linearized. This linear approximation was applied to various problems by Brown, Holstein and Primakoff, and Néel.

The study of single-domain particles, and in particular of the condition for single-domainedness, led to new applications of micromagnetics. For this purpose Néel used a simple model, and Kondorsky treated a more elaborate one by a Ritz approximation. Recently it was discovered independently by Brown and by Frei, Shtrikman, and Treves that for this model the condition for single-domainedness can be determined rigorously; the equations required are linear, and the rigorous calculation is actually simpler than the approximate one. These authors also used numerical methods, programmed for electronic digital computers, to study the behavior of a particle too big to be single-domained.

By augmenting the equations of micromagnetics with gyromagnetic and damping terms, and by neglecting certain static terms, one obtains equations used in the study of ferromagnetic resonance, of "semi-classical" spin waves, or of switching times. The linear equations of the single-domain problem are closely related to those of ferromagnetic resonance. In fact the critical or nucleation fields of the static problem are identical with the resonance fields at zero frequency, provided the complete equations are used in the resonance calculation; and the various modes of small deviation from an initial uniform magnetization (rotation in unison, magnetization curling, etc.) are the zero-frequency limiting forms of the resonance modes.

Four methods of attack have now been used in micromagnetics: study of one-dimensional cases, study of linearizable problems, the Ritz method, and numerical calculus. Domain theory has relied almost exclusively on the first. The fruitfulness of a broader approach has now been demonstrated, and challenging problems lie ahead.

1. F. Bitter, Introduction to Ferromagnetism (1937), p. 185; M. Shirobokov, Dokl. Acad. Sci. URSS 24, 426 (1939); JEPT 15, 57 (1945). For references to other authors mentioned, see W. F. Brown, Jr., Phys. Rev. 75, 1959 (1949); 105, 1479 (1957); J. Appl. Phys. 29, 470 (1958).

28. SOME RECENT DEVELOPMENTS IN MICROMAGNETICS AT THE WEIZMANN INSTITUTE OF SCIENCE
(Invited Paper)

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Recent theoretical studies carried out in micromagnetism at this Institute are reviewed, and preliminary results are given for theoretical problems which are now under study.

The coercive force of an infinite circular cylinder is calculated as a function of the radius and of the inclination of the cylindrical axis to the applied field. For this calculation it is assumed that only the curling and the rotation in unison modes take place; and that whenever the curling is associated with a discontinuous jump, the magnetization is brought to the values tabulated by Stoner and Wohlfarth, who assumed only rotation in unison. Using the same assumptions, the rotational hysteresis loss and integral are calculated both for an aligned and for a random assembly of cylinders. The results are found to be in fair agreement with the measurements of Jacobs and Luborsky on elongated particles.

The remanence curves of a random assembly of infinite cylinders are calculated for the same model as a function of the applied field and of the radius of the cylinders.

The rotation in unison and the curling are proved to be the easiest modes for magnetization reversal in a ferromagnetic sphere. The nucleation field associated with the curling mode is calculated as a function of elongation and size for a ferromagnetic prolate spheroid. For a rather wide range of elongations this suffices as an approximation for the coercive force, which should be larger than the nucleation field but smaller than the coercive force of the infinite cylinder.

As an attempt to introduce inter-particle interactions the following model is treated. A square lattice of infinite cylinders with a square cross section is assumed with all cylinders parallel to the applied field. Rotation in unison of the spins is assumed for each column of cylinders, and rotation in opposite directions but with equal magnitudes of the angle is assumed for neighbouring columns. The coercive force of this model is found to be only slightly less than that given by Néel's formula which is valid for coherent rotation in a random distribution of infinite cylinders of any cross-section. The dependence of the critical size and of the coercive force on the packing factor is discussed and compared with experiment.

A first approach to the study of the dependence of coercive force on imperfections is carried out by treating each of two mathematical models for a material which is infinite in all directions. The first model is a slab of finite width in which the anisotropy constant K is zero. The second one is a linear reduction of K through a slab of finite width, from its constant value to zero. For both models the nucleation field is given as a function of the imperfection width. For the first model the behavior after nucleation is also discussed.

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29. THEORETICAL APPROACH TO THE ASYMETRICAL MAGNETIZATION CURVE

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The method previously used to calculate the magnetization curve of an infinite ferromagnetic cylinder[1] is applied to the new Meiklejohn and Bean[2] material, which is made of Co particles in a Co0 shell. For this calculation it is assumed that the interface of the ferromagnetic and antiferromagnetic materials is held parallel to the cylindrical axis and does not change its direction for any value of the applied field. The crystal anisotropy is neglected throughout the calculation.

The nucleation field is calculated, and it is found that the easiest nucleation mode for small radii is "buckling" and for large radii is "curling". The transition from buckling to curling is at about $RI_sA^{-1/2} = 2$. Here R is the radius of the cylinder, I_s is the saturation magnetization and A is the exchange constant.

The calculation of the hysteresis curve for the curling mode involves the solution of a non-linear differential equation. This is done numerically using the WEIZAC - the Electronic Computer of this Institute. Two branches are found which are both stable with respect to curling perturbations. The general stability is not tested.

A similar calculation of the magnetization curve is carried out for an infinite slab with the spins on the surface held at a fixed direction and with the crystal anisotropy neglected.

In the two cases considered the coercive force is approximately equal to the nucleation field. This coercive force is found to agree with the experimental one for a radius of 220 Å for the cylinder or a width of 270 Å for the slab.

1. A. Aharoni and S. Shtrikman, Phys. Rev., 109, 1522 (1958).
2. W. H. Meiklejohn and C. P. Bean, Phys. Rev., 102, 1413 (1956); Phys. Rev. 105, 904 (1957); Proc. Boston Conf. on Magnetism and Magnetic Materials, 1957, p. 16.

30. DOMAIN BOUNDARY CONFIGURATIONS DURING MAGNETIZATION REVERSALS

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The observation of ferromagnetic domain boundaries by magnetic colloid methods has two kinds of limitations. First, it is restricted to static configurations. Second, the structure observed with magnetic colloid may, except under special conditions, be a complicated surface closure domain structure not necessarily representative of the domain structure of most of the interior of the material. A new electrical technique has been developed that gives information about the total area of domain boundary in motion during the entire course of a magnetization reversal. The method depends on the known experimental behavior of the low-field velocity of an individual domain wall

$$v = k(H - H_c)$$

and is essentially the measurement of the incremental response of moving walls. If the applied field H causing the reversal is modulated by an additional small AC field, the velocity of the wall will be modulated and an AC component will appear in the reversal voltage. Since the wall velocity is linear with field, the amount of modulation is independent of the average velocity and proportional only to the area of moving wall. It thus becomes possible to tell whether variations in reversal voltage with time during a reversal are due to variations in wall velocity or variations in wall area.

The method has been used to demonstrate two entirely different modes of reversal in different specimens. In a magnetically annealed 65 Permalloy tape core, reversal takes place by the area of moving domain walls building up to a maximum with time and gradually dwindling down to zero again. In a silicon-iron single-crystal picture frame, the reversal is accomplished by one wall moving through the specimen with practically constant area.

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31. INITIAL PERMEABILITY PROCESSES IN NICKEL-COBALT FERRITES OF VARIOUS DENSITIES

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Initial permeability has been measured at a frequency of 10 Mc/s on ferrites of composition $Ni_{1-\alpha}Co_{\alpha}Mn_{.02}Fe_{1.9}O_{4\pm}$ with varying densities. Here α = 0, .005, .01, .015, .02, .025, .03, .04, and .06, and density is varied for each composition between 3.8 gms/cm^3 and 5.10 gms/cm^3.

In an earlier paper[1] it was shown that initial permeability in high density nickel ferrite is determined to a large extent by domain wall motion, a result in accordance with the work on Rado and others[2]. With a reduction in density, it was expected that domain wall contributions would decrease. The present experiments are a new way of making a semi-quantitative determination of the contributions of wall motion and domain rotation to the initial permeability.

In this paper the data are presented in two families of curves. One family consists of initial permeability (μ) versus density with α, the cobalt content, as a parameter. The other family consists of μ' versus α with density as a parameter. Inasmuch as the first order anisotropy constant K_1 varies with α (becoming zero near $\alpha = .025$), the initial permeability due to rotations (μ'_r) varies with α. Also the initial permeability due to domain wall motion (μ'_d) varies with density (it also varies with α, as discussed in reference 1). Thus the shapes of the curves in the two families demonstrate the relative contributions of the two processes. In particular it is shown that wall motion predominates in high density nickel ferrite, and that rotation predominates in low density nickel ferrite. Although a semiquantitative breakdown of these contributions is given for various densities, it must be emphasized that the conclusions in the preceding sentence are not dependent on any particular model for wall motion; it is this fact which gives the experiments some power.

1. J. E. Pippin and C. L. Hogan, International Conference on Solid State Physics and its Applications in Electronics and Telecommunications, Brussels, June 2 - 7, 1958.
2. G. T. Rado, Rev. Mod. Phys., 25, 81 (1953); G. T. Rado, V. J. Folen, and W. H. Emerson, London Conference on Ferrites, Proc. I.E.E., Part B Supplement No. 5, 198 (1957).

32. INTERNAL STRUCTURE OF CROSS-TIE WALLS IN THIN PERMALLOY FILMS THROUGH HIGH RESOLUTION BITTER TECHNIQUES*

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The use of a water immersion objective with the optical microscope for Bitter pattern studies has resulted in a significant improvement in resolution. A discussion of technique in using such an objective is presented.

Applied to the study of cross-tie domain walls in thin Permalloy films, this technique has revealed details of internal wall structure. In the proposed model[1] for such walls the magnetization within the wall is thought to be predominantly in the plane of the film, with periodic transition regions in which the magnetization is normal to the film. This configuration reduces the large magnetostatic energy which would be associated with a conventional 180° wall. Areas of low particle density are observed at the intersection of the main wall and cross-ties and in the main wall midway between cross-ties. From conventional ideas of colloid-pattern formation, these areas might be expected to have a high particle density because they are the transition regions in which the magnetization is normal to the film. The apparent conflict is resolved by assuming that these regions are large compared to the colloid particle size so that the fringing field at the edge of the region governs the particle distribution. In support of the model, convincing evidence is presented of the reported shift of colloid particles when an external field is applied normal to the film.

*The research in this document was supported by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

1. E. E. Huber, Jr., D. O. Smith and J. B. Goodenough, J. Appl. Phys. 29, 294 (1958).

33. OBSERVATIONS MADE ON DOMAIN WALLS IN THIN FILMS

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Domain walls in thin films of permalloy were previously found, by Huber, et al, to frequently exhibit periodically spaced "cross ties". These wall structures, have been studied in some detail in a variety of metals and the model advanced by Huber, et al, largely substantiated. Of some interest is the great sensitivity of the position of normal spin orientation between cross ties to externally applied fields. A non-magnetic overcoating on a thin film, and dark-field illumination with restricted azimuth are methods which are valuable in such observations using the Bitter technique.

Other characteristic wall configurations peculiar to thin ferromagnetic films have been observed and models have been devised for the magnetization distribution.

Long Néel wall segments have been observed on thin films by the Bitter technique, and by the use of fields in the plane of the film and at right angles to the wall. It has been found possible to reversibly change the direction of the magnetization in the Néel wall with such fields without introducing wall motion.

34. CORRELATION OF ENERGY LOSSES WITH PERFECTION OF CRYSTAL ORIENTATION AND DOMAIN STRUCTURE.

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Hysteresis and core loss measurements were made on single crystal strips of the (110) [001] orientation, the commercial grain-oriented material with a (110) [001] texture, and the newly developed material with a (110) [001] cube texture. All these specimens were 3% Si-Fe, had a thickness of 0.012" and were measured using an Epstein frame.

The d.c. and a.c. losses were found to be the lowest in the single crystals at all inductions. At low inductions (1-3 kilogauss), the a.c. core losses showed little difference among the three specimens. In the range of 10 to about 17 kilogauss, the cube textured material showed slightly higher losses than the commercial grain-oriented material. However, at still higher inductions, the cube-textured material exhibited lower losses than the commercial grain-oriented material.

A theory of energy loss based on a domain model using the ratio of the domain spacing to the sheet thickness was tested with the present experimental results. Taking some of the data obtained from the single crystal specimen as an example, the average domain spacing λ was 0.3 mm, hence the ratio of domain spacing λ to strip thickness d, was equal to one. The ratio of the observed eddy current loss in this work to the calculated classical loss, W_o/W_c, and that of the domain model loss to the classical loss, W_d/W_c as given by Pry and Bean,[1] are listed in the following Table for comparison:

B (Kilogauss)	W_o/W_c	W_d/W_c
10	4.00	1.81
15	3.17	1.89
19	2.63	2.02

The discrepancy between these two ratios is large, and the change of these ratios as a function of induction shows opposite trends. There is apparently little correlation of the observed eddy current loss with the domain model; however, the data given in the paper support a strong relationship between eddy current losses and perfection of crystal orientation.

1. R. H. Pry and C. P. Bean, J. Appl. Phys. 29, 532 (1958).

35. HYSTERESIS AND EDDY LOSSES IN SILICON IRON AS A FUNCTION OF SHEET THICKNESS

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Pry and Bean[1] have calculated energy losses in magnetic sheet materials using a simple domain model. A quantitative verification of these results for actual commercial magnetic sheet material has been attempted. The thickness of samples from three lots of oriented 3% Si-Fe was decreased through a 3:1 range. This was done by uniform chemical etching of the 30.5 x 3.0 cm strips in order to keep grain size and orientation constant while changing the thickness. At every stage of this procedure, 60 cycle losses and hysteresis curves at several flux densities as well as magnetostriction measurements have been made. In addition, a study of domain wall spacing versus thickness was made on similar materials by similar methods. The results will be discussed in the light of the domain model and compared to other available data, in order to show the applicability of the model. Some of the unique experimental details will be described.

1. R. H. Pry and C. P. Bean, J. Appl. Phys. 29, 532 (1958).

36. ENERGY LOSSES RESULTING FROM DOMAIN WALL MOTION

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As a function of frequency, f, the power dissipated in a ferromagnetic body due to cyclical magnetization generally is written as $P = W_h + Kf^2$, where W_h is the statis hysteresis loss per cycle and Kf^2 the "eddy-current" loss. The discrepancies between the above expression and various measurements are explained on the basis of domain wall dynamics.

SESSION III-B

MAGNETIC PROPERTIES OF METALS AND ALLOYS

J. J. BECKER, Presiding

37. MAGNETIC CONTRIBUTION TO THE ANOMALOUS γ-LOOP SHEAR OF Fe-Al ALLOYS

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The free energy of the Fe-Al system is calculated using the Cluster-Variation Method of cooperative phenomena on the Ising type scalar spin model under the assumptions that there is a direct positive (ferromagnetic) interaction between nearest neighboring Fe atoms and an indirect negative (antiferromagnetic) superexchange interaction between a pair of Fe atoms separated by an Al atom. These assumptions have proved to be quite successful in explaining the magnetic properties over the entire body centered cubic range of the Fe-Al system.[1] It is found that the magnetic free energy of the system can be lowered by adding Al atoms even though the Curie point is also lowered. It has been known that the γ-loop of the Fe-Al system has an upward shear contrary to the expectation from the concentration dependence of the Curie point of this system based on Zener's theory, if the corresponding state idea concerning the magnetic free energy is used. The above calculation thus removes the difficulty concerning the anomalous upward shear of the γ-loop. This type of conclusion cannot be reached from the nearest neighbor interaction model.

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1. H. Sato and A. Arrott; J. Appl. Phys. 29 515 (1958).

38. REMARKS ON MAGNETICALLY DILUTE SYSTEMS

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Because of the inadequacies of previous treatments of the magnetic properties of magnetically dilute systems when used to interpret experimental results, a re-examination of the problem starting from a simple model is made. The treatments of the problem discussed here using the Ising Model show that a Curie or a Neel temperature does not appear until a finite concentration of magnetic atoms is obtained, if the atomic distribution is random. This concentration depends on the coordination number of the lattice and on the range of interaction, but not on the strength of the interaction. The results given here for nearest neighbor interactions describe the general behavior observed in magnetically dilute solutions. Such things as anomalously high values of "effective magnetic moments" per magnetic atom and its concentration dependence, curvature in inverse susceptibility against temperature plots, and parasitic paramagnetism in the weakly ferromagnetic alloys, etc., are reasonably well explained. When the system has antiferromagnetic interactions, it is found that the inverse susceptibility shows a complicated temperature dependence varying with concentration and that the existence of a maximum in the susceptibility does not necessarily mean the onset of antiferromagnetism.

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39. SATURATION MAGNETIZATION AND CURIE POINTS IN DILUTE ALLOYS OF Fe

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The elements to the left of iron in the first transition series, managanese, chromium, vanadium, and titanium, are added to iron in amounts of one-quarter, one-half, one and two percent. Results are reported for saturation magnetizations, Curie temperatures, densities, and residual resistivities. The dependence of these quantities upon heat treatment is examined. The results are discussed in terms of recent speculations on the localized d-states of iron and their energies relative to the top of the conduction band. Particular interest is focused on the iron-titanium alloys. The decrease in saturation magnetization at the rate of 3.3 Bohr magnetons per titantium atom is far from simple magnetic dilution. On the other hand, titanium raises the Curie temperature of the alloys above that of pure iron. Some findings on the saturation magnetization and magnetic hardness of filings of iorn-titanium alloys as a function of annealing temperature will be discussed. The recrystallization of the highly strained particles is accompanied by a sharp increase in saturation magnetization. This result is consistent with the anomalous results of x-ray determinations of lattice parameter of these alloys.[1]

1. J. Noakes et al, 4th International Congress of Crystallography (1957).

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40. THE SATURATION MAGNETIZATION AND FERROMAGNETIC INTERATION IN TERBIUM METAL

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ABSTRACT

In general, in order to determine the absolute moment of an atom or ion, it is necessary to measure directly the magnetization in the saturation range, where the magnetic polarization is nearly 100 percent as in certain compounds[1] at 1.5°K and in a field of 60,000 gauss. Sometimes, even with a large positive ferromagnetic exchange, medium range fields are not sufficient at low temperatures to obtain saturation. Such is the case with terbium[2].

The present investigation is suggested by previous work[3] on Nd, Gd, and Dy in which absolute saturation was measured. The magnetization for terbium is found to be 1.53 Bohr magnetons per atom at 295°K and at 59,000 gauss. At 100°K the magnetization changes only from 6.77 to 6.80 Bohr magnetons per atom when the magnetic field changes from 48,000 gauss to 58,000 gauss. At 4.2°K the magnetization is 7.54 Bohr magnetons per atom of terbium in a field of 58,000 gauss. This appears to be the obsolute saturation magnetization since the value at 1.3°K is also 7.54 Bohr magnetons per atom.

1. W. E. Henry, Phys, Rev. 88, 559 (1952).
2. H. Leipfinger, Zeit. fur Physik, 150, 415 (1958); W. Klemm and H. Bommer, Z. Anorg. Allg. Chem. 231, 138 (1937); F. H. Spedding, Progress in Low Temperature Physics, Vol. II, (Amsterdam, 1937) p. 382.
3. W. E. Henry, J. Appl. Phys. 29, No. 3, 524 (1958); Proc. Grenoble Colloquium on Magnetism, Paper No. 45, 1958.

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41. THE EFFECT OF CHEMISORBED HYDROGEN ON THE MAGNETIZATION OF NICKEL AT LOW TEMPERATURES

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Magnetizations have been measured for nickel particles down to 4.2°K. and up to 10^4 oersteds. Measurements have been made prior to, and after, the admission of hydrogen to the nickel at room temperature. The nickel is supported on silica in the manner familiar in heterogeneous catalysis. The nickel particle sizes range up to about 80 A. in diameter, and cover the superparamagnetic range.

The samples are suspended in such a manner that reduction at 350°C. in flowing hydrogen, and subsequent evacuation at the same temperature may be carried out in situ. Quantitative admissions of hydrogen at room temperature are made after a series of magnetizations have been obtained at 4.2°K. The maximum residual hydrogen pressure over the sample rarely exceeds 0.15mm. in a dead space of 92 ml. and is, therefore, negligible in comparision with the approximately 1 ml. of hydrogen actually chemisorbed by a 400 mg. sample containing 40 to 50 per cent nickel.

The magnetizations are measured by pulling the sample from a set of Helmholtz-type coils mounted axially to the field, and noting the effect of the induced current on the deflection of a fluxmeter.

Chemisorption of hydrogen on superparamagnetic nickel causes a loss of magnetization. For a particle containing n atoms of which s are on the surface the fractional change of magnetization near saturation is given by $\Delta\sigma/\sigma = -se/n\mu_{Ni}$ where e is the number of d-electrons paired per chemical bond formed, and μ_{Ni} is the moment per atom of nickel (0.60). This is on the assumption that a monolayer of hydrogen chemisorbed on nickel involves one hydrogen atom for each surface atom of nickel. There is considerable other evidence that this assumption is correct.

The above considerations give a method for finding the quantity e both at complete surface coverage and lower. It has been found that the ratio of d-electrons paired to hydrogen atoms absorbed is less than one. On sintered samples in which the average nickel particle is about 80 A., as determined by X-ray line width broadening, the ratio is about 0.7. On smaller nickel particles the ratio may be a little less. This ratio is independent of surface coverage by hydrogen up to substantially complete formation of the monolayer.

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42. STRUCTURAL AND MAGNETIC PROPERTIES OF MN-CO-C ALLOYS

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A localized model is used to consider magnetic interactions between Mn atoms. Parallel or antiparallel alignment is expected if the separation between nearest neighbors is greater or less than 2.82 A, respectively. Examples of ordered psuedo ''FCC'' and ''BCC'' crystal structures which would have resultant magnetic moments are given. Ordering is necessary to (1) produce Mn atoms with uniform separations of more than 2.82 A and thereby produce parallel ailgnment (ferromagnetism) or (2) produce Mn atoms with different environments and consequently different moments so that if the separation is less than 2.82 A complete cancellation of antiparallel vectors does not result (ferrimagnetism). One such ferrimagnetic structure is a hypothetical Mn_4C lattice in which the C atom is in the central position and the Mn atoms are arranged on a ''FCC'' lattice such that there is parallel alignment of Mn atoms within each (001) and (002) layer, but antiparallel alignment between adjacent (001) and (002) layers. The corner Mn atom is in a different electronic state than the face Mn atom, and a small net moment should result. This investigation was undertaken to produce such an ordered psuedo ''FCC'' structure. Since preliminary experiments were not successful in producing such a phase in the Mn-C binary system, ternary alloys of Mn-Co-C were made and studied for magnetic and structural properties. Co was selected because it forms with Mn a continuous FCC phase at elevated temperature.

An ordered single-phase alloy having a central stoichiometric composition of $Mn_2Co_2C_1$ was found to be magnetic below about 600°C. In the stoichiometric alloy the carbon atom occupies the central position with the Mn atoms occupying the face (001) planes and the Co atoms the central (002) planes. At -196°C the saturation magnetization of $Mn_2Co_2C_1$ was determined to be $3.14\mu_B$.

Magnetic data were determined for the range of alloys from $Mn_3Co_1C_1$ to $Mn_1Co_3C_1$. By extrapolating a portion of the saturation magnetization vs. composition curve, semi-quantitative values for the magnitude of electron transfer from the carbon atom to its nearest neighbors (two face Co atoms and one face Mn atom) could be obtained.

The lattice parameter of $Mn_2Co_2C_1$ was determined to be 3.79 A, so that the separation between Mn atoms (2.68 A) favors antiparallel alignment. The magnetic structure of $Mn_2Co_2C_1$ can be subdivided into interpenetraing base centered or simple tetragonal sublattices of Mn and Co each with a different net moment. Because of the tendency of transition elements to favor antiparallel alignment as the separation between atoms decreases and because of the apparent electron transfer, it is believed that the net magnetic vectors of the sublattices have parallel alignment.

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43. EFFECTS OF HIGH TEMPERATURE ON MAGNETIC PROPERTIES OF CORE MATERIALS

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An experimental study has been made of the effects of temperature on the magnetic properties of the following ferromagnetic alloys: Orthonal, 4-79 Mo Permalloy, AEM 4750, L and Z Silectron, Transformer A, Audio Transformer A, 11.7 Alfenol, 15.5 Alfenol, 3 Mo Thermenol, 7-70 Perminvar, and Supermendur. Measurements were made of the d-c and 60 cps magnetic properties in the temperature range of 24°C to 800°C. The materials were also temperature cycled several times and evaluated after each temperature cycle.

The results indicate that, in general, high temperature decreased the maximum induction and the residual induction from their 24°C values. For all materials tested, with the exception of Supermendur and 11.7 Alfenol, the coercive force continually decreased with increase in temperature. The maximum permeability increased with increasing temperature until the Curie temperature was approached, then it started to decrease. The initial permeability also increased with increasing temperature, but unlike the maximum permeability, it generally started to decrease at a lower temperature.

For all materials tested, with the exception of Supermendur and 11.7 Alfenol, the total core losses continually decreased with increase in temperature. Supermendur exhibited an increase in total core losses in the 24°C to 300°C temperature range, whereas 11.7 Alfenol displayed an increase in total core losses in the 500°C to 600° C temperature range.

Grain oriented materials were more affected by temperature cycling than were unoriented materials. The effectsof temperature cycling on the magnetic properties generally appeared as an increase in the coercive force, a decrease in the maximum permeability, a decrease in the residual flux density, and a decrease in the squareness ratio.

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44. TEMPERATURE DEPENDENCE OF THE MAGNETIC PROPERTIES OF NICKEL-IRON ALLOYS

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The effect of temperature on the magnetic properties of six commercially available nickel-iron alloys is reported for the temperature range -60°C to +250°C. The trade names of the alloys are: Hipernik, Deltamax, Hipernik V, Supermalloy, 4-79 Mo-Permalloy and Hymu 80.

The temperature dependence of both a-c and d-c magnetic properties was determined experimentally over the temperature range. D-C properties were measured by the standard ballistic testing method. At each test temperature sufficient data was taken to plot a normal magnetization curve. Remanent induction and coercive force were also determined at each temperature, these properties being measured relative to magnetizing forces in excess of 100 oersteds. A-C properties were measured by means of a modified Hay bridge, the tests being conducted at frequencies of 60, 400 and 1000 cycles per second. At each test temperature, for each frequency, total core loss and rms exciting volt amperes were measured at various inductions in the range characteristic of the alloy being tested. The data presented are the average of the results of tests on six samples of each alloy.

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45. THE EFFECT OF MAGNETIC ANNEALING ON THE PROPERTIES OF (100) [001] ORIENTED 3-1/4 PER CENT SILICON-IRON STRIP

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Polycrystalline 3-1/4 per cent silicon-iron strip with (110) [001] texture was heat treated in a magnetic field. Watt losses, magnetostriction and d-c hysteresis loops were measured before and after magnetic annealing with the field parallel to the <100>, <110> and <111> directions. Distinct improvements in properties were obtained, particularly in the <110> and <111> directions. The hysteresis loops became square, or nearly so, and the magnetostriction in the <110> direction substantially decreased. This improvement is believed to be the result of the realignment of domain boundaries to <100> directions that more nearly coincide with the direction of the applied field. From considerations of the change in shape of the hysteresis loop measured in the <110> direction, the anisotropy energy that arises from the magnetic annealing is calculated to be about 700 ergs/cm^3.

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46. PRECIPITATION IN A BETA BRASS—Fe ALLOY*

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The development of iron precipitate particles during the annealing of single crystals of beta brass containing 0.1 percent iron has been examined by means of various magnetic measurements. The samples were initially quenched to retain essentially all of the iron in solution. Measurements were made at intervals during anneals at 300°C and 400°C. The measurements included saturation magnetization, torque, rotational hysteresis, remanence, coercive force, and initial susceptibility.

During the early stages of the anneals, the temperature dependence of the initial susceptibility and approach to saturation corresponded to that of the Langevin relation. Therefore, these data were used to determine the precipitate particle sizes in the subdomain region[(1)]. Particle sizes as small as 15 Å were measured in this manner. Particle sizes increased with annealing time, corresponding to the successive appearance of sub-domain single domain and multi-domain behavior.

The torque was first observable when the precipitate particle size was less than 30 Å. For all particle sizes the angular dependence of the torque indicated a positive magnetocrystalline anisotropy coefficient, K_1. Therefore, it was concluded that the precipitate particles were iron single crystals with the same crystal habit as the matrix. When the particles were in the sub-domain region, it was extremely difficult to saturate the torque. Thus, it was not possible to determine the extrapolated value of K_1 with much precision. However, the available data indicated a greater temperature dependence for K_1 than exists for pure iron. A similar situation existed with respect to the saturation magnetization at room temperature. Thus, it appeared that the very small particles may have a lower saturation magnetization and/or Curie temperature (implying a greater temperature dependence for K_1) than pure iron. This behavior may be a consequence either of the particle size, or of the presence of a non-equilibrium concentration of zinc or copper in the iron precipitate particles.

Magnetic annealing effects were also observed in this system during the growth of the precipitate particles.

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1. C. P. Bean and I. S. Jacobs, J. A. P. 27, 1448 (1956)
J. J. Becker, Trans. A.I.M.M.E. 209, 59 (1957).

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47. THE EFFECT OF COMPOSITION AND PROCESSING ON THE ACTIVITY OF SOME MAGNETOSTRICTIVE MATERIALS

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The dynamic magnetostrictive properties of a number of magnetic materials were determined as a function of composition and processing. The materials investigated include some Ni-Fe, Al-Fe, Co-Ni, and Co-Fe alloys as well as a group of ferrites represented by the formula $Ni_{1-x-y}Co_x Fe_{2+y}O_4$ with $0.00 \leq x \leq 0.04$ and $0.00 \leq y \leq 0.08$. The parameters measured were: electromechanical coupling coefficient, k, reversible permeability, μ_r, dynamic magnetostrictive constant, λ, and Young's modulus E. The stress sensitivity of a magnetic material i.e., the change in flux due to a change in stress at constant applied field, is proportional to the product $\lambda\mu_r$.

The values of $\lambda\mu_r$ for both the Al-Fe alloys and the cobalt-substituted nickel ferrous-ferrites are sensitive to cooling rate. Ordered Al-Fe samples in the vicinity of 12.5% aluminum, obtained by slow cooling, were more stress sensitive by a factor of four than were disordered samples of the same compositions. The disordered samples were obtained by water quenching from above the ordering temperature (approximately 600°C). When 4% of the nickel in cobalt-substituted nickel ferrite was replaced by divalent iron, the value of $\lambda\mu_r$ increased by approximately 50% for quenched samples but reamined relatively constant for slow cooled samples.

The largest value of $\lambda\mu_r$ observed in the Ni-Fe alloys (approximately 10^6) occurred in the range of 40% to 52.5% nickel. Various processing techniques were employed on the

Ni-Fe alloys in this range: slow cooling, quenching, magnetic annealing, and variation in annealing temperature between 900°C and 1220°C. Such variations in processing failed to produce more than a 10% change in the value of $\lambda\mu_r$.

48. THE INFLUENCE OF VARIOUS HEAT EXPOSURES ON ALNICO V MAGNETS

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Alnico V magnets were exposed to temperatures between 500 and 550°C for as long as 1000 hours. Remances was measured at room temperature intermittently during the exposures. The changes of remanence appeared to be caused by metallurgical as well as magnetic processes (aging). The two effects were separated and it was found that metallurgical equilibrium was reached in a rather short time. Changes of remanence occurring thereafter were ascribed to magnetic aging which was considerably greater than at room temperature.

The metallurgical equilibrium established at various temperatures resulted in slightly different hysteresis loops. We take this as an indication that the composition of the phases in Alnico V still changes at about 500°C. This interpretation is also supported by the reversible changes of remanence with temperature; these depend on the foregoing treatment.

Temperature limits and stabilizing processes are established to obtain predictable remanence values for Alnico V magnets at elevated temperatures.

SESSION IV-A
FINE PARTICLES
T. O. PAINE, Presiding

49. THE ANGULAR VARIATION OF THE COERCIVITY OF PARTIALLY ALIGNED ELONGATED FERROMAGNETIC PARTICLES

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Abstract. Apart from conclusions about the rotational hysteresis the recent theoretical studies 1,2 on incoherent irreversible rotations in fine particles lead to interesting results about the variation with angle θ of the coercive force H_c. This problem has been studied further, both from the point of view of coherent and incoherent rotations, for particle assemblies which are only partially aligned and as such have some practical significance. Since partial alignment can be attained in many ways, it was necessary to shoose a few simple models:

(1) A fraction p of the particles is aligned parallel to the orienting field ($\theta = 0$), the remainder perpendicular to it ($\theta = \frac{\pi}{2}$) and lying in the plane containing the orienting and measuring fields.

(2) As with (1), but with the unaligned fraction of particles randomly oriented in the plane $\theta = \frac{\pi}{2}$.

(3) A two-dimensional distribution of particles lying in the plane containing the orienting field and making alternating angles $\pm\theta_o$ with it.

(4) A 'conical' distribution of particles all making a constant angle θ_o with the orienting field. A further model (a fraction of particles fully aligned and the remainder at random in space or in a plane containing the measuring field) has already been discussed[1]. The parameters p, θ_o etc. can in principle be estimated from the remanent magnetization.

The following results were obtained:

(1) The coercive force, assuming coherent rotations, decreases rapidly for small values of θ but reaches a finite value at $\theta = \frac{\pi}{2}$, such that r, the ratio of the perpendicular to the parallel coercivities, equals $(1 - p)/p$.

(2) Here the ratio r is greatly reduced.

(3) Here the $H_c(\theta)$ curve, assuming coherent rotations, reaches a maximum, at $\theta = \theta_o$; such maxima have been observed, but have previously been interpreted solely in terms of incoherent rotations. In fact, if these occur, assuming the particles to be infinite cylinders[2], the maxima in the $H_c(\theta)$ curves are reduced or suppressed; in one example H_c actually has a slight minimum at $\theta = \theta_o$. An interesting result of this last calculation is that for certain ranges of θ_o and of the cylinder radius the ratio r exceeds 1. This would be impossible for coherent rotations, although even here r values approaching 1 are possible.

(4) Assuming coherent rotations, the $H_c(\theta)$ curve may again have a maximum, although much less pronounced than in (3), as long as θ_o is not too small. Calculations assuming incoherent rotations could be carried out in the same way, but this has not yet been done. The reduced remanence may here be obtained in closed form as a function of θ and θ_o, and is found to vary more rapidly with θ than does the coercive force.

For models (3) and (4) some results of interest may also be obtained for the remanence coercivity, whose ratio in the perpendicular and parallel directions is more frequently greater than 1 than is the case for the normal coercivities H_c.

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50. SUPERPARAMAGNETISM

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Neel observed some years ago that the magnetization vector of single-domain ferromagnetic particles is caused by thermal fluctuations to execute a type of Brownian rotation. If the thermal energy is large enough, compared to the barriers against rotation, a system of these particles can come to thermodynamic equilibrium in a short time. In this state there is no hysteresis in the process of magnetization and, in fact, the magnetization is that of an assembly of paramagnetic particles. The principal difference between the Langevin paramagnetism of moment bearing atoms and the phenomenon described above arises from the fact that the magnetic moment of the particle may be 10^4 times as large as that of the atom. This difference in moment causes such a dramatic change in the ease of magnetization that this state of affairs has been termed superparamagnatism. We shall review the theoretical and experimental foundations of this effect and indicate the information on fundamental magnetic problems that has been gained through its study. In addition, we shall indicate some applications of these concepts in fields as diversed as geomagnetism and precipitation in metals.

51. ON THE MAGNETIC PROPERTIES OF MULTIDOMAIN PARTICLES*

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Experimental evidence indicates a continuous size-dependence of the magnetic properties of fine powders. The coercive force (which reaches its maximum in the single-domain size range) is found to decrease as the mean particle diameter increases, thereby suggesting that even beyond the single domain size range, the powder properties are still strikingly different from the bulk properties of the material. Yet relatively little has been done to reach a theoretical understanding of the magnetic behavior of these particles.

A critical review of the few theoretical papers on this subject (Kittle[1], Neel[2], Ohuyama[3]) points out some of the major difficulties and leads us to suggest a distinction between two classes of multidomain particles, according to their relative size. Immediately above the single-domain size, particles would exhibit a non-uniform magnetization strongly dependent on shape and surface accidents. The best suited methods of analysis of these "wall-like" particles are those of "micromagnetics" initiated by W.F. Brown, Frei & Schtrickman[4]. For larger particles, one can reasonably expect a relatively simple domain configuration. This expectation is based on the numerous observations on whiskers with cross-section ranging from 2 to 100 microns. In this work emphasis is put on these large "whisker-like" particles. A regularly shaped particle bounded by closure domains would have no remanence and no coercive force. Hysteresis properties would arise from odd shapes, surface irregularities and particle interactions. Initial susceptibility and saturation fields add their size dependence are calculated. It is found in particular that as soon as the magnetization process reaches a stage where surface charges begin to replace the closure domains, the magnetization may become very hard, in accordance with earlier work by the author[5]. A derivation of the size dependence of the coercive force is proposed. The concept of coercive force H_c is discussed, since one has to depart from the conventional definition and use either an "energy definition" or equate H^c to the larger of the two fields called by Néel[2] nucleation and propagation fields.

*This work was sponsored by the Aeronautics Research Laboratories, Wright Air Development Center.

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52. RECENT DEVELOPMENTS IN THE FIELD OF ELONGATED SINGLE-DOMAIN IRON AND IRON-COBALT PERMANENT MAGNETS

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The experimental physical and magnetic properties of Elongated Single-Domain permanent magnets have been previously reported (1) (2) and are briefly reviewed in respect to their means of preparation. The progress made in completing facilities for making ESD magnets available commercially, at a limited initial rate, is described. The successful solution of processing difficulties involved in converting a laboratory discovery to a manufacturing process is discussed in view of the unique materials and processes used. The material to be produced is described, and contains elongated single-domain particles of iron or iron-cobalt embedded in a metallic matrix to protect them from environmental attack.

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2. J. Appl. Phys. 29, 304 (1958) "Physical and Magnetic Properties of Elongated Single-Domain Iron and Iron-Cobalt Permanent Magnets by R. C. Lever, E. J. Yamartino, and R. B. Falk.

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53. MAGNETIC PROPERTIES OF SOME FERRITE MICRO-POWDERS*

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Micropowders of stoichiometric copper, nickel, and cobalt ferrites were prepared by low temperature ($< 800^oC$) treatment of the co-precipitated metal oxalates. The properties of each ferrite were determined as functions of particle or crystallite size in the range from 90 Å to 2000 Å. Structural properties were examined with electron micrographs, x-ray spectra, and x-ray line broadening. Magnetic measurements included saturation magnetization, Curie temperature, coercive force, remanence, initial permeability, and rotational hysteresis.

The micropowders exhibited sub-domain, single domain, or multi-domain behavior depending on the crystallite or particle size. The critical size for single domain behavior, depending on composition, was between 300 Å and 700 Å. In this size range high coercive forces were observed ($\sim$1000 oe. for copper ferrite and 2000 oe. for cobalt ferrite at room temperature) and remanence/saturation $\approx$ 0.5. The magnitude and temperature dependence of the coercive force indicated that crystalline anisotropy determined the magnetic properties of the single domain powders. This conclusion was supported by the observations that insignificant shape anisotropy was present, and that the x-ray line broadening was in good agreement with particle sizes measured on the electron micrographs. The presence of a considerable degree of sintering among the particles did not result in appreciable interactions between neighboring particles or crystallites.

Particles in the range below 300 Å showed the very strongly temperature dependent properties associated with sub-domain or superparamagnetic particles. Above the single domain size range, remanence and coercive force diminished rapidly. At 2000 Å, hysteresis properties were quite small.

Copper ferrite powders were quenched from a number of temperatures in order to examine the influence of variations in ionic distribution. The saturation magnetization increased with quenching in the manner previously observed[1]. The coercive force and remanence were generally diminished by quenching. The influence of magnetic annealing on the cobalt ferrite powders was also investigated.

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1. E. W. Gorter, Philips Res. Rep. 9, 321 (1954).

54. SHAPE DISTRIBUTION OF MAGNETITE POWDERS

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The shape distribution curves of single domain magnetite powders calculated magnetically do not agree with that observed in the electron microscope. The Stoner-Wholfarth theory from which the magnetic unaveraging process was derived, ignores magnetocrystalline anisotropy. However, this may be one of the contributory causes to the lack of agreement. To establish this, the shape curves were measured magnetically on both acicular and equant magnetite powders at various temperatures. The magnetocrystalline anisotropy of magnetite is temperature dependent changing from about -1×10^5 ergs/cc at room temperature to $+1 \times 10^5$ ergs/cc at -165^oC.

The magnetically calculated shape curves change little with temperature, evidently indicating a small contribution from the magnetocrystalline anisotropy.

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55. RELAXATIONAL BEHAVIOR OF FINE MAGNETIC PARTICLES

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Weil and others[1] have used the temperature variation of remanence to determine volume-distribution curves for a powder of single-domain particles. The basic principle is that the time constant for spontaneous reversal of the magnetization, under the influence of thermal agitation, is effectively infinite for particles of more than a certain critical volume v_c (a function of absolute temperature T), and effectively zero for particles of less than this volume; hence the former contribute to the remanence and the latter do not. Interpretation of the data has been based on a formula derived by Neel[2]. Neel's derivation is open to criticism, in that the gyromagnetic properties of the particles are taken into account only up to a certain point in the argument and are thereafter ignored. A new formula has been derived by adaptation of a method of Kramers[3] to angular coordinates and to a gyroscopic equation of motion. In either theory, the mean rate of transition from one orientation to the other is of the form $\nu = c \exp(-W/kT)$, with no uncertainty about the value of W. According to Neel, c depends on the rigidity and the saturation magnetostriction. In the new theory these quantities do not occur explicitly; at zero field intensity, $c = (\gamma'/2)(vJ_sH_c/2\pi kT)^{1/2}$ Here v = particle volume, H_c = critical field for static reversal, J_s = spontaneous magnetization, $\gamma' = (2\eta J_s)\left[(\eta J_s)^2 + 1/\gamma^2\right]^{-1}$ = ratio of magnetic moment to angular momentum, η = coefficient in the damping torque $-\eta\vec{M} \times (d\vec{M}/dt)$ in Gilbert's[4] equation of motion; $\gamma' \le \gamma$. Thanks to the dominance of the exponential factor in ν, the recalculated values of v/T vs time constant do not differ seriously from Neel's, or from those based on the intuitive formula $c = \gamma H_c/2\pi$ (= gyroscopic precession frequency).

1. C. P. Bean and I. S. Jacobs, J. Appl. Phys. 27, 1448 (1956).
2. L. Neel, Ann. Geophys. 5, 99 (1949).
3. H. A. Kramers, Physica 7, 284 (1940).
4. T. L. Gilbert, Phys. Rev. 100, 1243 (1955).

56. MAGNETISM OF SUBMICROSCOPICAL IRON PARTICLES

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The magnetic fields around submicroscopical iron particles were tested with iron oxide colloid. The colloid particles usually spread evenly by diffusion unless some force concentrates them at certain spots. By electron microscopy we found colloid concentrated around iron particles to various degrees. The colloid was attracted less by smaller particles. Particles smaller than 100 Å in diameter and only fractions of a micron long did not bring about any visible concentration; they seemed not to attract the colloid.

According to the colloid distribution, the particles were grouped into three categories:

a) particles with many domains,
b) particles with a few domains,
c) particles without well-developed domains.

The sizes of these particles were measured and statistically evaluated.

57. A NOVEL LIGHT-WEIGHT MOLDABLE PERMANENT MAGNET MATERIAL

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A novel, light-weight moldable permanent magnet material is described. Elongated single-domain particles of iron-cobalt are coated with a thermo-setting plastic which serves as a matrix. The particles are magnetically aligned, after which the matrix is polymerized. The agglomerate is ground to a 30-mesh free-flowing powder. Each of the particles of this powder is made up of submicroscopic elongated aligned particles. This powder can then be directionally pressed to produce magnets of complex shape to precision dimensions. Energies of 2.0×10^6 gauss-oersteds have already been achieved in magnets whose density is 4 gms/cm^3

58. STABILITY STUDIES OF MAGNETS COMPOSED OF ELONGATED SINGLE-DOMAIN IRON PARTICLES

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Magnetic and physical stability of permanent magnets compacted from elongated single domain iron particles with metallic and organic matrices were evaluated. Changes in overall magnetic characteristics plus dimensional and weight changes as a result of up to two years exposure to cycling humidity (95% R. H.) and temperatures of 100°, 200° and 250°C were measured. Effects of compacting temperatures, pressures, powder sizes, and additives are reported. Compacts with lead matrices exposed to 100°C and 95% relative humidity show gradual magnetic and dimensional changes from insignificant variations after one month exposure to maximums of 1.5% over a two year period. This compares favorably with Alnico V. Aging temperatures of 200° and 250°C produce magnetic changes in the order of 1% after one month. Physical degradation of the compacts becomes apparent after two months at 250°C. Organic matrix compacts evidenced magnetic changes of 1% and weight and volume changes in the range of 3-6% after one month at 100°C, with 5-10% changes at exposures of one year. Magnetic changes resulted from oxidation of the iron particles producing a decrease in total magnetic iron, and an increase in the spacing between particles. A permanent decrease of intrinsic saturation induction and a corresponding increase of coercive force was noted in every case.

SESSION IV-B

AMPLIFIERS; MICROWAVE APPLICATION

A. G. Fox, Presiding

59. MICROWAVE AND LOW FREQUENCY OSCILLATIONS DUE TO RESONANCE INSTABILITIES IN FERRITES

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Microwave and low frequency oscillations have been observed in single crystal yttrium iron garnet disks placed in a microwave cavity with an applied dc field normal to the disk. These oscillations occur when the microwave power incident on the cavity exceeds a certain critical value in the milliwatt range. The oscillations occur as sidebands above and below the incident frequency and can also be observed as a modulation of the microwave output of the cavity.

The above phenomenon is associated with the ferromagnetic resonance instability due to the fact that the resonant frequency of a disk depends on M_z and thus on the rf magnetic field used to drive it. The combination of the disk and the resonant cavity with high power, provides the conditions necessary for relaxation oscillations to be set up.

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60. MAGNETO-ACOUSTIC RESONANCE IN YTTRIUM IRON GARNET

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Oscillations in the range of 7 to 30 mcs have been observed in polished spheres of single crystal yttrium iron garnet (YIG) when excited by microwave energy at 9,300 mcs and 3,000 mcs. Experiments were performed which show that the low frequency oscillations are acoustic, and that parametric amplification is involved to enhance the effective coupling between the magnetic spin system and the elastic vibrations.

The following observations were made which indicate that the oscillations are acoustic:

(1) The low frequency oscillations are inversely proportional to the diameters of the YIG spheres, e.g., being 8.966 mcs for a 0.0141-in. diameter sphere and 7.222 mcs for a 0.0175-in. diameter sphere.

(2) Using acoustic techniques a fundamental resonance (in a water bath) was measured to be 8.685 mcs on the 0.0141-in. sphere.

(3) The frequency of oscillation could be pulled by only 20 kcs with any combination of microwave power and dc field.

(4) By reducing the acoustic loading on the YIG sphere the frequency of oscillations increase.

(5) The frequencies of the two lowest fundamental oscillations agree to within 3 percent with the calculated frequencies of the fundamental radial mode (involving longitudinal sound velocity) and the fundamental spheroidal mode (involving transverse sound velocity) of an isotropic elastic sphere. The velocities used in the calculations were measured on stoichiometric polycrystalline YIG samples.

(6) The acoustic frequency remains constant when the microwave frequency is varied by a factor of 3.1.

There is good evidence that parametric amplification is present to enhance the magnetoelastic coupling between the magnetic spin system and the acoustic vibrations. If the acoustic frequency f_a is considered to be the signal frequency and the microwave frequency f_p the pump, then the idler would be the difference frequency $f_p - f_a$. Measurements show that the dc field for acoustic resonance is the field for uniform precessional resonance at $f_p - f_a$. The system then acts as a magneto-acoustic amplifier in which the pump power is sufficiently strong to cause regenerative oscillation. The phase relations involved in this type of amplification are such as to enhance the signal at $f_p - f_a$ and diminish any signal at $f_p + f_a$. Using a spectrum analyzer, the lower frequency signal appears 30 decibels larger than the higher.

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61. EXPERIMENTAL STUDY OF THE MODIFIED SEMI-STATIC FERRITE AMPLIFIER

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Suhl has proposed three basic types of ferromagnetic amplifiers[1]. The electromagnetic type and the semistatic type have been realized and studied by M. T. Weiss[2]. The present work reports experimental results on a novel type of ferromagnetic amplifier whose theory of operation is described in Reference 3.

The amplifier consists essentially of a circular cylindrical cavity, resonant at a signal frequency of 6000 Mcs. and a pump frequency of 9000 Mcs. The cavity contains a coaxial ferrimagnetic rod which is axially magnetized. The signal frequency magnetic field is along the ferrite rod, the pump frequency field is transverse to it and is circularly polarized. The d.c. magnetic field is adjusted for resonance of the uniform precession at the difference between the pump and signal frequencies. The amplifier has continuously adjustable window coupling at the signal frequency and can be operated as either a transmission or reflection amplifier.

Emphasis of the paper will be upon comparison of theory and experiment. As predicted in Ref. 1, the imaginary part of the z directed susceptibility at signal frequency exhibits a negative peak when the d.c. field is tuned to the difference between pump and signal frequencies and a positive peak when tuned to their sum. The predicted threshold r.f. pumping field for net gain, which is the minimum theoretical pumping field for oscillation, has been verified within the experimental error and within the uncertainty in pertinent ferrimagnetic linewidth.

Experiments have been conducted using several polycrystalline yttrium-iron garnets and a polycrystalline magnesium-aluminate ferrite (TT414). The ferrite has been found to be superior to the garnets, even though its linewidth to saturation magnetization ratio is approximately four times that of the garnets. The garnets were found to exhibit anamolous magnetic losses in the z direction at the signal frequency with the d.c. field at its 400 oersted operating value. The results quoted in this abstract were obtained using a polycrystalline verrite rod, .290-inches in diameter by 1.00-inch long. The d.d. magnetic field was 800 oersteds for maximum amplification. Because the d.c. field was far from ferromagnetic resonance at the signal and pump frequencies, high cavity Q's are possible. Unloaded Q of the pump cavity was 6000 and that of the signal frequency cavity was 8000.

Threshold for net gain was found to be approximately 10 r.f. oersteds at the pump frequency, which corresponds to a pumping power of 400 watts. Operating the device as a two-port amplifier with window Q's of 11,000, the predicted pump power for oscillation is approximately 1000 watts. Experimentally, using pulsed pump power up to 2.5 mico-seconds in length, oscillation, in the sense of a steady large amplitude microwave output, was not observed with pump powers as high as 10,000 watts. Instead extremely large gains were measured; and, as the signal input was reduced, amplified room temperature noise became dominant, with noise output levels up to several milliwatts. A typical measurement yielded 60 db gain for -60 dbm signal input with a peak pump power of 7000 watts. Under the same conditions, for 0.35 milliwatts signal input power, a power output of 350 watts was measured. At gains below 10 db, theoretical and measured gain-bandwidth product agree well, but for gains above 10 db, the bandwidth does not appear to decrease appreciably.

A tentative explanation of these extremely high gains lies in the fact that the time constant of the amplifier becomes longer than the duration of the pump pulse. This is exhibited as a decrease in the rate of rise of amplifier gain with time and has been observed experimentally. Noise initiated oscillations, therefore, do not have time to reach their equilibrium value.

Because amplified noise is easily observable, a measurement of amplifier noise figure is possible, and experimental noise results will be presented.

1. H. Suhl, Phys. Rev. 106, 384 (1957).
2. M. T. Weiss, Phys. Rev. 107, 317 (1957).
3. A. D. Berk, L. Kleinman, C. E. Nelson, "Modified Semistatic Ferrite Amplifier" presented at Quebec Tube Conference, 1958, and WESCON, 1958.

62. LIMITATIONS OF ELEMENTARY MODE CONSIDERATIONS IN FERRITE LOADED WAVEGUIDE

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A consideration of the fundamental TE modes in a waveguide containing a low loss ferrite slab leads to a mode with a group velocity corresponding to power transfer in a single direction only[1]. A completely reactive isolator, however, is prohibited by general energy conservation principles. We have analyzed a rectangular waveguide with a ferrite slab against one wall. We have found that there are higher order propagating modes wherever the unidirectional TE mode is cutoff. Furthermore, it can be experimentally demonstrated that these modes can be excited from a simple boundary with no variations along the magnetic field. A possible mechanism for this excitation will be described. It is suggested that these modes may carry the power when the unidirectional TE mode is cutoff. An experimental situation in which the proposed reactive isolator is tried will be described. Where the reactive isolator should be cutoff and perfectly reflecting, it is highly absorptive. This can be explained by the lossiness of the higher order gyromagnetic modes.

1. K. J. Button and B. Lax, Electromagnetic Wave Theory Symposium, p. 531-537, IRE Transactions on Antennas and Propagation, Vol. AP4 #3, July, 1956.

63. A NEW Y-TYPE CIRCULATOR

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It is well known that the field distribution in a rectangular waveguide containing a magnetized ferrite can be asymmetrical even though the physical configuration is symmetrical. By properly choosing the ferrite, its shape, and location, it is possible to concentrate the energy on one side of the waveguide. Reversing the field or changing the direction of propagation will cause the energy to concentrate on the other side of the waveguide. This phenomenon has been utilized to construct a new type of circulator. A ferrite post has been placed at the junction of three waveguides intersecting at 120 degrees. The d-c field is applied transverse to the broad side of the waveguide. Circulator action can be obtained by using a ferrite rod of the correct size and applying a d-c field of the proper magnitude. Similar results have been obtained by using single and double slab configurations as well as with wedges.

A waveguide switch can be obtained by reversing the direction of the applied field.

Results to date indicate that it is possible to build this Y-type circulator with a loss less than 0.5 db and isolations and reflections of less than 20 db over a 500-megacycle band at X-band. A four-port junction operating on this same principle is also under investigation.

64. THE REGGIA-SPENCER MICROWAVE PHASE SHIFTER

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The essential properties of the magnetically variable waveguide phase shifter reported by F. Reggia and E. G. Spencer [Proc. IRE 45 1510 (1957)] are explained by means of a composite phenomenological model. The aim of the model is to exhibit the several phenomena which contribute to the overall effect and to reduce the problem to such a degree of simplicity that it can be solved without recourse to numerical methods. It thus provides an advantageous starting point for such calculations, as well as a qualitative guide to further experimental development.

The device is composed of a ferrite rod mounted on the axis of rectangular waveguide and magnetized longitudinally. Large variations in the phase of the transmitted radiation occur in the range of applied fields in which the ferrite is partially magnetized. It is shown that the contributing phenomena are: i. geometry of the guide cross-section such that only a single (elliptically polarized) mode propagates; ii. a variation in the diagonal component μ of the permeability tensor, associated with the magnetic disorder of the unsaturated ferrite; iii. a dielectric-waveguide effect associated with the large volume of dielectric-magnetic loading of the guide. Numerical comparison with the available data verifies that the relative importance of these contributions is as represented in the model.

The model furnishes insight into the characters of the modes of propagation under conditions resembling those of the Faraday rotator but subject to complications, such as elliptic waveguide symmetry. It also suggests modifications of the structure which may lead to additional devices having novel and useful properties.

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65. COMPACT PASSIVE NONRECIPROCAL STRUCTURES FOR UHF FREQUENCIES

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Techniques employed in forming passive nonreciprocal circuitry at microwave frequencies prove awkward at the lower frequencies. A new means is discussed employing lumped parameter circuitry for providing compact constructions in this lower range of frequencies. Experimantal resonance isolator structures have provided successful results at both 500 mc and 130 mc for which isolation ratios of better than 10:1 have been achieved over significant bandwidths.

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66. LOW-LOSS GYROMAGNETIC COUPLING THROUGH SINGLE CRYSTAL GARNETS

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This paper describes methods of synthesizing filters and gyrators using strong coupling of a small volume of ferrimagnetic material to an electromagnetic circuit. The small volume of material is treated as a lumped element resonator and it is shown that energy can be coupled through this resonator with low loss. The device uses the material for low-loss transmission of microwave energy.

The practical realization of devices using this principle depends upon strong coupling of the material to the circuit and the use of "low-loss" materials such as single crystal garnets.

The synthesis leads to the design of physically small electronically tunable filters, compact circulators and isolators. Such techniques may also be useful for the realization of low frequency lumped element devices. Calculations and preliminary tests indicate that devices of this type will lead to the practical realization of solid state T-R cells.

67. HIGH POWER EFFECTS IN FERRITE SLABS AT X-BAND

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Measurements will be reported of the attenuation as a function of power of a number of different geometries of ferrite slabs in waveguide at X-band. The ferrites are biased with a dc magnetic field corresponding to subsidiary resonance and for some geometries the ferrite behaves as a limiter in which the output power is a constant for imput powers above a certain critical level. The dependence of the critical power and the limiting action on the ferrite geometry will be discussed.

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68. A STUDY OF MICROWAVE FERRIMAGNETIC MULTIPLE SIGNAL CONVERSION PROCESSES WITH APPLICATION TO MILLIMETER WAVE GENERATION AND FERRIMAGNETIC AMPLIFICATION

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A multiple signal conversion process has been studied which combines effects independently observed in microwave harmonic generation and mixing in ferrites. It may be shown that when a linearly polarized rf signal ω_1 is incident upon a magnetized ferrite, the higher order solution of the torque equation $\dot{\vec{M}} = \gamma(\vec{M} \times \vec{H})$ consists of a series of terms representing the amplitudes of the harmonics of ω_1. In the lossless case the harmonic amplitudes attain maximum values for an internal magnetic field equal to ω_1/γ.

Pippen(1)has shown that when linearly polarized rf signals ω_1 and ω_2 are incident upon a magnetized ferrite, the Z component solution of the torque equation contains a sum frequency term with an amplitude proportional to $(\gamma^2H^2 - \omega_1^2)^{-1} + (\gamma^2H^2 - \omega_2^2)^{-1}$ Thus it is seen the sum signal amplitude can be maximized by internal magnetic fields equal to ω_1/γ or ω_2/γ.

It is seen from these analyses that the amplitudes of the harmonics of ω_1 will be maximized by an internal magnetic field identically equal to the magnetic field ω_1/γ required to maximize the sum frequency generated by the mixing of the signal ω_1 with any other frequency.

From this fact the following multiple signal conversion process is suggested. The magnetizing field on a ferrite is adjusted to near gyromagnetic resonance at ω_1. The second harmonic $2\omega_1$ is filtered from the output, fedback in proper phase to the chamber containing the sample, and mixed with the frequency ω_1 to produce a sum signal at $3\omega_1$ which exhances the third harmonic of ω_1 present in the output.

The experimental confirmation of this multiple conversion process has been obtained in single polycrystalline specimins of ferrites and garnets at X-Band. The test sample was shaped to provide maximum outputs for both processes of harmonic generation and sum signal mixing. A microwave feedback ring circuit resonant to the second harmonic was employed to filter and re-admit the frequency $2\omega_1$ into the sample chamber. The loaded Q at frequency $2\omega_1$ of the feedback ring was 1.3 x 10^3. For peak input powers of 50 kilowatts at 9.37 kmc the third harmonic output arising from

the multiple conversion process was 126 watts corresponding to a conversion loss of -26 db. This conversion efficiency represents a 5 db increase in the output of the third harmonic over the maximum third harmonic amplitude attained by harmonic generation alone. From experimental data accumulated in the independent studies of harmonic generation and signal mixing in ferrites it is concluded that the maximum realizable conversion efficiency to the third harmonic achievable by use of the multiple signal conversion process could exceed -19 db. This represents a minimum improvement of 12 db over the harmonic generation process.

A study of the magnetic field dependence of the process has yielded results in general accord with the theory. Results from investigations of the dependence upon sample linewidth varied from theoretical predictions.

The multiple signal conversion process has potential application to the generation of millimeter waves. In addition this principle may be employed to construct a ferrimagnetic amplifier capable of amplifying microwave signals at frequencies much greater than the source power frequency.

(1) Pippen, Proc. I. R. E., August 1956.

69. HARMONIC GENERATION IN FERRIMAGNETIC ELLIPSOIDS

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This paper will deal with the general problem of harmonic generation in ferrimagnetic ellipsoids. The effect of these harmonics on the susceptibility tensor will also be given.

SESSION V-A
RESONANCE

M. T. WEISS, Presiding

70. FERRIMAGNETIC RESONANCE IN RARE EARTH IRON GARNETS NEAR THE COMPENSATION POINT (Invited Paper)

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The ferrimagnetic garnets are very convenient materials for studying the two sublattice theory of ferrimagnetic resonance, in the vicinity of the magnetic compensation temperature. At this temperature the two modes of resonance of the two sublattice system can be seen at ordinary microwave frequencies. Results on Gd-Fe garnet, whose magnetic compensation point is at 13.1°C will be emphasized. From ferrimagnetic resonance measurements in the vicinity of the compensation temperature, accurate information on the exchange field acting between the two sublattices, their difference in g-values and their anisotropies can be obtained.

71. FERROMAGNETIC RESONANCE NEAR THE UPPER LIMIT OF THE SPIN WAVE MANIFOLD

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Measurements of line widths in polycrystalline yttrium iron garnets have been made as a function of frequency from 1,500 mc. to 18,000 mc. at room temperature; and as a function of temperature from -77°C to 200°C at 2,600 mc. The variation of these parameters allows the uniform precessional mode to rise above the K - 0 upper limit of the Suhl spin wave manifold so that this mode is no longer degenerate with spin waves of low and medium k values. When this occurs the uniform precession can no longer relax to the lattice via these spin waves. One would expect a reduction in line width with the elimination of this relaxation process.

The measurements reported show a radical change in the line width as the upper limit of the spin wave spectrum is crossed. The exact nature of the change depends upon which parameter (i.e., frequency or temperature) is varied.

The variations in line width observed can be explained in the terms of the recently proposed theories of magnetic relaxation[1,2,3]. In the polycrystalline case[1,2] the uniform precession is coupled to short and medium k value spin waves due to variation in crystalline anisotropy arising from the granular structure of the material. In the single crystal case[3] the uniform mode relaxes to high k value spin waves due to random fluctuations of the pseudo-dipolar fields. Thus when the uniform precessional mode is inside the spin wave spectrum and degenerate with the short and medium k value spin waves the polycrystalling explanation should be applicable. But when this mode moves to a position above the $k = 0$ upper limit of the spectrum and is thus degenerate with only the high k value spin waves, the theory of Clogston, et al should hold.

It is believed that the measurements reported indicate convincingly the utility of the spin wave analysis of ferromagnetic relaxation.

1. S. Geschwind and A. M. Clogston, Phys. Rev. 108, 49, 1957; A. M. Clogston, J.A.P. 29, 334, 1958.
2. E. Schlomann, Raytheon Technical Report R-22 1957.
3. A. M. Clogston, H. Suhl, L. R. Walker and R. W. Anderson, J. Phys. Chem. Solids 1, 129, 1956.

72. IONIC DISTRIBUTION AND FERRIMAGNETIC RESONANCE IN MAGNESIUM FERRITE

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Three different ionic distributions have been achieved in the same magnesium ferrite single crystal sphere by appropriate heat treatment. The magnetic moment, anisotropy constants, g value and magnetic resonance halfwidth have been measured as a function of temperature from -200°C to +250°C for the different ionic distributions. The treatments resulted in room temperature magnetic moments of 123, 192 and 118 cgs units per cubic centimeter. At nitrogen temperature K_1 was observed to be higher for higher values of the magnetization in agreement with Folen and Rado[1]. The resonance halfwidth depends on the crystalline direction and was narrower in the hard 100 direction for the original ionic distribution. Successive treatments broadened the halfwidth in the hard direction while the easy direction 111 remained relatively unchanged. After the treatments the narrower halfwidth was observed in the easy direction. The room temperature g value of about 2.01 was relatively independent of the ionic distribution. A slight dependence of g value on temperature was observed.

1. V. J. Folen and G. T. Rado, J. of Appl. Phys. 29, 438 (1958).

73. MICROWAVE RESONANCE IN HEXAGONAL FERRIMAGNETIC SINGLE CRYSTALS

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The anisotropy energy of hexagonal single crystals which have easy directions in the basal plane and hard directions normal to this plane may be described by

$$E = K_0 + K_1\alpha_3^2 + K_2\alpha_3^4 + K_3\alpha_3^6 + K_4\left[\alpha_1^6 - 15\alpha_1^4\alpha_2^2 + 15\alpha_1^2\alpha_2^4 - \alpha_2^6\right]$$

where $\alpha_1, \alpha_2, \alpha_3$ are the direction cosines of the angles between orthogonal x, y, and z axes and the magnetization. The z axis corresponds to the c axis of the hexagonal crystal. In the basal plane $\alpha_3 = 0$ this expression reduces to $E = K_0 + K_4 \cos 6\phi$, and for a sperical sample the resonance conditions in the basal plane are found to be

$$\omega^2 = \gamma^2\left\{H\cos\left[\phi - \phi^H\right] + \frac{2K_1}{M}\right\}\left\{H\cos\left[\phi - \phi^H\right] - 36\frac{K_4}{M}\cos 6\phi\right\}$$

$$H\sin\left[\phi - \phi^H\right] = 6\frac{K_4}{M}\sin 6\phi$$

In this equation the external field H is applied in the basal plane at an angle ϕ^H with an a axis; ϕ is the angle between the magnetization and the same a axis. Ferrimagnetic resonance measurements on hexagonal single crystals show a distinct anisotropy of hexagonal symmetry which allows the evaluation of K_4. The temperature dependence of this hexagonal anisotropy has been investigated.

74. FERROMAGNETIC RESONANCE IN POLYCRYSTALLINE FERRITES WITH HEXAGONAL CRYSTAL STRUCTURE

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A theory is developed for the shape of the ferromagnetic resonance line of polycrystalline ferrites with a hexagonal crystal structure. It is assumed that the anisotropy field is much larger than the saturation magnetization. Under these conditions the single crystal grains behave approximately independently and the absorption as a function of the magnetic field is essentially proportional to the number of grains that go through resonance in a given range of applied fields. This distribution is calculated using methods previously described.[1] Because the resonance lines of the single crystal grains have a finite width, the measured absorption curves should be smeared out images of the calculated distributions.

The general behavior of the distribution is similar to that reported previously for the case of cubic materials.[1] The distributions have a logarithmic singularity at a field strength corresponding to resonance in the intermediate directions and finite steps at their end points which correspond to resonance in the easy and the hard directions. The steps of the distribution give rise to shoulders of the absorption line or to distinct absorption maxima. The theory thus predicts the occurrence of one, two, or three absorption maxima depending on the signs and magnitudes of the various anisotropy constants. For materials with a preferential plane (negative uniaxial anisotropy) the distribution is sensitively dependent on the magnitude of the anisotropy in the preferential plane. The separation of the two lowest absorption maxima is essentially proportional to this anisotropy term, which is the fourth member of an expansion of the anisotropy energy in powers of the directional cosines. Similarly, the anisotropy constants of lower order can be inferred from the observed locations of the absorption maxima and the shoulders of the absorption line.

Measurements were taken at X-band and KU-band on various samples of $Ba_2Mg_2Fe_{12}O_{22}$. Three absorption maxima were observed. The measured absorption curves are in good qualitative agreement with the theory. The analysis of the experimental results indicates that the material has a preferential plane and that the anisotropy in this plane is fairly large.

1. E. Schlomann and J. R. Zeender, J. Appl. Phys. 29, 341 (1958)

75. MEASUREMENT OF FERROMAGNETIC RELAXATION BY A MODULATION TECHNIQUE

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A modulation technique is employed to determine the resonance relaxation time of yttrium iron garnet samples. A fixed frequency X band microwave field, amplitude modulated to 10 megacycles, is used to drive a single crystal sphere at resonance. The rotating component of magnetization of the sample is detected by a crystal fed by a one turn loop located in the plane containing both the DC and RF applied field. The a m part of this detected signal is observed to fall off as the frequency of modulation approaches the reciprocal relaxation time. This effect allows observation of the inability of the resonance spin system to follow rapid variations in the intensity of the driving RF field. The monotonic decrease in susceptibility with increasing modulation frequency is shown to be related to the relaxation time of the sample via the standard phenomenological equations of motion. This technique has been successfully employed to measure relaxation times of various samples of the order of 10^{-8} seconds.

76. THE COUPLING OF MAGNETOSTATIC MODES

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It has been observed, in ferromagnetic resonance, that for certain regions of temperature (and hence magnetization) there exist striking anomalies in intensity and resonant field of several of the magnetostatic modes. These anomalies are most apparent under conditions where the resonant fields of two modes as predicted by the simple theory coincide. Under these conditions the sample responds to an r.f. magnetic field in a manner typical of two coupled tuned circuits, i.e., exhibiting a double-peaked resonant response with the minimum inter-peak spacing determined by the intermode coupling. These couplings occur at small signal levels and are quite distinct from the non-linear effects discussed by Suhl. It will be the subject of this paper to discuss two mechanisms which cause this coupling effect (a) propagation and (b) boundary perturbations.

In the static limit for which they are derived, the magnetostatic modes are orthogonal in the sense that an r.f. magnetic field of exactly the proper configuration to drive one mode will leave the remaining modes inert. When the sphere becomes large enough so that the magnetostatic approximation is no longer valid, certain of the modes become scrambled. Experimentally the coupling appears between modes with designation n, m, r (modified Walker notation) and modes n + 2p, m, q, where all indices are integers. The strength of the coupling appears to be proportioned to R^{2p} where R is the radius of the sphere. Examples of this type of coupling which have been observed occur between the 110-311, 110-512, and 220-421 modes.

Boundary perturbation effects also serve to couple the modes. Surface roughness will couple low order modes to high order modes, an effect which shows up mostly as additional line-width. Surface irregularities of larger wavelength will couple together lower order magnetostatic modes. Because of the anisotropy of the irregularities, the resulting coupling is extremely anisotropic. An example of two modes coupled by shape irregularities but not by propagation is the 110-311 pair.

Movies will be shown demonstrating the behavior of the magnetostatic modes in the presence to the two types of coupling discussed above.

77. OBSERVATIONS ON LINE WIDTH IN FERRIMAGNETIC RESONANCE

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The most successful recent attacks on the problem of the origin of ferrimagnetic resonance line width have proceeded by calculating the rate at which the uniform precession is dissipated into disturbances of shorter wavelength by scattering due to various mechanisms. The scattering perturbations have been taken to be: magnetic ion randomness of inter-atomic wavelength,[1] inhomogeneities of M or H or long wavelength,[2] micro-crystal effects in polycrystalline materials.[3] The terminal states were taken in all cases to be the spin wave spectrum of Clogston et al.[1] These theories all predict a strong and specific dependence of the line width upon specimen shape. Some experimental evidence in substantiation of this prediction has been presented,[4] but owing to the large contribution of surface roughness to resonance line width, the comparison between samples of widely differing shape, size, surface to volume ratio, and finish is probably highly suspect.

A cleaner experiment can be done in which different magnetostatic modes of the same sample are compared as to line width. Such modes can be excited which extend from the bottom to well above the top (for small k) of the Clogston spin wave spectrum. We have done such experiments on a variety of samples and find results clearly at variance with the predictions of the above theories, narrowly interpreted. Better agreement with the experimental evidence can be obtained by (a) modifying the terminal states to be the full set of magnetostatic modes (b) assuming that the scattering mechanisms are characteristically of fairly large wavelength (10^{-3} - 10^{-4}mm). Possible origins of such irregularities, and the manner in which such a line width explanation fits with other line width data (e.g., temperature dependence) will be discussed.

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2. S. Geschwind & A. M. Clogston, Phys Rev. 108, 49, (1957).
3. E. Schlomann, Raytheon Report #R-22, December 1957.
4. J.F. Dillon, Jr., Bull. Amer Phys Soc. II vol 2, 128 (1957).

78. FERROMAGNETIC RESONANCE g-VALUES TO ORDER $(kR_o)^2$

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The mathematical description of the normal modes of ferromagnetic resonance for non-conducting spheroids has been given in the static approximation, and the prediction of this theory for spheres verified substantially for a sizeable number of modes. Experimentally observed size dependent shifts and couplings of the various modes have, however, rendered desirable a solution of the resonant mode problem including propagation.

The static approximation, $\nabla \times \vec{H} = 0$, can be improved in an iterative fashion by calculating the displacement current generated by the motion of the "static" fields and using this current as the source of vorticity in the next higher approximation of the actual field. In this way the influence of finite propagation is retained but without the complexity of the retarded potentials. Essentially one adds the proper amount of vorticity to the potential field to account for its motion. This is a self consistent iterative procedure and may be repeated as desired to give a power series solution in $(kR_o)^n$, where k is the free space propagation number and R_o the sample radius.

This procedure has been carried out to $(kR_o)^2$ for the "uniform" mode of ferromagnetic resonance. The static distribution of M (and thus the potential solution) must be altered slightly to satisfy the requirement of a normal mode. The frequency of the uniform mode is given by:

$$\omega = \gamma \left\{ H_o - \frac{8\pi}{9} M_o \left[1 + \frac{\epsilon}{5} \right] \left[kR_o \right]^2 \right\}$$

to second order in (kR_o), predicting a g factor

$$g = g_o \left\{ 1 - \frac{8\pi}{9} \frac{M_o}{H_o} \left[1 + \frac{\epsilon}{5} \right] \left[kR_o \right]^2 \right\}$$

This result will be compared with experimental data at X and K_a bands.

79. A SURFACE-INDEPENDENT RELAXATION IN FERROMAGNETIC RESONANCE OF YTTRIUM IRON GARNET

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Four relaxation parameters which are measurable in a ferromagnetic resonance experiment are ΔH, T_2, T_1, and ΔH_k. ΔH is the measured line width (full width), T_2 and T_1 are the spin-spin and spin-lattice relaxation times determined, respectively, from the rate of decay of the transverse and longitudinal components of rf magnetization after a microwave pulse is turned off abruptly, and ΔH_k is a spin wave "line width" determined from the rf field, h_{crit}, at which nonlinear effects first occur.

The information of greatest value in understanding relaxation processes is obtained from those quantities which are characteristic only of the volume (or bulk) properties of a material and are essentially surface independent. It has been shown[1] that ΔH at 3000 mcs and 9000 mcs on single crystal spheres of yttrium iron garnet (YIG) varies from about 15 oe to 0.52 oe as the spheres are polished. This is explained on the basis of the excitation of spin waves by surface nonuniformities. Furthermore, there are indications that the ultimate polish has not yet been achieved. It has been found that T_2 varies similarly as the polishing proceeds.

T_1 is generally considered to be an intrinsic relaxation parameter associated with the bulk material. It is shown, however, that T_1 also depends on the surface but to a lesser degree than T_2. An explanation of this is proposed.

The fourth quantity ΔH_k is different in a significant respect. It has been shown[2,3] that the peak of the main resonance (under non-coincidence conditions) decreases at a value of rf field in excess of $h_{crit} = \Delta H \sqrt{(\Delta H_k / 4\pi M_s)}$. The decrease is due to the unstable growth of a z-directed spin wave, of "line width" ΔH_k, with a wavelength in YIG of approximately 300 magnetic lattice constants (~1100 Å). This is much less than the mean size of surface pits and scratches encountered in sample preparation. Hence ΔH_k might (but not necessarily) be expected to be surface independent.

Experiments have been made at 3000 mcs using cavity perturbation techniques and single crystal YIG spheres approximately 0.015 in. in diameter. (The temperature was 125°C to decrease $4\pi M_s$ and thus avoid coincidence of the main and subsidiary resonances.) Spheres with ΔH's of 4.4 oe and 0.38 oe, differing by a factor 11.5 due to surface preparation alone, both yielded a ΔH_k of 0.11 oe. This is the narrowest line width yet indicated for any ferromagnetic material.

From the 0.11 oe one obtains a surface-independent relaxation time of a z-directed spin wave of 1.03 microsecond. This relaxation is of theoretical interest in two principal respects. It is at present the only measurable surface-independent relaxation in narrow line width ferromagnetic materials. In addition the availability of a spin wave of known wavelength comparable to microwave phonon wavelengths makes possible the study of phonon-magnon interactions of the type discussed recently by Kittel.[4]

1. R. C. LeCraw, E. G. Spencer, and C. S. Porter, Phys. Rev. 110, 1311 (1958).
2. P. W. Anderson and H. Suhl, Phys. Rev. 100, 1788 (1955).
3. H. Suhl, Proc. Inst. Radio Engrs. 44, 1270 (1956).
4. C. Kittel, Phys. Rev. 110, 836 (1958).

80. FERROMAGNETIC RESONANCE OF IRON WHISKER CRYSTALS

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The ferromagnetic resonance absorption characteristics of iron single crystals have been examined[1] between -196°C and 850°C. The crystals are of filamentary growth habit and are commonly known as whiskers. The selected crystals have <100> growth directions, and their square cross sections are bounded by [100] crystal planes. Their sizes are in the vicinity of a few millimeters in length and a few microns in breadth. Resonance absorption is observed using standard techniques at 9. and 20.Kmc/s, with the d.c. magnetic field parallel to the length of the whisker. The microwave energy penetrates only a small fraction of the volume due to eddy current limitation. Two resonance modes may be observed. One is driven by the uniform microwave magnetic field, the other by its curl component. The curl mode is equivalent to resonance in a flat plane of infinite extent and no edge corrections are required. The uniform mode is subject to an additional field arising from the uncompensated magnetic pole distributions at the specimen edges. After identification, the uniform mode is uninteresting because of distortions that result from the inhomogeneities of the edge demagnetizing field. The curl mode on the other hand exhibits a line shape and width that, in some cases, may be evaluated from first principles. The line width in these cases is accounted for almost entirely by exchange and conductivity effects, no phenomenological damping mechanism being required. Because other crystals of iron exhibit much broader resonance line widths, these results suggest that crystal perfection, particularly surfaces in the case of metals, may be the determining factor of ferromagnetic resonance line widths in bulk crystals.

The data yield for the spectroscopic splitting factor, g, a temperature and frequency independent value of $2.05 \pm .01$. The exchange stiffness parameter, A, determined in a self-consistent way with this splitting factor, is $25 \pm 5 \times 10^{-7}$ erg/cm at 20°C.

1 For preliminary account, see Rodbell, D. S., Bull. Am. Phys. Soc. II, 128 (1957).

SESSION V-B

METALLURGICAL CONSIDERATIONS

J. A. OSBORN, Presiding

81. THE INFLUENCE OF PLASTIC DEFORMATION ON THE TIME-DECREASE OF PERMEABILITY IN TRANSFORMER STEEL

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Laboratory tests have been carried out on the influence of plastic deformation on the time-decrease of permeability in transformer steel containing about 4% of Si and about 0.025% of C, hot rolled and showing a loss of about 1.03 - 1.3 W/kg and a permeability at 20 mOe higher than 700 Gs/Oe/DINE 41301/; this steel being obtained from normal steel works and used in telecommunication for transmission transformers and transmission chokes.

Some additional measurements have been performed with the transformer, cold rolled /Trafoperm 25 N 1/, vacuum melted steel, containing about 2.5% of silica and possessing a smaller quantity of impurities /$C \approx 0.01\%$/.

Earlier experience has shown that the phenomenon of time-decrease of permeability appears in a high degree in cores stamped out from such a steel - and here the time of permeability decrease at low magnetising fields is in the range of 24 hours and the relative increase of permeability is reaching 30%. After the annealing process of such cores in low temperatures /about 800°C/ the time of permeability decreases to about 8 hours, and after the annealing process in high temperatures /about 1250-1300°C/ in hydrogen this time is reduced to a few minutes.

Silicon steel is containing - conformably to its technology - impurities /such as carbon, nitrogen/, which are causing the phenomenon of time-decrease of permeability. These impurities are producing strong internal stresses which are bringing changes in magnetic properties. Also external stresses are affecting magnetic properties and permanent plastic deformation is their result. Such deformations appear at the edges of stampings cut out from transformer steel and they may have some affect on the time-decrease of permeability.

To examine this influence, plastic deformations have been made in samples of 30 x 6 x 0.035 cm in nearly the whole mass of material by pulling them at a tensile testing machine or by rolling them. The elongation of the sample gave the measure of plastic deformation. In thus prepared samples the course of permeability in low magnetising fields has been masured immediately after their demagnetisation by means of strong alternating fields decreasing until zero. From measurements the time of permeability t_u and the maximal increase of reluctivity r_1 have been reported.

Endeavours have been made to use samples the time-decrease of permeability of which would not exceed one hour. Therefore samples with a relatively small quantity of impurities and with a relatively high permeability have been used. Such samples have been obtained by annealing in hydrogen at high temperatures; also unannealed samples but possessing such properties have been chosen.

Measurements on "pulled" samples have shown that for steel with a greater quantity of impurities [$C \approx 0.025\%$] the time-decrease of permeability varying from a few minutes till many a ten minutes was increasing to a certain maximum with the increase of plastic deformation. A little after the maximum was reached samples were broken. This maximum appeared more distinctly in cold rolled samples containing a smaller amount of impurities [$C \approx 0.01\%$]. The time of permeability increased from many a ten seconds until the maximal value of a few hundred seconds, and then it decreased to a few seconds immediately before the sample was broken.

From these measurements results that the maximum appears at smaller elongations along with the increased quantity of impurities - and it also becomes more flat.

Similar results of measurements are being obtained for rolled samples with such difference that the method of introducing plastic deformation is allowing to get considerable elongations. Yet the maximum appears here at smaller elongation than in "pulled" samples.

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82. THE DEVELOPMENT OF METALLURGICAL STRUCTURES AND MAGNETIC PROPERTIES IN IRON SILICON ALLOYS.

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A brief review of the history of the evelopment of iron silicon alloys for magnetic application will be given with emphasis on the development of oriented sheet materials. The growth in understanding of both the metallurgical processes and the magnetic properties will be touched upon with reference to the general scientific knowledge existing at the time each development occurred.

The present status of development of these alloys will then be reviewed with emphasis on some of the metallurgical and physical problems still remaining in the field.

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83. SOLUBILITY OF CARBON IN IRON AND SILICON IRON AS DETERMINED BY MAGNETIC AFTEREFFECT

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The solubilities are being taken as given by that temperature, for a particular carbon content, above which there is no further increase in the value of the time decay of permeability. The use of this latter parameter as a measure of dissolved interstitial has been recently initiated[1,2] Values of the time decay within each sample, on the way up to the temperature of complete carbon solubilization, give heats of solution which are to be compared with that given by plotting the respective leveling-off temperatures for each composition. At the time of this writing (August '58), the data are not sufficiently complete to report the values, although it may be stated that the solubility of carbon in iron appears to be somewhat less than that given by Dijkstra[3] and Lindstrand[4] as obtained from internal friction. The grain size effect noted by Stark, Averbach and Cohen[5] is also being studied.

1. E. S. Anolick and Joseph Singer; Nov. 1957 AIEE Conference on Magnetism, J Appl. Phys., 29, 412, (1958).
2. G. W. Rathenau; ibid, p. 239.
3. C. J. Dijkstra; Trans. AIME 185, 253, (1949).
4. E. Lindstrand; Acta Met. 3, 431, (1955).
5. P. Stark, B. L. Averbach, and M. Cohen, Acta Met. 6, 149, (1958).

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84. BRITTLENESS IN IRON-COBALT ALLOYS

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The brittleness in iron-cobalt alloys which contain cobalt from 35 to 68 percent is often attributed to ordering. In addition to short range order and long range order, the interstitial atoms, carbon and nitrogen may also act as hardening mechanisms. In this paper the yield strength associated with these three mechanisms has been estimated for an alloy of the composition FeCo. The relative values of the estimated yield strength do not indicate that ordering can account fully for the extremely brittle behavior for iron-cobalt alloys using the criterion that the yield strength must be larger than the fracture strength for brittle failure. Furthermore, if carbide and nitride farming elements such as vanadium and zirconium are absent, the theoretical calculations show that the effect of the interstitial elements on hardening of iron-cobalt alloys may be more important than the hardening mechanisms associated with ordering.

Initial experiments on iron-cobalt alloys containing a total of 0.036% carbon, oxygen and nitrogen have shown that brittle fracture is intergranular. However, each of the mechanisms proposed above is based on a transcrystalline mode of fracture. Therefore, additional data have been obtained on alloys of high purity as well as on alloys containing small amounts of zirconium and vanadium to remove the carbon and nitrogen from solid solution. The data obtained in this work suggest that unless grain boundary segregation of impurities is prevented, the strengthening effect of ordering cannot be fully evaluated.

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85. ROOM-TEMPERATURE DECOMPOSITION OF AUSTENITE IN FIFTY PER CENT NICKEL - FIFTY PER CENT IRON MAGNETIC ALLOY TAPES

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The possibility of a room-temperature decomposition of the austenitic, annealed fifty per cent nickel - fifty per cent iron alloy tapes (0.002 inch thick) was investigated by optical and electron microscopy, and by X-ray and electron diffraction. Of the tapes from several heats of the alloy examined, only two showed partial transformation upon room-temperature storage for about eighteen months.

Lightly etched specimens of these partially transformed alloys showed a well-defined and abundant precipitate of the Widmanstätten type in the austenitic matrix, under both optical and electron microscopes. Repeated attempts to detect the presence of the precipitate by X-rays were unsuccessful. The precipitate disappeared upon deep etching. Electron diffraction, however, readily revealed the presence of the precipitate in unetched and lightly etched specimens. The general indication is that the transformation occurs very slowly and is confined largely to the surface of the tapes.

Analysis of electron diffraction patterns enabled the structure of the precipitate to be identified as either orthorhombic or tetragonal. Neither of these probable structures is the expected equilibrium structure[1], viz., the body-centered cubic structure. On the other hand, the structure of the precipitate appears to be similar to the intermediate structures that have been observed during the early stages of precipitation.[2]

An epitaxial relationship between the precipitate and the matrix was evident in the electron micrographs and could be identified from the electron diffraction patterns. The relationship could be described as one or more planes of the (101) type in the precipitate lying parallel to the (110) planes of the matrix. Because of the multiplicity of the precipitation planes in the matrix, the electron diffraction patterns were hard to interpret and the structure and orientations described must be regarded as tentative.

A slow decomposition of austenitic fifty per cent nickel - fifty per cent iron alloy tapes is of interest because it indicates the possibility of aging of the magnetic properties of these tapes, and hence, of the performance characteristics of magnetic amplifier cores made from them. The 0.002 inch thick tapes which showed the transformation have been kept under observation. To date, covering over three years, periodic observations show that the transformation remains restricted to the surface of the tapes and progresses only very slowly. Work presently under way includes 1) studies on the progress of the transformation and its effect upon the magnetic properties of the tapes and 2) extension of these studies to ultra-thin tapes (<0.001 inch thick).

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2. Geisler, A. H., National Research Council Symposium on "Phase Transformations in Solids," pp. 387-544, 1951.

86. MERCURY PROCESS FOR MnBi PRODUCTION*

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A method for producing manganese bismuthide has been investigated wherein the manganese and bismuth are first "dissolved" in mercury by heating at atmospheric pressure. The mercury is subsequently vacuum distilled at a low temperature, leaving a strongly ferromagnetic residue of MnBi. Material made by this basic mercury process had a magnetic moment at liquid nitrogen temperature as high as 70 e.m.u./gm, representing about 83 per cent reaction Furthermore, when this material was annealed at about 400°C, a moment of 83 (or 99 per cent reaction) was obtained.

The MnBi prepared by this method was shown to be identical with that prepared by other methods. X-ray diffraction showed only lines that could be attributed to MnBi. In addition, the lattice constants agreed with those reported by other investigators. The first anisotropy constant was determined for this material as well as for known MnBi. These anisotropies were found to be similar. The magnetic moment of the material produced by the mercury process was found to depend on the stoichiometry of the product, the maximum being obtained for that computed for the formula, MnBi.

Mechanical stirring during the heating and distillation steps was found beneficial for the attainment of high yields. Regrinding the charge between the two steps also helped as did amalgamation of the bismuth before incorporation of the manganese. Although the initial heating may be done in air, distillation of the mercury must be done under vacuum to prevent oxidation. The presence of excess manganese seems to drive the reaction to completion, although the ratio of mercury to the other elements is not critical. A ratio of 2:1 appears satisfactory.

The presence of a mercury-containing tenary was ruled out as an intermediate in the reaction. The function of the mercury appears to be the dispersion of the manganese and bismuth into a homogeneous fine-particle mixture. The particle size of the produce was often quite small, sometimes sparking spontaneously on exposure to air.

* This work was partially supported by the Wright Air Development Center, Air Force Contract No. AF33(616)-309.

87. INVESTIGATION OF A PRECIPITATION HARDENING ELINVAR

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In a nickel-iron-chromium alloy of the Elinvar type containing 2.5 percent titanium,[1,2] it is possible to retain the titanium in solid solution by a quench from 1000°C. Aging at temperatures near 600°C can then produce a nonmagnetic precipitate of an intermetallic compound (Ni_3Ti) dispersed throughout the ferromagnetic matrix. The presence of this precipitate can be detected by changes in mechanical and magnetic properties. The variation of internal friction has been used to follow the precipitation process; the internal friction was measured by resonating a rod in the longitudinal mode over a frequency range from 40 KC to 125 KC. The internal friction was found to be correlated with the amount of precipitate as measured by the Curie point of the depleted matrix and the internal strain as measured by the coercive force. A low value of internal friction ($Q^{-1} = 5 \times 10^{-5}$) was obtained by the proper combination of titanium content, plastic deformation, and aging temperature. Severe plastic deformation before aging increased both the rate of aging and the maximum value of inverse Q after age. The amount of precipitate was insensitive to cold-work prior to aging; the internal friction and coercive force, however, were sensitive to degree of dispersion and the precipitation mechanism. Both continuous and discontinuous precipitation were observed depending on the aging temperature. The temperature coefficient of modulus is known to be a function of Curie point and the internal strain developed during the aging. The decrease in strain-induced magnetostriction as a result of aging in this allow raised the elastic modulus and changed the shape of the modulus versus temperature curve below the Curie point. Over-aging due to particle growth occurred as in the simplier iron-carbon system.[3]

1. Ni-SpanC, U. S. Patent No. 2,266,482.
2. N. B. Pilling and A. M. Talbot, Age Hardening of Metals, p. 253 (1940).
3. L. J. Dijkstra and C. Wert, Phys. Rev. 79, 979 (1950).

88. VARIATION IN ORIENTATION TEXTURE OF ULTRA THIN MOLYBDENUM PERMALLOY TAPE

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It is necessary to select certain heats of molybdenum permalloy in order to manufacture cores of ultra thin tape which have satisfactory properties for use in computer applications. In an effort to aid this selection process quantitative pole density stereograms of <111> poles of 1/8 mil tapes from six production heats in both cold rolled and annealed conditions were developed in order to reveal possible variations in texture and magnetic properties.

Cold rolling the tape developed (110) [$\bar{3}$35] and (110) [3$\bar{3}$5] end orientations as major texture components together with a previously unnoticed cube-on-edge or (110) [001] orientation as a minor texture component whose intensity varies according to a combination of many possible processing variables.

Annealing the tape at 771°C developed (120) [001]+ (210) [001] ; (113) [$\bar{7}$85] + (113) [78$\bar{5}$] ; and previously unnoticed (110) [001] cube-on-edge texture components. The intensity of each individual texture component depends on the combined effect of many processing variables.

Switching coefficient, squareness of hysteresis loop (Br/Bm) and coercive force were used as magnetic parameters for evaluation of the tape cores. It was found that amont other possible combinations of texture components a strong (110) [001] annealed texture component seems to associate with the highest squareness ratio and lowest coercive force of the tapes studied in the present investigation. No correlation was found between texture and switching coefficient.

89. ON THE TEMPERATURE DEPENDENCE OF THE (110) [001] TEXTURE IN SILICON IRON

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In a previous publication by the authors it was postulated that tne (110) [001] texture forms because (110) [001] grains posses lower free energy than grains in other orientations. The formation of the (110) [001] texture was shown to be controlled by second phase inclusions. When the inclusions dissolved at high temperatures, the (110) [001] texture did not develop to as great an extent as it would have if annealed at a lower temperature. One might argue that at higher temperatures grains of other than (110) [001] orientation are more stable than (110) [001] grains.

Starting with high purity alloys, specific impurities are added to silicon iron by vacuum melting and casting. In the present report it is shown that the temperature at which the (110) [001] texture forms can be increased and is controlled by the amount and stability of second phase inclusions. From this we infer that in materials with impurities processed as we have described, (110) [001] grains possess lower free energy than grains in other orientations even at the increased temperatures. That is, we suppose that the sum of the specific surface energy and residual strain energy is minimum for (110) [001] grains.

90. PROGRESS IN ULTRATHIN MO-PERMALLOY TAPES WITH SQUARE HYSTERESIS LOOPS

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Commercial production of ultrathin cold rolled tapes of 4-79 Mo-Permalloy has been accompanied by research on melting, processing and annealing procedures leading to improved quality control. A wide range of magnetic properties with pulse magnetization is available by selection of tape thickness and final annealing temperature of the cores.

The effect of reduced thickness is a generally higher coercivity and increased squareness. The switching coefficient is lowest for 1/8 mil tape, but at drives below about .25 oersted the switching time is not less than for 1/4 mil because of the higher coercive force.

With increasing temperature of the final anneal, both squareness (measured by static B_r/B_m ratio) and coercive force decrease. The decrease in coercive force is accompanied also by a decrease in the switching coefficient until a minimum value of the switching coefficient is reached after which it increases with further decrease in coercive force. This point of minimum switching coefficient appears to be related to a crystal structure in which the grains extend through the sheet thickness with minimum lateral growth. Data illustrative of the uniformity of static and dynamic magnetic properties between lots of material with present technology are given.

SESSION VI-A

FUNDAMENTAL INTERACTIONS

G. T. RADO, Presiding

91. THE EXPERIMENTAL DETERMINATION OF THE HYPERFINE COUPLING IN FERROMAGNETIC METALS AND ALLOYS (Invited Paper)

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The unbalanced electron spins or orbits, which form the elementary magnets in ferromagnetics (and paramagnetics) produce a strong magnetic field at the nucleus of the atom. If the nucleus has a spin and hence a magnetic moment, there is an interaction between the electron and the nuculeus. This is the hyperfine coupling, so-called because it was first discovered and determined in the hyperfine structure (h.f.s.) of spectral lines.

The h.f.s. coupling is really a measure of the effective magnetic field (H_{eff}) acting on the nucleus. Its value is usually several hundred Kilogauss, and depends, among others, on the state of the magnetic electron. For instance an s-electron, which gets close to the nucleus, produces a stronger H_{eff} than a d- or f-electron. Also, the H_{eff} due to s-electrons is insensitive to changes of crystalline symmetry, while this is not so for d-or f-electrons. A study of h.f.s. coupling can therefore help in establishing the nature of the electronic states in ferromagnetics.

The "classical" method for determining the h.f.s. coupling, namely by optical or microwave spectroscopy, is not applicable to ferromagnetics, because the spectral lines are too broad and usually cannot be resolved into their h.f.s. components. The methods developed for ferromagnetics are based on the following considerations.

When the temperature is sufficiently low for the interaction energy $\mu_n H_{eff}$ between nuclear spin and electron spin (μ_n is the nuclear magnetic moment) to be comparable with the energy of thermal agitation kT, the nuclear spins, instead of pointing at random, will tend to orient themselves parallel to H_{eff}. This will occur only at very low temperatures, usually below 0.1°K.

Two methods have been used so far for detecting this ordering process and thereby determining H_{eff}. One method relies on the fact that the γ-radiation emitted by a radioactive nucleus is usually anisotropic. As long as the nuclei point at random (which is always the case at high temperatures) the total emission from a sample is isotropic. At low temperatures, however, each nucleus will point preferentially in the direction of H_{eff} which, at every point, is parallel to the magnetization. If therefore all domains in a ferromagnetic are made to point in the same direction, the nuclei too will be oriented and the γ-emission from the specimen as a whole will be anisotropic. The method consists in replacing a small fraction of the stable atoms by their radioactive isotopes (e.g. 59Co by ^{60}Co), and measuring the γ anisotropy. From this one can calculate the degree of orientation and, if the temperature is known, one obtains H_{eff}.

In the other method one measures the specific heat and observes the anomaly connected with the ordering of the nuclear spins with respect to H_{eff}.

Both these methods have been applied to Co and various Co alloys, and the second method to Tb. The experiments will be described, and the results discussed, particularly in the light of W. Marshall's theoretical treatment.

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92. THE ELECTRONIC STRUCTURE OF TRANSITION METALS (Invited Paper)

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Several distinct lines of experimental work now point towards a new conception of the electronic structure of the transition metals. Recent X-ray work by R. J. Weiss suggests that metals of atomic number less than Fe and Fe itself have few 3d electrons and many conduction electrons while for metals above Fe this is reversed. These results are discussed and the ideas to which they lead described. On this basis the magnetic properties of all the pure metals are easily understood and the variation of the saturation moments of all the binary ferromagnetic alloys can be explained. Results of neutron diffraction on ferromagnetic alloys also support the new ideas and further experiments should provide very clear tests of them. It is shown that these alloys can be divided into four types, each with a characteristic behaviour which will be described. Further evidence, coming from recent work on nuclear orientation in ferromagnets is also briefly mentioned.

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93. NUCLEAR MAGNETIC RESONANCE IN MAGNETIC MATERIALS

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In a nuclear magnetic resonance experiment the relation between the resonance frequency and the magnetic field is $\omega = \gamma_N \times H$ where γ_N is the nuclear gyromagnetic ratio. In general the resonance frequency for a nucleus in a magnetic substance is different from the resonance frequency in a diamagnetic environment because the internal magnetic fields contribute a time average component to H at the nuclear site. By measuring the resonance shifts one can obtain information about the distribution of magnetic electrons in the material and the magnetization, including the elusive sublattice magnetization in antiferromagnetic crystals. Measurements of resonance shape and relaxation time contribute to our understanding of the time dependence of the electronic states.

94 NUCLEATION OF FERROMAGNETIC DOMAINS IN IRON WHISKERS

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An ideal single-crystal specimen of iron initially fully magnetized along one of its cube-edge directions should theoretically remain magnetized in that direction of easy magnetization until an effective magnetic field acting in the opposite direction reaches a value of $H_K = 2\,K_1/M_S$, where K_1 is the first magnetocrystalline anisotropy constant and M_s is the saturation magnetization. For iron $2\,K_1/M_S$ is about 560 oersteds at 25°C. In actual specimens of pure iron the observed coercive forces are generally of the order of 1 oe to 10^{-2} oe. This disparity, for an initially saturated specimen, is generally attributed to the nucleation of domains at inhomogeneities in the specimen, such as occur at surface pits, inclusions, and grain boundaries, where local demagnetizing fields exceeding $2\,K_1/M_s$ may exist.

Recent experiments on ferromagnetic domain-wall motion in iron whiskers by the authors indicated that coercive forces for nucleation of domains of reversed magnetization in selected nearly perfect specimens would be near the theoretical upper limit if the region near the damaged base of the whisker were excluded from the applied reversing field. This prediction has been confirmed. We have located regions in several iron whiskers where reversal of magnetization does not occur until fields of about 480 oersteds are reached. This result, within 15% of the theoretical limit of 560 oersteds, appears to confirm the correctness of the theory.

95. DIRECT OBSERVATION OF SPIN WAVE RESONANCE*

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It has been possible to excite spin waves by a uniform microwave field and to observe spin wave resonance, distinct from the uniform precessional mode, according to the the spin wave dispersion relation $\omega_o = \frac{2A\gamma}{M}k^2 + \omega$, and the Kittel condition for spin wave resonance $k = \frac{p\pi}{L}$, where A is the exchange coupling constant, L the sample thickness and p an integer. (See 1 below for complete references). These simple relations must be modified in two ways. First, since the experiments are carried out in thin permalloy films, account has to be taken of the r.f. field gradient. This leads to modification of spin wave modes $p \leq 3$ only, but permits in general excitation of even as well as odd modes. Second, observed deviations from the p^2 law are interpreted as incomplete pinning of the spins at the sample surface. From the location (or separation) and shape of the isolated spin wave modes, the exchange constant A and damping of spin waves have been computed. $A \cong .5 \times 10^{-6}$ erg/cm. for 80% - 20% permalloy films at room temperature. Further experimental results using this method will be reported, as well as theoretical extensions necessary to interpret the data.

1. M. H. Seavey, Jr. and P. E. Tannenwald, Phys. Rev. Letters 1 (1958).

* The research reported in this document was supported jointly by the Army, Navy and Air Force under contract with Massachusetts Institute of Technology.

† Staff members.

96. TEST OF SPIN-WAVE THEORY WITH PRECISION MAGNETIZATION MEASUREMENTS*

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On examination of the classic experiments on polycrystalline ferromagnetic metals, it appears that quantitative tests of spin-wave theory are not feasible because the quantity of data is limited and is influenced, among other factors, by temperature-dependent anisotropy contributions. In order to study the contribution of ferromagnetic spin-waves to the magnetic properties while avoiding complications introduced by polycrystalline materials, we have reexamined the low temperature magnetic moment of a spherical, single-crystal of nickel using a vibrating-sample magnetometer.(1) With this instrument, differential changes of magnetic moment as small as one part in 10^4 could be observed in a uniform field as a function of both applied magnetic field and temperature. Detailed measurements along the principal crystallographic directions are presented as a function of temperature and field, estimates of the precision required to accurately test spin-wave theory are given, the problems of interpreting data at low applied fields in single-crystal and polycrystalline samples are reviewed, the effects of the applied field are indicated, and the difficulties of extrapolating data to very low temperatures are described. Two new results are obtained. First, the single-crystal nickel data show that $[M_s(4.2^oK) - M_s(300^oK)]/M_s(4.2^oK)$ is slightly higher than the earlier polycrystalline data, thus indicating a smaller exchange constant. Second, if we assume that $[M_s(O,H) - M_s(T,H)]$ varies as T^n, at an applied field of 18 kilogauss $n = 1.5$ from $T \cong 30^oK$ to $T \simeq 150^oK$ in agreement with spin-wave predictions, and $n \simeq 2.2$ for T greater than 200°K. At lower fields n is less than 2 in the low temperature region, and n is less than 2.5 in the higher temperature region.

97. MAGNETIC CONTRIBUTIONS TO THE ELASTIC CONSTANTS OF Ni AND AN Fe-30% Ni ALLOY AT HIGH MAGNETIC FIELDS.

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The velocity and attenuation of 10 megacycle sound waves in single crystals of nickel and an Fe-30%Ni alloy have been measured at a magnetc field high enough to saturate the ordinary E effect. An effort was made to extract the intrinsic contribution of the spontaneous

1. S. Foner, Rev. Sci. Instr. 27, 548 (1956); Bull. Am. Phys. Soc. Ser. II, 2, 237 (1957).

* The research reported in this document was supported jointly by the Army, Navy and Air Force under contract with Massachusetts Institute of Technology.

magnetization to the elastic constants so that the nature of the interaction between the constituent magnetic moments could be studied.[1]

In the case of nickel the elastic constants reach a field independent value only if the field is along certain crystallographic directions. For the field in other directions, they only approach this value gradually as the field is increased. Thus the high field elastic constants of nickel show a dependence upon the field direction with respect to crystallographic directions which is of the order of one tenth of a percent. An explanation in terms of a "morphic effect" does not describe the present experiment, but one based on the coupling of the magnetization direction to the applied stress through magnetostriction accounts for the experimental results.[2] The intrinsic contribution, if any, to this direction dependence seems to be rather small.

In the Fe-30%Ni alloy, the high field elastic constants were observed to decrease linearly with applied field up to the highest fields available (10 kilo-oersted). Since the Curie temperature of this alloy is low (approximately 200°C) the elastic constants were measured as a function of temperature in this region. Above the Curie temperature the three masured constants $C = C_{44}$, $C' = 1/2(C_{11} - C_{12})$ and $C_L = 1/2(C_{11} + C_{12} + 2C_{44})$ decreased linearly with increasing temperature as is usual. However, near the Curie temperature the constants fall continuously below the high temperature extrapolation values, and, in fact, near room temperature, the constants C' and C_L are actually increasing with increasing temperature. A large part of these effects may be explained by the large volume magnetostriction in this alloy but a detectable fraction may arise from changes in the magnetic contributions to the interatomic forces. The large effect of passing through the Curie temperature has been interpreted by Döring as resulting from the volume magnetostriction through the changes in magnetization accompanying the volume changes of the stress field. Since C' and C are obtained from isovolumic deformations, this explanation should not apply to them.

98. SOME CONSIDERATIONS ON OBTAINING POLARIZED PHOTOELECTRONS FROM MAGNETIZED METALS

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The production of beams of magnetically polarized electrons is a recently revived problem of long standing interest in physics. One method proposed long ago in a general way but never previously discussed in much detail in the published literature involves the use of photo-electrons emitted from magnetized metals by radiation of wavelength approximating the emission threshold. Such electrons originate in states lying just below the Fermi level in the metal. These electrons, before being excited to an emission state, have a net polarization which depends upon the intimate details of the band structure. Depending on these details they may be much more strongly polarized than the average d-shell electrons and indeed may have an orientation either with or against the net d-shell moment. A qualitative discussion is given of the relationship of this polarization to band structure and the factors which tend to reduce the polarization of the promoted electrons, including competition of s-shell electrons. A further discussion is given of the depolarization which accompanies the transport of a promoted electron to and through the surface of the metal. Although the probability that such an excited electron is scattered (with depolarization) is greater than for a normal conduction electron, nevertheless depolarization of the finally emitted current is relatively small since most scattering processes rob the scattered electron of its necessary escape energy. It is concluded that room temperature photoelectrons from most magnetized metals are likely to have significant polarization, which in some especially favorable cases might approach 100% and can be of either sign with respect to the moment of the metal.

1. H. Sato, J. Appl. Phys. 29, 456 (1958).
2. G. Simon, Zeit. f. Naturf, 13A, 84 (1958).

99. ANTIFERROMAGNETIC MAGNON DISPERSION LAW AND BLOCK WALL ENERGIES IN FERROMAGNETS AND ANTIFERROMAGNETS*

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ABSTRACT

The exact eigenstates of the exchange Hamiltonian

$$H = 2J \sum_l \left[\vec{S}_l \cdot \vec{S}_{l+1} - \tfrac{1}{4} \right]$$

are found for short chains of 4, 6, 8, and 10 atoms of spin 1/2. A linear dispersion law for magnons in an antiferromagnet is exhibited by the energy spectrum. The periodic boundary conditions are then removed and the ends of the chain held fixed, both parallel or antiparallel. The energy of the 180° Bloch wall is computed and compared with the classical result. It is found that the semi-classical ferromagnetic wall is a good approximation to the exact wall. The energy of the semi-classical antiferromagnetic wall is not a very good approximation to the exact wall energy, but the semi-classical energy appears to have the correct dependence on the wall thickness.

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** National Science Foundation Predoctoral Fellow.

SESSION VI-B

INSTRUMENTATION

E. BOTH, Presiding

100. STRONG EDDY-CURRENT APPLICATIONS OF PERMENENT MAGNETS

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Small eddy-current applications of permanent magnets, like brakes for KWh-meters, have a practically linear torque-speed characteristic, because the induced current increases proportionally to the low relative speed between eddy-current disc and magnetic poles.

In bigger models a considerable reaction of the induced-current field shifts the eddy-current paths in the direction of movement, so that the electrodynamic force between current and magnetic poles deviates from the linear relation, reaches a maximum at a critical speed and decreases asymptotically to zero at infinite speed, whereas the dissipated power becomes a maximum.

Some investigations were made on the behaviour of permanent magnets with full-scale models, including a water-cooled set-up with p.m.-rotor and an air-cooled device with p.m.-stator, both of cylindrical shape with 30 cm effective diameter and a length of 15 cm; maximum torques of respectively 390 ft.-lb. and 304 ft.-lb. were obtained. Measurements were carried out with iron as conducting material and iron coated with a thin copper layer, where the main effect occurs in the copper.

For the latter combination the influences of the pole pitch, copper thickness and temperature on the critical speed and maximum torque were determined.

Pole pieces may sometimes increase the static flux, but do not always improve the dynamic behaviour. The ideal solution would possibly be obtained with a high-induction permanent magnet without pole pieces, but the induction is limited by the self-demagnetising effect of free poles.

The demagnetising effect of the eddy-currents was estimated from working-point measurements on top of the magnets; near the critical speed the rotor is self-centering in the stator.

One of the possible applications could be found in a non-fading retarder for heavy trucks in mountainous regions.

101. A THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE FERROMAGNETIC EXPLOSIVELY SHOCKED CURRENT PULSE GENERATOR[1]

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To most effectively utilize the potential capability of the ferromagnetic explosively actuated current generator one must understand the effect of variation of parameters upon the device output into a given load. This report presents theories of operation of the device, an approximate theoretical analysis of the effect of variation of the basic circuit and device parameters and a comparison of theory with experimental results.

Theoretical and experimental curve data are presented and compared for i_{peak} versus circuit load inductance, device load coil turns and magnetic core width (for a fixed thickness). There is a gratifying similarity between theoretically predicted and experimentally determined curve data. Further experimental data are presented showing typical current and voltage versus time curves, a calculated B-H curve at time of shock, and i_{peak} versus explosive charge volume for different transformer steels.

Guiding criteria are given for an optimum ferromagnetic current pulse generator system.

1. Work Performed Under AEC Contract AT-(29-1)-789

102. AN ELECTROMAGNETIC SUPPORT ARRANGEMENT WITH THREE DIMENSIONAL CONTROL; THEORETICAL

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University of Virginia

The original electromagnetic support developed by Holmes and Beams[1,2] in the late 1930's and used by Beams and coworkers since that time is a one dimensional system. Servoed control is obtained in one direction and only inherent stability due to the field shape is obtained in the lateral directions. In a rather specialized double ended arrangement developed by Breazeale[3] the inherent stability was quite large.

The more general problem of a three dimensionally controlled support has been treated theoretically. The starting point is the general expression for the force $\bar{F}$ on a magnetic dipole of strength $\bar{M}$ in a magnetic field $\bar{B}$.

$$\bar{F} = (M.\Delta)\ \bar{B}$$

By virtue of making certain assumptions which seem reasonably close to practical feasibility two basic three dimensional support schemes have been devised, in which ideally the three mutually perpendicular forces are uncoupled. The two arrangements are described and the theory is applied to predict support performance and to predict the amount of coupling to be expected due to deviations from the ideal system.

1. F. T. Holmes R. S. I. 8, 444 (1937)
2. J. W. Beams, Rev. Mod. Phys. 16, 245 (1938)
3. Breazeale, McIlwraith, and Dacus: Factors limiting a magnetic suspension, J. App. Phys. 29, No. 3, 414-415, (March 1958)

103. AN ELECTROMAGNETIC SUPPORT ARRANGEMENT WITH THREE DIMENSIONAL CONTROL; EXPERIMENTAL

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University of Virginia

The first gradient coil configuration described in part I of this paper has been constructed. In this system the axis of one pair of gradient coils is parallel to the magnetizing field. The details of the mechanical, magnetic, optical, and electronic aspects of this implementation will be presented and discussed. It has been convenient in this case to use a Varian four inch electromagnet to produce the magnetizing field. The optical and gradient coil systems have been mounted on heavy aluminum plates attached to the magnet. In this way a rigid mounting is assured and adjustments in the optical system are facilitated.

The performance of this system has been experimentally investigated. The method used in making measurements on overall performance will be presented and discussed. In particular, some of the properties examined are:

1. The elastic constant associated with the restoring force due to the magnetic field gradient.
2. The cross-coupling between the three forces produced by the three pairs of coils. This applies both to the case of displacement of the supported sample, as well as zero displacement.
3. Steady state and transient force limits which the sample can withstand and still remain in support.
4. The bandwidth of the overall system, i.e. the displacement resulting from an artifically inserted a.c. error signal.

The difficulties encountered in this system will be discussed and means for making improvement will be presented. Some of these improvements will be incorporated in the second system, which is presently under construction. In this system the gradient coils are symmetrically located relative to the magnetizing field. In both cases the greatest difficulty lies in the optical system used to sense the three components of sample position.

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104. MAGNETIC RECORDING HEAD WITH D-C RESPONSE

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A magnetic recording head has been developed that can directly record and playback low frequency signals down to, and including 0 cps, without using amplitude, frequency, or pulse width modulation.

Two problems are encountered in d-c magnetic recording. The more obvious problem is caused by the small voltage induced in the playback head when the flux changes at a very slow rate. At low frequencies, the output of a conventional playback head is proportional to the time rate of change of flux in the head; therefore, at d-c, the playback signal has zero amplitude. The second problem encountered in reproducing d-c signals is the disappearance of the magnetic field at the gap of a ring type head when wave lengths of considerable lengths are recorded on the tape. The magnetic field at the gap of a ring type head becomes too small to be used when a recorded wave length is longer than a few inches.

Combining a perpendicular head with flux sensitive playback has eliminated these problems. A perpendicular head magnetizes the recording tape perpendicular to the direction of tape motion, i.e., the tape is magnetized through its thickness. The pole pieces of the head are spring loaded against the tape to maintain consistent contact while the tape passes through the head. Vicalloy, a thin homogeneous metal tape was selected for this purpose because it contains many of the magnetic and physical characteristics desired, including a high coercive force, high remanence, and mechanical flexibility when it is rolled into a thin tape. A frequency response of d-c (0 cps) to 10 cps is achieved at a tape speed of 0.04 inches per second. Pre-emphasis is not required in recording and equalization is not used during playback. Cross talk between adjacent heads in a multi-channel system is below 50 db at moderate track separations.

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105. SHAPE ANISOTROPY IN A WIDE RANGE GAUSSMETER

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A direct-reading, wide-range, stable gaussmeter is described. It consists of a thin ferromagnetic film mounted on a shaft. This film reacts with a magnetic field to produce a torque whose magnitude is a function of the applied field intensity. The magnetic torque developed is indicated by the angular rotation of the shaft restrained by a spiral spring. Because the magnetic torque is derived from shape anisotropy of the film, the instrument has three most valuable characteristics. First it cannot be decalibrated by any magnetic field; second it can cover any useful range from 200 to 20,000 gauss; finally the gaussmeter can be used for alternating as well as unidirectional fields.

An analysis of the torque-angle characteristics of this instrument has been made on the assumption that the film is an oblate spheroid in which the magnetization is uniform and constant in magnitude. The direction of the magnetization varies as the field direction and magnitude are changed. Stoner and Wohlfarth's analysis for the spheroid which precludes domain boundary formation is used to calculate the anisotropy torque as a function of the applied field. Good agreement between theory and measurement has been found. This analysis should prove of interest to those engaged in research on thin films. The gaussmeter itself has proved a valuable tool to applied materials research.

106. THE DESIGN OF AUTOMATIC RECORDING INSTRUMENTS FOR MAGNETIC MEASUREMENT IN A HOT CELL*

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To study the effects of nuclear radiation on the magnetic properties of ferromagnetic single crystals, a torque magnetometer (crystal anisotropy measurements) and a magnetostrictometer (magnetostriction measurements) have been designed and constructed. Both are remote controlled, automatic recording instruments.

The torque magnetometer system consists of a specimen holder rigidly fixed to a shaft supported by nonmagnetic precision bearings, a coupling strip connecting the shaft to a strain gauge transducer, a framework which supports the transducer and shaft and a gear drive to rotate the instrument in a magnetic field. The electrical system consists of a motor, a recorder, a current supply for the transducer bridge circuit and suitable adjustment for initial zero positioning of the recorder pen.

The entire unit can be moved in and out of the magnet on two parallel rods. This allows easy access to the unit for remote insertion or removal of samples by a manipulator. The magnetometer automatically plots torque as a function of the angular displacement of a reference direction in the sample with respect to the direction of the applied field. Its sensitivity is 2000 ergs/mv.

The magnetostrictometer is simply a cylinder that fits over the magnetometer shaft housing and is fixed to the magnetometer frame. Hence, it can be rotated or moved in and out of the field with the same mechanisms used with the magnetometer. Within the cylinder is a strain gauge Wheatstone bridge with the exception of one arm. This arm is the strain gauge which is bonded to the sample to measure magnetostriction. The gauges in the cylinder are arranged so that they compensate for temperature, magnetoresistance and inductive pickup. The output voltage of the bridge circuit is directly proportional to the strain. The magnetostrictometer automatically plots strain as a function of applied field. Its maximum sensitivity is $.2 \times 10^{-6}$ inch/inch mv.

Accurate sample location is important. To do this remotely, the single crystal samples are held in brass discs which have the same outside dimensions (1 inch dia. x 3/16 inch thick). Three holes are similarly located in each holder. Three pins are correspondingly fixed to the heads of both the magnetometer and magnetostrictometer. Hence, the samples can be aligned and fixed to either instrument by simply placing the holder on the pins. The holders have a novel internal cutout to allow transfer of the samples from the aluminum holders in which they were radiated.

The problem of bonding tiny strain gauges having an active area of 1/16 inch x 1/16 inch in a preferred direction on disc-shaped samples was solved by using jigs for alignment and a tubular vacuum pickup for handling the gauge. Connection of the gauge to the bridge circuit is accomplished by prewiring the gauge to a miniature coaxial plug which connects directly to a socket attached to the magnetostrictometer head.

Hot cell time is expensive and remote control manipulation can be awkward. For this reason devices were devised such as a spring-loaded screwdriver for handling 0-80 machine screws and a hydraulic lift table for the bulk of the apparatus so that it could be lowered beneath the working plane while others used the cell.

Emphasis will be placed on the design features that enable these instruments to be used under remote control.

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* The development of the instrumentation reported in this paper has been supported by the Aeronautical Research Laboratory at WADC, Air Force Contract No. AF33 (616)-5555.

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107. A FLUX INSTRUMENT FOR RAPID COMPARISON OF CRYSTAL ANISOTROPIES

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A rotating disk instrument for rapid comparison of crystal anisotropies is described. In it a circular disk rotates in a magnetic field parallel to the plane of the disk. Because of crystal anisotropy the magnetization I makes an angle θ with the magnetic intensity H. Some instruments, called torque magnetometers or magnetic torquemeters, measure the torque per unit volume, HI sin θ. In our instrument the disk rotates at 1800 rpm with its axis perpendicular to H. The changes in I sin θ, the component of the magnetization perpendicular to H, induce an emf in pick-up coils, which are placed with their axis perpendicular to the axis of the rotating disk and perpendicular to H. If the pick-up coils are spherical, as in the similar instrument built by Siegel,[1,2] the ratio of the flux through the coil to the magnetic moment of the specimen can be accurately calculated. Without such an absolute calibration the flux instrument is nevertheless convenient for rapidly comparing disks of oriented polycrystalline silicon-iron with a single crystal disk of the same dimensions. The emf from the pick-up coils is integrated electronically and displayed on an oscilloscope. Some torque curves do not have the exact form of the curve of a single crystal. For this reason, comparison signals of frequencies 60 cps and 120 cps with controllable amplitude and phase are provided so that all components of the signal may be measured.

1. S. Siegel, Phys. Rev. 61, 390 (1942).
2. J. K. Stanley, AIME Technical Publication 1635 (1943).

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108. MAGNETIC DOMAIN MOTION OBSERVED BY ELECTRON MIRROR MICROSCOPY

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Following a brief introduction to the basic physics of electron mirror microscopy and its application in magnetic investigations, recent results are reported. It is shown that electron mirror microscopy reveals magnetic domain structures not only on magnetic materials having a uniaxial direction of easy magnetization but also on materials exhibiting basically flux closure domain configurations. Image contrast formation with these materials having several directions of easy magnetization is less satisfactory, however, than in materials in which inhibition of flux closure leaves large surface densities of free magnetic poles. Magnetic image contrast is formed by the component of the magnetic field normal to the surface acting on the radial component of the electron's velocity. This fact leads to somewhat distorted images with a definite preference in magnetic image contrast for magnetic elements of radial extension if the normal component of the magnetic field is weak or of narrow extension. There might still be some advantage, however, in utilizing electron mirror microscopy even for the observation of magnetic domains in materials of this type, particularly in cases where the study of magnetic domain motion is desirable or for investigations at temperatures which exclude domain observation by conventional methods. Observation of domain evolution and domain movements near the Curie-point might be another application for electron mirror microscopy. To demonstrate observation of domain motion and to present for discussion the electron mirror microscope's merits and shortcomings in regard to magnetic studies, a motion picture of the movements in the domain patterns of silicon iron is shown as photographed from the screen of the electron mirror microscope.

SESSION VII-A

THIN FILMS

C. J. KRIESSMAN, Presiding

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109. PARTIAL SWITCHING OF THIN PERMALLOY FILMS

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The switching processes in thin permalloy films have been investigated by means of partial switching. A short, rectangular magnetic field pulse was produced at the film sample, followed by a longer pulse of equal amplitude. The polarity of this pulse sequence was then reversed to return the film to its original state of saturation. These magnetic field pluses were parallel to the uniaxial axis of anisotropy in the plane of the film, and the d.c. transverse magnetic field was also zero.

The duration of the shorter magnetic field pulse for a given pulse amplitude was adjusted to be shorter than the time required for a complete reversal of the film. It was then found that the film remained in a partially reversed state until the following pulse completed the reversal. These partial switching processes were observed as voltage transients induced on a balanced pick-up loop surrounding the film.

Voltage transients obtained in this way indicated that the process responsible for the slower reversals was different from that which predominated at higher speeds. The transition between these two regions occurred when the pulsed field amplitude was made approximately $\frac{2K}{M_S}$, the uniaxial anisotropy field of the film. For the pulses less than $\frac{2K}{M_S}$, the partial switching results were consistent with a domain wall motion model. However for pulses greater than $\frac{2K}{M_S}$, the results were consistent neither with simple domain wall motion nor with coherent rotation. This fact is presented as further experimental evidence indicating the existence of a third type of reversal process.

The domain structure of these partially switched states has been observed through use of the Kerr Mangeto-optic effect. Details of this structure will be given, and further implications of the partial switching results will be discussed.

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110. ROTATIONAL HYSTERESIS IN THIN FILMS

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Rotational losses in films of nickel-iron have been studied over a wide range of frequencies and applied fields by means of the rotating-field experiment, which consists in measuring the torque exerted on a thin ferromagnetic sample by a uniformly rotating magnetic field. The experimental techniques used were designed to minimize spurious torques caused by electrical forces acting on the sample holder, by stray magnetic fields, and by distortions of the rotating-field locus (anisotropy-field-locus effect). Experiments employing rotational velocities from 10 cps to 4 mc and field intensities from zero to 100 oersteds were performed on films from 70% to 90% in nickel content, from 400 Å to 12,000 Å in thickness, and from 2 to 30 oe in rotational coercivity.

For applied fields less than the maximum anisotropy field 2 K/M, the observed losses agree well with the theory of rotational hysteresis in materials with uniaxial anisotropy. When combined with standard torque or hysteresis loop data, these losses yield information regarding the uniformity of the effective anisotropy within the sample. In fields considerably greater than 2 K/M the loss per cycle for any given sample is found to be independent of the rotational frequency, for frequencies at least as great as 1 mc. According to the analysis of Gilbert and Kelly, the high-field losses should be proportional to the instrinsic damping parameter, so that these experimental results would imply an inverse frequency dependence of the damping parameter. The observed high field loss varies greatly from one sample to another; however, it has been found that the ratio of this loss to the maximum loss occuring at $H=\frac{K}{M}$ varies only slightly from sample to sample. It has further been found, in auxiliary experiments designed to detect the instantaneous changes in magnetization, that the irreversible mechanism associated with low-field hysteresis does not completely vanish for $H > 2$ K/M as would be predicted by the simple theory. These results indicate that, over most of the frequency range investigated, the high-field losses are of essentially the same origin as the low-field losses and are not a measure of the instrinsic rotational damping.

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111. A STUDY OF SLOW WALL MOTION SWITCHING OF THIN VACUUM DEPOSITED IRON-NICKEL FILMS

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A study has been made of the wall motion velocity in a selected group of vacuum deposited films composed of 82 to 83% nickel and the rest iron deposited on a hot glass substrate in a magnetic field to impart a uniaxial magnetic anisotropy. The primary studies were made with an apparatus which permitted observations over a moderate temperature range or angle of the domain patterns on these deposited films using the Kerr magneto-optical technique. These studies were supplemented with measurements on the deposited films in the 60-cycle hysteresis loop display apparatus, a check on the magnetostriction properties, studies of the chemical composition and rotational switching properties and surface studies using a metallographic microscope. The films selected for study were all made in the same vacuum system under somewhat different conditions but were characterized by the fact that they exhibited a remarkably rectangular hysteresis loop both in the Kerr apparatus and on the 60-cycle loop apparatus. In the type of film selected for study, once a domain wall or walls have been nucleated they move to saturation without further increase in the nucleating field applied in the "easy" direction; that is, the nucleation field, coercive field and saturation field are identical. Films of this type have been found to exhibit a wide range of wall velocities from very fast (>>1 cm/sec) to very slow (<1 cm/hr). This wall motion velocity has been found to increase with increasing drive field ($H-H_c$) and to increase rapidly with increasing temperature. These data have been compared with reported expressions for the switch time as a function of the applied driving field and the applied termperature. There is frequently a large anisotropy in the wall velocity for the two magnetic senses in the easy direction and the reason for this phenomenon has not been completely explained. The fact that the pattern of nucleated domain walls is different in these two cases certainly plays a role. In the type of film studied, wall motion normally proceeds with few if any observable Barkhausen jumps. This is in sharp contrast to other deposited magnetic films. Apparently there is an absense of non-uniform inclusions of high average potential energy in a film of this type. At higher temperatures the increased thermal energy apparently is sufficient to overcome much of the interaction between the wall and any inclusions that may be present. The factors necessary for the production of this type of film have not been completely established even though most of these films were made in one particular system capable of a lower ultimate vacuum than our normal systems. These films appear to be no more free of physical defects or composition variation than any other group of films.

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112. STRESS ANISOTROPY IN Ni-Fe THIN FILMS

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Stress systems, existing in evaporated magnetic Ni-Fe thin films, arise from a number of physical factors introduced during the deposition process such as 1) a planar tension system due to a differential contraction caused by the difference in the coefficients of thermal expansion of the metal and the glass substrate; 2) a stress system due to inherent impurities and imperfections; and 3) either a compression or tension system arising from magnetostriction as induced by a magnetic field on cooling from the substrate temperature to room temperature. All stresses will effect magnetostrictively the magnetic properties of the film.

The effective domain anisotropy energy of Baltzer[1] has been extended by a directional averaging process to the simple model: a Ni-Fe thin film of randomly oriented cubic micro-crystals with a linear and a planar stress system. The resulting average energy,

$$\overline{U}_\alpha = \frac{(K_1)\text{eff}}{5} + \frac{(K_2)\text{eff}}{105} - \sigma\left(\frac{\Lambda}{10} + \frac{4h_4+h_5}{35}\right)\left(3\cos^2\phi\cos^2\psi - 1\right) + \pi\left[\left(\frac{\Lambda}{10}+\frac{h_5}{35}\right)\left(3\sin^2\psi - 1\right) + \frac{2h_4}{105}\left(18\sin^2\psi - 1\right)\right]$$

where σ is the linear stress, π an isotropic planar stress, $\Lambda = 2\ \lambda 100 + 3\ \lambda 111$, $\lambda 100$, $\lambda 111$, h_4 and h_5 being the usual magnetostriction constants, and ϕ and $\psi = 90^o - \theta$ are the spherical polar coordinate angles of the magnetization, $\underset{\sim}{M}$, with subsequent experimental evaluation indicates that the magnetic anisotropy observed in Ni-Fe thin films is dependent to a large extent upon the induced planar and linear stress patterns.

Energy equilibrium conditions state that the average effective rotational anisotropy field is $Hs = 3\sigma \Delta/5M$, and also lead to a qualitative explanation of the directional hysteresis loops observed in the films. Utilizing the single crystal magnetostriction and effective anisotropy constants of Bozorth and Walker[2], predictions of the anisotropy fields are in qualitative agreement with measured values.

1. Baltzer, P. K., Phys. Rev., 106, 890 (1957)
2. Bozorth, R. M. and Walker, J. G., Phys. Rev., 89, 624 (1953)

113. ANISOTROPY AND COERCIVITY IN THIN FILMS

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An arbitrary classification of thin films into three types may be made on the basis of the relative values of the anisotropy field, H_K, and the intrinsic coercive force of the material, H_C. These three types are:

(a) $H_K > H_C$

(b) $H_K = 0$

(c) $H_K < H_C$

In case (a) the magnetization will seek the easy direction in the absence of an applied field and the film will have a rectangular hysteresis loop in the easy direction only. This is the behavior observed for the most commonly used nickel iron thin films. Certain films have isotropic magnetic properties in all directions. The magnetization in such films will remain in any direction to which it is moved by a field larger than the coercive force. These films are therefore classified as $H_K = 0$ films. The third type of film has rectangular hysteresis loops in all directions but different apparent coercive forces, H_F, in different directions. The apparent coercive force as a function of angle is given by

$$H_F = H_K \cos^2\theta + \left[H_K 2(\cos^4\theta - \cos 2\theta) + H_C{}^2 \right]^{1/2}$$

where $H_K = 2K/M_s$ and K is the first anisotropy constant. Experimental data is found to agree with this expression.

114. ANISOTROPY IN PERMALLOY FILMS*

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Evaporated films of Permalloy are found to be uniaxially anistropic under all the conditions of preparation studied so far, including deposition in D.C., zero, and rotating-circular magnetic fields. At least five different mechanisms have been identified as contributing to this anisotropy, namely: 1) the formation of directed Fe pairs in the Ni matrix, 2) isotropic stress acting on the directed Fe pairs, 3) anisotropic stress in combination with the isotropic magnetostriction, 4) thickness gradients leading to anisotropic demagnetizing energy, and 5) residual domains which exert a torque on the remanent magnetization. The evidence for directed pairs comes from the compositional dependence of the anisotropy; isotropic stress is observed by the mechanical bending of thin substrates and the magnetic effect is demonstrated by stripping the film intact from the substrate and measuring the change in anisotropy; the contribution from anisotropic stress is again demonstrated by the stripping experiment, which shows a minimum at the composition corresponding to zero isotropic magnetostriction; thickness gradients, measured by interferometry, are the source of the anisotropy which appears in films deposited in rotating circular fields; the effect of residual domains is demonstrated by the different value of anisotropy obtained when measured by a) initial susceptibility (domains present) and b) ferromagnetic resonance in a D. C. field (domains absent).

The simultaneous presence and interaction of the above effects is thought to be the reason for the lack of reproducibility of the anisotropy which is encountered in Permalloy films.

* The research in this document was supported by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

115. MAGNETIC EFFECTS OF ISOTROPIC STRESS IN PERMALLOY FILMS*

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Evaporated Permalloy films are found to be in a state of isotropic planar tension. The magnitude of this tension has been measured and correlated to an unusual magnetic phenomenon for compositions having negative magnetostriction. For such films the isotropic stress intorduces a magnetic anisotropy which favors the film normal; simultaneously, shape anisotropy causes $\vec{M}$ to strongly favor the plane of the film. It is found that the ratio of stress induced anisotropy to shape anisotropy need only be 1/2 percent for a new domain structure to form above a certain critical thickness. The details of this structure are not yet completely known, but it has the following properties: 1) The coercive force increases by an order of magnitude, 2) the remanant flux per unit of thickness decreases linearly with increasing thickness, 3) the Bitter pattern shows a characteristic "mottled" appearance and no wall switching can be observed, 4) certain relaxation effects are observed in the hysteresis loop which are thought to be due to interactions between domains.

Upon freeing such films from their substrates by means of a stripping technique, all such anomalous effects disappear. The film behaves normally, including the appearance of "cross-tie" walls and the full value of remanent flux.

* The research in this document was supported by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

116. ANISOTROPY FIELD MEASUREMENTS ON Ni-Fe THIN FILMS

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Rotation anisotropy fields have been determined in vacuum deposited permalloy films using pulsed external fields. The signal producing field is applied at right angles to the direction of easy magnetization, while the effective reset field is applied at a variable acute angle to the direction of easy magnetization. A special type of permeability curve is constructed using the integrated output signal. Values of the effective rotation anisotropy and the distribution of the anisotropy are determined from this curve. Results of the pulse measurements are compared with information from static and 60 cycle experiments.

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117. MAGNETO-OPTICAL STUDY OF THE BARKHAUSEN EFFECT IN EVAPORATED NICKEL IRON FILMS

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The Kerr magneto-optical rotation has been combined with a phototube sensing mechanism for the observation of magnetization reversals in evaporated nickel-iron films. An independent hysteresis loop for any region of the film may be obtained by suitably varying the light spot size and location, and considerable detail is achieved in each hysteresis loop since a signal to noise ratio of better than 100 to 1 is possible with a band pass of one kilocycle and a light spot of one square millimeter.

Using this technique, a statistical study of Barkhausen jumps in evaporated nickel-iron films has been made. Individual domain wall segments sweeping through the film are found to stop at some locations more frequently than at others; however, the pattern of stopping places in any one reversal is not predictable. The distribution of jump sizes in a large number of reversals is well described by $N/N_0 = e^{-\tau M^{1/n}}$ where N/N_0 is the fraction of jumps larger than M, and and n are film dependent parameters. This distribution is the same as has been obtained for wires by previous workers[1], but the nearness of n to one in films suggests that the statistical distribution may be derived from a simple model of wall motion in which the probability of a wall stopping in an interval of distance dx is equal to τ dx.

1. R. S. Tebble and V. L. Newhouse, Proc. Roy. Soc. B66, 633-41, (1953).

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118. SOME OBSERVATIONS ON EVAPORATED PERMALLOY FILMS

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Permalloy-type films prepared by evaporation in vacuo have been studied in some detail regarding their chemical and physical characteristics. This paper presents the preliminary results of this work, showing and discussing the observed chemical heterogeneity, impurities, internal strains, imperfections, and surface roughness. Analytical techniques developed and employed for this work are briefly discussed.

Also reported are observations made on the effects of applied strains on magnetostrictive films during pulse testing, and those on the results of magnetic annealing with various orienting fields. It has been noted that the net effect of applied strains are similiar to those of transverse fields as shown by kinetic data for magnetization reversals. In addition, annealing films at 300 C with fields applied at 90 degrees to the original direction of easy magnetization and in the plane of the films establishes new preferred directions, and results in reduction and leveling of the anisotropy field values of these films. Hysteresis and pulse data are presented to show the changes incurred with magnetic annealing.

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119. STRUCTURAL AND MAGNETIC PROPERTIES OF PERMALLOY FILMS

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Insufficient control over the numerous parameters associated with thin nickel-iron film deposition has prevented a firm substantiation of many of the theories pertaining to the origin of their magnetic properties. Not the least important of these theories was presented by Neel to explain the dependence of wall motion coercive force on surface roughness and thickness. Variations in such properties as strain and composition can obscure the effects upon which this theory is based. Electroplating techniques, however, have been developed which allow better control over these factors and a series of experiments were performed to investigate the dependence of the wall motion coercive force (H_c) upon surface roughness, thickness (t) and chemical composition. The results of these experiments are discussed in the light of the theoretical supposition that the energy of the wall is a sum of exchange, demagnetizing, and anisotropic energies. A comparison of the experimental results is made with Néel's prediction that $H_c = Ct^{-4/3}$. The proportionality constant, C, is shown experimentially to depend critically on the surface roughness, whereas rotational threshold field is independent of surface roughness.

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120. THE INFLUENCES OF SUBSTRATE PROCESSING ON THE MAGNETIC PROPERTIES AND REPRODUCIBILITY OF EVAPORATED NICKEL-IRON FILMS

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Numerous evaporations of nickel-iron films having an average composition of 80 per cent nickel and 20 per cent iron have been performed in a commercial bell jar system on soft glass substrates. Initially, large differences were found among the several magnetic properties. Statistical analysis was employed to investigate the variation of the properties within a run and from one run to another, maintaining the evaporation parameters as constant as possible. When no dependence of wall motion threshold on thickness could be established, it was concluded that influences other than the evaporation parameters were predominant. It was felt that the major influence was the substrate and its processing prior to evaporation. Therefore, several techniques have been tried to minimize these effects. These techniques include chemical cleaning with and without ultrasonic agitation, annealing of the substrate and evaporation of Si O undercoating. It is shown in the paper, that both wall motion and rotational thresholds have been decreased, and also that the standard deviation has decreased. Furthermore, these techniques have permitted a correlation of wall motion threshold with thickness. When plotting the average wall motion threshold (for the bits within a plane) versus the thickness (as represented by the output voltage obtained from a hysteresis loop tracer) on double loganthmic paper a straight line may be plotted, indicating the degree of reproducibility obtainable.

SESSION VII-B

NEUTRON DIFFRACTION AND IRRADIATION

J. S. SMART, Presiding

121. NEUTRON DIFFRACTION INVESTIGATIONS OF MAGNETIC PHENOMENA IN CRYSTALLINE COMPOUNDS (Invited Paper)

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The general characteristics of neutron diffraction investigations of magnetic materials will be reviewed in this paper, and the types of information that can be obtained from these investigations will be illustrated by recent experiments on antiferromagnetic compounds. Since some of these compounds have magnetic ordering transitions at very low temperatures, it has been necessary to develop the single crystal technique for use in the liquid helium temperature region. Furthermore, the application of an external magnetic field to the samples has been very beneficial in determining some of their magnetic properties. Many of the antiferromagnetic structures require an indirect coupling of the magnetic electrons via non-magnetic ions, so that information has been obtained pertinent to the mechanisms involved in the coupling processes. The nature of the magnetic ordering transitions has also been investigated, and observations have been made on the behavior of antiferromagnetic domains in an applied magnetic field.

122. SYMMETRY OF MAGNETIC STRUCTURES*

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One of the principle objectives of the neutron diffraction study of magnetic materials is the detailed description of magnetic structures in terms of the magnitude, position, and spin orientation of individual magnetic atoms as well as the positions of non-magnetic atoms. Trial and error procedures have proved generally successful in the description of relatively simple structures but are inadequate for the solution of complex structures and may fail to reveal the finer details in simple structures.

The most complete description of magnetic structure is given by the magnetic space group. The transformation properties of magnetic moments under symmetry and antisymmetry operations lead to 1651 possible magnetic groups. These transformation properties are discussed and a systematic procedure for magnetic structure determination is described, which takes into account the restrictions imposed on spin direction by space groups. The space group approach, in addition, exhibits atomic displacements which may be related to magnetic interactions. The general principles of the application of space groups to magnetic structures are illustrated by recent results on several anti-ferromagnetic compounds.

*Research performed under the auspices of the U.S. Atomic Energy Commission.

123. NEUTRON DIFFRACTION INVESTIGATION OF A POSSIBLE FERRO-ANTIFERROMAGNETIC PHASE TRANSITION IN $Mn_{0.2}Cr_{0.8}Sb$*

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R. NATHANS
Pennsylvania State University and Brookhaven National Laboratory

The magnetic properties of some mixed antimonides with the NiAs structure (chemical formula: $Mn_{1-x}Cr_xSb$) have been investigated by Lotgering and Gorter[1] and by Hirone et al[2]. These solid solutions of antiferromagnetic CrSb and ferromagnetic MnSb are characterized by unusual magnetic susceptibilities, and the measurements indicate that a phase change from the antiferromagnetic to the ferromagnetic state may be occuring in the composition range x = 0.7 - 0.9. Powder neutron diffraction patterns, which should offer evidence for such changes, have been taken on MnSb (T_C = 590°K) and $Mn_{.2}Cr_{.8}Sb$ (T_N = 600°K; T_C = 120°K). The structure of antiferromagnetic CrSb, already established by Snow[3], has hexagonal layers of ferromagnetically coupled Cr spins with alternating layers antiparallel, the spin direction being the hexagonal c axis. Room temperature patterns of MnSb show that the layers of Mn spins are ferromagnetically coupled and also have the spin along the c direction. The room temperature data on $Mn_{.2}Cr_{.8}Sb$ confirm that this material is antiferromagnetic, its structure being of the CrSb type, and exclude any nuclear ordering of the Mn and Cr atoms on the lattice positions. At liquid helium temperature the neutron data exhibit a number of weak additional lines, the main group of reflections remaining essentially unchanged. The smallest unit cell on which these additional peaks can be indexed requires that the a axis be tripled. While it is doubtful that the extra peaks are sufficient to obtain a unique spin structure, their very appearance would seem to rule out the suggestion of Lotgering and Gorter that the Mn spins acting independently of the Cr are responsible for the ferromagnetism. Such behavior should result in short range order, in view of the fact that the Mn atoms are not ordered on the crystallographic positions and are not likely to become so at the Curie point. On the other hand, Hirone and Adachi[4] have suggested an angular arrangement of spins with a magnetic unit cell the same as given by the neutron data. If this model is correct, and the deviation from the CrSb structure is small, one would indeed expect the extra reflections to be weak and the fundamental diffraction peaks to be changed only slightly.

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* This work was carried out at Brookhaven National Laboratory under the auspices of the Atomic Energy Commission and the National Security Agency.

1. F. K. Lotgering and E. W. Gorter, J. Phys. Chem. Solids 3 (1957) 238
2. T. Hirone, S. Maeda, I. Tsubokawa and N. Tsuya, J. Phys. Soc. Japan 11 (1956) 1083
3. A. I. Snow, Phys. Rev. 85, (1952) 365
4. T. Hirone and K. Adachi, J. Phys. Soc. Japan 12 (1957) 156

124. THE EFFECT OF NEUTRON IRRADIATION ON THE MAGNETIC PROPERTIES AND DEGREE OF ORDER OF MAGNETIC METAL ALLOYS

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The effect of neutron irradiation on the magnetic properties and degree of order have been studied for a selected series of commercially available magnetic metal alloys. All of the alloys are characterized by compositions approximating Ni_3Fe and NiFe plus additions of either silicon or molybdenum and are known to undergo order-disorder transformations. Since the ordering temperatures for these materials were not available selected thermal treatments were made which indicated the ordering temperatures for all the materials to be between 400°C and 700°C. The samples in the shape of toroids were thermally annealed to various states of order and assembled with magnetizing and flux coils attached. Then 60 cycle hysteresis loops were made, and the stage of ordering process attained was inferred from the shapes of these curves[1]. The samples were then irradiated at the Brookhaven graphite reactor for one month at temperatures not exceeding 90°C and hysteresis loops were again obtained. Significant changes occurred in the magnetic characteristics of all the samples indicating considerable effects on the degree of final order. In some cases it appeared that long range order resulted from the neutron irradiation.

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1. S. Kaya, Rev. Mod. Phys. 25, 49 (1953).

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125. IN-PILE MEASUREMENTS OF RADIATION EFFECTS IN MAGNETIC MATERIALS

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Experiments have been performed to determine the effects of nuclear reactor radiation upon the characteristics of ferrites and metallic magnetic materials. Measurements were made at Brookhaven National Laboratory. Photographs of 60 cycle hysteresis loops and bridge measurements of 1000 cycle inductance were made before irradiation, periodically during irradiation, and after reactor shutdown. The samples were irradiated for 11 days, resulting in an integrated fast flux of 1.6×10^{17} neutrons/cm^2.

No permanent effect was observed in any ferrite. In-pile changes in ferrite properties are attributed to temperature changes which resulted from gamma ray absorption.

Permanent damage was observed in all metallic samples tested. Supermendur and Deltamax were least affected, showing increases of the order of 50 per cent in coercive force and small decreases in initial permeability. Various samples of 4-79 Mo-Permalloy were affected differently, but all showed change in shape of hysteresis loops, several hundred per cent increase in coercive force, and about 80 per cent decrease in initial permeability. Supermalloy was most damaged by radiation, showing marked effects after 24 hours, and progressively greater effects throughout the exposure period.

126. THE REDUCTION OF MAGNETIZATION OF γ-Fe_2O_3 AND Fe_3O_4 BY PILE IRRADIATION

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Washington, D. C.

When substances are exposed to radiation the magnetic properties may undergo marked changes, due to (1) creation of magnetic species, (2) reduction of magnetic species, and (3) redistribution of existing atoms. In view of this, the saturation magnetization has been measured on samples of gamma iron oxide III and magnetite before and after exposure to pile irradiation. The saturation magnetization decreased from 1.18 to 1.14 Bohr magnetons per atom of iron in the γ-Fe_2O_3 and from 1.26 to 1.08 Bohr magnetons per atom of iron in the magnetite. The total exposure time was 30 days. The reactor operated at 14 megawatts for 7779 megawatt-hours. The flux of thermal neutrons was 2.72×10^{12} per second with an integrated flux of 5.4×10^{18} neutrons.

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127. RADIATION EFFECTS ON THE ANISOTROPY OF SINGLE CRYSTALS OF SEVERAL SOFT MAGNETIC MATERIALS INCLUDING ALLOYS OF NiFe, SiFe, AND AlFe*

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Radiation damage effects on the anisotropy and magnetostriction of single crystals of a number of soft magnetic materials are being studied.

Magnetic anisotropy and magnetostriction tests prior to irradiation were run on crystals of iron, nickel, alloys of nickel-iron, silicon-iron, and aluminum iron, and several other materials. The latter include crystals of magnetite and alloys in the systems cobalt-nickel, cobalt-iron, nickel-cobalt-iron, molybdenum-nickel-iron, and molybdenum-aluminum-iron. These crystals represent pure metals, random solid solution alloys, and order-disorder alloys both in the ordered and disordered state.

The crystals have been irradiated in an air-cooled hole of the nuclear pile at the Brookhaven National Laboratory. The dosage was about 1.7×10^{18} total neutrons per square centimeter.

Magnetic tests subsequent to the irradiation are being performed in a hot cell by remote control. The instrumentation for these measurements will be presented in a separate paper. In the present paper preliminary results of the radiation damage effects on crystal anisotropy will be discussed. Radiation effects on magnetostriction will be considered if data has become available by conference time.

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SESSION VIII-A

GARNETS AND OTHER COMPOUNDS

M. E. CASPARI, Presiding

128. MAGNETIC PROPERTIES OF THE RARE EARTH GARNETS (Invited Paper)

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The rare earth ferrites with the garnet structure, discovered in 1954 at the Laboratoire d'Electrostatique et de Physique du Metal at Grenoble, have interesting magnetic properties which stimulated a great deal of fundamental and applied research. The author has demonstrated the existence of two rare earth ferrites. The first, with the composition $Fe_2O_3.M_2O_3$ has the perovskite structure, and the second, with the composition $5Fe_2O_3.3M_2O_3$ has the garnet structure. The properties of the garnets are described and some information on the preparation and crystal structure of these compounds is presented. At a fixed temperature the magnetization is, in general, the sum of a ferromagnetic and a paramagnetic term. The variation with temperature of the spontaneous magnetization of the ferromagnetic term shows a compensation point for the garnets of Gd, Tb, Dy, Ho, Er, Tm. The Curie points of these compounds are approximately 550°K. The magnetic properties of these compounds can be interpreted in terms of a ferrimagnetic behavior of the iron ions on the sublattices a and b; the resultant magnetization of these ions is coupled ferrimagnetically with the magnetization of the rare earth ions on the sublattice c. This model has been investigated by neutron diffraction. The values of the magnetizations at absolute saturation show that the moments of the rare earth ions must be partially quenched at low temperatures. Values are given for the coefficients of the molecular field, which represent the strength for the different interactions between the magnetic ions. Some magnetic properties of substituted garnets and some results of ferrimagnetic resonance experiments are discussed. In conclusion the author describes some applications of these new materials and some new information which the study of these compounds has added to the subject of magnetism.

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129. MAGNETIC ANNEALING OF YTTRIUM IRON GARNET

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The hysteresis loops, at liquid nitrogen temperature, of certain polycrystalline cores of yttrium iron garnet are drastically affected by the application of a large magnetic field to the core as it is cooled. In order to obtain yttrium iron garnet cores which exhibit this annealing effect, the preparation conditions must be carefully controlled. The cores must be quenched rapidly from a high firing temperature (1430° or 1450°C.). The annealed state is established by passing sufficient current (either d.c. or 60 cps.) through a winding on the toroid to produce a field of approximately ten times the coercive force in the core. When the cores reaches -195° C and the a.c. annealing field is slowly reduced to zero, the core is left in a remanent state and cannot be demagnetized. As the field is increased, the hysteresis loop initially is a straight line. At a critical value of the field, the loop abruptly opens. The reversal of the magnetization of an annealed yttrium iron garnet core involves a nucleation process which requires a larger magnetic field than is needed during the remainder of the reversal. The switching speeds of these annealed cores are slow, values of the switching parameter S_W ranging from 10 to 40 oersted-microseconds. The reversible permeability of annealed cores is approximately 12 at remanence and changes only slightly as a superposed d.c. bias field is varied. The permeability at remanence is independent of frequency up to 100 mc. Any domain walls which may be present in the annealed cores apparently do not move under the influence of small changes in magnetic field.

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130. TEMPERATURE DEPENDENT LAG IN POLYCRYSTALLINE YTTRIUM-IRON GARNET*

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Magnetic relaxation phenomena similar to those occurring in certain nickel-zinc and magnesium ferrites[1,2] have been observed in dense specimens of polycrystalline yttrium-iron garnet (YIG). Room temperature measurements of complex initial permeability show two well defined regions of dispersion. The principal one, centered at lmc and covering about two decades in frequency, we identify with a domain wall relaxation process. A second region of dispersion, less than a decade wide, occurs at about 300 mc, and is presumably gyromagnetic in origin. Chief interest, at the moment, is centered on the lower-frequency dispersion.

The radio-frequency branch of the spectrum, when plotted as a Cole-Cole[3] diagram, conforms to a circular arc. From this plot, we conclude that 75 per cent of the static initial permeability ($105\mu_0$) is due to wall displacements, the remainder to the reorientation process.

The radio-frequency dispersion can be represented by a simple relaxation expression modified to include a logarithmically symmetric distribution of relaxation time constants. To fit the data a 5:1 range of time constants is needed; this spread in τ is a factor 20 to 30 times smaller than required to explain similar relaxation effects in polycrystalline nickel-zinc ferrites[1].

As in the nickel-zinc and magnesium ferrites, wall dispersion in the garnet is strongly temperature dependent. The effect of temperature was studied by making a series of permeability runs as a function of temperature at several fixed r.f. frequencies, and observing the shift in the maximum of the magnetic loss tangent ($\tan \delta_m$) as a function of frequency and temperature. This shift proceeds according to the relation $\nu = c \exp\left[-U/kT_m\right]$ where ν is the measuring frequency, c is a constant and T_m is the temperature at which the maximum in $\tan \delta_m$ occurs. The activation energy U is found to be 0.25ev, a value which suggests that, as in the ferrites, the activation is associated with electron diffusion.

At liquid nitrogen temperature extremely slow magnetic switching is observed. The switching behavior appears to be very sensitive to thermal and magnetic prehistory.

Measurements of electric resistivity and dielectric permittivity will also be reported.

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131. MAGNETIC-ION INTERACTION IN $Gd_3Mn_2Ge_2GaO_{12}$ AND RELATED GARNETS

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The existence of appreciable (a)-(c) antiferromagnetic exchange interaction in the garnet structure has been established by the observation of ferrimagnetism in $\{Gd_3\}[Mn_2](Ge_2Ga)O_{12}$. (The dodecahedral, or 24(c), ions are enclosed by $\{\ \}$, the octahedral, or 16(a), ions by [ ] and the tetrahedral, or 24(d), ions by ( ).) The Neel temperature is about 8°K; the $1/\chi$ vs. T curve is linear for T 35°K with an intercept of -8°K at $1/\chi = 0$ and a Curie constant of $5.6 \cdot 10^{-3}$ B deg./oersted. The magnetic moment at 0°K probably correspond to $3n_B \{Gd^{3+}\} - 2n_B [Mn^{2+}] = 11$ because the moments observed at temperatures between 4.2 and 1.5°K extrapolate to not less than $9.6\mu_B$ at 0°K. The moment decreases for the compositions, $\{MnGd_2\}[Mn_2](Ge_3)O_{12}$ and $\{CaGd_2\}[Mn_2](Ge_3)O_{12}$, in that order. In these three cases the $1/\chi$ vs. T curves are concave downward below 20°K, as would be expected in the case of ferrimagnetism.

No spontaneous magnetization is observed in $\{MnY_2\}[Mn_2](Ge_3)O_{12}$ and $\{CaY_2\}[Mn_2](Ge_3)O_{12}$ down to 1.3°K. For these compounds the $1/\chi$ vs. T curve is concave upward below 20°K as would be expected for a weak (a)-(a) antiferromagnetic interaction. Only a very weak (a)-(c) interaction is present in the first case as a consequence of one-third occupancy of dodecahedral sites by Mn^{2+} ions.

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132. SOME ELECTRICAL AND MAGNETIC PROPERTIES OF GARNETS

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Measurements of lattice constants, magnetic moments and d.c. conductivity have been made on polycrystalline yttrium-iron garnets (YIG) and several other garnets containing partial substitutions for either yttrium or iron. In addition, data is given on the frequency variation of the permeability and permittivity from d.c. to the microwave region. The latter measurements were made on toroidal specimens of rectangular cross section. Windings were used below 10 mc/s for the permeability measurements and a parallel-plate capacitor was used for the low-frequency dielectric constant measurements. Coaxial lines were used at high frequencies. Conductivity measurements were made by applying electrodes to the two flat faces of the specimens.

The changes observed in the Curie temperature, magnetic moment and lattice constant due to gallium substitution are in agreement with values previously reported by Gilleo and Geller.[1] In the case of holmium and dysprosium substitutions for yttrium, no change in lattice constant or Curie temperature was noted when as much as 16% of the yttrium was replaced. However, the magnetic moment decreased about 28% when 16% of the yttrium was replaced by magnetic ions whose moments are aligned anti-parallel with the net moment due to the iron ions.

The substitution of Ga for 12% of the Fe increased the d.c. conductivity by approximately two orders of magnitude while it lowered the low-frequency permeability and dielectric constant. No significant changes in the permeability and permittivity were observed when 9% of the yttrium was replaced by holmium.

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133. EVIDENCE FOR TRIANGULAR MOMENT ARRANGEMENTS IN $MO.Mn_2O_3$

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The spontaneous magnetization at absolute zero of a number of ferrimagnetic compounds with spinel-type structure is significantly lower than predicted by the simple Neel model with tetrahedral A-site moments antiparallel to octahedral B-site moments. An explanation may be found in the suggestion by Yafet and Kittel of triangular arrangements. Specifically they noted that when A-A or B-B antiparallel interactions are comparable to the A-B interaction, the moments on the A or B sites will divide into two parts, making an angle with each other, but with the resultant moment antiparallel to the moments on the other kind of site (B or A). Direct evidence for this triangular moment arrangement has been difficult to obtain. A consequence of this moment arrangement is that at fields higher than those required for ferrimagnetic domain alignment there should be a linear increase in the net magnetization with field. This high field susceptibility is absent in the simple antiparallel ferrimagnetic arrangement. Measurements of magnetization curves at 4.2°K in pulsed field up to 140 kilooersteds show this susceptibility in several compounds and thus directly measure the strength of the B-B (or A-A) interaction. The compounds studied are Mn_3O_4 and manganites of Zn and of Co. The observed variation of spontaneous moment with composition may be roughly predicted by a molecular field model with simple assumptions. In this interpretation the magnitude of the net A-site moment in Mn_3O_4 is greater than the net B-site moment and the B-site moments are subdivided. The spontaneous magnetization of Mn_3O_4 is 1.60 ± 0.07 Bohr magnetons per molecule. The observed high field susceptibilities are in approximate agreement with predictions based on Bongers' data of high temperature susceptibility in isomorphous antiferromagnetic manganites; i.e., a volume susceptibility of $3 \pm 1 \times 10^{-4}$ c.g.s.

134. THERMOMAGNETIC BEHAVIOR OF NICKEL OXIDE

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This study is concerned with the thermomagnetic properties of pure nickel oxide, and nickel oxide containing foreign cations dissolved into its lattice.

Polycrystalline samples of nickel oxide, which did not contain any ferromagnetic impurity and with known thermoelectric behavior, were sealed in vacuum at room temperature in quartz vessels and subjected to magnetic susceptibility determinations by the Faraday method. The initial heating cycle was performed at increasing temperatures from 80 to 1000° K.

Pure nickel oxide, with an excess oxygen of $\leqslant 0.013\%$, was found to have a maximum value of the susceptibility at $\approx 660°$K. Below this temperature the susceptibility was field dependent and showed typical antiferromagnetic behavior; above 660° K the susceptibility was found independent of the field (3,200 to 6,100 Oe.). Between 800 and 1308°K the susceptibility may be represented by means of the relationship $\chi(T+\Delta) = const, \Delta \cong 3{,}000$ K. It is possible that a volume anomaly sets in at $\approx 800°$K.

The solid solution $Mg_{0.01}\ Ni_{0.99}\ O_{1.003}$ was found to have a susceptibility independent of the magnetic field (2,000 to 7,700 Oe, 84 to 1526 K) and showed a maximum value of the susceptibility at about 625° K. Above 850° K the susceptibility behavior was found similar to that of pure NiO. At lower temperatures, the susceptibility was very much affected by the thermal history of the sample and varied up to 10% at 268°K. When the solid solution was quenched from a temperature T_t in a magnetic field H_t, it acquired a residual magnetization, σ, which could be controlled at will and vanished for $T \leqslant T_C - 543$ K. The relationship $\sigma_t = f(H_t)\ T_t$ and $G_t = f(T_t)\ H_t$ are well defined. The effective temperature range for quenching was 425 to 543 for $H_t =$ 7,550 Oe and $T = 286°$ K. The residual magnetization did not increase for $T_t > T_C$, and did not set in whenever H_t was removed before reaching $T_C = 543°$ K. This residual magnetization is quite weak for pure, nearly stoichiometric, nickel oxide. It was also observed in several antiferromagnetic compounds (Pd_3Mn_2, CrSb, $CoCl_2$), and it seems to be characteristic of the Neel transition.

Solid solutions $Li_xNi_{1-x}O$, where $0.01 \leqslant x \leqslant 0.3$, showed a magnetic phase with density increasing with x and a ferrimagnetic Curie point between 260 and 225° K, depending on the previous thermal treatment. For x=0.2, a magnetic phase appeared at 232°K with a complex behavior: between

232 and 100°K, the susceptibility had a maximum and a minimum. The type and position of these points were dependent on the applied magnetic field. At successive lower temperatures, the value of the susceptibility increased considerably, indicating the possible presence of ferromagnetism. For H = 1,150 Oe the minimum was found larger by about a factor of two. This is due to a strong magnetic anisotropy which vanishes at the point of maximum susceptibility ($T = 198°K$, $\chi = 3.4 \times 10^{-3}$). The ferrimagnetic state was obtained in the direction of the field for high values of $\chi (3.1 \times 10^{-3})$ and in the opposite direction for small values of $\chi (\sim 10^{-4})$. For $H \geq 2,050$ Oe the magnetic anisotropy disappeared and increased sharply after the minimum ($T \simeq 103°K$, $\chi = 2.5 \times 10^{-3}$).

Magnetic effects have also been observed for other solid solutions, especially $NiO + Al_2O_3$. In this case the sample did not show any metallic conduction. The interpretation of these effects will be given in a forthcoming publication.

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135. DEFECTS IN THE CRYSTAL AND MAGNETIC STRUCTURES OF FERROUS OXIDE

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The monoxides of Fe, Co, Ni and Mn are antiferromagnetic and the magnetic structures have been established by neutron diffraction. The compounds crystallize in the NaCl type structure and the magnetic arrangement can be understood in terms of superexchange in which there is antiparallel coupling between spins on next nearest neighbor cations. Iron oxide (Wüstite) is unique in that there are large deviations from stoichiometry, the ratio of oxygen to iron being appreciably greater than unity. The present work describes the results of a neutron diffraction study undertaken to elucidate the nature of the atomic arrangement in Wüstite and to ascertain the consequences of nonstoichiometry to the magnetic structure.

Neutron diffraction patterns at 290°K and 4.2°K were obtained from nonstoichiometric FeO (Wüstite) specimens prepared by quenching powders from the high temperature equilibrium state. The neutron scattering shows the presence of defects which consist of cation vacancies in octahedral sites and interstitial cations in tetrahedral sites. On the average, there are two vacancies per interstitial cation. The vacancy-interstitial defect complex produces diffuse neutron scattering which indicates the atomic arrangement in the vicinity of the defect is similar to that in magnetite. The magnetic moment of iron atoms in octahedral positions was determined by measuring the magnetic scattering in the antiferromagnetic state. The average moment is less than that expected for the spin only value and decreases with increasing defect concentration. The results support the idea that the vacancy-interstitial defect complexes form superparamagnetic islands in the antiferromagnetic structure.

136. LOW TEMPERATURE MAGNETIC PROPERTIES OF THE CHROMIUM (III) HALIDES

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The paramagnetic susceptibilities of powdered samples of CrF_3, $CrCl_3$, $CrBr_3$, and CrI_3 have been determined from ca. 60 to 400° K by the Gouy method. All were found to follow the Curie-Weiss law above ca. 100° K. (Other workers have previously made this type of measurement on CrF_3 and $CrCl_3$.). The values we observed for the paramagnetic Curie temperature and the effective magnetic moment (in Bohr magnetons) are for each compound as follows: for CrF_3, -124°K and 3.85; for $CrCl_3$, 31°K and 3.69; for $CrBr_3$, 51°K and 3.94; and for CrI_3, 70°K and 4.03. Below 70°K the susceptibility of CrF_3 suddenly becomes large, indicating ferromagnetism or ferrimagnetism.

The magnetization curves of CrF_3, $CrBr_3$, and CrI_3 were determined at 4.2°K by measuring the intensity of magnetization periodically as the field was cycled between 16,000 and -16,000 gauss. CrF_3 exhibited hysteresis with a remanent moment of 0.04 Bohr magnetons per chromium atom and a coercive force of 200 gauss. A saturation magnetization of ca. 0.1 indicates that CrF_3 is ferrimagnetic! CrI_3 showed hysteresis and under conditions used showed a remanent moment of 0.34 and coercive force of 1300 gauss. At 14,500 gauss the magnetization was 1.0 or one third of saturation. $CrBr_3$ showed no hysteresis, and the magnetization was linear with field for the first 300 gauss. $CrBr_3$ is the most susceptible of the halides, being 86% saturated at 5000 gauss.

The initial susceptibilities of CrF_3 and $CrCl_3$ have been determined from their Curie-Weiss law regions down to about 1°K using an inductance bridge. CrF_3 exhibits an enormous peak in its susceptibility curve with a maximum at 70°K and with another small peak superimposed at 46°K. $CrCl_3$ also exhibits two maxima, one at 15.9°K and one at 8.3°K.

The above data, together with magnetic data on $CrCl_3$ already in the literature and the crystal structures and heat capacities known for these compounds, give insight into the basic nature of the magnetism here exhibited. For example, arguments can be given which indicate that the magnetic electrons do not remain localized on the chromium atoms and that exchange forces span distances greater than generally thought possible.

137. SOME NEW MAGNETIC PHENOMENA OF HEMATITE SINGLE CRYSTALS

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Three sets of magnetic measurements of pure natural hematite single crystals have been carried out in the temperature range from 488°K down to 4.2°K. The first set is the magnetization curves along a certain direction in the basal plane, the second set is along the ternary axis and the third set is the remanent magnetization along the ternary axis. The analysis of the isotherms of the first set shows that the spontaneous magnetization of the weak ferromagnetic effect becomes practically zero below 250°K. This phenomenon suggests that there is no isotropic component of the ferromagnetic effect in the hematite single crystal.

The isotherms of the second set display some very unusual forms. (All the curves and their interpretations will be presented at the conference.) If the extrapolation along the linear portion of the isotherm is carried out the σ_o -T curve shows that above 360°K σ_o is practically equal to zero. The phenomen, together with that in the basal plane appears to indicate that σ_o along the ternary axis is anisotropic and observable. The above two phenomena are apparently contradictory to the results obtained by Neel and Pauthenet[1].

Both the σ_o - T curves and the χ - T curves obtained from the first two sets of our data show that the transition period is over a wide range of temperature (from 360°K to 250°K). This fact together with the unusual form of the isotherms along the ternary axis seems to suggest that the transition of the magnetization vector from the basal plane to the ternary axis takes place gradually instead of sharply; i.e. there are intermediate orientations between the basal plane and the ternary axis at intermediate temperatures between 360°K and 250°K.

The third set of our data shows that the remanence versus temperature curve in the whole range of temperature from 488°K to 77°K is very similar to the σ_o - T curve from the second set of data in every respect. This similarity seems to indicate that the procedure used in obtaining the σ_o - T curve along the ternary axis was correct. If a high enough magnetic field (about 2000 Oe) was applied to the sample along the ternary axis at a proper temperature, (about 488°K), the remanence would not recover for the whole range of temperature under consideration. It seems that the ferromagnetic effect was destroyed by the field. The field required to destroy the ferromagnetism depends upon the temperature at which the field is applied, the lower the temperature the higher the field. This phenomenon was unexpected.

Haigh[2] has performed an extensive experiment of remanent magnetization of hematite powder, and found the difficulty in the application of Neel's interpretation of the magnetic behavior of hematite to the recovery of the remanence of the anisotropic component after his sample was cooled down to 80°K and warmed up to room temperature again. From the above suggestions, Haigh's result seems to be a natural consequence. Because the remanence is still anisotropic and not reduced to zero when the sample was cooled down to 80°K it should have recovered when the temperature was raised up again.

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138. UNIFORM ROTATION IN FERRITE TOROIDS

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A model is presented for the high speed uniform rotational reversal of ferrite toroids. This model eliminates the prohibitively high demagnetizing energy usually associated with uniform rotation in toroids. Analysis of the model, to a very good approximation, leads to results identical with those obtained from uniform rotation in isotropic thin films. Experimental confirmation of a high speed switching mode in ferrite toroids is given.

SESSION VIII-B

ANISOTROPY, OTHER THAN IN THIN FILMS

R. M. BOZORTH, Presiding

139. THE EFFECT OF ORBITAL DEGENERACY ON ANISOTROPY AND MAGNETOSTRICTION

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Recently we have shown that the large anisotropy of cobalt-iron ferrite ($Co_xFe_{3-x}O_4$) was caused by the orbital degeneracy of the cobalt ion[1]. For small values of x the energy levels of the cobalt ion in the crystal electric field, calculated to first order in spin-orbit energy, gave a satisfactory account of the cubic anisotropy and the anisotropy induced by magnetic annealing.

However, it is known that when an orbital state of a molecular configuration is degenerate or nearly degenerate, the electrostatic field of the electron charge distribution tends strongly to displace the atomic nuclei from their normally symmetric positions. This effect influences the energy levels of the system and therefore, in our case, the magnetic anisotropy. Also, the dependence of the resulting elastic strain on magnetic state may be interpreted as magnetostriction.

In the present paper we will discuss these effects for the case of a trigonal crystal field in the limit where the coupling of the electron motion to the lattice vibrations is weak. First, the lattice vibrations are neglected altogether and the magnetostriction is calculated by considering the coupling of excited states to the two states of the ground level by the spin-orbit operator and by the increment of crystal field proportional to elastic strain. The resulting formulae for magnetostrictive strain have the following characteristics: (1) At sufficiently low temperatures an expansion of the strain in the customary powers of the direction cosines of the magnetization vector would converge very slowly. (2) The magnitude of the effect is greater than in the case of a non-degenerate atom or ion by a factor of the order $(\Delta E/\lambda)$ where ΔE is an appropriate crystal field splitting (10^3 - 10^4 cm^{-1}) and λ is the spin-orbit parameter (10^2 cm^{-1}). (3) The temperature dependence is stronger than in the case of a non-degenerate atom or ion.

The effects of lattice vibrations are next considered. An expression for the vibrational correction to the anisotropy is derived and it is shown that the corresponding correction to magnetostriction is of the same relative order of magnitude. Since the uncorrected calculation of anisotropy agrees satisfactorily with the experiments on $Co_xFe_{3-x}O_4$ for small x, our uncorrected expressions for magnetostriction may also be applicable to this substance.

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140. EXCHANGE ANISOTROPY IN DISORDERED Ni-Mn ALLOYS

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Magnetization and torque measurements have been made on disordered polycrystalline Ni-Mn alloy specimens of approximately 20, 25, and 30 atomic percent Mn, that were cooled from 300°K to 4.2°K in a magnetic field. Their magnetic hysteresis loops measured at 4.2°K parallel to this field are found to be displaced from their symmetrical positions about the origin. Upon warm-up, the asymmetry of the loops decreases monotonically, vanishing at about 20°K, 45°K, and 80°K for the 20, 25, and 30 percent Mn specimens, respectively. The disappearance of this asymmetry with increasing temperature is accompanied by a large increase in the areas of the loops (which become small again at still higher temperatures).

Torque measurements were made on the same specimens cooled in a field perpendicular to the axis of rotation. For all compositions, the torque measured at 4.2°K is found to have a dominant component of the form sin θ where $\theta=0$ corresponds to the direction of the field applied during cooling; hence, the anisotropy is unidirectional. The amplitude of the sin θ torque component decreases monotonically with increasing temperature, vanishing at the same temperature as the asymmetry of the hysteresis loops. At this temperature, the rotational hysteresis, which at a given temperature is observed to be essentially field-independent at high fields, rises to a maximum.

It is concluded that the coexistence of ferromagnetism and antiferromagnetism at low temperatures in these alloys, as previously reported, gives rise to exchange anisotropy interactions of the type conceived by Meiklejohn and Bean for the ferromagnetic Co - antiferromagnetic CoO system. However, important differences in detail between the Ni-Mn alloys and the Co-CoO system are suggested by the experimental results.

141. EXCHANGE ANISOTROPY IN AN Fe-Al ALLOY AT VERY LOW TEMPERATURES

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A polycrystalline Fe-Al alloy specimen of approximately 30 atomic percent Al, having FeAl-type order, was cooled from 300°K to 1.8°K in a magnetic field. Its magnetic hysteresis loop measured at 1.8°K parallel to this field is found to be asymmetrical with respect to the origin and considerably "squared-up" as compared to the loop for zero field applied during cooling. Torque measurements made on the same specimen cooled from 300°K to 1.8°K in a field perpendicular to the axis of rotation gave large sin Θ and sin 2θ components of torque, where $\Theta = 0$ corresponds to to the direction of the field applied during cooling. All these effects of cooling in a field vanish at about 10°K where the area of the loop and the rotational hysteresis are maximum. The mechanism for these effects is believed to be an exchange anisotropy arising from a coexistence of ferromagnetism and antiferromagnetism in this alloy at very low temperatures.

142. ON THE MAGNETIC ANISOTROPY IN MANGANESE-IRON SPINELS

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Magnetic anisotropy measurements have been made by the torque method on ground single crystal spheres of manganese ferrite as a function of composition, temperature (-197°C. to 50°C.), and heat treatment. The crystals investigated are in the $Mn_xFe_{3-x}O_4$ composition series with x varied from 0 to 1.9, and were grown from the melt in an atmosphere which according to previous phase equilibrium studies[1] established a stoichiometric oxidation state. The growth of large crystals for x greater than 1.9 was limited by the cubic to tetragonal phase transformation[2] known to exist in this composition region.

The anisotropy energy as a function of the magnetization direction in crystals with x between 0.0 and 1.8 is generally negative and is described within experimental error by the ordinary phenomenological expression for cubic symmetry, with K_1 as the principal constant at all temperatures. A pronounced dip in a curve of $|K_1|$ versus composition in the x = 0.4 to 1.0 composition region is observed. Also, $|K_1|$ is a minimum in this region between x = 0.6 and 0.8 and is only slightly temperature dependent. K_1 actually becomes positive in this region for temperatures greater than approximately 30°C. In the x = 1.0 to 1.8 composition range, the anisotropy energy at fixed temperatures decreases gradually with increasing x and is strongly temperature dependent. The effect on the above anisotropy variations due to heating portions of the crystal in air to various temperature below the melt is described. Between x = 1.8 and 1.9, the cubic symmetry shown by the anisotropy energy undergoes a transition to a purely uniaxial symmetry, presumably as a result of the cubic to tetragonal transformation.

A minute magnetic annealing effect is observed in crystals with a composition in the vicinity of x = 0.5 and takes place at 100°C. in a few minutes time. This effect produces a uniaxial anisotropy energy, the magnitude of which is of the order of 5% of the cubic anisotropy and is a maximum for an annealing field along a [100] and a minimum or zero for a [110].

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143. THE ANISOTROPY CONSTANTS OF IRON AND 3% SILICON-IRON AT ROOM TEMPERATURE AND BELOW

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The anisotropy constants K_1 and K_2 have been determined from torque measurements on a (110) single-crystal disk of Armco iron, and the constant K_1 from similar measurements on a (100) disk of 3.1% silicon-iron, at temperatures of 77, 195, and 300°K. Measurements were made in fields up to 20,000 oersteds, and the constants were obtained by extrapolation to infinite field. The results are as follows:

Material	Temperature	K_1 ergs/cm^3	K_2 ergs/cm^3
Fe	77°K	$(520\pm10)\times10^3$	$(0\pm50)\times10^3$
	195	(505 ± 10)	(0 ± 50)
	300	(480 ± 10)	(0 ± 50)
3.1% Si-Fe	77°K	$(425\pm10)\times10^3$	
	195	(405 ± 10)	
	300	(365 ± 10)	---

The room-temperature values are in good agreement with other recent determinations, but are substantially higher than most of the earlier published values. This is especially true for iron, where most of the previous determinations were made at relatively low fields.

The low-temperature data show that K_1 varies much less rapidly with temperature than had previously been believed. For iron, K_1 varies approximately as the fourth power of the magnetization from 0 to 300°K; for 3.1% silicon-iron, approximately as the 6.5 power. According to a highly-regarded theory and previous experimental results, the variation was as the tenth power of the magnetization.

144. ANISOTROPY OF SUPERPARAMAGNETIC COBALT PARTICLES AS MEASURED BY TORQUE AND RESONANCE

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The magnetocrystalline anisotropy of fine particles of cobalt formed by precipitation in single crystals of a copper-2% cobalt alloy has been measured by torque and ferromagnetic resonance techniques.[1,2] When the particle sizes are in the "superparamagnetic" range, the superparamagnetic behavior not only allows the determination of particle size from the susceptiblity,[3] but also introduces an interesting field and temperature dependence of the apparent anisotropy as determined by torque or resonance. The anisotropy values obtained for complete saturation of the particles give K_1 for f.c.c. cobalt as a function of temperature and particle size. The dependence of the apparent anisotropy on field at various temperatures yields insight both into superparamagnetism and into the difference between torque and resonance measurements of the anisotropy.

Simple statistical reasoning has been applied to the case of an assembly of crystallographically aligned superparamagnetic particles at a given field and temperature. The apparent anisotropy as measured both by torque and resonance techniques has been deduced, and compared to the experimental results. Certain features of the experimental results can be explained, including the observation that at high temperatures the anisotropy measured by resonance is higher than that measured by torque. At present, however, the observed field dependence of the apparent torque anisotropy at low fields is inconsistent with simple theory.

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145. THE SYNTHESIS OF A (110) [001] TYPE TORQUE CURVE IN SILICON IRON

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The magnetic torque curve of a (110) [001] silicon-iron single crystal disk is reasonably well represented[1,2] by the following equation with variables T and θ:

$$T = -a\left[2\sin 2\theta + 3\sin 4\theta\right]$$

where $a = K_1/8$, K_1 is the anisotropy constant for 3-1/4% silicon iron, θ is the angle between the direction of measurement and the [001] direction of the crystal and T is the torque. Torque curves from polycrystalline disks with a (110) [001] texture, whether the texture is strong or weak may also be represented by the same type of equation, but with the value of "a" always less than $K_1/8$. Such a torque curve, therefore, may be classified as a (110) [001] type curve, but the statement that a (110) [001] type torque curve determines the presence of a (110) [001] texture cannot be made. A complex texture with appropriate components, among which (110) [001] is either missing or very weak, may also produce the (110) [001] type torque curve. The curve is synthesized from a variety of curves, which, individually can be calculated[3] from sufficient orientation data.

High-purity silicon-iron of 3-1/4% Si, in annealed sheet form 0.012" thick, has been used to provide an illustrative example for the synthesis of a (110) [001] type curve. Orientation data are obtained and used to calculate the expected torque curve, which is compared with the measured curve.

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146. STONER-WOHLFARTH CALCULATION ON PARTICLE WITH BOTH MAGNETOCRYSTALLINE AND SHAPE ANISOTROPY

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Previously, it had been assumed that the presence of magnetocrystalline anisotropy along the long axis of an acicular single domain particle would increase the coercive force.

A theoretical calculation using the Stoner-Wohlfarth model with a magneto-crystalline energy term and performing the energy calculation indicates this is not always true. For acicular single domain particles with cubic magnetocrystalline anisotropy, it is assumed that the particles are ordered with the 1 1 1 direction parallel to the long axis, and the other directions randomly oriented around the 1 1 1 direction.

Carrying out the Stoner-Wohlfarth calculation with various ratios of magneto-crystalline anisotropy to shape anisotropy shows the presence of certain stable states of magnetization which are inaccessible by merely traversing the hysteresis loop. Also, the coercive force is related in a complex way to the anisotropy ratios.

AUTHOR INDEX

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