Fifth Conference

MAGNETISM & MAGNETIC MATERIALS

NOVEMBER 16-19, 1959
SHERATON CADILLAC
DETROIT

MAGNETICS EXHIBIT

(Founders Room, Sheraton-Cadillac Hotel.)

A Magnetics Exhibit has been arranged 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 0900 to 1730 each day. Exhibiting companies include:

	Booth
The Arnold Engineering Co., Marengo, Ill. Permanent Magnets and High Permeability Core Materials.	6 and 7
Bell Telephone Laboratories, Inc., Murray Hill, N. J. Magnetic Memory Modules using Twisters.	12
Columbian Carbon Co., New York 17, N. Y. Synthetic Iron Oxides as Raw Materials for Magnetic Ceramics.	22
Crucible Steel Co. of America, Pittsburgh 30, Pa. Permanent Magnets and Magnetic Components.	5
Dynacor, Inc., Kensington, Md. Tape Wound Cores and Bobbin Cores.	13
GRH Halltest Co., Valparaiso, Ind. Magnetic Test Equipment, Hall Generators, and Magnetic Multipliers.	24
General Electric Research Laboratory, Schenectady, N. Y., and **Magnetic Materials Section**, Edmore, Michigan.	20 and 21
General Magnetic Corp., Detroit, Mich. Magnetic Materials	15
Indiana Steel Products Co., Valparaiso, Ind. Complete Line of Indox, Alnico, and Cunife Permanent Magnets.	23
Leyman Corp. - Magnetics Div., Cincinnati 38, O. Permanent Magnets	8
Magnetic Metals Co., Camden 1, N. J. Electromagnetic Core Parts and Shields.	17
Magnetic Shield Div. - Perfection Mica Co., Chicago Ill. Magnetic Shielding, Non-Radiating, and Non-Pick up Cables.	19
Microwave Chemicals Laboratory, Inc., N. Y. 1, N. Y. Polycrystalline Garnets, Single Crystal Garnets, and MCL Ferrites.	10
Radio Frequency Laboratories, Inc., Boonton, N. J. Magnet Charging and Treating Equipment and Gaussmeters.	18
Rese Engineering, Inc., Philadelphia 6, Pa. Power Frequency, Sine Wave Core Testers and High Frequency Pulse Type Magnetic Pulse Testers and Core Handling Equipment.	14
Varian Associates, Instrument Div., Palo Alto, Calif. Electromagnets and Power Supplies.	16

The purpose of this conference is to bring together in a stimulating environment those individuals who are concerned with some aspect of the manifold field of magnetism. All such individuals are invited to attend.

This, the Fifth Annual Conference on Magnetism and Magnetic Materials, is sponsored by the American Institute of Electrical Engineers in cooperation with the American Physical Society, the Institute of Radio Engineers, the Metallurgical Society of the A.I.M.E., and the Office of Naval Research. The Conference will be held November 16-19, 1959 in the Sheraton-Cadillac Hotel, Detroit, Michigan.

Inquiries should be directed to D. M. Grimes, Local Chairman, Department of Electrical Engineering, University of Michigan, Ann Arbor, Michigan.

SUMMARY OF ACTIVITIES

Monday, November 16

0800 - 1630	*Registration*
0945 - 1200	*Session I* - General Session with Opening Remarks and Invited Papers, Grand Ballroom
1400 - 1700	*Session II-A* - Garnets, Grand Ballroom
1400 - 1700	*Session II-B* - Permanent Magnets, Crystal Ballroom
0900 - 1730	*Magnetics Exhibit and Photography Exhibit*

Tuesday, November 17

0900 - 1200	*Session III-A* - Spin Waves - Magnetostatic Modes, Grand Ballroom
0900 - 1200	*Session III-B* - Computers - Switching, Crystal Ballroom
1400 - 1700	*Session IV-A* - Anisotropy, Grand Ballroom
1400 - 1700	*Session IV-B* - Techniques and Devices, Crystal Ballroom
0900 - 1730	*Magnetics Exhibit and Photography Exhibit*
1730 - 1830	*Crucible Quench Room* - Crystal Ballroom

Wednesday, November 18

0900 - 1200	*Session V-A* - Resonance, Grand Ballroom
0900 - 1200	*Session V-B* - Soft Magnetic Materials, Crystal Ballroom
1400 - 1700	*Session VI-A* - Ferrites, Oxides, Grand Ballroom
1400 - 1700	*Session VI-B* - Magnetic Films, Crystal Ballroom
0900 - 1730	*Magnetics Exhibit and Photography Exhibit*
1730 - 1830	*Cocktail Hour*
1830	*Dinner*, Crystal Ballroom

Thursday, November 19

0900 - 1200	*Session VII-A* - Metals and Alloys, Grand Ballroom
0930 - 1200	*Session VII-B* - Magnetic Salts, Crystal Ballroom
1400 - 1700	*Session VIII-A* - Magnetic Compounds and Neutron Diffractions, Grand Ballroom
1400 - 1700	*Session VIII-B* - Ferrimagnetic Resonance Effects, Miscellaneous, Magnetism in Medicine, Crystal Ballroom
0900 - 1730	*Magnetics Exhibit*
0900 - 1200	*Photography Exhibit*

Preregistration

A preregistration form accompanies this program. To avoid any risk of missing the opening session, as well as to aid the Conference Committee in its planning, you are urged to preregister. Make checks to "Conference on Magnetism and Magnetic Materials" and mail to R. H. Campbell, General Magnetic Corp., 10001 Erwin, Detroit 34, Michigan. Preregistration forms received after November 6 cannot be accepted.

Registration and Proceedings

Registration will be on the fourth floor of the Sheraton-Cadillac Hotel from 0800 to 1630 on Monday, November 16 and from 0830 to 1630 on the other days of the Conference.

The registration fee will be $10.00. Each registrant will receive a copy of the Proceedings which will appear as a separate issue of the Journal of Applied Physics to be issued in the Spring of 1960. The Proceedings will be published later in book form by the McGraw-Hill Book Company.

Hotel Reservations

A block of rooms have been reserved at the Sheraton-Cadillac Hotel. Please either utilize the enclosed card or mention the Conference when writing for reservations. If difficulties develop please contact the Local Chairman or contact F. R. Bryan, Ford Motor Company, at LOgan 3-3000, Ext. 2277.

Recreational and Cultural Activities

Guests will find the manifold cultural and recreational activities of the Detroit area at their ready disposal. Possibilities include a trip through Greenfield Village, a style show at the exclusive Rooster Tail, a trip via the only international tunnel on this continent to our neighbors on the south—the Canadians. Detailed information on these and the many other activities of the Detroit area will be available at the registration desk.

Exhibits

In addition to the usual high level of technical exhibits, this year the Conference is sponsoring a photographic exhibit. The photographs will be displayed in Parlor C of the Conference Hotel. The photographs will be judged prior to Conference time. That photograph judged best will be used as the cover photograph for the Proceedings issue of the Journal of Applied Physics.

Publicity

A press room will be maintained by the Conference. The Local Committee will notify those individuals the press wishes to interview.

Social Gatherings and Banquet

On Tuesday evening all conferees will be welcomed at this year's Crucible Quench Room, the Crystal Ballroom, Sheraton-Cadillac, by their host, the Crucible Steel Co.

On Wednesday evening the social activities will be climaxed by a banquet in the Crystal Ballroom and preceded by a cocktail hour.

The banquet fee this year is $5.00. The principle speaker will be J. H. Van Vleck on a topic to be announced. The number of banquet attendees is limited to 375 on a first come, first served basis. To assure tickets, place your order with your preregistration form.

Information for Speakers

The meeting rooms will be provided with a standard projector for 3 1/4" x 4" slides. The projectioners should receive all slides prior to the start of the session. Slides should be picked up at the end of the session.

CONFERENCE ON MAGNETISM AND MAGNETIC MATERIALS

DETROIT, NOVEMBER 16-19, 1959
SHERATON-CADILLAC HOTEL

TECHNICAL PROGRAM

Monday, November 16, 1959
0945 Hours

Session I Grand Ballroom

GENERAL SESSION
J. E. Goldman, Presiding

Opening Remarks:

C. L. Hogan, General Chairman

Invited Papers:

1. THE STATE OF d-ELECTRONS IN TRANSITION METALS
   C. Herring, Bell Telephone Laboratories.
2. THEORY OF FERROMAGNETIC RESONANCE IN RARE EARTH GARNETS: g-VALUES LINE WIDTH, AND ANOMALOUS ANISOTROPY
   C. Kittel, University of California.
3. CRYSTAL DISTORTION IN MAGNETIC COMPOUNDS
   Junjiro Kanamori, University of Chicago.
4. RELATIONS BETWEEN SUPERCONDUCTORS AND FERROMAGNETS
   Bernd Matthias, Bell Telephone Laboratories.

1400 Hours

Session II-A Grand Ballroom

GARNETS

E. Schlomann, Presiding

5. MAGNETIC INTERACTIONS AND DISTRIBUTION OF IONS IN THE GARNETS (Invited Paper)
   S. Geller,
   Bell Telephone Laboratories.
6. TRANSMISSION, REFLECTIVITY AND FARADAY ROTATION MEASUREMENTS ON SOME RARE-EARTH IRON GARNETS, AND ON α - Fe_2O_3
   P. C. Bailey,
   Westinghouse Electric Corporation.
7. HIGH SIGNAL LEVEL RESONANCE EXPERIMENTS ON YIG
   Ronald L. Martin,
   Bell Telephone Laboratories.
8. INSTABILITY OF MAGNETIC RESONANCE IN SINGLE CRYSTAL SPHERES OF YTTRIUM IRON GARNET
   Joseph I. Masters,
   Air Force Cambridge Research Center.
9. FERRIMAGNETIC RESONANCE IN IMPURITY DOPED YTTRIUM IRON GARNET
   J. F. Dillon, Jr., and J. W. Nielson,
   Bell Telephone Laboratories.
10. SAMARIUM SUBSTITUTIONS IN YTTRIUM-IRON GARNET
   J. Richard Cunningham, Jr., and Elmer E. Anderson,
   U. S. Naval Ordnance Laboratory.
11. INITIAL PERMEABILITY CHARACTERISTICS OF MIXED YTTRIUM-GADOLINIUM IRON GARNETS
   G. E. McDuffie, Jr., J. Richard Cunningham, Jr., and Elmer E. Anderson, U. S. Naval Ordnance Laboratory.
12. RESONANCE EXPERIMENTS WITH SINGLE CRYSTAL YTTRIUM IRON GARNET IN PULSED MAGNETIC FIELDS
   Martin R. Stiglitz and Frederic R. Morgenthaler,
   Air Force Cambridge Research Center.
13. SPECIFIC HEAT OF SOME RARE EARTH IRON GARNETS BETWEEN 1.4 - 20°K$^+$
   Horst Meyer and A. B. Harris,
   Harvard University.
14. AN IMPROVED METHOD FOR THE GROWTH OF CRYSTALS OF YTTRIUM-IRON AND YTTRIUM-GALLIUM GARNETS
   J. W. Nielsen,
   Bell Telephone Laboratories.
15. PARAMAGNETIC RESONANCE OF Yb^{3+} IN GALLIUM GARNET
   John W. Carson and Robert L. White,
   Hughes Research Laboratories.

1400 Hours

Session II-B Crystal Ballroom

PERMANENT MAGNETS

W. F. Brown, Jr., Presiding

16. ON THE REMANENCE OF FERROMAGNETIC POWDERS (Invited Paper)
   S. Shtrikman and D. Treves,
   The Weizmann Institute of Science, Rehovot, Israel.
17. ANGULAR VARIATION OF THE MAGNETIC PROPERTIES OF E.S.D. PARTICLES
   F. E. Luborsky and T. O. Paine,
   General Electric Research Laboratories.
18. THE MAGNETIC PROPERTIES OF ESSENTIALLY SPHERICAL IRON, COBALT, and IRON-COBALT ALLOY PARTICLES
   F. E. Luborsky and T. O. Paine,
   General Electric Research Laboratory.
19. EFFECT OF COMPOSITION AND PREPARATION ON THE MAGNETIC PROPERTIES OF ELONGATED SINGLE-DOMAIN PARTICLES OF COBALT-NICKEL
   R. B. Falk and G. D. Hooper,
   General Electric Company, Edmore, Michigan.
20. COMPARISON OF THE CRITICAL SINGLE-DOMAIN SIZE FOR Fe_3O_4 and γ-Fe_2O_3
   L. A. K. Watt and A. H. Morrish,
   University of Minnesota.
21. PRECIPITATION OF DISPERSED FINE-PARTICLE MAGNETITE
   L. E. Slaten,
   IBM Research Laboratory, Poughkeepsie.
22. A NEW MATERIAL FOR PERMANENT MAGENTS ON A BASE OF MANGANESE AND ALUMINUM
   A. J. J. Koch, P. Hokkeling, M. G. v.d. Steeg and K. J. de Vos, N. V. Phillips', Eindhoven, the Netherlands.
23. AN INTERACTION ANISOTROPY MODEL OF THE STRUCTURE OF ALNICO
   T. O. Paine and F. E. Luborsky
   General Electric Research Laboratory.
24. TRANSMISSION ELECTRON DIFFRACTION OF ALNICO V
   K. J. Kronenberg,
   The Indiana Steel Products Company.
25. LONG TERM MAGNETIC STABILITY OF ALNICO AND BARIUM FERRITE
   K. J. Kronenberg and M. A. Bohlmann,
   The Indiana Steel Products Company.
26. HOT WORKING OF ALNICO 5 ALLOYS
   C. L. Kolbe and D. L. Martin,
   General Electric Research Laboratory.

0900 Hours

Session III-A Grand Ballroom

SPIN WAVES - MAGNETOSTATIC MODES

H. Suhl, Presiding

27. THE USE OF MAGNETOSTATIC MODES AS A RESEARCH TOOL (Invited Paper)
    Robert L. White,
    Hughes Research Laboratories.
28. ELECTRON SPIN RELAXATION IN FERROMAGNETIC INSULATORS (Invited Paper)
    R. C. LeCraw, R. C. Fletcher, E. G. Spencer,
    Bell Telephone Laboratories.
29. ON THE THEORY OF FERROMAGNETIC RESONANCE IN SMALL FERRIMAGNETIC ELLIPSOIDS
    Frederic R. Morgenthaler,
    Massachusetts Institute of Technology.
30. HARMONIC GENERATION IN A FERRIMAGNETIC DISC
    Glenn E. Bennett,
    Air Force Cambridge Research Center.
31. THEORY AND APPLICATION OF DIPOLAR FERRITE MODES
    William H. Steier, Paul D. Coleman,
    University of Illinois.
32. MAGNETIC ANISOTROPY FROM THE MAGNETOSTATIC MODES
    I. H. Solt, Jr., P. C. Fletcher,
    Hughes Research Laboratories.
33. FERRIMAGNETIC RESONANCE AT HIGH POWER
    M. T. Weiss,
    Hughes Aircraft Company.
34. MAGNETOSTATIC MODES OF A FERROMAGNETIC SLAB
    R. W. Damon and J. R. Eshbach,
    General Electric Research Laboratory.
35. FINITE AMPLITUDE ELECTROMAGNETIC WAVES IN GYROMAGNETIC MEDIA
    B. A. Auld,
    Stanford University.
36. SPIN WAVES IN COMPLEX EXCHANGE-COUPLED LATTICES AND NEUTRON SCATTERING
    A. W. Saenz,
    U. S. Naval Research Laboratory.

0900 Hours

Session III-B Crystal Ballroom

COMPUTERS - SWITCHING

C. J. Kriessman, Presiding

37. FLUX REVERSAL IN SOFT FERROMAGNETICS (Invited Paper)
    E. M. Gyorgy,
    Bell Telephone Laboratories.
38. OPERATION OF MAGNETIC FILM PARAMETRONS IN THE 100 TO 500 mc REGION
    A. V. Pohm, A. A. Read, R. M. Stewart, Jr., and R. F. Schauer,
    Iowa State University, Ames.
39. FERRITE FILMS - NEW LOGIC AND STORAGE DEVICES
    J. M. Brownlow, W. L. Shevel, Jr., O. A. Gutwin,
    IBM Research Laboratory, Poughkeepsie.
40. ELECTRODEPOSITED MEMORY ELEMENTS FOR A NONDESTRUCTIVE MEMORY
    T. R. Long,
    Bell Telephone Laboratories.
41. THE DEVELOPMENT OF HIGH SPEED COINCIDENT CURRENT MEMORY CORES
    Barlane R. Eichbaum,
    IBM Research Laboratory, Poughkeepsie.
42. MINIATURE MEMORY PLANES FOR EXTREME ENVIRONMENTAL CONDITIONS
    A. Heuer, B. Kane, R. Straley, G. Tkach,
    General Ceramics.
43. A NEW APPROACH TO HIGH SPEED STORAGE - LOW FLUX DENSITY MATERIALS
    W. L. Shevel, Jr., H. Chang,
    IBM Research Laboratory, Poughkeepsie.
44. A NEW MULTI-APERTURE MAGNETIC LOGIC ELEMENT
    David R. Bennion,
    Stanford Research Institute.
45. FAST SWITCHING BY DOMAIN WALLS IN FERRITES
    W. Wiechec and C. M. Kelly,
    Stanford Research Institute.
46. EFFECT OF PREVIOUS HISTORY ON SWITCHING RATE IN FERRITES
    R. W. McKay and K. C. Smith,
    University of Toronto.
47. ELASTIC SWITCHING PROPERTIES OF SOME TAPE AND FERRITE MATERIALS
    W. C. Seelbach and J. R. Kiseda.

1400 Hours

Session IV-A Grand Ballroom

ANISOTROPY

H. B. Callen, Presiding

48. ANISOTROPY PROPERTIES OF HEXAGONAL FERRIMAGNETIC OXIDES (Invited Paper)
U. Enz, F. K. Lotgering and J. Smit,
Philips Research Laboratories, Eindhoven-Netherlands.
49. FERROMAGNETISM, ANTIFERROMAGNETISM, AND EXCHANGE ANISOTROPY IN DISORDERED ALLOYS (Invited Paper)
J. S. Kouvel,
General Electric Research Laboratory.
50. THE INTERNAL STRUCTURE OF BLOCH WALLS
S. Shtrikman and D. Treves,
The Weizmann Institute of Science, Rehovot, Israel.
51. ANISOTROPIC MAGNETIZATION
Earl R. Callen,
U. S. Naval Ordnance Laboratory.
52. TEMPERATURE DEPENDENCE OF ANISOTROPY AND SATURATION MAGNETIZATION IN IRON AND IRON-SILICON ALLOYS
C. D. Graham, Jr.,
General Electric Research Laboratory.
53. MAGNETIC ANISOTROPY AND MAGNETOSTRICTION OF THE COBALT-IRON ALLOYS AND THE ORDER-DISORDER TRANSFORMATION
R. C. Hall,
Universal-Cyclops Steel Corporation.
54. ROLL MAGNETIC ANISOTROPY OF IRON-ALUMINUM CRYSTALS
Soshin Chikazumi,
University of Tokyo.
55. MAGNETIC ANISOTROPY IN FERRIMAGNETIC CRYSTALS
R. F. Pearson,
Mullard Research Laboratories, Surrey, England.
56. EXCHANGE ANISOTROPY IN MiAs TYPE STRUCTURES
R. H. Pry, J. S. Kouvel, E. Miksch,
General Electric Research Laboratory.
57. EXCHANGE ANISOTROPY IN ROCK MAGNETISM
W. H. Meiklejohn and R. E. Carter,
General Electric Research Laboratory.
58. INFLUENCE OF IONIC ORDER ON THE MAGNETOCRYSTALLINE ANISOTROPY AND CRYSTALLINE ELECTRIC FIELD PARAMETS IN LITHIUM FERRITE MONOCRYSTALS
V. J. Folen,
U. S. Naval Research Laboratory.

1400 Hours

Session IV-B Crystal Ballroom

TECHNIQUES AND DEVICES

P. P. Cioffi, Presiding

59. THE TETRAHEDRAL JUNCTION
Jerald A. Weiss,
Bell Telephone Laboratories.
60. A HIGH-SPEED FERRITE ROTATING HALF-WAVE PLATE
Franklin S. Coale,
Melabs, Palo Alto.
61. DOUBLE PUMP DEGENERATE FERRITE AMPLIFIER
Peter Gottlieb,
Hughes Aircraft Company.
62. BROADBAND RECIPROCAL FERRITE PHASE SHIFTERS
T. G. Geiszler and R. A. Henschke,
Melabs, Palo Alto.
63. MULTIMODE PROPAGATION IN GYROMAGNETIC RODS AND ITS APPLICATION TO TRAVELING WAVE DEVICES
J. E. Tompkins, F. Reggia, L. Joseph
Diamond Ordnance Fuze Laboratories.
64. MICROWAVE DETERMINATION OF CURIE TEMPERATURE
A. D. Krall, E. T. Hooper, Jr.,
U. S. Naval Ordnance Laboratory.
65. INSTRUMENTATION APPLICATIONS OF INVERSE-WIEDEMANN EFFECT
J. A. Granath,
Armour Research Foundation.
66. A PRACTICAL HYSTERESIGRAPH
R. R. Bockemuehl and W. E. Sargeant,
General Motors Research Laboratories.
67. THE RICTOMETER SYSTEM FOR CALIBRATING TRANSMITTERS OF REMOTE INDICATING COMPASSES
L. I. Mendelsohn,
General Electric Company, West Lynn, Massachusetts.
68. A SIMPLE TORQUE MAGNETOMETER
Peter W. Neurath,
General Electric Company, Pittsfield Massachusetts.
69. ULTRASONIC MAGNETOMETER
R. J. Radus,
Westinghouse Electric Corporation.
70. PERMANENT MAGNET LEAKAGE PERMEANCE EVALUATION BASED ON POLAR RADIATION ANALOGY
J. E. Foy and R. J. Parker,
General Electric Co., Edmore, Michigan.
71. THE EFFECT OF GEOMETRY ON THICK FILM TOROIDS
M. Teig, R. L. Ward and J. C. Sagnis,
IBM Corporation, Yorktown Heights, New York.
72. EXPERIMENTAL FLUX PATTERN DETERMINATION IN MAGNETIC CORES
R. L. Ward,
IBM Corporation, Yorktown Heights, New York.
73. A METHOD FOR MEASURING IRON LOSSES IN ELLIPTICALLY POLARIZED MAGNETIC FIELDS
F. J. Young and H. L. Schenk,
Westinghouse Research Laboratories
74. LOCALIZED FIELD PERMANENT MAGNET ARRAYS
H. L. Stadler,
Bell Telephone Laboratories.

0900 Hours

Session V-A Grand Ballroom

RESONANCE

G. T. Rado, Presiding

75. INTERACTION OF MAGNETIC CRYSTALS WITH RADIATION OF 10^4 to 10^5 Cm^{-1} (Invited Paper)
    A. M. Clogston,
    Bell Telephone Laboratories.
76. NUCLEAR RESONANCE IN FERROMAGNETIC COBALT (Invited Paper)
    A. M. Portis and A. C. Gossard,
    University of California.
77. INITIAL-PERMEABILITY SPECTRA OF MICROSCOPIC IRON-OXIDE PARTICLES
    W. F. Brown, Jr., J. P. Hanton and A. H. Morrish,
    University of Minnesota.
78. GALVANOMAGNETIC EFFECTS IN FERROMAGNETIC RESONANCE
    M. H. Seavey, Jr.,
    Lincoln Laboratory, MIT.
79. INITIAL SUSCEPTIBILITY SPECTRA OF PERMALLOY FILM
    R. F. Soohoo,
    Lincoln Laboratory, MIT.
80. FERRIMAGNETIC RESONANCE AS A FUNCTION OF LATTICE CONSTANT
    I. P. Kaminow,
    Harvard University.
81. RESONANCE LINE WIDTH IN DISORDERED FERRIMAGNETICS
    E. Pittelli and H. Callen,
    University of Pennsylvania.
82. EFFECTS OF SURFACE INHOMOGENEITIES ON SINGLE CRYSTAL RESONANCE PARAMETERS
    C. R. Buffler,
    Harvard University.
83. SATURATION EFFECTS IN FERRIMAGNETIC RESONANCE
    P. E. Seiden, Lockheed Missiles and Space Division and Stanford University. H. J. Shaw, Stanford University.
84. RESONANCE LINE WIDTHS OF SINTERED NICKEL FERRITES HAVING LOW POROSITIES
    L. G. Van Uitert, R. R. Soden and F. W. Swanekamp,
    Bell Telephone Laboratories.

0900 Hours

Session V-B Crystal Ballroom

SOFT MAGNETIC MATERIALS

R. M. Bozorth, Presiding

85. A NECESSARY FACTOR FOR HEAT TREATMENT OF THE PERMALLOYS IN A MAGNETIC FIELD
    E. A. Nesbitt, R. D. Heidenreich and A. J. Williams,
    Bell Telephone Laboratories.
86. STUDY OF HEAT TREATMENTS FOR LOW COERCIVE FORCE 14 TO 17 PERCENT ALUMINUM IRON ALLOYS
    D. Pavlović and K. Foster,
    Westinghouse Electric Corporation.
87. EFFECT OF DIRECTIONAL ORIENTATION ON THE MAGNETIC PROPERTIES OF CUBE ORIENTED MAGNETIC SHEETS
    K. Foster and J. J. Kramer .
    Westinghouse Electric Corporation
88. SECONDARY RECRYSTALLIZATION IN VACUUM-ANNEALED SILICON-IRON
    G. Baer, G. Ganz, and H. Thomas,
    Vacuumschmelze, A. G., Hanau, Germany.
89. ANOMALOUS TRANSIENTS FOR SUPERMENDUR AT HIGH TEMPERATURES
    M. Lauriente and G. E. Lynn,
    Westinghouse Air Arm.
90. EFFECT OF HYDROSTATIC PRESSURE ON PROPERTIES OF MAGNETIC MATERIALS
    R. E. Alley and V. E. Legg,
    Bell Telephone Laboratories, Whippany
91. RADIATION EFFECTS ON DOMAIN WALL STABILIZATION IN ALLOYS AND REMANENCE IN A FERRITE (2 papers)
    A. L. Schindler, E. I. Salkovitz and G. C. Bailey,
    U. S. Naval Research Laboratory.
92. RADIATION EFFECTS IN GARNETS, FERRITES, AND MAGNETIC ALLOYS
    S. I. Taimuty, J. S. Mills, C. A. Rosen, L. G. Wright, and B. S. Deaver, Jr.,
    Stanford Research Institute.
93. THE EFFECTS OF DIRECTIONAL ORDERING ON THE DAMPING OF ZONE-MELTED IRON
    R. E. Maringer,
    Battelle Memorial Institute.
94. MAGNETIC CONTRIBUTION TO THE ULTRASONIC ATTENUATION IN ANNEALED AND DEFORMED STEEL (SAE 1020)
    U. M. Martius, W. J. Bratina, D. Mills,
    Ontario Research Foundation.
95. D.C. MEASUREMENTS ON TAPE-WOUND CORES
    R. C. Barker and R. M. Brownell,
    Yale University,
96. RIGOROUS SOLUTIONS OF EDDY CURRENT LOSSES IN RECTANGULAR BAR FOR SINGLE PLANE DOMAIN WALL MODEL
    P. D. Agarwal, University of Massachusetts, and L. Rabins,
    General Electric Company, Pittsfield.
97. THE EFFECT OF EDDY CURRENTS ON DOMAIN WALL CONFIGURATION AND WALL MOTION AND LOSS FOR A DOMAIN MODEL OF CUBE-ON-EDGE MATERIAL
    P. D. Agarwal, University of Massachusetts, and D. C. Graham,
    General Electric Company, Pittsfield.

1400 Hours

Session VI-A Grand Ballroom

FERRITES, OXIDES

H. Sato, Presiding

98. ROLE OF CATION VACANCIES IN MAGNETIC ANNEALING EFFECTS OF COBALT-IRON FERRITES (Invited Paper)
Shuichi Iida,
University of Tokyo.

99. INTRINSIC AND ANNEAL-INDUCED ANISOTROPY IN COBALT-SUBSTITUTED W-TYPE HEXAGONAL OXIDES
L. R. Bickford, Jr.,
IBM Research Laboratory, Poughkeepsie.

100. THE VALENCE AND DISTRIBUTION OF MANGANESE IONS IN FERROSPINELS
Arthur Miller,
RCA Laboratories.

101. HIGH FIELD MAGNETIZATION STUDY OF FERRIMAGNETIC ARRANGEMENTS IN CHROMITE SPINELS
I. S. Jacobs,
General Electric Research Laboratory.

102. THE HIGH TEMPERATURE SUSCEPTIBILITY OF FERRIMAGNETIC SPINELS
Peter J. Wojtowicz,
RCA Laboratories.

103. TIME DECREASE OF INITIAL PERMEABILITY IN $Mn_xFe_{3-x}O_4$
W. A. Crapo.
Research Laboratory, Poughkeepsie.

104. SQUARE LOOP PROPERTIES OF COPPER-MANGANESE FERRITES
Robert S. Weisz and Daniel L. Brown,
Telemeter Magnetics, Inc., Los Angeles.

105. THE TEMPERATURE DEPENDENCE OF THE SATURATION MAGNETIZATION OF FERRITES WITH MAGNETOPLUMBITE STRUCTURE
G. Heimke, Hochschule Fur Verkehrswesen,
Physikalisches Institut, Dresden, Germany.

106. THE MAGNETIC BEHAVIOR IN THE TRANSITION REGION OF A HEMATITE SINGLE CRYSTAL
S. T. Lin,
MIT.

107. THE METAMAGNETIC BEHAVIOR OF MANGANESE ARSENIDE
D. S. Rodbell and P. E. Lawrence,
General Electric Research Laboratory.

108. MAGNETIC PROPERTIES OF THE $Mn_{1-x}Li_xSe$ SYSTEM
Thomas R. McGuire, U. S. Naval Ordnance Laboratory, and Robert R. Heikes, Westinghouse Research Laboratories.

1400 Hours

Session VI-B Crystal Ballroom

MAGNETIC FILMS

D. O. Smith, Presiding

109. SOME PHYSICAL PROPERTIES OF THIN MAGNETIC FILMS
A. C. Moore and A. S. Young,
Royal Radar Establishment, Malvern, England.

110. MILLIMICROSECOND MAGNETIZATION REVERSAL IN THIN MAGNETIC FILMS
W. Dietrich and W. E. Proebster,
IBM Research Laboratory, Zurich, Switzerland.

111. FLUX REVERSAL BY NONCOHERENT ROTATION IN THIN FILMS
K. J. Harte,
Lincoln Laboratory, MIT.

112. MAGNETISATION REVERSAL IN UNIAXIAL FILMS NEAR TO THE PREFERRED DIRECTION
E. M. Bradley and M. Prutton,
International Computers and Tabulators, Ltd., Hertfordshire, England.

113. THE INFLUENCE OF NEARBY CONDUCTORS ON THIN FILM SWITCHING
J. S. Eggenberger,
IBM Research Laboratory, Poughkeepsie.

114. PREFERRED ORIENTATION AND ORDERING IN EVAPORATED FILMS OF Fe, Ni and Fe-Ni
Robert F. Adamsky,
Laboratory for Electronics, Boston.

115. ELECTRON DIFFRACTION AND MICROSCOPY OF PERMALLOY FILMS
M. S. Cohen,
Lincoln Laboratory, MIT.

116. MAGNETIC ANISOTROPY IN EVAPORATED IRON FILMS
E. W. Pugh, J. Matisoo, D. Speliotis and E. L. Boyd,
IBM Research Laboratory, Poughkeepsie.

117. INVERTED FILMS
E. E. Huber, Jr., and D. O. Smith,
Lincoln Laboratory, MIT.

118. TECHNIQUES FOR UNIFORMITY IN MAGNETIC FILM PRODUCTION
T. S. Crowther and G. P. Weiss
Lincoln Laboratory, MIT.

119. A MICROCALORIMETRIC TECHNIQUE FOR THE STUDY OF DAMPING AND HYSTERESIS IN FERROMAGNETIC FILMS
J. R. Mayfield,
IBM Research Laboratory, Poughkeepsie.

120. ANNULAR UNIAXIALLY-MAGNETIZED DOMAINS IN THIN Ni-Fe FILMS
O. W. Muckenhirn, A. E. LaBonte and P. J. Besser,
University of Minnesota.

121. DOMAIN WALL VELOCITIES IN THIN IRON NICKEL FILMS
N. C. Ford, Jr.
IBM Research Laboratory, Poughkeepsie.

122. BLOCHWALLS IN THIN MAGNETIC Ni-Fe-FILMS
S. Methfessel, S. Middelhoek and H. Thomas,
IBM Research Laboratory, Zurich, Switzerland.

123. CROSS TIE DOMAIN WALLS IN THIN FERROMAGNETIC FILMS
Harvey Rubinstein and Robert J. Spain,
Laboratory for Electronics, Boston.

124. STATIC AND DYNAMIC STUDIES OF MAGNETIZATION DISTRIBUTION IN THIN FILMS BY ELECTRON MICROSCOPY.
Harrison W. Fuller and Murray E. Hale,
Laboratory for Electronics, Boston.

0900 Hours

Session VII-A Grand Ballroom

METALS AND ALLOYS

A. Arrott, Presiding

125. MAGNETIC PROPERTIES OF MANGANESE COPPER ALLOYS (Invited Paper)
R. Street,
The University, Sheffield, England.

126. MECHANISM OF ANTIFERROMAGNETISM IN DILUTE ALLOYS (Invited Paper)
A. W. Overhauser,
Ford Motor Company.

127. LONG-RANGE MAGNETIC INTERACTIONS VIA CONDUCTION ELECTRONS
Arthur Paskin,
Ordnance Materials Research Office.

128. HYPERFINE INTERACTION IN MAGNETIC MATERIALS BY ANGULAR CORRELATION MEASUREMENTS
M. E. Caspari and S. Frankel,
University of Pennsylvania.

129. MAGNETIC PROPERTIES OF FERROMAGNETIC SUPERCONDUCTORS
R. M. Bozorth and D. D. Davis,
Bell Telephone Laboratories.

130. STRONG FIELD MAGNETIZATION AT LOW TEMPERATURES AND APPROACH TO ABSOLUTE SATURATION OF THULIUM METAL
Warren E. Henry,
U. S. Naval Research Laboratory.

131. MAGNETIC BEHAVIOR OF POLYCRYSTALLINE NEODYNIUM, HOLMIUM AND ERBIUM FROM 300°K to 1500°K
Sigurds Arajs, A. D. Damick and D. S. Miller,
U. S. Steel Corporation Research Center.

132. ANALYSIS OF MAGNETIC INTERACTIONS IN ALLOYS OF PLATINUM WITH IRON GROUP TRANSITION ELEMENTS
Hiroshi Sato,
Ford Motor Company.

133. THE EFFECT OF IMPURITIES ON THE LOW TEMPERATURE SPONTANEOUS MAGNETIZATION OF CUBIC FERROMAGNETIC CRYSTALS
A. A. Maradudin and P. A. Dixon,
University of Maryland.

0930 Hours

Session VII-B Crystal Ballroom

MAGNETIC SALTS

D. M. Grimes, Presiding

134. PARAMAGNETIC RESONANCE ABSORPTION OF NICKEL IN SAPPHIRE SINGLE CRYSTALS
S. A. Marshall and A. R. Reinberg,
Armour Research Foundation.

135. THE MAGNETIC SUSCEPTIBILITIES OF SEVERAL PARAMAGNETIC SALTS BETWEEN 1.3°K AND 21°K.
R. Flippen and S. A. Friedberg,
Carnegie Institute of Technology.

136. MAGNETIC PROPERTIES OF URANIUM DIGERMANIDE
Clayton E. Olsen,
Los Alamos Scientific Laboratory.

137. DISLOCATION MAGNETISM IN ANTIFERROMAGNETIC CRYSTALS
E. S. Dayhoff,
U. S. Naval Ordnance Laboratory.

138. AN INTERPRETATION OF THE MAGNETIC AND CRYSTALLOGRAPHIC PROPERTIES OF SEVERAL IRON, NICKEL, AND IRON-NICKEL NITRIDES
John B. Goodenough, A. Wold, R. Arnott,
Lincoln Laboratory, MIT.

139. MAGNETIC TRANSITIONS IN Ti_2O_3 and V_2O_3
P. H. Carr and S. Foner,
Lincoln Laboratory, MIT.

140. LOW TEMPERATURE X-RAY DIFFRACTION STUDIES ON VANADIUM SESQUIOXIDE
E. P. Warekois,
Lincoln Laboratory, MIT.

141. THE PROPERTIES OF MANGANESE FERRITES PREPARED AT VARIOUS OXYGEN PRESSURES
Aleksander Braginski,
Research Laboratory for Magnetic Materials "Polfer", Warsaw, Poland.

142. EFFECT OF POTASSIUM IONS ON THE REACTION AND FINAL PROPERTIES OF Mn-Zn
Stefan Makolagwa,
Research Laboratory for Magnetic Materials "Polfer", Warsaw, Poland.

143. IONIC ORDERING EFFECTS IN THE FERROMAGNETIC RESONANCE OF LITHIUM FERRITE MONOCRYSTALS
A. D. Schnitzler, V. J. Folen, G. T. Rado,
U. S. Naval Research Laboratory.

1400 Hours

Session VIII-A Grand Ballroom

MAGNETIC COMPOUNDS AND NEUTRON DIFFRACTIONS

S. Smart, Presiding

144. THE PRECISE MEASUREMENT OF MAGNETIC FORM FACTORS (Invited Paper)
Robert Nathans,
Pennsylvania State University and Brookhaven National Laboratory.
145. ON THE ANTIFERROMAGNETIC STRUCTURE AND DOMAINS IN SINGLE CRYSTAL NiO
Walter L. Roth and Glen A. Slack,
General Electric Research Laboratory.
146. NEUTRON DIFFRACTION INVESTIGATION OF THE MAGNETIC STRUCTURE OF NICKEL OXIDE
H. A. Alperin,
University of Connecticut, and U. S. Naval Ordnance Laboratory.
147. NEUTRON DIFFRACTION INVESTIGATION OF THE $Fe_{1-\sigma}S$ SYSTEM
J. T. Sparks, W. Mead and A. J. Kirschbaum, University of California, Livermore,
and W. Marshall, Atomic Energy Research Establishment, Harwell, England.
148. NEUTRON DIFFRACTION INVESTIGATIONS OF THE MAGNETIC ORDERING IN RARE-EARTH NITRIDES
M. K. Wilkinson, H. R. Child, J. W. Cable, E. O. Wollan, and W. C. Koehler,
Oak Ridge National Laboratory.
149. THEORY OF LOW LYING STATES OF SOME RARE EARTH COMPOUNDS
G. T. Trammell,
Oak Ridge National Laboratory.
150. ON THE CLASSICAL THEORY OF SPIN-CONFIGURATIONS IN THE CUBIC SPINEL
T. A. Kaplan,
Lincoln Laboratory, MIT.
151. ON THE DIRECT CATION-CATION INTERACTIONS IN PRIMARILY IONIC SOLIDS
John B. Goodenough,
Lincoln Laboratory, MIT.
152. MAGNETO STRUCTURAL STUDIES ON GADOLINIUM-IRON ALLOYS
R. C. Vickery W. C. Sexton, V. F. Novy and E. V. Kleber,
Nuclear Corporation of America, Burbank.
153. MAGNETIC MOMENTS OF ALLOYS OF GADOLINIUM WITH SOME OF THE TRANSITION ELEMENTS
William M. Hubbard, Edmond Adams, John V. Gilfrich,
U. S. Naval Ordnance Laboratory.
154. FERROMAGNETIC ALLOY PHASES NEAR THE COMPOSITIONS Ni_2MnIn, Ni_2MnGa, Co_2MnGa, Pd_2MnSb, and PdMnSb.
F. A. Hames,
Queen's University, Kingston, Canada.
155. ASYMMETRIES IN THE MAGNETIC FORM FACTOR OF Fe_3AL
Robert Nathans, Pennsylvania State University and S. S. Pickart, Naval Ordnance Laboratory.

1400 Hours

Session VIII-B Crystal Ballroom

FERRIMAGNETIC RESONANCE EFFECTS MISCELLANEOUS MAGNETISM IN MEDICINE

S. M. Rubens, Presiding

156. FERRIMAGNETIC RESONANCE IN RARE EARTH GARNETS (Invited Paper)
R. V. Jones,
Harvard University.
157. RECENT DEVELOPMENTS IN FERROMAGNETIC RESONANCE AT HIGH POWER LEVELS (Invited Paper)
E. Schlomann, Raytheon, J. J. Green, Harvard University and U. Milano, Raytheon.
158. PULSED FERRIMAGNETIC MICROWAVE GENERATOR
B. Elliot, T. Schaug-Petersen, and H. J. Shaw,
Stanford University.
159. SWITCHING BEHAVIOR OF LOW REMANENCE FERRITES
F. B. Hagedorn and E. M. Gyorgy,
Bell Telephone Laboratories.
160. TRANSFER FUNCTION AND ERROR PROBABILITY OF A DIGITAL MAGNETIC TAPE RECORDING SYSTEM
John Wenchung Hung,
IBM Corporation, Poughkeepsie.
161. PARTICLE INTERACTION IN MAGNETIC RECORDING TAPES
J. G. Woodward,
RCA Research Center.
162. THE ANALYSIS OF A PRACTICAL PERPENDICULAR RECORDING HEAD FOR DIGITAL MAGNETIC TAPE SYSTEMS
George Fan,
Ampex Corporation, Redwood City, California.
163. GROWING SPINWAVES IN FERRITES IN UNSTABLE EQUILIBRIUM
Tor Schaug-Petersen,
Stanford University.
164. NUCLEATION EXPERIMENTS ON THIN MAGNETIC MnBi FILMS
Ludwig Mayer,
General Mills.
165. MAGNETISM IN MEDICINE TODAY AND TOMORROW
Michael W. Freeman, M. D.,
Detroit.
166. USE OF NUCLEAR MAGNETIC RESONANCE TECHNIQUES FOR BLOOD FLOW MEASUREMENTS
J. R. Singer,
University of California.

SESSION I

INVITED PAPERS

J. E. GOLDMAN, Presiding

---

1. THE STATE OF d ELECTRONS IN TRANSITION METALS (Invited)

C. HERRING
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

Existing theoretical speculations on the state of d electrons in magnetic and nonmagnetic transition metals will be reviewed. Current ideas on the many-electron theory of metals indicate that a precise meaning can be attached to the question of the bound versus itinerant nature of these electrons, and that for some metals the one type of state may occur, and for others the opposite. Theoretical considerations bearing on the charge distribution of these electrons will also be discussed.

---

2. THEORY OF FERROMAGNETIC RESONANCE IN RARE EARTH GARNETS: g-VALUES, LINE WIDTH, AND ANOMALOUS ANISOTROPY (Invited)

C. KITTEL
University of California
Berkeley, Calif.

This talk will review recent theoretical and experimental work on the resonance properties of rare earth garnets and doped YIG. The g-values are explained simply on the assumption that in the relevant temperature range the rare earth ions relax rapidly in comparison with the rare earth - iron exchange frequency. The line widths, as shown by Portis, de Gennes, and Kittel, can be accounted for qualitatively on the same model. It is proposed that the giant peaks in the anisotropy discovered by Dillon and Nielsen in rare earth doped YIG at low temperatures are caused by near crossings of the ground state energy levels of the rare earth ions. Data on the ground states will be reviewed.

---

3. CRYSTAL DISTORTION IN MAGNETIC COMPOUNDS (Invited)

JUNJIRO KANAMORI
Institute for the Study of Metals, University of Chicago
Chicago 37, Illinois*

The spontaneous crystal distortion observed in various magnetic compounds is discussed from the microscopic point of view. The main origins of the distortion are the exchange interaction among the spins and the Jahn-Teller effect. The latter effect is caused by the magnetic ion whose electronic orbital level is degenerate in the undistorted structure. The substances which show the distortion can be divided into three classes. In the first class the distortion is caused by the Jahn-Teller effect only. The spinel-type

and perovskite- (or ReO_3-) type crystals containing Cu^{2+} or Mn^{3+} belong to this class. In the second class the distortion is due to the combined action of the exchange interaction and the Jahn-Teller effect. FeO and CoO are the typical examples of this class. Substances such as MnO and NiO belong to the third class. In this case only the exchange interaction is responsible for the distortion.

When Cu^{2+} or Mn^{3+} is in the octahedral site, the orbital level is doubly degenerate and the spin-orbit coupling is not effective in this level. The discussion of this case is based on the Hamiltonian which consists of the elastic energy, the lattice vibrations and the interaction between the magnetic ion and the elastic strain or the lattice vibrations (the Jahn-Teller effect term). The state of lowest energy and the statistical treatment are studied in various approximations. It is shown that the transition from the distorted to the undistorted structure is of either the first kind or the second kind, depending on the type of distortion. The sound velocity in the distorted structure and the temperature dependence of the distortion are discussed as well. A detailed discussion of the complicated distortion in MnF_3 is given. In FeO and CoO the Jahn-Teller effect is associated with the exchange interaction through the spin-orbit coupling. The exchange interaction is responsible for the cooperative phenomena, while the Jahn-Teller interaction gives rise to the distortion at the Néel temperature. The results of the calculation agree well with the experimental data. MnO and NiO will be discussed briefly.

*On leave from Department of Physics, Osaka University, Osaka, Japan.

4. RELATIONS BETWEEN SUPERCONDUCTORS AND FERROMAGNETS (Invited)

BERND MATTHIAS
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

Ferromagnetic interactions of the rare earth elements in dilute solutions or in compounds with nonmagnetic elements have been discovered and will be described. The Curie points are essentially proportional to the spin while the saturation moment follows the value for the effective moment. This ferromagnetic interaction, known to take place via the conduction electrons, follows criteria resembling closely those for the occurrence of superconductivity.

It is shown that by suitable combination of similar superconductors and ferromagnets both phenomena can happen simultaneously in the same crystal.

SESSION II-A

GARNETS

E. SCHLÖMANN, Presiding

5. MAGNETIC INTERACTIONS AND DISTRIBUTION OF IONS IN THE GARNETS (Invited)

S. GELLER
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

Since the discovery of the magnetic yttrium and rare earth iron garnets, a systematic investigation has been made of the interactions of magnetic ions and the distribution of both magnetic and nonmagnetic ions in the garnets. In the course of these investigations many new garnets have been discovered. Several of these have enabled us to observe *directly* interactions between magnetic ions in: dodecahedral and octahedral sites, octahedral sites only and in tetrahedral sites only. The substitution of the tetravalent tin ion for Fe^{3+} ion in yttrium iron garnet (balanced by substitution of Ca^{2+} for Y^{3+} ions) has led Gilleo to extend the quantitative understanding of the octahedral-tetrahedral Fe^{3+} ion magnetic interactions. These ideas have been further strengthened by results obtained from zirconium substituted yttrium-iron garnet.

The work on the garnets has already been adequately extensive to lead to the establishment of some rather simple rules pertaining to site preference of ions entering the garnets.

Note: Collaborators in various parts of this work have been Drs. M. A. Gilleo and R. M. Bozorth.

6. TRANSMISSION, REFLECTIVITY AND FARADAY ROTATION MEASUREMENTS ON SOME RARE-EARTH IRON GARNETS, AND ON α-Fe_2O_3*

P. C. BAILEY
Magnetic Materials Development Section
Materials Engineering Departments
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

The transmission of thin (0.00025") single crystal sections of α-Fe_2O_3 was measured in the wavelength range 5000Å to 10,000Å. The absorption in this region strongly resembles that of the rare earth iron garnets. At wavelengths shorter than 5500Å, the absorption is very large but falls off rapidly with increasing wavelengths. Room temperature measurements show a large, broad absorption between 7500Å and 9200Å, and there is the suggestion of a further absorption anomaly at about 6000Å. This latter absorption becomes quite pronounced at liquid nitrogen temperature.

Reflectivity measurements were carried out on yttrium and gadolinium iron garnets in the visible and in the infrared to 25μ, enabling the true absorption coefficient for these materials in this spectral region to be determined.

Faraday rotation measurements were also made on thin, normally magnetized single crystal and polycrystalline sections of yttrium and gadolinium iron garnets in the infrared. For yttrium iron garnet, a rotation of about 350°/cm was measured at 1μ. This decreased rapidly with increasing wavelength to a value of 80°/cm at 3.5μ and then remained essentially constant to 11μ. For gadolinium iron garnet, the rotation measured at 1.0μ was only about 150°/cm; for a wavelength greater than 4.0μ no rotation was observed.

Preliminary absorption measurements will be reported on Yb, Er, Ho, Dy, and Tb iron garnets from the visible to the near infra-red.

*This work was supported in part by the Electronics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF19(604)-5529.

---

7. HIGH SIGNAL LEVEL RESONANCE EXPERIMENTS ON YIG

RONALD L. MARTIN
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

High signal level resonance experiments at X-band have been performed on spherical samples of single crystal yttrium iron garnet and europium substituted yttrium iron garnet. The experiments were performed for various degrees of surface roughness of the samples. The highest r.f. magnetic fields at the samples were well above the critical fields for the onset of the nonlinear behavior of the garnets. Measurement of X" of the garnets as a function of signal level will be reported. The effect of substitution of europium in the garnet is similar to that observed[1] with holmium substitution in that the linewidth, ΔH_k, of the spin wave which becomes unstable is increased by a much larger ratio than the linewidth of the uniform precession. The X" of the samples of YIG with a high degree of surface polish give a good qualitative fit to a theory by Suhl[2] over a considerable range of signal level above threshold. The X" of the rougher samples does not fit the theory as well.

1. J. J. Green, unpublished.
2. H. Suhl, to be published in J.A.P.

---

8. INSTABILITY OF MAGNETIC RESONANCE IN SINGLE CRYSTAL SPHERES OF YTTRIUM IRON GARNET

JOSEPH I. MASTERS
Air Force Cambridge Research Center (CRRCSM-4)
Bedford, Mass.

Instabilities in YIG spheres that exist above certain threshold power values of c. w. microwave field are studied using samples of about 0.5 - 1.0 mm dia., that have low power line widths of 1 Oe or less. Whereas the characteristic behavior such as assymetrical line shape, "jump" effect etc. is somewhat similar to that reported for discs, the phenomenon is generally different.

It has been determined that this instability, which occurs at power levels below the threshold for significant spin wave growth, is due entirely to the heating effect of resonance absorption upon the anisotropy energy of the crystal lattice. As a result, the instability threshold curve follows both the extrema and summetry of the anisotropy curve for a given orientation, and in addition, the instability phenomenon can be made vanishingly small if special precautions are taken to reduce self heating in the resonant sample. A straightforward theoretical explanation based on familiar relationships is outlined which fits the instability vs orientation curve.

---

9. FERRIMAGNETIC RESONANCE IN IMPURITY DOPED YTTRIUM IRON GARNET

J. F. DILLON, JR., and J. W. NIELSEN
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

A research program aimed at understanding our earlier line width and anisotropy measurements on YIG has led to a study of ferrimagnetic resonance in doped crystals. YIG crystals have been grown containing appropriate concentrations (~.01% to 5%) of various impurities. These include the 4f rare earth elements, members of the iron transition group, and several non-magnetic ions. The quantities being measured are the line width and field for resonance as a function of temperature and crystal direction, as well as the g-value for various temperatures and crystal directions. One of the first results of these experiments has been the demonstration that highly convoluted field for resonance surfaces may result from the presence of rare earth ions in the YIG lattice. There are large anisotropies in line width, some of which are associated with the anomalies in the field for resonance. Studies of these doped crystals are thus yielding information on the anisotropies associated with the rare earth ions in the garnet lattice, much of which would be much more difficult to obtain from the rare earth garnets. Silicon has been introduced in order to force the presence of divalent iron in the lattice, and thus to study its effects on line width and field for resonance. A summary will be given of the effects of various impurities on resonance in YIG, and of the implication to our understanding of line width and anisotropy mechanisms.

---

10. SAMARIUM SUBSTITUTIONS IN YTTRIUM-IRON GARNET

J. RICHARD CUNNINGHAM, JR. and ELMER E. ANDERSON
U. S. Naval Ordnance Laboratory
White Oak, Maryland

Polycrystalline garnets of the form $(3\text{-}x)Y_2O_3 \cdot xSm_2O_3 \cdot 5Fe_2O_3$ have been prepared where x was varied from 0 to 3 in six steps. Lattice constants were found to vary linearly from 12.374±.005A for yttrium-iron garnet (x = 0) to 12.533 ±.005A for samarium-iron garnet (x = 3). The theoretical x-ray densities were calculated and vary from 5.17 gms/cm^3 for x = 0 to 6.23 gms/cm^3 for x = 3. Magnetic moments were measured from 77°K to 580°K. No magnetic compensation points were observed. The low temperature magnetization shows a small uniform decrease with samarium addition. This decrease in low temperature magnetization is coupled with an increase in the Curie temperature from ~287°C for x = 0.5 to ~321°C for x = 3. Several possible explanations for these variations have been explored and are discussed.

---

11. INITIAL PERMEABILITY CHARACTERISTICS OF MIXED YTTRIUM-GADOLINIUM IRON GARNETS

G. E. McDUFFIE, JR., J. RICHARD CUNNINGHAM, JR. and ELMER E. ANDERSON
U. S. Naval Ordnance Laboratory
White Oak, Maryland

Complex initial permeability measurements have been made on polycrystalline garnet toroids of the form (3-x) $Y_2O_3 \cdot xGd_2O_3 \cdot 5Fe_2O_3$ where x ranged from zero (yttrium-iron garnet) to three (gadolinium-iron garnet). Both the real initial permeability μ'/μ_0 and the imaginary initial permeability μ''/μ_0 were measured at 23°C, -68°C, and -196°C over a frequency range of 1000 c/S to 2000 Mc/S. At room temperature the low frequency value of μ'/μ_0 was found to decrease with increasing gadolinium content. At lower temperatures the low frequency value of μ'/μ_0 exhibits a minimum in x caused by the temperature dependent behavior of the two different magnetic sub-lattices.[1] The frequency at which the maximum value of μ''/μ_0 occurs was found to increase with the addition of gadolinium; the value of the loss tangent at this frequency is relatively independent of gadolinium content as well as temperature. No thermal relaxation was observed in these garnets, but rather the peaks in the μ''/μ_0 curve shifted to slightly higher frequencies with decreasing temperature.

1. E. E. Anderson, J. R. Cunningham, Jr., and G. E. McDuffie, Jr., Bull. Am. Phy. Soc., Ser. II 4, 241 (1959).

---

12. RESONANCE EXPERIMENTS WITH SINGLE CRYSTAL YTTRIUM IRON GARNET IN PULSED MAGNETIC FIELDS

MARTIN R. STIGLITZ and FREDERIC R. MORGENTHALER
Air Force Cambridge Research Center
Cambridge, Mass.

A single crystal sphere of YIG has been placed in a doubly resonant, transmission type, coaxial cavity and immersed in a uniform magnetic field. A low power microwave signal in the S band frequency range (CW or pulsed) was used to excite resonance at the lower cavity frequency. Current pulses of approximately one microsecond duration and low duty cycle, sent through a low impedance coil which is wound around the cavity, induce pulsed magnetic fields of the order of 1000 gauss which add to the existing dc field. A microwave receiver attached to the cavity output detected weak oscillations at the higher cavity frequency. Shifts up to 250 mc. have been obtained. The effect is strongly dependent on the dc biasing field and on the crystal orientation, but less so on the magnitude of the current pulse. The detected signal appears to be associated with the decay portion of the current pulse rather than with its rise.

Experiments at higher microwave powers, as well as at other frequencies, are contemplated, and will be carried out in both nonresonant structures and multiply resonant cavities. If possible, their results will be discussed.

---

13. SPECIFIC HEAT OF SOME RARE EARTH IRON GARNETS BETWEEN 1.4 - 20°K*

HORST MEYER and A. B. HARRIS
Gordon McKay Laboratory
Harvard University

We have started a study of the thermal properties of rare earth iron garnets by measuring the specific heats between 1.4 and 20°K of the garnets of yttrium, gadolinium, ytterbium, erbium and holmium. These results will be presented and discussed in terms of the Weiss molecular field approximation and other recent theories.

We have assumed that in first approximation the specific heat can be written as

$$C = C_L + C_{RE} + C_{Fe}$$

where C_L is the lattice contribution, C_{RE} is the magnetic specific heat of the rare earth "c" sublattice and C_{Fe} is that of the "a" and "d" iron sublattices. Assuming also that $C_L + C_{Fe}$ is approximately the same for all the measured garnets, C_E can be obtained to a good accuracy by subtracting the specific heat of yttrium iron garnet (YIG) from that of the other rare earth garnets. In general $C_{Fe} + C_L$ was found to be much smaller than C_E over the whole temperature range. C_E is particularly interesting since it leads to the determination of the molecular field acting on the rare earth ions, and whose value can be compared to that derived from Pauthenet's magnetization measurements. For gadolinium garnet, for example, we find that the effect of molecular field below 20°K is about 2.80×10^5 oersted, in good agreement with Pauthenet's[1] results. For ytterbium garnet, the field is approximately 1.50×10^5 oersted.

The lattice specific heat of our YIG sample was found to be appreciably smaller than the one measured by Edmonds and Petersen.[2] The spin wave contribution was approximately the same as that measured by these authors, and the lattice contribution agreed with that calculated from velocity of sound measurements by McSkimin.[3] Measurements of another YIG sample with appreciable orthoferrite impurities were made in a magnetic field of 4 kilooersted. The effect of this field on the specific heat was found to be very small.

*Research jointly sponsored by contracts AF 19(604)-5487 and Nonr-1866(33).

1. R. Pauthenet. Journal de Physique et Radium 20, 388, 1959.
2. D. T. Edmonds and R. G. Petersen, Phys. Rev. Letters 2, 499, 1959.
3. Private communication.

14. AN IMPROVED METHOD FOR THE GROWTH OF CRYSTALS OF YTTRIUM-IRON AND YTTRIUM-GALLIUM GARNETS

J. W. NIELSEN
Bell Telephone Laboratories, Inc.
Murray Hill, N. J.

Molten mixtures of lead oxide and lead fluoride have been found to be greatly superior to pure lead oxide[1] as solvents from which yttrium and rare-earth garnets may be crystallized. The maximum size of crystals obtained by this method is about ten times that obtained in pure PbO. An appreciable improvement in crystal quality is also observed. For instance, from melts weighing 2kg. it is possible to obtain several crystals weighing from 14 to 20 grams. In many cases 70% of the material in such crystals is completely unflawed.

Two other major advantages gained by the use of PbO-PbF_2 mixtures are lower operating temperatures and a wide range of melt compositions from which only garnet crystallizes. Examples of (1) conditions, and (2) ranges of composition are:

(1) Holding time 4 hours at 1250°C., cooling rate 0.5°C. per hour to 950 - 1000°C.

(2) For YIG 10 mole per cent Y_2O_3, 20 mole per cent Fe_2O_3, 30 mole per cent PbO and 40 mole per cent PbF_2; for YGG 5.8 mole per cent Y_2O_3, 14 mole per cent Ga_2O_3, 39.4 mole per cent PbO, and 40.8 mole per cent PbF_2.

Various solid solutions of gallium and iron garnets have also been grown as single crystals. Crystals of rare-earth iron garnets containing Sm, Eu, Gd, Tb, Dy, Ho, Er, and Yb have been prepared using the PbO-PbF_2 solvent.

The addition of another component, PbF_2, to the pseudo-ternary system PbO-Y_2O_3-Fe_2O_3, so complicates the study of the crystal growth of garnets from the standpoint of phase equilibrium that a strictly empirical approach is dictated. Thus, the effects observed on the growth and the chemistry of the melts when various experimental conditions are changed will be discussed.

1. J. W. Nielsen & E. F. Dearborn, J. Phys. & Chem. Solids 5, No. 3, 202 (1958).

15. PARAMAGNETIC RESONANCE OF Yb^{3+} IN GALLIUM GARNET

JOHN W. CARSON and ROBERT L. WHITE
Hughes Research Laboratories
Culver City, California

The paramagnetic resonance spectrum of the Yb^{3+} ion has been observed in Y Yb Ga garnet at 34 Kmc for temperatures of 77°K, 4.2°K and 1.8°K. The experimental results indicate that there are 6 magnetically inequivalent sites for the Yb^{3+} ion in the garnet, giving rise in general to 6 absorption lines. For certain orientations of the magnetic field with respect to the crystal axes the number of lines observed is reduced to as few as two. Accompanying the main lines are a large number of less intense satellite lines presumably due to nuclear hyperfine interactions.

The principal values of the g tensor were measured to be 2.85, 3.60 and 3.73. These values are about 3% lower than those of Wolf et al.[1] A calculation of the g tensor has been performed using a crystalline potential which is predominantly cubic but includes also perturbing potentials of the symmetry known to exist in the garnet crystal. From this calculation and the data the relative values of the perturbing potentials have been computed.

Values of linewidths and relaxation times as a function of temperature and Yb^{3+} concentration will be presented. For a concentration of $\frac{1}{2}$% Yb relative to Y, linewidths at liquid helium temperatures are typically about 25 gauss. At 77°K the linewidths are approximately 200 gauss. Of special interest is the longitudinal relaxation time T_1. At 4.2°K T_1 is in the range of .1 to .01 sec.

1. W. P. Wolf, private communication, and Boakes, Garton, Ryan and Wolf, Proc. Phys. Soc., to be published.

SESSION II-B

PERMANENT MAGNETS

W. F. BROWN, Jr., Presiding

16. ON THE REMANENCE OF FERROMAGNETIC POWDERS (Invited)

S. SHTRIKMAN and D. TREVES
The Weizmann Institute of Science
Department of Electronics
Rehovot, Israel

The angle, α, dependence of the maximum remanence parallel to the applied field, I_p, and the one perpendicular to it, I_t, is considered; and it is theoretically shown that for a rather wide range of materials the relation $I_t = \frac{dI_p}{d\alpha}$ should hold.

For the case of an assembly of noninteracting uniaxial single domains it is shown that the distribution of the easy axes in the assembly can be calculated from $I_p(\alpha)$ or $I_t(\alpha)$ and that $2\int_0^{\pi/2} I_p \sin\alpha \, d\alpha = I_s$, where I_s is the saturation magnetization. The above method, which yields[1] a Legendre series for the distribution, is deficient in that the high terms are quite sensitive to small changes in the remanences.

Measurements of I_p and I_t using a vibrating sample magnetometer were carried out on commercially oriented ferroxdure; magnetically oriented ferroxdure powder; oriented elongated single domain iron particles and anisotropic alnico. For the first three materials I_t was found to be a few per cent lower while for the last one it was up to 20% higher than that theoretically expected from the relation between I_p and I_t.

For ferroxdure the above discrepancy might be due to the large size of the particles. This results in their splitting into domains, in spite of their high crystalline anisotropy, after they are momentarily saturated in directions near to the hard one, thus reducing I_t.

For the elongated single domain particles the above explanation cannot hold because they are small enough. If, however, agglomeration in pairs is assumed, each pair having three possible maximum remanence values, the lowering of I_t is to be expected.

Further magnetic evidence for agglomeration of particles in magnetic powders is obtained from the remanence measurements made by Johnson and Brown[2] on elongated γ-F_2O_3 powders. A relation is derived for the pair model between the remanences acquired by the three methods used in these experiments. This relation is in much better agreement with the results of the above experiments, than the previous relations derived by Wohlfarth.[3] It is also shown that the anhysteretic remanence is related, for this model to the remanence curves discussed by Wohlfarth.

1. Frei, Shtrikman and Treves, J. Appl. Phys. 30, 443 (1959).
2. C. E. Johnson and W. F. Brown, Jr., J. Appl. Phys. 29, 1699 (1958).
3. E. P. Wohlfarth, J. Appl. Phys. 29, 595 (1958).

17. ANGULAR VARIATION OF THE MAGNETIC PROPERTIES OF E.S.D. PARTICLES

F. E. LUBORSKY and T. O. PAINE
General Electric Research Laboratory
Schenectady, New York

The demagnetization curves of oriented elongated single-domain-iron and iron-cobalt particles have been measured as a function of angle and packing fraction. The results are discussed in terms of the distribution of particle orientations and in terms of the magnetization reversal mechanism. It is shown that a straight chain-of-spheres interaction anisotropy model cannot account for the observed angular variation of properties, and an extension of this model is proposed that is consistent with observed particle structure and magnetic behavior.

18. THE MAGNETIC PROPERTIES OF ESSENTIALLY SPHERICAL IRON, COBALT, AND IRON-COBALT ALLOY PARTICLES

F. E. LUBORSKY and T. O. PAINE
General Electric Research Laboratory
Schenectady, New York

Previous work on the size dependence of coercive force, remanence, and the magnetization curve of essentially spherical iron and cobalt particles has been extended to cover the range from 25 to 1000 Å diameter. Zero-crystal-anisotropy 55:45 iron-cobalt alloy particles have also been measured. The particles were prepared by low-temperature electrodeposition into mercury, followed by thermal growth; size and shape distributions were determined by electron microscopy and magnetization curve analysis. The magnetic properties and superparamagnetic transitions are discussed in terms of the major anisotropies acting in each case: shape predominates in the 55:45 iron-cobalt alloy particles, crystal in the cobalt particles, and a combination of shape and crystal in the iron particles.

19. EFFECT OF COMPOSITION AND PREPARATION ON THE MAGNETIC PROPERTIES OF ELONGATED SINGLE-DOMAIN PARTICLES OF COBALT-NICKEL

R. B. FALK and G. D. HOOPER
Metallurgical Products Department
General Electric Company
Edmore, Michigan

Single-domain particles of Cobalt-Nickel have been prepared by electrodeposition into a mercury cathode. The particle composition was varied over the range 99% Cobalt-1% Nickel to 12% Cobalt-88% Nickel. The effects on magnetic properties caused by variations in electroplating conditions as well as variations in particle composition are described.

Coercive force measurements, electron photomicrographs of individual particles, and demagnetization curves of particle compacts are shown. Intrinsic coercive forces of 1800 oersteds have been obtained with particles containing 87% Cobalt and 13% Nickel.

20. COMPARISON OF THE CRITICAL SINGLE-DOMAIN SIZE FOR Fe_3O_4 AND γ-Fe_2O_3

L. A. K. WATT* and A. H. MORRISH
University of Minnesota
Minneapolis 14, Minnesota

The critical single-domain size for Fe_3O_4 (magnetite) and γ-Fe_2O_3 has been calculated by Morrish and Yu. They assumed that both oxides crystallized in the cubic spinel structure, that the particles were perfect prolate spheroids, and that the effects of crystalline anisotropy and cavities could be neglected. They found that the critical size for γ-Fe_2O_3 was somewhat larger than for Fe_3O_4. Thus, a particle of Fe_3O_4 could behave as though it were multidomain whereas, when oxidized to γ-Fe_2O_3, it would act as a single domain. Experimental evidence has been obtained in support of this conclusion.

Measurements have been made of the coercive force as a function of temperature and as a function of compression for a single powder in both the Fe_3O_4 and γ-Fe_2O_3 forms. The results were then compared with similar measurements made on powders which were believed to contain either mostly single- or mostly multidomain particles. In the Fe_3O_4 form the powder behaved as though most of the particles were multidomain in both the temperature and compression experiments. For the γ-Fe_2O_3 form, on the other hand, the results of both experiments indicated that the powder contained mostly single-domain particles.

The size and shape distribution of the particles was determined by means of an electron microscope. This distribution was plotted along with the theoretical curves for the critical single-domain size as a function of axial ratio. It was found that about 50% of the particles had values of length and axial ratio which fell in the region between the two curves. Thus, the actual particle size and shape distribution was consistent with the calculated critical single-domain size and with the experimental conclusion that in the Fe_3O_4 form the particles were mostly multidomain while in the γ-Fe_2O_3 form they were mostly single-domain.

*Present address: Department of Electrical Engineering, University of Washington, Seattle 5, Washington.

---

21. PRECIPITATION OF DISPERSED FINE-PARTICLE MAGNETITE

L. E. SLATEN
IBM Research Laboratory
Poughkeepsie, New York

Particle agglomeration, an inherent problem with present methods of producing magnetic micropowders, has precluded investigation of the magnetic properties of completely dispersed fine particles. A method has been developed for preparing well-dispersed fine-particle magnetite and cobalt-substituted ferrites by precipitation *in situ*.

A solution of Fe^{++} and Fe^{+++} can be formed into a sol by the addition of agar-agar and polyvinyl alcohol. The magnetite particles can then be precipitated by diffusing NaOH into the resulting semi-rigid gel. The size range of these particles is from superparamagnetic to single domain, based on electron micrographs and magnetic data. Films of this material have been prepared in various shapes and thicknesses, ranging from a few angstroms to several millimeters.

A study of the precipitation reaction has shown that the properties of the resulting magnetic particles appear to be limited by factors intrinsic in the mechanism of the reaction rather than by the limitations imposed by the gel-resin system used.

The present investigation has included variation of some of the physical and chemical parameters of the precipitation reaction *in situ*, and in aqueous and non-aqueous solutions, with emphasis upon resulting particle size and shape, coercivity, and B_r/B_s ratio. Some of these variables have been temperature, concentration, precipitant, the Fe^{++} to Fe^{+++}ratio, time of precipitation, reaction solvent, and presence of $NaNO_2$ in the precipitant.

Typical magnetite films exhibit a coercivity of about 50 oe., with a B_r/B_s ratio of 0.4. Much higher coercivities can be obtained with cobalt substitution.

---

22. A NEW MATERIAL FOR PERMANENT MAGNETS ON A BASE OF MANGANESE AND ALUMINIUM

A. J. J. KOCH, P. HOKKELING, M. G. v. d. STEEG and K. J. de VOS
Metallurgical Laboratory
N. V. Philips' Gloeilampenfabrieken
Eindhoven, the Netherlands

Investigating the system manganese-aluminium it was found that in alloys within the composition region from 68% Mn to 75% Mn a phase can occur, which can be described from X-ray diffraction patterns as having a tetragonal crystal structure with lattice constants a = 2,77 Å and c = 3,54 Å and lattice positions 0,0,0 and $\frac{1}{2},\frac{1}{2},\frac{1}{2}$ with a preference of the manganese atoms for one of these positions. The tetragonal structure is not an equilibrium modification, but has a metastable character; it can only be obtained by a special heat treatment.

This metastable modification possesses remarkable magnetic properties. Having the bulk material an intrinsic coercive force $_IH_C$ of 600 - 1200 Oe, this value can be raised to more than 6000 Oe by pulverizing. However, the increase of the $_IH_C$ is accompanied by a decrease of the saturation magnetization $4\pi I_s$, which amounts to 6200 G at room temperature. By annealing the powders, the saturation magnetization increases and the coercive force decreases again. No fixed correlation exists between particle size and coercive force.

From the approach to saturation it appears that the tetragonal phase possesses a high magnetic anisotropy. However, an explanation of the phenomena based upon a high crystal anisotropy does not satisfy.

An anisotropic permanent magnet was made with the following properties:

$$B_r = 4200 \text{ G} \qquad {}_IH_C = 4600 \text{ Oe} \qquad {}_BH_C = 2700 \text{ Oe}$$

$$BH_{max} = 3,5 \times 10^6 \text{ G.Oe}$$

23. AN INTERACTION ANISOTROPY MODEL OF THE STRUCTURE OF ALNICO

T. O. PAINE and F. E. LUBORSKY
General Electric Research Laboratory
Schenectady, New York

The properties of Alnico have previously been accounted for in terms of the shape anisotropy of an elongated single-domain magnetic precipitate. Electron micrographs of Alnico show a precipitate structure not inconsistent in size and shape with that required.

This paper reports measurements of the angular variation of the magnetic properties of directional-grain Alnico which are inconsistent with this model. A new model is proposed in which the structure of Alnico is considered to consist of a continuous magnetic phase subdivided by a finely dispersed phase into a single-domain size network whose magnetic properties are controlled by interaction anisotropy. In its simplest form this structure can be visualized as a series of interconnected H-shaped units. Interaction anisotropy, previously shown to account for the properties of elongated-single-domain iron particles, can also account for the magnetic behavior of Alnico when magnetostatic interactions within the basic H-shaped structural unit are considered. The new model is consistent with the observed magnetic properties of Alnico and with the structure revealed in electron micrographs.

---

24. TRANSMISSION ELECTRON DIFFRACTION OF ALNICO V*

K. J. KRONENBERG
The Indiana Steel Products Company
Valparaiso, Indiana

Alnico V samples have been produced which allow transmission electron microscopy. Electron micrographs and diffraction patterns are presented which have been obtained from Alnico V at various stages of completeness. The development of the permanent magnet precipitate out of the matrix is shown in the material itself without replicating. The alterations in structure and the growth of crystals of both phases were followed in detail by diffracting electrons through the changing material.

*Research was supported by the United States Air Force under Contract AF33(616)-3385 monitored by the Aeronautical Research Laboratory, Wright Air Development Center.

---

25. LONG TERM MAGNETIC STABILITY OF BARIUM FERRITE AND ALNICO MAGNETS*

K. J. KRONENBERG and M. A. BOHLMANN
The Indiana Steel Products Company
Valparaiso, Indiana

The long term stability of Alnico III, V and VII was measured over periods of time up to $2\frac{1}{2}$ years. Samples of each material and of various shapes were studied with the emphasis on Alnico V. The measurements were performed with precision equipment using impulse compensation with a tolerance of 1/10,000 for changes of remanence.

For the Alnico materials, as well as for barium ferrite, the expression "aging" is not appropriate. Changes of the materials proper (as in martensitic steel) have not been observed at room temperature.

After magnetization the remanence adjusts to the conditions to which the magnet is exposed. This often results in a slight reduction of the original remanence. Several Alnico V bars had still 99.99% of their initial remanence a full year after magnetization. Magnets of Alnico III (the least stable Alnico) still had over 97% of their initial remanence one year after magnetization.

For applications where a greater stability is required magnets must be stabilized. Two basic stabilizing treatments were tested: temperature cycling and 60 cps a.c. fields. Temperature cycling between room temperature and -65°C was found more effective than cycling above room temperature. The better stabilizing method was a remanence reduction up to 10% by a.c. demagnetizing fields. We found this method to be more effective and more convenient to use.

The following generalizations for magnets at room temperature were made from the results:

1) The higher the coercive force the more stable is remanence.

2) The smaller the irreversible susceptibility at the operating point (the larger the L/D ratio of a bar magnet), the more stable is the remanence.

3) When remanence decreases in time, the change is proportional to the logarithm of the time elapsed after magnetization.

4) Remanence can be perfectly stabilized by reducing it 5-15%. Greater or very sudden knock-down treatments can result in erratic behavior.

5) Incompletely magnetized magnets are more stable than fully magnetized magnets, but not as stable as those fully magnetized and properly stabilized.

The remanences of barium ferrite magnets were closely observed over a period of several years. The magnets were stored at a nearly-constant temperature of 24°C. Both the crystal-oriented and the unoriented types of material were studied. Results show that the material itself is stable with time.

The remanences of these magnets are stable with time also when the intrinsic coercive force of the material exceeds about 2300 oersted. Most barium ferrites of the unoriented type, and some of the crystal-oriented type, are in this category. The remanences in barium ferrite magnets having $H_{ci} < 2300$ oersted decrease at rates proportional to the logarithm of time. Most of the available crystal-oriented materials belong to this category. The rates vary with the different coercive forces found in commercial materials.

The remanences in barium ferrite magnets are more stable than those in Alnico bars, even though the ceramic magnets in most designs have a much smaller shape (L/D) ratio. This can be expected because the barium ferrite magnets have smaller irreversible susceptibilities at the operating points than Alnico magnets.

To reduce instability to a minimum crystal-oriented barium ferrite magnets should be designed to have the whole magnet operating above the knee of the demagnetization curve. This increases magnetic stability with respect, not only to time, but also to temperature. Experiments on stabilizing remanences by exposing barium ferrite magnets to 60 cps a.c. fields are in progress.

*Research supported by the United States Air Force under Contract AF33(616)-3385 monitored by the Aeronautical Research Laboratory, Wright Air Development Center.

26. HOT WORKING OF ALNICO 5 ALLOYS

C. L. KOLBE and D. L. MARTIN
General Electric Research Laboratory
Schenectady, New York

Alnico 5, which has been considered an unworkable hard brittle permanent magnetic material, has been successfully fabricated into rod, wire and thin strip by hot working.

Commercial alloy compositions of nominal composition 8 Al, 14 Ni, 24 Co, 3.2 Cu, 0.25 Zr, Bal Fe were extruded from $3\frac{1}{2}$" diameter billets into $\frac{3}{4}$" rod, swaged into long lengths of 100" diameter wire and rolled into .005" thin strips.

Vacuum melting, ingot encasing, extrusion process techniques, temperature control and alloy additions of Zr, Ti, and Al all play an important part in the ease of fabrication.

The magnetic properties of the wrought materials are equivalent to the cast properties and the mechanical properties are improved.

SESSION III-A

SPIN WAVES-MAGNETOSTATIC MODES

H. SUHL, Presiding

27. THE USE OF MAGNETOSTATIC MODES AS A RESEARCH TOOL (Invited)

ROBERT L. WHITE
Hughes Research Laboratories
Culver City, California

The general characteristics of the magnetostatic modes of ferrimagnetic spheroids are by now quite well understood. The resonance characteristics of a sphere have been particularly well documented. This knowledge of the anatomy of the resonance phenomena permits usage of the modes for the measurement of material properties such as $\underline{M}$, the saturation magnetization; $\underline{\gamma}$, the gyromagnetic ratio; and $\underline{K_1}$ and $\underline{K_2}$, the first and second order anisotropy constants of cubic materials. Further, much information on relaxation processes and the interaction of the quasi-uniform precessions with the spin wave system can be deduced from magnetostatic mode data.

This paper will discuss the use of the magnetostatic modes for these purposes. Two areas will be emphasized: (1) Recent developments in the usage of modes; e.g., for the monitoring of transient variations in M due to spin wave disturbances (2) Recent developments in the theory of magnetostatic modes which may require re-examination of older data, e.g., on K_2 or on γ.

28. ELECTRON SPIN RELAXATION IN FERROMAGNETIC INSULATORS (Invited)

R. C. LECRAW, R. C. FLETCHER and E. G. SPENCER
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

A review is presented of the various approaches in the literature to describe electron spin relaxation in ferromagnetic insulators. Emphasis is placed on recent developments involving scattering into spin waves due to inhomogeneities in the magnetization,[1,2] particularly as it pertains to relaxation in narrow line width materials.

A new treatment of ferromagnetic relaxation will be described together with experimental data which demonstrate the adequacy of the approach. The equation of motion of the magnetization involves T_{10}, the relaxation time of the uniform precession to the lattice; T_{2k}, the relaxation time of the uniform precession to the k^{th} spin wave; and T_{1k}, the relaxation time of the k^{th} spin wave to the lattice. For the special case $T_{10} = T_{1k}$, the equation of motion is shown to reduce to the Bloch equation.

Measurements have been made at 6200 Mc/sec on a single crystal sphere of yttrium iron garnet (YIG) with the above relaxation times determined as a function of controlled amounts of scattering into spin waves, obtained by varying the surface roughness. The same sample is used throughout, with only the surface being varied. To make the measurements at rf power levels below the first evidence of saturation effects, required the development of a nonpulsed frequency modulation method in place of the usual pulsed decay scheme for measuring spin-lattice relaxation times. The principal features of this new technique will be discussed.

The theory provides an excellent fit to the experimental data. The theory, together with the modulation technique, permits the bulk property, T_{1k}, to be determined experimentally in the presence of large surface scattering (unpolished spheres with $\Delta H = 3.56$ oe). The other bulk property, T_{10}, is obtained by applying the theory to data for the smoothest surface ($\Delta H = 0.47$ oe). The relevance of these bulk properties for studying fundamental relaxation mechanisms is discussed. In particular, with respect to the high-purity YIG samples now available[3], it is believed that T_{10} and T_{1k} are of considerably more theoretical value than ΔH, because of the strong dependence of the latter on both volume and surface inhomogeneities.

1. Clogston, Suhl, Walker, and Anderson, J. Phys. Chem. Solids, 1, 129 (1956).
2. LeCraw, Spencer, and Porter, Phys. Rev. 110, 1311 (1958).
3. E. G. Spencer and R. C. LeCraw, Abstract, This conference.

---

29. ON THE THEORY OF FERROMAGNETIC RESONANCE IN SMALL FERRIMAGNETIC ELLIPSOIDS

FREDERIC R. MORGENTHALER
Department of Electrical Engineering
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

Part I of this paper derives the general equations of motion for the uniform component of magnetization for the case of a small ellipsoid magnetized in an arbitrary direction and excited by spatially uniform microwave magnetic fields of arbitrary frequencies and directions. The generalized Kittel frequency and tensor permeability are derived and possible frequency generation processes appropriate to the ellipsoidal geometry treated in detail.

In particular, it is found that subharmonics as well as harmonics may be created and an interesting process of fourth harmonic generation, of higher efficiency than would normally be expected (linear with respect to input power), appears possible. Unfortunately, the efficiency decreases very rapidly with increasing frequency but the conditions for maximizing the effect are given.

In addition, a mechanism of second harmonic parametric coupling is uncovered with is strongly dependent on sample shape.

Part II derives the general equations of motion for the magnetization in a small ferrimagnetic ellipsoid, magnetized in an arbitrary direction and excited by spatially uniform microwave magnetic fields of arbitrary frequencies and directions when a typical spin wave is present.

The generalized Suhl spin wave spectrum is derived together with the coupling relations between the uniform precession and the spin wave. The Suhl first and second order instability thresholds for a spheroid magnetized along its axis are formulated in a simple manner and the generalized thresholds are then discussed for the ellipsoid.

Direct parametric coupling between the pumping field and spin waves is discussed. Certain spin wave transients will also be considered.

---

30. HARMONIC GENERATION IN A FERRIMAGNETIC DISC

GLENN E. BENNETT
Air Force Cambridge Research Center
Bedford, Massachusetts

The theory of harmonic generation in small ferrimagnetic ellipsoids, magnetized in an arbitrary direction, has been developed by Morgenthaler[1]. For this paper, an S-Band transmission type structure has been constructed to experimentally check the shape dependent generating processes of this theory on thin garnet discs.

Conversion efficiencies for generating processes in the longitudinal and transverse planes - defined relative to the internal DC magnetic field of the disc - and their dependence upon the direction of internal magnetization will be given together with data checking the generalized Kittel frequency for the experimental geometries.

1. Morgenthaler, F. R., "On the Theory of Ferromagnetic Resonance in Small Ferrimagnetic Ellipsoids." Submitted to the 1959 Conference on Magnetism and Magnetic Materials.

---

31. THEORY AND APPLICATION OF DIPOLAR FERRITE MODES

WILLIAM H. STEIER and PAUL D. COLEMAN
Ultramicrowave Group
Department of Electrical Engineering
University of Illinois
Urbana, Illinois

Experimental verification at X- and K-band of theoretical calculations on the magnetodynamic resonant modes of a ferrite rod between parallel conducting sheets is reported. Mode Q's as high as 1100 have been measured. Preliminary data on a ferrite parametric amplifier using these modes is presented.

The characteristic equation which is derived includes propagation effects and dipolar coupling between electron spins. Mode charts for the symmetric modes have been numerically computed for biasing fields from 3 to 20 kilo-oersteds and for frequencies from 4 to 48 kmc. for both Ferramic R-1 and polycrystalline YIG. To facilitate the coupling to the modes, diagrams of $\overline{M}$, $\overline{B}$, and $\overline{E}$ fields for a typical mode are shown.

The modes have been experimentally observed in the ranges of 10 to 20 kmc. Comparison of theoretical and experimental data is made in these bands for both R-1 and YIG. The variation of the observed loaded Q with biasing magnetic field is described.

These ferrite modes offer advantages in application to engineering devices due to the large size of the ferrite sample and to the ease of coupling to the mode. One engineering application, an X-band ferrite parametric amplifier, is discussed. The amplifier employs two ferrite body modes: one is the magnetodynamic mode discussed herein and the other is the uniform precession mode.

---

32. MAGNETIC ANISOTROPY FROM THE MAGNETOSTATIC MODES

I. H. SOLT, JR. and P. C. FLETCHER
Hughes Research Laboratories
Culver City, California

It has generally been conceded that for "spherical" single crystal samples the variation in resonant magnetic field with crystal orientation is the same for all of the magnetostatic modes. We have re-examined this question by including anisotropy torques in the equations of motion for the modes and exact solutions have been obtained for the resonant fields of four of the lowest order modes. From the inclusion of anisotropy there result correction terms giving deviations from the simple theory. These correction terms vanish in the [100] and [111] crystal directions but give rise to sizeable differences in spacings of the line positions for these four modes in the [110] direction. These results are necessary for obtaining correct values of magnetization, g-factors and anisotropy constants from the modes.

Experimental measurements have been made on single crystal YIG spheres at 8500 Mc and are in good agreement with the theoretical predictions.

---

33. FERRIMAGNETIC RESONANCE AT HIGH POWER

M. T. WEISS*
Microwave Laboratory
Hughes Aircraft Company
Culver City, California

Ferrimagnetic resonance experiments have been performed on single crystal manganese ferrite at high microwave powers. The variation of the susceptibility with power level is in good agreement with Suhl's[1] recent theoretical treatment of the saturation process in which scattering of the uniform precession at impurities and imperfections is taken into account. Our results show that the ratio of intrinsic to scattering decay constants is close to zero, so that χ'' decreases gradually at power levels substantially below the theoretical critical signal level.

A variation of resonant frequency with power level was also observed in manganese ferrite spheres as well as in single crystal YIG spheres, with the sign of the frequency change being different for these two materials. It is believed that this anomolous effect can be explained on the basis of a g-factor variation with spin temperature.

---

*The data on which the above paper is based was taken while the author was at Bell Telephone Laboratories.

1. H. Suhl, "A Note on the Saturation of the Main Resonance in Ferromagnets," to be published in J. Appl. Phys.

34. MAGNETOSTATIC MODES OF A FERROMAGNETIC SLAB

R. W. DAMON and J. R. ESHBACH
General Electric Research Laboratory
Schenectady, New York

The characteristic modes of ferromagnetic samples have been previously derived in the magnetostatic limit for spheroids of revolution about the applied d-c magnetic field.[1] It is of interest to determine similar solutions in other geometries. In particular, the characteristic modes of a thin slab magnetized in its plane permit fairly straightforward solution. Although many of the properties of these modes are similar to those of the spheroid, the simplicity of the mathematical functions describing the modes in this geometry permit a more intuitive understanding of the mode spectrum and mode configurations.

It is found that the magnetostatic mode spectrum of a slab is bounded by the same frequency limits as for the spheroid; this spectrum thus also extends over a larger frequency range than the extrapolated spin-wave band for $k \to 0$. The transition between the magnetostatic and spin-wave modes is complicated in the case of spheroids by the difference in mathematical form of the two types of solution. Since the characteristic modes of a slab are plane waves for all wavelengths, the transition is more readily understood in this case.

It is found that the magnetostatic modes lying within the extrapolated spin-wave band have harmonic spatial variation extending throughout the sample. There are no modes below the bottom of the spin-wave band, but modes do exist above the extrapolated spin-wave band, as was also found for spheroids. These high-frequency modes are tightly bound to the surface of the slab and are therefore not found when one solves for the spin-wave modes in a medium of infinite extent.[2] The surface modes are qualitatively unchanged as the wavelength decreases, and yield modes above the spin-wave band even for wavelengths short compared with sample dimensions. However, the ratio of the number of surface modes to the number of volume modes varies as $\frac{1}{|k|}$, so the surface modes become statistically less important at shorter wavelengths.

In general, the characteristic functions are traveling waves which propagate along the slab transversely to the applied d-c magnetic field. Only a limited class of solutions are standing waves. The traveling wave modes are non-reciprocal, since reversal of the transverse propagation direction interchanges the unequal rf field amplitudes at the two surfaces.

For certain modes, the system is unperturbed by the presence of conducting boundaries, and we obtain the spectrum and configuration of some of the modes studied in connection with electromagnetic propagation in ferrite-loaded transmission systems.[3]

1. J. Mercereau and R. P. Feynman, Phys. Rev. 104, 63 (1956); L. R. Walker, Phys. Rev. 105, 390 (1957).
2. C. Herring and C. Kittel, Phys. Rev. 81, 869 (1951).
3. H. Seidel, Proc. IRE 44, 1410 (1956); R. C. Fletcher and H. Seidel, J. Appl. Phys. Suppl. 30, 1475 (1959).

35. FINITE AMPLITUDE ELECTROMAGNETIC WAVES IN GYROMAGNETIC MEDIA

B. A. AULD
Microwave Laboratory
Stanford University
Stanford, California

The theory of harmonic generation in gyromagnetic spheroids which are sufficiently small that propagation effects can be neglected has been considered in detail by a number of writers. It has been found experimentally, however, that rather large samples are required for high conversion efficiencies. For this reason it is desirable to investigate the question of non-linear propagation effects in gyromagnetic media.

A perturbation method has been developed for obtaining forced steady-state solutions to Maxwell's equations and the torque equation with a damping term, subject to the usual conditions on tangential E and H at boundary and discontinuity surfaces. The solution, expressed as a time Fourier series with the same period as the sinusoidal forcing function, is assumed to have the form of a power series in the amplitude of the forcing function. Substitution of this series into the Maxwell and torque equations and the boundary conditions leads to a separation of the harmonic components into terms of different order. This reduces the non-linear problem to a set of linear boundary-value problems for an anisotropic medium, characterized by the Polder permeability tensor, excited by specified distributions of magnetic sources. In the n^{th} order term the distributions of sources for the various harmonic components are determined from the terms of order less than n. Special consideration must be given to the zero frequency components of the higher order terms. This is a step-by-step procedure which may be repeated as desired to give the power series solution. Concise general expressions are obtained for the source distributions driving the harmonic components in the n^{th} order term.

As an example, this procedure is applied to the problem of non-linear scattering of uniform plane waves from a semi-infinite gyromagnetic slab, with bias field parallel to the face of the slab. An explicit solution up to terms of third order is obtained for the case of normal incidence, and numerical results are presented.

---

36. SPIN WAVES IN COMPLEX EXCHANGE-COUPLED LATTICES AND NEUTRON SCATTERING

A. W. SÁENZ
U. S. Naval Research Laboratory
Washington, D. C.

Recent experiments on the scattering of unpolarized[1] and polarized[2] neutrons by spin waves in Fe_3O_4, and possible extensions of this work to similar complex spin lattices, indicate the need for two closely related theoretical developments. The first is a spin-wave theory applicable to exchange-coupled lattices with an arbitrary number n of magnetic ions per primitive magnetic unit cell. The second is the derivation of cross-section formulas for the spin-wave scattering of neutrons of arbitrary polarization by such lattices. These two questions are treated here within the Holstein-Primakoff formalism.[3]

The Hamiltonian H of the magnetic ions is taken to have an exchange portion H_0 and a non-exchange portion H_1. The effect of lattice vibrations is neglected in H_0, where we assume that the exchange constants depend only on the pertinent equilibrium distances between the magnetic ions. In H_1, we include the effect of a hypothetical anisotropy field, introduced for familiar reasons of stability, and of an external magnetic field, both directed along the axis of spin alignment. The $\leq n$ distinct branches of the spin-wave spectrum are obtained from a determinantal equation, whose formal simplicity results from exploiting a relation between the matrices of the quadratic forms in the canonical coordinates and momenta occurring in our spin-wave approximation of H. In the limit $H_1 \to 0$ and for $|\kappa|$ sufficiently small, where κ is the magnon wave-number vector, we derive an explicit necessary condition for the non-degeneracy of the "acoustic" branch of the above spectrum, as well as a number of properties of the matrices which effect the transformation to normal coordinates and momenta. These properties are useful in the applications to neutron scattering which we shall now outline.

The scattering of neutrons of arbitrary polarization by the spin lattices considered here, for the case of one-magnon and zero-phonon processes, perhaps the situation of greatest current experimental interest, is treated by means of the above spin-wave formalism and the approach of Van Hove[4]. The rather complicated cross-section formulas obtained in this way take on very simple forms in the limit $H_1 \to 0$, provided that only acoustic magnons of sufficiently small $|\kappa|$ participate significantly in the scattering and that the acoustic mode is non-degenerate in the corresponding region in κ-space. These simple results are used to predict an interesting new spin-wave effect for polarized neutrons, which should be observable for suitable ferrimagnets, for example, for Fe_3O_4.

1. B. N. Brockhouse, Phys. Rev. 106, 859 (1957); 111, 1273 (1958).
2. These experiments are being carried out by Mr. G. Ferguson at the Naval Research Laboratory.
3. T. Holstein and H. Primakoff, Phys. Rev. 58, 1098 (1940).
4. L. Van Hove, Phys. Rev. 95, 1375 (1954).

SESSION III-B

COMPUTERS - SWITCHING

C. J. KRIESMANN, Presiding

---

37. FLUX REVERSAL IN SOFT FERROMAGNETICS (Invited)

E. M. GYORGY
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

Many aspects of flux reversal in soft ferromagnetic materials may be interpreted in terms of three types of flux reversal processes. These three types are domain wall motion, nonuniform rotation, and uniform rotation. It has been shown that in general wall motion is the predominant mechanism for values of the applied magnetic field slightly in excess of the coercive field, that nonuniform rotation predominates for intermediate magnetic fields, and that uniform rotation predominates for large fields. The salient features of these three types of flux reversal will be discussed and compared with experimental findings. Special emphasis will be given to polycrystalline, square-looped ferrites and thin permalloy films. The importance of geometric effects will be illustrated in a review of detailed models for the uniform and nonuniform rotational processes. Specific limitations of the existing models will be discussed, and possibilities for future advances will be briefly outlined.

---

38. OPERATION OF MAGNETIC FILM PARAMETRONS IN THE 100 TO 500 mc REGION*

A. V. POHM, A. A. READ, R. M. STEWART, JR. and R. E. SCHAUER
Electrical Engineering Department and Engineering Experiment Station
Iowa State University of Science and Technology
Ames, Iowa

An analysis of the behavior of thin magnetic films of Permalloy when used as time variable inductors has been made in terms of a modified Landau - Lifshitz equation. These results show that parametrons using time variable magnetic film inductors can be made to operate at reasonable power levels with large gains per cycle at oscillating frequencies in the 100 mc to 500 mc region. The analysis shows that with the proper bias field the build up time, decay time and power consumption can be optimized.

Ways of fabricating magnetic film parametrons with continuous dissipations in the 10 mw range which will operate at these frequencies are suggested.

Changes in the relative phases of the pump field and signal field during build up and saturation are considered. Ways of advantageously using these phase changes are discussed.

*The research reported in this paper was supported by a National Science Foundation Grant.

39. FERRITE FILMS - NEW LOGIC AND STORAGE DEVICES

J. M. BROWNLOW, W. L. SHEVEL, JR., and O. A. GUTWIN
IBM Research Laboratory
Poughkeepsie, New York

Magnetic devices for storage and switching applications in digital computers have been fabricated in the form of open flux path elements. The geometry employed is that of a planar film with thicknesses in the range of five to fifty microns and other dimensions in the fractional inch range. These elements have the advantages of a ferrite composition and of open flux paths without many of the disadvantages present in similar metallic devices. For use in storage systems, these devices possess excellent squareness characteristics and have coincident selection times comparable with ferrite toroidal devices. Properties of these devices are given in terms of switching curves, low frequency hysteresis loops, and one to zero signal ratios. Other aspects that are discussed include disturb sensitivity of storage elements, heating effects due to high pulse repetition frequency, and mechanical properties. For each of these, comparison is made with other types of magnetic elements such as toroids and metallic films. Proposals for applications are made in terms of drive requirements, packing densities and output signals.

---

40. ELECTRODEPOSITED MEMORY ELEMENTS FOR A NONDESTRUCTIVE MEMORY

T. R. LONG
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

Nickel-iron films are being electrodeposited on to a wire substrate to form memory elements for a fast, nondestructive memory. By plating in the presence of a directed magnetic field, an anisotropy favoring circumferential orientation is established. Axial interrogation fields cause reversible rotations of less than 90° and produce output signals across the ends of the wire. The apparatus and techniques used to make this wire are discussed together with the rationale back of the design. The choice of alloy composition and the plating conditions strongly affect the results. The amount of stress in the deposit, the residual stress in the substrate, the control of precleaning of the substrate, the use of a suitable wetting agent, and the degree of stirring in the electrolyte appear as the vital factors in obtaining consistent results. Moderate fields (~30 oersteds) applied during plating produce a preferred circumferential orientation with high anisotropy ($H_K/H_O = 3.0$) Squareness ratio in the easy direction is 0.99. Output signals appear during the rise time of the interrogation pulse with an amplitude inversely related to the rise time and directly proportional to the length interrogated. Very fast switching with unusually high output signals per unit length are possible. Selective write in is possible with current margins of 3:1. Preliminary investigations indicate that it would be feasible to make plated wire on a production basis with properties suitable for memory applications.

41. THE DEVELOPMENT OF HIGH-SPEED COINCIDENT CURRENT MEMORY CORES

BARLANE R. EICHBAUM
IBM Research Laboratory
Poughkeepsie, N. Y.

Present day computers have a memory cycle of the order of eight microseconds requiring memory cores which switch in 1.5 microseconds with 670 ma. full select 10% marginal drive currents. Three years ago a task was undertaken to develop a two microsecond memory which would require a memory core having a full select drive of approximately 1 amp. so as to utilize solid state driver components. The procedure used to develop such components from $MgO \cdot MnO \cdot Fe_2O_3$ compositions is described. The switching coefficient is reduced with an associated decrease in the drive requirements, by 30%, when Cr_2O_3 and Cao are partially substituted for Fe_2O_3 and MgO respectively in the $MgO \cdot MnO \cdot Fe_2O_3$ core composition.

---

42. MINIATURE MEMORY PLANES FOR EXTREME ENVIRONMENTAL CONDITIONS

A. HEUER, B. KANE, R. STRALEY, and G. TKACH
General Ceramics Corporation
Keasbey, New Jersey

Present memory systems using ferrite cores have been limited, among other things, by their relative bulk and narrow operating temperature range.

A marked reduction in size has been achieved by use of a "continuous wire" method of inserting drive lines through memory planes and then folding the planes. This method eliminates frames and solder connections between planes. By eliminating 90% of all solder connections, the new method increases reliability and facilitates assembly of stacked memory planes. A typical folded stack of memory planes occupies $\frac{1}{30}$ to $\frac{1}{50}$ the volume of its conventional counterpart. The new miniature memory planes perform equally well as conventional units, and it is indicated the new design may result in an improved signal to noise ratio.

The development of ferrite memory cores operable at ambients as high as 85°C, 100°C, and 125°C along with the greatly reduced volume of the memory stack, allows operation under extreme environmental conditions with a minimum of space and power requirements. The folded memory planes are packaged with a heating element and control circuit which maintains the temperature of the cores at the maximum ambient. A tested prototype of twelve (12) 16x16 memory planes, along with the heating element and control circuit measures 2" x $2\frac{1}{2}$" x $2\frac{1}{2}$" and has been successfully operated in the temperature range -55°C to +125°C.

Ferrite cores have been perfected of both the "fast" relative high drive and relative "slow" lower drive type. They are Mg-Mn ferrites with minor additions of other bivalent oxides.

43. A NEW APPROACH TO HIGH SPEED STORAGE - LOW FLUX DENSITY MATERIALS

W. L. SHEVEL, JR. and H. CHANG
IBM Research Laboratory
Poughkeepsie, New York

This paper presents a new approach toward overcoming the factors currently limiting the frequencies at which storage devices may be switched from one information state to another. Ferrite elements for random access storage have been developed which require a fraction of a microsecond for a cycle. Thus the ferrite switching time establishes a maximum switching rate given by the inverse of the total switching time in a cycle. However, operation of elements such as these in a large capacity memory at rates limited only by switching times is usually prevented by: deterioration of magnetic properties due to heating effects, increase in selection line impedance, and long transmission delays.

A series of ferrimagnetic oxides have been developed with properties such that the limits on minimum cycle time are appreciably extended. The most important of these properties is the saturation flux density. Over a range of composition flux densities have been obtained which extend from 100-500 gauss. The lower flux density results in an appreciably lower energy dissipation in the magnetic structure and consequently in higher switching rates for a given temperature rise within the magnetic material. In addition, temperature dependence of those magnetic properties which determine storage applicability is more favorable than with the better known ferrites.

Toroids have been fabricated with these materials which are suitable for random access memories. These elements have been operated successfully in free air at repetition frequencies in excess of 2 mc.

The improvements in array characteristics that result are discussed in terms of impedances and transmission delays.

---

44. A NEW MULTI-APERTURE MAGNETIC LOGIC ELEMENT

DAVID R. BENNION
Stanford Research Institute
Menlo Park, California

The simplest of the magnetic multi-aperture devices (MADs) developed at Stanford Research Institute for shift register use can be wired to perform AND and OR logic functions but not the NEGATION function. [1] However, a number of more complex MADs having the latter capability have also been designed and constructed at SRI. By simple modification of the winding arrangement, elements of some of these designs can be used for direct shifting of information as well. However, in the case of the earlier elements in this class, the required winding arrangements were quite complex, and drive tolerances were low.

One of the several magnetics research projects at SRI is directed towards the study of geometrical aspects of MADs with a view toward expanding their logic capability and quality of performance.[2] One outgrowth of this work has been the development of a new element of the type indicated above, i.e., one capable of direct shifting as well as AND, OR, and NEGATION logic functions when appropriately wired. The primary aims of this research have been the achievement of general logic capability in a single type of element with a minimum of wiring complexity, yet with substantial operating tolerances. Two methods for evolving the present basic shape of the element will be outlined, and some of the detailed design criteria indicated.

A number of these elements have been ultrasonically fabricated and then tested in their various modes of operation. The results obtained with this first design of an element having the new basic shape have been favorable enough to encourage a continued effort on this approach to a magnetic logic system composed of magnetic elements and wire only.

1. H. D. Crane, "A High-Speed Logic System Using Magnetic Elements and Connecting Wire Only," *Proc. IRE* 47, 1, pp. 63-73 (January, 1959).

2. This project is sponsored by the Office of Naval Research, Information Systems Branch.

45. FAST SWITCHING BY DOMAIN WALLS IN FERRITES

W. WIECHEC and C. M. KELLEY
Stanford Research Institute
Menlo Park, California

Experimental evidence indicates that small grain size is associated with faster domain wall switching in ferrite cores at low fields. It has been shown by H. Amar[1] that small grain size contributes an additional term to the wall energy, $\sigma\omega$. $\sigma\omega$ is incorporated into the power dissipation equation $H \cdot \frac{dM}{dt} = \lambda H_e^2$ by the relation:

$$H_e = -\left(\frac{v}{\gamma}\right)\left(\frac{d\theta}{dz}\right)$$

where $\frac{d\theta}{dz} = \left[\frac{g(\theta)}{A}\right]^{\frac{1}{2}}$ and $g(\theta)$ is the term containing the additional energy. Decreased grain size shows no increase of $H \cdot \frac{dM}{dt}$ when high density is maintained. Rather it is in the less dense, underfired cores that an increased magnetomotive force is noted. Therefore, if one assumes that H_e^2 increases in magnitude, λ must decrease. Following Galt, Andreas, and Hopper, the relation

$$v = \frac{2M_s \gamma^2 A^{\frac{1}{2}} H_0}{\lambda \int_0^{\pi} [g(\theta)]^{\frac{1}{2}} d\theta}$$ is obtained.

λ decreases as the square of H_e, but $g(\theta)$ increases only as the square root of H_e, and "v" increases (faster switching).

A qualitative explanation is given for faster switching by domain walls in magnetic materials. Because domain walls remain small in length, a demagnetizing field is generated in the wall. This field is perpendicular to the applied field and the magnetization. Closing fields to the demagnetizing field yield $\oint H \cdot dl = 0$. Since closing fields overlap into the reversed and unreversed magnetization, a transverse field effect is obtained—one side accelerating, the other side damping.

The significant variables in the switching coefficient equation are "d", T_c, K, and λ. Experimental data shows that decreases in the first three variables have the effect of lowering the switching coefficient. Considerably faster switching is predicted when similar cores with grain size less than one micron are made. The above explanation could also account for the faster switching now observed at high applied fields.

1. H. Amar, JAP, 28, 733 (1957).
2. J. K. Galt, J. Andrus, H. G. Hopper, Rev. Mod. Phys. 25, 93 (1953).

46. EFFECT OF PREVIOUS HISTORY ON SWITCHING RATE IN FERRITES

R. W. McKAY and K. C. SMITH
Department of Physics
University of Toronto
Toronto 5, Canada

Existing theories[1,2] of the inelastic switching of square-loop ferrites indicate that the rate of switching is a function of the present state of magnetization and of the applied field. Experiments are described in this paper which show that the switching rate is dependent on previous history also. Two cases have been studied. In the first, the ferrite is brought to the remanent state by pulses of different magnitudes and the resulting changes in switching rate for the reverse cycle with constant field are observed. In the second case the ferrite is demagnetized (half switched) in a variety of ways and the switching cycle is completed with a field of fixed magnitude.

In the second case when the field used to bring the core to the demagnetized state and the field used to complete the cycle are of the same magnitude the experiment resembles that of Gyorgi[3] on interrupted switching. In this case we find negligible changes in the switching curve due to the interruption of the pulse and suggest that the changes reported by Gyorgi were due to use of pulses with comparatively long rise and fall times.

Some results, including those obtained by bringing the core to the half switched state by means of a strong transverse field and then completing the switching cycle using a tangential field, lead to the suggestion that 180 degree domain-wall movements do not play the predominant part in ferrites which do not possess a strong uniaxial anisotropy.

1. M. K. Haynes, J. Appl. Phys. 29, 472 (1958).
2. F. M. Gyorgi, J. Appl. Phys. 29, 283 (1958).
3. F. M. Gyorgi, Conference on Magnetism, Boston, Nov. 1956.

47. ELASTIC SWITCHING PROPERTIES OF SOME TAPE AND FERRITE MATERIALS

W. C. SEELBACH and J. R. KISEDA

Elastic switching of tape or ferrite cores requires that the flux switched at the time of reading be essentially reversible. A correlation between the flux capacity of the core and the maximum elastic flux will be shown to exist by the introduction of the $S_{w(r)}$ concept and the consideration of R_o, the switching resistance of the core. $S_{w(r)}$ can be shown to be the slope of the $1/Pw$ versus H curve for a range of narrow elastic de-magnetizing pulses. R_o has been shown to be a switching resistance equal to the slope of the volts per turn versus NI curve. R_o can be plotted for inelastic and elastic switching and is shown, for all practical purposes, to be nearly equal for both cases. Since R_o can be expressed in terms of flux and S_w for inelastic and elastic switching, then the relationship between inelastic and elastic flux can be shown to exist as a simple ratio between the conventional S_w and $S_{w(r)}$.

Additional quantitative results for elastic switching are shown in the form of a plot of signal to noise ratios versus drive for various narrow pulse widths.

SESSION IV-A

ANISOTROPY

H. B. CALLEN, Presiding

48. ANISOTROPY PROPERTIES OF HEXAGONAL FERRIMAGNETIC OXIDES (Invited)

U. ENZ, F. K. LOTGERING and J. SMIT
Philips Research Laboratories
N. V. Philips' Gloeilampenfabrieken
Eindhoven-Netherlands

After a brief survey of the general properties of hexagonal oxidic ferrimagnetic compounds containing Barium special attention will be paid to their anisotropy properties. By appropriate substitutions the anisotropy fields can be varied over a wide range, from approximately 25.000 to 35.000 oersteds, where the negative sign corresponds to a preferential plane for the magnetization vector. Crystal-oriented specimens, obtained by the so-called topotactical reaction, can be used in resonance isolators without the application of an external field, or with a relatively small field. The operational characteristics strongly depend upon the degree of orientation and the density.

Some Cobalt containing compounds show anomalous behaviour at low temperatures (77°K). Although these materials are planar, the c-axis may be made a preferred direction by first applying a field along it. Moreover rotational hysteresis is observed. When measuring the torque curve in the basal plane it appears that the first direction in which a field, exceeding about 3000 oersteds, is applied, becomes a preferential direction with normal 180° symmetry. Subsequent applications of higher fields in other directions do not destroy this preferred axis. The material possesses an absolute memory. A tentative explanation of these phenomena will be given. Although the over-all effect of Cobalt on the anisotropy-energy usually is negative, each individual Co ion is bound to some preferred axis. The theory takes into account local fluctuations of the directions of these axes.

For the large divalent ion which occupies an Oxygen site Barium is usually chosen. In some Zinc containing materials Strontium is substituted. These materials show a behaviour similar to that which is found in metallic Dysprosium.

49. FERROMAGNETISM, ANTIFERROMAGNETISM, AND EXCHANGE ANISOTROPY IN DISORDERED ALLOYS (Invited)

J. S. KOUVEL
General Electric Research Laboratory
Schenectady, New York

The disordered alloy of composition Ni_3Mn was found two years ago[1] to have unusual magnetic properties. Although its estimated spontaneous magnetization and Curie temperature (approximately 130°K) testified to its ferromagnetism, the strong field-dependence of its magnetization at high fields and the peak (at about 25°K) in its magnetization measured in any given field suggested the possibility of some antiferromagnetically aligned moments in this alloy at low temperatures. This behavior was later shown to be qualitatively common to a range of disordered Ni-Mn compositions; the field dependence of their magnetizations was observed in fields up to 100,000 oe[2]. Quantitatively, however, the properties of these alloys were very sensitive to composition and could be interpreted in terms of an increased number of antiferromagnetically aligned moments with increased Mn concentration.

When these disordered Ni-Mn alloys were cooled to liquid helium temperatures in a magnetic field, it was discovered that their hysteresis loops were displaced from their symmetrical positions about the origin, i.e., the alloys could be magnetized more easily in the direction of the field applied during cooling than in the opposite direction[2,3]. Subsequent torque measurements confirmed this unidirectional anisotropy and also revealed a rotational hysteresis that did not vanish at high fields. All these properties and their variation with temperature are generally consistent with the exchange anisotropy model originally conceived for the ferromagnetic Co-antiferromagnetic CoO system[4]. It is therefore concluded that there are regions of ferromagnetic spin alignment in these disordered alloys. Moreover, the results of neutron diffraction and magnetic measurements indicate that these regions, if present, must be very small.

The origin of this magnetic inhomogeneity of the Ni-Mn alloys could be attributed to small ferromagnetic regions of ordered Ni_3Mn phase in an atomically disordered and presumably antiferromagnetic matrix. Recently, however, it was found that Co-Mn alloys (25 to 35 percent Mn) also exhibit exchange anisotropy properties, and there is no detectable tendency for long-range atomic ordering in these alloys. Hence, it is now believed that the statistical composition fluctuations inherent in a disordered alloy and the presence of competing magnetic interactions (antiferromagnetic for Mn-Mn nearest neighbor atom pairs and possibly Co-Mn pairs, and ferromagnetic for Ni-Ni, Ni-Mn, and Co-Co pairs) are together responsible for small regions of ferromagnetic and antiferromagnetic order in these alloy systems.

More recently, exchange anisotropy behavior has been discovered in a Cu-Mn alloy (25 percent Mn), confirming previous evidence for ferromagnetic and antiferromagnetic exchange interactions in this alloy system[5].

Fe-Al alloys, whose magnetization variations with field and temperature have been interpreted in terms of competing ferromagnetic and antiferromagnetic interactions[6], have also been found to have exchange anisotropy properties[7].

---

1. J. S. Kouvel, C. D. Graham, Jr., and J. J. Becker, J. Appl. Phys. 29, 518 (1958).
2. J. S. Kouvel, C. D. Graham, Jr., and I. S. Jacobs, J. Phys. Radium 20, 198 (1959).
3. J. S. Kouvel and C. D. Graham, Jr., J. Appl. Phys. 30, 312S (1959).
4. W. H. Meiklejohn and C. P. Bean, Phys. Rev. 102, 1413 (1956) and 105, 904 (1957).
5. Owen, Browne, Arp, and Kip, J. Chem. Phys. Solids 2, 85 (1957); R. W. Schmitt and I. S. Jacobs, J. Chem. Phys. Solids 3, 324 (1957).
6. H. Sato and A. Arrott, J. Appl. Phys. 29, 515 (1958).
7. J. S. Kouvel, J. Appl. Phys. 30, 313S (1959).

50. THE INTERNAL STRUCTURE OF BLOCH WALLS

S. SHTRIKMAN and D. TREVES*
Department of Electronics
The Weizmann Institute of Science
Rehovot, Israel

The fine structure of Bloch walls is calculated taking into account the self-magnetostatic energy due to free poles at the intersection of the wall with the surface of the ferromagnetic sample. The internal structure of the wall is assumed to be similar to the domain structure of a film whose thickness equals the width of the wall, and whose length equals the thickness of the sample, which is assumed a single crystal.

The period T of the domain configuration, which is actually composed of right and left hand walls divided by Bloch lines, is calculated assuming it to be small compared to the thickness L of the sample, thus neglecting the energy of interaction between the two edges of the wall. The usual method of energy minimization using "Domains" and "Walls" is used, because of its mathematical simplicity.

It is found that

$$T/L \approx (K/I_S^2)^{2/3}$$

where K is the magnetocrystalline anisotropy constant and I_S - the saturation magnetization. Taking for iron the appropriate constants, one finds $T/L \approx 0.3$ which compares favorably with values observed by Deblois and Graham[1] in iron whiskers.

The energy of the Bloch line, calculated by minimization of its exchange and self-magnetostatic energy, is, for iron, approximately $3 \cdot 10^{-5}$ erg/cm.

---

*Present address: Pomona College, Department of Physics, Claremont, California.

1. R. W. Deblois and C. D. Graham, J. Appl. Physics 29, 932 (1958). Also R. W. Deblois and C. D. Graham private communication.

---

51. ANISOTROPIC MAGNETIZATION

EARL R. CALLEN
U. S. Naval Ordnance Laboratory, White Oak
Silver Spring, Maryland

As the temperature of a magnetic system is raised, the angular width of the cone of spins widens, decreasing both the magnetization and the magnitude of the macroscopic magnetic anisotropy. The apparent anisotropy thus relaxes monotonically back toward zero value because, though the average magnetization is in some definite direction, many of the spins are sampling other directions. This is the Akulov mechanism. There is a conjugate effect of the atomic anisotropy back on the magnetization. As the magnetization is rotated, the magnetic anisotropy causes the spin cone to narrow in easy directions and to spread in hard directions. The atomic anisotropy thus causes the magnitude of the magnetization to depend not only upon temperature, but upon its direction with respect to the crystal axes.

The magnetization can be expanded in a series of polynomials with the crystal symmetry. The coefficients of these polynomials are temperature dependent. The leading isotropic term is the usual Langevin, Brillouin, or spin wave temperature dependence, depending upon the model. Using a classical molecular field model, we have worked out the temperature dependence of the anisotropic terms in the magnetization for all order polynomials, in ferromagnets, antiferromagnets, and ferrimagnets. As these higher terms are proportional to the ratio of the corresponding $T = 0^{o}K$ anisotropy energy to the exchange energy, they are often, but not always, extremely small.

In a ferromagnet with uniaxial symmetry the anisotropic magnetization rises as (T/T_C) times the inverse of the isotropic magnetization. It is of the order of one part in one thousand of the spherical term at intermediate temperatures. Very near the Curie temperature the P_2 term dominates the spherical term and becomes as much as one tenth of the saturation magnetization at $T = 0^{o}K$. This term greatly alters the temperature dependence of the magnetization in the immediate vicinity of the Curie temperature. Cobalt is not a good example of this behavior because of the transformation to the cubic phase below the Curie temperature. In the cubic ferromagnets iron and nickel the anisotropic magnetizations vary as P_4 and P_6. They are extremely small at all temperatures. There are, however, numerous other materials of large anisotropy and low exchange energy which should show appreciable anisotropy in the magnetization.

In the ferrimagnets there are interesting complications. If the several exchange interactions are such as to hold the reduced magnetization of one sublattice close to its saturation value while that of the other has decreased to a very small value, there will be a large angular dependence in the magnetization of the almost-saturated sublattice. Under propitious circumstances the angular terms will be large near a compensation point for the isotropic magnetization. The compensation temperature will then depend upon the orientation of the magnetization.

---

52. TEMPERATURE DEPENDENCE OF ANISOTROPY AND SATURATION MAGNETIZATION IN IRON AND IRON-SILICON ALLOYS

C. D. GRAHAM, JR.
General Electric Research Laboratory
Schenectady, N. Y.

The temperature dependence of the magnetocrystalline anisotropy and of the saturation magnetization have been measured on single crystals of iron, 3.2% Si-Fe, and 5.1% Si-Fe over the temperature range 77-550°K. The anisotropy values from 77 to 300°K have been previously reported. The additional measurements were undertaken because the early results seemed to undermine a theoretical triumph, namely the prediction that the anisotropy should decrease as the tenth power of the magnetization, at least at low temperatures $[K_t/K_o = (M_t/M_o)^{10}$, where K_t and M_t are the anisotropy and magnetization at any given temperature and K_o and M_o are the anisotropy and magnetization at absolute zero$]$.

The further data have confirmed the failure of the tenth-power law. In fact, the data do not even follow a simple law of the form $K_t/K_o = (M_t/M_o)^n$ over the entire range of temperature investigated. At low temperatures (below 200°K) *n* is clearly less than 5, but at high temperatures *n* increases to approximately 10. It is not even certain that *n* is a constant at low temperatures; the measured changes, especially in M, are so small at low temperatures that large errors in the derived value of *n* cannot be avoided.

The results show that the saturation of silicon-iron alloys decreases more rapidly with temperature than the saturation of pure iron; this agrees with results for other alloy systems.

---

53. MAGNETIC ANISOTROPY AND MAGNETOSTRICTION OF THE COBALT-IRON ALLOYS AND THE ORDER - DISORDER TRANSFORMATION

R. C. HALL*

Cobalt-iron alloys have for many years been of interest as magnetic materials because they have unusually high magnetic saturation values. This interest was increased recently by the discovery of Supermendur[1]. Supermendur is an alloy of 49 wt.% Co - 49 wt.% Fe - 2 wt.% V which was found by suitable purification and heat treatments, including a magnetic anneal, to possess excellent soft magnetic properties. Two factors which are important in determining the magnetic hysteresis properties are the basic magnetic properties of magnetostriction and anisotropy. Since very meagre data are available in the literature on the single crystal anisotropy and magnetostriction of the cobalt-iron alloys, the present program was undertaken to determine these two properties in the disordered and ordered states.

Ingots of the cobalt-iron alloys containing from 25% to 59% cobalt in iron were slowly cooled through their transformation temperatures for the growth of large grains. From these grains, single crystal disks were fabricated with either the (110) or (100) plane parallel to the faces of the disk. The crystals were heat treated to produce either the ordered state by cooling at a rate of 20°C per hour from 850°C or the disordered state by water quenching from 850°C. The spontaneous saturation magnetostriction was measured by the strain gauge technique and the anisotropy was measured from torque curves.

The magnetostriction in the (100) and (111) directions (λ_{100} and λ_{111} respectively) became large positive values as cobalt was added to iron. Values of λ_{100} reached 150×10^{-6} and λ_{111} reached 30×10^{-6} at equal percentages of iron and cobalt. Near the FeCo composition, λ_{100} was lowered and λ_{111} was raised as the degree of order was increased. Magnetostrictive strains normally associated with the movement of 90° domain boundaries is reduced in commercial alloys by employing a magnetic anneal.

The first anisotropy constant K_1 for the disordered state was lowered slightly with the addition of cobalt up to 30%. From 30% to 59% Co, K_1 dropped precipitously to large negative values. The easy direction of magnetization changed from the (100) to the (111) near 41% Co. Ordering shifted the zero - anisotropy composition to about 50% Co. From 37% to 59% Co, K_1 changed toward larger positive values with increased order.

*Formerly with Magnetic Materials Development Section, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania; now with Research and Development Laboratory, Universal-Cyclops Steel Corporation, Bridgeville, Pennsylvania.

1. H. L. B. Gould and D. H. Wenny, Conference on Magnetism and Magnetic Materials, Feb. 1957, pp. 675 - 681.

---

54. ROLL MAGNETIC ANISOTROPY OF IRON-ALUMINUM CRYSTALS

SŌSHIN CHIKAZUMI*
The Institute for Solid State Physics
The University of Tokyo
Komaba, Meguro, Tokyo, Japan

Magnetic anisotropy measurements and domain pattern observations were made on the rolled iron-aluminum alloys, for the purpose of investigating the roll magnetic anisotropy of body centered cubic crystal. The specimen was Fe_3Al crystal which is suitable for the present investigation because of its low crystal anisotropy and high dipole interaction. Rolling on (110), parallel to (001), induced the uniaxial anisotropy as high as 3.7×10^5 erg/cc under 10% roll reduction. Easy direction of this anisotropy was parallel to roll direction. Domain pattern shows also the regular domains running parallel to the roll direction. This orientation of anisotropy may promise a possibility of having the material which has a rectangular hysteresis loop by the rolling of the oriented body centered material.

Calculations were made on the anisotropy in terms of the slip-induced directional order by assuming the {110} <111> slip system. It was found that the dipole-dipole interaction between second nearest neighbors must be taken into consideration in order to explain the experimental results. This is consistent to the results of magnetic annealing on Fe_3Al crystal.

*Temporarily staying in IBM Research Center, Poughkeepsie, N. Y.

---

55. MAGNETIC ANISOTROPY IN FERRIMAGNETIC CRYSTALS

R. F. PEARSON
Mullard Research Laboratories
Cross Oak Lane, Salford, Surrey
England

Absolute values of K_1 the first order anisotropy constant have been determined at different temperatures from torque measurements on single crystals of the following compositions:

$Mn_xFe_{3-x}O_4$	where x = 1.0, 0.91, 0.87, 0.76, 0.70.
$Co_x\ Mn_{1-x}Fe_2O_4$	where x = 0, 0.01, 0.02, 0.04, 0.06, 0.08, 0.10, 0.25.
$Co_{.04}\ Mn_{x-.04}Fe_{3-x}O_4$	where x = 0.91, 0.87, 0.76, 0.70.
$Ga_xFe_{3-x}O_4$	where x = 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 0.8.
$Al_yFe_{3-y}O_4$	where x = 0, 0.5, 0.1, 0.2.
$Sm_3Fe_5O_{12}$	
$Gd_3Fe_5O_{12}$	

The magnetocrystalline anisotropy of mangenese ferrous ferrite was found to vary considerably with the concentration of ferrous ions (Fe^{2+}), some compositions even possessing a positive value of K_1 at room temperature. In these cases, K_1 becomes negative at low temperatures in contrast with the behaviour of cobalt substituted crystals which are found to have rapidly increasing positive values of K_1 as the temperature is reduced. The anisotropy contribution of cobalt ions (Co^{2+}) substituted in manganese ferrous ferrite varies with crystals of different compositions.

The experimental values of K_1 are compared wherever possible with present theories of magnetic anisotropy. In particular, the recent theory proposed by Slonczewski (1958) to explain the anisotropy of cobalt ions substituted in magnetite (Fe_3O_4) is found to be unsuccessful in the case of Co^{2+} ions in manganese ferrite ($MnFe_2O_4$).

Measurements at low temperatures on the gallium substituted magnetite crystals reveal an additional interesting effect. For certain crystals the torque curves at 80°K exhibit considerable rotational hysteresis in fields above 10,000 oersteds, when the material should certainly be saturated. This hysteresis is shown to be related to the ordering of the ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions which takes place on the octahedral sites at low temperatures.

---

56. EXCHANGE ANISOTROPY IN NiAs TYPE STRUCTURES

R. H. PRY, J. S. KOUVEL, E. MIKSCH
General Electric Research Laboratory
Schenectady, New York

Many of the AB compounds formed from the combination of a transition element and one of the sub group elements of the fifth and sixth column of the periodic table have structures of the NiAs type. Some of these compounds are ferromagnetic and some antiferromagnetic.

Previously, solid solutions have been found to exist between selected ferromagnetic and antiferromagnetic compounds, both of this structure type, completely across the pseudo-binary phase diagram. Moreover, evidence has been found for the coexistance of antiferromagnetism and ferromagnetism in these alloys. [1,2]

A series of alloys of one of these systems, i.e., $Cr_xMn_{1-x}Sb$, has been reinvestigated by the authors. Magnetization and torque measurements will be presented and the results interpreted on the basis of the existance of an exchange anisotropy in this alloy system. Thus, not only do the experimental measurements support the notion of the coexistance of antiferromagnetic and ferromagnetic regions but also suggest that an exchange coupling exists between them in this solid solution system.

1. T. Hirone, S. Maeda, I. Tsubokawa, and N. Tsuya, J. Phys. Soc. Japan, 11, No. 10, 1083 (1956).
2. F. K. Lotgering and E. W. Gorter, J. Phys. Chem. Solids, 3, 238 (1957).

57. EXCHANGE ANISOTROPY IN ROCK MAGNETISM

W. H. MEIKLEJOHN and R. E. CARTER
General Electric Research Laboratory
Schenectady, New York

Some igneous rocks are magnetized in a direction opposite to that expected, if they had been cooled in the earth's magnetic field. These rocks are said to have a reverse thermo-remanent magnetization (RTRM). Nagata, Ishikawa, Akimoto, and Uyeda[1,2,3,4] have done considerable work on the RTRM of the Haruna deposit in Japan. Uyeda has shown that the RTRM of the Haruna rock is due to an ilminite-hematite solid solution and has synthesized in the laboratory a solid solution that has a RTRM when cooled in fields as high as 16,000 oersteds. Uyeda has put forth a theory which contains a mechanism similar to that found in the cobalt-cobaltous oxide system[6].

Based upon Uyeda's explanation of the RTRM we postulated that the material should have a shifted hysteresis loop and that it should be shifted in the opposite direction to that found in the Co-CoO system. We found that the solid solution— .6 $FeTiO_3 \cdot 4\ Fe_2O_3$—was shifted by 350 oersteds in the opposite direction to Co-CoO when cooled in a field.

The loop was symmetrical when cooled in zero field. Moreover, we have shown that when the material is cooled in a magnetic field through the Morin[5] transition the loop is shifted in the same direction as Co-CoO.

These results confirm the general features of Uyeda's model, although the detailed mechanism is still being studied.

We believe that Uyeda's work definitely establishes the RTRM of the Haruna deposit as due to a magnetic phenomena and not due to the reversal of the earth's magnetic field. We believe that the type of magnetic investigation reported in this paper may be applied to other deposits that have a RTRM to establish if they are also due to a magnetic phenomena.

1. S. Uyeda, Japanese Journ. Geophys., Vol. II, No. 1, 1958.
2. Y. Ishikawa, J. Phys. Soc. of Japan, Vol. 13, No. 8, p. 828-837, Aug. 1958.
3. Y. Ishikawa, S. Akimoto, J. Phys. Soc. of Japan, Vol. 13, No. 10, p. 1110-1118, Oct. 1958.
4. Y. Ishikawa, S. Akimoto, J. Phys. Soc. of Japan, Vol. 13, No. 11, p. 1298-1310, Nov. 1958.
5. F. J. Morin, Phys. Rev. 78, p. 819, 1950.
6. W. H. Meiklejohn and C. P. Bean, Phys, Rev. Vol. 105, No. 3, p. 904, Feb. 1957.

58. INFLUENCE OF IONIC ORDER ON THE MAGNETOCRYSTALLINE ANISOTROPY AND CRYSTALLINE ELECTRIC FIELD PARAMETERS IN LITHIUM FERRITE MONOCRYSTALS

V. J. FOLEN
U. S. Naval Research Laboratory
Washington 25, D. C.

The X-ray work of Braun[1] has shown that a 3 to 1 long range "ordering" of the cations occurs on octahedral sites in lithium ferrite. In this paper a study is made of the influence of this cation "ordering" on magnetocrystalline anisotropy and the various ferric ion crystalline electric field parameters in lithium ferrite. Measurements of the first order anisotropy constant (K_1), utilizing the torque method, are reported for various states of cation "order" in this ferrite. The degree of long-range "order" was determined by X-ray diffraction analysis of powdered lithium ferrite subjected to the same thermal treatments as the monocrystals used in the anisotropy measurements.

We find that the degree of cation "order" in the octahedral sites strongly influences K_1. For example, measurements at 77°K yield the values -127×10^3 ergs/cm^3 and -162×10^3 ergs/cm^3 for K_1 in the "ordered" and "disordered" states, respectively. The ferric ion cubic crystalline electric field splitting parameters for the octahedral sites (a_B) and tetrahedral sites (a_A) were deduced from our measurements of the temperature dependence of anisotropy and saturation magnetization, using Yosida-Tachiki anisotropy theory.[2] For the purpose of calculating the sublattice magnetizations from the saturation magnetization measurements, use was made of an analytical method[3] for the determination of the molecular field coefficients. The cubic crystalline electric field splitting parameters in "disordered" lithium ferrite are, respectively, $a_B = +0.0246$ cm^{-1} and $a_A = -0.0118$ cm^{-1}, in excellent agreement with the parameters determined previously in magnesium ferrite[4] which is also a "disordered" ferrite. The experimental temperature dependence of K_1 in the "disordered" lithium ferrite is in quantitative agreement with that obtained from the cubic spin Hamiltonian.

Analysis of the experimental data on K_1 in the "ordered" state on the basis of the cubic electric field yields an a_B which is considerably smaller than that obtained for the "disordered" state and an a_A opposite in sign to the a_A obtained for the "disordered" state.

As shown by Wolf[5], the quadratic and quartic axial terms in the ferric ion spin Hamiltonian

$$H = g\beta H \cdot S + \frac{a}{6}(S_x^4 + S_y^4 + S_z^4) + dS_\zeta^2 + fS_\zeta^4$$

can contribute to the cubic anisotropy. From our X-ray studies of the lithium ferrite crystalline structure and consideration of the temperature dependence of the change in anisotropy associated with the "order-disorder" transition, ΔK_1 (T), we find that ΔK_1 (T) is not likely to be accounted for by changes in either the cubic parameter or the quartic axial parameter or simultaneous changes in both of these parameters. However, the possible contributions of quadratic axial terms associated with octahedral ferric ions are found to be consistent with our X-ray data as well as with ΔK_1 (T).

1. P. B. Braun, Nature 170, 1123 (1952).
2. K. Yosida and M. Tachiki, Progr. Theoret. Phys. (Kyoto) 17, 331 (1957).
3. G. T. Rado and V. J. Folen. Paper submitted for Publication.
4. V. J. Folen and G. T. Rado, J. Appl. Phys. 29, 438 (1958).
5. W. P. Wolf, Phys. Rev. 108, 1152 (1957).

SESSION IV-B

TECHNIQUES AND DEVICES

P. CIOFFI, Presiding

---

59. THE TETRAHEDRAL JUNCTION

JERALD A. WEISS
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

A novel microwave-ferrite device which appears to have a number of interesting and useful applications is the structure for which the name *tetrahedral junction* is proposed. A typical version is a junction between two rectangular waveguides which are mutually cross-polarized; a ferrite rod is mounted symmetrically on the axis and magnetized in the axial direction. For other types of transmission line, such as finline, stripline, or coaxial line, there exist analogous structures having the same basic properties.

The junction may be regarded as a variable coupling element between two lines which are not coupled in the absence of the ferrite. This suggests applications as a variable mismatch (reactive modulator) or switch. It is particularly significant that the junction exhibits its useful properties in a range of applied dc magnetic fields below that required to saturate a sintered ferrite. In this range it possesses a considerable bandwidth: of the order of ten percent.

The property of requiring a magnetic field which is small and which is applied in the longitudinal direction makes the device attractive for use where the application calls for changes of state at high speed.

It is apparent from symmetry considerations that the junction is a gyrator: it may be regarded as the waveguide equivalent of a pair of crossed inductors coupled by magnetic induction. The required value of 180° nonreciprocal phase is intrinsic to the structure and can therefore be obtained, in a suitable design, without serious restrictions on applied field, bandwidth, etc. It is also easily and rapidly reversible.

Contrary to intuitive expectations, the device is capable of presenting an extremely good broadband match. To account for this property, it must be observed that the scattering at the plane of the joint involves coupling into cross-polarized nonpropagating modes of the type encountered in structures such as the Reggia-Spencer phase shifter.[1,2] A simplified model, along the lines of that employed in the phase-shifter analysis in Reference 2, shows that such a condition of match is indeed contained in the principle of operation, that it occurs at small values of applied field, and that it can be made relatively insensitive to variations in the magnetic parameters of the ferrite.

A further result of the theoretical model is that under the proper conditions it is possible to produce a state of linear polarization at the plane of the joint, with the rf fields oriented at $\pm 45^{\circ}$ with respect to the major axes of structure. The double sign refers to the direction of propagation, or alternatively to the direction of applied field. Such a condition of polarization has also been observed experimentally. The phenomenon offers attractive possibilities for a matched switch, modulator, or isolator. The name tetrahedral derives from the basic symmetry character of the junction.

1. F. Reggia and E. G. Spencer, "A New Technique in Ferrite Phase-Shifting for Beam Scanning of Microwave Antennas," Proc. IRE, Vol. 45, pp. 1510-1517; November, 1957.
2. J. A. Weiss, "A Phenomenological theory of the Reggia-Spencer Phase Shifter," Proc. IRE, Vol. 47, pp. 1130-1137; June, 1959.

---

60. A HIGH SPEED FERRITE ROTATING HALF-WAVE PLATE*

FRANKLIN S. COALE
Melabs
Palo Alto, California

A novel approach for constructing a ferrite rotating half-wave plate for use as a frequency translator or an amplitude modulated single sideband modulator is presented. This is accomplished through the use of a four-wire balanced transmission line for generating both the rotating microwave fields and the rotating low frequency magnetizing fields. By this means, frequency translations of 1.0 mc/sec may be achieved. The principles of operation of this type modulator should allow modulation frequencies in excess of 10 mc/sec.

Eddy current losses which usually limit the high frequency modulation of ferrite single sideband modulators are minimized by passing high currents down the wires of the four-wire transmission line to generate the magnetizing field at the modulation frequency. The magnetic fields which are developed are sufficient to cause 180° relative phase shift between the orthogonal microwave components. The magnetizing fields are phased in quadrature so that a rotating magnetic field is developed whose speed of rotation is determined by the frequency of the magnetizing field. The resultant microwave frequency shift is twice the frequency of the magnetizing field due to the inherent action of the half-wave plate.

An analysis is presented which gives the output frequency spectrum as a function of the operation of the half-wave plate and the excitation of the four-wire line. If the amplitude of the magnetizing field is varied then the relative phase shift produced by magnetic birefringence is no longer 180° but may be some value between 0° and 180°. This in effect produces a frequency translated signal whose amplitude varies with the magnitude of the magnetizing field. Ordinarily the amplitude of a sideband of a 100% modulated A-M signal is 6 db below the unmodulated carrier. However, in this case all the energy appears in the sideband when 100% modulation is used. When frequency modulated magnetizing fields are employed the resultant frequency translation is twice the F-M bias frequency. The modulation then appears as sidebands about the translated frequency. This device may also be used as a phase shifter. An analysis of temperature dependence shows that the resultant phase shift is not dependent on temperature but the insertion loss will change with temperature.

This type of device may find application in microwave repeaters (frequency translators), single sideband modulators, F-M modulators, and phase shifters. If bandpass filters are placed at either end of this system and tuned to the proper frequency, multiple traversals of the frequency translator by the microwave energy will produce correspondingly higher translations from the input frequency and consequently frequency translations much greater than the modulating frequency may be obtained.

*This work was supported by the U.S. Army Signal Corps under Contract DA 36-039 SC-78169.

61. DOUBLE PUMP DEGENERATE FERRITE AMPLIFIER

PETER GOTTLIEB
Microwave Laboratory
Hughes Aircraft Company
Culver City, California

A theoretical discussion of the possibilities for the design of a parametric amplifier using a pump frequency lower than the signal frequency (but higher than one half the signal frequency) is given. In particular, a detailed mechanism for the operation of a ferrite amplifier with such properties is described. The amplifier operation is similar to that used by Bloom and Chang[1] for a diode amplifier with cubic nonlinearity. Hogan, Jepsen, and Vartanian[2] have proposed a ferrite device to serve the same purpose as the present amplifier; however, their scheme is quite different, and a detailed comparison is given in this paper.

The main feature of the present amplifier is a doubling of the pump frequency to obtain an effective pump frequency which is larger than the signal frequency. By an efficient method of mixing the pump with itself, a doubled pump frequency, which can be as large as 10 or 20 percent of the original pump, is obtained. The whole amplifier requires four resonances: the pump frequency, twice the pump frequency, the signal frequency, and twice pump minus signal (idle). The most efficient assignment of the modes uses cavity resonances for the signal and pump, and then uses either cavity or ferrite resonances for the other frequencies.

Since the pump doubling is a result of nonlinear mixing, the efficiency of doubling will be greater for larger pump fields. This is limited in practice by the onset of saturation in the ferrite. For pump fields close to saturation the required pump field is calculated to be five to ten times larger than that required to produce the same gain in an ordinary three resonance amplifier.

1. S. Bloom and K. K. N. Chang, J. Appl. Phys., 29, 594 (1958).
2. C. L. Hogan, R. L. Jepson, and P. H. Vartanian, J. Appl. Phys., 29, 422 (1958).

62. BROADBAND RECIPROCAL FERRITE PHASE SHIFTERS*

T. G. GEISZLER and R. A. HENSCHKE
Melabs
Palo Alto, California

Operation of a phase shifter over the entire waveguide band can be obtained by utilizing various axially magnetized ferrite slabs mounted on the broadwall of the waveguide. The percentage deviation in phase shift for frequencies between 8.2 and 12.4 kmc can be minimized by the proper selection of slab dimensions, degree of dielectric loading, and of guide structure. The phase shift for these configurations is characterized by a linear dependence of phase shift for fields above magnetic saturation. Consequently with a bias field which magnetically saturates the ferrite the constant slope characteristic enables one to construct a device whose phase shift is a linear function of the driving current. A configuration biased to saturation will also exhibit negligible hysteresis effects. This type of phase shifter should also have high average power capabilities because of the placement of the ferrite large dimension against the waveguide wall.

Measurements of ferrite (Trans Tech TT-390) slabs mounted in rectangular guide have been made for axial fields up to 900 oersteds. Phase shift data for slabs of constant length and thickness but of varying width indicate an optimum range of values for maximum bandwidth. The placement of two ferrite slabs of identical dimensions on opposite waveguide walls yields an improvement in bandwidth and magnitude of phase shift.

Measurements for single slabs of varying height but constant length and width also indicate a height limit for optimum bandwidth. An increase in thickness beyond that required for broadband performance results in a large increase in phase shift. It appears that this is caused by a rapid collapse of energy into the ferrite at a given frequency and critical slab height.

An examination of the phase shift characteristics for a given frequency reveals a resemblance between the variation in phase shift with magnetic field and the variation of the ferrite infinite medium propagation constants with magnetic field. The phase shift as predicted by infinite medium theory should vary inversely with frequency. This, however, is not the case for rectangular guide phase shifters where the opposite frequency dependence has been observed. This may be qualified by noting that the dispersive properties of the guide as well as energy concentration effects in the ferrite completely mask or overshadow the predicted inverse frequency dependence. However, if the waveguide is sufficiently loaded with dielectric and ferrite the dispersion is greatly reduced. It can be reduced to a degree where the inverse frequency dependence of the intrinsic properties of the ferrite is minimized by the remaining waveguide dispersion. This has been accomplished to some extent and the phase shift obtained had a total deviation of less than 20% for frequencies between 8.4 and 12 kmc. The minimum phase shift was 195°, accompanied by a maximum loss of .7 db. With the application of a saturation bias field, phase shifts which are linear functions of the driving current may be obtained with no increase in loss or reduction in bandwidth. The magnitude of phase shift is, however, reduced by a factor of about 25%. Similar results were obtained in ridged guide for less complex and shorter configurations.

For variations in temperature of 22^{o} to 100^{o}C the devices have a phase shift variation of 11% to 50% over the band. The saturation biased phase shifters had a very slight temperature dependence at the higher frequencies.

*This work was supported by the U.S. Army Signal Corps under Contract DA 36-039 SC-78169.

---

63. MULTIMODE PROPAGATION IN GYROMAGNETIC RODS AND ITS APPLICATION TO TRAVELING WAVE DEVICES

J. E. TOMPKINS, F. REGGIA, and L. JOSEPH
Diamond Ordinance Fuze Laboratories
Washington, D.C.

This paper summarizes the results of rigorous calculations, made on a digital computer, of the propagation constants of traveling waves in longitudinally magnetized gyromagnetic rods. Specifically described are: (a) the behavior of these propagating modes inside cylindrical waveguides (assumed excited from a TE_{11} mode) as a function of rod diameter and applied magnetic field for a lossless material in the initial-field region, (b) a comparison of the calculations with experimental results concerning the nature of the microwave fields inside a longitudinally magnetized ferrite rod placed at the center of a rectangular waveguide (excited from a TE_{01} mode), and (c) the mode structure inside a very narrow-linewidth material for fields near resonance with its possible application to "active" devices.

This paper also describes an experimental technique for investigating the microwave fields inside a ferrite rod as a function of the applied magnetic field. The results of this sampling technique has brought about the development of a new broadband microwave switch or absorption modulator.

---

64. MICROWAVE DETERMINATION OF CURIE TEMPERATURE

A. D. KRALL and E. T. HOOPER, Jr.
U.S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

A microwave technique has been developed for the determination of the Curie temperature of powdered ferromagnetic materials. It has been used to study the effects of temperature on several ferromagnetic elements and alloys up to temperatures of 1300^{o}C.

The method uses waveguide parameters of "voltage standing wave ratio" and "voltage minimum position," which undergo radical changes at the Curie temperature. Since no externally applied magnetic field is necessary, the high temperature waveguide can be inserted directly into a conventional furnace. The geometry of the sample and the configuration of the waveguide are not critical, and protective atmospheres can be maintained around the sample. The technique, which overcomes many difficulties of more conventional methods, has proved useful in studying alloy systems having very high Curie temperatures.

65. INSTRUMENTATION APPLICATIONS OF INVERSE-WIEDEMANN EFFECT

J. A. GRANATH
Armour Research Foundation of
Illinois Institute of Technology
Chicago, Illinois

The literature on applications of torsional magnetostriction and inverse-Wiedemann effect is limited and widely scattered. A brief review of some of the literature on instrumentation applications for measurement of torque, force, and other physical quantities is presented.

For use as a guide in transducer design, a simplified mathematical representation of the torque-signal relationship for one mode of operation is developed from the equations of crystal anisotropy, mechanical strain, and applied magnetic field energy. Shape and general character of experimental torque-signal curves check with analytical predictions.

Some consequences of the analysis in terms of design guides for devices are outlined.

---

66. A PRACTICAL HYSTERESIGRAPH

R. R. BOCKEMUEHL and W. E. SARGEANT
General Motors Research Laboratories
Warren, Michigan

Measurement of the D. C. magnetization and hysteresis characteristics of a material requires the integration of very low D. C. potentials. Techniques involving high gain amplifiers and mutual inductance feedback loops are useful for this purpose but such equipment has been prohibitively expensive and delicate for most applications.

A relatively low cost, accurate hysteresigraph has been developed which is suitable for both laboratory and industrial application. This instrument employs mutual inductance feedback and utilizes standard components to obtain a stable D. C. voltage gain of 20×10^6, a sensitivity equivalent to 2.5 maxwell turns and an integrating time constant of several hours. The instrument is reasonably insensitive to environment. It permits direct recordings of hysteresis loops and magnetization curves to be made in less than one minute. Both theoretical and practical considerations of the instrument are presented.

---

67. THE RICTOMETER SYSTEM FOR CALIBRATING TRANSMITTERS OF REMOTE INDICATING COMPASSES

L. I. MENDELSOHN
General Electric Company
Instrument Department
West Lynn, Massachusetts

Calibration of the sensor (transmitter), of a remote indicating compass system, must be carried out in a magnetic field whose magnitude and direction simulate closely those of the earth at a specified point. Major disturbances of the earth's magnetic field by electrical equipment occur in most laboratories. Where conventional Helmholtz calibrating schemes are used, accuracy can be achieved only by lengthy averaging of repeated measurements and exercising extreme care. This paper describes a measurement system which the writer has chosen to call a RICTOMETER, which permits precise transmitter calibration with much greater ease than conventional Helmholtz coils.

The RICTOMETER consists of a system of shields which reduces the earth's vertical field component from 580 milligauss to 6 milligauss, and its horizontal component from 200 milligauss to about 1/4 of a milligauss. A pair of Holmholtz coils suitably placed within this shielding system produces the equivalent of the earth's vertical field component in the vicinity of the compass transmitter. Two additional sets of Helmholtz pairs within the shielding system restore the horizontal component of the earth's field. By proper selection of currents in each of these sets of coils, this horizontal component can be rotated in discrete steps through 360° for calibration purposes. The RICTOMETER allows the experimenter to calibrate a compass transmitter readily with a repeatability of plus or minus 0.1 degrees in normal laboratory fields. Deliberate immersion of the RICTOMETER'S shielding system in a 50 gauss field causes a maximum transmitter calibration change of plus or minus 0.15°. Thus the system should prove valuable for reliable sensor calibration under most adverse field conditions.

---

68. A SIMPLE TORQUE MAGNETOMETER

PETER W. NEURATH
General Electric Company
Pittsfield, Mass.

A recording torque magnetometer has been designed and constructed, using commercially available components in conjunction with commonly available laboratory equipment. It appears to be much simpler than any described heretofore and needs no calibration. The sample disc is mounted at the end of a shaft which is supported in two fixed radial non-magnetic precision ball bearings of low starting torque. The other end of the shaft carries a 10 cm long lever arm which exerts a force on a Statham Instruments, Inc. 0.3 oz. transducer (Model G7A).

The rotation is converted to an electrical signal by use of a 360° continuous rotation Helipot potentiometer. Both torque and rotation signals are recorded on an XY-millivolt recorder. The electrical circuits consist only of batteries and resistors and the factory supplied transducer calibration is entirely adequate. The assembly can be rotated manually. At $\pm 40 \times 10^3$ ergs full scale, errors are about 1%.

Slight alterations in the design to cover full scale ranges from 10×10^3 to 100×10^3 ergs or more are possible.

69. ULTRASONIC MAGNETOMETER

R. J. RADUS
Materials Engineering Departments
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

The detection and measurement of magnetic field intensity for purposes of field plotting and uniformity studies is a most important consideration in the field of magnetics. Field plotting and uniformity studies can be conducted on certain sizes of magnetic geometries with rotating coil instruments and Hall generators. The obvious limit of such devices is their minimum resolving power which can be defined in terms of sampling area. The sampling area of rotating coil instruments is roughly 1.2×10^{-2} sq. in. The active area of Hall generator probes are of the order of 3.2×10^{-3} sq. in. The more recent work with the vibrating quartz crystal magnetometer has been used to measure flux density normal to surface of permanent magnets. The sampling area of this type equipment is roughly 0.56×10^{-6} sq. in.

The flux measuring equipment being described in this paper has a sampling area of approximately 2.5×10^{-5} sq. in. and a sensitivity of approximately $.003 \times 10^{-3}$ volts per gauss. The probe consists of a single turn inductor of length 1/16" which vibrates $\pm$ .0002". The inductor is fastened to a probe of .025" thickness and the $\pm$.0002" motion is perpendicular to this .025" probe thickness. The physical geometry and size of this probe permits measurements in a variety of positions relative to the magnetic circuit. This type of probe is also applicable for measuring flux density in air gaps as small as .025".

The driving device for this equipment is a 60 Kcps magnetostrictive ultrasonic transducer. In the present setup, the entire probe consists of the transducer reactor, a coupling bar of nonmagnetic stainless steel and the thin strip of the nonmagnetic stainless to which the inductor is fastened. The geometry and size of this thin strip can be changed to accommodate variations in both inductor length and displacement.

The technique of using high-frequency magnetostrictive displacement to vibrate a pickup coil in a magnetic field for the purpose of measurement provides a new approach in practical magnetometers. The basic equipment can be modified rather simply to accommodate a wide variety of magnetic field geometries and intensities.

---

70. PERMANENT MAGNET LEAKAGE PERMEANCE EVALUATION BASED ON POLAR RADIATION ANALOGY

J. E. FOY and R. J. PARKER
General Electric Company
Edmore, Michigan

This paper is based on the premise that the permanent magnet can be considered as an equipotential body and hence electrostatic analogies can be used to advantage in evaluating magnet leakage. The spherical pole formula which is based on the substitution of a sphere having dimensions which will make it the equivalent of the actual magnet limb in leakage effect is derived, and its application to permanent magnet limb geometry is described.

Evershed used this approach extensively with his work on the early steel permanent magnet. The authors review this work and explore the conditions affecting the use of this technique in modern permanent magnet materials.

Permeability and limb magnet area to cross-section area ratios are found to be influential in the location of the center of the effective polar regions. Today's high coercive force permanent magnet with shorter limb lengths is found to be particularly well-suited to this polar radiation analogy, since the departure from the spherical shape is less extreme than was the case with the earliest low coercive steel magnets. Calculation of demagnetization factors for rods, rings, "U" and "C" shaped magnets are convenient and accurately arrived at by this approach. A geometric criterion is developed which allows magnet configurations to be considered either (a) open circuit (permeance due to limb radiation, or (b) closed circuit magnets where the proximity of the polar regions is such as to increase the free polar radiation. In closed circuit magnet arrangements, the free polar radiation occurs for at least half the magnet limb area so that the spherical pole formula represents a very useful technique in the evaluation of any permanent magnet configuration.

To demonstrate the breadth of usage possible with the spherical pole formula a tubular-shaped magnet used as a magnetron field supply is analyzed to show the utility of this approach in estimating the shape of the axial field characteristic and its relationship to geometry and permanent magnet unit properties.

---

71. THE EFFECT OF GEOMETRY ON THICK FILM* TOROIDS

M. TEIG, R. L. WARD and J. C. SAGNIS
International Business Machines Corp.
Yorktown Heights, N.Y.

In the study of thick-film magnetic circuits, it has been found that a thick film core of certain physical size could not be totally switched if a concentrated drive winding was used. In addition, the induced voltages differed in wave-shape as a function of the location of the sense winding with respect to the concentrated drive winding. Both phenomena were obviously detrimental to the normal operation of the device as a magnetic storage or logical element. Further studies of these phenomena were conducted using toroidal thick film structures in planar configurations manufactured from 1/4 mil. and 1/2 mil. thick 4-79 Mo-permalloy. These studies have traced the root of the problem to the relative reluctance of the air path around the drive winding at a given point on the toroid, as compared to the reluctance of the path inside the magnetic material. The above mentioned theories have led to an investigation of the effect of geometry on thick film toroids. The results of these studies and experiments are presented in the form of graphs, which may be used to determine the critical sizes of thick film toroids which will render them useful for normal operation using concentrated windings. In addition, a qualitative explanation of the above mentioned phenomena is offered based on experimental evidences.

*1-20 microns thick

72. EXPERIMENTAL FLUX PATTERN DETERMINATION IN MAGNETIC CORES

R. L. WARD
International Business Machines Corp.
Yorktown Heights, N.Y.

This paper presents a new technique for the determination of flux patterns in non-linear, magnetic structures, e.g. multipath cores with the resolution and flexibility commonly associated with electrolytic tank and resistance paper analogues. The positioning of movable, conductive probes on the surfaces of thin, metallic magnetic structures permits the measurement of voltages, induced by flux changes within related regions of the structures without the usual deformation of the structure geometry resulting from the holes required for exploratory windings. The external detector is coupled via the movable probes to the loop formed by the conductive path in the material between the points of probe contact. It is shown that this loop is equivalent to one with simple defined geometric topology.

Two methods are presented; one consisting of the determination of flux changes along selected cross sections of the magnetic sample, the other a technique for detecting properties of the average flux density vector in the neighborhood of any given point of the sample. Where an initial or reference flux state may be assumed for the test sample the data derived by the first method may be incorporated in a simple graphical construction to determine the final flux state resulting from an arbitrary excitation. These techniques are analyzed theoretically, and verified experimentally for several structural geometries. In addition, a detailed description of the testing apparatus and experimental procedure is provided.

Extensions of these concepts to situations not covered by our stated restrictions and to analogues for general non-linear problems are briefly described. Finally, several device applications are considered.

---

73. A METHOD FOR MEASURING IRON LOSSES IN ELLIPTICALLY POLARIZED MAGNETIC FIELDS

F. J. YOUNG and H. L. SCHENK
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

A method for measuring iron losses in elliptically polarized magnetic fields has been devised. The fields are produced in a laminated one inch cubic specimen by the superposition of two mutually perpendicular magnetic fields whose magnitudes and time phase angles can be varied. Orthogonal fields are obtained by the use of two "C" cores with air gaps large enough to contain the specimen. The flux density is ascertained from the voltages induced in two coils wound on the specimen in such a manner that their areas are parallel to the two field components. The iron loss is determined by thermocouples and associated instrumentation which measures the heating transient in the specimen. Precautions have been taken to minimize the effects of room temperature fluctuations and of heat transfer between the cores and the specimen. To check the accuracy of the new method, alternating magnetic field iron losses are compared to standard Epstein test results. Loss

data are presented for various elliptically polarized fields in a typical specimen. The losses resulting from circularly polarized fields are in agreement with those predicted by other researchers. The anisotropy in losses due to alternating magnetic fields is also determined as special cases of elliptically polarized field excitation.

---

74. LOCALIZED FIELD PERMANENT MAGNET ARRAYS

H. L. Stadler
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

Linear arrays of very short bar magnets can be grouped in such a way as to give a more localized field than does a single solid magnet of about the same size. Shaping the field from small magnet arrays is particularly important in the design of permanent magnet memories where the information is stored by the presence or absence of a permanent magnet.[1] To achieve high bit densities, it is necessary to design magnet structures with very localized fields. Various arrays made from both Vicalloy and Ferroxdure will be discussed as well as an approximate method of calculating the switching flux in a sensing bit near the magnet array.

1. D. H. Looney, Proceedings of the Western Joint Computer Conference, March, 1959.

SESSION V-A

RESONANCE

G. T. RADO, Presiding

---

75. INTERACTION OF MAGNETIC CRYSTALS WITH RADIATION OF 10^4 TO 10^5 Cm^{-1} (Invited)

A. M. CLOGSTON
Bell Telephone Laboratories
Murray Hill, New Jersey

It is becoming increasingly evident that there are interesting and important interactions between ferromagnetic and antiferromagnetic crystals, and radiation in the range 10^4 to 10^5 cm^{-1}. A discussion will be given of a number of different examples including the absorption spectra of various oxides and fluorides, Faraday rotation in some ferrimagnetic oxides, and charge transfer spectra. Some new experiments that give a direct measure of exchange energy will be presented.

---

76. NUCLEAR RESONANCE IN FERROMAGNETIC COBALT (Invited)

A. M. PORTIS AND A. C. GOSSARD
Department of Physics
University of California
Berkeley 4, California

The first observation of nuclear resonance in a ferromagnetic material, cobalt, is described. The resonance frequency for finely divided face-centered-cubic material is 213.1 Mc/s. This frequency implies a local field of 213,400 oersteds at the site of the cobalt nuclei. This field, which arises from both core and conduction electron contributions, is very nearly equal to that deduced from specific heat and nuclear orientation measurements in hexagonal cobalt. A calculation by Marshall based on the Van Vleck model suggested that the field in cubic cobalt would be smaller than in hexagonal cobalt by 81,000 oersteds. The theoretical implications of the near equality of these two fields will be discussed. The resonance has a half width of 275 kc/s. The line width presumably arises from lattice imperfections coupling to the quadrupole moments of the cobalt nuclei. The resonance is remarkably intense, being some 10,000 times stronger than an ordinary nuclear resonance. The resonance is excited by domain rotation rather than by the external radio frequency field directly and this accounts for the enhancement. The resonance intensity is reduced by an external field to support this interpretation. The resonance is quite easily saturated. The variation in signal with modulation frequency yields a spin-lattice relaxation time at room temperature of 0.13 milliseconds. With a spin-lattice time of this duration and static broadening it should be possible to obtain adiabatic rapid passage. Rapid passage effects are not observed, suggesting strong spin-spin coupling. This coupling may well be through spin waves as has been suggested by Suhl.

77. INITIAL-PERMEABILITY SPECTRA OF MICROSCOPIC IRON-OXIDE PARTICLES*

W. F. BROWN, JR., J. P. HANTON and A. H. MORRISH
University of Minnesota
Minneapolis 14, Minnesota

The magnetic resonance of single-domain ferromagnetic particles in zero applied steady magnetic field has been studied theoretically and experimentally. The particles are assumed to have the shape of prolate ellipsoids of revolution. The rotation of the magnetization vector is then determined by the applied alternating field and by a demagnetizing field with constant and alternating components. An isotropic distribution of particle orientations is assumed. If damping is neglected, the value of the out-of-phase component of the susceptibility ($X_2 = \mu_2/4\pi$) at any one frequency is determined by the fraction of particles with a certain difference of demagnetization factors, $D_b - D_a$. This result in principle permits the determination of the shape distribution of the particles of the powder. When damping is included, the curve is widened and flattened, but to first order the position of the maximum is not changed. The permeability of various powders of γ-Fe_2O_3 was determined by standard transmission line techniques. The powders differed in the shape distribution of their particles, but in each case the particles were acicular. There was a maximum in the μ_2 curves in the neighborhood of 5 kmc. The axial ratio deduced for the maximum of μ_2 is in reasonably good agreement with the mean axial ratio determined with the electron microscope. Similar results were obtained for magnetite powders. This is strong support for our theory of the origin of the resonance.

*This research was supported in part by the United States Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command under Contract No. AF 18(603)-113.

---

78. GALVANOMAGNETIC EFFECTS IN FERROMAGNETIC RESONANCE*

M. H. SEAVEY, JR.
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts

The DC voltage generated across the surface of a thin ferromagnetic film during ferromagnetic resonance (FMR) is described.[1,2] The effect is believed to be due to the combined action of the extraordinary Hall effect and a magnetoresistance effect.[3] The DC character arises since the voltage is proportional to double products of microwave fields. Data on voltage versus magnetic field are presented for S-Band and X-Band frequencies. It is shown by an electromagnetic calculation that values for the extraordinary Hall parameter α and the magnetoresistance term $(\rho_{\parallel} - \rho_{\perp})$ may in principle be obtained provided the tensor permeability components are measured. Since the voltage is essentially independent of film thickness, the effect provides an extremely sensitive method of detecting FMR in ultrathin films.

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

1. W. G. Egan and H. J. Juretschke, BAPS, Washington Meeting, Spring 1958.
2. P. E. Tannenwald and M. H. Seavey, Jr., J. Physique et Radium, 20, 323 (1959).
3. Suggested by H. J. Juretschke.

---

79. INITIAL SUSCEPTIBILITY SPECTRA OF PERMALLOY FILMS*

R. F. SOOHOO
Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, Massachusetts

The initial susceptibility of permalloy films at and below microwave frequencies (100 to 10,000 Mc) is studied in detail both theoretically and experimentally. The exact boundary value problem of a film placed in a cavity is solved, with the effect of exchange, conductivity, and surface anisotrophy upon the value of the initial susceptibility considered. This result is compared with the simpler perturbation solution. Because of the unique geometry of the film (filling the entire cavity cross section) and its conducting properties, it is possible to solve the problem exactly and thereby enable one to determine the limits of validity of the perturbation theory. As may be expected, the exact solution reduces to that obtained from perturbation theory when the film thickness and the value of the initial permeability are sufficiently small.

Measurements on the initial susceptibility of permalloy films of various thicknesses and anisotropy constants were carried out to check the predictions of the above theory. Both transmission[1] and cavity[2] methods were used for the measurement of the initial susceptibility. Since the fractional cavity volume occupied by, and the initial susceptibility of permalloy films are small at microwave frequencies, high resolution microwave circuits had to be employed for its measurement.

The theoretical results show that the r.f. magnetic field is quite uniform across the thickness of the film for ordinary values of the initial susceptibility and thickness of permalloy films. Furthermore, it can be shown that in general the zero applied field point does not correspond to the natural frequency of a spin-wave whose wave length λ is given by the relation $\lambda = 2\,\delta/(2n+1)$ where δ is the thickness of the film and n is an integer including zero. These considerations justify the neglect of the exchange term in the equation of motion of the magnetization leading to a considerable simplification of the calculation. Thus, in a self-consistent way, we can show that exchange effects can sometimes be neglected as far as initial susceptibility values are concerned.

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

1. D. O. Smith, Phys. Rev. 104, No. 5, 1280-1281 (December 1956).
2. R. F. Soohoo, Lincoln Laboratory Group Report No. 53-15, p. 32 (June, 1959) (unpublished).

80. FERRIMAGNETIC RESONANCE AS A FUNCTION OF LATTICE CONSTANT*

I. P. KAMINOW**
Gordon McKay Laboratory
Harvard University
Cambridge, Massachusetts

The interactions in a ferrimagnet, such as exchange and crystalline field, depend upon the separation of ions in the crystal. All the inter-ionic spacings in a cubic crystal may be reduced in approximately the same proportion by the application of hydrostatic pressure. Consequently, one would expect the application of pressure to result in variations of the *magnitudes*, but not the symmetry, of macroscopic properties, which are manifestations of the fundamental interactions.

By combining microwave resonance and high pressure techniques we have measured K_1/M, K_2/M, g_{eff} and linewidth as a function of pressure for YIG, YbIG, ErIG, $Ni_{1-x}Co_xFe_2O_4$($x = 0, 0.05, 0.10$) and $MgFe_2O_4$ (with different ionic distributions). For YIG and $MgFe_2O_4$, in which the linewidth is sufficiently narrow, we have also measured M as a function of pressure using the change in separation of magnetostatic modes. Although the volume decreases only 0.7 per cent in 10,000 atmospheres for these materials, it is found that the changes in magnetic properties, which can be measured quite precisely, are an order of magnitude larger than the volume change.

Some of the experimental results will be discussed in the light of current theories, in particular, the crystal field theories of anisotropy for Fe^{+++}[1] and Co^{++}[2] ions and the theory for g-value[3] and linewidth[4] in rare earth garnets.

*Research supported by Contract AF 19(604)-5487 with Air Force Cambridge Research Center.
**Bell Telephone Laboratories CDTP Fellow.

1. V. J. Folen and G. T. Rado, J. App. Phys. 29, 438 (1958); T. Yosida and M. Tachiki, Prog. Theor. Phys. (Japan) 17 331 (1957); W. P. Wolf, Phys. Rev. 108, 1152 (1957)
2. J. C. Slonczewski, Phys. Rev. 110 1341 (1958).
3. C. Kittel, to be published in Phys. Rev.
4. P.-G. deGennes, C. Kittel and A. M. Portis, to be published in Phys. Rev.

---

81. RESONANCE LINE WIDTH IN DISORDERED FERRIMAGNETICS*

E. PITTELLI and H. CALLEN
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania

Clogston, Suhl, Anderson, and Walker[1] have discussed the source of loss, and hence of resonance line width, in disordered magnetic materials. They point out that processes in which only two excitations are involved, such as destruction of one magnon with creation of either another magnon or a phonon, are possible because of the lack of translational symmetry. This is in contrast to an ordered structure, in which only multiple-excitation processes are permitted. Consequently, the loss in a disordered sample can, in principle, be relatively large.

Clogston et al assume further that the magnon scattering process dominates the observed loss in Ferrites[2]. They compute the magnon scattering induced by the fluctations of dipole-dipole interactions in a simplified ferromagnetic material. We find that in a ferrimagnetic, as contrasted with a ferromagnetic, the fluctuations in the exchange integral produce a magnon scattering. Physically, this occurs because neighboring ions are not strictly antiparallel in the ferrimagnetic ground state; this non-classical angular deviation calls into play the exchange interaction and produces scattering of spin-wave excitations.

The loss has been computed for a body centered cubic ferrimagnetic model. The predicted line width is an order of magnitude larger than that obtained by Clogston et al and is in good agreement with the line widths typically observed in ferrites. The dependence of the line width on the short range order parameter, and thence on the quenching temperature, has been computed. The dependence of line width on sample shape also follows from the model.

*Supported by ONR

1. Clogston, Suhl, Anderson, and Walker. Phys. and Chem. of Solids Vol. I, Nov. 1956, p. 129.
2. This is the special case (1) of the general classification of magnetic losses in ordered and disordered samples, given by H. Callen, Phys. and Chem. of Solids. Vol. 4, No. 4, 1958 p. 256.

---

82. EFFECTS OF SURFACE INHOMOGENEITIES ON SINGLE CRYSTAL RESONANCE PARAMETERS*

C. R. BUFFLER**
Gordon McKay Laboratory
Division of Engineering and Applied Physics
Harvard University
Cambridge, Massachusetts

Measurements of ferromagnetic resonance line widths, anisotropy of line widths, magnetocrystalline anisotropy and g values of yttrium garnet and nickel zinc ferrite single crystals as a function of surface conditions and frequency are presented. These measurements indicate that the present picture of degenerate scattering must be modified slightly to explain the behavior of these parameters. The data indicates that in single crystals with extremely narrow intrinsic lines, such as yttrium iron garnet, the behavior of the line width and anisotropy of line width can be explained by the loss of energy from the uniform precession to the degenerate medium k states in the spin wave manifold due to the irregularities in the surface of a corresponding size. In single crystals with larger intrinsic line widths such as nickel zinc ferrite, it is shown that the scattering to medium k states is negligible. Here the primary broadening from surface effects arises from a simple classical inhomogeneity broadening which is equivalent to the excitation of modified long wave length spin waves or magnetostatic modes. These results are then applied to explain the existing data on resonance line width anisotropy. They also explain the recent, seemingly contradictory results of White on magnetostatic mode line widths.

The measurements of magnetocrystalline anisotropy and effective g values or both yttrium garnet and nickel zinc ferrite indicate that these parameters are independent of frequency over the range 2 to 15 kmc and independent of surface condition for surfaces with mean irregularity sizes from 0 to 100 microns.

*This work was conducted under sponsorship of Air Force Cambridge Research Center, Contract AF 19(604)-1084.

**Present address, Varian Associates, Palo Alto, California.

---

83. SATURATION EFFECTS IN FERRIMAGNETIC RESONANCE

P. E. SEIDEN
Lockheed Missiles and Space Division
Palo Alto, California
and
Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California
H. J. SHAW
Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

Saturation curves of susceptibility as a function of rf magnetic field have been measured for a number of samples of polycrystalline yttrium iron garnet of varying yttrium-to-iron ratio. The curves exhibit a region of susceptibility proportional to $1/h_{rf}$ at high rf powers. The region of initial decline of susceptibility has been attributed by Schlomann[1] to the scattering of uniform precession magnons into spinwaves by sample inhomogeneities. He predicts a decline in susceptibility proportional to h^2_{rf}. Suhl[2] has also calculated a saturation relation predicting an initial decline in susceptibility proportion to h^4_{rf}. We have derived a saturation relation by extending an analysis by Callen[3] to the case of an rf driving field. We predict a decline in susceptibility given by

$$\frac{\chi''}{\chi_0''} = \frac{1}{1 + \frac{\pi\gamma}{H_0\lambda_{k\sigma}} h^2}$$

which has the same form as Schlömann's relation for the initial decline in susceptibility where $\pi\lambda h^2 / H_0\lambda_{k\sigma} \ll 1$.

Experimental data fit the square-law dependence quite well in the region of the initial decline in susceptibility and fit a 1/h dependence at higher rf fields. Deviations from this 1/h dependence are noticed at even higher rf fields where the susceptibility is below .25 of the small signal value.

1. E. Schlomann; Bull. Am. Phys. Soc. 4, 53, (1959).
2. H. Suhl; J. Appl. Phys. (to be published).
3. H. B. Callen; J. Phys. & Chem. Solids 4, 256 (1958).

84. RESONANCE LINE WIDTHS OF SINTERED NICKEL FERRITES HAVING LOW POROSITIES

L. G. VAN UITERT, R. R. SODEN and F. W. SWANEKAMP
Bell Telephone Laboratories, Inc.
Murray Hill, New Jersey

Ferrimagnetic resonance line widths of a number of nickel ferrites (into which copper, manganese, zinc, aluminum, chromium, and cobalt are substituted) have been measured at 16 k.m.c. and related to processing conditions and saturation magnetizations.

The measurements show that there is no simple relationship between density and line width in low porosity samples of a given ferrite composition. However, as has been previously shown for yttrium iron garnet[1], there are systematic dependencies of line widths upon sintering conditions. These can be accounted for by considering the effects of gas generation in bodies which have very high relative densities. Subtle changes in sintering conditions can produce line widths differing by a factor of four or better in samples of the same composition which have identical densities.

Line width appears to be considerably affected by the distribution or shape of the voids present and their interaction with the anisotropy field. Measurement on several series of nickel ferrites having saturation magnetizations ranging from 600 gauss to 5000 gauss and which vary in cobalt content show that under optimum sintering conditions, line width increases linearly with cobalt additions. However, under non ideal conditions, minima in line width (of the kind discussed by Sirvetz and Saunders[2], and Pippin and Hogan[3]) occur at optimum cobalt contents.

These minima indicate that certain effects that increase line width at other cobalt concentrations are not significant in their concentration range. This supports the view that some property related to the anisotropy field can be minimized by cobalt additions. However, under ideal sintering conditions, the line widths obtained on cobalt free samples are invariably less than those obtained on the cobalt containing samples. Hence, these data do not support the contention that a minimum in magnetocrystalline anisotropy itself, acting to reduce the anistropy field and thus the intrinsic line width of the material, is realized by adding cobalt.

In certain samples, which were sintered under conditions which produced line widths much greater than the minimum values realized under optimum conditions, line widths were found to decrease slowly with time. This also supports the view that there is an interaction between demagnetizing effects and some anisotropy dependent quantity other than the magnetocrystalline anisotropy itself.

The minimum values of line width obtained vary as the reciprocal of magnetization, as would be expected from anisotropy field or dipole narrowing considerations. Dipole narrowing is evident since the values obtained are much lower than those expected from anisotropy field considerations alone. Line width values as low as 42 oersteds on polycrystalline $Ni_{.5}Cu_{.1}Zn_{.4}Fe_{1.9}Mn_{.1}O_4$ have been found.

1. L.G. Van Uitert, F.W. Swanekamp and S. Preziosi, "Ferrimagnetic Resonance Line Widths and Phase Distributions in Sintered Yttrium Iron Garnets," to be published

in J. Am. Ceram. Soc., presented at Fall Meeting of Electronics Div. at Ashbury Park, Sept. 1958.

2. M. H. Sirvetz and J. H. Saunders, "Resonance Widths in Polycrystalline Nickel Cobalt Ferrites," Phys. Rev., Vol. 102, pp. 366-367 (1956).
3. J. E. Pippin and C. L. Hogan, "Resonance Measurements on Nickel Cobalt Ferrites as a Function of Temature and on Nickel Ferrite Aluminates," I.R.E. Trans. on Microwave Theory and Techniques, Vol. 6, pp. 77-82 (1958).

SESSION V-B

SOFT MAGNETIC MATERIALS

R. M. BOZORTH, Presiding

---

85. A NECESSARY FACTOR FOR HEAT TREATMENT OF THE PERMALLOYS IN A MAGNETIC FIELD

E. A. NESBITT, R. D. HEIDENREICH and A. J. WILLIAMS
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

Recently, we have been able to show that Perminvar (Nl-Fe-Co alloy) has an inhomogeneous structure (Nesbitt and Heidenreich, J. App. Physics, 30, 1000 (1959)) and that this inhomogeneity is due to an impurity fault (Heidenreich and Nesbitt, J. App. Physics, 30, 995 (1959)). Evidence was obtained that small amounts of oxygen as an impurity in Perminvar caused both the faulting and the heat treatment in a magnetic field. It was exceedingly difficult, however, to remove sufficient oxygen from this material to prevent heat treatment in a magnetic field. More conclusive experiments have now been done to demonstrate the effect of oxygen on the response to magnetic annealing in the nickel-iron alloys without cobalt (Permalloys). Magnetic torque curves on a single crystal of 63% Ni-35% Fe-2% Mo for two different heat treatments illustrate this point. When the crystal was purified in hydrogen and then was heat treated in a magnetic field, it did not respond. However, after a slightly oxidizing heat treatment (pot annealing at 1000°C. for 16 hours), it did respond to the field heat treatment by developing a uniaxial anisotropy of approximately 2000 ergs per cm^3.

The intimate connection between the presence of impurity faults and the ability to respond to heat treatment in a magnetic field is shown by observations on single crystals of 68% Ni-31.9% Fe-.1% Mg which were grown for this purpose. The (100) surfaces of these crystals showed heavily and lightly faulted regions. The work on the Perminvars has shown that the heavily faulted areas contain more oxygen than the lightly faulted areas. The magnetic torque measurements on the 68% Ni alloy confirm this idea. The heavily faulted crystal had a uniaxial anisotropy of approximately 3000 ergs per cm^3 while the lightly faulted crystal had a value of only 1000 ergs per cm^3.

---

86. STUDY OF HEAT TREATMENTS FOR LOW COERCIVE FORCE 14 TO 17 PERCENT ALUMINUM IRON ALLOYS*

D. PAVLOVIC** and K. FOSTER
Magnetic Materials Development Section
Materials Engineering Departments
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

Previous investigations[1,2] have determined the dependence of magnetic properties, particularly the coercive force, on the ordering reaction occurring in the aluminum-iron system between 10 and 20 weight percent aluminum. A study of the effects of atmosphere, temperature, and composition on the coercive force of 14 to 17 percent aluminum-iron alloys is presented in the present paper. Optimum heat treatment conditions which result in low coercive force values of these alloys are presented and mechanisms of these heat treatments are discussed on the basis of a new aluminum-iron phase diagram.[3,4] Economical processing conditions, particularly effects of air heat treatments, are also described.

A combined effect of heat treatment atmosphere and temperature is shown to exist in this alloy region and is discussed in terms of a possible influence of purification and different atomic ordering arrangements. The unique feature of these alloys is that heat treatments in air at 900°C produce lower coercive force values than heat treatments in dry hydrogen at the same temperature. This factor would make the heat treatments of these alloys more economical than those of other standard high-permeability alloys.

Observations made on the binary aluminum-iron alloys apply to the heat treatment of aluminum-iron alloys containing ternary additions. It is further shown that the heat treatment controls both the grain size and the distribution of inclusions in ternary alloys, which in turn affect the magnetic properties.

---

*This work was supported in part by the Aeronautical Research Laboratory, Wright Air Development Center, Air Force Contract No. AF33(616)-309.

**Presently with Westinghouse Electric International Company, East Pittsburgh, Pa.

1. J. F. Nachman and J. W. Buehler, U. S. Naval Ordnance Laboratory Report 4130 (1955).
2. D. Pavlovic and K. Foster, Conference on Magnetism and Magnetic Materials (American Institute of Electrical Engineers, February, 1957) p. 256.
3. A. Taylor and R. M. Jones, J. Phys. Chem. Solids, 6, 16 (1958).
4. H. J. McQueen and G. C. Kuczynski, Transactions of the Metallurgical Society, AIME, 215, 619 (1959).

---

87. EFFECT OF DIRECTIONAL ORIENTATION ON THE MAGNETIC PROPERTIES OF CUBE ORIENTED MAGNETIC SHEETS

K. FOSTER and J. J. KRAMER
Magnetic Materials Development Section
Materials Engineering Departments
Westinghouse Electric Corporation
East Pittsburgh, Pennsylvania

A process for obtaining cube oriented magnetic sheet by secondary recrystallization has recently been reported.[1] When carried out properly, this process results in a very high degree of orientation of the {100} plane with respect to the plane of the sheet. The orientation of the <100> direction with respect to the rolling direction, on the other hand, can vary considerably. The purpose of the present investigation has been to study the effect of this variation in directional orientation on magnetic properties of thin silicon iron sheets. A number of .004" thick 3 percent silicon iron sheets was annealed to obtain essentially complete secondary cube-on-face grain growth. Orientation studies were made on these sheets using a domain pattern technique. Deviations of the <100> direction from the rolling direction were measured, and the percentages of grains with <100> within given angles from the rolling direction were calculated. These sheets showed variations in the number of grains with <100> within 10° of the rolling direction ranging from 0 to 90 percent. Magnetic tests using both 25 cm Epstein strips and toroidal cores were made. The induction reached for a field of 10 oersteds (B_{10}) was plotted as a function of the percent of grains with <100> within 10° of the rolling direction. A sharp increase in B_{10} was observed as the percent of grains with <100> within 10° of the rolling direction approached the maximum value. The results indicate that a high degree of directional orientation is necessary to obtain the optimum magnetic properties in cube oriented sheets.

---

1. F. Assmus, K. Detert, and G. Ibe, Zeitschrift fur Metallkunde, 48, 341-349 (1957).

---

88. SECONDARY RECRYSTALLIZATION IN VACUUM-ANNEALED SILICON-IRON

G. BAER, G. GANZ and H. THOMAS
Vacuumschmelze, A. G.
Hanau, Germany

The magnitude of the surface energy is of importance in the problem as to which crystals grow preferentially during secondary recrystallization. In this connection, it is essential to create well defined conditions on the surfaces of the specimens in order to investigate this phenomenon of growth. The influence of environment may be eliminated if the recrystallization anneals are carried out in a high vacuum in high-purity ceramic tubes.

In thin silicon-iron strips of suitable thickness, we obtain, under these conditions, a secondary recrystallization in the (100) orientation. It is possible for crystals to grow with a (100) as well as a (110) orientation in thicker strip, which, among other things, determines the choice of annealing temperature.

The surface of the strip is least disturbed if the sample is directly heated by the passage of an electric current, and by this means is allowed to attain its highest temperature within the evacuated annealing chamber. Under these conditions, crystals with a (110) orientation grow preferentially in the thicker strips. However, this result is also influenced by the thickness of the strip and the annealing temperature. The investigations yielded definite conclusions regarding the differences in surface energy of low index planes and regarding the temperature-dependence of the constants responsible for the selection.

Internal memo. Results taken from Lab. Report V/386 dated 10th April, 1959, Dr. Baer/Dr. Ganz. Lab. Report II/629A dated 27th Jan., 1959, Dr. Ganz/Dr. Baer.

89. ANOMALOUS TRANSIENTS FOR SUPERMENDUR AT HIGH TEMPERATURES

M. LAURIENTE and G. E. LYNN
Westinghouse Air Arm
Baltimore, Md.

Exposures to temperatures above 500°C have been found to have a pronounced effect on the room temperature properties of Supermendur. A gradual degradation was dramatically displayed for toroidol cores of Supermendur when the magnetic properties were measured at temperatures between 500 and 600°C on a constant current flux-reset tester. This test is designed to simulate the action of a half-wave self-saturating magnetic amplifier. Normally a steady state cyclic flux change is achieved within one cycle of the applied alternating magnetizing field. A delay of several minutes (equivalent to several thousand cycles of alternating field) was observed instead for this alloy. An analysis of the flux change versus time relationship indicates that the transient is a complex rate phenomenon. An attempt is made to assay the contributions of the most probable causes which are considered to be oxidation, magnetic fields due to the tester, order-disorder and oriented domain relaxation.

---

90. EFFECT OF HYDROSTATIC PRESSURE ON PROPERTIES OF MAGNETIC MATERIALS

R. E. ALLEY and V. E. LEGG
Bell Telephone Laboratories, Inc.
Whippany, New Jersey

A review of the literature on hydrostatic pressure effects on magnetic materials showed a lack of information on technologically important properties such as initial permeability and the hysteresis loop. Measurements of these properties up to 20,000 p.s.i. showed that most solid materials are only slightly affected. These include tape cores of supermalloy, supermendur, 4-79 Mo-permalloy and grain-oriented Si-steel, as well as S.5 ferrite memory cores, and compressed powder cores of 2-81 Mo-permalloy or of carbonyl iron. Some types of NiZn and MnZn ferrite show increases of coercive force and decrease of permeability with pressure. Measurements were made of permeability vs. frequency of MnZn ferrite to find the relaxation frequency. At atmospheric pressure the permeability shows a sharp decline above .85 Mc. At 20,000 p.s.i. the decline in permeability does not occur until 1.6 Mc.

---

91. RADIATION EFFECTS ON DOMAIN WALL STABILIZATION IN ALLOYS AND ON REMANENCE IN A FERRITE

A. I. SCHINDLER, E. I. SALKOVITZ and G. C. BAILEY
Metallurgy Division
U. S. Naval Research Laboratory
Washington 25, D. C.

Previous results[1] have indicated the similarity in magnetic properties resulting from thermally induced ordering and irradiation induced ordering in permalloy type materials (i.e., Fe-Ni Alloys). The constricted hysteresis loops resulting from ordering can be attributed to uniaxial anisotropy and domain wall stabilization induced along magnetization vectors oriented in easy directions of magnetization present during the ordering treatment[2]. In the case of magnetic thermal annealing the induced uniaxial anisotropy results in an easy direction of magnetization parallel to the direction of the magnetic field applied during annealing. Consequently, the magnetization process is due to the displacement of 180° domain walls and thereby square hysteresis loop characteristics are obtained. Similar results have now been obtained by irradiating permalloy type samples with an applied magnetic field present during irradiation. Two toroidal samples each of permalloy, mu-metal, 48% Ni - 52% Fe and 43% Ni - 54% Fe - 3% Si were irradiated in the Brookhaven reactor for two weeks. In each case, one sample was magnetized to saturation during irradiation by sending an electric current through a magnetizing coil wrapped on the sample. All of the samples irradiated in the unmagnetized state gave results similar to those previously described[1]. The samples magnetized during irradiation, however, exhibited an increase in the remanence and coercive force and a decrease in the low field permeability. For these latter samples a square hysteresis loop was obtained indicating that a uniaxial anisotropy has resulted in the direction of the field applied during the irradiation.

Previous investigations at this Laboratory have indicated that the magnetic properties of various ferrites may be altered by continuous exposure to pile irradiation. In order to better understand the inception of radiation damage as well as the inception of recovery, if any, in these ferrites, a NiZn Cu ferrite was irradiated intermittently in the NRL swimming pool reactor. The experiment consisted of observing the magnetic remanence, B_R, at 60 cycles and the temperature of the ferrite as a function of the cyclic irradiation and recovery time. In general, all of the irradiation took place at 100KW, 8 hours a day, 5 days a week for a period of 4 weeks. To properly evaluate the recorded raw data, a study was made of the temperature coefficient of the magnetic remanence.

The net radiation effect on the magnetic remanence was a 4% decrease for a time-integrated-fast flux of 1.1×10^{16} nvt. This agrees well with a corresponding interpolated 2% decrease for the same flux on a similar sample continuously irradiated in the Brookhaven reactor. The results of the experiment indicate that the damage was accumulative over the four weeks of intermittent irradiation. Further, damage and recovery occur primarily in the initial period when the reactor is turned on and when it is turned off, respectively. This suggests that the rate of damage is greatly decreased after the first two hours of exposure, and that most of the recovery occurs very shortly after the reactor is turned off, and that this process is repeated with each radiation cycle.

---

1. A. I. Schindler, E. I. Salkovitz, and G. S. Ansell, J.A.P. 305, 2825 (1959).
2. S. Taniguchi, Sci. Rept. R.I.T.U., A1269 (1955).

92. RADIATION EFFECTS IN GARNETS, FERRITES, AND MAGNETIC ALLOYS*

S. I. TAIMUTY, J. S. MILLS, C. A. ROSEN, L. G. WRIGHT, and B. S. DEAVER, JR.
Stanford Research Institute
Menlo Park, California

Experiments have been performed to determine the effects of reactor radiations on the structure-sensitive magnetic properties of garnets, ferrites, and magnetic alloys. Hysteresis loops were photographed with a hysteresigraph that covers a frequency range from 400 cps to 100,000 cps. Complex permeability measurements were also made with an impedance bridge over a frequency range of 15 kcps to 15 mcps. Some of the materials tested could not be measured throughout the entire frequency range of either instrument, for either structural or geometrical reasons. Samples were irradiated at General Electric's Test Reactor at Vallecitos, California, in a combined thermal and fast flux of approximately 6×10^{13} neutrons/cm^2/sec. Integrated fast neutron doses ranged from 10^{15} to 10^{18} neutrons/cm^2.

Temperature-controlled and gamma-ray heating experiments were performed on the same type of samples to establish the effect of gamma-ray heating. Environmental and sample temperatures were determined by means of in-pile temperature measurements.

Measurements were made on two garnets (yttrium-iron and samarium-iron), five ferrites (MnO·ZnO**, NiO·ZnO***, MnO·MgO), and two alloys (Supermalloy and Deltamax). A minimum of three samples of each type were measured. Measurements of coercive force, remanance, loss, and complex permeability as a function of both fast neutron dose and frequency will be reported.

*The research reported in this paper has been sponsored by the Electronics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract AF 19(604)-4141.

**Supplied by two different manufacturers — Ferroxcube and General Ceramics.

***Two variations of this composition were supplied by the same manufacturer—General Ceramics.

---

93. THE EFFECTS OF DIRECTIONAL ORDERING ON THE DAMPING OF ZONE-MELTED IRON

R. E. MARINGER
Battelle Memorial Institute
Columbus, Ohio

Damping measurements (~1cps) have been made as a function of temperature on zone-melted, high-purity iron, to which up to forty parts per million carbon have been added. Measurements were made with and without a superimposed, saturating magnetic field. The difference between these measurements has been ascribed to the magneto-elastic contribution of moving domain walls.

The difference curve is roughly sigmoidal in shape, with the magneto-elastic contribution being low at low temperatures (below about 0 C) and high at higher temperatures (above about 50 C). The shape of this curve has been analyzed and shown to yield a relaxation time appropriate for the interstitial diffusion of carbon.

Damping has also been measured as a function of time and temperature after the removal of a superimposed magnetic field. The damping is observed to decrease as a function to time to a minimum value which is almost identical with the low damping of the magnetically saturated material. These data have been analyzed and also shown to yield a relaxation time equal to that for the interstitial diffusion of carbon.

Interpretation of the data suggests that the mechanism responsible for these observations is directly analogous to that proposed to explain the time decrease of magnetic permeability of iron. That is, each of these effects are derived from the interaction of ferromagnetic domain walls with solute interstitial atoms and the concurrent directional ordering of these interstitial atoms.

This research is being conducted under Sponsorship of the Office of Naval Research.

---

94. THE MAGNETIC CONTRIBUTION TO THE ULTRASONIC ATTENUATION IN ANNEALED AND DEFORMED STEEL (SAE 1020)

U. M. MARTIUS, W. J. BRATINA and D. MILLS
Ontario Research Foundation
Toronto, Ontario, Canada

PART I - EXPERIMENTAL DATA. Ultrasonic attenuation variations occurring in ferromagnetic materials subjected to elastic or plastic stresses received relatively little attention,[1,4] in contrast to the amount of work done on non-ferromagnetic materials. This paper deals with the attenuation changes induced by elastic strain and/or magnetic field in annealed and plastically deformed polycrystalline low carbon steel (SAE 1020) with a particular emphasis on the attenuation characteristics of deformed material.

Cylindrical specimens, 12 inches in length and 1/2 inch in diameter were employed. Frequencies of approximately 3 megacycles per second were used and the Sperry Ultrasonic Attenuation Comparator was employed for attenuation measurements. The values obtained cannot be regarded as absolute for the particular material; the losses due to ultra sound absorption in the coupling medium between the crystal and the specimen, and the loss occurring at the end face for example, are also included in the experimental values. From this point of view long specimens as used in our experiments are to be preferred since in this case the contribution of coupling medium and end face are kept as low as possible. Highly reproducible results were obtained as a rule.

Hydrogen annealed and plastically deformed (1% permanent elongation) specimens were investigated. The attenuation was measured (a) as a function of externally applied stress (in the elastic range) in the presence of constant magnetic fields between 0 and approximately 1100 oersteds, and (b) as a function of externally applied fields in the presence of constant tensile stresses. The attenuation changes occurring during the plastic deformation process itself, however, are not dealt with here, and plastically deformed specimens should be considered to be fully strain aged. The corresponding magnetization curves and the linear magnetostriction of the specimens were also determined. Representative results will be shown.

PART II - INTERPRETATION OF THE RESULTS. The results of the experiments described show that a large portion of the ultrasonic attenuation can be accounted for by ferromagnetic mechanisms. The measurements permit a separation of the attenuation components due to dislocation mechanisms and due to ferromagnetic mechanisms. It is usually assumed that the changes in ultrasonic attenuation are closely related to the changes in the domain *configuration,* caused in a ferromagnetic material by the application of stress or magnetic fields. However, we observed a continual decrease in attenuation even at fields which were well above the level at which changes in domain configuration can occur. These results together with the magnetization curves of the material give a good indication of basic mechanisms involved. These will be discussed in detail.

A comparison of the attenuation of the annealed and deformed materials obtained under otherwise identical experimental conditions show their characteristic differences. While the attenuation of the annealed material shows consistent decrease with increasing stress or field, the deformed material exhibits a maximum of the attenuation with increasing field or stress which can be related to the internal stresses introduced into the material through plastic deformation. It appears possible to estimate the level of these internal stresses, from this type of attenuation measurement.

1. A. Hikata, Gov. Mech. Lab. Bulletin No. 1, Tokyo, Japan (1954).
2. K. Winterton (Unpublished) (1955).
3. A. Hikata and R. Truell, Report WAL, 143/14-51 Metallurgical Research Lab., Brown University (1958).
4. W. J. Bratina, Canadian Journal of Physics 37, 579 (1959).

95. DC MEASUREMENTS ON TAPE-WOUND CORES

R. C. BARKER and R. M. BROWNELL
Yale University
New Haven, Conn.

This paper reports hysteresis-loop measurements made on tape-wound cores of commercial-grade grain-oriented 50Ni-50Fe material at very low domain wall velocities. The experimental equipment includes a low-output-impedance core driver, a low-drift electronic integrator, and a 30" x 30" X - Y recorder. The duration of a complete flux reversal can be varied between 5 seconds and 30 minutes. The rate-of-change of flux during a reversal can be held constant within 1%, so that variations in the ease of domain wall motion (which appears as Barkhausen discontinuities in conventional measurements) are constrained to appear as variations of magnetomotive force. The coarse structure of these variations is repeatable on successive measurements; the fine structure, for the most part, is not.

In addition to showing these variations of mmf, the experimental arrangement displays minor loops in their correct locations with respect to the major loop. These measurements indicate that, under dc conditions, flux changes always begin at the inner circumference of the core, as predicted by a previously proposed model of flux change in polycrystalline tapes.[1] Many other aspects of these minor-loop measurements can be explained by this model, which is currently being further developed.

On the basis of the model, the recorded variations in mmf can easily be used to find the variations in the energy required to move domain walls in various portions of the core, under conditions of constant rate-of-change of flux. (Under such conditions, the product of wall velocity and wall area is a constant.) The repeatability of the coarse variations indicates their dependence on local metallurgical variations within the core. The non-repeatability of the fine variations probably indicates a randomness in the configuration of the domain walls as they pass through the same region on successive measurements.

1. Barker, R. C., Magnetization in Tape-Wound Cores. Proceedings, Conference on Non-Linear Magnetics and Magnetic Amplifiers, AIEE Special Publication, 1958, Pages 1-46.

96. THE EFFECT OF EDDY CURRENTS ON DOMAIN WALL CONFIGURATION AND WALL MOTION AND LOSS FOR A DOMAIN MODEL OF CUBE-ON-EDGE MATERIAL

P. D. AGARWAL
Associate Professor of Electrical Engineering
University of Massachusetts
Consultant for the General Electric Company
D. C. GRAHAM
General Electric Company
Power Transformer Department
Pittsfield, Massachusetts

Domain wall motion in single crystals and polycrystalline material has been observed and studied by many physicists and metallurgists under different conditions of excitation. The field has been applied in the rolling direction and in the cross rolling direction and observations made on the surface of the domain wall motion. In these studies the rate of change of wall motion of necessity must be slow because of the limitations of the procedure for following and photographing the wall motion. It has been recognized that at higher frequencies, the wall tends to bow, but the actual motion has not been defined. The published data under d-c excitation conditions, along with the required minimum energy relationship, establishes the boundary conditions that must be met by a domain model for polycrystalline cube-on-edge material. A domain model has been developed which appears to fit these boundary conditions under d-c excitation.

An analysis of the induced voltage and resulting eddy currents was made on the assumption that the domain wall remain straight and that the velocity was such as to give sinusoidal flux change. The actual flow of eddy currents dictated that the wall must bow. By modifying the domain wall motion to fit the conditions as dictated by the eddy currents, the eddy current losses were calculated and compared with losses measured in present-day material. The variations of magnetizing force with time are also calculated and show reasonable agreement with expected excitation curves versus time.

---

97. RIGOROUS SOLUTION OF EDDY CURRENT LOSSES IN RECTANGULAR BAR FOR SINGLE PLANE DOMAIN WALL MODEL

PAUL D. AGARWAL
Associate Professor of Electrical Engineering
University of Massachusetts
and Consultant to the General Electric Company
L. RABINS
General Electric Company
Power Transformer Department
Pittsfield, Massachusetts

Williams, Shockley and Kittel[1] and other authors have presented a simple domain model in which magnetization takes place by the movement of a single plane domain wall. The net flux is zero when the domain wall is in the middle of the cross section and the material is magnetized fully when the wall moves to the surface.

In this paper the validity of such a model is discussed from the electro-magnetic field point of view and it is shown that such a model is permissible under certain conditions.

Maxwell's equations for the case of a rectangular bar are rigorously solved for any position of the wall and expressions are derived for x and y components of the electric field in both regions I and II. The general expressions for power loss in the two regions are presented as the wall moves from one edge to the other. The stream function was calculated using an IBM 705 computer and is shown for various positions of the wall and for several ratios of the sides of the rectangle. The power loss for sinusoidal applied induction is calculated and compared with known experimental results. The wall traverses its full distance in each half cycle. The results show that the loss in the material increases as the distance traversed by the wall i.e. the dimension of the rectangle at right angles to the domain wall increases.

This solution also applies to thin laminations where the domain model proposed by several authors, comprises of domains of equal width alternately magnetized in opposite directions to give the unmagnetized state. The domain walls are perpendicular to the plane of the sheet and magnetization in the sheet plane takes place by lateral movement of these domain walls. For any given thickness of the laminations a domain wall spacing can be determined to correlate the power loss with experimental values.

---

1. Williams, Shockley & Kittel, Physical Review, 80, No. 6, 1090, (1950)

SESSION VI-A

FERRITES AND OXIDES

H. SATO, Presiding

---

98. ROLE OF CATION VACANCIES IN MAGNETIC ANNEALING EFFECTS OF COBALT IRON FERRITES (Invited)

SHUICHI IIDA
Department of Physics, Faculty of Science
University of Tokyo
Tokyo, Japan

Although important advances have been made recently for the mechanism of the magnetic annealing effects of iron-cobalt ferrites in a low cobalt concentration range,[1,2] there are still many questions remained in the effects, especially concerning to the change in character of the effects associated with the change in concentration of cation vacancies.[3,1] Several attempts have been made in order to describe the kinetics of the effect analytically. First a rather rigorous theoretical treatment is given starting from the simplest model of 16d sites in which a group of tetrahedrons are considered. Each unit tetrahedron has one vacancy, one cobalt ion, and two iron ions at its corners and therefore be able to take 12 different configurations A, A', A''; B, B', B''; C, C', C''; D, D', D'', each of which can change to one of the other three through an elementary process of the vacancy diffusion mechanism. Calculating statistically the population of each configuration, it can be deduced that the change in population number of each configuration (N_A, $N_{A'}$, $N_{A''}$, . . .) is expressed rigorously by a superposition of five simple relaxation processes; $N_\xi(t) = \sum_{i=1}^{5} n_\xi^i \exp(-t\, \tau_i)$. By extending this conclusion to the actual crystal having infinite number of cations and vacancies, the presence of a dispersion in relaxation time in the magnetic annealing effects has been derived quite generally. In order to get an actual distribution function of the relaxation times as a function of vacancy concentration and diffusion constant, a calculation based on a rather stochastic approach has been made. It is assumed that there are L. lattice points of 16d sites in which L.ξ sites are the vacancies which are distributing statistically. It is further assumed that each vacancy begins to itenate round the crystal by making a flight from the old position to the arbitrary one of the six nearest neighbour lattice sites repeatedly at a rate of exactly once in a time interval τ. Calculations are made for L(N), which indicates the number of lattice sites which have been occupied already at least once by any one of the vacancies, after each vacancy has executed the flights N times. By assuming that $\Delta L = L(N) - L(N-1)$ represents the volume fraction of the lattice which has a relaxation time $N\tau$, the distribution function of the relaxation time has been obtained. This shows a rather wide range of the dispersion and agrees well with the conclusion deduced from the measurements of the isothermal reorientation process of the uniaxial anisotropy. It is shown that the effective range of the relaxation time τ shifts linearly with the inverse of the vacancy concentration $1/\xi$ but there is little change in the shape of the distribution curve as a function of Log $\zeta\tau$. This conclusion seems to be contradictory to the experimental results by Pinoyer et al. The fact that the magnetic cooling is much more effective than the isothermal magnetic annealing can be understood easily by the presence of the rather wide range of dispersion in relaxation time.

Experimental studies of $Co_xFe_{3-x}O_4$ $(0.0625 \leq x \leq 1.5)$ concerning to the magnitude and the relaxation character of the uniaxial anisotropy are now going on.

1. R. F. Penoyer and L. R. Bickford, Jr., Phys. Rev. 108, 271 (1957).
2. J. C. Slonczewski, Phys. Rev. 110, 1341 (1958).
3. S. Iida, H. Sekizawa, and Y. Aiyama, J. Phys. Soc. Japan, 13, 58 (1958).

99. INTRINSIC AND ANNEAL-INDUCED ANISOTROPY IN COBALT-SUBSTITUTED W-TYPE HEXAGONAL OXIDES*

L. R. BICKFORD, JR.
IBM Research Laboratory
Poughkeepsie, N. Y.

Torque measurements of the intrinsic and anneal-induced magnetocrystalline anisotropy of a series of oriented polycrystalline samples belonging to the composition series $BaCo_xFe_{17.9-x}O_{27}$ are discussed. This series corresponds to cobalt-substituted ferrous W compounds, which have the nominal composition $BaO{\cdot}2MeO{\cdot}8Fe_2O_3$. (Me represents a divalent metal ion.) The compositions were purposely prepared under somewhat oxidizing conditions in order to create some vacancies in the lattice sites normally occupied by metals. All of the hexagonal compounds of the ferroxdure type can be described in terms of cubic spinel blocks sandwiched between hexagonal barium-containing layers. The W series was chosen for the present investigation because the spinel portion of its structure is thicker than that of any other hexagonal oxide. Therefore, if it is assumed that the cobalt ions are located in the spinel portion of the structure, it is to be expected that they would have approximately the same environment as they have when substituted into ferrites. The results tend to verify this assumption and indicate that the contribution of the cobalt ions to the anisotropy is approximately the same as in the case of cobalt-iron ferrites. The kind of information presented includes the dependence of the intrinsic and anneal-induced anisotropy on cobalt concentration, the relaxation times characterizing the annealing process, and the variation of anneal-induced anisotropy with temperature of anneal. Measurements performed on one single crystal with relatively large cobalt concentration are also described. Such measurements provide more detailed information about the orientation-dependence of the anneal-induced anisotropy and also make possible a more accurate determination of the intrinsic anisotropy constants than can be obtained using oriented polycrystalline specimens.

*Based on experimental work performed while the author was guest scientist in the laboratories of the Philips Gloeilampenfabrieken, Eindhoven, Netherlands.

100. THE VALENCE AND DISTRIBUTION OF MANGANESE IONS IN FERROSPINELS

ARTHUR MILLER
RCA Laboratories
Princeton, New Jersey

Anomalous values of the magnetic moments observed for ferrospinels containing manganese have suggested that on octahedrally ligated spinel sites the ion pair $[Fe^{+2}Mn^{+3}]$ is more stable than $[Fe^{+3}Mn^{+2}]$. Such behavior is opposed to that observed in aqueous solutions, and to what is usually expected in oxidic compounds. The magnetic measurements, however, cannot be interpreted unequivocally, since they can also be explained by invoking spin quenching, or deviations from the simple antiparallel coupling scheme such as Yafet-Kittel angular coupling.

A crystallographic rather than a magnetic criterion was devised to elucidate the valence behavior in these compounds. When a sufficient fraction of the octahedrally ligated spinel sites are occupied by Mn^{+3}, a macroscopic tetragonal distortion, due to the Jahn-Teller effect, occurs. For appropriately selected spinel systems the compositions for which this distortion is observable at room temperature depend on whether $[Fe^{+3}Mn^{+2}]$ or $[Fe^{+2}Mn^{+3}]$ are the stably coexisting species. Various compositions in the systems $Zn_{1-.5x}Ge_{.5x}[Fe_xMn_{2-x}]O_4$ and $Zn_{.5+.5x}Ge_{.5-.5x}[Fe_xMn_{2-x}]O_4$ were synthesized, and x-ray powder diffraction photographs were made to determine whether they were cubic or tetragonal. The findings confirmed that the stable ion pair on octahedrally ligated sites is indeed $[Fe^{+2}Mn^{+3}]$. Furthermore, the axial ratios observed for the tetragonal compositions are in good agreement with those calculated from the theory of cooperative distortions set forth by Wojtowicz, provided that the valence assignment $[Fe^{+2}Mn^{+3}]$ is assumed. The reversal of valence stability can be explained reasonably as arising from crystal field effects.

There is evidence that on octahedrally ligated spinel sites at elevated temperatures, and on tetrahedrally ligated sites, the ion pair $[Fe^{+3}Mn^{+2}]$ is more stable than $[Fe^{+2}Mn^{+3}]$. In view of the current findings, the method of predicting the actual valence and ionic distributions in manganese-containing ferrospinels is discussed.

101. HIGH FIELD MAGNETIZATION STUDY OF FERRIMAGNETIC ARRANGEMENTS IN CHROMITE SPINELS

I. S. JACOBS
General Electric Research Laboratory
Schenectady, New York

The observation of a differential susceptibility at high magnetic fields and low temperatures in spinel-type compounds has been shown to be useful for detecting non-collinear ferrimagnetic arrangements. Such an increase in net magnetization with field is not expected for the Néel model of tetrahedral A-site moments antiparallel to octahedral B-site moments. It is, however, expected for the triangular arrangements proposed by Yafet and Kittel in which the moments on one kind of site subdivide into two groups making angles with each other. The latter arrangements have frequently been suggested for chromium-containing spinels, usually on the basis of the observed anomalously low spontaneous magnetizations. Measurements of magnetization curves at 4.2°K in pulsed fields up to 140 kilo-oersteds reveal high field susceptibilities in $MnFe_{2-t}Cr_tO_4$, $t > 0$; $CuCr_2O_4$; $FeCr_2O_4$; and $NiFe_{2-t}Cr_tO_4$, $t > 1$. These are interpreted as triangular ferrimagnetic arrangements and choices are made between alternative triangular models. In some cases the sign of the dominant anisotropy is suggested. Néel antiparallel ferrimagnetic arrays are confirmed for $MnFe_2O_4$ and for $NiFe_{2-t}Cr_tO_4$, $t < 1$. The present evidence for these conclusions is of a new and occasionally more direct type.

---

102. THE HIGH TEMPERATURE SUSCEPTIBILITY OF FERRIMAGNETIC SPINELS

PETER J. WOJTOWICZ
RCA Laboratories
Princeton, New Jersey

The theory of the high temperature susceptibility and Curie temperatures of the cubic Heisenberg ferromagnets has recently been carried to a high degree of approximation through the introduction of exact series expansion methods by Brown and Luttinger[1] and by Rushbrooke and Wood[2]. The corresponding theory for the ferrimagnets, however, has not yet reached this stage of development. The only attempt at a higher approximation than the molecular field theory is Smart's[3] extension of the Bethe-Weiss method to certain simple cases of ferrimagnetism with spins of $\frac{1}{2}$ only. The present communication describes preliminary progress in the derivation of a theory for the susceptibility of ferrimagnets which parallels the high degree of approximation already achieved for the simpler ferromagnets.

Power series expansions of the susceptibility and its inverse in ascending powers of the reciprocal temperature have been obtained for ferrimagnetic spinels by using the methods of Rushbrooke and Wood[2]. The Heisenberg form of exchange is assumed, and in this paper, interactions between nearest neighboring spins from different sublattices (A-B exchange) only are considered. The coefficients in the series are derived for general values of the spins on the two sublattices. The calculations have been carried out to terms including the fifth power of the reciprocal temperature; the molecular field approximation by contrast is rigorously valid only to the first power term of its expansion. Representative curves of the inverse susceptibility *vs.* temperature and selected derived values of the Néel temperature are compared with the earlier work. It is anticipated that these expansions will prove useful in the interpretation of accurate susceptibility data for the purpose of deriving meaningful values for the exchange interactions in spinels.

1. H. A. Brown and J. M. Luttinger, Phys. Rev. 100, 685 (1955).
2. G. S. Rushbrooke and P. J. Wood, Molecular Physics 1, 257 (1958).
3. J. S. Smart, Phys. Rev. 101, 585 (1956).

103. TIME DECREASE OF INITIAL PERMEABILITY IN $Mn_xFe_{3-x}O_4$

W. A. CRAPO
International Business Machines Corporation
Research Laboratory
Poughkeepsie, New York

The time decrease of initial permeability has been observed in several magnetic materials[1]. Recently, Enz[2] observed this phenomenon in a manganese ferrite crystal, and suggested that this effect may be identified with electronic transitions between ions in different valence states. In order to obtain more information about these possible electronic migrations we have investigated the time decrease of the initial permeability in several manganese ferrites as a function of manganese concentration and vacancy content. The samples used were polycrystalline toroids with Mn/Fe ratios of 0.5/2.5, 0.7/2.3, 0.85/2.15, and 0.9/2.1. Samples of each Mn/Fe ratio were fired in two different atmospheres, one selected so that the total metal-oxygen ratio was 3/4 and the other selected to obtain a maximum vacancy content without precipitation of any second phase.

The permeabilities were measured in the temperature range of -15°C to 25°C with a driving field of 2×10^{-3} oe. at 10 kc/sec. The permeability was recorded during the first 1.5 hours after demagnetization. Values of μ_∞ (the completely relaxed value of μ) were obtained by measuring the permeability after a period of 24 hours. The relative changes in the initial permeability $\frac{\mu_0-\mu_\infty}{\mu_\infty}$, where μ_0 is the value of permeability immediately after demagnetization, depend on the vacancy content and are larger for the non-stoichiometric samples than for the stoichiometric. For the stoichiometric samples, the relative change in permeability decreases with increasing manganese content. The decrease in initial permeability cannot be described by a single relaxation process. Processes with three distinct relaxation times are required to represent the data for each composition. These relaxation times have a temperature dependence of the form $\tau = \tau_0 e^{Q/h\Gamma}$. The activation energies Q, for all three processes in one sample are equal and independent of manganese concentration within experimental error. The experimental results will be discussed in terms of possible models involving electron migrations.

1. Bosman, A. J., Brommer, P. E., Van Daal, H. J., Rathenau, G. W., Physica 23, 989 (1957).
2. Enz, V., Physica 24, 609 (1958).

---

104. SQUARE LOOP PROPERTIES OF COPPER-MANGANESE FERRITES

ROBERT S. WEISZ and DANIEL L. BROWN
Telemeter Magnetics, Inc.
Los Angeles, California

Square hysteresis loops have been found in ferrites containing (a) divalent copper, or (b) trivalent manganese. It was, therefore, felt that the system copper oxide-manganese oxide-iron oxide would be of unusual interest magnetically. The present paper is chiefly concerned with a survey of this system from the standpoint of preparing square loop ferrites useful in high speed memories. Over 50 compositions were prepared and each studied under a variety of firing conditions.

The following properties are discussed as a function of composition: saturation flux density, Curie temperature, coercivity, hysteresis loop shape, and switching constant. Dynamic properties determined from pulse response data are compared with static characteristics. Finally, the temperature dependence of some magnetic properties are given for representative examples.

General conclusions are: (1) both divalent copper and trivalent manganese contribute to squareness in mixed compositions, and (2) memory cores of certain copper-manganese ferrites have strikingly low switching times at relatively low driving currents.

---

105. THE TEMPERATURE DEPENDENCE OF THE SATURATION MAGNETIZATION OF FERRITES WITH MAGNETOPLUMBITE STRUCTURE

G. HEIMKE
Hochschule Für Verkehrswesen
Physikalisches Institut
Dresden, Germany

The magnetic oxides with magnetoplumbite structure show an anomalous temperature dependence of their saturation magnetization: it nearly linearly decreases with increasing temperature. As the remanent magnetization is half of the saturation magnetization, presuming the crystals are small enough and their directions of easy magnetization are distributed isotropically, this is the reason for the high temperature dependence of the remanent magnetization $(\Delta B_r/B_r\Delta T) = -.002/^0C$. In this work some possibilities for an alteration of the temperature dependence of the saturation magnetization will be derived from a consideration of the interaction scheme of the five crystallographically distinguished sublattices of the iron ions: The unit cell of this material can be regarded as consisting of blocks in which the arrangement of the oxygen ions is the same as in a spinell type ferrite. These "spinell blocks" are separated by layers containing barium ions besides oxygen ions. In this layer and in its very neighbourhood the crystallographic distances and angles on which the superexchange interaction forces depend permit three interaction schemes. It has been supposed that these rivalling possibilities of the interaction sequence may be the reason for the anomalous $4\pi J_S$ (T) behaviour.

By substitution of ions with a magnetic moment which is much smaller than that of the trivalent iron ion on octahedral lattice sites just above and below this layer one or two of the rivalling possibilities can be avoided.

The conditions under which such a substitution seems to be possible are derived from a consideration of the special properties of the lattice sites concerned. The result is that a suitable ion M should be added to the original mixture of oxides (or carbonates) as a compound XM_2O_3 (with X = Ba, Sr or Pb) which is thermally stable enough to enter the magnetoplumbite structure as a whole group keeping the ion M in the close neighbourhood of the barium containing layer.

For an experimental test of these conclusions only a compound with one smitable ion for each barium ion could be found: $BaTiO_3$. Using special precautions for the sintering and alteration of the $4\pi J_S$ (T) curve below room temperature could be achieved. Above this temperature the former linear slope is preserved but the *Curie* point is found to be more lowered than is expected for a statistic distribution of the Ti ions on all octahedral lattice sites available.

---

106. THE MAGNETIC BEHAVIOR IN THE TRANSITION REGION OF A HEMATITE SINGLE CRYSTAL

S. T. LIN
Massachusetts Institute of Technology,
Cambridge, Massachusetts

From the previous article[1] it is evident that the weak anisotropic ferromagnetism of natural hematite (α-Fe_2O_3) single crystal from Elba can be observed not only in the basal plane perpendicular to the [111] direction above transition (the conventional transition is at about 250°K) but also along the [111] direction of the rhombohedral structure below transition, and that in a wide region of over 100°K the transition takes place gradually and continuously instead of rapidly and discontinuously. The first experimental fact, the essence of the controversy of this material, can be explained qualitatively by extending the magnetic model proposed by Dzyaloshinsky[2] and Vonsovsky[3] to a more general one of canted antiferromagnetism with unequal sublattice moments, as has been described briefly in reference 1. The second phenomenon belongs to the mechanism of the rotation of the sublattice spin system in the transition region, to which practically no attention has been paid.

The present investigation has been devoted to the study of the magnetic behavior in the transition region. A sphere about 3/16" in diameter cut from a single crystal from Elba has been used for measuring the remanence of a virgin sample. Three remanence-temperature and thermal hysteresis curves (i.e. the remanence is a double-valued function of the temperature) have been obtained along three mutually perpendicular directions (including the [111] direction) in the temperature range between 488°K and 77°K. These three curves can be combined to reveal a great deal of information of the weak ferromagnetism in the transition region. The remanent magnetization plot in polar coordinate has been constructed from this data for the whole transition region, showing the magnitude, the direction, and the rotation of the magnetization vector with the temperature. Another experiment, measuring the remanence through a complete circle containing the [111] direction and the direction of magnetization in the basal plane, has also been carried out for three different temperatures to show the direction and the magnitude of the remanence. Within experimental error these two measurements are in good agreement.

These experimental data show that in the transition region, the magnetization vector of the ferromagnetic part continuously changes its orientation and magnitude with the temperature. If the weak ferromagnetism is interpreted as the result of the canted antiferromagnetism, the mean direction of the antiferromagnetic spin of each sublattice would turn between the [111] direction and the basal plane when the temperature changes through the transition region. In other words at each temperature in the transition region, the mean antiferromagnetic spin of each sublattice would have a more or less definite orientation (governed by the thermal hysteresis) between the [111] direction and the basal plane.

1. S. T. Lin, J. Appl. Phys. Suppl. 30, 306S (1959).
2. I. B. Dzyaloshinsky, J. P. C. A. 4, 241, (1958)
3. S. V. Vonsovsky and B. A. Turov, J. Appl. Phys. Suppl. 30, 9S (1959).

107. THE METAMAGNETIC BEHAVIOR OF MANGANESE ARSENIDE

D. S. RODBELL and P. E. LAWRENCE
General Electric Research Laboratory
Schenectady, New York

The compound MnAs exhibits certain interesting and unusual physical properties. At a temperature near 35°C it undergoes a first order transformation that has associated with it a thermal hysteresis, a latent heat, a discontinuous change in the electrical resistivity and a discontinuous change in density. The magnetic state also changes in an interesting way. The ferromagnetism that exists at lower temperatures vanishes abruptly at 35°C. Between 35° and 125°C the material appears to be antiferromagnetic as judged by magnetic susceptibility, specific heat and magnetocaloric measurements[1]. Above 125°C MnAs is paramagnetic.

We have examined MnAs* in high magnetic fields and find that between 35° and 125°C there exists a threshold magnetic field strength at which a large and steep increase of the net magnetization occurs. At 35°C the critical field is 40 K-oersteds; the critical field strength increases with increasing temperature. There is a large hysteresis associated with the magnetization change. This behavior resembles that exhibited by a material that is metamagnetic in the sense of Neel's description[2].

1. A. J. P. Meyer and P. Taglang, Comptes Rend. 246, 1820 (1958).
2. L. Neel, Bulletin of the Academy of Sci. USSR, Physical Series 21, 889 (1957).

*Samples kindly supplied by G. E. Bacon (British Atomic Energy Establishment, Harwell, England) and G. Fischer (National Research Council, Ottawa, Canada).

108. MAGNETIC PROPERTIES OF THE $Mn_{1-x}Li_xSe$ SYSTEM

THOMAS R. McGUIRE
U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland, and
ROBERT R. HEIKES
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania

The occurrence of ferromagnetism[1] in this system for x = .10 has been further investigated by varying the lithium content in the material to values of x = .03, .05 and .07. The presence of the monovalent lithium causes an equal amount of the normally divalent manganese to become trivalent. The two samples of higher lithium content ($Mn_{.95}Li_{.05}Se$ and $Mn_{.93}Li_{.07}Se$) exhibited a spontaneous magnetic moment. The .03 sample had no spontaneous moment, but a break in the magnetic susceptibility curve occurred at approximately 80°K.

The reciprocal susceptibility of the $Mn_{.97}Li_{.03}Se$ sample suggests that the material becomes antiferromagnetic at 80°K. The susceptibility curve has the form of the Neel hyperbola but flattens out below 80°K. This behavior is not typical of an antiferromagnet. Neutron diffraction measurements are not available for this composition.

The .05 lithium sample showed a spontaneous moment between 40° to 80°K. Below 40° it is paramagnetic (or antiferrimagnetic) but there is no sharp transition such as found in the .10 lithium samples. The neutron diffraction results of Pickart, Shirane and Nathans[2] indicate that this sample is antiferromagnetic at all temperatures below 83°K, evidently in disagreement with the magnetic measurements over the 40 to 80°K range.

The .07 sample has a spontaneous magnetic moment from 90°K to the lowest temperature measured of 4.2°K. The magnetic moment depends on the thermal history. At the present time this dependence is not yet understood. In the .07 sample the neutron diffraction results show general agreement that a spontaneous moment exists; however, the neutron diffraction results[2] are complex, showing a different behavior above and below 73°K. The corresponding magnetic moment data do not indicate any important differences, although a slight change in slope of the magnetization curve seems to be present at this temperature.

The reciprocal magnetic susceptibility above the Curie temperatures of these three compositions showed a curvature indicative of double exchange or ferrimagnetism. It was found that the molar-Curie constant agreed with a zero magnetic moment for the trivalent manganese, a result[1] also obtained for the $Li_{.10}$ specimen. In general, it appears that the magnetic properties of this system are extremely sensitive to the Li content.

1. R. R. Heikes, T. R. McGuire, and R. J. Happel, Bull. Am. Phys. Soc. Ser II, 1, 52 (1959).
2. S. J. Pickart, G. Shirane and R. Nathans. To be published.

SESSION VI-B

MAGNETIC FILMS

D. O. SMITH, Presiding

---

109. SOME PHYSICAL PROPERTIES OF THIN MAGNETIC FILMS

A. C. MOORE and A. S. YOUNG
Royal Radar Establishment
Malvern, England

The magnetic properties of evaporated thin nickel iron films of most interest are (a) domain wall coercivity, (b) anisotropy which determines the onset of "rotation" and (c) speed of change of magnetization—particularly in the fast mode.

The theory of domain wall coercivity is not fully worked out although Kersten and Neel suggest that it is caused by microstresses and non magnetic inclusions in the material. Electron microscopy and diffraction show the imperfect nature of the evaporated films.

The anisotropy can arise in various ways.

(1) *Magnetocrystalline.* The chemical composition of the films has been measured by polarography and X-ray diffraction determination of the lattice parameter. No significant effect has been found on the scale used. The size of the crystallites is estimated to be less than 1000 Å and no preferred, or fibre, orientation has been found when a glass substrate is used.

(2) *Magnetostriction.* As it proved impossible to eliminate strain in the films the nickel/iron ratio used as the starting material for the evaporation was chosen to give zero mean magnetostriction in the film. The starting material must be fixed to better than 0.2% and the conditions of evaporation are rigidly controlled.

(3) *Demagnetization.* Scratches and polishing marks on the substrate can introduce a marked anisotropy in the film, for example the preferred direction of magnetization can lie along the polishing marks.

(4) *Magnetic field anisotropy.* The exact cause is not known for certain. Some extra lines in the electron diffraction pattern of the films can be explained by oxide in the film but this does not appear to be orientated in the plane of the film.

Speed of change of magnetization is measured at a fixed angle to the preferred direction. The switching constant depends on many factors but the composition of the film exercises a marked effect.

Uniformity of domain wall coercivity over a sheet is checked by reversing the magnetization in selected areas with a suitable field gradient and observing the extent of the change in magnetization by Bitter patterns.

Constancy of preferred direction in a sheet is observed by magnetizing at right angles to the nominal direction and observing in which direction the magnetic vector falls back.

110. MILLIMICROSECOND MAGNETIZATION REVERSAL IN THIN MAGNETIC FILMS

W. DIETRICH and W. E. PROEBSTER
International Business Machines Corporation
Research Laboratory
Zurich, Switzerland

Switching times of about 1 mμs for the coherent rotation of the magnetization in thin permalloy type films have been predicted from results of ferromagnetic resonance experiments.[1] D. O. Smith[2] reported measurements of switching times of about 3 mμsec obtained with a travelling wave oscilloscope of 2 mμsec response time.

By means of a special pulse equipment which includes a pulse sampling oscilloscope[3] the overall response time was reduced to about 0.5 mμsec. The principles of the construction of the equipment and the ways by which the various disturbances were reduced are briefly discussed.

Two types of pick-up arrangements permitted the measurement of the longitudinal and the transverse flux components. Coherent rotation of the magnetization in permalloy films with uniaxial anisotropy could be clearly observed by this method. It was found that the switching times depend on the amplitude of the applied field and its angle relative to the easy axis. Switching times down to 1.2 mμsec have been observed. From the resulting signals it is concluded that the film can be completely switched by coherent rotation. No delay of the output pulse with respect to the driving pulse as reported by D. O. Smith[1] has been noticed.

1. Smith, D. O., "Static and Dynamic Behaviour of Thin Permalloy Films," J. Appl. Phys. 29 (1958): 264-273.
2. Smith, D. O., Weiss, G. P., "Steady-State and Pulse Measurement Techniques for Thin Magnetic Films in the vhf-uhf Range," J. Appl. Phys. 29 (1958): 290-291.
3. Sugarman, R., "Sampling Oscilloscope for Statistically Varying Pulses," Rev. Sci. Instr. 28 (1957): 933-938.

---

111. FLUX REVERSAL BY NONCOHERENT ROTATION IN THIN FILMS*

K. J. HARTE
Lincoln Laboratory
Massachusetts Institute of Technology

A model of noncoherent rotational switching in thin ferromagnetic films is proposed for the case of a switching field applied antiparallel to the initial magnetization, and a non-zero bias field in the plane of the film perpendicular to this direction. The model is based on excitation of certain spin wave modes, initially induced by a small angular dispersion of the magnetic easy axis through the film. It is shown that for switching fields above a critical value that varies inversely with the bias field, uniform rotation is rapidly completed in a time less than that required for the onset of noncoherent modes. The predictions of the model are in reasonable agreement with the experimental results of Olson and Pohm, Humphrey and Gyorgy, et. al. for Fe-Ni films and switching times $\simeq .1\ \mu$sec.

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

---

112. MAGNETIZATION REVERSAL IN UNIAXIAL FILMS NEAR TO THE PREFERRED DIRECTION

E. M. BRADLEY and M. PRUTTON
International Computers & Tabulators, Ltd.
Stevenag, Hertfordshire, England

It is now well known that uniaxial thin magnetic films can be made which have almost ideal square hysteresis loops in the preferred direction and almost straight line hysteresis loops in the hard direction.

For this type of film, which can be prepared by evaporation from ingots of approximately 81:19 NiFe alloy, it is found that the switching time constant of the reversal process which occurs when magnetic fields are applied exactly in the easy direction can be very large.

The switching process occurring when fields are applied at angle of 10° to the preferred direction has been studied in detail, both by a new pulse response technique and by observation of the domain structure revealed by use of the Kerr magneto-optic effect.

In the latter experiment, short pulses have been applied to the specimen and photographs taken of the domain pattern after each pulse. It was found that the specimen breaks into small domains whose area increases after each pulse and that eventually the film could be completely reversed if the pulse amplitude was between certain critical values. Curves were plotted of the pulse amplitude against the proportion of the film switched found by measuring the reversed area in the photographs. It was shown that the process is very well approximated by an equation of the form $S_W = \tau(H - H_0)$ which implies a viscous damped process, and there is a critical nucleation field which is less than the field required to move the walls.

In the pulse response experiments, the switching time has been derived from the response to a reset pulse which was applied after a variable number of set pulses of variable amplitude. It was found that in some films there can be a rapid switching process, which is complete after about 100 mμsec, followed by a slow process lasting up to 10 μsec under the same conditions. From the experiments performed it has been possible to compute a switching time constant which can be very large in some films. This constant is found to be correlated with the ratio $p = H_c/H_k$, where H_c is the coercivity in the easy direction and H_k is the rotational coercivity.

If the film obeyed the simple coherent rotational model the p ratio would be 1, and films which have $p = 0.9$ have been found to have $S_W = 0.3 \times 10^{-6}$ oe. μsec whereas for $p = 0.3$, $S_W = 7 \times 10^{-6}$ oe. μsec.

113. THE INFLUENCE OF NEARBY CONDUCTORS ON THIN FILM SWITCHING

J. S. EGGENBERGER
IBM Research Laboratory
Poughkeepsie, New York

The usual concept of a thin film, or other open flux path magnetic element, consists of the material itself, closely encircled by drive and sense conductors. Strips of conductor of width approximately that of the element are attractive for several reasons (i.e., low resistance, low skin effect, and low line impedance). However, these strips, being closely coupled to the element, can severely influence its dynamic properties by means of induced eddy currents.

These conductors manifest themselves in three ways:

1. A slowing of the switching due to the air return flux path of the element passing through a conductor and being dampened.

2. A dynamic distortion of the air return flux due to shielding effects.

3. A dynamic distortion of an applied field to shielding effects.

All of these effects can be detrimental to the operation of the element.

In this paper, approximate calculations are presented to show the extent of these effects. The geometry considered is that of a "conventional" flat thin film element, driven and sensed by strip transmission lines. Several drive and sense configurations are considered, and experimental evidence is presented in support of these calculations. Although the cases considered are somewhat arbitrary, the methods and many of the results are applicable to other cases of utilization of open flux path elements.

---

114. PREFERRED ORIENTATION AND ORDERING IN EVAPORATED FILMS OF Fe AND Fe-Ni*

ROBERT F. ADAMSKY
Computer Products Division
Laboratory for Electronics, Inc.
Boston, Mass.

In studies of evaporated ferromagnetic films, an effect due to the angle of incidence between the substrate and the depositing beam has been observed to influence uniaxial anisotropy and has been attributed by Knorr and Hoffman,[1] in the case of iron films, to the formation of a single texture axis inclined toward the incident beam.

The angle of incidence effect has been investigated for evaporated films of Fe, Ni and alloys of Fe-Ni, by use of transmission electron diffraction and microscopy, and by X-ray diffraction, for certain conditions of film formation, which included variation of evaporation geometry to produce angles of incidence from 0 to 66°, and variation of substrate material and substrate temperature.

Over a wide range of conditions, the Fe, Ni or permalloy films produced were essentially unoriented and very little effect of angle of incidence on orientation was noted for the cases in which slight fiber textures were developed. Angle of incidence effects were significant in producing thickness gradients and particle size variation, the latter related in part to radiant energy from the evaporant source.

Thickness and particle size were observed to be greatest at normal incidence, decreasing for lower angles. Weak fiber textures were observed for Fe films at substrate temperatures above 175°C.

Ni films of large thickness (2000 - 10,000 Å) on glass substrates have a [111] fiber texture, and X-ray diffraction has been used to obtain pole figure data.

Annealing experiments have been conducted which show that long-range ordering occurs in thin films of Fe-Ni around the composition Ni_3Fe at temperatures of 200° for annealing periods of 15 minutes or more. The experiments indicate that ordering probably occurs in permalloy films at even lower substrate temperatures, perhaps resulting in 'inclusions' of ordered material within the unordered matrix with consequent influence on magnetic properties. The domain structure of annealed permalloy films, observed by electron microscopy, is usually extremely complex, apparently due to a complicated pattern of nonhomogeneous stress in the film. In some cases the domain structure is simple, resembling non-annealed permalloy, and indicating a well-defined easy axis in the film.

*This work supported in part by Bell Helicopter Corporation.

1. Knorr, T. G., Hoffman, R. W., Physical Review 113, No. 4, 1039-1046 (1959).

115. ELECTRON DIFFRACTION AND MICROSCOPY OF PERMALLOY FILMS*

M. S. COHEN
Lincoln Laboratory
Massachusetts Institute of Technology

Permalloy films evaporated under standard conditions, and films prepared by special techniques (e.g., very low evaporation rates, low angles of incidence of the permalloy beam, or specially prepared substrates) were investigated by electron microscopy, electron diffraction, and various magnetic techniques.

Electron micrographs were taken of permalloy evaporated on thin carbon substrates. These micrographs show an increase in crystallite size as the permalloy film increases in thickness. Striking variations in appearance of the micrographs for different evaporation conditions were not found, however, except for an observed increase in crystallite size for evaporations at higher substrate temperatures.

The films deposited on carbon substrates were studied by transmission electron diffraction, while films on glass were investigated by reflection diffraction. Within the accuracy of the measurements the permalloy takes the f.c.c. nickel lattice. Electron diffraction patterns reveal that the crystallites are randomly oriented in the thinner films, but that some preferred orientation (110 or 211 fiber axes) develops for thicker films. The fiber axis is perpendicular to the substrate for normal incidence of the permalloy beam but shows a tendency to incline towards this beam for low angles of incidence. This cannot, however, explain the anisotropy caused by low incidence angles.[1]

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

1. D. O. Smith, J. Appl. Phys. 30 (Suppl.) 264S (1959).

116. MAGNETIC ANISOTROPY IN EVAPORATED IRON FILMS

E. W. PUGH, J. MATISOO, D. SPELIOTIS, and E. L. BOYD
International Business Machines Corporation
Research Laboratory
Poughkeepsie, New York

It has recently been suggested[1] that the magnetic anisotropy of evaporated iron films is strongly influenced by a (111) fiber axis and an associated anisotropic stress produced during evaporation. A detailed calculation of this effect has been programed on a 704 for varying values of stress and tilt of the fiber axis relative to a normal to the film surface. These results indicate that, for all angles of tilt up to 20°, the anisotropy energy is well expressed by

$$E = K_u \quad \sin^2\theta$$

and

$$K_u = - AS_x + BS_y - C$$

where θ is measured from the x axis, chosen to be perpendicular to the projection of the fiber axis in the plane of the film. The stresses, parallel and perpendicular to the projection of the fiber axis, are represented by S_y and S_x respectively, and A, B, and C are positive constants dependent only on the angle of tilt of the fiber axis.

For fiber axis tilts and anisotropic stresses of the size observed by Knorr and Hoffman, the calculations show that the dependence of the magnetic anisotropy on the angle of tilt of the fiber axis is too small to be detected within the apparent accuracy of their B-H loop method. However, the practical importance of the fiber axis should not be discounted since it may be intimately associated with the origin of anisotropic stresses in evaporated films.

The dependence of A, B, and C on the tilt angle of the fiber axis suggests that independent proof of the existence of a fiber axis in magnetic films could be obtained by making direct torque measurements of the magnetic anisotropy, especially if these measurements could be made as a function of applied stress. A sensitive torque balance with this capability has been built and is now in use. Results thus far obtained with this balance, on iron films in various states of strain, are not adequate for this purpose, but they do verify the magnitude of the stress effect as well as the importance of the angle of the incident metal flux during deposition. These measurements will be discussed in terms of the fiber axis and stress models.

1. T. G. Knorr and R. W. Hoffman, Phys. Rev. 113, 1039 (1959)

117. INVERTED FILMS*

E. E. HUBER, JR. and D. O. SMITH
Lincoln Laboratory
Massachusetts Institute of Technology

Depending on the particular means of production, many permalloy films exhibit "inversion" which shall be defined as $H_w/H_k < 1$, where H_w is the wall coercive force and H_k is the anisotropy field. Such films are observed to switch by walls in the easy direction and to have a square hysteresis loop. These observations impose a contradiction, since one would expect the easier and faster process of rotation to occur first and switch the film before wall motion gets underway.

This contradiction has been explained by Bitter pattern studies which show a "locking" mechanism to occur. As a D.C. reversing field is increased many short wall segments appear at right angles to the easy axis and homogeneously cover the entire film surface. They increase in density and intensity until finally domains of reverse magnetization begin to sweep through and leave behind clear areas containing no wall segments. Apparently many local regions of the film start to rotate, but in opposite directions, leading to an energy condition favorable for the introduction of short wall segments perpendicular to the easy axis. This in turn causes a locking to occur and makes it more difficult for a domain wall to sweep through the locked areas.

This type of switching is observed at all angles up to 80° to the easy axis and the general features are the same if stress has been applied to rotate the easy axis 90°, with the wall segments now appearing at 90° to the original direction. Strain effects of the substrate do not play a role since inverted films stripped clean from the substrate continue to show locking phenomena. The conclusion is that there are local, strain independent inhomogeneities which are isotropic and which cause a very large dispersion in M.

Some type of structural imperfection, e.g., voids, which will act as demagnetizing centers, is suggested. Density measurements have indicated that if voids are present, they must be less than 5-10 percent of the volume. Resonance line widths are found to increase with inversion, however, in agreement with the postulate of local magnetic inhomogeneities.

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

---

118. TECHNIQUES FOR UNIFORMITY IN MAGNETIC FILM PRODUCTION*

T. S. CROWTHER and G. P. WEISS
Lincoln Laboratory
Massachusetts Institute of Technology

The fabrication of large thin film memories requires the development of those techniques which are capable of producing uniform memory arrays with a sufficiently high yield to make their production economically feasible.

This paper deals with the current techniques used both in testing and in fabricating these memory arrays. Described in detail are the cleaning procedures, which include an ion bombardment prior to evaporation, and the testing procedures, which examine both the steady state and the pulsed response of these films.

Preliminary results indicate that the present yield is considerably greater than for previous techniques which resulted in the fabrication of the 32-word ten-bit thin film memory installed in the TX-2 computer.[1] These techniques lend themselves quite readily to a degree of automation which is capable of producing large numbers of arrays.

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

1. J. I. Raffel, J. Appl. Phys. 30, 60S (1959).

---

119. A MICROCALORIMETRIC TECHNIQUE FOR THE STUDY OF DAMPING AND HYSTERESIS IN FERROMAGNETIC FILMS

J. R. MAYFIELD
International Business Machines Corporation
Research Laboratory
Poughkeepsie, New York

Experience with experimental techniques for the study of damping and hysteresis in thin films has suggested that many of the difficulties and complications encountered might be avoided by the direct approach of measuring the heat generated by the irreversible processes which are of interest. This suggestion has led to the development of a simple and reliable apparatus, best described as a "microcalorimetric loss spectrograph," with which accurate loss determinations may be made over a frequency range at least as broad as 1 kc to 100 mc.

The loss detector in the MCL spectrograph is a differential thermometer which measures the heat flux through a thin dielectric plate separating the ferromagnetic film from a heat sink. This thermometer is fabricated of thin metal films, so that its own eddy-current losses will not "swamp" the losses in the sample. With this type of loss detector the time constant for re-establishment of steady-state heat transfer after an abrupt change in the magnetic losses may conveniently be made as small as 5 seconds or less. Such a response time is short enough that it is practical to employ low-frequency square-wave modulation of the magnetic losses to eliminate the zero drift of the heat-detecting system and to reduce its overall "noise." The radio-frequency magnetic field applied to the sample is "chopped" at a sub-audio frequency, the resulting a.c. component in the output voltage of the heat detector is amplified by a high-gain narrow-band amplifier, and the amplifier's output is rectified by a synchronous commutator, so as to obtain a d.c. signal directly proportional to the variations in the heat flux emerging from the sample. A motor-driven sweep system slowly varies one parameter of the applied magnetic field (such as the magnitude of a rotating field, or the magnitude of a d.c. bias field superposed on an oscillating field of fixed amplitude) while an

X-Y recorder continuously plots the energy loss versus the field parameter being varied. The resulting curve is essentially an isothermal one, since the temperature difference being detected need not be more than a small fraction of a degree.

Data obtained with the MCL spectrograph are illustrated by some typical curves for nickel-iron films and are compared with previous data obtained by other methods.[1,2]

1. D. O. Smith, J. Appl. Phys., 29, 264-273 (1958).
2. J. R. Mayfield, 30, (supplement), 256S-257S (1959).

120. ANNULAR UNIAXIALLY-MAGNETIZED DOMAINS IN THIN Ni-Fe FILMS

O. W. MUCHENHIRN, A. E. LaBONTE and P. J. BESSER
Electrical Engineering Department
University of Minnesota

Stable annular uniaxially-magnetized domains have been observed in thin circular Ni-Fe films using both the Kerr and Faraday magneto-optical effects. The films were prepared by direct evaporations onto glass substrates from temperature-controlled Ni-Fe alloy sheets. Film thickness is approximately 700 Å; film compositions vary in the range from 70% Ni-30% Fe to 80% Ni-20% Fe; and spectrographic analyses have shown no impurity traces.

The films exhibit unusual magnetic behavior in both the "easy" and "hard" directions. Generally the magnetization reversal begins at the circumference of the film with the appearance of a uniaxially magnetized annular domain whose inner radius decreases with increasing applied field. In a number of films, the mechanism of magnetization reversal in an outer annular region appears to be distinctly different from that in the central region. In the annular region, the low-frequency magnetization reversal in the easy direction proceeds by wall motion with the Bloch walls approximately parallel to the direction of the applied field, but there is evidence that the reversal in the hard direction occurs by a rotational process. After the annular region is completely reversed, the center region is reversed by a radially inward motion of the circular boundary between the two concentric uniaxially magnetized domains.

The magneto-optical observations are qualitatively correlated with 60 cps $d\phi_M/dt$-versus-H and ϕ_M-versus-H loop data. Based on the assumptions of uniform magnetization per unit volume, M, and uniform film thickness, quantitative correlation of ϕ_M versus H as obtained from Kerr effect photographs and from normalized 60 cps hysteresis loop measurements have been made and are reported.

121. DOMAIN WALL VELOCITIES IN THIN IRON NICKEL FILMS

N. C. FORD, JR.
International Business Machines Corporation
Research Laboratory
Poughkeepsie, New York

An apparatus based on the Kerr magneto-optical effect has been used to measure the velocity of domain walls in thin iron-nickel films. Polarized light, after being reflected by a film, is detected by means of a Venetian blind type of photo multiplier. The slope of an oscilloscope trace resulting from the photo multiplier signal gives the velocity of a domain wall directly as the wall traverses a light spot of known size. The drive field consists of the sum of a d.c. field just below the coercive force of the film and a small fast rise time pulse field. Wall velocities are found to be well described by an equation of the form $v = m(H - H_O)$ where m is the mobilitv of the domain wall, H is the total applied field, and H_O is a field which is very nearly equal to the d.c. coercive force of the film.

Measurements have been made on films varying in thickness from 4,000 Å to 1,000 Å with corresponding mobilities of 0.4 x 10^4 cm/sec oe. for the thicker film and 2.2 x 10^4 cm/sec oe. for the thinner film. The mobilities of the domain walls are found to be proportional to $1/B_S\sigma d$ where σd, the product of electrical conductivity and film thickness, is measured by a four probe resistance method. This indicates that even in metal films as thin as 1,000 Å the wall velocities are limited by eddy-currents rather than by an intrinsic damping term of the form found in the Landau-Lifshitz equation.

122. BLOCH WALLS IN THIN MAGNETIC Ni-Fe-FILMS

S. METHFESSEL, S. MIDDELHOEK and H. THOMAS
International Business Machines Corporation
Research Laboratory
Zurich, Switzerland

Néel[1] proposed a transition from the normal type of Bloch wall (i.e. rotation of the magnetisation vector in the plane of the Bloch wall) to the Neel type (i.e. rotation of the magnetisation vector in the plane of the film) at a certain film thickness, which is due to the thickness dependence of the magnetostatic energy. It is believed that the cross-tie walls[2] observed in thin Ni-Fe films with uniaxial anisotropy correspond to such a transition, in which the cross-ties serve to decrease the magnetostatic energy.

According to this explanation such a structure should occur in a certain thickness range only. Experimental observations on Ni-Fe wedge-shaped films show the occurrence of the cross-tie structure in the thickness range 400-900 Å, which is approximately that predicted by theory. The coercive force shows an anomaly in the same range.

The energy-reducing function of cross-ties is also shown by the Bitter patterns around scratches in the easy direction in negative magneto-strictive material. In a region along the scratch the magnetisation in the plane of the film is found to be perpendicular to the original easy direction, due to the local stresses and again a cross-tie structure is observed.

1. L. Néel, C. R. Acad. Sc. 1955, 241, 533.
2. E. E. Huber, D. O. Smith and J. B. Goodenough, J. Appl. Phys. 1958, 29, 294.

123. CROSS TIE DOMAIN WALLS IN THIN FERROMAGNETIC FILMS*

HARVEY RUBINSTEIN and ROBERT J. SPAIN
Computer Products Division
Laboratory for Electronics, Inc.
Boston, Mass.

An analysis of domain wall energies in thin films is presented which leads to an explanation for cross-tie domain walls and a model for the associated spin distributions. The existence of narrow, well-defined cross ties is shown to be the result of a magnetostatic interaction.

From approximations made for the actual spin distributions in Bloch and Néel walls expressions for magnetostatic energy are obtained which are used in constructing the cross tie model. The model which results seems self-consistent and capable of explaining the experimental observations made of cross tie walls through the use of Bitter patterns and the electron microscope. Inconsistencies in present models for cross tie walls are indicated.

The periodicity of the cross ties along a cross tie wall is explained on the basis of a model which approximates the magnetostatic characteristics of the wall. This periodicity is discussed in light of the magnetization "buckling" suggested by Fuller and Rubinstein.

In addition, some experimental observations made of the effect of external fields upon cross-tie domain walls are included and discussed in terms of the proposed model.

*This work was supported by the Office of Naval Research.

---

124. STATIC AND DYNAMIC STUDIES OF MAGNETIZATION DISTRIBUTION IN THIN FILMS BY ELECTRON MICROSCOPY*

HARRISON W. FULLER and MURRAY E. HALE
Computer Products Division
Laboratory for Electronics, Inc.
Boston, Massachusetts

When an electron passes through a thin magnetic film the electron undergoes a deflection by interaction with the magnetization of the specimen in addition to deflections by normal scattering processes. This magnetic deflection has been applied to view domain walls in thin magnetic films using a standard electron microscope.[1]

Expressions are derived for the electron intensity distribution at an observation plane as a function of the magnetization distribution in the specimen and some instrumental parameters. The inverse relations give the magnetization distribution from experimentally measured intensity distributions on a photomicrograph. A comparison of theoretical and experimental intensity distributions is made assuming simple domain wall models.

A phenomenon described as magnetization ripple occurs in some observations which, when interpreted, allows the detailed deduction of the magnetization distribution in complicated cases. Operating a standard electron microscope in a modified way allows magnetization distribution measurements to be made at a resolution approaching the rated resolution capabilities of the instrument in ordinary use.

A motion picture of observations of domain walls in thin films using transmission electron microscopy demonstrates the method to be of considerable value in the study of domain-wall motion. The film was taken with an Arriflex 16 camera using a short-distance lens covering a small angular field. The arrangement allowed the operator to adjust all normal microscope controls while observing the image in a reflex viewer. Some dynamic subjects that can be studied effectively by the technique are the behavior of cross-tie walls in motion, the interaction of domains with areas of stress, and the change in grain structure and magnetic characteristics with rapid film heating in the electron beam.

*This work was supported in part by the Office of Naval Research and Bell Helicopter Corporation.

1. M. E. Hale, H. W. Fuller, H. Rubinstein, J. Appl. Phys. 30, 789 (1959).

SESSION VII-A

METALS AND ALLOYS

A. ARROTT, Presiding

125. MAGNETIC PROPERTIES OF MANGANESE COPPER ALLOYS (Invited)

R. STREET
Department of Physics
The University
Sheffield, England

The magnetic properties of the manganese-copper alloy system have been investigated using a number of experimental techniques. Long range antiferromagnetic order is possible in alloys of high manganese concentration, the disappearance of ordering is associated with a face centred tetragonal face centred cubic martensitic transformation. At lower manganese concentrations it is likely that short range antiferromagnetic ordering occurs and in addition at sufficiently low temperatures ferromagnetic behavior becomes apparent. These results and possible interpretations of them will be discussed.

126. MECHANISM OF ANTIFERROMAGNETISM IN DILUTE ALLOYS (Invited)

A. W. OVERHAUSER
Scientific Laboratory
Ford Motor Company
Dearborn, Michigan

A mechanism for the antiferromagnetic ordering of a dilute paramagnetic solute in a metal is proposed and discussed in relation to the phenomena that occur in Cu-Mn alloys. Long range antiferromagnetic order results from a static spin density wave in the electron gas of the metal. This new state of the gas is dynamically self-sustaining as a result of the exchange potentials arising from the spin density distribution. The paramagnetic solute atoms are then oriented by their exchange interaction with the spin density wave. The resulting interaction energy more than compensates the increase in energy associated with the formation of the spin density wave. The theory predicts correctly the magnitude and concentration dependence of the critical temperature, the anomolous low temperature specific heat, and the anomolous electric and magnetic properties of the alloys.

127. LONG-RANGE MAGNETIC INTERACTIONS VIA CONDUCTION ELECTRONS

ARTHUR PASKIN
Materials Research Laboratory
Ordnance Materials Research Office
Watertown, Massachusetts

Yosida has shown that the long-range Zener ferromagnetic term arising from the exchange interaction between conduction electrons and unfilled-inner-shell electrons, does not appear explicitly when the calculation is extended to second-order perturbation. The magnetic interaction term to second-order perturbation, decreases rapidly with distance and is short-range relative to the Zener interaction which extends uniformly throughout the solid. Re-examining the Yosida calculation, we find that the long-range magnetic term disappears because of non-interacting electron approximations made for the energy and denisty of states of the conduction electrons. In a more general formulation of these terms, the long-range magnetic interaction appears with a coefficient proportional to $[(\partial^2E/\partial n^2)^{-1} - \rho(E_F)]$ where $\rho(E_F)$ is the density of states evaluated at the Fermi energy, n, the number of conduction electrons (of a given spin) and E their energy. This coefficient can be estimated both from theoretical calculations of Pines on electron interaction effects in metals as well as from nuclear magnetic resonance data. From the calculations of Pines, we conclude that the coefficient is in general such that the long-range magnetic interaction may not be neglected. Using nuclear magnetic resonance data, we estimate that the magnitude of the long-range term and the short-range interaction term are the same for the Cu-Mn alloys studied by Yosida.

128. HYPERFINE INTERACTION IN MAGNETIC MATERIALS BY ANGULAR CORRELATION MEASUREMENTS*†

M. E. CASPARI and S. FRANKEL
University of Pennsylvania

In a paramagnetic atom or ion it is possible to measure the hyperfine interaction by $\gamma - \gamma$ angular correlation experiments if the spins of the atoms or ions are ordered by the exchange interaction in ferro- ferri- or antiferromagnetic materials. This experiment can be carried out at any temperature below the Néel point and large external magnetic fields are not required. In a ferro- or ferrimagnetic substance which has been saturated by an external magnetic field perpendicular to the plane of the γ counters, one measures the rotation of the angular correlation pattern in the very large effective magnetic field, H_{eff}, which is acting at the nucleus due to the hyperfine interaction. If τ is the lifetime of the intermediate excited nuclear state and the magnetic moment of this state is $g_N\mu_N$ where μ_N is the nuclear Bohr magneton, the average rotation $\theta = +g_N\mu_N H_{eff}\,\tau/\hbar$. The field H_{eff} is probably of the order of 10^5 gauss in the transition elements Fe, Co, Ni and 10^6 - 10^7 gauss in at least some of the rare earths. Decay schemes in which the intermediate states have lifetimes in the range 10^{-9} - 10^{-11} sec. can be investigated by this technique. The rotation gives information regarding the "g" factor of ultra short lived nuclear excited states, if the mean lifetime τ and H_{eff} are known from other experiments. Conversely, H_{eff} can be determined if the "g" factor of the excited state is known. In an antiferromagnetic or a polycrystalline ferro- or ferrimagnetic substance without an applied magnetic field, the same information can be obtained from the partial wipe-out of the angular correlation. The experiment can also be carried out in paramagnetic materials as long as the temperature is low enough that H_{eff} does not average to zero over a period equal to the lifetime of the intermediate state. Paramagnetic spin relaxation times of the order of 10^{-9} - 10^{-11} sec. could be determined in this way.

An experiment was carried out on the 1415-122 kev γ-γ angular correlation following the K- capture decay of Eu^{152} to Sm^{152} in neutron irradiated polycrystalline samples of Europium iron garnet as a function of temperature. Below the Curie point and with a weak magnetic field applied perpendicular to the plane of the γ counters, the rotation of the angular correlation was observed. The effect of the temperature dependence of the sublattice magnetization of the Europium ion on the angular correlation could be demonstrated. An estimate of the effective magnetic field acting at the Eu nuclei was made, but the experiment is complicated by the large quadrupole interaction and possible K-capture effects.

*This work was supported in part by the Office of Ordnance Research, Office of Naval Research and the National Science Foundation.

†We wish to thank Dr. M. A. Gilleo of the Bell Telephone Laboratories for supplying us with Europium iron garnet samples and many helpful discussions.

129. MAGNETIC PROPERTIES OF FERROMAGNETIC SUPERCONDUCTORS

R. M. BOZORTH and D. D. DAVIS
Bell Telephone Laboratories

In ferromagnetic superconductors, discovered by Matthias, magnetic measurements show Curie points, superconducting transitions, negative susceptibility, and the hysteresis loops that are due to ferromagnetism and to superconduction. In the alloy containing 4 per cent of $GdRu_2$ in $CeRu_2$ minor hysteresis loops indicate that ferromagnetism and superconduction are present at the same time. Data for 4 and 8 per cent $GdRu_2$ in $CeRu_2$ are analyzed and show deviations from molecular field theory and a virtual Curie point that varies with temperature.

130. STRONG FIELD MAGNETIZATION AT LOW TEMPERATURES AND APPROACH TO ABSOLUTE SATURATION OF THULIUM METAL

WARREN E. HENRY
U. S. Naval Research Laboratory
Washington, D. C.

Magnetization studies of metallic thulium have been carried out at low temperatures and in magnetic fields up to 70,000 gauss. In the range of 100° K. the magnetization is linear in the field and reaches 0.8 Bohr magneton per atom at 70,000 gauss. The pronounced non-superposition of the ascending and descending S-curves indicates hard hysteresis. For example, at 26,000 gauss and 4.2° K, the ascending value of magnetization of 0.7 Bohr magneton per atom of of thulium while the descending value is 1.8 Bohr magneton per atom. A magnetization of 3.4 Bohr magneton per atom is reached at 70,000 gauss and 4.2° K. at 1.3° K, the magnetization is slightly lower at equivalent fields, but approaches the same 70,000 gauss value as at 4.2° K. The remanence is 0.3 Bohr magneton per atom at 4.2° Kand 0.4 Bohr magneton per atom at 1.3° K. Although the triply ionized thulium ion has a $^3H_6$ ground state, the thulium neutral atom has a $^2F_{7/2}$ ground state, with J = 7/2 and g = 8/7. Thus, the g J produce (the expected saturation magnetization) is 4.0. The experimentally determined magnetization value of 3.4 Bohr magnetons per atom of thulium is less than the simple theoretical value, and the increase of only 0.05 Bohr magneton per atom between 60,000 gauss and 70,000 gauss suggests that a value less than 4.0 Bohr magnetons per atom is being approached. This possible reduction in the saturation magnetization may result from the lifting of orbital degeneracy of the $^2F_{7/2}$ ground state of the thulium atom by the crystalline electric field.

131. MAGNETIC BEHAVIOR OF POLYCRYSTALLINE NEODYMIUM, HOLMIUM AND ERBIUM FROM 300°K TO 1500°K

SIGURDS ARAJS, A. D. DAMICK and D. S. MILLER
Edgar C. Bain Laboratory
For Fundamental Research
United States Steel Corporation
Research Center
Monroeville, Pennsylvania

The magnetic susceptibilities of polycrystalline Nd, Ho and Er have been determined from about 300° K to 1500° K by the Faraday method.

The inverse magnetic susceptibility versus temperature ($1/\chi$ vs. T) curve for neodymium at high temperatures shown two anomalies associated with a solid state phase transformation (1135° K) and the melting point (1297° K), respectively. It is of interest that no discontinuities in $1/\chi$ vs. T curve occur at either of these temperatures. This observation is different from that found in Fe where the α - γ and the γ - δ transformations and the melting process produce discontinuities. The magnetic susceptibilities of hcp Nd from the Neel temperature (7° K) up to high temperature phase transformation do not satisfy the Weiss-Curie law (possibly due to partial population of $4f^3$ $^4I_{11/2}$ levels, paramagnetism of d-electrons and polarization of conduction electrons).

The mass paramagnetic susceptibility of Ho is representable by the Weiss-Curie law $\chi(T-87.7) = 8.79 \times 10^{-2}$ up to 1500° K. The experimental effective Bohr magneton number μ_{eff} = 10.8 ± 0.2 compares favorably with the theoretical value of 10.6 for a system of Ho^{+++} in the spectroscopic state $4f^{10}$ $^5I_8$.

The magnetic susceptibility of Er can also be described by the Weiss-Curie law $\chi(T-47.2) = 7.16 \times 10^{-2}$ up to about 1400° K. The effective Bohr magneton number in this region is 9.79 ± 0.15 while the tripositive ion model for the ground state $4f^{11}$ $^4I_{15/2}$ gives μ_{eff} = 9.6. At about 1400° K. an anomaly in $1/\chi$ vs. T curve occurs. It is suggested that a phase transformation takes place at about this temperature similar to that found in Pr and Nd.

The high temperature magnetic susceptibility together with the previous low temperature work on Nd, Ho and Er indicates that the tripositive ion model is a good first order approximation for paramagnetic behavior of the rare earth metals.

132. ANALYSIS OF MAGNETIC INTERACTIONS IN ALLOYS OF PLATINUM WITH IRON GROUP TRANSITION ELEMENTS

HIROSHI SATO
Scientific Laboratory,
Ford Motor Company
Dearborn, Michigan

The magnetic properties of alloys of platinum with iron group transition elements are analyzed and interpreted on the basis of a localized model of ferromagnetism. It is found that in the wide ranges of compositions of the face-centered-cubic alloys of Ni, Co, Fe, Mn and Cr with Pt there is systematic change with atomic number in the dependence of Curie temperature and saturation magnetization on concentration of magnetic atoms or on the formation of superlattices. A qualitative conclusion concerning the dependence of magnetic interactions upon distance is drawn. The general behavior of the interaction is consistent with the generally accepted picture of the location of these elements with respect to the "Bethe-Slater curve" of exchange interactions if the distances are short, but not if the distances are longer.

---

133. THE EFFECT OF IMPURITIES ON THE LOW TEMPERATURE SPONTANEOUS MAGNETIZATION OF CUBIC FERROMAGNETIC CRYSTALS*

A. A. MARADUDIN** and P. A. DIXON
University of Maryland
College Park, Maryland

The effect of substitutional impurities on the low temperature spontaneous magnetization of cubic ferromagnetic crystals is investigated in the spin wave formalism with the aid of techniques developed previously for the study of defect problems in lattice dynamics. The impurities considered have an exchange integral with their nearest neighbors different from that between neighbors in the pure crystal. The results of these calculations show that the Bloch $T^{3/2}$ law is still obeyed, but that the coefficient of the $T^{3/2}$ term is a function of the impurity concentration whose form is determined in the limit of low impurity content.

*This research was supported by the United States Air Force through the Air Force Office of Scientific Research, Air Research and Development Command under Contracts #AF 49(638)399 and AF 18(600)1315.

**A portion of this work was carried out while this author was a consultant to the General Motors Research Laboratories, Warren, Michigan

SESSION VII-B

MAGNETIC SALTS

D. M. GRIMES, Presiding

---

134. PARAMAGNETIC RESONANCE ABSORPTION OF NICKEL IN SAPPHIRE SINGLE CRYSTALS

S. A. MARSHALL and A. R. REINBERG
Physics Division
Armour Research Foundation
Chicago 16, Illinois

Paramagnetic resonance absorption of divalent nickel ion in sapphire has been observed using 3 centimeter wavelength microwave radiation. The single crystals are Linde golden sapphire whose prefusion nickel ion concentration is roughly one per cent. Two methods are used to orient the crystals. Before cutting, a polarizing microscope establishes the axis of four fold symmetry to within one degree of arc. After cutting, the paramagnetic resonance absorption of trivalent iron and chromium ions reduces the orientation uncertainty to 0.1 degree of arc. At 0° orientation, which is the most difficult to obtain, an iron line is observed at 10,075 oersteds ($h\nu = 0.31513$ cm^{-1}.) This field strength is compared with 10,079 oersteds predicted by Kornienko and Prokhorov[1] for trivalent iron in the sapphire lattice. At 90° a chromium line field strength position showed the same order of agreement with data reported by Kikuchi, Lambe, Makhov, and Terhune.[2] The resonance absorption spectrometer is of conventional design and uses a cylindrical cavity operating in the TE_{011} mode with a loaded Q of 7500.

The spectrum of the divalent nickel ion resonance is interpreted by the following spin Hamiltonian

$$\mathcal{H} = \beta H \cdot g \cdot S + D\,[S_z^2 - \tfrac{1}{3} S\,(S+1)]$$

where the best fit is obtained by setting $D = 1.375 \pm 0.003$ cm^{-1},

$$g_x = g_y = 2.187 \pm 0.004, \quad \text{and} \quad g_z = 2.196 \pm 0.004.$$

At the 0° orientation, a nickel absorption line is observed at 10,347 oersteds having a total width of 42 oersteds at inflection points. This absorption corresponds to the transition $M_s = 0 \rightarrow -1$. No other absorption is observed at this orientation for field strengths below that of this transition because $h\nu < D$. At 90°, an absorption due to nickel is observed at 7159 oersteds having a total width of 50 oersteds at inflection points. This absorption corresponds to the transition $M_s = 0 \rightarrow 1$ where the quantum numbers refer to the high field spin states. No other transitions are possible at this orientation for microwave energy of 0.31513 cm^{-1}. Since the highest field attainable by the electromagnet is 11,000 oersteds, the 0° transition $M_s = -1 \rightarrow 0$ which occurs at 16,500 oersteds was not observed.

The spin-lattice relaxation time for the single transition at the 90° orientation was measured at 77°K by the method of progressive saturation. With 50 milliwatts power coupled to the cavity resonator an absorption diminution of

46% was observed. This diminution corresponds to a spin-lattice relaxation time of 6 microseconds.

1. L. S. Kornienko and A. M. Prokhorov, J.E.T.P., 33, 805 (1957).
2. C. Kikuchi, J. Lambe, G. Makhov, R. W. Terhune, J. Appl. Phys., 30, 1061 (1959).

135. THE MAGNETIC SUSCEPTIBILITIES OF SEVERAL PARAMAGNETIC SALTS BETWEEN 1.3°K AND 21°K*

R. FLIPPEN and S. A. FRIEDBERG
Carnegie Institute of Technology
Pittsburgh, Pennsylvania

A mutual inductance-audio frequency bridge arrangement has been used in the measurement of the susceptibilities of several hydrated paramagnetic salts in the temperature intervals 1.3° to 4.2°K and 14° to 21°K. Data on powdered specimens of $Co\,Cl_2 \cdot 6H_2O$, $Ni\,Cl_2 \cdot 6H_2O$, $Mn\,Cl_2 \cdot 4H_2O$, $Co(C_2\,H_3\,O_2)_2 \cdot 6H_2O$, $Ni(C_2\,H_3\,O_2)_2 \cdot 6H_2O$, and $Mn(C_2\,H_3\,O_2)_2 \cdot 4H_2O$ have been obtained. In addition, the single crystal susceptibilities of $Co\,Cl_2 \cdot 6H_2O$, $Ni\,Cl_2 \cdot 6H_2O$ and $Mn(C_2\,H_3\,O_2)_2 \cdot 4H_2O$ have been studied. With the exception of the Co^{++} and Ni^{++} acetates, all of these salts become antiferromagnetic in the temperature range covered. The powder data on the chlorides are in good agreement with findings of previous investigators. In the case of $Ni\,Cl_2 \cdot 6H_2O$, only single crystal data provide convincing evidence for antiferromagnetism supporting the conclusion of Robinson and Friedberg drawn from their recent specific heat observations. Measurement in the neighborhood of the Néel point ($T_N \simeq 5.3$°K) is impractical by most methods while below 4.2°K the powder susceptibility is temperature independent. This effect is associated with the fact that $\chi_\perp$ rises with falling temperature below T_N. Various implications of the single crystal results will be discussed.

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

136. MAGNETIC PROPERTIES OF URANIUM DIGERMANIDE*

CLAYTON E. OLSEN
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico

The magnetic properties of the intermetallic compounds of uranium have been investigated and reveal the existence of ferromagnetism in uranium digermanide. Measurements of its magnetic susceptibility show it to have a remanent moment of greater than 0.5 Bohr magnetons** per uranium atom at 3.96°K and a curie point of 48°K.

Electrical resistivity measurements have been made on the same sample. They show the material to have a resistivity of the order of 10,000 μ ohm cm at 276°K and a residual resistivity of 500 μ ohm cm at 1.3°K. Resistivity vs. temperature shows a very close correlation to the magnetic behavior. Uranium digermanide will be compared to uranium disilicide which does not seem to be ferromagnetic.

*Work performed under the auspices of the Atomic Energy Commission.

**$U\,(Ge)_2$ is magnetically very hard and we are not sure whether saturation was reached at 1000 Oe, our maximum field.

137. DISLOCATION MAGNETISM IN ANTIFERROMAGNETIC CRYSTALS

E. S. DAYHOFF
U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

A dislocation edge in an otherwise perfect antiferromagnetic crystal interrupts the magnetic ordering of the lattice. The extra half plane of magnetic atoms inserted into the crystal lattice can in some cases experience exchange forces with neighboring layers of atoms which produce no preferred spin direction. The extra layer of atoms may be thought of as rather free to rotate in spin orientation, inhibited by the crystalline field anisotropy, and therefore acting somewhat like a paramagnetic inclusion. Some effects which might be produced by such paramagnetic dislocation planes are: (1) rise of susceptibility at very low temperatures, (2) paramagnetic resonance at low temperatures, (3) a relatively temperature independent contribution to the breadth of the antiferromagnetic resonance, (4) a magnetic contribution to the strain energy of the dislocations. Some effects of these kinds have been reported though no proof exists that the proposed mechanism is the principal cause. These effects should be of observable magnitude, however, because each dislocation line is associated with a half plane of excess spins and therefore a relatively large number of atoms are involved. Various details and consequences of the model will be discussed.

138. AN INTERPRETATION OF THE MAGNETIC AND CRYSTALLOGRAPHIC PROPERTIES OF SEVERAL IRON, NICKEL, AND IRON-NICKEL NITRIDES*

JOHN B. GOODENOUGH, A. WOLD and R. ARNOTT
Lincoln Laboratory
Massachusetts Institute of Technology

The saturation moment of 4°K and the room-temperature structure of the following nitrides have been examined: $Fe_{4-x}Ni_x$ with $0 \leqslant x \leqslant 3$ (Fe_4N-type structure); tetragonal, ordered FeNiN; hexagonal $Fe_{3-y}N$ with $0 \leqslant y < 1$; hexagonal $Ni_3N_{1.16}$; and orthorhombic Fe_2N. The atomic ordering, nitrogen solubility, and atomic moments are interpretable from a model of the band structure of the structure of the transition elements of the first long period and their alloys in which it is explicitly assumed that the crystalline fields split the d bands into separable components.

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

139. MAGNETIC TRANSITIONS IN Ti_2O_3 AND V_2O_3*

P. H. CARR and S. FONER
Lincoln Laboratory
Massachusetts Institute of Technology
Lexington, Massachusetts

The magnetic susceptibility and conductivity of the oxides of titanium and vanadium simultaneously undergo a large change at a transition temperature T_O. Below T_O, the conductivity of these oxides is characteristic of semiconductors, and above T_O, it is characteristic of metals.[1] Long range antiferromagnetic ordering below T_O has been suggested.[2] Morin[1] has recently proposed a model in which the long range antiferromagnetic interaction splits the 3d band, thus producing the large change in conductivity. In order to examine the "antiferromagnetic region," we have measured the temperature dependence of the magnetic susceptibilities of single crystals of Ti_2O_3 and V_2O_3 from 4.2°K to 300°K by means of a vibrating sample magnetometer.[3] In Ti_2O_3 (T_O occurs between 473°K and 573°K) the susceptibilities parallel and perpendicular to the $\underset{\sim}{c}$ axis, $\chi_{\parallel}$ and $\chi_{\perp}$, are 6×10^{-7} and 3×10^{-7} cgs per gram respectively and are temperature independent. The fact that both are small and temperature independent implies that Ti_2O_3 would be antiferromagnetic only if the anisotropy field were negligible and the localized moment were simultaneously very small. More likely, the non-vanishing temperature independent susceptibility is due to Van Vleck temperature independent paramagnetism. This viewpoint is supported by recent neutron diffraction experiments,[4] which indicate that the localized moment must be less than $0.5\mu_B$. In the case of V_2O_3 (T_O occurs in the range 165-172°K) $\chi_{\parallel}$ equals 8.4×10^{-6} cgs per gm and is temperature independent below T_O. $\chi_{\parallel}$ is greater than $\chi_{\perp}$ below T_O, and $\chi_{\parallel}$ is less than $\chi_{\perp}$ above. Both $\chi_{\parallel}$ and $\chi_{\perp}$ increase rapidly as T increases through T_O, and thermal hysteresis of susceptibility is also observed. Although some of the magnetic characteristics are similar to those of Ti_2O_3, an additional complication occurs in that an increased ordering[5] of the lattice is observed below T_O. The results for both Ti_2O_3 and V_2O_3 support the bonding theory of Goodenough.[6]

---

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

1. F. J. Morin, Phys. Rev. Letters 3, 34 (1959).
2. J. Wucher, J. des Recherches du C.N.R.S. 4, 254 (1952).
3. S. Foner, Rev. Sci. Inst. 30, 548 (1959).
4. G. Shirane, S. J. Pickart and R. Newnham (private communication).
5. E. P. Warekois, preceding abstract.
6. J. B. Goodenough, preceding abstract.

---

140. LOW TEMPERATURE X-RAY DIFFRACTION STUDIES ON VANADIUM SESQUIOXIDE*

E. P. WAREKOIS
Lincoln Laboratory
Massachusetts Institute of Technology

Experimental data[1,2] have been presented that show marked changes in the electrical and magnetic properties of many of the transition metal oxides. Various theoretical considerations[1,3] have suggested that these effects are due to changes in the bonding configuration and associated crystal lattice distortions. Changes in the x-ray diffraction patterns have been observed for some of these metal oxides[4]. A study of the changes in the x-ray diffraction patterns from polycrystalline and single crystal vanadium sesquioxide has been made at liquid nitrogen temperatures. An abrupt change in the x-ray pattern was noted at about 150°K. The change was characterized by the appearance of new x-ray diffraction peaks only in the vicinity of the (hkℓ) reflections where ℓ was non-zero. New doublet or triplet lines appeared depending on the magnitude of the h, k, and ℓ indices.

The data are interpreted in terms of the directional properties of the crystal distortions relative to the original hexagonal lattice.

---

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

1. F. J. Morin, Phys. Rev. Letters 3, 34 (1959).
2. P. H. Carr and S. Foner: Following Abstract.
3. J. B. Goodenough: Preceding Abstract.
4. M. Foex, et al., J. Recherches Centre Nat'l., Recherche Sci. Labs, Bellevue, Paris, 4, 259 (1952).

---

141. THE PROPERTIES OF MANGANESE FERRITES PREPARED AT VARIOUS OXYGEN PRESSURES

ALEKSANDER BRAGIŃSKI
Research Laboratory for Magnetic Materials
"Polfer"
Warsaw, Poland

Manganese ferrite solid solutions $Mn_yFe_{3-y}O_{4\pm\gamma}$, $0{,}87 \leqslant y \leqslant 1{,}14$, are investigated. The samples are sintered at various temperatures and then cooled at various oxygen pressures. It is shown that the lattice defects are formed during sintering these facilitating both the reduction or oxydation processes during cooling depending on the oxygen pressure applied. The concentration of defects at constant sintering temperature increases with the iron content, especially at $y < 1$.

---

142. EFFECT OF POTASSIUM IONS ON THE REACTION AND FINAL PROPERTIES OF Mn-Zn FERRITE

STEFAN MAKOLĄGWA
Research Laboratory for Magnetic Materials
"Polfer"
Warsaw, Poland

A Mn-Zn ferrite containing slight iron surplus is investigated. Small additions of potassium ions introduced into the initial mixture of raw oxides volatilise during the sintering and accelerate the reaction process, facilitating the reduction or oxydation of the ferrite, depending on the oxygen pressure applied. Thus the basic magnetic properties are greatly influenced. The effect may be explained by the formation of lattice defects.

143. IONIC ORDERING EFFECTS IN THE FERROMAGNETIC RESONANCE OF LITHIUM FERRITE MONOCRYSTALS

A. D. SCHNITZLER, V. J. FOLEN, and G. T. RADO
U. S. Naval Research Laboratory
Washington 25, D. C.

Ferromagnetic resonance experiments have been carried out on monocrystals of lithium ferrite for the purpose of determining whether ionic ordering influences the line width, ΔH, and the magnetocrystalline anisotropy constants, K_1 and K_2. Resonance measurements have not been published previously on single crystals of this material, and in no other ferromagnetic oxide have such ordering effects been observed. In Li-ferrite, moreover, all the magnetic ions are of the same kind, and the degree of inversion is independent of the heat treatment

Measurements were made at both room temperature and liquid nitrogen temperature with a tunable transmission type cavity operating at 24,200 Mc/sec in the TE_{102} mode. The Li-ferrite single crystals, grown from a PbO flux, were made into small spherical samples (having diameters between 80 and 250 microns) and mounted on a polystyrene post in the center of the cavity. The surface polish as well as heat treatment of the spheres was varied, and their degree of ionic order was determined by X-ray analysis of Li-ferrite powder heat treated simultaneously with the spheres.

At first it seemed impossible to observe an influence of ionic ordering on ΔH because a large and strongly anisotropic ΔH was exhibited even by those spheres which had been subjected to the final polishing (using 0.1 micron sapphire particles) and appeared smooth under high (300 X) magnification. However, it proved possible to reduce drastically such previously unreported spurious effects. This could be accomplished not only by a prolongation of the final polishing but also by proper annealing, and these effects were attributed to a plastic deformation in a thin layer underlying the spherical surface.

The drastic reduction in the spurious effects led to reproducible observations of a difference between ΔH in the (long-range) ordered state and in an almost ($\approx 90\%$) disordered state. This difference may arise both from the ionic rearrangement and from the resulting changes in the spontaneous lattice distortions. Numerical data on the magnitude and anisotropy of this order-disorder effect will be reported and possible modifications in the scattering models of Clogston et al.[1] will be discussed. The microwave values of K_1 for various degrees of ionic order and the corresponding static values of K_1 measured by Folen[2] are in good agreement.

1. A. M. Clogston, H. Suhl, L. R. Walker, and P. W. Anderson, J. Phys. Chem. Solids 1, 129 (1956); S. Geschwind and A. M. Clogston, Phys. Rev. 108, 49 (1957).
2. V. J. Folen, paper presented at this Conference.

SESSION VIII-A

MAGNETIC COMPOUNDS AND NEUTRON DIFFRACTIONS

S. SMART, Presiding

144. THE PRECISE MEASUREMENT OF MAGNETIC FORM FACTORS* (Invited)

ROBERT NATHANS
Pennsylvania State University
University Park, Pennsylvania
and Brookhaven National Laboratory
Upton, New York

The polarized neutron spectrometer has now been used to measure the magnetic form factors in metallic nickel, iron,[1] f.c.c. cobalt, hex. cobalt[2] and the ordered alloy Fe_3Al.[3] In all of these substances a careful analysis of the higher angle reflections has revealed deviations from spherical symmetry of the magnetic electron cloud. The effects of nonspherical charge distribution on these neutron form factors has been calculated by Weiss and Freeman in terms of a mixing of doubly and triply degenerate orbitals.[4] Using the analysis indicated by these authors a fair estimate of the proper mixture for each of the above materials can be established on the basis of the experimental data. Further, we can prepare a two dimensional magnetic electron density map. Data on some of the most recently studied materials is now judged sufficiently complete to attempt this type of calculation.

Since the quantitative determination of these departures from spherical symmetry involves very precise scattering amplitude measurements at large angles where the magnetic scattering amplitude has been considerably reduced, it is necessary to properly allow for all the corrections entering into the final values. These corrections include depolarization, extinction, absorption, and half wave length contamination. While the experimental conditions are arranged to reduce their total effect to a minimum, nevertheless, the influence of each must be estimated independently and the proper corrections applied where necessary.

A general review of the polarized beam technique, and in particular, its application to neutron form factors, will be given. Also, a summary of the most recent experimental data in terms of some of the more recent theories on the outer electronic configuration in these transition elements will be discussed.

*Work performed under the auspices of the U.S. Atomic Energy Commission and the National Security Agency.

1. Nathans, Shull, Shirane, and Andresen, J. Phys. Chem. Solids (to be published)
2. Nathans and Paoletti, Phys. Rev. Letters 2, 254 (1959).
3. Pickart and Nathans (to be presented at the 1959 Conference on Magnetism and Magnetic Materials).
4. Weiss and DeMarco, J. Phys. Chem. Solids (to be published).

145. ON THE ANTIFERROMAGNETIC STRUCTURE AND DOMAINS IN SINGLE CRYSTAL NiO

WALTER L. ROTH and GLEN A. SLACK
General Electric Research Laboratory
Schenectady, New York

Previously reported neutron diffraction measurements showed the magnetic moments in antiferromagnetic NiO were probably arrayed in ferromagnetic sheets parallel to (111), with reversed directions of magnetization in alternate sheets. An attempt to distinguish this single-spin axis structure from alternative multispin axis models was rendered inconclusive by the presence of twins in the crystals then available.

Crystals with essentially no rhombohedral twinning have been produced by an anneal at 1600°C, followed by room temperature compression along [111]. The presence of twin boundaries can be detected by inspection of polished ($\bar{1}10$) and ($11\bar{2}$) faces, and this was confirmed by neutron scattering measurements. In a crystal studied in some detail, the distribution of rhombohedral twins was 98.7% (111), 1.3% ($11\bar{1}$), 0% ($1\bar{1}1$), 0% ($\bar{1}11$). The neutron diffraction data unambiguously confirm the single spin axis structure. The data further show the moments are distributed in domains such that the magnetization direction varies within the (111) ferromagnetic sheet.* The essentially random domain configuration persisted even after application of fields up to 16×10^3 oe.

The rotational torques in ($\bar{1}10$), ($11\bar{2}$) and (111) of untwinned crystals have been measured as a function of field up to 15×10^3 oe. The results confirm the above conclusions and provide good estimates for the anisotropies of the susceptibilities. The (111) rotational torque is particularly interesting: rotational hysteresis sets in at $H = 2.4 \times 10^3$ oe., and remains constant out to 16×10^3 oe.; the torque curve appears to reflect the crystal shape. Experiments are underway to discover whether the effects are the result of rotation of the antiferromagnetic spin system, movement of antiferromagnetic domain walls, or an exchange anisotropy involving parasitic ferrimagnetism associated with deviations from stoichiometry.

---

*We understand from private communications that Harvey Alperin independently has arrived at similar conclusions from work carried out at the Naval Ordnance Laboratory.

---

146. NEUTRON DIFFRACTION INVESTIGATION OF THE MAGNETIC STRUCTURE OF NICKEL OXIDE

H. A. ALPERIN
University of Connecticut
Storrs, Connecticut
and U. S. Naval Ordnance Laboratory
Silver Spring, Maryland

A neutron diffraction study of nickel oxide was performed at the Naval Research Laboratory reactor utilizing a single crystal sample to investigate the possibility of a multi-axis spin structure. For unambiguous interpretation, it is essential that the twinning caused by the rhombohedral distortion which sets in below the Néel temperature, be greatly reduced. Our best data were obtained on a single crystal which was stress-annealed[1] to remove the twinning. After correction for absorption and secondary extinction, the diffracted intensities show approximately 80% of the total intensity of the {111} form to come from one of the (111) planes, the remaining 20% being distributed equally among the remaining three planes of this form. Because this result indicates that 80% of the volume of the crystal was rendered free of twins by the stress-annealing, we are able to rule out a multi-axis spin structure for nickel oxide.

Analysis of several magnetic reflections reveals the structure to have a single magnetic axis lying in a (111) plane but within this plane there are domains such that the directions of the moments of these domains are distributed symmetrically. This model is the one discussed by Keffer and O'Sullivan for manganese oxide.[2] These results are also in agreement with magnetic torque measurements made on the same specimen by Professor Kondoh.[3] A second specimen[4] prepared by annealing at 1500°C with slow cooling (1°C per minute) also exhibits the same structure. No attempt was made to determine the easy directions in the (111) plane.

A previous neutron diffraction study of a single crystal of nickel oxide reported by Roth[5] was unable to distinguish some polydomain-single magnetic axis spin arrangements from a single domain multi-axis spin structure. Both this investigation and more recent work of Roth[6] are in agreement as to the proposed spin structure and clarify this difficulty.

---

1. This crystal was prepared, stress annealed and kindly lent to us by Prof. Kondoh, Univ. of Osaka Prefecture.

3. F. Keffer and W. O'Sullivan, Phys. Rev. 108, 637 (1957).
3. H. Kondoh, E. Uchida, Y. Nakazumi, T. Nagamiya, J. Phys. Soc. Japan 13, 579 (1958).

4. This crystal was grown by Dr. E. J. Scott, U. S. Naval Ordnance Laboratory.

5. W. Roth, Phys. Rev. 111, 772 (1958).

6. Private communication.

---

147. NEUTRON DIFFRACTION INVESTIGATION OF THE $Fe_{1-\delta}S$ SYSTEM*

J. T. SPARKS, W. MEAD, and A. J. KIRSCHBAUM
Lawrence Radiation Laboratory
University of California
Livermore, California
W. MARSHALL
Theoretical Physics Division
Atomic Energy Research Establishment
Harwell, England

A neutron diffraction investigation of iron sulfide has been undertaken in an attempt to clarify some of the interesting magnetic anomalies encountered by previous investigators. The system $Fe_{1-\delta}S$ consists of a series of homogeneous compounds over the range $0 \leq \delta \leq 0.125$ which possesses the NiAs structure for $0.04 < \delta < 0.125$ and closely related structures for smaller values of δ. The magnetic properties of these substances have been studied extensively by Haraldsen[1] and others--principally by means of susceptibility measurements. The magnetic structure is basically antiferromagnetic, but vacancy ordering leads to ferrimagnetic behavior in the region for which $\delta \gtrsim 0.09$.

Polycrystalline samples of iron sulfide having specific iron-to-sulfur ratios have been prepared and examined with the neutron spectrometer. Particular attention has been focused on the temperature-dependent behavior of the (001) magnetic reflection characteristic of the antiferromagnetic spin alignment. The existence of an abrupt change in the susceptibility at a temperature of 120°C (for samples with $\delta = 0.02$) has lead to the suggestion that a rotation of spins may occur at this temperature, and such a rotation would produce a corresponding change in the intensity of the (001) reflection. A number of samples were prepared with $\delta = 0.02$ and the intensity of the (001) peak carefully examined from room temperature to above the Néel temperature (320°C). The abrupt increase in intensity observed at approximately 120°C--together with the absence of large superstructure peaks—confirms the suggested spin rotation. The gross characteristics of the change in intensity may be accounted for by the assumption that the spins rotate from directions along the C-axis at room temperature to new directions that lie in the hexagonal plane above the transition temperature. Further investigation of the intensity of the (001) reflection has shown the existence of a signficiant room temperature peak and its behavior indicates that the spin alignments below the transition temperature depend strongly on the thermal history of the sample.

Samples in the sulfur-rich region for which ferrimagnetic behavior occurs have also been examined with the spectrometer. Sharp variations in the magnetization of such samples as a function of temperature were observed by Lotgering[2], and interpreted in terms of the competitive ordering of spins and vacancies. Preliminary temperature-dependent magnetic scattering data for samples with $\delta = 0.107$ tend to support this interpretation. These results will be discussed in relation to existing magnetic data. The compound $Fe_{0.902}S$ ($\delta = 0.098$) shows ferrimagnetic behavior in the temperature range 190° to 220°C and antiferromagnetic behavior outside this interval.[2] The intensity of the (001) reflection was observed as a function of temperature for such a sample in an attempt to see if the spin arrangement differs in the two antiferromagnetic regions. Tentative results indicate that the spin arrangements are the same from the Néel temperature to room temperature.

---

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

1. H. Haraldsen, Z. anorg. u. allgem. Chem. 231, 78 (1937).
2. F. K. Lotgering, Philips Res. Rep. 11, 190 (1956).

---

148. NEUTRON DIFFRACTION INVESTIGATIONS OF THE MAGNETIC ORDERING IN RARE-EARTH NITRIDES

M. K. WILKINSON, H. R. CHILD, J. W. CABLE, E. O. WOLLAN, and W. C. KOEHLER
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Neutron diffraction investigations have been initiated on a series of rare-earth nitrides to determine the existence of magnetic ordering in these compounds at low temperatures, because these nitrides have the simple rock-salt structure and might be amenable to relatively easy theoretical analyses. Experimental results have been obtained on HoN and TbN, and both of these compounds were found to become ferromagnetic with Curie temperatures of about 18°K and 42°K, respectively. The paramagnetic moments obtained from the diffuse scattering at room temperature are consistent with those moments calculated for the free tri-valent ions, but the observed ferromagnetic moments are lower than the calculated values. Values of about 7 Bohr magnetons have been obtained for the atomic magnetic moments in the ordered ferromagnetic lattices of both compounds, whereas the calculated values are 10.0 Bohr magnetons for Ho^{+3} and 9.0 Bohr magnetons for Tb^{+3}. The low value of the ferromagnetic moment in HoN is consistent with that expected on the basis of recent calculations by Trammell[1] which investigated the effect of crystalline field interactions in this compound. Measurements of the ferromagnetic reflections from HoN in an external magnetic field indicate that the moments are directed along the edges of the cubic unit cell and this direction is also predicted from Trammell's calculations. The diffraction patterns at 1.3°K from both compounds (particularly HoN) show a large amount of inelastic magnetic scattering, and this scattering appears to be a type of ferromagnetic short-range-order with characteristics that are different from those usually associated with critical magnetic scattering.

---

1. G. T. Trammell - Private Communication.

---

149. THEORY OF LOW LYING STATES OF SOME RARE EARTH COMPOUNDS

G. T. TRAMMELL
Oak Ridge National Laboratory
Oak Ridge, Tennessee

In the rare earth compounds the splitting of the rare earth levels in the crystalline field may be comparable to or larger than the exchange energy. Thus in the rare earth nitrides studied by Wilkinson, Wollan, et al. the field has cubic symmetry and may be estimated to give overall splittings of some hundreds of wave numbers, whereas the observed Curie points indicate exchange energies corresponding to some tens of wave numbers.

Taking

$$H = \sum_{i} V_{ci} - \frac{1}{2} \sum_{i,j} \mathcal{J}_{ij} \vec{J}_i \cdot \vec{J}_j \, .$$

where the first sum represents the crystal field energy and the second the exchange energy, then the ground state will not generally be a state of good $\vec{J}_i \cdot \vec{J}_j$, and $\langle \vec{J}_i \cdot \vec{J}_j \rangle$ for the ground state will be a function of the separation distance of atoms "i" and "j".

An approximation scheme based on Bogoliubov's perturbation procedure is developed to treat the ground and weakly excited states and used to analyze the neutron diffraction results on the rare earth nitrides.

If z, x, y are axes such that $\langle J_x \rangle = \langle J_y \rangle = 0$ for the ground state (this axis is usually simple to determine from the form of Vc), we write

$$H = \sum_i (V_{ci} - \sum_j \bar{\mathcal{J}}_{ij} \langle J_z \rangle J_{zi}) - \tfrac{1}{2} \sum_{i,j} \bar{\mathcal{J}}_{ij} [(J_{zi} - \langle J_z \rangle)$$

$$(J_{zj} - \langle J_z \rangle) + J_{xi}J_{xj} + J_{yi}J_{yj}] + \tfrac{1}{2} \sum_{i,j} \mathcal{J}_{ij} \langle J_z \rangle^2$$

where

$$\langle J_z \rangle = (w_o, J_z w_o), \quad (V_c - \sum_j \mathcal{J}_{ij} \langle J_z \rangle J_z)\, w_m = e_m w_m$$

and w_o is chosen to minimize e_o. The self consistent field solution, $\pi_i\, w_{o,i}$, is then the best product wave function approximation to the ground state.

The last term in H is constant and of no interest, but the second term gives configuration mixing. Using the $w_{m,s}$ as bases the operators $\bar{J}$ may be written out explicitly.

$$J_\mu(i) = \langle n \,|\, J_\mu \,|\, m \rangle\, \bar{a}_n^i\, a_m^i$$

where μ is x, y, or z, i indicates a particular rare earth ion, and $\bar{a}_n^i$ and a_m^i are creation and destruction operators for states n and m of the "i" ion. Symmetry serves to restrict the values of the $\langle n \,|\, J\mu \,|\, m \rangle$, and the number of states n such that $\langle n \,|\, J\mu \,|\, O \rangle$ is appreciable are usually small. The second term in H is of the fourth power in the a's and $\bar{a}$'s, and the Bogoliubov approximation consists of keeping only those terms quadratic in the a_o, $\bar{a}_o$'s and, after replacing $\bar{a}_o^i a_o^i$ by $1-\bar{a}_l^i a_l^i \ldots$, replacing a_o and $\bar{a}_o$ by 1. A discussion of the limits of validity of this approximation will be given together with the usual spin wave approximation. With these replacements H becomes quadratic in the field amplitudes and may be diagonalized in the usual manner by introducing normal mode coordinates. The effect of magnetic dipole-dipole forces in H is treated in the same manner.

1. N. N. Bogoliubov and S. V. Tiablikov, Izvestia Akad. Nauk SSSR, Seria Fiz. Vol. 21, No. 6, June 1957.

150. ON THE CLASSICAL THEORY OF SPIN-CONFIGURATIONS IN THE CUBIC SPINEL*

T. A. KAPLAN
Lincoln Laboratory
Massachusetts Institute of Technology

It has recently been pointed out[1] that the Néel configuration (C_N) in the cubic spinel is unstable when a parameter y is greater than a critical value, y_o, where y is essentially the ratio of B-B to A-B interactions and y_o is about 10 percent less than the corresponding critical value found by Yafet and Kittel;[2] (A-A interactions are neglected). The "small" spin-deviations from C_N that lower the energy when $y > y_o$ will be discussed. In particular, the configuration of this class with minimum energy (calculated to terms quadratic in the deviations) may be described as a sinusoidal plane wave with propagation vector in [110], and wavelength $\lambda = \lambda_o\,(1 + \delta)$, where $\delta \cong 0.1$ and λ_o = twice the primitive translation in [110]. In addition, there are nonzero angles between the spins on the tetrahedral, as well as the octahedral sites. These properties are suggestive in connection with the experimental results of Corliss and Hastings[3] on $MnCr_2O_4$ and Caspar's results[4] on Mn_3O_4. An idea of the size of the deviations from C_N is obtained by a simplified calculation based on the lowest energy mode with $\lambda = \lambda_o$. The possibility of determining the true minimum energy configuration (i.e. including terms in the energy higher than quadratic) when $y - y_o$ is small and positive will be discussed.

1. T. A. Kaplan, to appear in Phys. Rev.
2. Y. Yafet and C. Kittel, Phys. Rev. 87, 290 (1952).
3. L. Corliss and J. Hastings, private communication.
4. J. S. Kasper, Bull. Am. Phys. Soc. 4, Series II, p. 178 (1959).

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

151. ON THE DIRECT CATION-CATION INTERACTIONS IN PRIMARILY IONIC SOLIDS*

JOHN B. GOODENOUGH
Massachusetts Institute of Technology
Lincoln Laboratory.

It is pointed out that there is considerable experimental evidence for direct cation-cation interactions in several oxides. The most favorable crystallographic configuration for such interactions is one where cation-occupied octahedra share a common octahedral face, as in the corundum and NiAs-type structures: in this case cations with outer-electron configuration nd^m, where $0 < m \leqslant 5$, may have direct interactions that profoundly influence the physical properties of the material. It is further pointed out that if cation-occupied octahedra share a common edge, important interactions occur between cations with outer-electron configuration nd^m, where $0 < m \leqslant 3$. These interactions may be sufficiently strong that band formation, and therefore metallic-type conduction, can occur. It is suggested that the semiconducting $\rightleftharpoons$ metallic transitions frequently observed in such cases are due either to the formation at low temperatures of covalent-type bonds or of bonding bands, the bonding configuration introducing a crystalline change that at least partially removes the degeneracy of the atomic orbitals contributing to the original metallic-type band. This model makes definite predictions about the paramagnetic susceptibility, cation magnetic moments, antiferromagnetic order, and crystallographic changes to be associated with the electrical transitions in these materials. Finally it is pointed out that if $m \leqslant 3$, indirect magnetic interactions are reduced to become comparable to, or even smaller than, the direct magnetic interactions. However, direct interactions cannot occur if the cation-occupied octahedra share only a common corner.

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

152. MAGNETO STRUCTURAL STUDIES ON GADOLINIUM-IRON ALLOYS

R. C. VICKERY, W. C. SEXTON, V. F. NOVY and E. V. KLEBER
Research Chemicals Division
Nuclear Corporation of America

Magnetic and constitutional data have been established for a series of alloys in the gadolinium-iron system, ranging from 2-98% Fe. Five intermetallic compounds have been found and some correlation has been derived between their crystal structures and magnetic properties.

Saturation magnetization and Curie temperatures found are:

		σ(30°C)	Curie Point (°C)
$GdFe_2$	f.c.c.	45	600
Gd_2Fe_5	ortho.	38	350
$GdFe_3$	tet.	36	750
$GdFe_5$	hex.	36	500
Gd_2Fe_{17}	ortho.	69	750

Correlation of observed data with theory suggests that antiferromagnetic exchange coupling is responsible for discontinuities in the plot of magnetic susceptibility versus composition. The extent of such coupling can be related to the distances between the gadolinium and iron atoms in the intermetallic lattices and the extent of orbital overlap. It does not seem that the addition of small amounts of gadolinium to iron has a magnetic diluent effect, but rather the opposite.

Except for gadolinium, the minimal value of magnetic susceptibility, or conversely, the maximum degree of parallel spin alignment, is found between the tetragonal $GdFe_3$ and hexagonal $GdFe_5$ structures. At this point, assuming lattice interaction, the internuclear distance between gadolinium and nearest-neighbor iron atoms is of the order 2.85A and approach of unfilled, 4f and 3d, orbitals 1.52A. Since no physical overlap of orbitals can thus be realized, spin coupling at this level must be considered of the long range interaction type suggested by Pratt as existing between the 4f shells of neighboring gadolinium atoms. It would seem, therefore, that both ferro- and antiferromagnetism can develop from such a long range reaction.

Comparison is drawn between the magnetic properties of Gd-Fe compounds and similar intermetallics developing in Gd-Co and Gd-Ni systems.

---

153. MAGNETIC MOMENTS OF ALLOYS OF GADOLINIUM WITH SOME OF THE TRANSITION ELEMENTS

WILLIAM M. HUBBARD, EDMOND ADAMS and JOHN V. GILFRICH
U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

Alloys of gadolinium with some of the transition elements were prepared and examined by X-ray and magnetic techniques in an effort to determine their structure, Curie temperatures and magnetic moments.

Values obtained for the saturation magnetization for some compositions in the gadolinium-cobalt system and for the Curie temperature of the intermetallic compound $GdCo_5$ were higher than those reported by Nesbitt et al[1], but the data agree qualitatively with their theory of an antiferromagnetic interaction. An increase in saturation magnetization at room temperature and below was noted for some compositions that were cooled from their Curie points in a magnetic field. The lattice parameters for a tetragonal and two hexagonal phases were calculated from the X-ray data.

The structure of the gadolinium-manganese system was found to be extremely complex and only the compound $GdMn_2$ was identified. Magnetic moment versus temperature values were also determined for various compositions. The Curie temperature for the composition $Gd_{0.2}Mn_{0.8}$ was found to be approximately 250°C.

---

1. E. A. Nesbitt, J. H. Wernick and E. Corenzwit, JAP 30 365 (1959).

---

154. FERROMAGNETIC ALLOY PHASES NEAR THE COMPOSITIONS Ni_2MnIn, Ni_2MnGa, Co_2MnGa, Pd_2MnSb, AND PdMnSb

F. A. HAMES
Queen's University
Kingston, Ontario, Canada

In a search for further examples of Heusler-type alloys, ferromagnetic alloys were found near the compositions Ni_2MnIn, Ni_2MnGa, Co_2MnGa, Pd_2MnSb, and PdMnSb. X-ray powder patterns of all of these alloys showed the fundamental lines of a body-centered cubic structure plus superlattice lines. Ni_2MnIn probably has the Heusler ($L2_1$) -type structure. Difficulties were encountered in positively fixing the atomic positions in the other alloys, due to unfavorable differences in atomic scattering factors of the atoms. Possible structures for these alloys are discussed. Atomic arrangement and inter-atomic distances in Heusler ($L2_1$) and Fluorite (Cl_b) structures as related to the occurrence of ferromagnetism are discussed.

---

155. ASYMMETRIES IN THE MAGNETIC FORM FACTOR OF Fe_3Al*

S. J. PICKART
Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland
and Brookhaven National Laboratory,
Upton, New York
R. NATHANS
Pennsylvania State University
University Park, Pennsylvania
and Brookhaven National Laboratory
Upton, New York

Using the polarized neutron technique[1], we have extended the measurement of the magnetic form factor of ordered Fe_3Al to higher scattering angles, and obtain clear evidence of the asphericity of the charge distribution of the d electrons. The data so far collected confirm the previously observed difference[2] between the moments of the iron atoms at the body centers of the unit cell (completely surrounded by iron) and those at the corners (partly surrounded by aluminum). For the outer reflections, where the effect of asymmetries in the wave functions is expected to be most pronounced[3], we find noticeable deviations from a "smooth" form factor, i.e. one calculated for a spherically symmetric charge distribution. Specifically, different values of the form factor are observed for a pair of superlattice reflections such as (511,333) or (600,442), which have reciprocal lattice vectors of equal magnitude but different orientation. If we interpret these differences in terms of a mixing of e_g and t_{2g} symmetry wave functions, different proportions of admixture are required for the two types of iron atoms mentioned above, suggesting that the observed moment difference in Fe_3Al is intrinsic.

---

*Work performed under the auspices of the U.S. Atomic Energy Commission and the National Security Agency.

1. Nathans, Shull, Shirane, and Andresen, J. Phys. Chem. Solids (to be published).
2. Nathans, Pigott, and Shull, J. Phys. Chem. Solids 6, 38 (1958).
3. Weiss and Freeman, J. Phys. Chem. Solids (to be published).

SESSION VIII-B

FERRIMAGNETIC RESONANCE EFFECTS, MISCELLANEOUS, MAGNETISM IN MEDICINE

S. M. RUBENS, Presiding

---

156. FERRIMAGNETIC RESONANCE IN RARE EARTH GARNETS (Invited)

R. V. JONES*
Gordon McKay Laboratories
Division of Engineering and Applied Physics
Harvard University
Cambridge, Mass.

A general review is presented of the results of a series of experiments at this laboratory involving ferromagnetic resonance in yttrium and rare earth iron garnets. These experiments have measured the temperature and volume dependence of the resonance parameters of anisotropy, g-factor, and linewidth. In addition, the behavior of these parameters at high r.f. power levels has been studied.

A fairly complete interpretation of these experiments in terms of recent theoretical models can now be made. Much of the magnetocrystalline anisotropy data is found to be in good agreement with the independent ion-crystalline field approximation. The g-factor and linewidth data can be discussed in terms of the recent garnet relaxation model of Kittel and co-workers. The high r.f. power data clarifies many of the details of the relaxation processes associated with large amplitude uniform precessional mode.

---

*The research reported has been sponsored by contract no. AF 19(604)-5487 with Air Force Cambridge Research Center.

---

157. RECENT DEVELOPMENTS IN FERROMAGNETIC RESONANCE AT HIGH POWER LEVELS (Invited)

E. SCHLÖMANN
Raytheon Company
Waltham, Massachusetts
J. J. GREEN,*
Gordon McKay Laboratories
Harvard University
Cambridge, Massachusetts
U. MILANO
Raytheon Company
Waltham, Massachusetts

According to Suhl's theory[1] the saturation of the ferromagnetic resonance line involves the excitation of spin waves. If the signal frequency is sufficiently large the frequency of the potentially unstable spin waves equals the signal frequency. It is shown that under these conditions the presence of inhomogeneities has a pronounced effect on the saturation behavior. Such inhomogeneities scatter energy from the uniform mode into higher order spin waves. The saturation effects then do not set in abruptly as predicted by Suhl's original theory[1].

In the region of moderate power levels the imaginary part of the susceptibility at resonance χ'' depends linearly on the square of the rf field h. The magnitude of the slope $\partial\chi''/\partial h^2$ depends on the nature of the dominant scattering mechanism. If the uniform mode scatters primarily to spin waves of very large wavelength, the slope should be negative. Scattering to spin waves of short wavelength gives a positive contribution to the slope and can lead to a reversal of the sign. The theoretical predictions agree with measurements at X-band on various polycrystalline garnets and ferrites.

At very high power levels the opening angle of the precessing magnetization should approach a limiting value, which is related to the "linewidth" of z-directed spin waves having the same frequency as the uniform mode. This has been confirmed by measurements at X-band on single crystals and polycrystals of yttrium iron garnet with small substitutions of rare earth ions. The polycrystals contained Gd, Ho, Sm, Dy, Yb, or Er, whereas the single crystals contained Gd, Sm, Ho, or Dy. Kittel[2] has shown that the presence of rare earth ions other than gadolinium leads to a rapid relaxation of the magnetic moment. The linewidth measurements on single crystals as well as polycrystals are consistent with this picture. Small substitutions cause a rapid increase in the single crystal linewidth which is proportional to the degree of substitution. Similarly, the increase in the spin wave linewidth is found to be proportional to the percentage of rare earth substitution and shows a strong correlation with the change in linewidth of the uniform mode as measured in single crystals.

It is shown that at sufficiently high power levels a microwave magnetic field applied parallel to the dc field can also give rise to unstable growth of certain spin waves. The spin waves which are most susceptible to this instability have frequencies equal to half the signal frequency and their propagation vectors lie in the plane perpendicular to the dc magnetic field. Measurements of the critical rf field as a function of the dc field should give information about the dependence of the spin wave decay constants on the wave number.

---

*The portion of the work performed by J. J. Green was supported by the Air Force Cambridge Research Center (Contract No: AF 19(604)-87).

1. H. Suhl, J. Phys. Chem. Solids 1, 209 (1957).
2. C. Kittel, post deadline paper presented at APS meeting in Cambridge, Mass., April 1959.

---

158. PULSED FERRIMAGNETIC MICROWAVE GENERATOR

B. ELLIOT, T. SCHAUG-PETERSEN, and H. J. SHAW
Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

This report describes a new microwave generator which is now to be the first reported operation of such a device.

There has long been an interest in the generation of microwave signals using a ferrimagnetic material subjected to pulsed magnetic fields. Theoretical work by Morgenthaler[1] and Schaug-Petersen has disclosed serious practical limitations to such schemes. Recent two-level pulsed maser developments at Hughes Aircraft Company and Lincoln Laboratories suggested an alternate approach to the ferrimagnetic problem. While this approach is being used in the present device, it is, nevertheless, not strictly a maser.

In the present scheme, a microwave signal (pump signal) is applied to the garnet sample, exciting a uniform spin precession with the spin system adjusted for resonance by means of a continuous DC magnetic field. A pulsed DC magnetic field is then applied along the direction of the continuous DC field, which raises the resonant precession frequency of the spin system and adds energy to the spin system. When the pulsed DC field has reached its final amplitude, the spins precess freely and radiate their energy coherently into a microwave transmission circuit at a frequency which is higher than the pump frequency by an amount γH_{pulse}.

The present device is a special case of a general class of RF generators in which a system, which is oscillating at resonance, has its resonant frequency increased adiabatically, but rapidly with respect to its relaxation time, resulting in the addition of energy to the system, and leaving the system free to radiate this energy at the higher frequency.

For convenience, the present device is now operating in the S-band region, with RF output power of one watt peak, output RF pulse width of several millimicroseconds, and output frequency 600 megacycles above the pump frequency. Work is now in progress to investigate operation at higher frequencies, with higher ratios of output frequency to pump frequency, and with higher energy per pulse. Operating frequencies up into the millimeter-wave range should eventually be possible. The difference between output frequency and pump frequency is limited only by pulsed field technology, and means for increasing this difference greatly over the present value seem to be at hand. With CW pumping, as at present, the energy per pulse is limited by Suhl type instabilities. By proper use of pulsed RF pumping, it should be possible to materially exceed this limit.

Compared to paramagnetic maser-type generators, the present device offers the advantages of much higher energy per output pulse because of the higher spin density in the ferrimagnetic material, and room-temperature operation as compared to low-temperature operation for the maser.

---

1. Frederick R. Morgenthaler, IRE Transactions on Microwave Theory and Techniques, January, 1959.

---

159. SWITCHING BEHAVIOR OF LOW REMANENCE FERRITE

F. B. HAGEDORN and E. M. GYORGY
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

Switching studies have been made on a ferrite which has a B-H loop similar to the loop of an anisotropic permalloy thin film when the externally applied magnetic field is perpendicular to the easy axis. The remanent flux in this ferrite is less than 10% of the saturation induction, and at 3 oersteds the induction is within 90% of saturation. The switching time measurements have been extended to times shorter than 5 millimicroseconds by using a sampling oscilloscope with a response time of 0.4 millimicroseconds.

The ferrite switching curve taken from remanence to saturation is very similar to the switching curve of a thin film taken under similar conditions. The ferrite switching coefficient is about 0.04 oersted-microseconds, and the extrapolated threshold field is near zero. These observations are consistent with the assumption that the same type of flux reversal process predominates in both the ferrite and thin films under these conditions.

Switching measurements were also made when the ferrite toroid was biased to an initially saturated state. It was found in this case that the switching curve differed substantially from that of a thin film similarly biased. This difference is attributed to the predominance of nonuniform rotational flux reversal in the magnetically biased thin film.

---

160. TRANSFER FUNCTION AND ERROR PROBABILITY OF A DIGITAL MAGNETIC TAPE RECORDING SYSTEM

JOHN WENCHUNG HUNG
International Business Machines Corp.
Product Development Laboratory
Poughkeepsie, N. Y.

In spite of the complexities of the digital magnetic recording system, it has been discovered that the output of the system to the input of a unit step of current can be approximated by a Gaussian probability function e^{-ax^2}. The value "a" in e^{-ax^2} is a figure of merit of the system.

This yields an analytic expression for the transfer function of the system. Experimental results correlate quite well with those based on this approximate transfer function.

Using this transfer function, the output of the system for any "Non Return to Zero" recording method can be predicted. For example, the reduction in system output with increasing bit densities is established. In addition when Gaussian noise is introduced into the system the error probability is obtained. The effect of the input rise time to the output amplitude is discussed. For simulation purposes a simple network consisting of passive elements is derived.

---

161. PARTICLE INTERACTION IN MAGNETIC RECORDING TAPES

J. G. WOODWARD
RCA
Daniel Sarnoff Research Center
Princeton, N. J.

The magnetic coating of recording tape is assumed to be composed of an assemblage of small, single-domain particles. Each particle is assumed to have a symmetrical, square hysteresis loop when the reversible component of magnetization is neglected and when the particle is not influenced by the fields of neighboring particles. When influenced by the fields of its neighbors, the particle may exhibit an asymmetrical loop when the loop is plotted relative to an external applied field. In this case the positive and negative switching fields for the particle are not equal, and their difference gives an indication of the particle interaction. While it is not possible to measure the switching fields of a single particle on the recording tape, the distribution of switching fields in the assemblage of particles can be measured, along with the distribution of magnetic moments associated with the switching fields. The two switching fields and the magnetic moment define a 3-dimensional distribution function which describes the magnetic properties of the tape, and in terms of which both d.c. and anhysteretic magnetization processes may be described.

The distribution functions have been measured for two recording tapes. While the functions for the two tapes are markedly different in detail, both show that particle interaction is very appreciable in recording tapes and that it is a significant factor in determining the bulk magnetic properties and the recording performance of tapes.

---

162. THE ANALYSIS OF A PRACTICAL PERPENDICULAR RECORDING HEAD FOR DIGITAL MAGNETIC TAPE SYSTEMS

GEORGE FAN
Ampex Corporation
Redwood City, California

It is generally known that the perpendicular recording head offers a substantial improvement of digital recording technique in terms of reliability. Since this design obviates the need for intimate contact between the head and the magnetic tape, such a head is substantially free from dropouts caused by failings in this respect. Up to date, however, analytical accomplishments dealing with this type of head configuration have been slight. In this paper it is intended to give a more detailed mathematical analysis than has previously been published.

When analysing the perpendicular recording head under discussion, the author applied a Fourier method to calculate and plot the magnetic field in the vicinity of the head's pole piece. This alternative to the Schwarz-Christoffel mapping techniques method previously used has advantages for some applications.

The sensitivity of a perpendicular head is investigated in terms of frequency, for ease of calculation, rather than pulse response and the relationship between frequency response and pulse response is established. From these results the pulse response of the head is predicted and the appropriate electronics equalization curve for digital application of the head is drawn.

The resolution of the head as predicted by the Fourier method analysis is compared with data obtained from an experimental model and good correlation is obtained. This experimental model has a pole piece of 0.5 mils and gap length of about 3 mils. It will resolve sine wave of 1.5 mils wavelength and pulse of about 5 mils wavelength on tape.

163. GROWING SPINWAVES IN FERRITES IN UNSTABLE EQUILIBRIUM*

TOR SCHAUG-PETERSEN
Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

It seems reasonable to suppose that the equation of motion of the magnetization in a ferrite, including exchange forces,

$$\frac{d\bar{M}}{dt} = -\gamma\bar{M} \times \left(\bar{H} + H_{ex}\ell^2\nabla^2\frac{\bar{M}}{M_O}\right) \qquad (1)$$

is equally valid for the case when $\bar{M}$ is nearly antiparallel to $\bar{H}$ as when it is nearly parallel to $\bar{H}$. The former case arises when a ferrite sample is saturated and the external field is suddenly reversed in direction, as in ferrite switching, or when 180° pulsing is used in the ferrite pulse generator proposed by Pound and analyzed by Silver and Levinthal,[1] and by Morgenthaler.[2]

In particular, the linear approximation for small deviations of $\bar{M}$ from the antiparallel direction must lead to Suhl's dispersion relation,[3]

$$\omega_k^2 = \gamma^2 (H_O - N_Z M_O + H_{ex}\ell^2 k^2)(H_O - N_Z M_O + H_{ex}\ell^2 k^2 + 4\pi M_O \sin^2\theta). \qquad (2)$$

for plane spinwaves traveling at an angle θ with the dc field.

The interesting thing is now that when $H_O - N_Z M_O < O$ (thus in particular when $H_O < O$), then ω_k^2 can take on negative values. If $\omega_k^2 = -\Omega_k^2$, then the corresponding spinwave has the time factor $e^{\Omega_k t}$ or $e^{-\Omega_k t}$, depending on the initial condition. These waves are nontraveling; their components behave as $\cos(\bar{k}\cdot\bar{r})\, e^{\pm\Omega_k \cdot t}$, which cannot be resolved into traveling waves as in the case of a real ω_k.

The growing exponential $e^{\Omega_k \cdot t}$ is by no means excluded, energetically or otherwise. In fact, these spinwaves do not gain or lose energy as they change their amplitude. As the spins move from their initial position antiparallel to the dc field, they lose potential energy, but this is compensated for by the volume demagnetizing fields and, for shorter wavelengths, by the exchange fields. The situation is very similar to the aperiodic motion of an inverted pendulum.

We shall now calculate the rate of growth of these unstable spinwaves, putting $N_Z = O$ for simplicity. Then

$$\omega_k^2 = \gamma^2 (H_O + H_{ex}\ell^2 k^2)(H_O + H_{ex}\ell^2 k^2 + 4\pi M_O \sin^2\theta). \qquad (3)$$

For $O > H_O > -2\pi M_O$ the minimum of ω_k^2 occurs at $k = O$, $\theta = \pi/2$, and is

$$(\omega_k^2)_{min} = 4\pi\gamma^2 H_O M_O = -\left|\frac{\omega_H \omega_M}{2}\right|, \quad (O > H_O > -2\pi M_O). \qquad (4)$$

For $H_O < -2\pi M_O$, the minimum occurs at $H_O + H_{ex}\ell^2 k^2 + 2\pi M_O = O$, and is

$$(\omega_k^2)_{min} = -4\pi^2\gamma M_O^2 = \frac{\omega_M^2}{4}, \quad (H_O < -2\pi M). \qquad (5)$$

For the latter case, the spinwaves grow extremely rapidly. The number of unstable spinwave modes is extremely large, even for moderate field strengths.

These growing spinwaves seem to offer a partial explanation to the short switching times observed in ferrites, in that they show how rapidly an initial disturbance develops. Their presence also seems to make the ferrite pulse generator with 180° pulsing impractical.

---

*This research was supported in part by the United States Air Force under Contract No. AF 49(638)—415 monitored by the Air Force Office of Scientific Research of the Air Research and Development Command.

1. S. Silver and E. C. Levinthal, "Study of magnetic resonance power source," Levinthal Rep. No. 106, Levinthal Electronics Products, November, 1956.
2. F. Morgenthaler, "Microwave radiation from ferrimagnetically coupled electrons in transient magnetic fields," Trans. MTT-7, No. 1, 6-11, January, 1959.
3. H. Suhl, "Theory of ferromagnetic resonance at high signal powers," J. Phys. Chem. 1, 209-227, April, 1957.

---

164. NUCLEATION EXPERIMENTS ON THIN MAGNETIC MnBi FILMS*

LUDWIG MAYER
Mechanical Division of General Mills, Inc.
Minneapolis, Minnesota

Observations made during the vacuum heat treatment necessary to develop ferromagnetic MnBi films from their nonmagnetic constituents suggested that the nucleation behavior of this transformation might be responsible for the poor reproducibility in the preparation of MnBi films. Experiments were therefore devised which should provide information about the nucleation probability in such films. For that purpose a variety of glass discs containing Bi layers above Mn substrate layers were prepared simultaneously, i.e., the Mn-Bi layers on all the discs were deposited in one and the same evaporation run and all the discs containing the layers were subjected simultaneously to the same vacuum heat treating run for the transformation of the double layers into the ferromagnetic MnBi films. Among the variety of discs prepared were three main types. One type of disc contained Mn-Bi double layers uniformly deposited across the entire area of the disc. Another type contained a two-dimensional array of small squares of this Mn-Bi double layer prepared by vacuum evaporation through a grid. The third type of disc also contained such a two-dimensional array of squares, this time evaporated onto an already ferromagnetic MnBi film premagnetized to saturation. In successful heat treating runs all those discs containing uniform Mn-Bi double layers were transformed completely into perfect homogeneous ferromagnetic MnBi films across the entire disc area. However only a few, randomly distributed squares of the two-dimensional array were transformed at the same time into squares of ferromagnetic MnBi film whereas again practically all of the Mn-Bi double layer squares deposited onto the already ferromagnetic MnBi films became ferromagnetic, this time however exhibiting mostly extremely large domains. From this and other experimental evidence one has to conclude that the nucleation behavior is of considerable importance in determining failure or success in the preparation of magnetic MnBi films. Further study aimed at controlling the nucleation behavior in MnBi films is therefore indicated.

---

*Research supported by the Aeronautical Research Laboratory, WCLJL, WADC.

165. MAGNETISM IN MEDICINE TODAY AND TOMORROW

MICHAEL W. FREEMAN, M.D.
Detroit, Michigan

Magnetism has had specific and important medical therapeutic applications; for example, for removal of ferromagnetic foreign bodies from eyes and intestinal tracts, and in the treatment of traumatic gastritis, etc.

In recent years important studies have been undertaken of the biological effects of magnetic fields: the response of proteins to an electromagnetic field; the influence of the magnetic field upon the leucocytes; magnetic techniques for in vitro isolation of leucocytes; and the biological effects of a magnetic field and the radiation syndrome in relation to the reduction of metastasis in cancer.

There will be given a summary of the theories involved in the deployment of the science of magnetism in medicine for biochemical studies and diagnosis, and in the treatment of various diseases.

There will be presented a review of the science of magnetism as applied to medical problems presently under study, and a glimpse will be afforded at the projects outlined for the immediate future.

---

166. USE OF NUCLEAR MAGNETIC RESONANCE TECHNIQUES FOR BLOOD FLOW MEASUREMENTS

J. R. SINGER
University of California
Berkeley 4, California

We have developed a practicable sensitive method of measuring human or animal blood flow velocities using nuclear magnetic resonance techniques. Several means of performing such measurements are available. In one procedure, one may compare the longitudinal relaxation time T_1' of the flowing fluid with T_1 of the static fluid. The difference in these times Δt may then be used to solve the flow equation,

$$\Delta t = T_1\left(1 + \frac{V}{hT_1}\right)^{-1}$$

where V is the volume of fluid enclosed by the r-f field, and h is the volume flow per second.

Another procedure utilizes the saturation factor and its dependence on T_1 to obtain the flow rate.

A third method provides a direct measurement without consideration of T_1 except that it must be longer than the measurement time. This latter scheme provides measurements of a rate such that one may discriminate between the blood flow velocity when the heart is pumping and the rate between heart beats.

AUTHORS INDEX

Fifth Conference

Sheraton Cadillac · Detroit