conference

on magnetism and magnetic materials

A E E I

hotel sheraton-park
washington, d.c.
nov. 18, 19, 20, 21, 1957

The third national conference sponsored by the American Institute of Electrical Engineers in cooperation with the American Physical Society, the American Institute of Mining, Metallurgical and Petroleum Engineers, the Institute of Radio Engineers and the Office of Naval Research.

The Conference is designed to bring together people with interests ranging from basic research in magnetism, to the application of magnetic materials in equipment.

GENERAL PROGRAM

Monday, Nov. 18

8:00 A.M. - 4:30 P.M.	Registration, Foyer
9:30 A.M. - 12:00 Noon	Session I - Opening Remarks by General Chairman and Invited Papers, Sheraton Hall
2:00 P.M. - 5:00 P.M.	Session IIA - Magnetization Reversal and Thin Films, Sheraton Hall
2:00 P.M. - 5:00 P.M.	Session IIB - Small Particles and Permanent Magnets, Continental Room
9:00 A.M. - 5:00 P.M.	Magnetics Exhibit, Caribar Room

Tuesday, Nov. 19

9:00 A.M. - 12:00 Noon	Session IIIA, -- Ferromagnetic Resonance: Line Structures, Sheraton Hall
9:00 A.M. - 12:00 Noon	Session IIIB, - Magnetic Alloys: Mostly Oriented, Continental Room
2:00 P.M. - 5:00 P.M.	Session IVA, - Magnetic Moments and Crystal structures of Oxides, Sheraton Hall
2:00 P.M. - 5:00 P.M.	Session IVB, - Applications and Testing, Continental Room
9:00 A.M. - 5:00 P.M.	Magnetics Exhibit, Caribar Room

Wednesday, Nov. 20

9:00 A.M. - 12:00 Noon	Session V, - Ferromagnetic Resonance: Nonlinear Effects and Garnets, Sheraton Hall
2:00 P.M. - 5:00 P.M.	Session VI, - Anisotropy and Magnetostriction, Sheraton Hall
9:00 A.M. - 5:00 P.M.	Magnetics Exhibit, Caribar Room
7:00 P.M.	Dinner, Burgundy Room

Thursday, Nov. 21

9:00 A.M. - 12:00 Noon	Session VIIA, - Magnetization Processes: Reversals and Losses, Sheraton Hall
9:00 A.M. - 12:00 Noon	Session VIIB, - Magnetic Apparatus and Techniques, Burgundy Room
2:00 P.M. - 4:00 P.M.	Session VIIIA, - Magnetic Moments and Crystal Structures of Metals, Sheraton Hall
2:00 P.M. - 5:00 P.M.	Session VIIIB, - Domain Patterns and Theory, Burgundy Room
9:00 A.M. - 12:00 Noon	Magnetics Exhibit, Caribar Room

Registration

Registration will be at the Sheraton Park Hotel from 8:00 A.M. to 4:30 P.M. on Monday, November 18 and from 8:45 A.M. to 4:30 P.M. on Tuesday, Wednesday, and Thursday. Admission badges will be ready for preregistrants without waiting. You will conserve your time and assist in conference planning by registering in advance.

The registration fee of $6.00 includes admission to the technical sessions and the magnetics exhibit. Make checks payable to the Conference on Magnetism and mail to Dr. J. R. Weertman, Code 6452, Naval Research Laboratory, Washington, D. C.

Technical Sessions

The meeting rooms will be provided with a standard slide projector for 3-1/4'' x 4'' slides, blackboard, and a reading stand. For other facilities, available by special arrangement, write to Dr. A. D. Franklin, Division 9, National Bureau of Standards, Washington 25, D. C. Contributors are requested to furnish completed manuscript to the session chairman at the time the paper is given.

Conference Room

The Madison Room will be available to small groups for informal discussions throughout the entire conference. Inquire at registration desk for special reservation of space in this room. Monday afternoon the ASTM Committee C-21 IIA5 will meet here on the subject of Nonmetallic Magnetic Materials.

Dinner

A dinner of roast capon with mushroom dressing and wild rice will be served in the Burgundy Room of the Sheraton Park Hotel on Wednesday evening. After dinner speakers will be Mr. W. J. Barrett, President of the American Institute of Electrical Engineers who will speak on the Organization of the Engineering Profession, and Mr. Hugh Odishaw, Executive Director of the U. S. National Committee on the International Geophysical Year who will talk about the Current Program of the International Geophysical Year.

Due to space restrictions, attendance is limited to 325 registrants. Tickets will be sold in advance; any tickets remaining will be sold at the registration desk on a first come - first serve basis. To be sure of attending the dinner, purchase tickets in advance.

Conference Proceedings

Through cooperation with the Journal of Applied Physics, it is planned to publish the Conference Proceedings as one of the issues of this magazine to appear in the spring of 1958.

Hotel Reservations

Accommodations are available at the Conference Headquarters, the Sheraton Park Hotel. The Shoreham Hotel is within walking distance of the Sheraton Park.

Entertainment for the Ladies

Arrangements are being made for entertainment for the ladies. Further details will be provided at the registration desk.

TECHNICAL PROGRAM

Monday, November 18, 1957

OPENING REMARKS
J. E. Goldman, Conference Chairman

9:30 A.M. Session I Sheraton Hall

INVITED PAPERS
G. T. Rado, Presiding

1. Some Magnetic Properties of Garnets
   L. Néel, Institut Fourier, Grenoble, France

2. Physical Phenomena Involved in Maser Operation
   C. L. Hogan, Harvard University

3. Masers
   C. H. Townes, Columbia University

4. Time Decrease of Permeability in Iron
   G. W. Rathenau, Natuurkundig Laboratorium, University of Amsterdam, Netherlands

5. Observations on Magnetism Research in Europe
   J. S. Smart, U. S. Office of Naval Research, London

2:00 P.M. Session IIA Sheraton Hall

MAGNETIZATION REVERSAL AND THIN FILMS
C. P. Bean, Presiding

6. Magnetic Anisotropy and Relaxation in Thin Films (Invited Paper)
   D. O. Smith, Lincoln Laboratory, Massachusetts Institute of Technology

7. Magnetization Reversal in Thin Films of Permalloy (Invited Paper)
   C. D. Olson and A. V. Pohm, Remington Rand Univac

8. Rotational Model of Flux Reversal in Square Loop Soft Ferromagnets
   E. M. Gyorgy, Bell Telephone Laboratories, Inc.

9. Transverse Flux Change in Soft Ferromagnets
   F. B. Humphrey, Bell Telephone Laboratories, Inc.

10. The Effects of Heat Treatment of Thin Ferromagnetic Films at Intermediate Temperatures
    E. N. Mitchell, Remington Rand Univac

11. Reversible Rotation in Magnetic Films
    R. M. Sanders and T. D. Rossing, Remington Rand Univac

12. Steady-State and Pulse Measurement Techniques for Thin Ferromagnetic Films in the Frequency Range 0.3 to 5000 mc
    D. O. Smith and G. P. Weiss, Lincoln Laboratory, Massachusetts Institute of Technology

13. Ferromagnetic Resonance in Ultra-Thin Films
M. H. Seavey, Jr., and P. E. Tannenwald, Lincoln Laboratory, Massachusetts Institute of Technology

14. Domain Walls and Patterns in Thin Permalloy Films
E. E. Huber, Jr., D. O. Smith, and J. B. Goodenough, Lincoln Laboratory, Massachusetts Institute of Technology

15. Motion Pictures of Magnetic Writing on Thin Films of MnBi
H. J. Williams and R. C. Sherwood, Bell Telephone Laboratories, Inc.

2:00 P.M. Session IIB Continental Room

SMALL PARTICLES AND PERMANENT MAGNETS
W. F. Brown, Jr., Presiding

16. Electron Microscopical Investigation of the Metallographic Structure of Ticonal-G (Alnico V)
J. J. deJong, J. M. G. Smeets and H. B. Haanstra, Philips Research Laboratories, Eindhoven, Netherlands

17. Relation Between Colloid Pattern and Permanent Magnet Precipitate During the Magnetization Reversal in Alnico V
K. J. Kronenberg and R. K. Tenzer, The Indiana Steel Products Company

18. Phase Analysis of Alnico V Based on Temperature Effects
R. K. Tenzer and K. J. Kronenberg, The Indiana Steel Products Company

19. Physical and Magnetic Properties of Elongated Single-Domain Fine Particle Iron & Iron-Cobalt Permanent Magnets
R. B. Falk, E. J. Yamartino, R. C. Lever, Measurement Laboratory, General Electric Company

20. Effects of Magnetic Fields Upon Anisotropic Iron Crystals
J. H. L. Watson, Edsel B. Ford Institute for Medical Research; A. Arrott, Scientific Lab., Ford Motor Company; M. W. Freeman, M. W. Freeman Company

21. Loss of Exchange Coupling in the Surface Layers of Ferromagnetic Particles
F. E. Luborsky, Instrument Dept., General Electric Company

22. Ferromagnetic Resonance Studies of Some Solid State Transformations
D. S. Rodbell, General Electric Research Laboratory

23. Magnetic Determination of Shape Distribution of Single Domain Powders
C. E. Johnson, Jr., and W. F. Brown, Jr., Minnesota Mining and Manufacturing Company

24. Magnetic Measurements on Some Precipitating Systems
A. E. Berkowitz and P. J. Flanders, The Franklin Institute Laboratories

25. Precipitation and Magnetic Annealing in a Copper-Cobalt Alloy
J. J. Becker, General Electric Research Laboratory

Tuesday, November 19, 1957

9:00 A.M. Session IIIA Sheraton Hall

FERROMAGNETIC RESONANCE: LINE STRUCTURES
J. K. Galt, Presiding

26. Resonant Modes of Ferromagnetic Spheroids (Invited Paper)
L. R. Walker, Bell Telephone Laboratories, Inc.

27. Multiplicities of the Uniform Precessional Mode in Ferrimagnetic Resonance
I. H. Solt, Jr., R. L. White and J. E. Mercereau, Hughes Research Laboratory

28. Ferromagnetic Resonance and Nonlinear Effects in Yttrium Iron Garnet
R. C. LeCraw, E. G. Spencer and C. S. Porter, Diamond Ordnance Fuze Laboratories

29. Low Temperature Spin Wave Resonance at 3000 and 4000 Mc/sec in a Permalloy Having Nearly Zero Magnetrocrystalline Anisotropy
J. R. Weertman and G. T. Rado, Naval Research Laboratory

30. Effect of Electronic Mean Free Path on Spin Wave Resonance in Ferromagnetic Metals
G. T. Rado, Naval Research Laboratory

31. Ferromagnetic Dynamical Response
H. B. Callen, Dept. of Physics. Univ. of Pennsylvania

32. Dipole Narrowing of Inhomogeneously Broadened Ferromagnetic Resonance Lines
A. M. Clogston, Bell Telephone Laboratories, Inc.

33. Origin of Ferromagnetic Resonance Line Broadening in Manganese Rich Manganese Ferrites
S. E. Harrison, RCA Laboratories; H. S. Belson and C. J. Kriessman, Remington Rand Univac

34. Ferromagnetic Resonance in Uniaxial Polycrystalline Materials
C. A. Morrison and N. Karayianis, Diamond Ordnance Fuze Laboratories

35. Ferromagnetic Resonance in Polycrystalline Nickel Ferrite Aluminate
E. Schlömann and J. R. Zeender, Raytheon Manufacturing Company

36. Damping and the Dispersion Relations in Antiferromagnetic Resonance
E. S. Dayhoff, U. S. Naval Ordnance Laboratory

9:00 A.M. Session IIIB Continental Room

MAGNETIC ALLOYS: MOSTLY ORIENTED
J. K. Stanley, Presiding

37. Magnetic Anisotropy Induced by Magnetic Annealing and by Cold Working of Ni_3Fe Crystal (Invited Paper)
Sōshin Chikazumi, Dept. of Physics and Chemistry, Gakushuin University, Mejiro, Tokyo, Japan

38. The Effect of Sample Thickness on the Field Annealing of 6.5% Si-Fe
P. A. Albert, Magnetic Materials Dev. Section, Westinghouse Electric Corporation

39. Recrystallization of MnBi Induced by a Magnetic Field
O. L. Boothby, D. H. Wenny and E. E. Thomas, Bell Telephone Laboratories, Inc.

40. Effects of Composition and Processing Variables on the Magnetic Properties of the Nominal 50% Nickel, 50% Iron Alloy
M. J. Savitski, Mtls. Eng. Dept., Westinghouse Electric Corporation

41. Orientation Study of Ultra-Thin Molybdenum Permalloy Tape
P. K. Koh, Allegheny Ludlum Steel Corporation

42. The Development of Preferred Orientations in Silicon-Iron
J. R. Brown, Metal Physics Section, G.K.N. Group Research Laboratory, Birmingham New Road, Lanesfield, Wolverhampton, England

43. The (110)[001] Secondary Recrystallization Texture in Silicon-Iron
H. C. Fiedler, General Electric Research Lab.

44. Magnetic Properties of Cube Textured Magnetic Sheet
J. L. Walter, W. R. Hibbard, H. C. Fiedler, H. E. Grenoble, R. H. Pry and P. G. Frischmann, General Electric Company

45. Cube Texture in Body Centered Cubic Magnetic Alloys
G. Wiener, P. A. Albert, R. H. Trapp, Westinghouse Electric Corporation, and M. F. Littmann, Armco Steel Corporation

46. Low Magnetic Remanence in the High Aluminum Iron Alloys
D. Pavlovic and K. Foster, Materials Eng. Dept., Westinghouse Electric Corporation.

47. Effects of Elastic Bending on Magnetic Properties of Oriented Silicon-Iron
R. W. Cole, Crucible Steel Company of America

2:00 P.M. Session IVA Sheraton Hall

MAGNETIC MOMENTS AND CRYSTAL STRUCTURES OF OXIDES
L. R. Maxwell, Presiding

48. The Effect of Hydrostatic Pressure and Temperature on the Magnetic Properties of a Nickel-Zinc Ferrite
C. Q. Adams and C. M. Davis, Jr., U. S. Naval Ordnance Laboratory

49. The Preferential Volatilization of Cations From Ferrites During Sintering
J. M. Brownlow, International Business Machines Corporation, Research Center

50. Some Properties of Quenched Magnesium Ferrites
D. J. Epstein and B. Frackiewicz, Laboratory for Insulation Research, Massachusetts Institute of Technology

51. Ionic Valences in Manganese-Iron Spinels
A. H. Eschenfelder, International Business Machines Corporation, Research Center

52. Substitution for Iron in Ferrimagnetic Yttrium-Iron Garnet
M. A. Gilleo and S. Geller, Bell Telephone Laboratories, Inc.

53. Some Ferrimagnetic Properties of the System $Li_xNi_{1-x}O$
J. B. Goodenough, D. G. Wickham, Lincoln Laboratory, Massachusetts Institute of Technology, and W. J. Croft, RCA Laboratories

54. Effect of Thermal History on the Antiferromagnetic Transition in Zinc Ferrite
D. M. Grimes and E. F. Westrum, Jr., University of Michigan

55. Magnetic Germanates Isostructural with Garnet
A. Tauber, U. S. Army Signal Eng. Laboratories; E. Banks, Polytechnic Institute of Brooklyn; and H. Kedesdy, U. S. Army Signal Eng. Laboratories

56. Some Magnetic and Crystallographic Properties of the System $LaMn_{1-x}Ni_xO_3$
A. Wold, R. J. Arnott and J. B. Goodenough, Lincoln Laboratory, Massachusetts Institute of Technology

57. Crystal Growth of Magnetic Garnets
J. W. Nielsen, Bell Telephone Laboratories, Inc.

58. Antiferromagnetic Structures of MnS_2, $MnSe_2$, and $MnTe_2$
L. M. Corliss, N. Elliott and J. M. Hastings, Brookhaven National Laboratory

2:00 P.M. Session IVB Continental Room

APPLICATIONS AND TESTING
A. D. Franklin, Presiding

59. Measurement of Losses of Magnetic Materials at High Inductions, at Frequencies up to 100 Megacycles
I. Bady, U. S. Army Signal Eng. Laboratories

60. Measurements of the Property of Various Ferrites Used in Magnetically Tuned Resonant Circuits in the 2.5 to 45 Mc Region
P. P. Lombardini, R. F. Schwartz and R. J. Doviak, University of Pennsylvania

61. The Behavior of the TE Modes in Ferrite Loaded Rectangular Waveguide in the Region of Ferrimagnetic Resonance
W. J. Crowe, Bell Telephone Laboratories, Inc.

62. Energy Distribution in Partially Ferrite Filled Waveguides
J. E. Tompkins, Diamond Ordnance Fuze Laboratories

63. A Miniaturized Resonant Antenna Using Ferrites
D. M. Grimes, University of Michigan

64. An Appraisal of Permanent Magnet Materials for Magnetic Focusing of Electron Beams
M. S. Glass, Bell Telephone Laboratories, Inc.

65. The Performance of Permanent Magnets at Elevated Temperatures
W. H. Roberts, General Electric Company

66. The Micro-Uniformity of Permanent Magnet Materials
L. I. Mendelsohn, General Electric Company

67. Understanding and Predicting Permanent Magnet Performance by Electrical Analog Methods
R. J. Parker, General Electric Company

68. Method for Measuring Saturation Magnetization in Ring Samples
C. D. Graham, Jr., General Electric Research Lab.

69. Some Aspects of Tempering 3-1/4% Silicon Iron via Time Decay of Permeability
E. S. Anolick and J. Singer, Transformer Laboratories Department, General Electric Company

70. Materials Problems in Magnetic Suspension Apparatus
J. B. Breazeale, Bill Jack Scientific Instrument Co.

Wednesday, November 20, 1957

9:00 A.M. Session V Sheraton Hall

FERROMAGNETIC RESONANCE:
NONLINEAR EFFECTS AND GARNETS
C. L. Hogan, Presiding

71. Origin and Use of Instability in Ferromagnetic Resonance (Invited Paper)
H. Suhl, Bell Telephone Laboratories, Inc.

72. A Solid State Microwave Amplifier and Oscillator Using Ferrite
M. T. Weiss, Bell Telephone Laboratories, Inc.

73. A New Type of Ferromagnetic Microwave Amplifier
C. L. Hogan, Harvard University, and P. H. Vartanian, Microwave Engineering Laboratory

74. Microwave Frequency Conversion Studies in Magnetized Ferrites
E. N. Skomal, Sylvania Electric Products, Inc., Microwave Physics Laboratory

75. Spin-Lattice Relaxation Time in Yttrium Iron Garnet
R. T. Farrar, Diamond Ordnance Fuze Laboratories

76. Ferrimagnetic Resonance in Gadolinium Iron Garnet
B. A. Calhoun, W. V. Smith and J. Overmeyer, International Business Machines Corporation, Research Center

77. Ferromagnetic Resonance in Yttrium Iron Garnet at Low Frequencies
E. G. Spencer, R. C. LeCraw, and C. S. Porter, Diamond Ordnance Fuze Laboratories

78. Microwave Properties of Polycrystalline Rare Earth Garnets
M. H. Sirvetz and J. E. Zneimer, Raytheon Manufacturing Company, Research Division

79. Ferromagnetic Resonance in Single Crystals of Rare Earth Garnet Materials
R. V. Jones, G. P. Rodrigue and W. P. Wolf, Gordon McKay Laboratory, Harvard University

2:00 P.M. Session VI Sheraton Hall

ANISOTROPY AND MAGNETOSTRICTION
R. M. Bozorth, Presiding

80. Temperature Dependence of the Magnetocrystalline Anisotropy Coefficients in Cubic Crystals
E. Callen, National Security Agency; J. L. Jackson, National Bureau of Standards; H. B. Callen, Department of Physics, University of Pennsylvania

81. Temperature Dependence of Ferromagnetic Anisotropy
W. J. Carr, Jr., Westinghouse Electric Corporation

82. Magnetocrystalline Anisotropy of Mg-Fe Ferrites: Temperature Dependence, Ionic Distribution Effects, and the Crystalline Field Model
V. J. Folen and G. T. Rado, Naval Research Laboratory

83. Magnetic Annealing in Cobalt-Iron Ferrite Single Crystals
L. R. Bickford, Jr., J. M. Brownlow and R. F. Penoyer, International Business Machines Corporation, Research Center

84. Magnetization Processes in Heat-Treated Single Crystal Cobalt Ferrite
S. Foner, Lincoln Laboratory, M.I.T., and J. O. Artman, Gordon McKay Laboratory, Harvard University

85. Crystallographic and Magnetic Studies of the System $NiFe_{2-x}Mn_xO_4$
P. K. Baltzer and J. G. White, Radio Corporation of America, David Sarnoff Research Center

86. Origin of Anisotropic Effects in $Co_xFe_{3-x}O_4$
J. C. Slonczewski, International Business Machines Corporation, Research Center

87. Theory of Magnetostriction and g-Factor in Ferrites
Noboru Tsuya, Research Institute of Electrical Communications, Tohoku University, Sendai, Japan

88. The Relationship Between Single Crystal and Effective Polycrystalline Anisotropy Constants in Ferrites
C. J. Kriessman, Remington Rand Univac; S. E. Harrison, RCA Laboratories; and H. S. Belson, Remington Rand Univac

89. Exchange Anisotropy in the Iron-Iron Oxide System
W. H. Meiklejohn, General Electric Research Lab.

90. Magnetostriction and Elastic Properties of Ferromagnetic Substances at High Magnetic Fields
H. Sato, Scientific Laboratory, Ford Motor Company

Thursday, November 21, 1957

9:00 A.M. Session VIIA Sheraton Hall

MAGNETIZATION PROCESSES: REVERSALS AND LOSSES

J. R. Weertman, Presiding

91. Domain Wall Motion in Metals (Invited Paper)
R. W. DeBlois, General Electric Research Lab.

92. Preparation and Properties of Crystal-Oriented Ferroxplana Samples
A. L. Stuijts and H. P. J. Wijn, Philips Research Laboratories, Eindhoven, Netherlands

93. A Rigorous Approach to the Theory of Ferromagnetic Microstructure
W. F. Brown, Jr., Central Research Department, Minnesota Mining and Manuracturing Company

94. The Magnetization Curve of the Infinite Cylinder
A. Aharoni and S. Shtrikman, Department of Electronics, The Weizmann Institute of Science, Rehovot, Israel

95. A Model for Non-Linear Flux Reversals of Square Loop Polycrystalline Magnetic Cores
M. K. Haynes, International Business Machines Corporation, Research Center

96. Temperature Dependence of Microwave Permeabilities for Polycrystalline Ferrite and Garnet Materials
J. Nemarich and J. C. Cacheris, Diamond Ordnance Fuze Laboratories

97. The Effect of Cobalt on the Relaxation Frequency of Nickel-Zinc Ferrite
F. J. Schnettler and F. R. Monforte, Bell Telephone Laboratories, Inc.

98. The Switching Properties of Permalloy Cores of Varying Coercivity
T. D. Rossing and V. J. Korkowski, Remington Rand Univac

99. Rotational Loss Measurements on Some Ferrites
J. M. Kelly, Armour Research Foundation of Illinois Institute of Technology

100. The Temperature Dependence of the Attenuation of Ultrasound in a Nickel Single Crystal from 77° to 650° K
F. West, Texas Instruments, Inc.

101. Magnetic Fluctuations in Molybdenum Permalloy
J. J. Brophy, Armour Research Foundation of Illinois Institute of Technology

9:00 A.M. Session VIIB Burgundy Room

MAGNETIC APPARATUS AND TECHNIQUES

T. R. McGuire, Presiding

102. A New Concept in Large Size Memory Arrays — The Twistor
A. H. Bobeck, Bell Telephone Laboratories, Inc.

103. Analysis and Operation of a Ferrite Plate Switch Driven Memory System Using 2 Holes Per Bit
V. L. Newhouse and M. M. Kaufman, Bizmac Engineering, Radio Corporation of America

104. Recent Advances in the Design of High Field DC Solenoid Magnets
H. H. Kolm, Lincoln Laboratory, Massachusetts Institute of Technology

105. Further Development of the Vibrating Coil Magnetometer
K. Dwight, N. Menyuk and D. Smith, Lincoln Laboratory, Massachusetts Institute of Technology

106. An Improved Torque Magnetometer
W. S. Byrnes, Westinghouse Electric Corporation

107. A Transparent Ferromagnetic Light Modulator Using Yttrium Iron Garnet
C. S. Porter, E. G. Spencer and R. C. LeCraw, Diamond Ordnance Fuze Laboratories

108. Design of Optimum Inductors Using Magnetically Hard Ferrites in Combination with Magnetically Soft Materials
J. T. Ludwig, Minneapolis-Honeywell Regulator Company

109. Pulse Generator Based on High Shock Demagnetization of Ferromagnetic Material
R. W. Kulterman, Sandia Corporation

110. A New Magnetic Core Loss Comparator
R. E. Tompkins and L. H. Stauffer, General Electric Company

111. The Preparation of Alnico VII Castings with Improved Physical Properties
D. H. Wenny and K. M. Olsen, Bell Telephone Laboratories, Inc.

112. Skull-Cap Method for Magnetizing Bowl-Shaped Magnetron Magnets
F. X. MacDonough, Jr., Bomac Laboratories, Inc.

2:00 P.M. Session VIIIA Sheraton Hall

MAGNETIC MOMENTS AND CRYSTAL STRUCTURES OF METALS
J. J. Becker, Presiding

113. Magnetometallurgy Applications and Methods (Invited Paper)
A. Arrott, Scientific Lab., Ford Motor Company

114. Suggestions Concerning the Role of Covalence in Transition Elements and Their Alloys
J. B. Goodenough, Lincoln Laboratory, Massachusetts Institute of Technology

115. Transitions from Ferromagnetism to Antiferromagnetism in Iron Aluminum Alloys
A. Arrott and H. Sato, Scientific Laboratory, Ford Motor Company

116. Some Unusual Magnetic Properties of Ni_3Mn
J. S. Kouvel, C. D. Graham, Jr., and J. J. Becker, General Electric Research Laboratory

117. Magnetic Properties of Dilute Magnetic Alloys and of the Rare Earth Metals
G. W. Pratt, Jr., Lincoln Laboratory, Massachusetts Institute of Technology

118. Further Magnetic and X-Ray Diffraction Studies on Iron-Rich Iron-Aluminum Alloys
A. Taylor and R. M. Jones, Westinghouse Research Laboratory

119. Magnetic Moments and Apparent Molecular Fields in Some Rare Earth Metals and Compounds
W. E. Henry, U. S. Naval Research Laboratory

2:00 P.M. Session VIIIB Burgandy Room

DOMAIN PATTERNS AND THEORY
T. O. Paine, Presiding

120. Magnetic Domain Patterns on Iron Whiskers
R. V. Coleman and R. G. Scott, Research Staff, General Motors Corporation

121. Domain Observations on Iron Whiskers
R. W. DeBlois and C. D. Graham, Jr., General Electric Research Laboratory

122. Magnetic Domain Wall Motion
P. R. Gillette and K. Oshima, Stanford Research Institute

123. A Calculation of the Energy Loss in Magnetic Sheet Materials Using a Domain Model
R. H. Pry and C. P. Bean, General Electric Research Laboratory

124. Growth of MnBi Crystals and Evidence for Subgrains from Domain Patterns
W. C. Ellis, H. J. Williams and R. C. Sherwood, Bell Telephone Laboratories, Inc.

125. Antiferromagnetic Domain Walls and the Magnetization Process in α-Fe_2O_3
I. S. Jacobs and C. P. Bean, General Electric Research Laboratory

126. Optical Properties of Several Ferrimagnetic Garnets
J. F. Dillon, Jr., Bell Telephone Laboratories, Inc.

127. Contribution to the Study of Ferromagnetic Multidomain Particles
H. Amar, The Franklin Institute Laboratories, Solid State Division

128. Constraint Principles in Ferromagnetic Domain Theory
L. Gold, Lincoln Laboratory, Massachusetts Institute of Technology

SESSION I

INVITED PAPERS

G. T. Rado, Presiding

1. SOME MAGNETIC PROPERTIES OF GARNETS

L. Néel
Institut Fourier
Grenoble, France

2. PHYSICAL PHENOMENA INVOLVED IN MASER OPERATION

C. L. Hogan
Harvard University
Cambridge, Massachusetts

Solid state Masers generally achieve amplification by means of the emission of energy through the coherent flipping of electron spins in a magnetic field. The basic paramagnetic theory which is pertinent to this phenomenon is reviewed in this paper. The paper covers the simpler aspects of electron spin, relaxation time, energy levels, spin orbit coupling and radiation mechanisms which make possible Maser action.

3. MASERS

C. H. Townes
Columbia University
New York, New York

Principles involved and characteristics of various types of maser oscillators and amplifiers will be reviewed and discussed. These involve a new type of amplification which utilizes frequencies inherent in atomic or molecular systems, and extracts electromagnetic energy from an unstable ensemble of such systems. As amplifiers, these devices are of interest because they are exceptionally free of noise and capable, at least in principle of giving amplification for wavelengths well below one millimeter. They also emphasize the possible importance of atomic and molecular resonances to electronics at very high frequencies.

One such device is the beam-type maser, which is particularly useful as a stable oscillator and frequency standard. Solid state devices using electron paramagnetic resonances are in general more suitable for amplifiers, since they are easily tunable by variation of a magnetic field, and characteristically have a larger gain bandwidth product. Principles and characteristics of the two-level and three-level electron spin masers, a maser using nuclear paramagnetism and perhaps other types of solid state amplifiers will be described.

Noise properties and sensitivity of these amplifiers will also be discussed. Theory shows that in the limit they should be capable of usefully amplifying one quantum of electromagnetic energy at a microwave frequency. Preliminary experiments indicate that amplifiers with a sensitivity within about one order of magnitude of this limit, or with a noise temperature at least as low as 25°K, can be built.

7. MAGNETIZATION REVERSAL IN THIN FILMS OF PERMALLOY (Invited Paper)
C. D. Olson and A. V. Pohm
Remington Rand Univac
Division of Sperry Rand Corporation
St. Paul, Minnesota

The magnetization reversal processes of Iron-Nickel films (nominally 83% Ni-17% Fe) deposited in the presence of a magnetic field to a thickness of about 1000 A^o to 4000 A^o have been examined by the application of appropriate fields. Experimental results indicate that at least two different magnetization reversal mechanisms are effective. The first, characterized by relatively long remagnetization periods involves domain-wall movement; the second, characterized by relatively short remagnetization periods is consistent with the simple rotation of the magnetization in the plane of the film. The threshold for the rotational process is altered by the application of transverse magnetic field in a manner consistent with a simple energy model.

8. ROTATIONAL MODEL OF FLUX REVERSAL IN SQUARE LOOP SOFT FERROMAGNETS
E. M. Gyorgy
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

The present paper analyzes a rotational model of flux reversal in ferromagnetic materials. A brief review of the experimentally established details of the flux reversal process in square loop ferrites is given. The discrepancies between the experimental results and the predictions of the domain wall motion theory are discussed. The switching coefficient, Sw, is examined in detail.

The rotation model is based on the solution of the modified Landau and Lifshitz Equation, but does not assume that the magnetization rotates uniformly throughout the sample. The model predicts the shape of the output voltage pulse, the relationship between the flux reversal time and the applied field, and the minimum switching coefficient that can be obtained for a given ferrite. The switching coefficients determined experimentally for ferrites, permalloy tape and thin evaporated metal films (with zero transverse field) are within a factor of three of the minimum value of S_W predicted by this model.

9. TRANSVERSE FLUX CHANGE IN SOFT FERROMAGNETS
F. B. Humphrey
Bell Telephone Laboratories, Incorporated
Murray Hill, New Jersey

The mechanism of rapid flux reversal in soft ferromagnets is usually studied by observing, in a pickup loop, the voltage transient caused by the flux changing in the direction of the applied field. In an effort to further the understanding of flux reversal, the flux change in the direction perpendicular to the applied field (transverse direction) has been studied. Particular attention is paid to thin (~2000Å) evaporated nickel iron films. The transverse flux change is considered in detail and compared to the corresponding flux change in permalloy tape and ferrite cores. Although it is found that no existing simple theory adequately describes all the details of the transverse flux change, the observations are consistent with a nonuniform rotation model. A comparison of the reversal time vs. drive plots in the parallel direction is included showing the effect of a d.c. transverse field on the parallel direction reversal time.

10. THE EFFECTS OF HEAT TREATMENT OF THIN FERROMAGNETIC FILMS AT INTERMEDIATE TEMPERATURE
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St. Paul, Minnesota

Iron-nickel films deposited in vacuo in the presence of a magnetic field have been annealed in an inert environment. It has been established that, when the annealing is performed in orienting field of 30 oersteds, the initial magnetic properties of these films can be altered provided that the initial temperature is high enough. If a field is applied at right angles to the original preferred direction and in the plane of the film, the magnitude of the magnetic anisotropy can be reduced without changing the preferred direction and the preferred direction of magnetization can be changed if the anneal temperature is sufficiently high.

11. REVERSIBLE ROTATION IN MAGNETIC FILMS
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The magnetization of permalloy films of 0.1μ to 0.3μ thickness vacuum-deposited in a magnetic field is reversibly rotated by a pulsed external field applied at right angles to the direction of easy magnetization. The total angle of rotation is deduced from the amplitude of the detected signal or from the strength of the applied field. Reversible rotations of 60° or more are repeated for at least 108 cycles in some films. An excessive drive field results in a loss of remanent magnetization after a few rotations. High wall-motion coercivity is a necessary but not sufficient condition for large rotation angles. Films giving large rotation tend to have open hysteresis loops in the difficult direction.

12. STEADY-STATE AND PULSE MEASUREMENT TECHNIQUES FOR THIN FERROMAGNETIC FILMS IN THE FREQUENCY RANGE 0.3 to 5000 mc.1/

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A special rf bridge has been developed to study ferromagnetic resonance and pulse switching in thin magnetic films (~1000 Å). Steady state response can be studied from essentially dc to 5000 mc; the Fourier components of the pulse response extends over the approximate range from 0.3 to 300 mc. Such wide-band performance is achieved by coaxial transmission-line techniques. The signal output from the bridge is balanced to ground: steady-state conversion to unbalanced detection equipment is achieved by use of a commercially available balun; pulse measurements employ the balanced deflection plates of a wide-band travelling-wave oscilloscope. A fast-rise-time (~0.2 mus) pulse field is generated by discharging a coaxial line through a mercury relay. Calibration of the magnitude of this field is accomplished in a completely unambiguous way by using some of the unique switching properties of thin magnetic films.

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

13. FERROMAGNETIC RESONANCE IN ULTRA-THIN FILMS1/

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One may consider a ferromagnetic film to be "ultra-thin" when its thickness is less than 200 Å. Interest in such films arises mainly because a study of their ferromagnetic properties gives information on the decay of spontaneous magnetization in media extremely thin in one dimension. It has been possible to observe microwave resonance absorption in 80% Ni - 20% Fe films down to approximately 15 Å thickness. Such ultra-thin films are partially optically transparent and give the appearance of a light haze on the glass substrate. The most remarkable feature of the measurements is that — contrary to most existing theories and previous measurements in Ni films — the room temperature magnetization retains its bulk value in film thicknesses down to approximately 200 Å and is still 50% of the bulk value at 15 Å. The room temperature g-value remains constant at 2.07 in all films. At $4^{\circ}K$, a 30 Å film showed anomalous behavior which appeared as a large g-factor, a small uni-directional anisotropy, and a room temperature bulk $4\pi M$ value. The line widths remain relatively narrow with decreasing film thickness, and line shape asymmetries can be accounted for in part by the nature of the film layer.

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

14. DOMAIN WALLS AND PATTERNS IN THIN PERMALLOY FILMS1/

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The domain structure of permalloy films in the thickness range 25 to 2000 Å has been studied by the Bitter technique. Films annealed in a uniaxial magnetic field exhibit uniaxial anisotropy which is reflected in the oriented nature of the magnetic domains and walls. Films annealed in a rotating magnetic field have no well-defined magnetic axis, and there is a corresponding lack of coherence in the domain structure.

Demagnetization of a film with an a.c. field usually results in domain walls forming at an angle between the easy axis and the direction of the applied field. The wall structure is unusual in that short, right-angle "cross-ties" are observed at regular intervals along the main wall. Unlike previously observed walls, these cross-ties terminate in free, single ends. Cross-tie period and length are dependent on film thickness, each becoming shorter with decreasing thickness. In films of smaller thickness than 50 Å, a new type of pattern is observed: multiple walls appear which twist and swirl with no apparent preferred direction. The behavior of these patterns and of the patterns which appear about film imperfections when subject to a d.c. field and/or to tensile stress are illustrated.

In a thin film, a conventional domain wall would have a large magnetostatic energy contribution coming from the large demagnetization factor normal to the film. Detailed interpretations of the domain patterns consider modifications of the wall structure which will decrease the magnetostatic contribution to the domain-wall energy. The appearance of cross-ties is interpreted in terms of a domain-wall structure which is intermediate between a thick-film, conventional wall within which the atomic magnetic moments rotate through a direction perpendicular to the plane of the film, and a thin-film wall within which the atomic moments remain in the plane of the film. The various observed patterns are correlated with the gradual transition from one type of wall structure to the other with changing film thickness.

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

15. MOTION PICTURES OF MAGNETIC WRITING ON THIN FILMS OF MnBi

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It has been found possible to write magnetically with a fine magnetic probe on thin films (~1000A) of MnBi. The films were prepared by the vapor deposition in a vacuum of a layer of Mn and then a layer of Bi on a glass substrate after which the films were heated to form the compound. The probes were either a fine permanent magnet of Vicalloy wire or a Supermendur wire with a magnetizing winding using ac or dc. The tips of the probes were electropolished to taper them to fine points. The films could be magnetized normal to the plane of the film so they were essentially single domains or demagnetized in which case the domains ranged in size from approximately 3000A to 6000A. When suspended by a fine nylon fiber in a strong magnetic field the films orient themselves perpendicular to the field. This indicates a preferred crystal orientation with the c axis of the hexagonal crystallites normal to the plane of the film. This preferred crystal orientation was substantiated by x-ray measurements which showed a spread of about 15° from the normal position. A field of approximately 3000 oersteds was required to magnetize a film normal to its plane. Magnetic traces approximately 0.01 mm in width were formed. It is estimated that a million bits of information could be written on a square centimeter of film. The domains and magnetic writing were observed with either normal transmitted or reflected light utilizing either the Faraday effect or the Kerr magneto-optic effect respectively.

SMALL PARTICLES AND PERMANENT MAGNETS

W. F. Brown, Jr., Presiding

16. ELECTRON MICROSCOPICAL INVESTIGATION OF THE METALLOGRAPHIC STRUCTURE OF TICONAL-G (ALNICO V)

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A series of electronmicrographs of Ticonal-G (Alnico 5) in the optimal magnetic condition are presented. The metallographic structure is shown on (100) planes either parallel or perpendicular to the external magnetic field in which the specimen has been cooled. This structure, which has been extensively verified, is characterized by primary elements which are 200-400 Å wide and 1500-2000 Å long. As the greatest dimension of these elements is parallel to the forementioned magnetic field there appears to be a marked preferred orientation. Because of a certain degree of intergrowth of the primary elements this orientation is not quite sharp however.

The results mentioned are not new in so far as they confirm earlier statements by other workers but our micrographs show a much enhanced resolution which makes a study of the response of the structure to different heat treatments with or without a magnetic field much more promising. The first results of such a study are presented.

17. RELATION BETWEEN COLLOID PATTERN AND PERMANENT MAGNET PRECIPITATE DURING THE MAGNETIZATION REVERSAL IN ALNICO V

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Improved electron microscope observation technique has confirmed some of the basic assumptions on the structure of Alnico V and has added knowledge on details. The permanent magnet precipitate was investigated at various states of its growth starting from nucleation. Pictures with details smaller than 20 Å reveal the completely developed structure of Alnico V which differs somewhat from former descriptions. It can be clearly recognized that the precipitated particles have grown together to a continuous anisotropic network subdividing the matrix.

Colloid patterns on these surfaces have been observed with electron microscope. During the reversal of magnetization, an anisotropic structure in the colloid covered areas of the pattern can be distinguished. The colloid particles line up preferring one of the two faces of the precipitated structure. This is most pronounced in the steep part of the demagnetization curve. It can be observed, however, as soon as the colloid starts to form patterns.

All electron micrographs presented are examples of many more similar ones selected in order to give the typical appearance of each case. The necessary surveying of magnet surfaces was possible by preparing very thin oxide replicas with a simple technique. Eliminating the formerly used floating method, replicas were stripped from the surface preserving the orientation without destroying the surface of the magnet.

18. PHASE ANALYSIS OF ALNICO V BASED ON TEMPERATURE EFFECTS

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The temperature coefficient of the remanence in Alnico V magnets is known to be different for various operating points. This behavior is ascribed to the presence of two phases whose composition is still unknown.

A magnetic analysis of the composition of these two phases is tried. Structure-independent properties, like saturation magnetization and temperature coefficient, serve to indicate the correctness of alloys supposed to represent these phases.

A model of the two-phase structure of Alnico V is derived from electron micrographs. The combined saturation magnetization and the combined temperature coefficient are calculated with this model using the measured properties of the single alloys.

The equations for these calculations are based on Maxwell's theory. Since internal demagnetization is considered they may be helpful also in other applications of fine-particle theory.

19. PHYSICAL AND MAGNETIC PROPERTIES OF ELONGATED SINGLE-DOMAIN FINE PARTICLE IRON & IRON-COBALT PERMANENT MAGNETS

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The physical and magnetic properties of permanent magnets compacted from elongated single domain particles with metal and organic matrices are described. Several unique properties permit design and application possibilities not previously attainable. Unique magnetic properties are: demagnetization curve flexibility; high energy to weight ratio; uniformity of pole face flux; and low temperature coefficient of remanence. Other properties include precise dimensional tolerances, machinability, solderability, low critical material content and short radioactive half life. Compacts have been prepared from iron and iron-cobalt particles with respective energies of 3.5×10^6 and 5.1×10^6 gauss oersteds. A magnetic change of less than 1% was exhibited by compacts exposed to 100°C for over one year.

20. EFFECTS OF MAGNETIC FIELDS UPON ANISOTROPIC IRON CRYSTALS

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Electron microscopic observations of the effects which magnetic fields have upon ultramicroscopic, single, crystalline particles of alpha iron[1/,2/] are reported. Magnetic fields as high as 25,000 gauss are used. The particles were studied first by subjecting them to magnetic influence while they were mounted upon a usual supporting film. They were also examined after being carbon replicated while under the influence of a magnetic field. A third method[3/] which involved the ultrathin sectioning of a block of plastic in which the particles were oriented proved to be the most informative procedure. It offers an opportunity to study by direct observation the arrangement and distribution of elongated, fine particles in a liquid medium either freely suspended, influenced by a force field, or packed and oriented. The particles are suspended at low concentration in a liquid monomer. The field is applied and the monomer allowed to polymerize about the particles in order to maintain their arrangement after the field has been removed. The block of solid plastic thus obtained is ultrathin sectioned at known angles relative to the field for microscopic examination.

Recent applications of the alignment-sectioning technique to a range of types of alpha iron crystals and magnetic field strengths, will be reported together with their significance for fine particle magnetics.

1/. John H. L. Watson and M. W. Freeman, Proc. Conf. Magnetism and Magnetic Materials, Am. Inst. Elec. Engrs., Magnetics Subcommittee, 33 West 39th St., New York 18, T-78, 150 (1955).

2/. M. W. Freeman and John H. L. Watson, Proc. Conf. on Magnetism and Magnetic Materials, Am. Inst. Elec. Engrs., Magnetics Subcommittee, 33 West 39th St., New York 18, T-91 (1956).

3/. John H. L. Watson, Journal of Applied Physics, 28, 7, 821 (1957).

21. LOSS OF EXCHANGE COUPLING IN THE SURFACE LAYERS OF FERROMAGNETIC PARTICLES

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Experiments with spherical iron particles 28 Å to 265 Å in diameter demonstrate that the proposed non-ferromagnetic surface layer on an iron particle must be less than 1 Å thick. This conclusion is based upon a comparison of the ferromagnetic iron indicated by magnetic saturation, and the total amount of iron as determined by chemical analysis.

For particles greater than about 100 Å in diameter a 1/H extrapolation was used to obtain the saturation induction. However, for particles in the superparamagnetic size range, i.e., less than 100 Å, the 1/H extrapolation gave values which were low. The high field approximation of the Langevin function had to be used, instead, taking into account the distribution of particle sizes present.

22. FERROMAGNETIC RESONANCE STUDIES OF SOME SOLID STATE TRANSFORMATIONS

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The dependence of the ferromagnetic resonance upon specimen anisotropies (shape and magnetocrystalline) is well known[1/]. Observations of the ferromagnetic resonance absorption of submicroscopic particles may be interpreted to yield useful information about these anisotropies. In particular the alloy 2% Co-Cu may be heat treated to precipitate cobalt containing about ten percent copper from the non-magnetic solid solution. In the early stages of precipitation the precipitate particles are shown to be essentially spherical. The copper matrix stabilizes the face-centered cubic structure of the cobalt even to liquid nitrogen temperature. By employing a single crystal of this alloy, the determination of the magneto-crystalline anisotropy of this cubic cobalt precipitate has been made using ferromagnetic resonance techniques. Further growth of precipitate particles (by subsequent heat treatment) is accompanied by aspherical shape changes which modify the resonance spectra.

An example of extreme shape anisotropy is to be found in the ferromagnetic martensite platelets formed by cold working an austenitic (non-ferromagnetic) stainless steel. Experimental observations and their interpretation are presented.

1/. C. Kittel, Phys. Rev. 73, 155 (1948).

23. MAGNETIC DETERMINATION OF SHAPE DISTRIBUTION OF SINGLE DOMAIN POWDERS

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By demagnetizing a magnetic powder specimen with diminishing alternating fields of various initial amplitudes and by interpreting the results with the Stoner-Wohlfarth model, one can obtain information about the shape distribution of the particles. We have done this with powders of acicular γ-ferric oxide at various temperatures; the temperature variation of the results gives information about the size distribution. The sample is first magnetized to saturation; the diminishing ac field is then applied and the remanance measured.

Since the particles are not aligned along the applied field, it is necessary to get the equivalent magnetization curve for an aligned sample by operating on the data mathematically. The results indicate that only a small volume fraction of the γ-ferric oxide particles are small enough to be para-magnetic. There is a relatively large volume fraction of particles with nearly zero critical field. We believe this is caused by particles which change their magnetization by a mechanism different from the Stoner-Wohlfarth uniform rotation.

On a volume basis, the shape distribution curves peak at a length-to-diameter ratio of about 1.6:1, which gives a coercive force of 300 oersteds. The coercive force agrees very well with measured values. The length-to-diameter ratio does not agree with electron microscopic observations, which give a mean of about 5:1.

24. MAGNETIC MEASUREMENTS ON SOME PRECIPITATING SYSTEMS[1/]

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Single crystals of the precipitating systems Au-Ni, β brass-Fe, and Cu-Co were studied in an effort to interpret their magnetic behavior in terms of the structural and magnetic properties of the precipitate particles. In these systems the precipitate is a nearly pure ferromagnetic element, and the matrix is non-magnetic. After successive anneals to develop the precipitate, the samples were examined magnetically and with the electron and optical microscopes. The magnetic measurements included saturation magnetization, torque curves, rotational hysteresis, and remanence. Shadowed silicon monoxide replicas were prepared for the electron microscope.

The magnetic data were analyzed, when appropriate, in terms of the following properties of the precipitate particle systems: degree of precipitation, percent precipitate in the single domain size range, size and shape distributions, coherence, orientation, and dominant magnetic anisotropy. The temperature dependence, symmetry and amplitudes of the torque curves were useful in determining the orientation and dominant magnetic anisotropy of the precipitate particles. The field dependence of the rotational hysteresis, W_r, defined the region in which the precipitate particles exhibited significant irreversible changes of magnetization; thus the distribution of anisotropies among the particles could be derived by using suitable models to synthesize the rotational hysteresis curves. The integral $\int_0^\infty \frac{W_r}{I_0}\, d\left(\frac{1}{H}\right)$ was employed to determine the degree of non-uniform rotation of magnetization exhibited by the precipitate particles. The low temperature measurements reflected the superposition of shape and magnetocrystalline anisotropy in the Au-Ni system. The electron micrographs showed reasonable agreement with the distributions determined from the rotational hysteresis data.

1/. This work was supported by the U. S. Air Force through the Air Force Office of Scientific Research.

25. PRECIPITATION AND MAGNETIC ANNEALING IN A COPPER-COBALT ALLOY

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In an alloy containing 2% cobalt, balance copper, it is possible to quench a non-magnetic solid solution from 1000° C and then produce a ferromagnetic precipitate in a non-magnetic matrix by aging at several hundred degrees. The magnetic properties of this precipitate can be correlated with the size and shape of the precipitate particles. Considerable information about the precipitation process can be obtained in this way. In these experiments, saturation magnetization, torque, rotational hysteresis, remanence, coercive force for zero magnetization, and coercive force for zero remanence (which behaves in a surprising fashion) have been observed during the course of aging. In particular, the effect of a field during aging in producing magnetic anisotropy ("magnetic annealing") has been studied and is shown to occur entirely during the growth of the particles, after the precipitation is complete.

The precipitation process is viewed as one in which the particles as they grow are first superparamagnetic, then stable single domains, and finally multi-domain. This point of view is consistent with all of the varied phenomena observed.

FERROMAGNETIC RESONANCE: LINE STRUCTURES

J. K. Galt, Presiding

26. RESONANT MODES OF FERROMAGNETIC SPHEROIDS (Invited Paper)

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A typical ferromagnetic resonance experiment measures the absorption of r.f. power in a saturated magnetic ellipsoid as a function of frequency or applied d.c. magnetic field. Thus, it studies the forced oscillations of a system of spins, each of which interacts with an external magnetic field and, perhaps, with an anisotropy field, and is coupled to the other spins by exchange (and pseudo-dipolar) forces and magnetic dipole forces. If losses are ignored such a system has a spectrum of modes of free, small-amplitude oscillations. The characteristic features of this spectrum are determined by the size and shape of the sample and the contrasting effects of the strong, short-range exchange fields and the relatively weak, long range magnetic dipole forces.

When the periodicity of the disturbance is sufficiently short for exchange to be important, it is usually small compared to the sample size. Boundary conditions may then be ignored and the disturbances treated as plane waves. For these, the spin waves, a dispersion relation may be found which is size-independent, but shape-dependent because of the effect of demagnetizing forces. Such spin waves account for most of the spectrum unless the sample is very small ($<10^{-5}$ cm).

If the periodicity of the disturbance is sufficiently long, exchange becomes insignificant and the modes are purely electromagnetic. If, in addition, the size of the ellipsoid is small compared to the wavelength of electromagnetic waves in the medium, propagation may also be ignored and the spectrum will contain purely magnetostatic modes. These modes are just the free oscillations of an array of magnetic dipoles, in free space. Their frequencies will depend upon the shape of this array, but not upon its size. The typical mode of this kind is that of uniform precession, usually observed in ferromagnetic resonance, for whose frequency the classical Kittel formula holds. It is possible to discuss the spectrum of these modes quite thoroughly and to determine its dependence upon field, frequency, magnetization and shape. The nature of the spectrum may be expected to influence the line width of the mode of uniform precession because of the existence of frequency degeneracies.

By the use of inhomogeneous exciting fields, Solt and White and Dillon have exicted many of these magnetostatic modes. The substantial independence of size which is predicted is observed to hold. Several series of lines observed by Dillon may be accounted for in terms of the symmetry of the exciting fields and their frequencies estimated with good accuracy. The variation of the spectrum with sample shape may be explained and also the dependence upon magnetization. The relative intensities of the observed absorptions are less clearly understood.

27. MULTIPLICITIES OF THE UNIFORM PRECESSIONAL MODE IN FERRIMAGNETIC RESONANCE

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In order to interpret correctly the experimental results obtained from ferrimagnetic resonance experiments, it is necessary to understand completely the multiplicity of lines that can be observed. Most of these lines have been shown1/ to be higher order precessional modes which are quite well understood. There still exists, however, some uncertainty connected with the uniform precessional mode. The uniform mode is of most importance since it is for this mode that values of line widths, g-values, and anisotropy constants are usually quoted in the literature. It can be distinguished experimentally from the higher order modes since (a) its intensity of absorption is proportional to the uniform component of the rf magnetic field over the sample, and (b) its intensity decreases much less rapidly with diminishing sphere size than for the higher order modes. We have observed, however, that there are several lines possessing these characteristics of the uniform mode. The relative intensities of these lines are strong functions of both temperature and frequency, they have different anisotropy constants, and their separation decreases with sphere radius. Data exhibiting these properties will be presented for experiments on spherical single crystals of Mn-Zn ferrites performed in the microwave frequency range of 8000 - 12000 mcps. A discussion of several possible mechanisms that might give rise to these phenomena will be given.

1/. R. L. White and I. H. Solt, Jr., Phys. Rev. 104, 56 (1956), J. E. Mercereau and R. P. Feynman, Phys. Rev. 104, 63 (1956), L. R. Walker, Phys. Rev. 105, 390 (1957).

28. FERROMAGNETIC RESONANCE AND NONLINEAR EFFECTS IN YTTRIUM IRON GARNET

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A study of ferromagnetic resonance line widths in single crystals of yttrium iron garnet has been made at 9300 mc using cavity perturbation techniques. The samples are polished spheres 9 to 11 mils in diameter. They are placed in a tunable TE_{106} rectangular transmission cavity at a point of maximum rf field away from all walls. A point by point "galvanometer" method rather than a "swept" technique is used for all measurements.

The line width in the linear region on this particular batch of single crystals (grown by C.S.P. using a flux method) has been found to be unusually low, being 3.0 oersteds with the dc field along the hard axis [100]. Along the medium and easy axes the line width is slightly higher. The anisotropy in the line width is in agreement with the observations of Dillon1/. It is believed this is the narrowest resonance line yet observed on spheres of ferromagnetic material at room temperature.

In view of the line width of these crystals, it is of particular interest to examine their nonlinear behavior. As the amplitude of the rf field is increased the height of the resonance line, which is proportional to μ'', is first observed to decrease at an h_{crit} of 60 millioersteds. (A pulse technique was used here to avoid any heating of the small sample). This is lower by a factor of six than the h_{crit} predicted by the spin wave treatment of Suhl2/ if the measured linear region line width of 3.0 oersteds is used for ΔH and ΔH_k, ΔH_k being the "line width" of the spin wave which first goes unstable. Since in Suhl's result h_{crit} varies as the three-halves power of ΔH, a possible explanation of the discrepancy is that the intrinsic line width of the crystal, assuming perfect polishing and no large-scale nonuniformities, is less than one oersted.

The theoretical implications of such narrow resonance lines occurring in ferromagnetic spheres are discussed in connection with recent treatments of line width mechanisms in ferromagnetic insulators.

1/. J. F. Dillon, Jr., Phys. Rev., 105, 759 (1957).
2/. H. Suhl, J. Phys. Chem. Solids, 1, No. 4, 209 (1957).
In this reference the rf field is assumed to be circularly polarized rather than linearly polarized, involving an extra factor of two in h_{crit}.

29. LOW TEMPERATURE SPIN WAVE RESONANCE AT 3000 AND 4000 Mc/sec IN A PERMALLOY HAVING NEARLY ZERO MAGNETROCRYSTALLINE ANISOTROPY

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The observation of spin wave resonance1/ (i.e., of ferromagnetic resonance exhibiting exchange effects) in specially prepared permalloy samples of extremely low anisotropy2/ has been extended to liquid nitrogen temperature. Measurements at both room and liquid nitrogen temperature have been carried out at 4000 Mc/sec as well as at 3000 Mc/sec. The low temperature apparatus was carefully designed to avoid thermal stresses on the sample and to insure a uniform and constant temperature. The data obtained were reproducible over a number of samples, including a single crystal. After the introduction of a refinement in the electropolishing technique the results were unchanged by repeated polishings. At room temperature the complete experimental resonance curve can be explained at both frequencies on the basis of the spin wave resonance theory of Ament and Rado3/ by using an exchange stiffness constant, A, of $3.3 \pm 0.5 \times 10^{-6}$ erg/cm. The agreement between experiment and theory would be destroyed if a Landau-Lifshitz or Bloch damping term were included. The use of longer rods, with the consequently smaller demagnetizing corrections, has led to a more accurate value for the g-factor than reported in the original experiment[1]. A value for g of $2.06 \pm .01$ is thus obtained. The theory[3] predicts that as the temperature is lowered the exchange broadening of the resonance line increases and the resonance field decreases. Both effects have been observed qualitatively but neither is as large as would be expected from the theory. The possibility that effects due to the electronic mean free path play a role in the low temperature experiment will be discussed by Rado in another paper at this Conference. With regard to the frequency dependence, it has been found that at a given temperature the plot of the imaginary versus real part of the equivalent permeability at 3000 Mc/sec differs only by a scale factor from the corresponding plot at 4000 Mc/sec. At room temperature, this frequency increase causes a scale factor increase of 30 percent as compared to a predicted 15 percent.

1/. G. T. Rado and J. R. Weertman, Phys. Rev. 94, 1386 (1954).

2/. Torque measurements were made by V. J. Folen (unpublished) on permalloy single crystals having the same composition as the samples used in the resonance experiments. Both sets of samples had been given the same heat treatment. The results are $|K_1| < 0.6 \times 10^3$ ergs/cm^3 at 300°K and $|K_1| < 1 \times 10^3$ ergs/cm^3 at 77°K.

3/. W. S. Ament and G. T. Rado, Phys. Rev. 97, 1558 (1955)

30. EFFECT OF ELECTRONIC MEAN FREE PATH ON SPIN WAVE RESONANCE IN FERROMAGNETIC METALS

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The magnetic properties of a metal at microwave frequencies cannot be deduced from the directly measurable surface impedance unless the functional relation between the current density $(\vec{J})$ and the electric field $(\vec{E})$ is known. In all previous work on ferromagnetic resonance in metals the implicit assumption was made that $(\vec{J})$ and $(\vec{E})$ are related by Ohm's law. However, numerous experiments on the anomalous skin effect[1] at very low temperatures have shown that at least in nonferromagnetic metals this assumption is not always justified. In the present paper it is suggested that under certain conditions the interpretation of ferromagnetic resonance phenomena in metals should not make use of Ohm's law because the electronic mean free path may not be negligible in comparison to an appropriately defined effective skin depth. Such conditions can exist even at moderately low temperatures provided the equivalent permeability[2],[3] is sufficiently large.

The role of the mean free path should be particularly important in spin wave resonance[2],[3], i.e., in a ferromagnetic resonance in which the smallness of the skin depth (in conjunction with a small effective field) produces experimentally observable[2] effects due to exchange interactions. Accordingly, the spin wave equation (i.e., the Landau-Lifshitz equation including the exchange term) is combined in this paper with Maxwell's equations and with the Reuter-Sondheimer[4] relation between $\vec{J}$ and $\vec{E}$, thus obtaining the basic integro-differential equation describing mean free path effects in spin wave resonance. A first-order calculation is then made of the surface impedance and of the equivalent permeability derived therefrom. The approximations of Appendix A of reference 3 are used, and it is assumed that the classical skin depth for permeability unity (δ) and the electronic mean free path (ℓ) satisfy the relation $\ell \ll \delta / |2\mu_e|^{1/2}$. In this approximation the result is found to be

$$\mu_{em} = \mu_e \left[1 + s(3\ell/8\delta)(2i\mu_e)^{1/2} \right] \quad (1)$$

where μ_e ($= \mu_1 - i\mu_2$) and μ_{em} are the equivalent permeabilities calculated on the basis of Ohm's law and the mean free path effect, respectively. The factor s is unity or zero depending on whether the conduction electrons at the surface of the metal are assumed to be scattered diffusely or specularly, and the sign of the square root is to be taken as positive or negative depending on whether $\mu_1 \geq 0$ or $\mu_1 < 0$ obtains.

The spin wave resonance experiment[2] has recently been extended by Weertman and Rado to liquid nitrogen temperature and will be discussed by them at this Conference. A preliminary interpretation of their results has been attempted by choosing s to be unity and calculating the temperature-dependent ℓ on the basis of the static conductivity and a reasonable number of free electrons per atom. It is found in this way that the use of Equation (1) accounts for a part of the discrepancy between the experimental and the theoretical[3] resonance lines at 77°K, and that it essentially preserves the existing agreement between these resonance lines at 300°K.

1/. A. B. Pippard, Advances in Electronics and Electron Physics (Academic Press, Inc., New York, 1954), Vol. VI, p. 1.

2/. G. T. Rado and J. R. Weertman, Phys. Rev. 94, 1386 (1954).

3/. W. S. Ament and G. T. Rado, Phys. Rev. 97, 1558 (1955)

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31. FERROMAGNETIC DYNAMICAL RESPONSE[1]

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A ferromagnetic dynamical equation seeks to describe the response of the magnetization, within a single domain, to an applied field. The most widely used equation at present is Gilbert's modification of the Landau-Lifshitz equation, which is based solely on the heuristic picture that the dissipative mechanisms introduce an effective field opposite in direction and proportional in magnitude to the rate of change of $\vec{M}$. It is possible, however, to relate the macroscopic dynamical equation directly to the spin-wave representation of the dissipative processes at the atomistic level. We accordingly derive a macroscopic dynamical equation containing three parameters: $\lambda_{o\sigma}$, λ_{ok} and $\lambda_{k\sigma}$. The parameter $\lambda_{o\sigma}$ is related to the probability of destruction of an infinite-wave-length magnon with the creation of phonons; λ_{ok} describes the probability of destruction of an infinite-wave-length magnon with the creation of another magnon; $\lambda_{k\sigma}$ describes the probability of destruction of such other magnons. These parameters are themselves functions of the applied field, of the state of the system, and of the intrinsic properties of the material. A simplified theory of the shape, size and field dependence of λ_{ok} is given. This contribution to the loss vanishes for very flat ellipsoids magnetized along the short axis. It also vanishes for flat ellipsoids of small size, magnetized along a long axis. The field dependence is obtained explicitly, but is rather complicated. The size effect predicted seems to be in general agreement with the size effect observed by H. Belson[2/] in thin permalloy films. And the work of Clogston, Suhl, Walker and Anderson[3/] suggests that λ_{ok} may indeed be the dominant loss mechanism in disordered alloys. More qualitative theories of $\lambda_{o\sigma}$ and $\lambda_{k\sigma}$ are given also. The resulting dynamical equation is valid only in the linear spin-wave or small-deviation region. The large-deviation response is complicated by non-linearities such as that treated by Suhl[4/].

1/. Supported by ONR.
2/. H. Belson, Unpublished reports (Remington Rand Univac, Div. of Sperry Rand Corp.).
3/. Clogston, Suhl, Walker and Anderson, Phys. and Chem. of Solids, 1, 129 (1956).
4/. H. Suhl, Phys. and Chem. of Solids 1, 209 (1957).

32. DIPOLE NARROWING OF INHOMOGENEOUSLY BROADENED FERROMAGNETIC RESONANCE LINES

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In a ferromagnetic body any inhomogeneity in the fields acting upon individual spins will broaden the resonance line. If the inhomogeneity has a mean square value H_p^2 and a characteristic length comparable to the distance a between spins, the line will be narrowed by the exchange field H_e to a width of order $\frac{H_p^2}{M}\left(\frac{M}{H_e}\right)^{3/2}$. If, instead, the characteristic length is greater than a $\sqrt{\frac{H_e}{4\pi M}}$ but is still short compared to the sample dimensions, exchange narrowing will no longer be important, but the line will still be narrowed by dipole fields to a width of order $\frac{H_p^2}{M}$. The expected width in this case will be strongly shape dependent, a narrower line being expected in most cases for a very flat oblate spheroid.

If the inhomogeneity has a characteristic length comparable to the size of the specimen, the theory is no longer simple but can be discussed in qualitative terms.

Applications of the theory of dipole narrowing can be made to help explain observed line widths in polycrystalline and single crystal specimens of magnetic ferrites and garnets.

33. ORIGIN OF FERROMAGNETIC RESONANCE LINE BROADENING IN MANGANESE RICH MANGANESE FERRITES

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The ferromagnetic resonance line broadening of dense polycrystalline manganese ferrites has been found to be proportional to the magnetic saturation, M_s, rather than the magnetocrystalline anisotropy field. We have measured the resonance line widths in polycrystalline and single crystal specimens, the magnetic moment and the anisotropy field (K_1/M_s), as a function of temperature. Between room temperature and the Curie point the excess resonance line width, which is given by $\Delta H(\text{excess}) = \Delta H(\text{polycrystal}) - \Delta H(\text{single crystal})$, is found to have the same temperature dependence as the saturation magnetization. This result is obtained even though the polycrystalline density (>98%) is sufficiently high to be in the region where the excess line width has usually been attributed to anisotropy broadening[2/]. The polycrystalline halfwidths at room temperature are approximately 150 oersteds. The compositions measured were $Mn_{1.34}Fe_{1.76}O_4$ and $Mn_{1.5}Fe_{1.5}O_4$. The polycrystalline g factor is greater than the single crystal g factor and both g factors are functions of the temperature. Discussion of the effects of polycrystallinity on ΔH and g will be given. The anisotropy constant, K_1, has been found to vary approximately as M_s to the fifth power for these ferrites.

1/. Now at RCA Laboratories, Princeton, N. J.
2/. Standley and Stevens, Proc. Phys. Soc., 69, 993 (1956).

34. FERROMAGNETIC RESONANCE IN UNIAXIAL POLYCRYSTALLINE MATERIALS

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The observed ferromagnetic resonance line-width of polycrystalline non-conducting materials such as the ferrites is on the order of several hundred oersteds. Single crystal measurements on the same materials yield values for the line-width of less than 100 oersteds. This paper attempts to correlate theoretically the measured line-width of polycrystalline materials with the line-widths measured on single crystals of the same material.

The theoretical analysis is made assuming that a polycrystalline material is composed of single crystals having a random spacial orientation of easy axes. A further assumption is that each crystallite has an intrinsic line width, and a uniaxial crystalline anisotropy energy of the form $K\sin^2\Theta$, where "K" is the anisotropy constant and "Θ" is the angle of inclination of the magnetization with the easy axis.

The susceptibility tensor of a crystallite oriented arbitrarily with respect to an applied static magnetic field is determined and expressed in the coordinate system having its "z" axis oriented parallel to the applied static field. This tensor, in general, has no zero component. However, when the integration is carried out to determine the measured susceptibility of the material, four of the off diagonal terms integrate to zero. The tensor may be diagonalized by transferring to circularly polarized transverse microwave fields to give:

$$\overline{X} = \begin{Vmatrix} \overline{X}_+ & O & O \\ O & \overline{X}_- & O \\ O & O & \overline{X}_{zz} \end{Vmatrix}$$

where each of the components is a complex quantity.

The quantities $\overline{X}_+$ and $\overline{X}_{zz}$ are plotted as functions of applied static magnetic field and two values of anisotropy field ($2K/M_s$). $\overline{X}_+$ for positive anisotropy falls off more sharply on the high field side and rises more sharply on the low field side for negative anisotropy – in agreement with measurements made on materials of cubic crystalline symmetry. Also, the greater the anisotropy field, the greater is the broadening of the resonance line – the line-width being approximately equal to three halves of the anisotropy field for small values of that field.

In single crystals when the applied static magnetic field is such that the magnetization is parallel to it, X_{zz} is zero, i.e., for small r.f. fields applied parallel to the static field, no change in the magnetization is produced. The measured $\overline{X}_{zz}$ of a polycrystalline material, however, is the integrated part of the transverse X of the various crystallites which has a projection onto the chosen "z" axis and is non-zero.

35. FERROMAGNETIC RESONANCE IN POLY-CRYSTALLINE NICKEL FERRITE ALUMINATE

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Recent measurements at X-band for various compositions and for various heat treatments will be reported. The observed absorption lines are compared with theoretical lineshapes calculated with the assumption that the linewidth for single crystals is zero and that the dipolar interaction between grains is negligible1/. Reasonably good agreement between measured and calculated lineshapes is found, if it is assumed that the first order anisotropy constant is negative and that all higher order anisotropy constants are zero. By adjusting the theoretical curves as closely as possible to the experimental ones it is possible to infer the spectroscopic splitting factor g and the anisotropy field. With the g-value and the anisotropy field determined in this way the theoretical absorption curves closely resemble the experimental ones. Because of the idealizing assumptions used in the calculation of the theoretical lineshape, better agreement cannot be expected. The theory accounts for the secondary absorption peak observed at low fieldstrengths. A similar secondary peak has previously been observed in lithium-ferrite-chromite by McGuire2/ and was attributed to the excitation of an exchange mode of the sublattice system3/. In the present case, it is attributed to large anisotropy and the fact that the sample is polycrystalline.

The g-factor obtained by comparing the theoretical and experimental absorption lines is smaller than the apparent g-factor inferred from the absorption maximum and may differ from it by as much as a factor two. It is only slightly temperature dependent, whereas the apparent g-value is quite strongly temperature dependent. The anisotropy field decreases rapidly with increasing temperature. The dependence of the g-factor on composition and on heat treatment will be compared with theoretical predictions.

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2/. T. R. McGuire, Phys. Rev. 97, 831 (1955).
3/. R. K. Wangsness, Phys. Rev. 97, 831 (1955).

36. DAMPING AND THE DISPERSION RELATIONS IN ANTIFERROMAGNETIC RESONANCE

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The two sublattice molecular field model for antiferromagnetics is able to provide expressions for the microwave tensor susceptibility with a variety of assumptions about the relaxation. It is useful to check these various expressions with the appropriate dispersion relation1/, as certain assumptions are found to lead to microwave susceptibility elements which are incompatible with known static susceptibilities. In particular we have calculated the complete microwave susceptibility for an antiferromagnetic with uniaxial anisotropy and no relaxation, adding the relaxation in the final result. This produces a null value for the axial susceptibility which is incompatible with the static axial susceptibility. Gerritsen and Garber2/ have calculated the susceptibility tensor for an orthorhombic antiferromagnetic including relaxation to the average sublattice magnetization direction. When reduced to uniaxial terms, this calculation also gives a null axial susceptibility. We have recalculated the uniaxial susceptibility tensors using a relaxation toward the equilibrium magnetization in the instantaneous field. Additional terms are thereby introduced which make the axial microwave and static susceptibilities compatible with respect to the dispersion relation.

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2/. H. J. Gerritsen and M. Garber, Physica 22, 481 (1956)

MAGNETIC ALLOYS: MOSTLY ORIENTED

J. K. Stanley, Presiding

37. MAGNETIC ANISOTROPY INDUCED BY MAGNETIC ANNEALING AND BY COLD WORKING OF Ni_3Fe CRYSTAL (Invited Paper)

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After a brief report on the experiments which have been performed as to the "permalloy problem", especially as to the effect of magnetic annealing, recent investigations on the magnetic anisotropy which is induced by cold working will be reported. The latter phenomenon was first found by W. H. Six, J. L. Snoek and W. G. Burgers in 1934 and has been applied to the magnetic material "isoperm". Interpretation of this phenomenon, however, has not been established.

The present investigation was made on the single crystal of Ni_3Fe through the observation of magnetic domain pattern and the torque measurement. In the case of (110) [001] rolling, well-defined domains having easy direction [1$\bar{1}$0], i.e., perpendicular to roll direction were observed. The magnitude of uniaxial anisotropy K_u in this case increases with an increase of roll-reduction, taking its maximum value 2.5 x 10^5 erg/cc at r=70% and then decreases. In the case of (001) [110] rolling, domain patterns on the rolled surface were complicated, while that on the side surface showed clear domains running nearly parallel to the easy-glided slip bands. The easy direction in this case is at first [1$\bar{1}$0], i.e., perpendicular to the roll direction, but it changes to [110], i.e., parallel to roll direction at about 30% reduction. Then K_u increases to its maximum value 2.0 x 10^5 erg/cc at about 80% reduction. In the case of (001) [100] rolling, the domain patterns on the rolled surface were very complicated, while that observed on the side surface resembles that of basal plane of cobalt.

These experimental facts are satisfactorily explained in terms of "slip-induced directional order (s.i.d.o.)". When previously ordered crystals are deformed by slips along a definite glide plane, it should be expected that the distributions of various atomic pairs AA, BB and AB connecting the both sides of the slipped plane are altered by this process, while that of atom pairs lying parallel to the glide plane are maintained unchanged. The unbalanced atom pairs thus induced (s.i.d.o.) give rise to the magnetic anisotropy. It turned out that the anisotropy thus induced is classified into two different types, i. e., long range order (fine slip) type and short range order (coarse slip) type according as the travelling of atoms by slip is confined within an original order domain or extends to the other anti-phase order domains. Calculations were made with respect to these two types of anisotropy for various cases of deformation. In the case of (110) [001] rolling, easy directions of both types coincide with each other. In the case of (001) [110] rolling, only short range order type which has its minimum in [1$\bar{1}$0] is effective at first stage, while the long range order type which has its minimum in roll direction become contributable at later stage on account of the crystal rotation. The reason why domain pattern is not clear for (001) [100] roll is also explained by assuming the contribution of short range type. Experiments were also made on polycrystal. Relation to order formation will be also discussed.

38. THE EFFECT OF SAMPLE THICKNESS ON THE FIELD ANNEALING OF 6.5% Si-Fe

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Iron alloys containing about 6.5 percent silicon are known to respond to heat treatment in a magnetic field. Since the degree of response has been observed to vary with sheet thickness, a study was made to better define this variation.

Different alloy compositions were cast in cylindrical molds. The ingots were drilled to form hollow cylinders which were sliced and polished to rings of final thicknesses of from 0.375 cm to 0.006 cm.

D-C and a-c data were obtained on samples as annealed 2 hours at 1000°C in dry hydrogen, and as cooled at 40°C/hour from 900°C in a field of 10 oersteds.

The efficacy of magnetic anneal is markedly affected by specimen thickness, and to a lesser extent by small differences in alloy content. The effects of thickness are in general most pronounced below some 0.1 cm although this may be altered somewhat by varying the composition.

A nucleation effect was observed in the reverse magnetization of all thicknesses of magnetically annealed samples. In those samples having thicknesses less than 0.075 cm, multiple nucleation was observed; the initial nucleus did not envelop the sample, and additional nuclei were formed to carry out the reverse magnetization.

39. RECRYSTALLIZATION OF MnBi INDUCED BY A MAGNETIC FIELD

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Polycrystalline MnBi has been found to recrystallize when subjected to a strong magnetic field at temperatures between ~270°C and the Curie point, ~350°C. A fiber texture develops in which the crystals are oriented with the easy direction of magnetization (the c axis) parallel to the applied field. This effect has not been observed before to our knowledge. The polycrystalline MnBi was prepared by chill-casting an alloy of the stoichiometric composition and then heat treating the casting at 300°C for 24 hours. Cast plates 0.5 inch thick containing about 90 per cent MnBi were prepared in this way. The initial heat treatment was made without a field to provide material with a random crystal orientation. The randomly oriented material was then heat treated in a field of 8000 oersteds to induce recrystallization and develop the fiber texture. Crystal orientations were determined by X-ray diffraction patterns taken from polished surfaces. Photomicrographs in which the magnetic domain patterns were made visible by means of the Kerr magneto-optic effect showed that recrystallization was involved in the development of the fiber texture. Possible mechanisms to explain the recrystallization and its utilization to orient the particles in fine powder magnets are considered.

40. EFFECTS OF COMPOSITION AND PROCESSING VARIABLES ON THE MAGNETIC PROPERTIES OF THE NOMINAL 50% NICKEL, 50% IRON ALLOY

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In a factorial experiment, a study has been made of the effects of small amounts of alloying elements and processing variables on the magnetic properties of the nominal 50% nickel, 50% iron alloy, with emphasis on its performance as a magnetic amplifier core material.

Twenty-four vacuum-melted ingots were made to contain the following composition variables:

Manganese	- 3 levels
Silicon	- 2 levels
Sulfur	2 levels
Oxygen	2 levels

The ingots were processed to 2 mil tape from which toroidal cores were fabricated. The variables were:

Hot rolling at two temperature levels.
Annealing and no annealing after hot rolling.
Core annealing at six temperature levels.

Dynamic tests at frequencies of 60 and 400 cycles/second were made and the magnetic parameters were plotted against the core annealing temperature. These plots indicated the extent of the annealing temperature range, if any, in which satisfactory cores were obtained. The width of this temperature range was used as a criterion to evaluate the material.

It has been found that small amounts of alloying elements added to the ingot strongly influence the magnetic performance. Best results were obtained from the ingot which had the combined addition of manganese and oxygen and which was hot rolled at a high temperature. The effect of the processing variables was found to be dependent on the composition.

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41. ORIENTATION STUDY OF ULTRA-THIN MOLYBDENUM PERMALLOY TAPE

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Quantitative pole density stereograms of {111}, {220}, {200} and {113} poles of 1/8 mil molybdenum permalloy tape were developed in order to establish its cold rolled deformation texture and annealed textures.

Cold rolling the tape induced multiple slip common to all face-centered-cubic metals and developed (110) $[3\bar{3}5]$ and (110) $[3\bar{3}5]$ end orientations which deviate 5^{o} about [110] from the recognized {110}<112>brass deformation texture.

On annealing at 771^{o}C the cold rolled tape was found to develop (120) [001] + (210) [001] and (113) $[\bar{7}\bar{8}5]$ + (113) $[78\bar{5}]$ orientations as components of the annealed texture which bear in general a 35^{o}-45^{o} rotation orientation relationship about <111>with the cold rolled end orientations.

Annealing at 1160^{o}C developed the same texture as that obtained after 771^{o}C annealing.

From the pole figures made on 927^{o}C annealed tape, the same annealed texture prevailed whether the pole figure was made on its full 1/8 mil thickness or on its central 0.00005'' section.

Hysteresis loop tracings made on the cold rolled tape revealed an apparent direction of easy magnetization along the rolling direction. No easy magnetization direction was revealed in the rolling plane of the annealed tapes. These findings support the deductions from the corresponding pole figures.

42. THE DEVELOPMENT OF PREFERRED ORIENTATIONS IN SILICON-IRON

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The (110) [001] texture in silicon-iron arises by a process of secondary recrystallization after cold reduction of the strip in two stages separated by an anneal. It is possible to produce the same texture by a one-stage or a three-stage reduction process. The rolling textures and primary recrystallization textures for each of these processes have been experimentally determined and are all different. In spite of this the (110) [001] secondary orientation develops in each case. It is concluded from this that some factor other than texture is responsible for oriented grain growth in silicon-iron. It is tentatively suggested that impurities in the steel, already known to be important in controlling grain growth in silicon-iron, also supply the directional forces leading to the (110) [001] texture.

43. THE (110) [001] SECONDARY RECRYSTALLIZATION TEXTURE IN SILICON-IRON

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In 1934 Goss[1/] patented a process by which there were obtained in polycrystalline silicon-iron magnetic properties that approached those of a single crystal. It was subsequently shown[2/] that this material had a (110) [001] texture, and the desirable magnetic properties were in the rolling direction. It is generally recognized that this texture is developed by secondary recrystallization. During secondary recrystallization a few grains grow at the expense of the fine grain primary recrystallized matrix. In silicon-iron that has been processed by Goss' procedure the grains that grow have a cube-on-edge orientation.

In his patent Goss specified that the hot rolled band be annealed before being rolled to an intermediate thickness. The intermediate thickness strip was then to be heat treated and cold rolled to the final thickness, and given a final heat treatment to develop the magnetic properties. It is during this latter heat treatment that the strip undergoes secondary recrystallization.

An examination of the primary recrystallization textures has been undertaken in order to relate the processing steps to the development of the final texture. The starting material was 80 to 100 mil-thick hot rolled band. Both mill and laboratory-made material were studied with similar results.

It was found that in order for a sample to undergo secondary recrystallization there had to be a (110) [001] component of the texture after primary recrystallization. This component appeared only if the strip had at least one recrystallization heat treatment before being cold rolled to the thickness of the sample examined. A (111) <112> doublet texture generally resulted from the first heat treatment and it was this orientation that became the (110) [001] component after cold rolling and recrystallizing, as predicted by single crystal studies[3/].

The completeness of the secondary recrystallization was related to the intensity of the (110) [001] component after primary recrystallization. Even though this component is discernible in the texture, the matrix will not be entirely consumed if there are too few grains with cube-on-edge orientation. In such a case normal grain growth will also occur. All primary grains with (110) [001] orientation are not capable of becoming secondary grains. However, if the total population is increased, the number that grow is also increased.

1/. N. P. Goss, U. S. Patent 1965559
2/. R. M. Bozorth, Trans. ASM, 23, 1107 (1935)
3/. C. G. Dunn and P. K. Koh, Trans. AIME, 206, 1017 (1956)

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44. MAGNETIC PROPERTIES OF CUBE TEXTURED MAGNETIC SHEET

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Since 1905 when silicon-iron magnetic sheet was first introduced the greatest improvement in magnetic properties occurred with the development of "grain oriented" silicon iron.

The grains of this material are oriented by secondary recrystallization such that [100] directions are aligned parallel to the rolling direction and (011) planes are parallel to the plane of the sheet. Since the [100] crystallographic directions of the silicon iron crystal lattice are most easily magnetized, the "grain oriented" sheet exhibits one direction of high permeability and low losses, parallel to the rolling direction. However, <011> and <111> directions also lie in the plane of the sheet. Thus the efficiency of the electrical device is decreased when the flux must travel in some direction other than the rolling direction to complete the magnetic circuit.

To overcome this loss of efficiency in different directions, magnetic sheet having two [100] directions of magnetization in the plane of the sheet has been developed at the General Electric Company Research Laboratory. The material exhibits strong textures in which 80% or more of the grains have (001) planes in the plane of the sheet and [100] directions parallel to the rolling direction. This is commonly called "cube texture". Cube texture components have been described by Sixtus[1/] and Bozorth and Williams[2/] prior to this investigation and recently by Ackermann et al[3/], Möbius[4/], and Assmus et al[5/].

This texture can be produced in aluminum or molybdenum-iron alloys as well as in silicon-iron alloys and in any thickness of sheet or strip.

The magnitude of the orientation was determined by torque magnetometer tests and X-ray diffraction pole figure analysis with the results compared to those obtained from single crystals.

D. C. magnetic properties were determined using 1/2" x 3" test strips cut both parallel to and at right angles to the rolling direction. Picture frame test pieces were also used for comparison with single crystals. Test strips 3 cm x 25 cm were used to determine A. C. watt losses and magnetostriction values in both directions of the sheet.

Maximum permeability and watt losses of the cube textured material are comparable to the properties of the grain oriented material when measured parallel to the rolling direction. The maximum permeabilities measured in the transverse direction are 4 to 8 times those measured in the transverse direction of the material with a single easy direction.

Cube textured silicon-iron sheet provides nearly equal magnetic properties in two directions in the plane of the sheet. These properties are comparable to those measured in the single easy direction of the "grain oriented" magnetic sheet.

1/. Sixtus, Physica (1935), Vol. 6, p.105.
2/. Bozorth and Williams, U.S.Pat. 2300336, Oct.27, 1942
3/. Ackermann et al, Tech. Mitt, Krupp (1957), Vol. 15, p.3
4/. Möbius, German Pat. 1009214, May 29, 1957
5/. Assmus et al, Z. Metallkunde 1957, Vol. 48, p.341

45. CUBE TEXTURE IN BODY CENTERED CUBIC MAGNETIC ALLOYS

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Recently, a new magnetic material, cube textured silicon iron was disclosed by Assmus et al1/. Studies of cube textured material have also been carried out by the present authors on both aluminum-iron and silicon-iron alloys. The present paper reports data for strip from 1/2 to 25 mils in thickness.

The silicon and aluminum-iron alloys with cubic texture are characterized by lower coercive force, and higher permeability than conventional materials of the same thickness. The improvement varies with thickness and is more pronounced in very thin gages. DC and AC properties comparable to those of the best direction of regular "cube-on-edge" material are observed both parallel and transverse to the rolling direction of the cubic-texture material.

The crystal orientation of the materials prepared in these Laboratories will be illustrated by that of silicon-iron. Textures with as much as 98% of the material having cube planes within 3° of the rolling plane are readily obtained. The angle between the cube edge and the rolling direction can be controlled by metallurgical processing. The orientation has been determined by etch pit, domain pattern, X-ray, and magnetic methods.

The new materials offer greater latitude in design of transformers. In additon, the presence of the cube face in the sheet surface appears to offer special advantage for rotating applications because of improved permeability in all directions of the sheet. The greatly improved properties in very thin gages are also expected to broaden applications involving high rates of magnetization.

1/. F. Assmus et al, Zeitschrift für Metallkunde, 48, 341-349 (1957).

46. LOW MAGNETIC REMANENCE IN THE HIGH ALUMINUM IRON ALLOYS1/

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Low remanence values, corresponding to a B_r/B_s ratio of less than 0.05, have been produced by proper heat treatments in the ferromagnetic aluminum-iron alloys which fall in the ordering region. The occurrence of the low remanence is particularly pronounced in the aluminum-iron alloys around the Fe_3Al composition (13.9 weight percent aluminum). Domain patterns which show domain walls extending as straight lines across the grains occur in these low remanence alloys but are not present in alloys of the same composition heat treated to produce remanence values up to 4,000 gausses.

Magnetic materials having random crystal orientation normally display a magnetic remanence of approximately half of the saturation induction. Low remanence values corresponding to a B_r/B_s ratio of 0.04 to 0.07 have been reported for 65 Permalloy given special heat treatments as well as for 6.5 percent silicon iron. Both of these materials have a low crystal anisotropy, especially the 65 Permalloy. Bozorth suggested that in strain-free materials with almost zero crystal anisotropy the domain walls increase in thickness until they envelop the whole specimen and the domain structure disappears. Under these circumstances, as suggested by Kittel, flux-closure is the predominant force, and the flux lines in large areas bend and form closed paths, both in the unmagnetized condition and when the field is removed. This condition would thus result in a remanence approaching zero.

It is questionable whether the above hypothesis on low magnetic remanence is applicable in the case of high-aluminum iron although the crystal anisotropy of these alloys, especially of the fast-cooled alloys in the Fe_3Al region, is low. On the other hand, it can be assumed that the appearance of magnetic domain patterns in the low remanence aluminum-iron alloys indicates a comparatively high value of anisotropy. Apparently, the fairly high magnetostriction of the alloys around the Fe_3Al composition and the stress produced by cooling through differently ordered regions contribute to a high "stress anisotropy" value resulting in pronounced domain patterns.

An attempt is also made to correlate the remanence values of the aluminum-iron alloys with heat treatment variables, ordering, and the constitution of the aluminum-iron phase diagram.

1/. This work has been supported by the Aeronautical Research Lab., Wright Air Development Center.

47. EFFECTS OF ELASTIC BENDING ON MAGNETIC PROPERTIES OF ORIENTED SILICON-IRON

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The magnetic properties of normally straight oriented silicon-iron strips when elastically bent were measured in an Epstein frame and in a Carr single-strip permeameter. Elastic bending of strips magnetized in the rolling direction increased the coercive force and a-c losses, reduced the permeability, and made the hysteresis loop less rectangular. Domain theory gives a rather simple approximate interpretation of the data on residual induction and the permeability for magnetic intensities between 1 and 10 oersteds.

MAGNETIC MOMENTS AND CRYSTAL STRUCTURES OF OXIDES

L. R. Maxwell, Presiding

48. THE EFFECT OF HYDROSTATIC PRESSURE AND TEMPERATURE ON THE MAGNETIC PROPERTIES OF A NICKEL-ZINC FERRITE

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The magnetic properties of anickel-zinc ferrite (15% NiO, 35% ZnO, 50% Fe_2O_3) were measured as functions of temperature and hydrostatic pressure. The pressure was varied from atmospheric to 40,000 psi and the temperature from room temperature to 110°C (the Curie temperature of the ferrite occurred at approximately 97°C).

Structure sensitive properties changed by as much as a factor of four when the sample was subjected to 40,000 p.s.i. The initial permeability, μ_0, and the maximum permeability decreased, the coercive force, H_c, increased while the remanence remained relatively constant. Structure insensitive properties such as saturation induction, B_s, and the Curie temperature were only very slightly affected by pressure.

It is shown that if changes in magnetization are limited by either crystalline or stress anisotropies rather than inclusions, the relation between H_c, B_s, and μ_0 is given by the equation

$$H_c = C\frac{B_s}{\mu_0}$$

where C is a proportionality constant. The experimental results obtained over the entire range of temperature and pressure verify the above relation. The value of C is 2.56.

49. THE PREFERENTIAL VOLATILIZATION OF CATIONS FROM FERRITES DURING SINTERING

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The magnetic properties (saturation moment (M), M vs. temperature (T), Curie temperature (T_c), permeability, etc.) of ferrites containing zinc show considerable variation with sintering treatment. These variations are partially explained on the basis of changes in the gross chemical composition due to preferential loss of Zn during sintering. A more complete understanding of these effects is achieved by the consideration of the newly observed gradient in Zn concentration and the associated gradient in magnetic properties near the ferrite sample surfaces. The nature of such concentration gradients is demonstrated in sintered (1250° to 1440°C) samples of four ferrite compositions containing zinc and one containg cadmium.

Plots of M vs T are analyzed which show the usual rapid drop in M near the expected value of T_C and a slowly decreasing 'tail' in M extending as much as 100°C above T_C. When the sample surfaces are removed they are found to have a lower zinc content and a higher T_C than the interior material. The observed concentration gradient implies that at the sintering temperature the bulk diffusion rate of zinc is lower than the rate of volatilization. It is found that a lower temperature anneal (800°-1000°C) reduces but does not eliminate the concentration gradient. The observed parasitic ferrimagnetism in samples of normal $ZnFe_2O_4$ and $CdFe_2O_4$ can be explained on the basis of a concentration gradient resulting from the observed loss of Zn or Cd.

In the sintering treatment the amount of material volatilized is too great to be accounted for by the vapor pressure of ZnO or CdO. Since the boiling point of Zn is 907°C and of Cd is 767°C any reduction reaction producing these metals would proceed irreversibly above these temperatures. It is proposed that the volatilizing species are the metals produced by the reducing agency of ferrous iron.

50. SOME PROPERTIES OF QUENCHED MAGNESIUM FERRITES[1/]

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An investigation of magnetic properties has been carried out for the system of quenched magnesium ferrites $Mg^{II}_{x} Fe^{III}_{1-x} (Mg^{II}_{1-x} Fe^{III}_{1+x}) O_4$, where x, the fraction of magnesium ions occupying tetrahedral positions varies from $0.15 \leq x \leq 0.30$. Measurements of saturation moment M_s, taken at low temperature, are in disagreement with results reported by Pauthenet[2/] but are in essential accord with data obtained by Kriessman and co-workers[3/].

The Curie temperature for the series of compounds exhibits a linear decrease with increasing x, a result consistent with Néel's theory. The low frequency initial permeability is proportional to M_s^2; the coercive force is proportional to M_s^{-1}.

A limited study of the kinetics of the cation redistribution has been carried out. Samples quenched from 1100°C and then tempered at 600°C require approximately 16 hours to attain an equilibrium cation distribution at the latter temperature. The approach to equilibrium is consistent with a model in which the rate of inversion is proportional to $\exp(-U_0 + U_1 x)/kT$, where U_0 and U_1 are activation constants.

1/. The work described was performed under government contract.

2/. R. Pauthenet, Ann de Physique 7, 710-47 (1952)
3/. C. J. Kriessman, S. E. Harrison and H. B. Callen, Phys. Rev. 98, 1562 (1955).

51. IONIC VALENCES IN MANGANESE-IRON SPINELS

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Because both manganese and iron assume multiple valences in oxide structures, it is possible to fabricate spinels over a continuous range of manganese to iron ratio from Mn_3O_4 to Fe_3O_4. The purpose of this paper is to report magnetic moment and Curie temperature data for samples fabricated within this range and an interpretation of the data in terms of the distribution of ions of manganese and iron.

The data agree with previous indications that manganese ferrite, $MnFe_2O_4$, is an almost completely normal spinel with Mn^{2+} on A sites and Fe^{3+} on B sites. In addition, the usual assumption that excess iron replaces manganese as Fe^{2+} on B sites is substantiated. However, the data are not compatible with a replacement of Fe^{3+} by excess manganese as Mn^{3+} as has been previously assumed. Instead, the variation of magnetic moments and Curie temperatures with composition is interpreted in terms of a model in which excess manganese replaces Fe^{3+} as Mn^{4+}, converting an equal amount of iron to Fe^{2+}. When the manganese content gets so high that all the iron is Fe^{2+} (Mn_2FeO_4), manganese then replaces the iron as Mn^{3+} and reconverts an equal amount of Mn^{4+} to Mn^{3+}. The Mn^{3+}, becuase of its tetragonal nature, introduces spinel twinning. Interaction constants which are proportional to the strength of the magnetic coupling between pairs of the different valences of iron and manganese have been obtained from Curie temperature data. An Fe^{3+}-Fe^{3+} interaction is shown to be appreciably stronger than a Mn^{2+}-Fe^{3+} interaction.

It is proposed that the Mn^{4+}-Fe^{2+} pair in octahedral coordination is stabilized with respect to a Mn^{3+}-Fe^{3+} pair because of the interaction of the manganese orbitals with the 2p orbitals of the surrounding oxygen anions.

52. SUBSTITUTION FOR IRON IN FERRIMAGNETIC YTTRIUM-IRON GARNET

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Solid solutions of yttrium-iron garnet with yttrium-gallium and yttrium-aluminum garnets are formed over the entire range of composition; the lattice constant variation is nearly linear (Vegard's law). In ceramic preparations ions of Sc, In and Cr may be substituted for Fe in yttrium-iron garnet to a limited extent - probably <2 in one formula unit, $Y_3Fe_2(FeO_4)_3$. Substitution proceeds on a steric basis for non-magnetic ions: those smaller than Fe, namely Al and Ga, preferentially occupy the smaller, tetrahedrally coordinated positions, 24(d); larger ions, In and Sc, preferentially occupy larger, octahedrally coordinated positions, 16(a). The Curie temperature of yttrium-iron garnet is decreased by the substitution of non-magnetic ions for iron on account of the decrease of the number of Fe^{3+}-O^{2-}-Fe^{3+} interactions. The magnetic moment initially rises with octahedral substitution of nonmagnetic ions and falls with tetrahedral substitution because the moment corresponds to the difference in moments of Fe^{3+} ions in octahedral sites (2) and tetrahedral sites (3) per formula unit.

53. SOME FERRIMAGNETIC PROPERTIES OF THE SYSTEM $Li_xNi_{1-x}O$ 1/

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Crystallographic and magnetic measurements of the system $Li^+_xNi^{++}_{1-2x}Ni^{+++}_xO$ for the entire range $0 \leq x \leq 0.5$ are reported. For values of $x \leq 0.3$, the lattice appears to be antiferromagnetic and is cubic above the Curie temperature. For the range of compositions $0.3 < x < 0.5$, the lattice is rhombohedral and ferrimagnetic, a maximum magnetic moment per gram of 31 c.g.s. cm^3/gm being observed at $x = 0.46$. A maximum ferrimagnetic Curie temperature of 241°K was observed for the composition of $x = 0.41$. These properies are interpreted in terms of a partial ordering of Li^+ and Ni^{+++} ions into alternate sets of (111) planes which couple antiparallel to one another the moments within any set being either ferromagnetically coupled or paramagnetic, depending upon the number of nonmagnetic near neighbors in the neighboring planes. This system is compared to the ordered rock-salt-type compound $Cu_{0.25}Co_{0.75}O$. The lack of ferrimagnetism and the tetragonal distortion to $c/a<1$ in $Cu_{0.25}Co_{0.75}O$ are explained.

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

2/. Now with R.C.A. Laboratories, Needham, Mass.

54. EFFECT OF THERMAL HISTORY ON THE ANTIFERROMAGNETIC TRANSITION IN ZINC FERRITE

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The activation energy for the movement of a zinc ion from the A to B sublattice of a ferrite is small and positive. On this basis, Brockman 1/, acting on advice of Uhlenbeck and Duffendack, observed that zinc ferrite could be made ferromagnetic by quenching from about 1400°C We have found that the heat capacity of annealed zinc ferrite has a lambda point at about 9.5°K 2/ due to an antiferromagnetic type of ordering, and that the shape and apparent height of the peak is a strong function of impurity content. Indeed, the low broad peak observed by Friedburg and Burk 3/ is believed due to slight sample nonstoichiometry.

As further evidence of the low activation energy, we have made a sample of zinc ferrite deliberately partially inverted by water quenching from 1100°C, and measured its heat capacity. Only elementary vestiga of the lambda point remain.

A similar effect was also observed in $Li_{.05}Zn_{.9}Fe_{2.05}O_4$ but the transition temperature of the annealed sample was about 7.6°K. This transition temperature decrease will be interpreted in terms of molecular fields and the sublattice ordering.

1/. F. G. Brockman, Phys. Rev. 77, 841 (1950)

2/. E. F. Westrum, Jr., and D. M. Grimes, J. Phys. Chem. Solids 2, (1957)

3/. S. A. Friedburg and D. L. Burk, Phys. Rev. 98, 1200 (1955)

55. MAGNETIC GERMANATES ISOSTRUCTURAL WITH GARNET

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The discovery of magnetic rare earth garnets, $A_3^{+3}B_5^{+3}O_{12}$ has led to the observation that a weak negative interaction exists between (1) the spins of magnetic cations on eight fold sites and (2) the resultant of a strong negative interaction between spins on four fold and six fold sites. Because this type of magnetic coupling is new, its nature is of fundamental interest.

The character of the magnetic interaction has been examined using systematic substitution of combinations of magnetic cations. The crystal chemistry of the $A_3B_5O_{12}$ compounds is not well established; the crystal chemistry of silicate garnets ($A_3^{+3}B_2^{+3}Si_3^{+4}O_{12}$), however, is better understood, therefore compounds with well known cation distributions can be prepared. Such syntheses have been frequently found to be difficult; as a result use has been made in beginning the present investigation of the substitution of germanium for silicon to synthesize germanium garnets isostructural with silicon garnets. The germanium reactions have the advantage of taking place at lower temperatures than similar silicon reactions.

Batch compositions corresponding with the compounds $Ca_3Cr_2Ge_3O_{12}$, $Ca_3Fe_2Ge_3O_{12}$, $Mn_3Fe_2Ge_3O_{12}$, and $Mn_3Cr_2Ge_3O_{12}$ have been prepared. These compounds were synthesized by solid state reaction between GeO_2 and the appropriate metallic oxides at elevated temperature. The preparation procedure will be given. Results obtained from thermal magnetization experiments will be discussed.

56. SOME MAGNETIC AND CRYSTALLOGRAPHIC PROPERTIES OF THE SYSTEM $LaMn_{1-x}Ni_xO_3$ 1/

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The system $LaMn_{1-x}Ni_xO_3$ has been prepared under varying conditions for the entire range of compositions $0 \leq x \leq 1$. This system has been examined both magnetically and crystallographically. Interest in this system stems from four principal sources: (1) The compound $LaMnO_{3+\lambda}$ has been reported variously in the literature as orthorhombic and monoclinic; it is shown that the value of λ varies with preparation and that the structure is orthorhombic (distortion decreasing with increasing λ) for $\lambda \leq 0.05$, rhombohedral for $\lambda = 0.1$, the magnetic moment increasing monotonically from less than $0.3\mu_B$/molecule to $2.71\mu_B$/molecule at $\lambda = 0.1$. (2) Perovskite-type systems in which approximately 75 per cent of the small cations are trivalent manganese commonly become ferromagnetic: the system $LaMn_{1-x}Ni_xO_3$ also exhibits this property. (3) If a compound could be synthesized in which the dominant magnetic interaction is between a transition element with less-than-half-filled d shell and one with more-thanhalf-filled d shell, the character of that magnetic interaction should give important information about the indirect magnetic interactions in oxide systems. There is a second maximum in the plot of saturation moment vs. x at $x \approx 0.5$ which is interpreted in terms of a preferential ordering of Ni^{2+} and Mn^{4+} cations on alternate (111) planes of the simple-cubic small-cation sublattice. (4) The compound $LaNiO_3$ is paramagnetic down to 4.2°K. The various magnetic characteristics of this system are interpreted, and its significance for a theory of indirect magnetic-exchange interactions is discussed.

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

57. CRYSTAL GROWTH OF MAGNETIC GARNETS

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Crystals of $Y_3Fe_5O_{12}$, $Sm_3Fe_5O_{12}$, $Er_3Fe_5O_{12}$,$Gd_3Fe_5O_{12}$, and $Y_3Fe_5O_{12}$ with some of the iron replaced by gallium have been grown from molten lead oxide containing the proper amounts of iron oxide and rare earth or yttrium oxide. A typical composition is 52.5 mol per cent PbO, 44 mol per cent Fe_2O_3 and 3.5 mol per cent M_2O_3 where M is Y, Sm, Er or Gd. The temperature required to dissolve these oxides in a convenient time is near 1325°C. Upon slow cooling the crystals begin to form at about 1250°C.

Parts of the phase equilibrium diagrams for the systems Fe_2O_3-Y_2O_3 and Fe_2O_3-Y_2O_3-PbO have been determined and the significance of these diagrams to the growth and composition of garnet crystals is discussed.

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58. ANTIFERROMAGNETIC STRUCTURES OF MnS_2, $MnSe_2$, and $MnTe_2$1/

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The antiferromagnetic structures of MnS_2, $MnSe_2$, and $MnTe_2$ have been obtained by neutron diffraction. These materials all crystallize with the pyrite structure, which is a NaCl-like arrangement of M and X_2 groups with the axes of the X_2 groups parallel to the various body diagonals. A salient feature of the structure is the presence of nearly regular tetrahedra whose corner positions are occupied by three metal atoms and one member of an X_2 group, and whose center is occupied by the other member of the X_2 pair. All three compounds become antiferromagnetic in the neighborhood of liquid nitrogen temperatures or below. Neutron diffraction patterns obtained at liquid helium temperatures show well developed superstructure lines which, in the case of MnS_2, can be indexed on a cell which is doubled along one of the original cube edges. In the case of $MnSe_2$ the chemical cell has to be tripled in one direction, whereas for $MnTe_2$ the magnetic and chemical unit cells are identical. The magnetic ordering scheme for MnS_2 is that of the "third" kind and for $MnTe_2$, that of the "first" kind. The structure exhibited by $MnSe_2$, on the other hand, is not homogenous, but is intermediate between these two. The spin direction in both the disulphide and diselenide is parallel to the axis along which the original unit cell is enlarged and in the ditelluride it lies within the ferromagnetic sheets. All three compounds, despite the variation in magnetic structure type, have the same nearest neighbor distribution; namely, eight antiparallel and four parallel. This nearest neighbor correlation can, perhaps, be explained on the basis of the aforementioned (Mn_3X)-X tetrahedra which could favor nearest neighbor coupling if one invokes an indirect exchange mechanism utilizing the nearly tetrahedral Mn-X-Mn linkages.

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

APPLICATIONS AND TESTING

A. D. Franklin, Presiding

59. MEASUREMENT OF LOSSES OF MAGNETIC MATERIALS AT HIGH INDUCTIONS, AT FREQUENCIES UP TO 100 MEGACYCLES

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Magnetic Materials are being increasingly used at high powers at radio frequencies, as for example, in broad band power transformers for antennas. This paper describes a method for evaluating magnetic materials for such applications at frequencies up to 100 megacycles.

The measuring circuit is a series resonant circuit with a variable capacitor and is coupled to a high power source through a capacitive variable attenuator. The test sample is a toroid. At the higher frequencies, (above 25 megacycles) a coaxial sample holder is used; at lower frequencies, an appropriate number of turns are uniformly wound around the toroid. A test procedure is described for determining the Q of the entire circuit, and then for separating out the losses due to the test sample from that of the remainder of the circuit. At the lower frequencies, this involves replacing the test sample with an air inductor of known Q. The Q of the circuit with the air coil is then determined by the "reactance variation" technique, and the stray losses in the remainder of the circuit determined from the difference between this Q and the known Q of the coil. At the higher frequencies, a modified technique is employed, because of the use of the coaxial sample holder. The above complicated procedure need be used at only one induction at a test frequency. For other inductions, a very much simpler technique is used, based on the calibration of the variable capacitive attenuator and the known relation between the setting of the variable attenuator and the equivalent losses introduced by the radio frequency power source. Measurements are made with continuous RF power up to inductions where the sample heats up. At higher inductions, pulsed RF power is used.

Test data on several materials, some of which have been successfully used in high power transformers, will be presented.

60. MEASUREMENTS OF THE PROPERTY OF VARIOUS FERRITES USED IN MAGNETICALLY TUNED RESONANT CIRCUITS IN THE 2.5 TO 45 Mc REGION

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A one year investigation was conducted directed toward securing data for choosing the best ferrite to be used in the 3 Bev high intensity proton synchrotron now being

built at Princeton University. The ferrite samples tested were from American and European manufacturers and were in the form of small rings 2 inches or less in diameter. Measurements were required of μ and Q under varying magnetic bias, at various r-f flux levels, in the band frequencies 2.5 to 45 megacycles per second. At the beginning of this research no clear method existed for a proper choice of ferrite, and generally speaking the manufacturers' data were inadequate. Therefore a novel technique of measurement was devised, and an effort was made to establish a minimum number of parameters for defining ferrite properties for this application. The present paper includes a description of the techniques used and a resumé of the results obtained.

61. THE BEHAVIOR OF THE TE MODES IN FERRITE LOADED RECTANGULAR WAVEGUIDE IN THE REGION OF FERRIMAGNETIC RESONANCE

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The results of an exact computation of the complex propagation constants, β, of the TE modes in transversely magnetized ferrite loaded rectangular waveguide operating in the region of ferrimagnetic resonance are presented. The particular case treated is that of a full height slab against the side wall. The value of the damping parameter, α, in the equation of motion of the magnetization, and the slab thickness, δ, as well as the frequency, ω, have been varied.

It is shown that the curves of propagation constant vs. frequency in passing through resonance, do not necessarily connect the same modes above and below, i.e., the TE_{10} like mode at high frequencies may join the cutoff TE_{20} like mode at low frequencies. Furthermore, the question of which TE_{no} like mode below resonance joins with which one above resonance depends upon the values of ferrite slab thickness and damping parameter. The propagation constants are found by obtaining roots of a complex transcendental equation, $f(\alpha,\beta,\omega) = 0$. If $f_\beta(\alpha;\beta,\omega) = 0$ simultaneously, a frequency and damping parameter are defined for which two solutions of the equation $f(\alpha,\beta,\omega) = 0$ become degenerate. It is at points such as these that a pair of TE_{no} like modes below resonance joining with some pair above resonance for some value of damping parameter suddenly interchange as the damping parameter goes through its critical value.

For not unreasonable values of damping coefficient, it is common to find that the TE_{10} like mode starting either above or below resonance joins with some cutoff mode at the other side of resonance. Thus, in passing through resonance, there must be some frequency for which the energy scattered into the ferrite loaded guide in these two modes is split in such a way that they scatter equal energy into the dominant mode at the end of the ferrite loaded portion of guide. Since the propagation constants of the two modes in the ferrite loaded guide are generally different, the relative phase of the waves scattered into the empty guide will depend on the length of the ferrite slab, as should the transmission loss. Thus, it seems clear that conclusions drawn from the measurement of resonance losses in the type of ferrite loaded waveguide here considered should be vastly complicated by this effect.

62. ENERGY DISTRIBUTION IN PARTIALLY FERRITE FILLED WAVEGUIDES

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In making use of ferrites in devices, it is necessary to know as completely as possible the configuration of the fields and energy distribution in the ferrite and in the waveguide containing the ferrite. The theory of wave propagation in circular waveguides containing coaxial ferrite rods is examined for cases where the rod diameter is too large for accurate perturbation treatment.

The formal theory of propagation in partially ferrite-filled waveguides has been given1/,2/ and yields a very involved transcendental equation. Solutions of this equation for the propagation constant would require extensive calculation. In this paper, a reverse approach is taken, in which the propagation constant has been measured, and the field components then calculated from the theoretical expressions. Values of the permeability tensor components used in this treatment are taken from initial-field measurements of LeCraw and Spencer3/. The transcendental equation is adequately satisfied in this procedure.

The measurements were made of the propagation constant for right-and left-rotating waves, using a series of magnesium manganese ferrite rods, 5.25 inches long, over a range of diameters 0.10 to 0.25 inches, in a circular waveguide of 0.94 inch inside diameter.

Field distribution-and energy concentration-data thus obtained are given for several values of the applied dc field in the initial region and for the special case of zero permeability. The phase-shift and energy distribution effects for the negative-rotating wave appear similar to those existing in a recently developed longitudinal field rectangular guide phase shifter.4/

1/. M. L. Kales, J. Appl. Phys. 24, 604-608, 1953.

2/. A. A. Th. M. van Trier, Appl. Sci. Res., III, Sec. B, 305-371, 1953.

3/. R. C. LeCraw and E. G. Spencer, IRE Conv. Record, vol 4, p.5, p.66, (1956).

4/. F. Reggia and E. G. Spencer, Proc. IRE (to be published).

63. A MINIATURIZED RESONANT ANTENNA USING FERRITES

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Utilizing general relationships, it is possible to show that a linear antenna immersed in a large sphere of ferrite would have identical electrical characteristics to a free space radiator a factor of $\sqrt{\mu\varepsilon}$ physically longer if the material is lossless and the characteristic impedance $\sqrt{\mu/\varepsilon}$ is equal that of free space1/. An important consideration is then just how much ferrite is necessary to be an effectively large sphere. Utilizing the criterion that the ratio of inductive energy stored per cycle in the ferrite to that stored in the air be large with respect to unity, it is concluded that the ferrite sphere can be reduced to a cylinder about the radiator provided that the ratio of inner to outer diameter is sufficiently large. This effect has been corroborated by measuring the frequency of zero inductive reactance of a linear radiator with and without a perturbing ferrite sleeve.

Since magnetic dipole radiation is proportional to ω while electric dipole radiation is not, it is concluded that the above technique permits the miniaturization of low frequency radiators not possible for wound ferrite rods. Material development to optimize available ferrite materials would seem in order.

1/. Since submission of this title, the author has become aware of an analogous miniaturizing conclusion reported by Julius Herman in DOFL Report TR-462, May 1957.

64. AN APPRAISAL OF PERMANENT MAGNET MATERIALS FOR MAGNETIC FOCUSING OF ELECTRON BEAMS

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This paper summarizes results of graphic analyses, confirmed in several cases by experimental data, to illustrate the requirements for special magnet materials in the focusing of traveling-wave tubes. A graphic method, recently published1/ by the author, enables one to estimate quickly and easily the minimum size and weight of a tubular permanent magnet, of known B-H characteristic, required to maintain a magnetic field of specified strength along a specified gap. This permits ready evaluation of various magnet materials for the application. These evaluations, supplemented by suitable experimental data, enable one to speak with some confidence of the magnet materials needed for focusing electron beams.

The paper also reviews recent improvements in design of focusing structures which permit the use, to good advantage, of magnet materials which do not have the highest values of energy product but which have other useful characteristics. From this study one arrives at a preferred list of magnet materials for these electronic applications. Some magnet materials which appear on the preferred list have been produced experimentally but are not easily available commercially. It is probable that final development and commercial production of these materials have lagged because of insufficient visible demand for them.

The development of focusing structures of minimum size and weight promises to expand rapidly the use of traveling-wave tubes, particularly in the field of air-borne equipment. This enlarged use of tubes which require magnetic focusing may well provide commercial demand for particular magnet materials which would be otherwise in small demand. A convincing forecast of such commercial demand should stimulate added effort toward the final development of these materials.

The experiences reported in this paper represent only one particular area of activity in the field of electron beam focusing. In order to arrive at a convincing forecast of demand for magnet materials it is necessary that other areas be heard from, so that the needs can be integrated. This paper will have served its purpose if it stimulates an interest in, and further discussion of this matter.

1/. August 1957 Issue, I.R.E. Proceedings

65. THE PERFORMANCE OF PERMANENT MAGNETS AT ELEVATED TEMPERATURES

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The objective of this investigation was to determine the effect of temperatures up to 600°C and the combined effects of temperature and vibration on the magnetic performance of Alnico V and Alnico VI magnets.

Data is presented on the effect of temperature cycling, temperature coefficient of remanance, the effect of aging, heat exposure and the combination of high and low temperatures and vibration.

The results of this investigation show that the use of Alnico V and Alnico VI for most instrument and control applications is entirely feasible up to but not above 500°C.

66. THE MICRO-UNIFORMITY OF PERMANENT MAGNET MATERIALS

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The micro-uniformity of the pole-face flux density of short cylindrical magnets has been determined. For certain applications such as the magnetic suspension, and in the electron microscope, circumferential uniformity of a magnet's field is important. This is best explored close to the pole face. A quartz crystal which could scan an area 0.028'' x 0.00002'' was used to measure the flux density variation. The device permitted measurement to within 0.010'' of the magnet surface.

The measurement system developed was used to evaluate cylinders of the following materials: cast and sintered Alnico V, cunico, cunife, cast and sintered cobalt-platinum, compacted cobalt-platinum powder and compacted and bonded Alnico. Variations in pole-face flux density of as much as 15% about the average were observed for cast Alnico V; for bonded and compacted Alnico, the variations were less than 4%. These results led to the conclusion that isotropic materials yield better micro-uniformity than high-energy directional materials.

67. UNDERSTANDING AND PREDICTING PERMANENT MAGNET PERFORMANCE BY ELECTRICAL ANALOG METHODS

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Permanent magnet performance problems are by their nature cut and try and an optimum solution in even a simple application requires considerable time and effort and is to some extent an art. As advances in the technology of making the permanent magnet allow a wider range of magnetic properties and physical arrangements the need increases for a firm Engineering approach in this problem area. In this paper the author describes a complete data system and apparatus using electrical analogs in which the unit properties of a permanent magnet and its external loading may be conveniently set up and varied.

Constant voltage sources and linear resistance elements with predetermined switching points allow the non linear B-H relationship to be set up for any permanent magnet material.

The magnet volume and the space surrounding the magnet structure is zoned in a unique manner which allows leakage permeance from each zone to be lumped and estimated from charts as a function of magnet surface area and circuit configuration in terms of resistance.

Zoning allows an accurate integration of magneto motive force and the effective magneto motive force is associated with each leakage zone so that each zone adjusts itself to a point on the B-H curve as dictated by the loading it sees, exactly simulating the actual magnet conditions. Rules of thumb and experience factors are minimized and accuracy is only limited by the correctness of the lumped permeance values.

The effective permeance of the more widely encountered air space configurations is presented in chart form as a function of geometry. Since magnetic permeance is proportional to electrostatic capacitance the convenience of measuring capacitance of air gaps has been used extensively in this analog program.

Easily changed electrical quantities allow rapid exploitation of combinations of unit properties and circuit geometry by reading meters calibrated in terms of B and H for each zone. Useful gap flux and the external energy in each space zone are also easily read on meters.

Having established the electrical circuit representing the permanent magnet and its external field it is also possible to simulate minor loop operation and to meter the change in potential energy as it is alternately stored in the magnet and returned to the external field as the external load is changed over the operating cycle. This simulation of the dynamic function of the magnet is of value in accurately estimating force-distance relationships in mechanical work applications and in the analysis of the permanent magnet generator problem involving stability and performance under various load conditions.

A voltage representing an external field applied to the network representing a permanent magnet and its load conditions allows the study of the magnetizing problem and of instability resulting from an external field.

As introduction and background to the subject the basic analogy between the electrical and the magnetic circuit is reviewed and the physics of the permanent magnet and its external field as a system involving energy transformation is discussed.

68. METHOD FOR MEASURING SATURATION MAGNETIZATION IN RING SAMPLES

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Some materials undergo drastic changes in magnetic properties, including saturation magnetization, when subjected to various thermal or mechanical treatments. Alloys near the composition Ni_3Mn, for example, are paramagnetic when disordered but gradually become quite strongly ferromagnetic as ordering takes place. With such a material, it may be useful to measure both saturation magnetization and low-field magnetic properties on the same specimen, to avoid possible differences in heat treatment between samples. However, good low-field measurements require ring-shaped samples, and ring samples are not suitable for determining saturation magnetization by the usual methods. This report describes a method by which saturation magnetization can be measured in a ring sample which is then suitable for low field magnetic measurements.

The method consists of saturating the sample in a strong electromagnet field directed perpendicular to the plane of the ring, changing the direction of the magnetization slightly by applying a small circumferential field, and measuring the resultant flux change in the ring. This measurement is repeated for a series of different electromagnet fields, and the data plotted to give a straight line whose slope is proportional to the saturation magnetization. The intercept of the line gives the actual cross-sectional area of the secondary windings on the specimen ring; this value is required for accurate low-field measurements on samples with low saturation magnetization. The method is most convenient for saturation determinations on materials with saturation inductions in the range 700 to 10,000 gauss; in this range, the error in measured saturation is less than 5%. A demagnetizing field correction is necessary for materials with saturation induction greater than about 2000 gauss. The procedure uses standard equipment, but is somewhat tedious.

69. SOME ASPECTS OF TEMPERING 3-1/4% SILICON IRON VIA TIME DECAY OF PERMEABILITY

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The time decay of permeability, $\Delta 1/\mu$, has been employed, as first discussed by Snoek[1/], as a measure of interstitial solute content, in this case to follow early precipitation in several transformer steels, in an extension of the work previously reported[2/]. Reversion was observed in the steels that had been slow-cooled; that is, solute content increased for some time after the inception of the 150° tempering. For quenched steels, or for steels of high carbon (>.003%), $\Delta 1/\mu$ decreased with heating time. All samples approached a common level which may represent the equilibrium solubility for 150°.

The reversion is thought to be due to re-solution of very fine particles occurring at the same time that equilibrium particles form, similar to the effect in alpha iron reported by Keefer and Wert[3/]. The technique lends itself to study of the transformer steel, since a frame of epsteins is used. The possibility of isolating individual modes of the relaxations, in order to identify specific effects of C and N, is being investigated.

1/. Snoek, L. J.; Physica, 6, 161, 1939.
2/. Anolick, E. S.; AIEE publication "Conference on Magtism and Magnetic Materials" Oct. 1956, p.438
3/. Keefer, D. and Wert, C.; Abstract CA8, Program of the 1957 March meeting, in the Bulletin of the American Physical Society.

70. MATERIALS PROBLEMS IN MAGNETIC SUSPENSION APPARATUS

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A magnetic suspension apparatus is described in which an object, at least in part ferromagnetic, is suspended freely in space between two servo-controlled electromagnets having a common axis. The use of two magnets provides an axis of support which is relatively rigidly fixed in the apparatus and permits suspension, free of any physical contact with the apparatus, to be maintained with the apparatus as a whole in any position, or in motion.

Such a suspension system has three interesting features.

1. It allows rotation of the supported member about the support axis with retarding torques many times smaller

than in conventional bearings. Retarding torques as low as 3×10^{-5} dyne-cm have been achieved for a 6 gram spindle magnetically suspended and rotating in vacuum.

2. It functions as a force balance in which forces acting on a supported object may be measured as signals in the servo-loop without physical contact with it.

3. The supported object has excellent electrical and thermal isolation from its surroundings.

Limitations on both the low rotational friction and the force measuring properties of magnetic suspension systems may be set by the properties of the magnetic materials used. The properties which most seriously limit the rotational freedom are resistivity, rotational hysteresis, magnetic anisotropy, and physical inhomogeneity. The effect of resistivity and rotational hysteresis has been investigated by recording the deceleration curves of magnetically supported samples rotating freely in vacuum. Deceleration curves for a number of magnetic materials are presented and from these curves the order of magnitude of the limitation on freedom of rotation due to resistivity and to rotational hysteresis for each of these materials is obtained. The limitations most commonly encountered in applications of magnetic suspension based on its force measuring features are non-linearity and hysteresis in the output signal vs. applied force curve. A method of improving the linearity based on the mode of operation of the support servo and the geometry of the apparatus is described. A report is given on the progress of work now being done to reduce the system hysteresis. Two methods are being investigated. One involves the use for the supported object of square hysteresis loop materials magnetized beyond the knee of the B-H curve and the other involves the use of high coercive force ceramic material (Cerromagnet) for the supported object.

The maximum mass which can be supported is ultimately limited by the saturation induction of the material. Because of the relatively large air gaps in the magnetic circuit, permeability is a relatively unimportant factor as long as it is at least a few hundred.

FERROMAGNETIC RESONANCE: NON-LINEAR EFFECTS AND GARNETS

C. L. Hogan, Presiding

71. ORIGIN AND USE OF INSTABILITY IN FERROMAGNETIC RESONANCE (Invited Paper)

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In recent years it has become clear that our conventional view of the ferromagnetic resonance phenomenon is inadequate when the applied r.f. power is sufficiently high. At high powers one must consider not only the dominant, uniform precessional motion of the magnetization in which all the electron spins remain parallel throughout the sample, but also the always present thermal excitation of non-uniform, wavelike disturbances, each with its characteristic frequency and damping constant. The reason is that the various characteristic motions are independent of each other only in the limit of vanishing excitation; in any actual case nonlinear terms from demagnetizing and sometimes exchange fields accompanying the disturbances couple pairs of disturbances together. The most important coupling term is proportional to the magnitude of the uniform precession induced by the applied r.f. field, and the most effective coupling occurs in those pairs of modes whose natural frequencies add up to the uniform precession frequency, provided their spatial patterns satisfy certain requirements. Such pairs of modes will actually go unstable when the power driving the uniform precession exceeds a certain threshold value, and then their initially small thermal excitations will grow to large values comparable with the uniform precession itself. The damping of the modes opposes the tendency to instability, were it not for their damping, the threshold power would be zero. As it is, in the more usual ferrite single crystal samples, the r.f. magnetic threshold field will range from a few millioersteds to several oersteds, depending on the experimental arrangements.

These effects have their uses. It is possible to inject a signal into one member of a potentially unstable mode pair, and to couple an output load to it. If now the applied r.f. power is sufficiently high so that the mode pair would be unstable were it not for the damping effect of the extra output load, the signal will be amplified. However, since the modes of the sample form a very dense spectrum, competition from neighboring unloaded modes would "choke" the uniform precession, so that useful gain might be difficult to obtain in this way. Fortunately we need not use the "sample" modes. Instead we may employ two electromagnetic modes of a microwave circuit, and use the sample only as a coupling element between them. Since the structure can be arranged so that the cavity modes are never close in frequency to any sample modes, no competition will occur. The intermediate scheme (one sample mode – one electromagnetic mode) is also feasible.

72. A SOLID STATE MICROWAVE AMPLIFIER AND OSCILLATOR USING FERRITE

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A microwave amplifier and oscillator has been built using, as the active element, a piece of magnetized ferrite at room temperature. The operation of this device is based on the proposal by H. Suhl in which microwave power at one frequency produces, through non-linear coupling in the ferrite, amplification of a lower frequency microwave signal. Theory preducts that such a device should be a low noise amplifier. In this experiment, pump power at 9,000 mc produced amplification of 30 db at 4,500 mc. When in an oscillating condition, power output of 100 watts was observed.

73. A NEW TYPE OF FERROMAGNETIC MICROWAVE AMPLIFIER

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Suhl[1] has recently shown that microwave amplification can be obtained in a ferromagnetic material via a mechanism which couples the energy of a local oscillator at frequency ω_p to the signal energy at frequency ω_s in a microwave cavity. In the proposal which Suhl made, it appeared necessary that the local oscillator or pump frequency, ω_p, be greater than the signal frequency in order for amplification to take place. It is the purpose of this paper to give a simple physical explanation of the mechanism by which energy is transferred from the pump to the signal and from this explanation to show how it is possible to obtain amplification at a frequency higher than the pump frequency.

1/. H. Suhl, Phys. Rev. 106, 384 (1957).

74. MICROWAVE FREQUENCY CONVERSION STUDIES IN MAGNETIZED FERRITES

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Upper and lower side band mixing have been studied as a function of power level, magnetic field and source frequencies in polycrystalline ferrites at X-band. Conversion efficiencies have been studied as a function of rf power, frequency, ferrite geometry, applied magnetic field, and ferrite composition. Optimum upper and lower side band conversion efficiencies of 13 db and 32 db respectively for magnesium manganese ferrites have been attained. Conversion efficiencies for upper and lower side mixing as a function of magnetic field and rf power for yttrium garnet samples will be discussed.

75. SPIN-LATTICE RELAXATION TIME IN YTTRIUM IRON GARNET

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The spin-lattice relaxation time in yttrium iron garnet (YIG) has been measured by a pulsed ferromagnetic resonance method similar to that of Bloembergen and Wang[1] and Damon[2], in which the z component of magnetization is directly observed.

A microwave pulse with 20 mμs rise and decay time, 0.5 μs long, and 100 watts peak, is applied to a TE_{102} rectangular cavity operating at 9,300 mcs. The z component of magnetization M_z changes at the beginning and at the end of the rf pulse. The time of decay of the changing M_z signal at the trailing edge of the pulse (at which time the applied rf field is zero) is a measure of the spin-lattice relaxation time.

A spherical sample of YIG, 0.030 inch diameter, is placed in a quartz tube, 0.050 inch outside diameter, about which a five turn coil of number 50 wire is wound. The coil with sample is inserted in the center of the cavity with the axis in the z direction. At this position, the rf magnetic field is maximum and the electric field is a minimum. The presence of the coil does not measurably change the properties of the cavity. The voltage induced in the coil is proportional to the change in M_z and is observed on a high speed oscilloscope. The time constant of the equipment is approximately that of the pulse. Thus the spin-lattice relaxation time can be accurately determined directly if it is appreciably larger than this value. Other techniques are available[1],[2] using the same apparatus if the relaxation times are shorter.

The ferromagnetic resonance line width is 13 oersteds and the measured spin-lattice relaxation time is 80 mμs. Discussion is given relating these measurements to those reported in the accompanying abstracts.

1/. N. Bloembergen and S. Wang, Phys. Rev. 93, 72 (1954).
2/. R. W. Damon, Revs. Mod. Phys. 25, 239 (1953).

76. FERRIMAGNETIC RESONANCE IN GADOLINIUM IRON GARNET

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We have observed ferrimagnetic resonance in single crystals of gadolinium iron garnet at 9300 mc. The samples used were spheres of approximately 0.020" diameter ground from small crystals obtained from an iron-gadolinium oxide melt. The measurements were made in a cylindrical transmission cavity over the temperature range from -195° to 200°C with the microwave frequency stabilized on the cavity resonance. The sphere was mounted on a copper post and its temperature was varied by conduction through the post. Both amplitude modulation and magnetic field modulation techniques were used in the temperature range near the compensation point where the integrated intensity becomes very small and the line width large. The data obtained by the two techniques were consistent.

From -20° to -190°C, the results are apparently not much affected by the existence of the compensation point and can be described by the usual ferromagnetic resonance equation. In this temperature range, the anisotropy constant K_1 is negative and very similar to that observed in yttrium iron garnet. K_2 is zero throughout this temperature range. g decreases monotonically from 2.15 at -190° to 2.06 at -20°. The resonance line width depends on both temperature and crystal orientation. At all temperatures, between 0° and -190°C, the line is narrowest in the [100] direction and widest in [111]. Line widths are smallest (280 oe. in [100]) from -90° to -130° and increase at both lower and higher temperatures. These results between -20° and -190° substantiate those previously obtained with polycrystalline samples. Above the compensation point, g, K_1 and the line widths decrease with increasing temperature.

The existence of the compensation point near room temperature has a profound effect on the results obtained at temperatures above -20°C. In gadolinium iron garnet, the situation is further complicated by the fact that the angular momentum and magnetization vanish at essentially the same temperature. The results obtained near the compensation point will be discussed in terms of a theory due to Wangsness on the effects of magnetic sub-lattices on ferrimagnetic resonance.

77. FERROMAGNETIC RESONANCE IN YTTRIUM IRON GARNET AT LOW FREQUENCIES

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Ferromagnetic resonance at low frequencies has been observed in single crystal yttrium iron garnet (YIG). Experiments at these frequencies are possible mainly because of the narrowness of the YIG ferromagnetic resonance line width, which is as low as 3.0 oersteds at room temperature, and because of the relatively low $4\pi M_s$ of 1700 gauss. All of the samples (grown by C. S. Porter) used in these experiments are from the same batch as those used in the accompanying abstracts. Measurements have been made of line width of polished YIG spheres as a function of frequency in the 1700 to 3000 mc range. At the lower end of this range the field required for resonance is slightly less than that necessary to saturate the sphere. The line width increases by an order of magnitude as the frequency is reduced from 1850 to 1700 mc. As domains begin to form, both the internal dc field and the internal rf field become non-uniform over the sample. These variations in local fields serve as generators of spin wave modes which cause line broadening.

Measurements are made of the same effect by using a fixed frequency and by changing the temperature. As temperature is increased $4\pi M_s$ decreases. Since for a sphere the resonant field is independent of magnetization this takes the sample from an almost saturated to a completely saturated state.

The extreme conditions for the disk have also been studied. For a dc field perpendicular to the disk ferromagnetic resonance was measured at several frequencies as low as 30 mc which required a field of 1680 oersteds. For a dc field parallel to the disk, ferromagnetic resonance occurs at 303 oersteds for a frequency of 2000 mc.

Saturation of the resonance line at extremely low rf powers has been observed at 2000 mc on a polished 19 mil sphere of YIG. The first observable decrease of the peak and broadening of the resonance line occurs with approximately 15 microwatts of rf power incident on the cavity. For comparison with the spin wave theory of Suhl[1/], calculations are being made of the rf field involved for the unusual geometry of the cavity. This field appears to be even smaller than the critical field at 9300 mc in the accompanying abstract. Because of the power involved and the indicated difference with frequency, this non linear effect will receive further careful study.

1/ H. Suhl, J. Phys. Chem. Solids 1, 209 (1957).

78. MICROWAVE PROPERTIES OF POLYCRYSTALLINE RARE EARTH GARNETS

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A number of garnets including yttrium garnet ($3Y_2O_3 \cdot 5Fe_2O_3$) and a number of mixed garnets of the form $(Y_2O_3)_{3-x-y} \cdot (Sm_2O_3)_x \cdot (Gd_2O_3)_y \cdot 5Fe_2O_3$ have been prepared. X-band ferromagnetic resonance and saturation magnetization have been measured as a function of temperature. At room temperature samarium substitution for yttrium produces an approximately linear increase of line width with samarium content. Gadolinium substitution on the other hand has a much smaller effect on line width but produces an approximately linear decrease in saturation magnetization. Possible microwave application of these materials will be discussed.

79. FERROMAGNETIC RESONANCE IN SINGLE CRYSTALS OF RARE EARTH GARNET MATERIALS[1/]

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The microwave ferromagnetic resonance absorption of some single crystals of rare earth-iron garnets have been observed in the temperature range from 77°K to 560°K. Recent measurements by Dillon[2/] of anisotropy fields and resonance line widths have stimulated considerable interest in the properties of the garnet structure. In this investigation the emphasis has been placed on the measurement of the changes in resonance behavior when the diamagnetic, trivalent yttrium is replaced by rare earth ions which have exchange interactions with the iron sublattices. In this respect, particular attention has been given to the ytterbium-iron garnet since among all the rare earth ions with non-zero orbital angular momentum ytterbium, in a $^2F_{7/2}$ state, is probably the simplest and should provide the most direct test for any model which seeks to relate anisotropic effects to crystalline field interactions. A survey of the resonance behavior in single crystals of samarium, holmium, dysprosium, and erbium garnets have also been made. It is interesting to note that the room temperature values of the resonance line widths of these crystals are in agreement with polycrystalline measurements[3/] if the appropriate corrections are made for the porosity effects in the sintered materials[4/].

From the angular variation of the magnetic field required for resonance the anisotropy energy of the ytterbium-iron crystals have been measured over the whole temperature range. At room temperature it was found that the energy surface can be represented reasonably well by a first order term, to yield an approximate value of 40 gauss for (K_1/M_s) and a g-value of 1.9. However, the anisotropy in the resonance field increases rapidly with decreasing temperature so that at -78°C (K_1/M_s) has tripled in value and higher order terms have become of importance. The resonance line width has also been observed to be highly anisotropic with the minimum value of approximately 205 oersteds when the magnetic field is parallel to the [100] axis. It should be noted that the temperature variation of line width along the various crystal axes is not the same. For example, in going from 23°C to -78°C the [110] width increases by a factor of 5, whereas the [100] width only by a factor of 1.5. At the lower temperatures, when the anisotropy fields have increased to the order of the applied field, we have noted the onset of double absorption peaks similar to those reported by Tannenwald in cobalt and manganese ferrites.[5/] Details on the temperature dependence of the various anisotropic effects will be presented.

1/ Research supported by Air Force Contract AF 19 (604)-1084.

2/ Dillon, J. F., Jr., Phys. Rev. 105, 759 (1957).
3/ G. P. Rodrigue, J. E. Pippin, W. P. Wolf, and C. L. Hogan, IRE Trans. M.M.T. (to be published).
4/ Schlömann, E., Boston Conference on Magnetism and Magnetic Materials, page 600 (1956).
5/ Tannenwald, P. E., Phys. Rev. 99, 463 (1955) and 100, 1713 (1955).

ANISOTROPY AND MAGNETOSTRICTION

R. M. Bozorth, Presiding

80. TEMPERATURE DEPENDENCE OF THE MAGNETO-CRYSTALLINE ANISOTROPY COEFFICIENTS IN CUBIC CRYSTALS

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The observed anisotropy coefficients in magnetic materials decrease rapidly with increasing temperature. It is generally postulated that this decrease results from an angular fluctuation of the local magnetic moment; at higher temperatures the intrinsic anisotropy is thus averaged over a wider angular distribution and this average becomes more nearly isotropic. Keffer[1/] has recently shown that the resulting temperature dependence is strongly influenced by the correlation in the fluctuations of neighboring atomic spins. Assumption of the limiting case of no correlation has been shown by Van Vleck[2/] to give a dependence of the form $K_1(T) \sim M^6(T)$, employing the most plausible model of a pseudoquadrupolar interaction. Introduction of some correlation into his calculation shifts the exponent from 6 to 10 at very low temperatures. In iron the empirical anisotropy agrees very well with a tenth-power law over the entire temperature range. It is therefore apparent that a strong local correlation persists over the major portion of the temperature range. Zener[3/] has given a classical treatment of the temperature dependence, in which he assumes strong local correlations, and he does obtain a tenth power law over the entire temperature range. Zener ingeniously produced the essence of the tenth-power behavior without undertaking a detailed consideration of the finer structure. Because of the striking qualitative success of this theory we have carried out a more detailed, classical, strong-correlation theory in the Weiss internal field approximation. Small local regions of magnetization fluctuate under the influence of a Weiss internal field and of an intrinsic anisotropy energy of cubic symmetry. Two contributions to the temperature dependence of the macroscopic anisotropy are distinguishable. The first effect is the general widening of the angular distribution with increasing temperature, decreasing the anisotropy. The second effect, omitted in previous treatments, is the differential widening of the distribution in different directions - wider along hard directions than along easy directions of magnetization. The first effect dominates at low temperatures, and the second dominates above about one-third of the Curie temperature. The result is in excellent agreement with the iron data, but is not a strict tenth-power law

The first anisotropy coefficient in nickel changes sign with increasing temperature. This behavior cannot be accounted for on the basis of the pure statistical theory described above. We have investigated a phenomenological model in which there are two states with different intrinsic anisotropy. The relative population of these two states is governed by a Boltzmann distribution. The angular distribution again averages over this temperature-dependent intrinsic anisotropy. The qualitative behavior of the anisotropy in nickel is obtained.

1/. F. Keffer, Phys. Rev. 100, 1692 (1955).
2/. J. H. Van Vleck, Phys. Rev. 52, 1178(1937).
3/. C. Zener, Phys. Rev. 96, 1335 (1954).

81. TEMPERATURE DEPENDENCE OF FERROMAGNETIC ANISOTROPY

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The temperature dependence of the crystalline anisotropy constants of iron, cobalt and nickel is discussed.

It is shown that Zener's result for iron (i.e., the first anisotropy constant varies as the tenth power of the magnetization) also may be derived from molecular field theory.

In cobalt a satisfactory agreement with experiment is obtained by using Zener's results together with the postulate that the intrinsic anisotropy varies with thermal expansion in the manner recently calculated by the author1/

For nickel the temperature dependence of K_1 seems to require, in addition to the tenth power of the magnetization, a multiplicative factor that is linear in the temperature. No explanation has been found for this latter term.

1/. Phys. Rev., to be published.

82. MAGNETOCRYSTALLINE ANISOTROPY OF Mg-Fe FERRITES: TEMPERATURE DEPENDENCE, IONIC DISTRIBUTION EFFECTS, AND THE CRYSTALLINE FIELD MODEL

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The magnetocrystalline anisotropy (K_1) and saturation magnetization (M_s) of magnesium-iron ferrite monocrystals containing 6 to 50 mole percent magnetite were measured as a function of temperature (T). The values of M_s at $T = 0^oK$, expressed by the number (n) of Bohr magnetons per molecule, were used in conjunction with the Néel theory to determine the ionic distribution in the particular inversion states in which K_1 was measured. This determination is necessary because K_1 had been observed1,2/ to depend on the ionic distribution. In samples containing 6 to 25 mole percent magnetite, K_1 was found to vary more rapidly with temperature when the ionic distribution corresponds to a "high M_s state" than when it corresponds to a "low M_s state".2/

Two of the low magnetite content samples which initially possessed a relatively high n were heat treated in order to alter the ionic distribution. The observed changes (Δ) are:

Magnetite content (mole percent)	$\Delta\|K_1\|$ (10^3 ergs/cm^3) 300°K	77°K	Δn (Bohr magnetons)	$\Delta\|K_1\|/\Delta n$ 77°K
6	3.5	-24.5	-0.63	38.9
18	4.4	-37.0	-0.95	39.0

This table shows that $\Delta|K_1|/\Delta n$ is constant at a sufficiently low temperature, thus providing additional evidence for the suggestion1/ that the individual ionic anisotropies are additive. On the basis of this additivity, we find that the sign of the anisotropy of a ferric ion on an A site is different from that on a B site. Since the sign of the crystalline field is known to be different on these two crystallographic sites, our result concerning the signs of the ferric ion anisotropies suggests that the crystalline field plays an important role in the anisotropy of these ferrites.

We used the data obtained on the 6 mole percent magnetite sample to test the applicability of the Yosida-Tachiki anisotropy theory3/ which involves the cubic crystalline field spin Hamiltonian and the molecular field approximation. For this purpose we assume that in this crystal K_1 is due to ferric ions only. To avoid "trial and error" procedures, we developed an analytical method2/ for determining directly those three molecular field coefficients that produce the best agreement between the Néel theory and a given experimental curve of M_s versus T. When calculated in this way, the theoretical M_s versus T curves for our ferrite crystals are in very good agreement with experiment. We have determined the cubic crystalline field splitting parameters a_A and a_B occurring in the theory3/ by using the experimental curves of $K_1(T)$ and $M_s(T)$ for the 6 mole percent magnetite crystal in each state of ionic distribution. The results are:

$a_A = -0.0092\ cm^{-1}$ and $a_B = +0.0232\ cm^{-1}$ for the high M_s state;

$a_A = -0.0135\ cm^{-1}$ and $a_B = +0.0250\ cm^{-1}$ for the low M_s state.

For this sample, the theoretical curves of K_1 versus T obtained by using these a-values are in very good agreement with experiment. These experimental anisotropy data extend from 300°K to 77°K for the high M_s state and to 4.2°K for the low M_s state. Additional support for the applicability of the crystalline field theory is obtained by comparing our a_B values with the value $a_B = +0.0205\ cm^{-1}$ determined by Low4/ from paramagnetic resonance measurements on ferric ions in MgO.

1/ V. J. Folen and G. T. Rado; G. T. Rado and V. J. Folen, Bull. Am. Phys. Soc. 1, 132 (1956). (The first of these abstracts contains a misprint: in the third line of the text, "0.1 to 0.5" should read "10 to 50".)

2/ V. J. Folen and G. T. Rado; G. T. Rado and V. J. Folen, Bull. Am. Phys. Soc. 2, 263 (1957).

3/ K. Yosida and M. Tachiki, Prog. Theor. Phys. 17, 331 (1957).

4/ W. Low, Phys. Rev. 105, 792 (1957).

83. MAGNETIC ANNEALING IN COBALT-IRON FERRITE SINGLE CRYSTALS

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The non-cubic anneal-induced anisotropy has been investigated experimentally in a series of cobalt-iron ferrite single crystals with compositions between Fe_3O_4 and $Co_{0.15}Fe_{2.85}O_4$. The observed dependence of the magnitude and symmetry of the effect on cobalt concentration favors an interpretation that the source of the anisotropy is an interaction energy between the individual cobalt ions and their non-cubic environment (the origin of this interaction is discussed in an accompanying paper by J. C. Slonczewski) and that the mechanism of the annealing process is a migration of cobalt ions to neighboring octahedral lattice sites.

In the original experiments the times required to induce a maximum annealing effect were surprisingly short; for example, the relaxation time characterizing the annealing process at 100°C was only about 10 minutes. One possible explanation of this phenomenon is that the presence of cation vacancies facilitates the migration of cobalt ions. Crystals with constant iron and cobalt content were grown in atmospheres of various partial pressures of oxygen in order to obtain crystals with different concentrations of vacancies. The annealing relaxation time for crystals grown with a minimum vacancy content was found to be considerably longer than that for the crystals used in the previous experiments. Experiments were also performed on a crystal which had been purposely oxidized to the extent that fine plates of Fe_2O_3 were precipitated from the matrix. The non-cubic portion of the anisotropy of this crystal was found to consist of two parts, one of which is insensitive to the magnetic field present during annealing and is presumably due to the shape anisotropy of the precipitates.

84. MAGNETIZATION PROCESSES IN HEAT-TREATED SINGLE CRYSTAL COBALT FERRITE1/

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Magnetization measurements as a function of applied field, crystal orientation and temperature are presented for a single crystal cobalt ferrite sphere (grown by the flame-fusion technique). The data were obtained using a vibrating sample magnetometer.2/ The magnetic properties of the non-heat-treated sample are complicated, but understandable, when compared with the magnetic behavior after heat-treatment. The sample was heat-treated with a magnetic field applied along [100].3/ The room temperature magnetization curves can be fitted over a wide range of applied field and crystal orientation if a uniaxial anisotropy K_{1U} is superimposed on the first order cubic anisotropy K_{1C}. The heat-treated data permit the various magnetization mechanisms to be analyzed for given applied field directions using simple domain configurations: along [100] magnetization proceeds by domain wall displacement; along [010] and [001] magnetization proceeds initially by domain rotation, then by a more complicated mechanism involving both domain nucleation and wall motion; along [011] magnetization proceeds initially by domain rotation, then wall motion, and finally again by domain rotation. Data along non-principal directions can be analyzed by combinations of these mechanisms. Values of K_{1U}, K_{1C} and M_s from 4.2°K up to 300°K are presented. It is demonstrated that the temperature dependences of K_{1U} and K_{1C} differ:4/ at 77°K $K_{1U} = 1.1 \times 10^7$ and $K_{1C} = 1.2 \times 10^7$, whereas $K_{1U} = 5 \times 10^5$ and $K_{1C} = 3.8 \times 10^6$ at 300°K. It is shown that, because of the high anisotropy, accurate low temperature measurements of M_s can be made only along [100] for fields below 20 kilogauss. The magnetic data are compared with numerous related measurements on cobalt ferrite5/ which include: torque reversal,6/ magnetostriction,7/ anisotropy,7,8/ sensitivity of heat-treatment to excess Fe and O,9/ x-ray diffraction measurements,10/ precipitate growth,11,6/ polycrystalline and permanent magnet properties,12/ and microwave ferromagnetic resonance data.13,14/ Arguments are presented which indicate that needle-shaped precipitates (probably Fe_3O_4) are formed along the field direction during heat-treatment. Order of magnitude estimates indicate that these precipitates produce internal stresses which, when combined with the large magnetostriction of cobalt ferrite, produce K_{1U}. This mechanism accounts for the large temperature dependence of K_{1U} and the remanence at low temperatures.

1/ The research reported in this document was supported jointly by the Army, Navy and Air Force under contract with Massachusetts Institute of Technology and was supported by the U. S. Air Force under contract with Harvard University.

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3/ The principal magnetic directions are thus the [100], [010], [001] and [011] where the [010] and [001] are magnetically similar; however, these cube edges are magnetically quite different from the [100].

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85. CRYSTALLOGRAPHIC AND MAGNETIC STUDIES OF THE SYSTEM $NiFe_{2-x}Mn_xO_4$

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The system $NiFe_{2-x}Mn_xO_4$ was selected to study the role of the Mn^{3+} ion in determining the crystallographic and magnetic properties of spinels. The ionic distribution was investigated by means of X-ray diffraction. A cubuc structure was obtained throughout the system, the lattice parameter increasing monotonically with x from 8.34 to 8.39 angstroms. It was found that in the range $0 \leq x \leq 1$ that Mn^{3+} progressively replaces Fe^{3+} on the six-coordinated sites. Whereas, in the range $1 \leq x \leq 2$, the Mn^{3+} progressively replaces Fe^{3+} on the four-coordinated sites. Therefore, the Mn^{3+} is not able to displace Ni^{2+} from the six-coordinated sites and $NiMn_2O_4$ is a cubic inverse spinel. These results are consistent with the thesis that the tetragonal distortions of $ZnMn_2O_4$, Mn_3O_4, $MgMn_2O_4$, and $Li_{.5}Mn_{2.5}O_4$ are due to the six-coordinated sites in these compounds essentially all being occupied by Mn^{3+} ions. The magnetization was found to be in agreement with the ionic distribution found by the X-ray study. Magnetostriction measurements were made as a function of applied field to determine the sign and order of magnitude of the magnetic anisotropy of the polycrystalline samples. The magnetic anisotropy was found to pass through zero with increasing x, becoming highly positive ($K \simeq +10^5$ ergs./cc.) at x = 1. Heretofore only the Co^{2+} ion has been found to produce a positive anisotropy in the spinel structure.

86. ORIGIN OF ANISOTROPIC EFFECTS IN $Co_xFe_{3-x}O_4$

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Torque measurements have shown that the substitution of a small amount of cobalt for iron in a single crystal of magnetite (Fe_3O_4) causes (1) a very large change in the magnetic anisotropy energy and (2) an anneal-induced anisotropy. A theory is proposed to explain these effects.

The crystalline electric field experienced by each Co^{2+} in a B-site has trigonal symmetry about one of four (111)-axes. We assume that there are two orbital states having the same lowest possible energy. The orbital angular momentum connecting these two states is given by

$$L_z = \begin{pmatrix} \alpha & 0 \\ 0 & -\alpha \end{pmatrix}, \quad L_x = L_y = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \qquad (1)$$

where α is a constant and the z-axis is the trigonal axis. In the ground state the component of spin S parallel to the exchange field and to the saturation magnetization M has its minimum value of -3/2. Therefore, the first order spin-orbit energy $\lambda L \cdot S$ is $\pm 3/2 \alpha \lambda \cos \theta_i$ where θ_i is the angle between M and the i-th trigonal axis. From these energy levels it follows that the anisotropic part of the free energy contributed by cobalt is

$$W = -kT \sum_{i=1,2,3,4} N_i \ \ln \cosh \left(\frac{3\alpha\lambda \cos \theta_i}{2kT} \right) \qquad (2)$$

where N_i is the cobalt population of the i-th sublattice.

If the N_i are all equal, then W has cubic symmetry. If we assume $|\alpha\lambda| = 132 cm^{-1}$, then equation (2) agrees well with the measured cubic anisotropy at all temperatures. Free ion wave functions lead one to expect that $1 < \alpha < 3/2$, and for the ground state of the free ion the spectroscopic value of λ is $-180 cm^{-1}$. Since λ is a function of the crystalline field, the agreement is considered satisfactory.

The annealing effect may also be explained with this model. Suppose the cobalt atoms are free to migrate over the B sublattice at an annealing temperature T_a. Then, because the energy levels depend on θ_i, the equilibrium N_i are functions of the direction of M during the anneal. If these values of N_i are frozen in by lowering the temperature to T, then W(T) will generally lack cubic symmetry. The calculated angular dependence of W(T) may be brought into agreement with torque data by including the effect of a second order correction to the energy levels. The agreement becomes poorer with increasing cobalt concentration.

Two additional effects are predicted. First, the mean orbital contribution to the magnetic moment is large and anisotropic. At 0°K and for all N_i equal, the predicted mean total moment per cobalt atom is $3+\alpha/\sqrt{3}$, $3+\alpha/\sqrt{6}$, and $3+\alpha/2$ Bohr magnetons in the [100], [110], and [111] directions, respectively.

Secondly, it is predicted that the effective anisotropy energy depends slightly on the applied field. The predicted relative change of the cobalt contribution to the anisotropy energy is of the order of 10^{-6} per oersted.

87. THEORY OF MAGNETOSTRICTION AND G-FACTOR IN FERRITES

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A quantum mechanical theory based upon the Heitler-London approximation has been developed to explain the spatial variation of magnetostriction and g-factor in ferrites. As a first step, the electronic wave functions of cations of transition elements in the crystal field were found, taking into account the crystal structure of ferrites. G-factors of various cations in ferrites were determined by a method similar to that of Abragam and Pryce, and the g-factors thus found were related to those of ferrimagnetic resonance absorption by the use of the theory of Wangsness and the author.

The magnetostriction was obtained by the perturbation method; the perturbation terms included spin-orbit interaction, inter-ionic dipolar force, intra-ionic spin-spin interaction, exchange interaction, etc., as well as the strain potential produced by the shift of ions from the original position by means of strain in addition to the crystal field.

A brief summary of the results obtained is as follows: (i) the electronic structure of various kinds of ferrites was determined from the one ion approximation; (ii) g-factors of ferrites observed in microwave resonance absorption could be reproduced from this theory within a small error by using the approximate crystal field obtained from a model which takes only the point charges of nearest neighboring oxygen ions and cations into account; (iii) the most predominant mechanisms for the magnetostriction phenomenon in each ferrite could be found with the aid of explicit formulas because the quantitative results for the magneto-elastic coupling terms coincided very well with the experimental ones.

It is concluded that there are four mechanisms predominant among those giving rise to magnetostriction. They are (1) the interplay of spin-orbit interaction with the strain potential mentioned above, (2) classical dipolar interaction, (3) the interplay of anisotropic exchange interaction with the strain potential, and (4) the interplay of the potential with the intra-spin-spin interaction. Other mechanisms were estimated to be ineffective. The predominant mechanisms in Ni-ferrite are (1) and (2); in Co-ferrite, (1); in magnetite, (1), (2) and (4). In Mn-ferrite and annealed Cu-ferrite, the mechanism (2) is most effective. In quenched Cu-ferrite, both mechanisms (2) and (3) are the most important.

The approximations used, as well as the temperature dependence of magnetostriction, will be discussed.

88. THE RELATIONSHIP BETWEEN SINGLE CRYSTAL AND EFFECTIVE POLYCRYSTALLINE ANISOTROPY CONSTANTS IN FERRITES

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The occurrence of the natural spin resonance in polycrystalline ferrites, i.e., the resonance of the electron in the anisotropy field, was first observed by Snoek[2] who expressed the resonance frequency in terms of the magnetocrystalline anisotropy, K_1, according to the equation

$$\nu = \frac{2\gamma}{3\pi}\frac{K_1}{M_S}$$

This holds for crystals whose easy axis of magnetization is along the [111] axis. However, the evaluation of the anisotropy constant from this equation gives a value which is too large. This calculated "effective anisotropy" (K_e) has been found to be directly related to the magnetocrystalline anisotropy in a series of ferrites $Mn_{1+x}Fe_{2-x}O_4$ ($x \leq 0.8$). K_e and K_1 are related by a constant multiplicative factor: $K_e/K_1 \approx 2$, and the linear variations of K_e and K_1 as a function of composition both extrapolate to zero at approximately x = .8. This ratio does not seem to be unique to manganese ferrite. Both natural spin resonance[3,4] and microwave resonance[5,6] measurements have been compared for nickel ferrite and Fe_3O_4. These ferrites also give a ratio of K_e to K_1 very close to 2. All polycrystalline samples used in our natural spin resonance experiments were high density ferrites (>98% X-ray density). It is suggested that the ratio K_e to K_1 may be a constant for all ferrites having a sufficiently small porosity.

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89. EXCHANGE ANISOTROPY IN THE IRON-IRON OXIDE SYSTEM

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Exchange anisotropy is the result of a magnetic interaction between a ferromagnetic and an antiferromagnetic system. This interaction[1] was discovered in the Co-CoO system, wherein cobalt is the ferromagnetic and cobaltous oxide is the antiferromagnetic system. The material consisted of fine particles (~200 Å) of cobalt which had a coherent cobaltous oxide film. Above the Néel temperature where the CoO is in the paramagnetic state the material had the expected behavior of a ferromagnetic. Below the Néel temperature the interaction between the ferromagnetic cobalt and the antiferromagnetic cobaltous oxide resulted in a displaced hysteresis loop and a non-vanishing value of the rotational hysteresis for applied magnetic fields greater than $2K/I_s$. Further investigation of the temperature dependence of this system has shown that the high field ($H>2K/I_s$) rotational hysteresis vanishes precisely at the Néel temperature of cobaltous oxide.

Work on the Fe-FeO system has shown a non-vanishing value of rotational hysteresis for temperatures below the Néel temperature of FeO and for magnetic fields greater than $2K/I_s$ for iron. The temperature dependence of this high field rotational hysteresis shows that it vanishes at precisely the Neel temperature of FeO. However, the material does not have a displaced hysteresis loop.

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90. MAGNETOSTRICTION AND ELACTIC PROPERTIES OF FERROMAGNETIC SUBSTANCES AT HIGH MAGNETIC FIELDS

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The manner in which the anisotropic forced magnetostriction contributes to the magnetostriction of ferromagnetic substances at high magnetic fields is discussed from a localized model of ferromagnetism. With this assumption, the free energy of a ferromagnetic substance can be conveniently divided into several terms and it can be concluded quite naturally that a free energy term corresponding to that of ferromagnetic anisotropy gives rise to an anisotropic forced magnetostriction. In the past, the isotropic forced volume magnetostriction has been considered to be the only cause of the forced magnetostriction. This is probably one reason for the discrepancies between the experimental value of the volume magnetostriction and the theoretical value expected from the pressure dependence of the Curie point, etc.

From a similar point of view, anomalous behavior of elastic properties of a ferromagnetic substance, such as the change of the temperature coefficient of the elastic constants at the Curie point, the dependence of the elastic constants upon the direction of the magnetic field, etc., are explained as an intrinsic change in the elastic constants with spontaneous magnetization. In the past, these effects have been explained only as a result of the deformation of the crystal lattice due to the spontaneous magnetostriction (volume effect, morphic effect).

MAGNETIZATION PROCESSES: REVERSALS AND LOSSES

J. R. Weertman, Presiding

91. DOMAIN WALL MOTION IN METALS (Invited Paper)

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The losses and reversal times in ferromagnetic materials that reverse by domain wall movement are determined by the number of domains and the speed with which domain boundaries move. The number of domain walls may be directly observed and to a considerable extent predicted. On the other hand, mobility of the domain wall is not well understood either experimentally or theoretically except for motion determined by eddy currents.

We report an extension of the Sixtus-Tonks experiment on square single crystal iron whiskers approximately 5 microns in width. Because of the small size and high degree of perfection, reversing fields over 250 oersteds may be applied to the whisker without causing multiple nucleation of domain walls. This fact allows one to move the domain wall with an axial velocity greater than 5×10^6 cm/sec — more than a factor of one hundred in excess of speeds previously observed. Non-linearities have been observed in the velocity as a function of applied magnetic field. At room temperature there is a discontinuity in the velocity in the region of the velocity of sound in iron. This suggests an energy loss due to magnetostrictive coupling between the spin system and crystal lattice. These results will be discussed in relationship to existing theory.

92. PREPARATION AND PROPERTIES OF CRYSTAL-ORIENTED FERROXPLANA SAMPLES

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A year ago some new groups of ferromagnetic oxides have been published, which have a hexagonal crystal structure. Several of these compounds, that are named ferroxplana, show an increased resonant frequency compared to cubic ferrites with the same permeability. This increase is caused by the fact that in the hexagonal crystals the magnetization is strongly fixed to a preferential plane by a large negative crystalline anisotropy energy.

The large crystalline anisotropy causes a strongly anisotropic permeability of each crystal. As a result the permeability of polycrystalline ferroxplana samples is restricted to rather low values. One can say that crystals with their preferential plane perpendicular to the magnetic lines of force have a large demagnetizing effect.

It appeared to be possible to use the large crystalline anisotropy in order to orientate the particles of a ferroxplana powder in an external magnetic field. In this way samples with two different textures have been obtained. In one case the preferential planes of the crystals have one direction more or less in common (fan textures); in the other case all preferential planes lie more or less parallel to each other (foliate texture). In both cases the permeability is appreciably increased, while the resonant frequency is only slightly decreased. It has turned out that this large increase in permeability is caused mainly by an elimination of the effect of the anisotropic permeability of the crystals.

93. A RIGOROUS APPROACH TO THE THEORY OF FERROMAGNETIC MICROSTRUCTURE

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The present theory of magnetic "domain" structure relies heavily on the Bloch wall concept and the Landau-Lifshitz model; though useful, it is far from rigorous. The basic steps in the formulation of a rigorous theory were taken long ago;1/ they led to non-linear partial differential equations. At that time no means of handling such equations were available. Now, thanks to electronic computers, numerical solution is a practical possibility.

Consider the descending hysteresis loop of a moderately fine elongated particle in a longitudinal field. At a certain negative field intensity, the magnetization begins to deviate from its initial state. To this point the theory is linear and resembles the theory of elastic stability;2,3/ beyond this point numerical methods are necessary.

The calculation is simplest for an infinitely long cylinder.3,4/ When the cylinder radius exceeds a certain value, the magnetization change occurs by the nonuniform process of "magnetization curling".3/ Numerical calculations for this case have been carried out independently by S. Shtrikman3,5/ and by the author. If allowance is made for the approximations inherent in numerical calculus, the results strongly suggest that complete reversal of the magnetization occurs in a single jump. The field intensity at which the jump occurs is smaller in absolute value than the Stoner-Wohlfarth critical field intensity; its magnitude decreases with increasing particle radius.

Thus particles too large to obey the Stoner-Wohlfarth equations may still behave as single-domain particles except during the magnetization reversal. In contrast to Stoner-Wohlfarth particles, they reverse at a smaller field intensity and by passage of the vector moment through zero, with no transverse component.

The calculations so far reveal no stable domain structure in an ideal, infinitely long cylinder. They do, however, suggest that such structures may occur in sufficiently large specimens when constraints prevent complete reversal. They also yield domain-like structures that are unstable in an infinite cylinder, but that become stable if one applies the usual simplified "demagnetizing field" correction.

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5/ S. Shtrikman, private communication.

94. THE MAGNETIZATION CURVE OF THE INFINITE CYLINDER

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In a previous paper1/ the nucleation field for the infinite circular cylinder was calculated, assuming certain modes of magnetization reversal, namely: Rotation in Unison, Magnetization Buckling and Magnetization Curling.

Recently Brown2/ has shown that the easiest and therefore the actual modes of nucleation are eigenfunctions of a set of partial differential equations. It was pointed out by Brown3/ that magnetization buckling is not an eigenfunction of his equations, so that our calculation for this case was only approximate.

A rigorous solution of Brown's equations is undertaken here. The whole eigenvalue spectrum is explored. The nucleation fields for cylinders with "large" radii are found to be those of the magnetization curling. For "small" radii the nucleation field is found to be somewhat smaller than that for the magnetization buckling. However the difference is only about 1%, and the exact mode of reversal is very close to the buckling. The transition from exact buckling to curling is abrupt. These two modes are shown to be the only modes for nucleation for any radius, the other modes giving higher nucleation fields.

As a result it is seen that contrary to current belief, rotation in unison never takes place in an infinite cylinder. It is shown that the magnetization reversal occurs in one jump which means that the magnetization curve for the cylinder is a rectangular loop. This agrees with the results obtained by Brown.3,4/

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3/ W. F. Brown, Jr., Private Communication.
4/ W. F. Brown, Jr., Paper submitted to this Conference.

95. A MODEL FOR NON-LINEAR FLUX REVERSALS OF SQUARE LOOP POLYCRYSTALLINE MAGNETIC CORES

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A qualitative theory of the reversal waveforms of polycrystalline magnetic cores has been proposed by Goodenough.[1] His theory is based on the growth of ellipsoidal domains of reverse magnetization which originate from nucleating centers at grain boundaries. The present model uses this theory, with the additional condition that the nucleating centers are assumed to be randomly distributed throughout the core volume, and radial field variations are neglected.

The average total area of the irreversibly moving and colliding walls is then calculated as a function of their position, starting from a Poisson distribution of nucleating centers, and then converted to a function of flux. The equation for rate of flux change is then derived as:

$$\frac{dx}{dt} = \frac{4.82}{S_w}(H-H_o)(1-x)\left(\log_e \frac{1-x}{2}\right)^{2/3}$$

where S_w is the switching coefficient, H_o the threshold field, H is the applied field, and x is the ratio of flux density to retentivity.

This non-linear differential equation is solvable in simple cases such as constant current drive, constant voltage drive, or a triangular current waveform in a hysteresis loop test. These solutions compare reasonably well with experimental data.

For more complicated circuit conditions, solutions of the core equations require numerical methods. Programs have been written for the IBM Type 704 DPM to calculate the behavior of circuits containing many such cores interacting and switching together. Results for a typical circuit are presented and compared with experimental waveforms.

1/ N. Menyuk and J. B. Goodenough, J. Appl. Phys., 26, 8 (1955).

96. TEMPERATURE DEPENDENCE OF MICROWAVE PERMEABILITIES FOR POLYCRYSTALLINE FERRITE AND GARNET MATERIALS

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Polycrystalline ferrite and garnet materials have applications in devices where linearly polarized microwave magnetic fields are either parallel or perpendicular to a static magnetic field. Analysis of these devices often reveals that it is desirable to know the behavior as a function of magnetic field of the quantities $\mu_{\parallel}$ and $\mu_{\perp} = \frac{\mu^2-K^2}{\mu}$. $\mu_{\parallel}$ and $\mu_{\perp}$ are defined from the Polder tensor permeability of unsaturated media,

$$\begin{pmatrix} \mu & -jK & 0 \\ jK & \mu & 0 \\ 0 & 0 & \mu_{\parallel} \end{pmatrix}$$

where the static magnetic field is along the z-axis. In addition, the environment or power level may be such that these materials are operating at elevated temperatures. These considerations have prompted the measurement of $\mu_{\parallel}$ and $\mu_{\perp}$ as a function of temperature and d.c. magnetic field. The temperature range covered was from 25° C to several hundred degrees C. The static field was varied from zero to values slightly below gyromagnetic resonance.

Commercial polycrystalline magnesium-manganese and nickel-zinc ferrites and experimental yttrium iron garnets were used for the measurements. A thin slab of the mateial was placed against the side wall of an X-band rectangular transmission cavity resonant in TE_{102} mode. The Bethe-Schwinger perturbation theory formula for the relative frequency shift of this type cavity loaded with a slab of ferrite or garnet material is:

$$\frac{\delta f}{f} = G(1-\mu_e)$$

where G is constant depending on the geometry of the cavity and slab, and μ_e is equal to $\mu_{\parallel}$ when the static and microwave magnetic fields are parallel and to $\mu_{\perp}$ when these fields are perpendicular. The resonant frequency shift of the cavity for each value of temperature and magnetic field was measured with a point by point technique using a tunable stabilized oscillator.

The use of samples in the form of thin slabs not only allowed direct measurement of $\mu_{\parallel}$ and $\mu_{\perp}$, but also permitted a relatively large perturbation size sample. Experimental results obtained are compared with expected temperature and magnetic field dependence of $\mu_{\parallel}$ and $\mu_{\perp}$.

97. THE EFFECT OF COBALT ON THE RELAXATION FREQUENCY OF NICKEL-ZINC FERRITE

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The complex permeability of a number of NiZnCo ferrites was measured as a function of frequency from 0.1 to 250 mc/sec. These ferrites were prepared under identical conditions from reagent grade chemicals. Their compositions differed in the relative amounts of cobalt, nickel, and zinc they contained, the amount of iron being held constant. A number of specimens of each composition were prepared at different firing temperatures, so as to include a variation in the degree of reaction.

An analysis of the data was made in which the initial permeability and relaxation frequency were correlated with certain composition and structure variables. They included the quantity of cobalt, the nickel-zinc ratio, the firing temperature, and the amount of shrinkage which occurred during firing. It was found that these variables would account for 88% of the variations of the initial permeability and 70% of the variations of the relaxation frequency. A further result of the analysis defines the conditions for obtaining maximum quality ($\mu_o f_o$) at a given value of initial permeability.

98. THE SWITCHING PROPERTIES OF PERMALLOY CORES OF VARYING COERCIVITY1/

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In attempting to develop a 4-79 Molybdenum Permalloy core for use in a memory with non-destructive readout, studies have been made of switching properties of Permalloy tape cores with coercivities ranging from 0.1-1.0 oersted, corresponding to heat treatments over a temperature range of 300-900°C. The switching time of a core can be shortened by means of auxiliary field pulses which help to nucleate domains of reverse magnetization but have little effect on their rate of propagation. In general, auxiliary field pulses applied perpendicular to the direction of remanent magnetization are more effective than those applied anti-parallel to it provided the latter are not large enough to cause switching by themselves. The timing of the auxiliary pulses is important. Many of the cores have a "preferred" direction presumably caused by small domains of extremely high coercivity. The experimental results are interpreted in the light of domain wall motion theory.

1/ This research was supported, in part, by the USAF.

99. ROTATIONAL LOSS MEASUREMENTS ON SOME FERRITES

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The results of rotational loss measurements on several ferrites will be reported. A magnetic field is created which rotates with respect to the disk-shaped samples and remains in the plane of the disks. At fields of the order of 0-700 oersteds, the rotating field is generated by two solenoids with their axes 90° out of space phase, fed by currents 90° out of time phase. For fields up to 11 kilo-oersteds, the magnetic field is stationary and the sample is rotated with respect to it using a rotating top. As the magnitude of the magnetic field is increased, it is found that the torque rises and goes through a maximum. At 60 cps it becomes essentially field independent above about 1000 oersteds and is of the order of 100 ergs/cm^3. The results of additional loss measurements now being made as a function of magnetic field amplitude and frequency will be reported.

100. THE TEMPERATURE DEPENDENCE OF THE ATTENUATION OF ULTRASOUND IN A NICKEL SINGLE CRYSTAL FROM 77° TO 650° K1/

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This paper describes some of the work done by the author between 1954 and 1957 at the Metals Research Laboratory in Brown University.

Measurements on the attenuation of ultrasound in the frequency range 10-110 mc sec.$^{-1}$ have been made from 77° to 365° K in a nickel single crystal in the demagnetized and saturated states. Additional measurements at 10 mc sec.$^{-1}$ in the demagnetized state have extended to 650° K. Compressional waves propagating in the principal directions [001], [111], and [1$\bar{1}$0] were used; the saturation magnetic field also being applied in these directions.

The results show only a slight dependence of the attenuation on temperature from 77° to 365° K when the sample is magnetized to saturation. However, the decrement vs. frequency curves indicate a relaxation loss mechanism of the Debye type with critical frequency in the above range. That this behavior may not be entirely a result of nonmagnetic ultrasonic loss mechanisms (dislocation damping, thermoelastic losses, etc.) is suggested by the fact that for a given direction of propagation there is a slight dependence of the attenuation on the orientation of the saturation magnetic field.

On the other hand, when the sample is in the demagnetized state, a large temperature dependence manifests itself; this effect is more pronounced the higher the frequency. A comparison of the slope of the curve for the difference between the values of the attenuation in the demagnetized and saturated states plotted against the square of the absolute temperature with the data of Brukhatov and Kirensky2/ on the temperature dependence of the first order magnetocrystalline anisotropy constant, K_1, shows that this difference is approximately proportional to K_1^{-n}, when n is of order one over the temperature range 77° to 365° K. This result is consistent with the assumption that the ultrasonic magnetomechanical coupling is directly proportional to the initial susceptibility in a ferromagnet with low internal stress. However, this result is in quantitative disagreement with the explanation of microeddycurrent losses accompanying domain rotation as presented by Mason.3/ Further considerations on the domain rotation model indicate that this mechanism is not responsible for the ultrasonic loss in nickel over this range of frequencies. Similarly, simple models based on domain wall motion are also in disagreement with the experimental results. This lack of agreement indicates the complexity of the situation and the necessity for more experimental and theoretical work on the ferromagnetic loss mechanisms in the metallic elements and their alloys in this frequency range.

1/ This work was done under Contract DA-19-020-ORD-3650, Office of Ordnance Research, U. S. Army.

2/ Brukhatov, N. L. and Kirensky, L. V.; Physik. Z. Sowjet Union 12, 602 (1937).

3/ Mason, W. P.; Revs. Mod. Phys. 25, 136 (1953).

101. MAGNETIC FLUCTUATIONS IN MOLYBDENUM PERMALLOY

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Considerations of generalized noise and irreversibility and magnetic viscosity suggest the existence of magnetic fluctuations in ferromagnets. Magnetic fluctuations in molybdenum permalloy tape cores have been detected by observing noise voltages at the terminals of a coil wound on the sample. The magnetic noise spectrum indicates the existence of a slow relaxation phenomenon having a relaxation time slower than 0.05 seconds and an activation energy of 0.04 electron volts. Core losses yield noise voltages in agreement with Nyquist's law and provide a means of studying ferromagnetic loss with zero magnetic excitation.

MAGNETIC APPARATUS AND TECHNIQUES

T. R. McGuire, Presiding

102. A NEW CONCEPT IN LARGE SIZE MEMORY ARRAYS -- THE TWISTOR

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Three methods have been developed for storing information in a coincident-current manner on magnetic wire. The resulting memory cells have been collectively named the "twistor". Two of these methods utilize the strain sensitivity of magnetic materials and are based on the century old Wertheim or Wiedemann effects, the third utilizes the favorable geometry of a wire.

The effect of an applied torsion on a magnetic wire is to shift the preferred direction of magnetization into a helical path inclined at an angle of 45° with respect to the axis. The coincidence of a circular and a longitudinal magnetic field inserts information into this wire in the form of a polarized helical magnetization. In addition, the magnetic wire itself may be used as a sensing means with a resultant favorable increase in available signal since the lines of flux wrap the magnetic wire many times. Equations concerning the switching performance of a twistor are derived.

An experimental transistor driven 320 bit twistor array has been built. The possibility of applying weaving techniques to future arrays makes the twistor approach appear economically attractive.

103. ANALYSIS AND OPERATION OF A FERRITE PLATE SWITCH DRIVEN MEMORY SYSTEM USING 2 HOLES PER BIT

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Present day random access core memories for Digital Computers use hand-wired planes of cores as the storage elements. Each core is threaded by at least four turns of wire. For memories larger than 100,000 bits, the concept of using a ferrite plate pierced with holes as a multi-bit storage element becomes attractive.1/ The use of an apertured magnetic plate becomes particularly attractive if some or all of the windings required can be printed on the plate.

The use of holes in a plate as storage elements poses a difficulty in uniformity. The conventional coincident current memory system requires careful grading of the cores used for storage. The larger present day core memories are driven by magnetic switches to reduce the number of current drivers required. This feature creates even greater tolerance problems in the cores required for storage and switching. To build a random access memory, particularly a switch-driven one, using available apertured ferrite plates, it is desirable to find techniques of memory operation which are considerably less demanding with respect to core or "hole" parameters than conventional coincident current systems.

The present paper is concerned with the operation of a switch-driven memory system which uses some of the techniques suggested by J. Rajchman.[2] It describes, analyzes, and presents waveforms obtained from, the system as it operated successfully in the Laboratory. The memory is of the 2-dimensional parallel digit type with the word access driven by a D.C. bias type matrix switch and the other access by transistor "digit" drivers. Two holes are used for each memory location. Both memory and switch use apertured ferrite plates.

In coincident current core memories, thin wall toroidal type cores offer the most advantages. It is shown in the analysis and verified by the Laboratory Model that the end fired memory has the greatest advantages when each element behaves like a hole in an infinite plate. This feature, together with the use of two holes per bit results in memory operation with tolerances which are several times as large as those of conventional coincident current core memories. The memory operation is analyzed in terms of the static plate switching parameters and the drive currents applied to the memory by the switch and the digit drivers.

The memory and switch portion of the system are connected by low resistance "address" wires. It is shown that this has a self-regulating effect on the currents supplied by the switch to the memory. This feature combined with the tolerance of the memory itself increases the overall memory-switch tolerance to a point where it appears possible to drive the magnetic switch driving the memory with yet another stage of switching. It has been possible to derive equations for the operation of the complete switch memory system in terms of the plate switching parameters and the drive currents supplied to the switch and the memory. The memory is shown to operate in one of two modes, depending on the amplitude of the excitation applied. In one mode, flux switching occurs around one of each of the two apertures which define a storage location; in the other mode, flux switching occurs around both. Both modes of memory operation, as well as operation under various limiting conditions are illustrated by means of waveforms taken from the 1800-bit experimental switch-driven memory system. The experimental results confirm the analysis and demonstrate the flux switching phenomenon associated with holes in an infinite plate.

1/ R. H. Meinken — "A Memory Array in a Sheet of Ferrite", AIEE Conference on Magnetism and Magnetic Materials Proc., February, 1957, p. 674.

2/ J. A. Rajchman — "Ferrite Apertured Plate for Random-Access Memory", Proc. IRE, Vol. 45, March, 1957, pp. 325-334.

104. RECENT ADVANCES IN THE DESIGN OF HIGH FIELD DC SOLENOID MAGNETS[1]

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The art of DC solenoid design is re-examined with the objective of maximizing magnetic field at the expense of volume and homogeneity, while providing axial access at the largest feasible angular aperture. Solenoids of this type would provide higher fields for the investigation of cyclotron resonance and magneto-optical effects in thin specimens at far-infrared frequencies where limitations of source intensity and detector sensitivity require large-aperture optics and preclude the use of pulsed magnets. Heat transfer experiments indicate that under conditions of nucleate boiling it is possible to transfer heat across a copper-water interface at more than ten times the rate of 200 watts/cm^2 which served as the basis for Bitter's design some twenty years ago. Transfer rates of 2500 watts/cm^2 were achieved in a 0.010 inch by 0.20 inch rectangular flow channel and at a copper temperature of only 114°C. Two modified Bitter solenoids and a new, tape-wound wide-aperture solenoid were designed to dissipate the maximum power of 1700 kilowatts supplied by Professor Bitter's generator at M.I.T. through a considerably reduced transfer area and thus provide higher fields in smaller volumes. The design and preliminary performance data are described.

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

105. FURTHER DEVELOPMENT OF THE VIBRATING COIL MAGNETOMETER[1]

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The vibrating coil magnetometer measures the magnetic moment of a small sample of magnetic material placed in an external magnetizing field by converting the dipole field of the sample into an A.C. electrical signal.[2] The great advantage of such a technique is the resulting freedom of environment for the sample.

Such an instrument has been built into a twelve-inch Varian electromagnet. The high quality of this magnet, combined with modifications of the vibrator design, has greatly improved the stability and useful sensitivity of the magnetometer.

A.C. signals from various pickup coils are mixed in a multi-channel circuit. The resultant signal is amplified, is converted into D.C., and is displayed on an automatic recorder. With these improved circuits, the noise limitation of the detection system alone is just the thermal noise from the pickup coils, about 5 x 10^{-6} of the signal from a saturated 1/8-inch nickel sphere.

The useful fixed-field sensitivity of the improved magnetometer is within a factor of ten of this ultimate thermal limitation. This constitutes an increase in sensitivity over the previous instrument[2] by a factor of about 100. Thus at 10,000 oe. the magnetization of a one-gram sample with a susceptibility of 0.2×10^{-6} can be determined to better than 10 per cent. Sample data demonstrates the versatility and sensitivity of the instrument.

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

2/ D. O. Smith, Rev. Sci. Inst. 27, 261 (1956).

106. AN IMPROVED TORQUE MAGNETOMETER

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The torque method is probably the most common method used today for the determination of magnetocrystalline anisotropy constants of ferromagnetic single crystals. The torque magnetometer that is described, automatically plots the torque exerted on a slowly-rotating thin ferromagnetic disk suspended in a uniform magnetic field as a function of the angle between a reference line in the plane of the disk and the direction of the applied magnetic field. The torque exerted on the disk is converted into a D.C. electrical signal. Conversion is accomplished by coupling the mechanical torque system to a strain gage transducer whose electrical output is used to drive a D.C. strip chart recorder. The instrument consists of three units, the mechanical system, the transducer and the electrical system.

The mechanical system consists of a specimen holder rigidly fixed to a shaft supported by precision non-magnetic bearings; a coupling strip connecting the shaft to a transducer, a framework which supports the transducer and shaft, and a gear drive to rotate the specimen in a magnetic field.

The transducer is an electromechanical unit consisting of strain gages arranged and wired in the form of a Wheatstone bridge. The output voltage of the bridge circuit is proportional to the force causing strain in the bridge elements. The force, in turn, is proportional to the torque exerted on the specimen.

The electrical system consists of a current supply for the bridge circuit, supply voltage for the synchronous motor driving the instrument and a D.C. recorder which automatically plots the torque as a function of motor speed.

The keynote of the entire instrument is the transducer which converts the torque to an electrical signal. The sensitivity of the instrument is dependent on the transducer and limited by the friction between bearings and shaft.

107. A TRANSPARENT FERROMAGNETIC LIGHT MODULATOR USING YTTRIUM IRON GARNET

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Faraday rotation of visible light by transparent disks cut from single crystals of yttrium iron garnet (YIG) is described. Photo micrographs of disks between crossed polarizers show details of the domain structure. The transmission spectrum at wavelengths from infrared ($\lambda = 16$ microns) through visible are shown. Six absorption lines are found to occur in this region at wavelengths of 14, 11.6, 10.9, 8.6, 7.8, and 5.7 microns. An absorption edge occurs at $0.75 \pm .02$ microns.

Three types of amplitude modulation of light are proposed and discussed. Using Faraday rotation with a polarizer and analyzer, modulation is achieved in the following ways: (A) from the unmagnetized to the magnetized condition in the plane of the slab of YIG; (B) from magnetized in the direction of light propagation to magnetized in the reverse direction; (C) magnetized in the plane of the disk and set into precessional resonance at the modulating frequency.

A model of modulator (A) has been made to operate with moderate success. Construction and operation of modulator (B) is more interesting and is as follows: the YIG disk is located in the gap between the pole pieces of a ferrite cup core. The polarized light beam is made coincident with the axes of the disc and of the cup core, passing through a hole along the axis of the cup core. In this experiment the dc modulation was of the order of 20%. This corresponds to an average rotation over the part of the spectrum used of approximately 2 degrees per mil. At higher modulation frequencies the amplitude of modulation is dependent on the modulating input power up to the frequency at which the permeability of the cup core begins to fall off. Data for successful design of modulator (C) can be extracted from experiments of the type described in an accompanying abstract on resonances of disks magnetized in their planes.

Relations are discussed of the physical properties of ferromagnetic garnets to the design parameters of light modulators.

108. DESIGN OF OPTIMUM INDUCTORS USING MAGNETICALLY HARD FERRITES IN COMBINATION WITH MAGNETICALLY SOFT MATERIALS

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A new method is developed for the optimum design of inductors carrying unsymmetrical currents and having magnetically soft ferromagnetic cores biased with magnetically hard gaps. These techniques will provide the optimum physical design without the use of trial-and-error procedures when the electrical requirements are given.

A method previously developed for the optimum design of air-gapped inductors has been generalized and extended to cover the design of those having permanent magnet biased cores. This method includes both resistance and heating as size-limiting factors, and it includes the effects of appreciable alternating inductions on both the incremental permeability and on the total losses. Techniques are given for obtaining designs to meet those specifications for which the optimum design has no air gap, and those specifications imposing limits on the maximum induction.

The synthesis method is based on solving the appropriate equations in such a manner that the resulting relations may be used to map the ferromagnetic characteristics into new sets of curves. Quantities which may be determined from the electrical specifications are the abscissas and parameters, and quantities specifying physical sizes, gap lengths and numbers of turns are the ordinates. Such curves may then be used for the direct design of inductors by calculating the required abscissa and parameter functions, reading the ordinate values from the curves, and calculating the physical quantities. These curves may be directly compared with those for the air-gap designs to determine the relative volumes occupied by the ferrite-gapped and air-gapped designs.

Methods of analyzing such inductors without the use of trial-and-error procedures are also presented. These analysis methods provide the electrical characteristics when the physical design is given. They make use of Karapetoff-type gap lines drawn on the various induction curves to obtain the inductance when either the current or voltage is specified.

109. PULSE GENERATOR BASED ON HIGH SHOCK DEMAGNETIZATION OF FERROMAGNETIC MATERIAL

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The shock wave from a pellet of high explosive is passed without attenuation through one leg of a closed ferromagnetic core which has been previously magnetized. The shock wave demagnetizes the core, reducing the flux from the remanent value to zero. This change in flux generates a voltage in any winding wound on the core. Idealized calculations indicate that the voltage pulse generated in this manner will be a square wave with an amplitude given by $V = NB_r vw \times 10^{-8}$ and a pulse width given by $t = \frac{l}{v}$ where N is the number of turns, B_r the remanent magnetization (gauss), and V is the shock velocity (cm/sec.). It is also assumed that the core has a rectangular cross section w being the width of the core (cm) in the direction perpendicular to B_r and v and l being the thickness of the core (cm) in the direction parallel to v.

Experimental tests have produced output pulses with an amplitude of 46 volts/turn cm where the length of the pulse was in fair agreement with the known shock velocity of the material used. At the present time it is believed that the operation of the device can be explained by a transducer mechanism which converts some of the energy of the shock wave into electrical energy. Some special laboratory measurements made on ferromagnetic cores in connection with this device will also be described.

110. A NEW MAGNETIC CORE LOSS COMPARATOR

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A new method has been developed for the rapid measurement of magnetic flux density and power loss in single sheet steel specimens. In use the sheet specimen is inserted into an exciting unit which generates an a-c magnetomotive force to provide the required flux density. A measuring head is then pressed against the surface of the specimen and the power loss and flux density are read directly on an indicating instrument. Localized measurements in areas as small as 1 square inch are possible.

Simultaneous pick-up of the E.M.F. induced in the specimen by the time varying flux, and the M.M.F. generated by the exciting unit is accomplished by a pair of probes and a Chattock coil. Specially designed amplifiers, integrating circuits and switching arrangements enable the operator to observe the hysteresis loop or to read the power loss directly. Specimens of varying shapes and sizes may be employed without cutting or stacking and power loss distributions are readily observed.

Operating principles and theory are presented together with data illustrating the performance characteristics of the device. Applications to development and manufacturing are described.

111. THE PREPARATION OF ALNICO VII CASTINGS WITH IMPROVED PHYSICAL PROPERTIES

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Alnico VII having the highest coercive force of the Alnico alloys is not generally available because of its excessive brittleness. Laboratory studies show that the cooling rate of the casting plays the dominant role in controlling brittleness. A high purity Alnico VII, prepared from selected raw materials, melted under a controlled atmosphere was exceedingly brittle and badly cracked when chill cast in a 1-1/2 inch section. The exceptional purity of this melt is illustrated by the fact that no one impurity is present in concentrations exceeding 0.005%.

On the other hand, sound crack-free Alnico VII castings were made using silica shell molds. These molds retarded the cooling rate to around 20°C per minutes from the melting point to 1200°C. With this molding procedure satisfactory magnetic quality, chemical uniformity, and freedom from cracking were obtained by air melting standard raw materials of commercial purity. The magnets withstand the handling and thermal shock of heat treating, are amenable to cutting and grinding, and have an excellent surface.

Though the silica shell molds are costly, and their fragile nature necessitates careful handling, they do afford a means for preparing good quality Alnico VII with improved physical properties.

112. SKULL-CAP METHOD FOR MAGNETIZING BOWL-SHAPED MAGNETRON MAGNETS

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The recent development of the bowl-shaped magnet for use on magnetron tubes has introduced a challenging magnetizing problem for the tube manufacturer. This new magnet design is most desirable, because it is more efficient than earlier designs and supplies a stronger, more uniform magnetic field, at the same time using less volume of magnetic material. Although it has been possible in the past to magnetize these magnets individually through conventional impulse and electromagnet methods, it has been difficult to successfully magnetize the units when they are assembled on tubes. Two factors making it advantageous to assemble the magnets before magnetizing are the problems of handling charged magnets and maintaining the gauss during assembly. The external "skull-cap" method of magnetizing was developed, therefore, to permit the saturation of bowl-shaped magnets after they have been assembled to the tube.

The skull-cap method utilizes the same type of magnetizer as that used in the impulse method; but single, high current capacity coils in the form of copper bowls (skull-caps) around the magnets replace the internal loop used in the impulse method. The walls of the caps are tapered to concentrate the larger part of the magnetic field in the area around the neck of the tube. By having each cap large enough to cover the exterior of the tube magnets and connecting the caps with large enough tabs, the potential cross magnetization and limited current capacity problems are eliminated. Tapered iron pole pieces, placed between the skull-caps and tube magnets, aid the magnetizing process by establishing a low reluctance path for the flux to follow. An additional aid to magnetizing is included in the form of an external magnetic return circuit.

Established principles for saturating Alnico V magnets, magnetizer output pulse conditions, and the magnetic circuit requirements determine the outline dimensions of the skull-cap.

A dummy tube was assembled with bowl-shaped magnets for testing the skull-cap device. The probe of a gauss-reading instrument was inserted through a hole in the dummy tube into the center of the magnetic field. Tests showed that the skull-caps alone produce a flux density equal to that obtainable by conventional magnetizing methods. With the addition of the pole pieces, it was possible to obtain a gauss value equal to the maximum limit set by the magnet manufacturer. Saturation with less magnetizer voltage and the magnetizing of marginal magnets was possible due to the use of the external magnetic return circuit. Since the bowl-shaped magnets were easily saturated in these tests, the skull-cap method of magnetizing has been adopted for production use.

Graphs showing the results of tests conducted in developing this new method of magnetizing, and a drawing of the magnetic circuit, including the return path, are an integral part of the original paper.

MAGNETIC MOMENTS AND CRYSTAL STRUCTURES OF METALS

J. J. Becker, Presiding

113. MAGNETOMETALLURGY APPLICATIONS AND METHODS (Invited Paper)

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Magnetic analysis has not become the common place tool in metallurgy that it has for instance in organic chemistry. Two reasons for this are that no simple laws have been formulated say for solid solutions like those of Pascal for chemical bonding and that experimentally the required information in alloys is likely to demand information at temperatures other than the room temperature which is sufficient in many magnetic investigations of organic materials.

However, the understanding of magnetic phenomena is sufficient to permit determination of such things as valence states, atomic positions, limits of solubility, degree of homogeneity, and particle sizes. A review of such applications will be given using examples from recent work as well as references to the literature. Typical examples are the determination of the presence of oxygen interstitials, ascertaining that solute atoms are in solution and not segregated, checking the degree of order in alloys and salts. Though the usual techniques of magnetic analysis require considerable investment of time and resources, there are a number of methods which offer convenience at small cost of accuracy. For instance, magnetic moments can be measured from 4.2°K inside ordinary liquid helium storage containers; curie points can be determined inside muffle furnaces without the use of an electromagnet; sensitive force measurements can be carried out with a magnetron magnet supplying the field and a commercial milliammeter adapted for a balance.

114. SUGGESTIONS CONCERNING THE ROLE OF CO-VALENCE IN TRANSITION ELEMENTS AND THEIR ALLOYS1/

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Past attempts to describe the d electrons of the transition metals have been based on one or the other of two extreme views: the one, the conduction-band model, treats the d electrons as though they belong to the lattice as a whole rather than to particular atoms; the other, the shell model, treats the d electrons as though they are completely localized. The purpose of this paper is to point out that the relative symmetries of d wave functions and the lattice geometry should determine which d electrons may be

The spin coupling can be explained by taking account of the direct exchange interaction between the paramagnetic atoms and the conduction electrons and by a superexchange interaction between the paramagnetic atoms by way of the conduction electrons.

The combination of direct and superexchange interaction leads to a new type of molecular field theory[2] which allows the possibility of an antiferromagnetic-ferromagnetic transition. The usual Weiss theory does not admit a magnetic transition unless the molecular field constants are temperature dependent. Such transitions have been observed[3] in erbium and dysprosium. Recent experimental work[4] on dilute alloys of Mn in Cu also indicates the presence of such a magnetic transition.

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

2/ G. W. Pratt, Jr., Phys. Rev. 106, 53 (1957).
3/ Elliott, Legvold and Spedding, Phys. Rev. 100, 1595 (1955) and 94, 1143 (1954).
4/ Owen, Browne, Arp and Kip, J. Phys. Chem. Solids 2, 85 (1957).

118. FURTHER MAGNETIC AND X-RAY DIFFRACTION STUDIES ON IRON-RICH IRON-ALUMINUM ALLOYS

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Previous X-ray studies[1] have revealed anomalies in lattice parameter in the region of Fe_3Al which could be associated with magnetic properties and order-disorder transformations. It has been discovered that severely cold working non-magnetic alloys in the region of 35 atomic per cent aluminum produces an extremely large lattice volume expansion which is of the order of 3 per cent and at the same time makes the alloys highly ferromagnetic. Annealing at 200°C continuously decreases the magnetic saturation moment and restores the lattice to its original size. The effects of cold work and annealing on the degree of order and magnetic saturation are discussed.

1/ Conference on Magnetism and Magnetic Materials, AIEE (T-91), p. 246, 1957.

119. MAGNETIC MOMENTS AND APPARENT MOLECULAR FIELDS IN SOME RARE EARTH METALS AND COMPOUNDS

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Recent magnetization measurements at low temperatures, and in high magnetic fields have made possible not only the classification of certain exchange interactions as ferromagnetic, ferrimagnetic, or antiferromagnetic, but also lead to the quantitative estimation of magnitudes of interatomic interactions. On the basis of studies made on elements in the iron group and their compounds,[1] a study has been made of certain elements and compounds of elements in the 4f (lanthanide group) as well as compounds in the actinide group. The following are examples: Gadolinium, which had been previously found ferromagnetic,[2] has been magnetized up to saturation using temperatures down to 1.3°K and in fields up to 60,000 gauss. Seven Bohr magnetons per atom of gadolinium verified the theoretical predictions on the basis of a half-filled 4f shell. A molecular field of one million gauss was deduced from the magnetization measurements. The magnetization of cerium gave only 0.17 Bohr magneton per atom of cerium even at 1.3°K and in fields of 60,000 gauss. A remanent magnetization in zero field indicated a possible ferrimagnetism in cerium. Magnetization studies of certain rare earth oxides have been made as well as on uranium dioxide, which shows a high antiferromagnetic exchange interaction of the order of two million gauss.

1/ W. E. Henry, Phys. Rev. 94, 1146 (1954); 99, 668A (1955); Henry, Hansen and Griffel, Trans. A.I.E.E. 78 (1955).
2/ F. Trombe, Comptes rendus 221, 19 (1945).

DOMAIN PATTERNS AND THEORY

T. O. Paine, Presiding

120. MAGNETIC DOMAIN PATTERNS ON IRON WHISKERS

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Ferromagnetic domain patterns on single crystal iron whiskers have been studied using the Bitter powder technique. These crystals have been grown by hydrogen reduction of ferrous chloride1/ and have perfect crystal geometry typical of the several commonly observed directions of growth. Patterns have been observed on whiskers growing in the [111], [100] and [110] directions. In all cases the patterns on unmagnetized whiskers are very simple and subject to straightforward interpretation. In certain cases boundaries have been observed in the unmagnetized whiskers which appear to have a discontinuous normal component of magnetization. These whiskers range in diameter from 50 to 200 microns. Slight differences in the domain patterns have been observed as a function of size for certain orientations.

The domain patterns have also been studied during application of magnetic fields both normal and parallel to the whisker axis. Interpretations can be given in several cases of fields applied to [111] and [100] direction grown whiskers.

1/ S. S. Brenner, Acta Met., 4, 62 (1956).

121. DOMAIN OBSERVATIONS ON IRON WHISKERS

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Domain patterns have been observed on iron whiskers with approximately square cross-sections, ranging in size from 5 to 100 microns on a side. The whiskers frequently have perfect {100} faces, and strikingly regular and simple domain patterns can be observed. Some of the structures have been worked out in three dimensions, by observation and deduction; the pattern observed on the bottom surface of a whisker may be quite different from that seen on the top. Only a few kinds of pattern are found on smooth-sided, strain-free whiskers in zero field. The motion of these domain walls in an applied field is quite continuous and smooth; this behavior will be illustrated with motion pictures.

The domain patterns observed can be greatly changed by applying a stress to the whisker. Certain kinds of stress distribution can produce domain walls which contradict the usual rules for possible wall configurations.

The domain patterns on whiskers smaller than about 15 microns on a side are quite different from those on larger whiskers. We believe the changes are associated with the transition from multi-domain to single domain behavior.

122. MAGNETIC DOMAIN WALL MOTION

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The behavior of homogeneous ferromagnetic materials under the application of (a) rectangular-current switching pulses, and (b) small a-c signals, has been studied by numerous investigators. Most attempts to explain the observed switching voltage pulse shapes and switching times or the observed initial permeabilities have been based on the assumption that magnetization changes occur either by domain wall motion or by simple rotation of the magnetic moment vector. In order to explain the phenomena on the basis of domain wall motion, it is necessary to analyze the motion of a domain wall in the medium under consideration. However, although a number of particular geometries and types of material have been considered (e.g., metal laminations, cylindrical ferrite bodies), no general treatments have been given. We have therefore developed equations of motion for domain walls in both an infinite slab and a cylinder of infinite length, of any homogeneous ferromagnetic material, taking into account the effects of both conduction and displacement eddy currents (the latter have not previously been considered), domain wall mass, viscous damping, and restoring forces. A general differential equation for each geometrical configuration is derived using Lagrange's equation for one coordinate. The resulting equations can be used in calculating the predicted output voltage wave form and switching constant, or the complex initial permeability, to any degree of accuracy by numerical methods. Approximate analytical expressions for these quantities can be derived from the differential equation if certain terms (including those involving the dielectric constant), which are negligible for most common materials, are neglected; the expressions thus obtained are presented for comparison with similar expressions given by other authors.

123. A CALCULATION OF THE ENERGY LOSS IN MAGNETIC SHEET MATERIALS USING A DOMAIN MODEL

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The energy losses due to eddy currents in magnetic sheet materials under ac field excitation are usually calculated on the basis of the assumption that the permeability of the material, although not necessarily independent of the applied field, is independent of position in the magnetic material. It is well known that, in general, the losses calculated using this assumption are considerably lower than the measured values, even when hysteresis effects are included.1/

It has been pointed out by Williams, Shockley and Kittel[2] that this anomalous loss, the difference between the calculated and measured loss, could in principle be accounted for if the domain structure of the magnetic material were considered.

A simple domain model for an infinite plane sheet of magnetic material has been used by Néel[3] and also by Brouwer[4] to calculate the eddy current configuration and the complex permeability at low fields as a function of frequency. In the demagnetized state this model consists of a series of equal width parallel 180° domains magnetized in the sheet plane and separated by boundaries or domain walls which are perpendicular to the sheet plane.

We have used this model to calculate the losses in magnetic sheet materials subjected to low frequency, sinusoidal induction, excitation. The result is obtained in closed form for any induction up to saturation, and is expressed in terms of the ratio of domain width to sheet thickness in the demagnetized state.

The calculation is in satisfactory agreement with measured losses on oriented 3% silicon iron sheet.

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3/ L. Néel, Annales de L'Institute Fourier III (1951).
4/ G. Brouwer, J.A.P. 26, p. 1297 (1955).

124. GROWTH OF MnBi CRYSTALS AND EVIDENCE FOR SUBGRAINS FROM DOMAIN PATTERNS

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MnBi crystals from a centimeter to a few centimeters in dimensions have been prepared by crystallization in a temperature gradient from a liquid solution of bismuth saturated with manganese. From measurements on one of these crystals a value of 8800 gausses has been estimated for the saturation magnetization of pure MnBi at room temperature. Informative domain patterns have been developed on surfaces of a crystal by the normal Kerr magneto-optic effect and by the Bitter powder technique. In some instances a differential collection of colloidal particles was obtained within a single domain to produce a block pattern, which has been interpreted as evidence for sub-grain structure. Domain walls were moved by application of external fields.

125. ANTIFERROMAGNETIC DOMAIN WALLS AND THE MAGNETIZATION PROCESS IN α-Fe_2O_3

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The magnetic properties of α-Fe_2O_3 are of interest in understanding rock magnetism. In addition this material is a prototype of a large class of antiferromagnetic substances. An extremely interesting property of this class is the existence of a weak ferromagnetism superimposed on the normal antiferromagnetic susceptibility. Néel and Li have postulated that this weak ferromagnetism is associated with domain walls in the antiferromagnetic structure. This paper develops further the topography of both moment bearing and non-moment bearing walls in α-Fe_2O_3 and other antiferromagnetic structures. In addition certain dislocations in the crystal can call these walls into being and anchor them. It is found that there are two modes of changing the direction of the net moment of the wall — one is displacement of the domain wall and another is motion of a boundary within the domain wall, i.e., a Bloch line. Static magnetization measurements, including measurements of rotational and alternating hysteresis are reported. From these it is suggested that an important magnetization process in α-Fe_2O_3 is the motion of Bloch lines. The role of these Bloch lines is discussed in connection with the α-Fe_2O_3 low temperature transition. Experiments are also described on the recovery effect in α-Fe_2O_3 reported by Haigh.

126. OPTICAL PROPERTIES OF SEVERAL FERRIMAGNETIC GARNETS

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All the ferrimagnetic garnets examined to date have been found to be transparent to visible light down to wavelengths of about 5200 AU. Thin section (e.g., .003" thick or less) of single crystals have been examined to determine the absorption and the specific Faraday rotation versus wavelength at several temperatures. The absorption and rotation curves show some structure within the visible which becomes sharper with decreasing temperature.

By virtue of the Faraday rotation, it is possible to observe the domain structure of these crystals at any temperature below the Curie point. A magnetic birefringence has also been observed. Thus we are obtaining for these materials spectroscopic information on energy levels several electron volts above the ground state. It seems possible that the transitions responsible for the absorptions are forbidden transitions within the 3d shell of the trivalent iron ions.

Since at least one of these materials, yttrium iron garnet, shows rather remarkable properties in ferromagnetic resonance experiments, we may consider the possibility of combined microwave and optical experiments. Several of these are possible. For instance, it seems possible that we can detect ferrimagnetic resonance optically at least in disc shaped samples. Depending on experimental configurations it should be possible to observe the variation of M_z from point to point in the sample, or under other conditions to examine the variation in $(dM_x)^2$. Thus, we should be able to observe some features of the magnetostatic modes.

127. CONTRIBUTION TO THE STUDY OF FERROMAGNETIC MULTIDOMAIN PARTICLES[1]

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We consider an iron particle in the shape of a parallelopiped of dimensions a, b, c ($a < b < c$), containing two ferromagnetic domains separated by a 180^o wall of width y. In a preliminary calculation[2] we had shown that the width and energy per unit area of the wall may be substantially modified by the mangetostatic field. We are concerned here not only with the characteristics of the wall but also and primarily with the energy and domain configuration of the particle as a whole. We therefore calculate the total energy E of the particle (sum of exchange, magnetocrystalline and magnetostatic energies) as a function of the domain width y and of the particle size parameter (the dimensional ratios b/a c/a being preassigned). This calculation is made possible by a few simplifying assumptions and using the interaction energies between rectangular charged surfaces, as computed by Wright[3] and by Rhodes & Rowlands.[4] We minimize (graphically) the energy E(y) for several values of the size parameter a, in an attempt to determine the optimum size ranges favoring the single domain and the two-domain configuration respectively. The dependence on particle size of the wall characteristics in the two-domain configuration is discussed.

1/ This work was supported by the U. S. Air Force through the Wright Air Development Center.
2/ H. Amar – Journ. App. Phys. 28 G, 732 (1957).
3/ Wright, C. E. – Phil. Mag. 10, 110 (1930).
4/ Rhodes & Rowlands – Proc. Leeds, Phil. Soc. G part 4, 191-210 (1954).

128. CONSTRAINT PRINCIPLES IN FERROMAGNETIC DOMAIN THEORY[1]

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Conventional single domain calculations are inherently defective in that wall volume is neglected; in the limit of small particles, thin films, etc., a constraint principle in the form of a volume restraint becomes important. It is interesting to note that both Néel and Kaczer[2] (N-K), independently, pointed out still a further deficiency for the particular case of thin sheets. They demonstrated that wall thickness (and energy) no longer remain invariant when the magnetostatic energy contribution from non-flux closure domain walls is included. This effect is, however, decidedly different from the constraint principle one. Thus for the sheet problem, the N-K theory is applicable for moderately thick sheets where the non-flux closure configuration is stable – whereas the present calculation applies in the region of thin films where the Landau-Lifshitz (L-L) flux closure pattern prevails in the proximity of the stable single domain. For the L-L pattern, the wall thickness does not alter appreciably until the transition to the single domain is approached. The N-K theory gives an entirely different dependence of wall thickness on sheet thickness which may not vary over as many orders of magnitude as for the thin film case observed, for example, by Williams and Sherwood.[3]

1/ The research reported in this document was supported jointly by the Army, Navy and Air Force under contract with the Massachusetts Institute of Technology.
2/ J. Kaczer, Czech. J. Phys. 6, 310 (1956).
3/ H. J. Williams and R. C. Sherwood, J. Appl. Phys. 28, 548 (1957).

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MAGNETICS EXHIBIT
(Caribar Room)

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. These include:

Arnold Engineering Company, Marengo, Illinois
Booths 7 and 8

Burroughs Corp., Electronic Instrument Div., Philadelphia, Pa.
Tape wound magnetic cores (bobbin core); Testing Equipment; Ferrite core testing equipment Booth 21

The Carpenter Steel Company, Reading, Pa.
Alloys for electronic, magnetic and electrical applications Booths 15 and 16

Columbian Carbon Company, New York, N. Y.
Booth 17

General Electric Company, Research Laboratories, Schenectady, N. Y.
Demonstrations of magnetic phenomena Booth 2

G-L Electronics, Camden, N. J.
Tape wound and bobbin cores Booth 14

Indiana Steel Products Company, Valparaiso, Indiana
Alnico, Indox, Indox V, Cunife, and other permanent magnets; also new high flux (one piece) wound cores Booth 22

Magnetic Metals Company, Camden, N. J.
Electromagnetic core parts and shields Booth 9

Magnetics, Inc., Butler, Pa.
Tape wound cores; Permalloy powder cores; Bobbin cores; Laminations; Shields Booth 18

Nuclear Magnetics Corp., Norwalk, Conn.
Booth 11

Perfection Mica Company, Magnetic Shield Div., Chicago, Ill. Magnetic Shields Booth 6

Radio Frequency Labs, Inc., Boonton, N. J.
Magnet charging and testing equipment Booth 10

Raytheon Mfg. Co., Waltham, Mass.
Ferrites and Ferrite Isolaters Booth 3

Rese Engineering Company, Philadelphia, Pa.
Pulse type magnetic test equipment Booth 1

Sensitive Research Instrument Corp., New Rochelle, N.Y.
Universal Magnetic Testing Set; Production Core Loss Testing Set; Epstein Frame Testing Booth 19

Stackpole Carbon Company, St. Marys, Pa. Booth 20

Westinghouse Electric Corp., Pittsburgh, Pa.
Cores and Coils Booth 4