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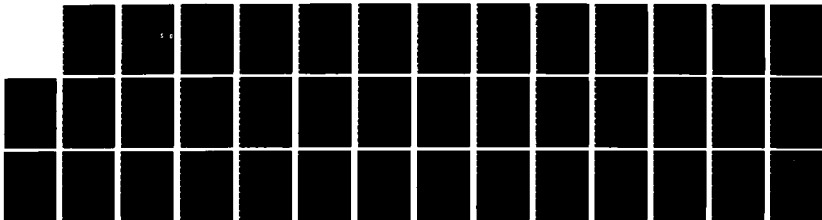
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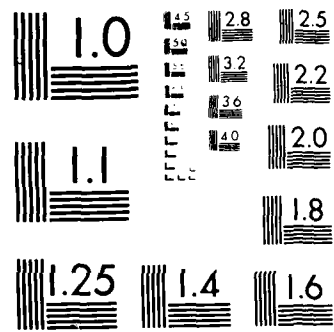
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RESEARCH OPPORTUNITIES IN MAGNETISM
FOR NAVAL APPLICATIONS

Report on a Workshop

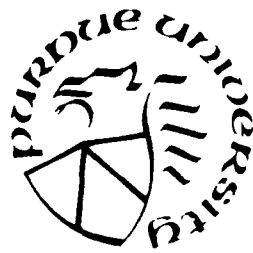
June 2-4, 1986

Purdue University

West Lafayette, Indiana

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- F. J. Friedlaender, Program Chairman
- J. M. Honig, Local Arrangements Chairman
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I. Introduction

Research in Magnetism was heavily supported by ONR during the years immediately following World War II. The successful development of magnetic-based devices such as magnetic mines, sonar systems and ship degaussing apparently convinced the Navy administration that support of magnetics research was both important and proper. This effort resulted in a steady stream of PhD theses dealing with topics in magnetism supported by the Office of Naval Research. A large number of the senior scientists in magnetism today owe their position to this large and continuing research support. In addition, core support of university research was also developed by the Office of Naval Research. The Laboratory for Magnetics Research at Carnegie Institute of Tech, which included the work of Professors J. E. Goldman and E.M. Pugh, is such an example. The Magnetism and Magnetic Materials Conferences as well as other conferences in magnetism were supported by ONR. To this was added support by the other Services as well as by the National Science Foundation.

Unfortunately, in the 70's, support for magnetics research by all of the funding agencies began to dwindle to the point that now there is only little and spotty support for magnetics research. The consequences of this diminished support has been far reaching. There has been a considerable shift in strength and activity in this area from the US to Japan, the Iron Curtain Countries, and Europe. Most importantly, the number of American PhD students in magnetism, who are the sources of new ideas and new developments, and who are required for new commercial ventures has diminished significantly.

In an effort to reverse this trend, the DOD recently sponsored a National Materials Advisory Board Study led by Dr. R.M. White to assess current progress in research and development in magnetic materials; to identify key problems and factors that may impede the use of future magnetic materials; and to recommend research and

development areas most likely to return the highest scientific and technological dividends within the next decade; and finally to present appropriate recommendations. Among the recommendations made were a request for increased support for magnetics research in certain strategic or growth areas and for an effort to regenerate a strong university based research program in magnetism and magnetic materials.

In that same spirit, the Office of Naval Research has recently sponsored this Workshop on "Research Opportunities in Magnetism for Naval Applications". The Workshop was planned to be a follow-up to the White study, but to be specifically focused on Navy-related research. The Navy has recognized that in those instances where programs in magnetism have been funded, the results have been far reaching and spectacular. A recent example is the new and exciting development of high energy product permanent magnets based on rare-earth-iron-boron compounds. One of the four scientists recently honored for that discovery is Dr. N. Koon who is supported by the Navy as a staff scientist at the Naval Research Laboratory. This development is certain to have important Naval applications. The Office of Naval Research has sponsored this Workshop to uncover other new ideas in magnetism appropriate for ONR support. The charge given to the Workshop organizers was straightforward: to identify areas of research in magnetism, magnetic materials, and magnetic devices, which may provide new and improved capabilities for the Navy.

The Workshop was organized into three groups of presentation. The agenda is given in Section IV. In the first session, Navy scientists presented and discussed important Navy activities which have been historically associated with magnetics research. Their presentations included discussions of Navy research presently underway, the status of these programs, and then concluded a review of Navy needs and related research issues in these areas. In the second session, presented by university and industrial scientists, the status, issues, and opportunities of a parallel series of topics were presented. The lead-off speaker for this session was Dr. R.M. White who gave a

synopsis of the NMAB report mentioned earlier. The final session consisted of presentations of special topics which were included because of their timely and novel nature. (Hard copies of the viewgraphs used are given in Section VI.)

At this juncture the Workshop participants broke into six discussion groups, each lead by a Navy and a Non-Navy discussion leader. They are:

1. Transduction and Magnetoelasticity
A. Clark and E. Callen
2. Microwave Ferrites and High Frequency Materials
P. Lubitz and G. Dionne
3. Magneto-optic Applications
J. Krebs and G. Connell
4. Magnetic Recording
R. Josephs and G. Bate
5. Magnetic Memories
L. Schwee and F. Humphrey
6. New Magnetic Materials Development
N. Koon and F. Luborsky

The objectives of the discussion groups were to identify *basic* (and if possible, to prioritize) research opportunities in Magnetism which were related to needs that the Navy speakers had previously identified. The results of these deliberations were presented to the entire Workshop for discussion on the final day. A written report summarizing these findings is provided in Section III.

Following the Workshop a selected group of participants, which included the Workshop organizers, consisting of Professors A. I. Schindler, F. J. Friedlaender, J. M. Honig and H. Sato, Dr. Kristl Hathaway, representing the Office of Naval Research,

and Dr. N. C. Koon of the Naval Research Laboratory, representing the Navy Labs, met to review the sense of the meeting and to establish a list of high priority recommendations. This list is included in this report in Section II. Also given are the discussion groups reports (Section III), and hard copies of the transparencies of the presented talks (Section VI).

II. High Priority Recommendations

A. Theory

Increased support is required to advance our understanding of fundamental magnetic properties and details of the magnetization process in important magnetic materials. Some high priority problems are presented.

- a. Ab initio calculations of fundamental magnetic properties are needed. These include calculations of magnetic anisotropy, magnetostriction, and magneto-optic effects which take into account spin-orbit interactions in a realistic fashion. Also required are calculations of the finite-temperature magnetic properties of important magnetic materials including weakly itinerant ferromagnets, heavy fermions, multilayers and superlattices, and small atomic clusters.
- b. Additional research is required to understand the dynamics of the magnetization process including mechanisms of domain wall propagation, domain wall structures (e.g., Bloch lines), coercive force mechanisms (e.g., pinning in amorphous materials), mechanisms of magnetization reversal in particles, and loss mechanisms and line widths down to mm wave lengths.

B. New Magnetic Materials Development

In the absence of adequate funding, there has been very little research on new magnetic materials development in the U.S. Recommendations to rectify this serious problem include the following.

- a. A national magnetic materials facility should be established that would satisfy the urgent need for research quantities of high-quality alloys, oxides, and magnetic compounds that are not commercially available. Specialized magnetic material in amorphous, polycrystalline, thin-film, or single-crystal form would be made

available to qualified investigators. (This facility should also have processing technology as described in (b) as a major mission.)

- b. Support for the development of advanced processing technology for new magnetic materials is urgently needed. This effort should include MBE grown artificial superlattice magnetic films, fine particles including the new nanometer-sized metallic and bimetallic clusters, MOCVD films and multilayers, rapidly quenched amorphous and microcrystalline alloys, and specialized (mm wave) ferrites. This effort should be coupled with the development of new analytical tools such as spin polarized photoemission, scanning electron microscopy with polarization analysis (SEMPA), and conversion electron Mössbauer spectroscopy.
- c. Research to capitalize on the new types of magnetic materials which are now available should be initiated and/or accelerated. Support should be provided for magnetic property measurements of (a) the newly available nanometer-sized metallic and bimetallic clusters, (b) MBE grown magnetic films and multilayers, (c) specialty ferrites, especially those for millimeter wave applications, (d) amorphous magnetic materials, and (e) the new RE-Fe-B permanent magnet materials.

C. Applications Oriented Magnetics Research

The Navy has a vital need to increase the capabilities of many devices which employ magnetic materials and concepts. Some key needs identified in the Workshop are given below.

- a. Research is required to improve the high temperature properties of the new RE-Fe-B permanent magnet materials and to optimize their properties for various applications. It is also important to search for new classes of magnetic materials with potential for use as permanent magnets.

- b. Studies are needed to find semimagnetic semiconductors or other magnetic materials with appropriate optical properties with large Faraday rotations above 77K, and to incorporate them into integrated optics structures.
- c. Studies are required to increase the magnetostrictive properties of promising materials including TbFe-based compounds, the high magnetic anisotropy cerium and actinide compounds, and artificially structured (MBE) superlattice materials.
- d. Research is required to develop superior Bloch line memories and other domain wall coded memories which offer the promise of phenomenal bit densities ($\geq 1\text{Gbit}/\text{cm}^2$).
- e. Research should be supported to improve microwave and millimeter wave ferrites by the study of ionic substitutions to increase remanent magnetization, and by the development of improved microstructures.
- f. Studies are needed to explore the potential of integrating magnetic films into semiconductor devices for a variety of electronic applications, such as isolators or circulators for very high frequency applications.

III. Reports of the Discussion Groups

A. New Magnetic Materials Development Discussion Group

Development of new magnetic materials take place at many different levels, ranging from control and modification of the characteristics, configurations, and microstructures of material which are basically already "known", to the creation of totally new material. Some of the most important advances of recent years in both areas have come about as a consequence of novel processing techniques which have permitted preparation of metastable material with totally new microscopic and macroscopic structures. Among the new classes of metastable materials are amorphous materials, heterogeneous granular material of metals, semiconductors and insulators, and multilayer films of all types ranging from amorphous to single crystal metals, insulators and semiconductors.

These new preparation techniques have been a major driving force for both potentially new applications and for new theoretical and experimental efforts to understand materials and their interfaces. For the first time it is possible to produce relatively well defined interfaces which are sufficiently controlled to permit comparison with theoretical predictions. Among the major new material developments are the (rare earth) R-Fe-B permanent magnet materials obtained through rapid quenching, and the discovery that very narrow resonance linewidths can be achieved in single crystal ferromagnetic metal films. These developments are of major importance to the Navy because of weight savings and performance improvements which result from application of the permanent magnets and from the potential of using low-loss, narrow linewidth material for very high frequency non-reciprocal devices, which may become components of future radar and communication systems.

Development of new and improved magnetic materials hinges on the interplay of several very important ingredients:

1. Advanced processing techniques, such as

- a) MBE
- b) MOCVD
- c) Sputtering and evaporation
- d) chemical intercalation
- e) rapid liquid quenching
- f) gas atomization
- and g) ion implantation

which can be utilized to produce novel artificial structure, such as

- a) multilayer film in all combinations of
metals/semiconductors/insulators/amorphous/single
crystal/polycrystalline
- b) granular solids of metals/semiconductors/insulators
- c) ultrafine nanometer size clusters and particles
- d) amorphous metals/alloys/semiconductors/insulators
- e) metastable crystalline materials

Some of these techniques are just now beginning to be utilized to their full potential in the generation of new and novel materials and in the synthesis of crystalline materials not heretofore found in nature. MBE grown films of various types of magnetic metals are being grown and examined at various laboratories. The results are exciting and sufficiently encouraging to justify expanded ONR support.

A new and very exciting area of materials synthesis just beginning to intrude on the scientific scene is that of nanometer sized clusters of metals and bimetals. Theoretical calculations on the effects of size of cluster on magnetic property have been carried out, but virtually no experimental examination has been performed. A back-of-the

envelope calculation by Mills indicated that the Kondo effect should be profoundly affected by the size of the cluster i.e., require large size clusters. In addition, alloying effects, in general, should be interesting and should be extensively studied. Artificial structures of arrays of this material offer unique research possibilities. ONR support would help stimulate research in this new and exciting area.

2. Modern characterization techniques such as

- a) spin polarized electron studies for analysis of surface magnetic characteristic
- b) light source X-ray and photoemission studies for various types of physical/electronic structure studies
- c) high resolution electron microscopy/Lorentz microscopy for structure and domain studies
- d) Conversion electron Mössbauer spectroscopy
- e) Neutron scattering technique for magnetic structure and magnetic excitation studies

3. Theoretical modeling

Magnetism has a number of major unsolved problems for which there are no ab initio calculations that explain the observed phenomena. These include the finite-temperature properties of both paramagnetic and weakly itinerant magnetic alloys, exotic materials such as heavy fermion systems, spin glasses and random field materials, systems with magnetic anisotropy, and lower dimensional materials as well as materials containing small particles, multilayers and superlattices. Significant progress has been made in such tasks as predicting magnetic moment formation at surfaces, but for the theory to be a full partner with experimental work, and to tailor the properties of the magnetic material, will require a more realistic inclusion of spin orbit effects to account for magnetic anisotropy and magnetostrictive effects. Also as potentially useful structures for electronic applications become smaller and more difficult to understand and

fabricate, it would be highly desirable to have really useful theoretical calculations for guidance and comparison with experiment.

4. Applications-Oriented Material Studies

In some cases the technological importance of an existing or newly discovered magnetic material is so great that an ongoing research effort into both property improvement as well as the search for potential replacement of critical material is of great significance. Examples are high performance permanent magnetics, soft magnetic material such as amorphous melt-quenched alloys, and both hard and soft ferrites. In case of the new rare-earth-iron-boron compounds, for example, many of their most fundamental properties have not yet been measured or modeled. Extensive measurements on high quality single crystals are needed to determine such important parameters as exchange, crystalline electric fields, and magnetic excitation energies. Efforts should be launched to look for new ternary, and quaternary phases which might serve a basis for new classes of permanent magnets.

Soft amorphous magnetic alloys are already finding application in small scale devices such as torque sensors and fiber-optic magnetostrictive magnetometers. The ability to control thickness, uniformity, anisotropy dispersion, surface smoothness, and other characteristics of these alloys will have an important impact on the utility of these materials and should be continued. Consideration should be given to establishing a resource institution for the preparation of high quality specialized research-grade amorphous magnetic alloys.

Ferrites remain one of the fundamentally most important material classes for both high frequency application and for inexpensive permanent magnets. As radar and communication frequencies move higher, the demands for larger effects and narrower linewidth leads to the need for better quality single crystals, and in the limit for uniformity and densification which results in good loop squareness. Processing of ferrites to

produce optimal magnetic properties still remains a problem of considerable practical importance.

In summary, we recommend support of the following kinds of programs:

1. Application of the newer characterization techniques to developing an understanding of the origin of (a) the properties of the new FeNdB permanent magnets; (b) the new very narrow line widths obtained in single crystal ferromagnetic films.
2. Utilization of new and advanced processing techniques to prepare new and novel materials.
3. Studies on nanometer size clusters of metals and bimetals; both experimental and theoretical.
4. Theoretical studies aimed at the calculation of magnetic anisotropy and magnetostriction; and at the finite temperature properties of both paramagnetic and weakly itinerant magnetic alloys, spin glasses, random field materials, and lower dimensional materials as well as materials consisting of small particles, multilayers and superlattices.
5. Applications oriented material studies should be supported on
 - (a) studies of the fundamental properties of high performance permanent magnets, amorphous metallic alloys and hard and soft ferrites.
 - (b) exploratory search for new ternary and quaternary phases which could be the basis for new classes of permanent magnets.
 - (c) the establishment of a resource institution for the study and supply of high quality specialized research grade amorphous magnetic alloys.
 - (d) processing studies to produce ferrites with optimal magnetic properties for particular applications.

B. Memories Discussion Group

The Memories Discussion Group addressed a number of issues which are outlined in the attached transparency copies (given in Section VI) and which are expanded on somewhat. The most important issues tended the process of research (including funding) rather than with the specifics of how to solve a given memory applications need.

There is a great need for funding of research leading to a fundamental understanding of the physics of magnetism, especially of those mechanisms useful for memories. As magnetic device needs become smaller and faster, such fundamental understanding becomes more critical. To engineer materials and to relate their properties to the best fundamental understanding, a proper modeling process is crucial; this is now not being adequately done. The need for basic research, for example, is important in garnet systems, for their potential application in vertical Bloch Line memory as applied here for the development of very high capacity memories. Funding agencies tend to see memory research as falling in the area of applied research, whereas there are still many basic physics questions which must be answered first. Basic research in these areas must be properly funded. Device design before the fundamentals are well understood can be a hazardous undertaking.

A second issue is that few individuals in funding positions are aware of the fundamental importance of magnetism in many applications areas, including memory. It is noted that the 1985 SDI call for white papers contained no mention of memory in general or magnetic memory in particular.

Memory calls for a multidisciplinary approach. This means that the decisions on how and where to best use magnetic memory concepts will require inputs from persons in EE, physics, computer science, mathematics, etc. This is especially true for the case of content addressable memory (CAM) which opens up a radically new approach to memory use. But this possibility can only be realized with the assistance and

cooperation of scientists in diverse areas. It should be noted that vertical Bloch line technology is unique in its applicability to real time search and comparison processes.

Concern was expressed in the discussion group over how to reach the most appropriate funding areas in various agencies. Historically magnetic memory research has been supported by the materials area of funding agencies. While materials and physics finally play a crucial role, the possible synergism of new memory concepts will require a wider range of contacts.

C. Magneto-optics Discussion Group

Introduction

Research in magneto-optics will impact two areas of future Navy need: namely, optical disk storage and optical signal processing. The increased bandwidth needs generated by the high data flow and analysis demands of Navy tactical systems in the 1990-2010 timeframe require strongly enhanced optical signal processing (here defined to include optical communications) and data storage capabilities. The Strategic Defense Initiative program may well raise these needs to a critical level.

This report will not attempt to specify what engineering programs should be undertaken to develop devices in these areas. Rather it will identify and prioritize what we consider to be the major basic physics and materials science issues that will underpin and impact on future development activities.

It is strongly suggested that the Office of Naval Research (or other DoD funding agencies) support basic research in the critical areas identified and listed in prioritized form below. This research naturally divides into physics related and optical/electronic materials related issues as shown.

A. Basic Physics Issues

Five issues were identified. In order of priority they are:

1. Improve the fundamental understanding of the magneto-optics of magnetic alloys and insulators through complementary first principles theoretical and experimental initiatives.
2. Improve the fundamental understanding of the magneto-optics and magnetic anisotropy of amorphous rare earth-transition metal (RE-TM) alloys via systematic studies of high quality materials.
3. Investigate the dynamic response of magneto-optic materials, particularly diluted magnetic semiconductors such as $Zn_{(1-x)}Mn_{(x)}Se$.
4. Investigate the magneto-optics of magnetic heterostructures with emphasis on interface phenomena.
5. Investigate the magnetic order in diluted magnetic semiconductors and other magnetic/semiconductor systems available through heteroepitaxial methods.

Of these, the first two are particularly timely and should provide results that go far beyond the specific Navy needs. The new theoretical work will establish the roles of spin-orbit splitting, spin polarization, and optical matrix elements in determining the magnitude of the magneto-optic effect in materials of interest and will provide an estimate of the limit achievable through materials development. It is also expected that a general understanding of exchange coupling in f-electron systems will evolve, particularly from studies of uranium compounds and, through carefully selected model band structure calculations, there will be a significant impact on the magneto-optics of amorphous RE-TM alloys. (Studies analogous to this last situation were especially illuminating for amorphous Si in the mid-70s). This work is made possible now through reasonable extensions of modern band theory computations.

The second topic, the magneto-optics of amorphous RE-TM alloys, is appropriate now because the availability of high quality material makes it possible to isolate the intrinsic properties of these amorphous magnetic materials for the first time. The results obtained will impact widely in the amorphous metals area. For example, simulations and measurements of the structure, structural anisotropy, and intrinsic magnetic anisotropy will not only affect the development of magneto-optic storage materials but will also indicate the mechanisms for generating amorphous anisotropies. Much will also be learned about the fundamental mechanisms of domain wall pinning and propagation in amorphous systems and the evolution of simple chemical trends based on a microscopic understanding of the electronic structure. The time is now ripe to pursue these studies.

B. Basic Materials Issues

Four issues were identified. In order of priority they are:

1. Investigate heteroepitaxial growth of magneto-optic materials on semiconductors and vice versa (e.g., garnets on Si or GaAs).
2. Develop materials with magneto-optic properties superior to those of existing garnets.
3. Optimize diluted magnetic semiconductors for magneto-optic effects.
4. Investigate thin film growth of crystals with superior magneto-optic figures of merit (e.g. uranium compounds).

The first topic is an important activity with the potential for high impact in the future. Nevertheless, it is out of the mainstream of semiconductor epitaxy studies and there is a danger that it might fall into a funding gap. The goal is very challenging and by pursuing it, there will be results which apply widely in the field of heteroepitaxial growth. Furthermore, such structures are inherently compatible with integrated

optics and would significantly impact that field.

The second topic is very important but may prove very difficult in view of the extensive work which has gone into the optimization of garnet magneto-optical properties.

Another high payoff area is to try to incorporate diluted magnetic semiconductors into integrated optics structures. This materials class exhibits giant Faraday effects but additional research is necessary to achieve larger effects at 77 K or above.

D. Magnetic Recording Discussion Group

Standard computer disks, tapes, and drives used by the Navy are satisfactory and their performance enhancements are driven by commercial requirement. No research or development is needed. Naval instrumentation tape recorders of the future, however, differ from commercial recorders in two respects; very high data rates are required (1-2Gb/sec) and the erasure of the tapes must be more complete than that of tapes used for civilian applications.

These data rates are not currently being achieved in commercial recording devices and require recording at higher linear densities (bits per inch), higher frequencies and higher scanning speeds of the heads over the tape. Higher densities ($\geq 100,000$ bpi) will be driven by commercial requirements and will be achieved by 1) reducing the head-tape separation, 2) increasing the tape coercivity without increasing its switching field distribution and 3) reducing the depth of recording. Since the technical problems of making commercial thin-film tapes have not been solved, it is assumed that only particulate tapes will be used. Higher frequencies call for the ability to make small head structures having permeabilities ~ 1000 out to frequencies of hundreds of megahertz. It should be noted that the MAGDART program with the goal of making a head structure having write-read capability out to 300 MHz has been funded by NSA and should

provide the technological vector for the Navy's requirements. The high scanning speeds of 3000"/sec and high track densities are most easily achieved by designs based on advanced commercial, rotating-head recorders, e.g., 8mm video, R-Dat, etc. High track densities imply the need for narrow ($\sim 1\mu\text{m}$) heads made of soft magnetic materials having high saturation induction ($B_s \geq 15,000$ Gauss), low coercivity (< 1 mOe), high resistivity ($> 10^{-4}\Omega\text{cm}$) and, to achieve long head life, great mechanical strength and toughness. The lack of materials having these characteristics (particularly B_s) are preventing the practical use of particles having coercivities greater than 0e. Both the number of tracks per head and the total number of heads per machine should be minimized in order to reduce costs (and crosstalk).

The possibility exists of finding radically different solutions to the problem of making high data-rate, narrow-track heads. For example, it may be possible to make scanning heads in which a mechanical pulse propagating across a wide track, activates the only region of the gap where the pulse is. There exists at present no materials with the magneto-mechanical properties to allow such writing heads to be made but the idea is sufficiently attractive to make research and development worthwhile. Reading could be accomplished magneto-optically or magneto-resistively and either would require the development of materials with improved performance.

Although many of these requirements involve the solution of problems that are primarily engineering in nature, some pose significant and fundamental questions in the physics of magnetic materials. These include,

- the mechanisms of magnetization reversal in particles
- the role of the surface of the particle in its switching behavior
- the role of the interactions between particles
- long- and short-term time effects

- the erasure problem
- the discovery of materials with large magneto-optic and magneto-resistive properties and materials with higher saturation magnetization.

Achieving the levels of erasure required by considerations of security call for research in several areas. Again, a much better understanding is required of the mode of magnetization reversal of particulate assemblies. For example, the strategy to achieve maximum erasure will depend on whether the reversal process involves rotation of the magnetization or domain wall motion. Similarly, a reduction in the observed distribution of switching fields will also be facilitated by a better understanding of the reversal process as well as by a more creative approach to the sequence of fields that is most likely to produce nearly total erasure. Finally, erasure must be achieved quickly. Ideally, the total complement of tapes on a ship or airplane should be erasable in seconds. This is not at all a trivial problem and its solution would be speeded up by a better understanding of switching processes. Cassette-loading machines are more appropriate with regard to bulk erasure and would also alleviate the present difficulties in loading tape into airborne recorders for example, on S3 aircraft.

Present tapes are not capable of withstanding the full range of operating temperatures (0-70 ° C), and this range is more likely to widen than to narrow. The lower temperature presents no problems but 70 ° C is uncomfortably close to the glass transition temperature of polyethylene terephthalate, the most commonly used tape base film. A tape based on polyimide film will probably be needed but this material is expensive and has its own technical problems; it can be permanently deformed by the repeated motion of a head over the same track.

The most immediate near-term requirement is to develop and implement measurement techniques and qualification criteria for both magnetic tape and heads. The manufacturers' specifications give only a bare minimum of information on some of the

functionally important properties; others such as the coefficients of friction are usually not specified at all. When magnetic tapes or heads fail in the field the reason is almost always found among the non-magnetic properties such as: cohesion, adhesion, compliance, roughness, friction, stiction, resistivity, transmissivity, hardness, toughness, dispersion, abrasivity etc., etc. These properties are imperfectly controlled because their physical and chemical origins are imperfectly understood and they are imperfectly understood because they are difficult, inter-disciplinary and infrequently studied. To buy heads and media cost-effectively the Navy must develop acceptance criteria for those functionally important properties not already covered by specifications and improve inadequate criteria and specifications.

E. Microwave Ferrites Discussion Group

For devices of the lower microwave frequency regime (i.e., 10 GHz and below), the general state of the art has not been "materials limited" for about a decade. The developments of low-cost lithium ferrites and magnetostriction-compensated garnets both occurred in the early 1970's and had the immediate impact of reducing the need for basic research in microwave ferrites. In recent years, emphasis placed on monolithic microwave integrated circuits (MMIC's) has led to significant advances in GaAs technology for millimeter wavelengths. However, limitations of power, efficiency, and reliability of semiconductors, together with the general need for nonreciprocal devices at these high frequencies (above 20 GHz), have given rise to renewed interest in upgrading ferrite capabilities for millimeter waves, where existing materials have serious drawbacks. The following paragraphs summarize basic research opportunities of immediate importance in this field, with priorities suggested by the order of discussion.

1. Single Crystal Growth (Film & Bulk)

The ceramic ferrites that have been very satisfactory for most lower microwave frequency applications are now causing problems because of a lack of microstructure control. At shorter wavelengths, dimensions and tolerances of device parts become smaller, and homogeneity, surface finish, and machinability are all the more critical. Cost factors rise dramatically where reproducibility (yield) is poor. With dimensions approaching millimeter scale, the use of single crystals becomes an obvious alternative in both film and bulk forms.

Much interest has moved towards solid state monolithic technology (GaAs, later InP) as a substitute for ferrite control devices. A marriage of semiconductor and ferrite epitaxial technologies (for example, GaAs on spinel or garnet ferrite or GaAs and ferrite on a common substrate) is being considered as a means to exploit the best of both capabilities.

Magnetostatic surface wave (MSW) technology remains a frontier area in radar signal processing and requires epitaxial ferrimagnetic media.

2. High Magnetization Ferrite

In the design of ferrite components for microwaves, the ratio of phase shift per wavelength to loss per wavelength, i.e., the figure of merit (F.O.M.), is usually optimized by employing the highest magnetization ($4\pi M$) allowed by nonlinear instability constraints. At 10 GHz for example, $4\pi M$ should be about 2000 G. If $4\pi M$ is scaled up for the 60 GHz requirement, however, the allowed value increased to 12000 G, which is more than double the 5000-G maximum available magnetization of existing microwave ferrites. As a consequence, the F.O.M. will of necessity reduce because of proportionately lower phase shifts per wavelength. Furthermore, parts fabrication problems are aggravated because the signal path length must be increased to compensate for the loss in phase shift, leading not only to the higher losses but to longer parts with smaller

cross sections. This requirement for higher $4\pi M$ impacts on the single crystal technology discussed above, but more immediately on ceramic ferrites for discrete devices or arrays. Any increase in $4\pi M$, particularly at remanence, either by raising the saturation magnetization or by improving hysteresis loop squareness, will translate directly into an improved F.O.M. Reductions of insertion losses by these material improvements would be critical in determining the cost and efficiency of large phased array radars.

In terms of specific ferrite compositions, the lithium and manganese spinel systems ($A[B_2]O_4$) offer the most promising possibilities, through cation site distribution changes. For the lithium ferrites, the magnetization may be increased by moving Li^{1+} ions from the B sublattice to the A sublattice. In the manganese system, this goal may be accomplished by moving Mn^{2+} ions from the A sublattice to the B sublattice. The substitution of Zn^{2+} for Mn^{2+} in A sites should also help to increase the room-temperature magnetization. To achieve the above cation site distributions, unconventional chemistry and ceramics will probably be required.

3. Optimum Ceramic Quality

For ceramic ferrite parts, there is an urgent need for improved microstructures (higher densities and more uniform grain sizes) which determine machinability, reproducibility, and surface finish quality, and also affect dielectric performance. Efforts should be addressed towards development of new powder preparation methods, and sintering techniques at lower temperatures for shorter durations to reduce the possibility of discontinuous grain growth.

4. Loss Mechanisms Studies

In spite of the large amount of excellent research reported on loss mechanisms at lower microwave frequencies, questions still remain concerning the dependence of dielectric loss on microstructure, particularly at millimeter wavelengths. In light of the foregoing discussion on the lack of high magnetization ferrites, it should be clear that these losses can be devastating.

The ferrimagnetic resonance (FMR) linewidths of any single crystal considered for a near-resonance device application must be small. It is therefore necessary to determine the limiting linewidth value for hexagonal ferrites, or any metal that may be considered, and the relaxation mechanism that controls it.

5. Characterization of Properties

A high magnetization NiZnMn spinel ferrite with stress-insensitive square hysteresis loop has recently been discovered. Its apparently superior dielectric and microstructural properties suggest that it will prove to be preferable to conventional lithium ferrites in most millimeter-wave applications. Before this material appears in commercial catalogues, it is important that its high frequency and high power properties be thoroughly characterized.

Hexagonal ferrite single crystals, in both bulk and film form, must be characterized in terms of the limiting FMR linewidth and hysteresis loop parameters, particularly the coercive field.

6. Device Considerations

Although most exploratory device work does not fall within the scope of basic research, there are innovative concepts that are worthy of mention in this context.

The use of single crystals with internal uniaxial or planar anisotropy fields in circulator or phase shifter applications is being considered for frequencies at least up to 140

GHz. The crystal growth and experimental evaluation tasks discussed above apply directly to this activity.

Recent investigations of iron films on semiconductor substrates suggest the interesting possibility of utilizing the very high magnetization of iron for nonreciprocal stripline devices. There are important questions concerning potential insertion losses that would arise from eddy current and ferromagnetic resonance effects. Studies of these two phenomena as part of the general device development activity would be essential.

As attempts to reduce fabrication and production costs, methods for integrating discrete devices (phase shifters) in arrays, in some cases using dielectric waveguide concepts, are being advanced in industry with government support.

F. Transduction and Magnetoelasticity Discussion Group

Magnetoelastic transducer devices fall into two categories; projectors and sensors. Because of the high power requirements of projectors, the materials of choice are oriented polycrystals, and even single crystals in special cases. On the other hand, the high sensitivity requirement of sensors dictates that future sensors will be based on amorphous materials. Hence, from a materials viewpoint, it is convenient to organize this report in two overall sections, crystalline compounds and amorphous materials.

I. Crystalline Compounds

1. High Magnetostriction: A Materials Challenge

The rare earths exhibit enormous magnetic anisotropy and magnetostriction. For example, the magnetostriction of Tb or Dy at 80 K is about $10,000 \times 10^{-6}$. But the exchange coupling of the rare earths is weak, so that at room temperature both Tb and Dy are only paramagnetic. To raise the ordering temperature, one alloys the rare earth

with a transition metal, Fe. Thus the magnetostriction of TbFe_2 at 80 K is 6000×10^{-6} , and at room temperature is 3600×10^{-6} , an unavoidable reduction of a factor of three from that of the pure rare earth at 80 K. Yet the best Terfenol-D materials now in use have a magnetostriction λ of only 1000 to 1200×10^{-6} at operating fields, a loss of another factor of three. Since the figure of merit varies as λ^2 this results in a degradation of performance by almost an order of magnitude, a factor which can be recaptured. A short term, limited effort in crystal synthesis is almost certain to yield significant pay-off.

2. Huge Anisotropy and Magnetostriction of Iron

Historically, Fe has a small anisotropy (Fe is in an S state, or witness permalloy). Yet in the $\text{R}_2\text{Fe}_{14}\text{B}$ hard magnets, Fe contributes about 30% or so of the magnetic anisotropy. Why is the Fe contribution so large?

Fe metal is noted for its small magnetostriction. Yet in the R_2Fe_{17} 's Fe exhibits a large magnetostriction. Why is the Fe contribution so large?

The physics of Fe in these environments is intriguing. Perhaps other compounds or metastable phases with Fe in similar environments can be created.

3. Magnetic Sandwiches and Superlattices

Magnetic superlattices is a wide-open new frontier. One can imagine many configurations. For example, consider a metamagnet layered between sheets of a soft ferromagnetic material. Magnetizing the ferromagnetic layers with a small field might magnetize the metamagnet and induce a large magnetostrictive displacement. This displacement, due to exchangestriction, could be much larger than the conventional anisotropy-driven linear magnetostriction.

4. Cerium and the Actinide Compounds

The important characteristic of these systems is their extremely large magnetic anisotropy (greater than 400 KOe in CeSb) - comparable to the exchange. Thus the potential for magnetoelasticity is tremendous but so far unexplored. As with terfenol, it might be possible to synthesize materials of opposite sign of anisotropy to obtain a low magnetic anisotropy but large magnetostriction.

5. Ab-initio Calculations: Band Theory of Magnetostriction

These calculations are now at a stage where they permit accurate estimates of magnetic moment. The next step is a study of magnetic anisotropy and the one after that, of magnetostriction. This would be the first, first principles, nonperturbative, band theoretic calculation of magnetostriction.

II. Amorphous Alloy

1. Theory

There is no viable theory of magnetoelasticity in random anisotropy amorphous alloys. What is the upper limit to the magnetoelastic coupling? How does it depend upon the local anisotropy and the exchange? Is there a lower limit to the coercivity? What is the temperature dependence of the magnetostriction and what is the field and temperature dependence of the magnetization? These are among the questions such a theory would address.

2. High Magnetomechanical Ribbons

Experiments on ribbons are limited by the quality of the materials. Because of a lack of commercial incentive, no work is going into fabricating, for example by melt-spinning in vacuum, materials with ultra high coupling factors. Internal defects,

impurities, surface irregularity impede elucidation of basic physical mechanisms and degrade device performance. An institutional route must be found to produce ribbons of the highest quality. The physics of domain rotation and dynamic magnetoelastic behavior needs to be explored.

3. Sputtered Sensors

By vapor deposition (high rate sputtering) one can fabricate all the liquid quenched metglasses and make many others not accessible by liquid quenching. Furthermore, samples of a broad range of thickness and of varying and controlled shape can be produced. Vapor deposition will allow the fabrication of sensors directly onto chips, with associated electronics.

4. Metastability

Amorphous alloys are the prime example of a system with many close-lying states within the ground state manifold. This leads to strong temperature dependence and to relaxation times in the magnetic and magnetoelastic properties- magnetization, permeability, magnetostriction. To characterize the thermal and temporal behavior will require theoretical and laboratory effort.

5. Non-linear effects

In amorphous materials the coupling factor approach unity and the modulus changes by a factor of ten in a magnetic field. The strong coupling causes non-linear effects such as period doubling. Amorphous materials may be the best controlled laboratory system in which to examine non-linear physical processes.

IV. Agenda

RESEARCH OPPORTUNITIES IN MAGNETISM FOR NAVAL APPLICATIONS

(Sponsored by The Office of Naval Research)

AGENDA

June 2 - 4, 1986

Stewart Center Room 310

Purdue University

Monday, June 2, 1986

- | | |
|--|-------------|
| Registration and Coffee & Donuts | 8:00- 8:30 |
| I. <u>Opening Session</u>
J. M. Honig, Chair | |
| A) Welcome - H. T. Yang, Dean, Schools of Engineering | 8:30- 8:40 |
| B) Introduction to Workshop - A. I. Schindler | 8:40- 9:00 |
| II. <u>Navy Presentations: Programs, Status, and Requirements</u>
K. B. Hathaway, Chair | |
| A) N. C. Koon (NRL*) - Part I Magnetic Field Sensors
Part II Hard & Soft Metallic Magnetic Alloys | 9:00- 9:45 |
| B) P. Lubitz (NRL*) - Microwave Ferrites for Naval
Applications | 9:45-10:15 |
| C) L. Schwee (NSWC**) - Radiation-Hard, Non-Volatile
Memories | 10:15-10:45 |
| Coffee Break | 10:45-11:15 |
| D) A. Clark (NSWC**) - Magnetomechanical Transduction | 11:15-11:45 |
| E) J. Krebs (NRL*) - Magneto-optic Applications | 11:45-12:15 |
| Lunch | 12:15- 1:15 |
| F) R. Josephs (NADC***) - Magnetic Recording | 1:15- 1:45 |
| III. <u>Overviews: Status, Issues, and Opportunities</u>
F. J. Friedlaender, Chair | |
| A) R. M. White (CDC) - NMAB "Magnetic Materials" Survey | 1:45- 2:15 |
| B) F. E. Luborsky (GE) - Amorphous Magnetic Materials | 2:15- 2:45 |
| C) G. A. N. Connell (Xerox) - Magneto-optics | 2:45- 3:15 |
| Coffee Break | 3:15- 3:30 |
| D) G. Bate (Verbatim Corp) - Recording - Fine Particles | 3:30- 4:00 |
| E) G. F. Dionne (Lincoln Lab) - Microwave Ferrites | 4:00- 4:30 |
| F) F. B. Humphrey (Carnegie-Mellon) - Large Scale
Associative Memories | 4:30- 5:00 |
| G) D. L. Mills (Univ. California-Irvine) - Outstanding
Theoretical Issues in Magnetism | 5:00- 5:30 |
| Workshop Dinner at "The Trails" (see transportation note) | |
| Cocktails | 6:30- 7:30 |
| Dinner | 7:30 |

Tuesday, June 3, 1986

- Coffee & Donuts 8:00- 8:30
- IV. Special Topics
H. Sato, Chair
- A) J. K. Furdyna (Purdue) - Diluted Magnetic Semiconductors 8:30- 8:45
B) G. Prinz (NRL*) - Layered Structures 8:45- 9:00
C) A. R. Williams (IBM) - Computational Approaches to Magnetism 9:00- 9:15
D) A. S. Arrott (Simon Fraser) - Engineering Magnetic Materials on the Atomic Scale 9:15- 9:45
- Coffee Break 9:45-10:30
- Break into Groups for Workshop Discussions 10:30- 3:00
(Lunch will be scheduled)
- Coffee Break 3:00- 3:30
- Resume Workshop Discussions 3:30- 6:00

Wednesday, June 4, 1986

- Coffee & Donuts 8:30- 9:00
- V. Final Session
A. I. Schindler, Chair
- A) Presentation of Findings/Discussion 9:00-12:00
- Completion of Workshop 12:00 (noon)

Open House: Make special arrangements with appropriate Purdue Host.

NRL* - Naval Research Laboratory, Washington, DC

NSWC** - Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD

NADC*** - Naval Air Development Center, Warminster, PA

Transportation Note: Bus 1 - leaves for Sheraton at 5:45 from the eastside entrance of the Purdue Memorial Union;
leaves for The Trails at 6:15 from the Sheraton
Bus 2 - leaves for The Trails at 6:15 from the eastside entrance of the Purdue Memorial Union

PLEASE NOTE: WEST LAFAYETTE, IN (PURDUE) IS ON EASTERN STANDARD TIME

V. Attendance List

CNR MAGNETISM WORKSHOP

June 2-4, 1986

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