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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research involved studies of the magnetic properties of multilayered magnetic films and high quality thin. Both ultra high vacuum sputtering and molecular beam epitaxy techniques were utilized to prepare the films. Both electrical transport and mageto-optic effects were use measure the magnetic properties of the films. The focus was the determination of the temperature dependence of the magnetic anisotropy energies of epitaxial iron films, the magnetization dynamics of thin films, and the transport properties of multilayers. In the anisotropy energy work the effects of interfacial strain and morphology were the focus. The dynamics effort has recently provided a model for slow dynamic systems. The transport effort utilized multilayers of magnetic and nonmagnetic metals to study the interfacial scattering. The combination of a magnetic and nonmagnetic metal in this work facilitates the origin of the scattering by use of the anisotropic magnetoresistance.

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TABLE OF CONTENTS

I. Statement of Work

This research program was directed at developing new models for a more fundamental understanding of magnetism and to investigate new magnetic phenomena such as the recent discovery of exchange coupled multilayers. The research focused on the use of advanced thin film preparation techniques to prepare high quality multilayered and single thin films. Much of the research utilized magneto-transport techniques to probe the magnetic properties of the magnetic films. The films were prepared by both ultra high vacuum sputtering and molecular beam epitaxy techniques. In particular, the magnetic phenomena investigated included both a fundamental understanding of the spin-orbit coupling, the above mentioned exchange coupling, and a variety of interfacial effects. The interfacial effects include exchange coupling between ferromagnetic and antiferromagnetic films, electrical transport in multilayered magnetic systems, and the effects of interfacial morphology on magnetization pinning. The spin-orbit coupling effects are very important from both a basic science view and for magnetics applications. In terms of applications, the spin-orbit coupling determines the crystalline anisotropy energies and various other magnetically important quantities.

II. Accomplished Research

As a mechanism of describing this research, we will list and discuss the publications which have been either published, submitted for publication, or are currently in draft form.

A. "A First Order Magnetic Field Induced Phase Transition in Epitaxial Iron Films Studied by Magnetoresistance," K.T. Riggs, E. Dan Dahlberg, and G. Prinz, Phys. Rev. B41, 7088 (1990).

This study focuses on the rotation of the saturation magnetization in the plane of the epitaxial iron films and utilizes the anisotropic magnetoresistance to follow the rotation of the magnetization in the presence of magnetic fields applied parallel to the plane of the films. As mentioned in A. above, the surface anisotropy energy in the (110) films is insufficient to rotate the magnetization out of the plane of the films. With the magnetization pinned in the plane of the film then the rotation of the magnetization in the plane of the films as a function of the magnitude and direction of a magnetic field applied in the plane of the film can be modeled as a first order transition. The easy way to understand this behavior is to consider two easy axes separated by a hard axis in the plane of the film. If the magnetization is required to rotate from one easy axis to the other by the application of a magnetic field, the applied magnetic field must be of sufficient strength that the magnetization can pass by the hard axis. Once this occurs the magnetization then abruptly (in a first order sense) makes the transition to the other easy axis. In the analysis of this behavior the uniaxial and fourth order anisotropy energies of the epitaxial films can be determined.

B. "Magnetic Domains in Epitaxial (100) Fe Thin Films," Jeffrey M. Florczak, P.J. Ryan, J.N. Kuznia, A.M. Wowchek, P.I. Cohen, R.M. White, G.A. Prinz, and E. Dan Dahlberg, Mat. Res. Soc. Symp. Proc. 151, 213 (1989).

This work shows how the surface morphology of the semiconductor substrate can influence the magnetic properties of the epitaxial magnetic films. It was found that the misfit dislocations which penetrate the surface of the InAs alloyed substrates can dominate the magnetic properties of the Fe films. The magnetics were investigated with both a magneto-optic magnetometer technique we developed (see below in other research) and with imaging Kerr microscopy. The most interesting feature of this research is the result that by correct preparation of the substrate the magnetization can be made almost isotropic in the plane of the film and controlled with modest applied magnetic fields (20 Oe).

C. Magnetic Anisotropy Constants of Epitaxial (110) Fe/GaAs Films From 77K to 293K Studied by Magneto-resistance," Daniel K. Lottis, G.A. Prinz, and E. Dan Dahlberg, Mat. Res. Soc. Symp. Proc. 151, 213 (1989).

Because the iron films are locked to the substrate the question arises as to the temperature dependence of various magnetic properties. In this paper we studied the temperature dependence of the anisotropy energies K_1 and K_u. A K_1 energy is also found in bulk iron whereas the K_u energy is unique to the epitaxial iron films. This paper determined that the K_u energy is consistent with a uniaxial strain arising from the growth of the metal film on the semiconductor at elevated temperatures. A comparison of the K_1 energy shows differences from that of bulk iron but the origin of the difference is uncertain.

D. "Detecting Two Magnetization Components by the Magneto-optical Kerr Effect," Jeffrey M. Florczak and E. Dan Dahlberg, published in the Jour. Appl. Phys. 67, 7520 (1990).

A novel technique for detecting two orthogonal in-plane magnetization components was developed. This technique utilizes the magneto-optical Kerr effects to sense the two components. These components of magnetization are parallel and perpendicular to the plane of incidence of the light beam. The ability to sense two components, individually or simultaneously, is a result of the disparity in the longitudinal and transverse Kerr effects. Based on the Fresnel reflection coefficients of these two effects, an analysis is presented describing this dual component sensitivity. The physical conditions are given for simultaneous and individual detection of the two in-plane magnetization components. To substantiate this analysis, magneto-optical measurements are made on single crystal Fe films. The results are discussed in the context of dual component sensitivity. This procedure is useful for determining the magnetization process of thin films and as a probe to determine in plane preferential growth ir polycrystalline films.

E. "Exchange effects in MBE grown iron films," Y-J Chen, D.K. Lottis, and E. Dan Dahlberg, J.N. Kuznia, A.M. Wowchak, and P.I. Cohen, published in J. Applied Physics 69, 4523 (1991).

The films prepared in the MBE system are allowed to form a passivating oxide on the free surface. We discovered that this oxide orders antiferromagnetically at temperatures on the order of 200K. A comparison of the ordering temperature with the known oxides of iron allowed us to identify the oxide as FeO, which is the main result of this publication. The ordering of this oxide is manifest by its effects on the magnetic properties of the underlying iron films. The hysteresis loops of the iron films exhibit both an increase in the coercivity of the iron films and a shift in the hysteresis loops due to the exchange coupling to the antiferromagnetic oxide. Our investigation of this phenomena focused on the temperature dependence of both of these quantities. The research on the exchange coupling between the surface oxide and the iron film is potentially very exciting. At the present time a need for a detailed understanding of exchange coupling is necessary for several technologies from magneto-optic recording media to bias elements in thin film magnetometers. For this reason, it is anticipated that research on this phenomena will continue.

F. "Simultaneous in-plane Kerr effects in Fe/GaAs (110) thin films," J.M. Florczak, E. Dan Dahlberg, J.N. Kuznia, A.M. Wowchak, and P.I. Cohen, published in J. Applied Physics 69, 4997 (1991).

In the case of the (110) grown films which have a hard or <111> direction separating the easy from intermediate directions, the magnetization process occurs via a discontinuous jump in the direction. The work on the use of magneto-optics to simultaneously measure the magnetization of two orthogonal components of the magnetization in a thin film (see D. above) was used to study how the magnetization in the epitaxial films evolves in the presence of an applied magnetic field. It is this technique which provided the data we used to model the effects of surface morphology on the magnetics of the epitaxial films described earlier. In this publication, the technique allowed the observation of the discontinuous jump in the magnetization when realigning past the hard or (110) direction. In the previous work we were not able to monitor the magnetization continuously. This indicates the great utility of the MO technique.

G. "A model system for slow dynamics," D.K. Lottis, R.M. White, and E. Dan Dahlberg published in The Physical Review Letters 67, 362 (1991).

The studies of the dynamics of the magnetization process in the thin iron films indicated a need to understand in greater detail the nucleation and magnetization process in magnetic systems. In this paper, we address how interactions in a magnetic system can give rise to slow dynamics. We used the dipolar coupling to provide the interaction in a planar system of spins. The remarkable result is that even when treated in the mean field limit, the system responds logarithmically in time. We were also able to show that the model replicates a stretched exponential over six decades in time. The most remarkable feature of the model is that it also predicts much of the behavior observed in the decay of the remanent magnetization observed in high temperature superconductors. In particular the quasilogarithmic decay and the nonmonotonic temperature dependence of the decay slope. In general, this paper indicates that interactions and not disorder may play a very important role in a number of physical systems from structural glasses to superconductors.

H. "Magnetization Reversal in (100) Fe Thin Films," Jeffery M. Florczak and E. Dan Dahlberg, accepted for publication in The Physical Review.

This publication utilizes the technique we developed using magneto-optics to provide a simultaneous measure of the magnetization in two orthogonal directions in a magnetic film. This work focuses on (100) oriented iron films. These films differ from those we investigated earlier in that they do not possess all three primary three crystallographic directions in the film planes but instead only have the <100> and the <110> directions. The lack of the <111> direction completely alters the magnetization process. The (100) films appear to magnetize in a much more uniform manner. The data taken on these films was modeled with a uniform rotation of the magnetization direction. In the modeling, we were able to determine the anisotropy energies and, as expected, show that prior to a jump in the magnetization direction that the magnetization process is dominated by wall formation.

E. "Magnetotransport Properties of Iron Thin Films," Youjun Chen, D.K. Lottis, and E. Dan Dahlberg, published in the Jour. Appl. Phys. 70, 5822 (1991).

Using our previous efforts in determining the oxide which forms on our epitaxial iron films, we have now begun in earnest an investigation of the effects of the exchange coupling on the magnetic properties of these coupled layers (Fe and FeO). In this paper we have studied and modeled the effect of the exchange coupling between an antiferromagnetic layer and an Fe MBE film on the magnetic reorientation phase transition (MRPT). The model of the MRPT works very well in the absence of the exchange coupling; this provides the confidence for the determination of the FeO and exchange coupling modifications to the MRPT. The main result reported in this work is that the exchange field can be rotated by the application of a rotating external field. It is interesting that the rotation of the exchange coupling is facilitated by a rotating external field and not by applying a field in a given direction. The model used does predict a rotation of the exchange field but incorrectly describes the hysteresis and other dynamics observed. It is my belief that model systems of such high quality as our films will ultimately be very instrumental in modeling the dynamics of the magnetization process in both single and multilayered films.

F. "Comparison of the Spin Valve Effect and the Anisotropic Magnetoresistance in Co/Cu Multilayered Films," Youjun Chen, J.M. Florczak, and E. Dan Dahlberg, accepted for publication in tyhe procee'ings of the International Conference on Magnetism.

Of current interest in the physics community is the recently discovered giant magnetoresistance (GMR) effect and the long range coupling (LRC) in magnetic/nonmagnetic multilayers. At the present time, a phenomenological model exists for the GMR (using the same physics as for the Stern-Gerlach experiment using spin projection) but a detailed understanding is lacking. This paper which we submitted to the ICM compares the GMR to the anisotropic magnetoresistance (AMR) in systems which exhibit the GMR. We have analyzed the data with a model of Fert which first was used to describe the AMR as a two-current system and in different limits, the GMR. The result of the work is that the AMR and the GMR are BOTH consistent with this two current model of Fe~t.

G. "Magnetization Reversal in Fe/GaAs (100) Thin Films," J.M. Florczak and E. Dan Dahlberg, accepted for publication in the proceedings of the International Conference on Magnetism.

We are continuing to pursue an understanding of the magnetization processes in thin films; this work is a continuation of that effort. In this work, the angular dependence of the magnetization process in Fe/GaAs (100) thin films was studied using the magneto-optical Kerr effects. The actual experiments relied upon the simultaneous measurements of the magnetization both parallel and perpendicular to the applied field using the technique we pioneered and reported on previously (Florczak and Dahlberg, J. Appl. Phys. 67, 7520 (1990). In the present work, we find the magnetization proceeds in two steps which require the nucleation of 90^{o} domain walls in the films. The interesting point is that there is an angular dependence to the second nucleation process but, within experimental error, not the second. At the present we don't understand this phenomena but are attempting model using the model developed in C. above and a nucleation model of Arrott.

H. "Magneto-transport in Sputtered Fe/Cu Multilayered Films," J.M. Florczak, Y.J. Chen, E. Dan Dahlberg, E.E. Fullerton, and Ivan K. Schuller, manuscript in preparation.

As mentioned in our last report, a focus of our future research is to understand the transport properties of magnetic/nonmagnetic multilayered systems. This research paper will be our first publication in this area, and will be submitted to the Physical Review upon completion. We have used two models to understand the transport in multilayered system; the parallel resistor model and the alloy model. In this work we have used the parallel resistor model with an allowance for the scattering from rough and smooth interfaces to model the transport properties. The analysis described in this work does not provide all the information to uniquely determined the grain-grain and defect intralayer scattering and the interfacial or interlayer scattering. It does provide insight as to the complexity of the transport and directs the future research directions to a detailed understanding of the x-ray diffraction patterns observed.

I. "Transport in Co/Ag Multilayered Films," Youjun Chen, P. Rider, E. Dan Dahlberg, E.E. Fullerton, and Ivan K. Schuller, manuscript in preparation.

In this work, we have used two models to understand the transport in multilayered systems; the parallel resistor model and the alloy model. In H. above only the parallel resistor model was used. In this work, both the parallel resistor model and the allov model were used to describe the transport properties of these films. Again, as in H., the result is that the simple models are lacking and measures of the AMR and the resistivity do not provide sufficient information to improve the models, i.e., we are left with too many adjustable parameters. We do not mean to trivialize the research in

H. and I. as they both are necessary as first steps in this exciting research area and both provide direction for the future work which is described below.

III. Invited Talks for Research Accomplishments

1. "The New Iron Age," Twin Cities IEEE Magnetics Society, Mpls., MN, 12 Jan., 1989.

2. "Epitaxial Iron Films: The New Iron Age," Physics Seminar, University of Indiana, Bloomington, Indiana, 20 Jan., 1989.

3. "Electrical Transport in a Multilayered System-Cobalt/Silver," Physics Seminar, Notre Dame University, 7 Dec., 1989.

4. "Transport in Magnetic Multilayers," Physics Seminar, Indiana University, 4 Dec. 1990.

5. "A Model System for Slow Dynamics," University of Bangor, Wales, U.K., European Community Action on Magnetic Storage Technologies (CAMST) Symposium, 9 September, 1991.

6. "A Model System for Slow Dynamics," Twin Cities IEEE Magnetics Society, Mpls., MN, 25 September, 1991.

7. "Giant Magnetoresistance in Magnetic Multilayers," Physics Department Colloquium, City University of New York, Queens College, 10 October, 1991.

8. "Transport in Magnetic Multilayers," National Institute of Standards and Technology, Solid State seminar, Washington D.C., 21 Feb., 1992

9. "A Model System for Slow Dynamics," Invited Speaker at Symposium on "Slow Relaxation" at the American Physical Society March meeting, Indianapolis, Indiana, 18 March, 1992.

IV. Personnel

A. Kuznia J.N., Graduate Student in Electrical Engineering, currently with APA Optics Inc.

B. Wowchak,A.M., Graduate Student in Electrical Engineering

C. Riggs,K.T., Graduate Student in Physics (PhD received in 1989 presently an Assistant Professor at Stetson College in Florida)

D. Lottis,D.K., PhD Graduate in Physics (recipient of IBM predoctoral fellowship, 88-89 and University of Minnesota Dissertation Fellowship, 89-90), Currently on a postdoctoral appointment in Orsay with Dr. A. Fert.

E. Florczak,J.T., PhD Graduate Student in Physics (recipient of IBM predoctoral fellowship, 89-90).

F. Chen, Y.-J., PhD Graduate Student in Physics.

G. Rider, P., Graduate Student in Physics

H. Tondra, M., Graduate Student in Physics.

I. Miller, B., Graduate Student in Physics.

J. Cleveland, J. was an undergraduate student in Physics, currently a fellowship graduate student in graduate school at U. C. Santa Barbara.

K. Truscott, A.T., Undergraduate Student in Physics. Currently a graduate student at UCSD with R.C. Dynes.

L. Berg, M.A., Undergraduate Student in Physics. Currently in Medical School at the University of Minnesota.

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O. Sankar, S., Undergraduate Student in Physics.