DOE/ER/45281--5

DE91 000702

MAGNETIC MULTILAYER INTERFACE ANISOTROPY

TECHNICAL PROGRESS REPORT

August 1, 1990 through December 31, 1990

Submitted to The USDOE Office of Basic Energy Sciences

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ABSTRACT

Ni/Mo and Ni/V multilayer magnetic anisotropy has been investigated as a function of Ni layer thickness, frequency and temperature. Variable frequency ferromagnetic resonance (FMR) measurements show, for the first time, significant frequency dependence associated with the multilayer magnetic anisotropy. The thickness dependence allows one to extract the interface contribution from the total anisotropy. Temperature dependant FMR (9 GHz) and room temperature magnetization indicate that strain between Ni and the non-magnetic layers is contributing significantly to the source of the interface anisotropy and the state of the interfacial magnetization. In order to examine the interface properties of other transition metal multilayer systems, investigations on Fe/Cu are underway and CoCr/Ag is being proposed.

ESR measurements have been reported on Gd substituted YBaCuO superconductors and a novel quasi-equilibrium method has been developed to determine quickly and precisely the transition temperature.

During the next project period the P.I. proposes to (1) extend the variable frequency FMR measurements to low temperature, where extremely large interface anisotropies are known to obtain in Ni/Mo and Ni/V and are proposed to exist in Ni/W; (2) obtain accurate dc anisotropies via a novel, variable temperature torque magnetometer currently under construction; (3) expand upon his initial findings in Fe/Cu multilayer investigations; (4) begin anisotropy investigations on Co/Ag and CoCr/Ag multilayers where the easy magnetization direction depends upon the Cr concentration; (4) make and characterize Bi based superconductors according to resistivity, thermal conductivity and thermoelectric power and construct YBaCuO based superconducting "loop-gap" resonators for use in his magnetic resonance work.

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INTRODUCTION

[Although this report *officially* covers only a month's worth of activity (8/1 to the present - 9/10/90) it will reflect the activities from the past year.]

Comparison between multilayer systems comprised of different constituents has produced exciting results in our recent research. These comparisons have given considerable insight into one of the most important questions in magnetic multilayer research - that being the source of the interface anisotropy. Temperature dependence of the interface anisotropy (IA) in both Ni/V and Ni/Mo multilayers strongly suggests the IA is rooted in crystal field effects. In addition, differences in magnetization versus layer thickness between these two systems is consistent with interfacial strain as a major player in the IA. Finally, comparison between IA temperature dependences in Ni/V and Fe/Cu give strong evidence that the IA has its source in crystal fields modified by strain effects. In the course of this report, I will discuss 1) work done to improve experimental techniques; 2) multilayer results; 3) superconductivity and 4) student involvement.

Experimental Details

The most basic indicator of magnetic anisotropy is provided by torque magnetometry, and we have been developing a novel system, which incorporates a commercially available transducer. The magnetometer has been designed from the beginning to operate between 300 K and liquid helium temperatures in conjunction with an Oxford Instruments CF1200 Flow Through Cryostat. The advantages offered by the particular transducer chosen are low cost, high sensitivity and, particularly, low compliance (which greatly facilitates system automation and precise calibration). A nagging (9 month) problem was overcome by replacing a rigid connection between the sample and the transducer with a flexible link made of human hair. This eliminated off axis loading of the transducer which, when integrated, resulted in unacceptably high output drift. The system now reliably measures torques up to 100 dyne-cm with a resolution of 0.01 dyne-cm and is briefly described in a recent article submitted to the Magnetism and Magnetic Materials Conference. Because of the low compliance (the sample rotates through only 0.08 minutes of arc when subject to a 15 dyne-cm torque), calibration can be accurately and absolutely accomplished by a current carrying coil with negligible parasitic torques from the lead-in wires.

Our quest to investigate Ni/Mo IA frequency dependence was aided by the development of a nonresonant structure (stripline) to provide the microwave field. The structure was designed to facilitate angular measurements as a check for in-plane anisotropies and functions well from 1 to 22 GHz with anomalies at approximately 8 and 17 GHz, where standing wave are likely set up inside the stripline housing. Our Wiltron, 0.01 to 40 GHz, swept frequency generator, provided by DOE funding, served admirably in this venture.

*Mathematica*TM was purchased to facilitate modeling of the torque data, and has proven invaluable. Least square fitting of data to complicated transcendental equations proceeds effortlessly within this environment, allowing the scientist to examine the applicability of a number of models or perturbations on a given model. Along these lines, a QBASIC program has been developed to fit FMR spectra to multiple Lorentzian and/or Gaussian lineshapes, thereby enabling accurate tracking of spectral features as a function of magnetic layer thickness, temperature, frequency and angle.

The advent of solid state microwave generators in FMR spectrometers has required the use of lock-in amplifiers as automatic frequency control devices, however the flexibility of commercial units are an expensive (>\$2K) overkill. Therefore we have designed a lock-in amplifier around the Analog Devices A/D630 modem IC which functions as well as our \$4K Ithaco lock-in and costs approximately \$100 using premium components. As a spin-off, this low-cost device also opens up a wealth of experiments to the multiple-station advanced undergraduate laboratory.

Multilayers

As mentioned above, examination of magnetic properties as a function of elemental constituent has revealed a more complete picture of the IA source. For example, as shown in Fig.

1, the IA in Ni/V is approximately 30 times more strongly dependant upon temperature than that in Fe/Cu. This correlates strongly with the factor of 100 difference in the respective bulk Ni and Fe crystal field anisotropy temperature dependences, implying the IA source is closely tied to the interfacial crystal fields. It can be shown that the factor of 30 in the multilayers rather than 100 in the bulk is consistent with interfacial strain arising from Ni/V lattice mismatch and magnetostriction.

FIG. 1. Absolute value of the Fe/Cu (open squares) and Ni/V (closed diamonds) interface anisotropies as a function of temperature. Fe/Cu values are negative, which implies the IA is pulling the moment out of the plane.

Comparisons between Ni/V and Ni/Mo also reveal surprising results. Although the temperature dependences of the IA in both Ni systems are roughly equivalent, the magnetization dependences upon Ni layer thickness are dramatically different [Fig. 2, Ni/Mo data measured by Schuller at Argonne and Ni/V data measured by PI at UCSD.]

FIG. 2. Room temperature magnetization of Ni/V (solid squares) and Ni/Mo (open squares) as a function of inverse Ni layer thickness. Dashed line indicates the room temperature value of bulk Ni.

This behavior can be understood to arise from strain at the interface according to the following reasoning: Like Co and the spin-orbit coupled rare earths, Ni is known to be significantly magnetostrictive. How, then, might the Ni layer be expected to respond to the influences of V as opposed to Mo if strain is important? Consider that the Ni lattice mismatch is -5% in Ni/V and -9% in Ni/Mo. Consider, also, the Young's moduli:

$$\frac{B_V}{B_{Ni}} = 0.87$$

$$\frac{B_{Mo}}{B_{Ni}} = 1.46.$$

Therefore, since V is somewhat softer than Ni, one would expect the stress arising from the small lattice mismatch in Ni/V to be manifest as strain in the V. This would leave Ni layers relatively unstrained with bulklike structural and magnetic properties, wherein the magnetic interface is localized to within a monolayer of the chemical interface. On the other hand, since the Ni is considerably softer than Mo, the stress due to a large lattice mismatch in Ni/Mo will be result in Ni layers bearing significant strain. This will cause significant Ni structural distortions (lattice expansion) at the interface which, according to Bethe calculations would result in a reduced Ni moment. And, as has been shown for Fe on GaAs, localized disruptions in magnetization can penetrate considerable distances into the magnetic layer. The Ni layers in Ni/Mo would, consequently, be decidedly non-bulk-like in magnetic behavior, with a considerable magnetic gradient at the interface. This qualitative agreement between observed results from the Ni/V-Mo experiments and expectations based upon strain as a interfacial influence, lead one to conclude that the interface anisotropy has its origin in crystal field coupling wherein magnetoelastic effects play a major role.

The torque magnetometer described above was utilized to investigate the Fe/Cu multilayer system at room temperature. Because of the very large anisotropy energies involved ($K_1 > 14 \times 10^6$ erg/cm³) and our relatively low measuring fields (< 8 kG), the torque peaks did not yield the anisotropy directly as is usually the case. Therefore, a low field analysis technique was developed which correctly describes the relation between the anisotropy and torque peak. In addition, extreme sensitivity of K_1 to uncertainties (introduced by domain effects) in the torque amplitude was pointed out. The analysis relies heavily upon *Mathematica*TM to fit, not just the torque amplitude, but all non-domain affected points on the curve, to the transcendental torque equations. As a result of this fitting process not only is K_1 accurately obtained, but M as well (see Fig.3).

FIG. 3. Fe/Cu multilayer M and K_1 determined by torque analysis described in the text. For comparison the value of M obtained from vibrating sample magnetometry is 1522 emu/cm³ and that of K_1 obtained from FMR is 14.2×10^6 erg/cm³.

Room temperature frequency dependence of the IA in Ni/Mo multilayers was investigated using the stripline structure mentioned above. Extensive measurements were made to account for in-plane anisotropies, which were observed to exist. The results were that, within the uncertainties

defined by the in-plane anisotropies, no discernable frequency dependence can be ascribed to the room temperature Ni/Mo anisotropy. Further studies will be carried out at low temperature, where the frequency dependence, if it exists, is expected to be the greatest.

Superconductivity

In order to concentrate the graduate student efforts primarily in magnetism, the PI's main area of expertise, the project's efforts in superconductivity are currently primarily limited to undergraduate research projects. The results of a quasi-equilibrium resistivity technique for determining superconducting transition temperatures, co-authored with an undergraduate student, appeared recently in The American Journal of Physics. Another undergraduate has been establishing a thermal conductivity apparatus for measuring transport properties of YBaCuO. The results will aid our research and undergraduate laboratory efforts with the addition of another important condensed matter research technique.

DOE SUPPORTED PUBLICATIONS AND PRESENTATIONS (for the past year)

Publications in Print

"Quasi-Equilibrium Determination of T_c in High Temperature Superconductors", Michael J. Pechan and Jonathon Horvath, Am. J. Phys. **58**, 642 (1990).

Publications Submitted

"Analysis of Magnetic Multilayer Anisotropy Using an Ultra-low Compliance Torque Magnetometer", Michael J. Pechan, Michael E. Bait and Bradley D. Paul. Submitted to Magnetism and Magnetic Materials Conference.

Publications in Preparation

"Crystal Field as a Source of Magnetic Multilayer Interface Anisotropy", Michael Pechan, Zhong Lu, Eric Fullerton, Ivan Schuller and Marcos Grimsditch.

"Magnetic Properties of Fe/Cu Superlattices", E. Fullerton, W. Robertson, H. Sowers, M. Pechan, I. Schuller and M. Grimsditch.

"Role of Strain in Ni-Based Multilayer Magnetic Properties", M. Pechan, Z. Lu and I. Schuller.

"Automatic Frequency Control for Solid State Oscillators in ESR Spectrometers", M. Pechan, J. Xu and L. Johnson.

Presentations Made

"Analysis of Magnetic Multilayer Anisotropy Using an Ultra-low Compliance Torque Magnetometer", Michael J. Pechan, Michael E. Bait and Bradley D. Paul. Presented by M. Bait and B. Paul at the Magnetism and Magnetic Materials Conference, San Diego, Oct. 1990.

"Variable Temperature, Low Compliance, dc, Torque Magnetometer", M.E. Bait and M.J. Pechan. Presented by M. Bait at the Ohio Section of the APS, Denison Univ., Apr. 1990.

"Role of Strain in Ni-Based Multilayer Magnetic Properties", M. Pechan, Z. Lu and I. Schuller. Presented by M. Pechan at the March APS Meeting, Anaheim, March 1990.

"Brillouin Scattering Studies of Magnons in Fe/Cu Superlattices", W. Robertson, C. Sowers, M. Grimsditch, E. Fullerton, I. Schuller and M. Pechan. Presented by E. Fullerton at the March APS Meeting, Anaheim, March 1990.

"Frequency Dependence of Magnetic Anisotropy in Ni/Mo Multilayers", D.E. Kingsbury and M.J. Pechan. Presented by M. Pechan at the Magnetism and Magnetic Materials Conference, Boston, Nov. 1989.

STUDENT INVOLVEMENT (for the past year)

Masters Theses Graduated

"Frequency Dependence of Ni/Mo Multilayer Magnetic Anisotropy", David E. Kingsbury. Aug. 1989.

"Temperature Dependent Torque Measurements on Transition Metal Multilayers", Michael E. Bait. May 1990.

Masters Theses Presently Directing

"Variable Frequency and Angular Determination of Ni/Mo Magnetic Anisotropy", Charles Kuehn. Dec. 1990.

"Analysis of Multilayer Anisotropy From Low Field Torque Data", Bradley Paul. May 1991.

"FMR Determination of Anisotropy in Unequal Layer Thickness Fe/Cu Multilayers", Jiansheng Xu. Aug. 1991.

"Variable Temperature Torque Measurements of Ni/X, X=V, Mo and W", Alan Runge. Aug. 1991.

Habib Aliabadi has just begun working on FMR in multilayers. Will graduate in 1992.

Undergraduate Student Participation

Jonathon Horvath

Jon pursued his interest in high-temperature superconductivity for two semesters as an incoming freshman before receiving the second DOE undergraduate summer appointment. Jon wrote a proposal for and was awarded one of Miami's Undergraduate Research Awards (most unusual for a freshman) which provided him modest funding to make the (then) new Bi based superconductors. After many trials he was successful, and he presented the resistivity measurements at the spring meeting of the Ohio Section of the APS. He received our department's annual Outstanding Undergraduate Researcher Award (again most unusual for a freshman). He spent the summer making the $T_c = 110K$ phase Bi compounds and working on our quasi-equilibrium technique which was subsequently published in the American Journal of Physics. His second Undergraduate Research Award, to make a superconducting FMR resonator, was judged by the committee to be the best proposal submitted that year and among the best ever.

• **James Middleton**

Started working on superconductivity as an incoming freshman. He set up a new furnace and controller for our laboratory and began making samples. His primary interests are in making the Bi based compounds and measuring their thermal transport properties. James built a thermal conductivity apparatus and is in the process of calibrating it on non-superconducting samples.

Jonathon Carpenter

Started working with me on a senior honors project. He made torque measurements on Fe/Cu multilayers and his analysis provided some new and significant insight into their properties.

Christopher Anderson

High school student who participated with Brad Paul and Mike Bait on the Fe/Cu torque analysis and data acquisition. Also built a bibliographical database from the many papers to which I make reference in my research.

END

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