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MAGNETIC MULTILAYER INTERFACE ANISOTROPY

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By Michael J. Pechan

Miami University

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MAGNETIC MULTILAYER INTERFACE ANISOTROPY

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.

INTRODUCTION

The past year our efforts were primarily concentrated on 1) identifying anomalous ferromagnetic resonance (FMR) modes in interlayer coupled magnetic multilayered systems; 2) improving our torque measurement capabilities to include low temperature operation; and 3) improving the state of torque data analysis techniques. In addition a novel design for controlling the frequency of a FMR spectrometer was built, tested and submitted for publication, and thermal conductivity of high temperature superconductor samples was measured as part of an undergraduate research project.

Apparatus and Techniques

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). The system now reliably measures room temperature torques up to 100 dyne-cm with a resolution of 0.01 dyne-cm and is briefly described in the *Journal of Applied Physics*. The past year we brought into operation a magnet which increases our field capabilities from 6 to 16 kG at low temperatures and from 9 to 21 kG at room temperature. This allows anisotropy determination of "harder" magnetic materials such as Fe and Co based systems. In addition a high precision, GPIB interfaced, gaussmeter was installed in the torque magnetometer to increase accuracy and facilitate automation. The system is controlled and monitored by LabView Software (National Instruments, Inc.). The system has been operated at low temperature both for calibration procedures and preliminary multilayer characterizations. Calibration constants have been observed to be temperature independent to within $\pm 0.5\%$ down to approximately 50 K, however below this temperature the system exhibits a tendency to freeze up (sample rod no longer free to rotate). This is apparently due to formation of frozen oxygen and/or nitrogen, as the rod frees up at around 80 K. Modifications to the sample rod support system are underway to alleviate this problem.

*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. The limitation of *Mathematica*TM however lies in its speed. Therefore once a procedure has been developed, we develop QBASIC programs to serve as the routine data analysis tools. Using these tools, a novel method of analyzing torque data has been developed which performs a least squares fit of the data to a uniaxial anisotropy model. This procedure utilizes data taken at any constant angle and variable field (experimentally less noisy than vice-versa) and extracts the magnetization (M) and first (K_1) and second (K_2) order anisotropy constants. Previous techniques were available which were limited to an angle of 45° and returned only M and K_1 . A report of this procedure will appear in the November issue of *IEEE Transactions on Magnetics*. Torque effects due to sample misalignment have also been investigated and we have shown that anomalous rounding of torque data often observed at the reversal point can be explained as arising from slight angular misalignments. The effect has been confirmed by initial measurements. Refinements are underway.

Several high frequency cavities were constructed for our FMR system to facilitate measurement of parallel resonances in fields which ensure single domain behavior in our multilayer samples. The four cavities, which provide nine resonances between 26.6 and 38.4 GHz, also allow characterization of frequency/field dependences in a given sample's properties.

The advent of solid state microwave generators in FMR spectrometers has required the use of lock-in amplifiers as automatic frequency control (AFC) devices, however the flexibility of commercial units are an expensive (>\$3K) overkill. We have designed an AFC 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. Improvements in signal-to-noise are 81 dB and 45 dB for single-side-band and white noise respectively. This design and its implementation have been submitted to *Review of Scientific Instruments*.

Multilayers

Observations of interlayer coupling of ferromagnetic layers across a nonmagnetic layer has led to a lot of excitement in the condensed matter community. Specifically the source of such coupling is of great interest, because it appears to be much longer range in these quasi-two dimensional systems than expected from the RKKY interaction (Which is not directly applicable because it assumes localized moments, but can serve as a reference point.) Several laboratories around the world have observed effects of antiferromagnetic interlayer coupling in simple trilayer structures, however we have observed in multilayer structures, anomalous FMR modes which suggest origins in interlayer coupling. Our samples have been obtained from Ivan Schuller's laboratory at the University of California-San Diego. FMR measurements have been made on forty two Fe/Cu multilayer samples with various combinations of Fe and Cu thicknesses and on six Fe/Cr samples with fixed Fe thickness of 30Å and Cr thickness ranging from 5 to 50Å. Anomalous modes were observed in 33% of the Fe/Cu and 100% of the Fe/Cr samples. It is not clear why modes were not observed in all the Fe/Cu samples, however many believe that interfacial structure plays an important role in the coupling and it is known that Fe/Cu structural integrity is quite sensitive to the Argon sputtering pressure. Based upon analogy with spin waves in a three dimensional system, we have proposed a rudimentary model for the modes expected for magnetically rigid Fe layers precessing in a field and coupled by a weak interlayer exchange interaction given by

$$J_{\text{interlayer}} = \frac{g \mu_B a N^2}{\pi^2 \lambda} (H_u - H_{\text{anom}})$$

where N is the number of bilayers in the sample, λ is the multilayer modulation wavelength, a is the average atomic lattice spacing, H_u is the field for resonance of the uniform mode and H_{anom} is the field for resonance of the anomalous mode. This model also assumes that the mode observed is the lowest frequency mode supported by the multilayer. Shown in Fig. 1 are results obtained from the Fe/Cr samples and a set of Fe/Cu samples prepared with Fe layer thickness held at 50Å.

Fig. 1. Interlayer coupling in Fe/Cr (diamonds) and Fe/Cu (squares) vs. nonmagnetic layer thickness. The J recorded here is the strength of the antiferromagnetic coupling in each system.

While the model is rudimentary and requires refinement, several general features are to be noted. First it is apparent that the Cr provides a much larger separation between the uniform and anomalous modes than Cu, inferring a much stronger dynamical coupling. This is consistent with the strong, static antiferromagnetic coupling observed in Fe/Cr trilayer systems, whereas Fe/Cu structures do not exhibit static antiferromagnetic coupling between Fe layers. Second, it is interesting to note the maxima in coupling strength at around 20Å of Cr and 30Å of Cu. This may be related to oscillatory static coupling strengths observed by several investigators in Fe/Cr systems. The picture is not entirely clear here yet but such systematic observances are encouraging. New samples are being prepared to further evaluate this effect.

Ni/W samples were prepared by Schuller's group to further investigate the source of interface anisotropy in transition metal multilayer systems. The samples were found to have unusually low values of magnetization and anisotropy, which were later presumed to arise from less than optimal sputtering conditions known to exist at the time of their making. New Ni/X (X=V, W, and Mo) samples will be prepared and tested during the 1992 budget period.

Torque measurements were made upon a series of Fe/Cu samples at room temperature and as a function of temperature down to 50 K. Because of the above mentioned low temperature problems of the cryostat, I will only discuss room temperature results at this time. Shown in Fig. 2 are the magnetization and first order anisotropy obtained from a representative Fe/Cu sample using our magnetometer and data analysis techniques. The results obtained agree well with values obtained from FMR and vibrating sample magnetometry.

Fig. 2. M (squares) and K_1 (diamonds) extracted from a 295Å/295Å Fe/Cu multilayer sample by the analysis technique described in the text. Alpha is the angle between the field and sample thin film plane. 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.

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. This year an undergraduate student designed and constructed a thermal conductivity apparatus for measuring transport properties of YBaCuO and BiCaSrCuO. Our results confirmed one of two conflicting results found in the literature on YBaCuO and agreed precisely with previous findings on BiCaSrCuO. The student will present his results at The Argonne Symposium for Undergraduate Research at Argonne National Laboratory and will publish the results in The Journal of Undergraduate Research.

DOE SUPPORTED PUBLICATIONS AND PRESENTATIONS (for the past year)

Publications in Print and Accepted

"Analysis of Magnetic Multilayer Anisotropy Using an Ultra-low Compliance Torque Magnetometer", Michael J. Pechan, Michael E. Bait and Bradley D. Paul, *J. Appl. Phys.* **69** (8), 5058 (1991).

"Generalized Torque Analysis of Magnetic Uniaxial Anisotropy", Bradley D. Paul and Michael J. Pechan, *IEEE Trans. Magn.*, November 1991.

Publications Submitted

"Automatic Frequency Control for Solid State Sources in Electron Spin Resonance", Michael J. Pechan, Jiansheng Xu and Lynn D. Johnson. Submitted to Review of Scientific Instruments.

Publications in Preparation

"Novel Variable Temperature Torque Magnetometer", Michael J. Pechan, Alan P. Runge and Michael E. Bait.

"Effects of Sample Misalignment on Uniaxial Torque Signals", Michael J. Pechan, Bradley D. Paul and Alan Runge.

Presentations Made

"Magnetic Multilayer Interface Physics", Michael Pechan. Invited talk presented at Denison University. Granville, Ohio, October 1991.

"Generalized Torque Analysis of Magnetic Uniaxial Anisotropy", Bradley D. Paul and Michael J. Pechan. Presented by Brad Paul at the Joint InterMag and Magnetism and Magnetic Materials Conference, Pittsburg, June. 1991.

"Variable Temperature, Low Compliance Torque Magnetometer", Alan P. Runge, Michael E. Bait and Michael J. Pechan. Presented by Alan Runge at the Joint InterMag and Magnetism and Magnetic Materials Conference, Pittsburg, June. 1991.

"Magnetic Multilayer Exchange Coupled Modes", Michael J. Pechan, Jiansheng Xu, Ivan K. Schuller and Eric Fullerton. Presented by Michael Pechan at the APS March Meeting, Cincinnati, March 1991.

"FMR Measurements on Ni/W Superlattices", Robert Radulovich and Michael Pechan. Presented by Robert Radulovich at the Ohio Section of the APS, Athens, Ohio, April 1991.

STUDENT INVOLVEMENT (for the past year)

Masters Theses Graduated

"FMR Study on the Antiferromagnetic Interlayer Coupling of Fe/Cu Multilayers", Jiansheng Xu. May 1991.

"Magnetic Multilayer Anisotropy Investigated with a Variable Temperature Torque Magnetometer", Alan P. Runge. May 1991.

"Uniaxial Anisotropy Theory and Analysis of Torque Data", Bradley D. Paul. May 1991.

Masters Theses Presently Directing

"Spatial Coexistence of the Transducer and Sample in a Torque Magnetometer", Matthew Braught. May 1992.

"Temperature Dependence of Ni/X (X=V, Mo and W) Multilayer Interface Anisotropy", Charles Lynn. August 1992.

UNDERGRADUATE STUDENT PARTICIPATION

James Middleton

Currently a senior, Jim 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 have been in making the Bi based compounds and measuring their thermal transport properties. Jim built a thermal conductivity apparatus including all the hardware, electronics and software to perform measurements on YBaCuO and BiCaSrCuO between room temperature and 4 K in our existing Oxford Instruments Cryostat. The results were in excellent agreement with reports published in Physical Review B and Solid State Communications. His sophomore year, Jim was having trouble finding himself and was on the verge of dropping out, but after several sessions of talking with him, he began to settle down and his brilliance started to become evident his junior year. This past summer James has proven himself to be an outstanding young experimentalist, with a genuine enthusiasm to continue his career in physics. He will be applying for graduate school at the top schools in the nation - programs into which, I believe, he will be admitted.

Rob Radulovich

Rob restored a surplus magnetic resonance spectrometer to working condition and then proceeded to make FMR measurements on Ni/W superlattices. He carried out the analysis of the results and made a superb presentation at the Ohio Section of the American Physical Society. He is now pursuing a Masters Degree in Nuclear Engineering at The Ohio State University.

David Karipedes

David was our resident electronics wizard in the department. It was all I could do to keep up with him on our project to modify the AFC design for use as a lock-in amplifier in the undergraduate laboratories. He designed a frequency independent phase shift circuit for the device; provided for either internal or external reference oscillation and designed an especially simple but elegant method to extract the real and imaginary susceptibilities of a test magnetic sample using the device in an undergraduate lab setting. He is now pursuing a Ph.D. in physics at Purdue.

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