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Nov. 17, 1990.

Progress to date on the AFOSR Grant 89-0432:"Sources of Anisotropy in Amorphous Magnetic Thin Films". Principal Investigator: Frances Hellman, assistant professor UCSD.

With the assistance of this grant, my laboratory has progressed substantially and is now beginning to produce results. This last year, in addition to lab build-up and student supervision, I have continued work on the amorphous rare earth transition metal alloys. There are several significant new results arising from this work. (This research is all currently being written up; the measurements are complete. Until the papers are in preprint form, I would however ask that readers of this document assume that the results described here are confidential and should not be discussed outside (comments to me are most welcome!).)

Research Results:

1) A model for the growth-induced macroscopic magnetic anisotropy: I have clear evidence against Takeshi Egami's "Bond-Orientational Anisotropy" model which attributes the anisotropy to "anelastic strain". He describes this model as a simple increase in the number of bonds in-plane compared to out-of-plane due to stress *during* the growth. I find a strong (more than an order of magnitude) dependence of the anisotropy on deposition temperature and essentially *no* dependence on the state of stress either during the growth or after. I believe the reason for the anisotropy is a "texturing" of the short-range order relative to the surface, which minimizes surface energy at every instant during the growth, and gets frozen into the structure. I gave a talk at the MMM conference immediately after Egami's student which was very well received, I believe. The abstract for the conference is attached, although it is not descriptive of the actual contents of the talk (since it was submitted six months before the talk). The paper will be submitted to Phys. Rev. B under the title: "Surface-mediated amorphous phase texturing: a model for anisotropy in amorphous rare earth-transition metal alloys".

2) I have found that the high field susceptibility of *a*-Tb-Fe does *not* increase with Tb concentration and does not depend on temperature, contrary to what would be expected from the Random Magnetic Anisotropy (RMA) model for this material. This susceptibility was part of the evidence that led to development of the RMA model. It was previously studied for Tb-Fe near the eutectic point (much higher Tb concentration) and is currently believed to be due to "closing the umbrella" of Tb spins (Tb and Fe are antiferromagnetically exchange-coupled; the Tb also is

subject to relatively strong local "crystal" fields which are random in orientation and which produce randomly-directed local anisotropy). I do not yet know what the susceptibility is instead due to and hence do not yet have a title, but since the original susceptibility work is widely quoted even in textbooks on amorphous magnetic alloys, I believe this result will be of sufficient general interest to submit it to Phys. Rev. Lett.

3) I have found more evidence of a "phase transition" in *a*-Tb-Fe (see earlier papers). Old results: with <22 at.%Tb, the magnetic anisotropy is a) a complicated function, depending upon many variables, and is no longer uniaxial and b) is fit most reasonably by assuming there are two phases present in the material. Note that 22 at.%Tb is the magnetic compensation composition at room temp (for a variety of reasons it is not possible to take advantage of shifts with measuring temp - we tried); it is very hard to think of a model in which compensation could have anything to do with the observed effects, but it is a peculiar coincidence.
New results: a) Ho-Fe shows similar effects, but the transition occurs away from the magnetic compensation composition, so this really is a metallurgical effect as I believed all along. b) the magnitude of the anisotropy and the moment of *a*-Tb-Fe show further anomalies near and below 22 at.%Tb. c) There is still absolutely no sign of a second phase in *any direct measurement*; in particular Mossbauer, X-ray, and TEM) show nothing unusual. If the explanation for the anomalous behavior really is a second phase, it must be amorphous.

I don't have a concrete model for what is going on but certainly the material is not behaving as a dense random packed alloy with only the expected relatively weak dependence of its properties on composition.

Planned paper title: "Anomalies in the composition dependence of the magnetic anisotropy of amorphous Tb-Fe and Ho-Fe". For Phys. Rev. B.

4) The coercive force doubles in *a*-Tb-Fe as the deposition temperature T_s is reduced from room temp to 77K. There is no change for T_s above room temp up to at least 200 C. Note that the anisotropy K_u shows the opposite dependence. This is not a contradiction as reversal in these materials is believed to occur by wall motion and to be wall-nucleation and motion-limited, but it is surprising. At least one paper in the literature suggests that randomness in the local anisotropy axes produces the (apparently reproducible) nucleation sites. Lower T_s might have suggested increased randomness in these local axes (since K_u decreases). It is possible that the walls get pinned at an increased number of defects such as voids. In any

event, understanding the observed change should produce insight into the reversal mechanism which is of technological importance. These thoughts are still in an early stage of development; I plan to work with Mansuripur at the Optical Sciences Center at U. of Arizona on this problem.
The paper will most likely be an Applied Phys. Lett. I don't have a title yet.

Laboratory Status:

I am supervising the thesis work of 4 graduate students and undergraduate projects for 2 physics majors. Two of the graduate students are entirely supported by the AFOSR grant. We have constructed a vibrating sample magnetometer with quadrature pick-up coils, currently being calibrated and tested. Temperature control for measuring the temperature dependence of magnetic properties of thin films or bulk samples will be built; currently the VSM is useable only at fixed temperatures such as room temperature, 77K, and 4.2K. The quadrature pick-up coils will allow us to obtain the components of M parallel and perpendicular to the field. This is necessary for the analysis of magnetic materials with large anisotropy (as well as work on vortices in superconductors described below). We have also built and tested a torque magnetometer for measurements of magnetic anisotropy, critical to the magnetic rare earth alloys. Again we plan to add temperature control but currently it is useful at fixed temperatures only. This apparatus still needs to be computer-interfaced to make proper data analysis possible.

We have built a resistivity probe for measuring the temperature dependence of resistivity from room temperature down to 1.4 or 4.2K. We are constructing an apparatus for heating samples in vacuum in a magnetic field while measuring resistivity or even specific heat possibly (we anticipate eventually making a higher vacuum apparatus with deposition and ion-mill cleaning facilities for the specific heat). This current apparatus will be useful for relaxation and crystallization studies of amorphous materials, as well as for high T resistivity measurements on other materials (for determination of the electron-phonon coupling parameter for example). The primary immediate goal is to look for unusual crystallization effects in the amorphous rare earth-transition metal alloys by annealing below the Curie temperature of the crystalline compounds but we will look at relaxation processes in the amorphous state as well.

We are also constructing apparatus to measure the specific heat of thin films at temperatures ranging from dilution refrigerator temperatures up to approximately 1100K. Below 10K, we will be able to measure films of less than 100 A thickness, weighing less than 1 μg. This is almost two orders of magnitude more sensitive than the only other apparatus in the world designed to measure thin films. Above 50K, we will require films on the order of 1000-5000 A (10-50 μg), still orders of magnitude more sensitive than anyone else is capable of. We will obviously be well positioned to make some rather unique measurements with this capability. In particular, the immediate plan is to investigate the physics of disordered or random magnetic systems in two and three dimensions as well as the materials science of vapor-deposited materials, such as relaxation effects in the extremely rapidly-quenched state of vapor-deposited amorphous alloys. The first devices with high temperature thermometers and heaters only are now complete and await testing. We have developed a new low temperature thermometer which has been tested and now must be incorporated into the devices. We are also constructing a less sophisticated specific heat apparatus, based on devices I developed during my doctoral work, to measure films of 1-2 μm thickness. This second apparatus is close to operational; the devices, the cryostat, and the electronics all exist and the student involved is currently writing the necessary software to control the data acquisition and analysis.

We still lack facilities for sample preparation and hence are dependent on samples I prepared last fall while on leave at Bell Labs. This lack of deposition facilities is of course a significant obstacle to the research; I am attempting to find used deposition chambers and to piece together used parts, in addition to writing proposals to obtain funding.

Some additional interesting work: I have been attempting to unravel some unexpected effects seen on applying a magnetic field at an angle to superconducting films and slabs; this work is particularly topical because of the level of interest in vortices in the anisotropic high T_c superconductors. We believe that a better understanding of these effects in the isotropic superconductors such as Nb will leave us poised to tackle the problem in the high T_c materials. This latter work is being performed in collaboration with E.M. Gyorgy and R.C. Dynes. We are studying both reversible (equilibrium) and irreversible (due to pinning) effects. I plan to use my new quadrature rotating VSM (vibrating sample magnetometer) to study the high T_c superconductors and to look for such effects as flux line "entanglement", melting, "flux pancakes", etc.

ANOMALOUS COMPOSITION DEPENDENCE OF ANISOTROPY IN AMORPHOUS Tb-Fe and Ho-Fe

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The magnetic anisotropy K_u of magnetron co-sputtered amorphous Tb-Fe has been found to drop precipitously when the composition is within several at. % of 22 at. % Tb, a composition which is the room temperature compensation point. The samples showing this low value for K_u are magnetically saturated (fields up to 100 kOe were used) and torque curves have the expected uniaxial behavior. The unexpected decrease is correlated with a previous finding of anomalous, non-uniaxial anisotropy for films prepared with less than 22 at. % Tb when non-perpendicular incident angles are used for the deposition. We hypothesized that an undetected phase separation was occurring in these Fe-rich samples. The present study examines films prepared on rotating substrates, essentially eliminating the effect of incident angles. As previously predicted, with no incident angles the phase separation is unobservable by magnetic anisotropy, but presumably is still present and may account for the observed drop in K_u. Analogous results have been seen in amorphous Ho-Fe; the relevant composition is far from magnetic compensation supporting the conclusion that the coincidence of compensation with the anomalies in Tb-Fe is accidental. This behavior of the anisotropy is inconsistent with simple models for the atomic structure and the source of K_u. The effect of deposition temperature will also be discussed.

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