REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
25/01/2007	final technical	9/2002 - 9/2006

4. TITLE AND SUBTITLE
Interface Effects on Magnetism in Model Thin Films

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-02-1-1026

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Max G. Lagally

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Board of Regents, University of Wisconsin-Madison
Madison, WI 53706

8. PERFORMING ORGANIZATION REPORT NUMBER
final

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release. Distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goals of the research were to explore the fundamental physical mechanisms that al-low interfaces between magnetic and nonmagnetic (as well as magnetic/magnetic and magnetic/vacuum) thin films to influence and control thin-film magnetic properties. We explored the relationship of magnetic properties to nano-scale chemical and physical interface morphologies. Our approach focused on obtaining a quantitative and microscopic description of these interface morphologies, and relating them quantitatively to magnetism. We grew our own films in-situ and used a unique combination of probes, to relate physical/chemical boundary morphology to behavior of magnetic moments at interfaces.

15. SUBJECT TERMS
interfaces, magnetism, roughness, soft-x-ray scattering,

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	8	Max G. Lagally
					19b. TELEPHONE NUMBER *(Include area code)* 608 263 2078

Interface Effects on Magnetism in Model Thin Films

Grant #N00014-02-1-1026

Max G. Lagally
University of Wisconsin-Madison
Lagally@engr.wisc.edu

Final Report

January 25, 2007

Summary

The goals of the research were to explore the fundamental physical mechanisms that allow interfaces between magnetic and nonmagnetic (as well as magnetic/magnetic and magnetic/vacuum) thin films to influence and control thin-film magnetic properties. We explored the relationship of magnetic properties to nano-scale chemical and physical interface morphologies. Our approach focused on obtaining a quantitative and microscopic description of these interface morphologies, and relating them quantitatively to magnetism. We grew our own films *in-situ* and used a unique combination of probes, to relate physical/chemical boundary morphology to behavior of magnetic moments at interfaces. This grant start date was Sept.15, 2002, and the end date was September 30, 2006 (one year no-cost extension).

Introduction

Advances in nanotechnology, especially in ultra-thin-film deposition, have led to the discovery of many new magnetic phenomena, whose rapid development into useful devices (like the spin valve, based on the giant magnetoresistive effect – GMR) has set the stage for a renaissance in studies of magnetism, emphasizing phenomena at the nanoscale. These phenomena have led to a new field, spin electronics, or spintronics. Spintronic devices use the spin of electrons as well as the charge to carry information.

Much current fundamental research centers on understanding new magnetic phenomena such as GMR, anisotropic exchange biasing, perpendicular magnetic anisotropy, and spin reorientation transitions, and developing novel magnetic hybrid structures such as magnetic tunnel junctions, spring magnets, magneto-optical heterostructures, non-volatile random access memory (NV-RAM, a potential route to instant-on computers), and spin electronics. Technology research and development focuses on optimizing the device structures and the materials that are needed to develop products based on these phenomena. Fundamental understanding and technological optimization meet at one critical juncture: the interface.

Magnetic coupling is itself a complex phenomenon, with interactions ranging from the short-range (e.g., dipolar and magnetocrystalline anisotropy) to long-range (e.g., magnetostatic and shape anisotropy). Adding interfaces creates greater complexity and can lead to transition regions between two films in which the magnetic properties differ from those of either film. Adding nonuniformities in the interfaces, such as physical roughness, chemical interdiffusion, contamination, or deliberately deposited barrier layers, will affect the behavior of the magnetic moments at the interface and hence the properties of the magnetic or spintronic device.

Our effort explored the fundamental physical mechanisms that allow interfaces between magnetic and nonmagnetic (as well as magnetic/magnetic and magnetic/vacuum) thin films to influence and control thin-film magnetic properties. Ultimately we also explored strain in semiconductor membranes, as a precursor to new approaches to nanomagnetism (which we did not get to in this grant period).

Personnel

The following personnel were involved in the research: M.G. Lagally, PI; D. E. Savage, Ph.D., staff scientist; John Kelly, Ph. D., Physics 2002; Bryan Barnes, Ph.D., Physics, 2004; Eric Wiedeman, MS, Materials Science 2005, Zhiwei Li, Ph.D. Materials Science, to be completed in March 2007, and Chanan Euaruksakul, grad student in Electrical Engineering. In addition, Jin Seo Noh, an a graduate student who was expert in oxide growth and microfabrication of tunnel junctions, spent some time with the group before obtaining his Ph.D. in Materials Science in 2003.

Publications

1. "Step-Induced Magnetic Hysteresis Anisotropy in Ferromagnetic Thin Films", D. Zhao, Feng Liu, D.L. Huber, and M.G. Lagally, J. Appl. Phys. 91, 3150 (2002).

2. "Comparison of Magnetic- and Chemical-Boundary Roughness in Magnetic Films and Multilayers", J.J. Kelly IV, B.M. Barnes, F. Flack, D.P. Lagally, D.E. Savage, M. Friesen, and M.G. Lagally, J. Appl. Phys. 91, 9978 (2002).

3. "Surface and Interface Roughness in Magnetic Thin Films: A Comparison Using Carbon-Nanotube Atomic Force Microscopy and Soft-x-ray Resonant Scattering",

B.M. Barnes, F. Flack, J.J.G. Kelly IV, D. P. Lagally, D.E. Savage, and M.G. Lagally, SPIE Proceedings 4780, 61 (2002).

4. "Quantifying the Thickness of Magnetically Active Layers Using X-ray Resonant Magnetic Scattering", B.M. Barnes, Z. W. Li, D.E. Savage, E. Wiedemann, and M.G. Lagally, J. Appl. Phys. 95, 6654 (2004).

5. "Observation of Inverse Magnetoresistance in Perovskite Oxide Tunnel Junctions", J.S. Noh, C.B. Eom, M.G. Lagally, J.Z. Sun, and H.C. Kim, Phys. Stat. Sol. B241, 1490 (2004).

6. "Influence of Interfacial Roughness on the Magnetic Transition Layer in Ferromagnetic-Paramagnetic Thin-Film Interfaces," B.M. Barnes, J.J.G. Kelly IV, F. Flack, Zhiwei Li, D.E. Savage, E. Wiedemann, and M. G. Lagally, in preparation.
7. "Determination of Local Strain in Silicon Nanomembranes via X-Ray Absorption Measurements", Zhiwei Li, Fan Zheng, F. Himpsel, Chanan Euaruksakul, D. E. Savage, Xiaosong Liu, and M. G. Lagally, in preparation

8. "Surface roughness effect on magnetic thin films probed by XRMS and XMCD", Zhiwei Li, B. M. Barnes, D.E. Savage, and M.G. Lagally, in preparation

9. "Effect of Oxygen as a Surfactant on the Interface Properties of Magnetic Thin Films Probed by XRMS and XMCD", Zhiwei Li, B.M. Barnes, D.E. Savage, and M.G. Lagally, in preparation

Ph. D. Dissertations

1. John J. Kelly, IV (2002), "Surface and Interface Magnetization Probed by Soft-X-Ray Resonant Magnetic Scattering".

2. Bryan Barnes (2004), "Correlating the Physical Interfaces and Magnetically Active Thickness of Ultrathin Cobalt Films".

3. Zhiwei Li (2007), "Investigations of Thin-Film Surfaces and Interfaces Using Synchrotron-Generated Soft X-Rays".

Achievements

Our measurements have shown that moments can be pinned in the magnetic-interface region, thus preventing them from rotating with the applied field. Such pinning could result from an anisotropy at the interface that makes out-of-plane alignment energetically favorable or from a reduced exchange coupling of moments in the interface region to bulk moments, caused by roughness induced in-plane demagnetization. Moments at a disordered interface have lower coordination, and lower coordination could cause interface moments with fewer nearest neighbors to have a reduced exchange coupling to moments in the bulk. Both predict that moments do not follow the applied magnetic field, but in one case the moments are frozen in place, and in the other they are "flopping about." Roughness induced in-plane demagnetization is the primary cause of the magnetic transition layer ("dead layer") in sputter-deposited Co films on both smooth and KOH-etched rough Si(100) wafers.

To improve the reliability of our conclusions, we grew Al-Co-Al film sandwiches, with variable Co thickness. These sandwiches are grown in-situ onto smooth Si wafers and also onto rough, sputter-deposited Ta layers on Si. Sputter-depositing the Ta layer at different thicknesses and sputter gas pressures allows tailoring of the rms roughness of the Ta substrate. The magnetic transition layer thickness is then determined and the magnetic resonant response of the layers is modeled by adding a term to the complex index of refraction that depends on magnetization. Figure 1 shows our results on transition layer measurements.
Computation and analysis will be part of the papers still to be published.

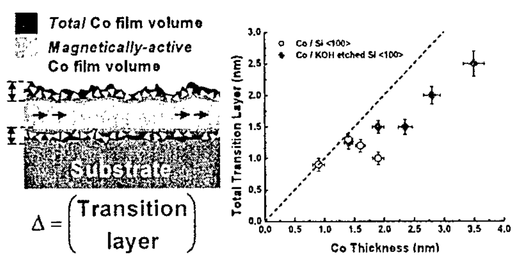
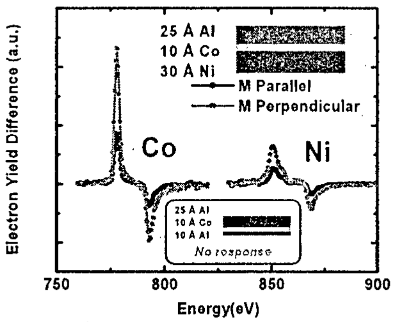


Figure 1: (left) Schematic of non-magnetic transition layer formation in ferromagnetic thin film; (right) Comparison of total transition layer thickness as a function of thickness for two ranges of roughness. The dotted line represents no magnetic response; the region above dotted line is unphysical.

Because of geometry, only magnetization in the plane of the sample can be measured with x-ray resonant magnetic scattering (XRMS). We used a second technique, x-ray magnetic circular dichroism (XMCD), to measure out-of-plane magnetic response, to assure that the "missing" volume of non-magnetic material is not simply pointing out of the sample. XMCD is a total-electron-yield measurement of all photoelectrons created through absorption in the film. It is magnetically sensitive at transition edges in the presence of circularly polarized light. Figure 2 shows an example of our XMCD measurements, on an Al/Co/**Ni** film on Si. A similar Al/Co/**Al** film on Si showed no magnetic signal ($d_{Co} \sim 1$ nm). However, a strong out-of-plane response and a weak in-plane response are measured in equal proportion in the Ni layer and the Co layer. This result indicates that Ni is a poor choice to use as an underlayer as it will produce out-of-plane magnetization that will be invisible to the XRMS experiment. As Co films at all thicknesses usually exhibit in-plane magnetization, we can reaffirm our initial assertion that a ferromagnetic film can "heal" a magnetic boundary in a neighboring ferromagnetic film that would have shown little to no response if sandwiched between Al films.



Data: Mark Bissen and Bob Pedlev of SRC

Figure 2: XMCD data for a 10 Å Co layer and its 30 Å Ni underlayer; (inset) A 10 Å Co film sandwiched between Al layers offers little or no magnetic response to either in-plane (parallel) or out-of-plane (perpendicular) magnetization

We also performed angle-resolved photoemission studies to determine the interplay between interfacial roughness and chemical and electrical states. We chose Cu single-crystal substrates because they have been used by many people without careful characterization of surface topography before deposition. With either Cu or Si as a substrate, we can vary the roughness of the substrate and hoped to see changes in the band structure at the surface with the density-of-states information near the Fermi level that can be gained through photoemission. Although we saw some effect, the results were not conclusive.

We explored Si surfaces more fully; in particular looking at strain with another method, x-ray absorption spectroscopy (XAS). A primary use of strain in semiconductor devices is to enhance electronic transport properties. Tensile and compressive strains modify the band structures of Si and Ge. The changes in the band structure in turn influence the mobility of charge carriers. The mobility of electrons in tensilely strained Si increases because the reduction of degeneracy of the conduction band minima reduces the scattering rate in electron transport. Strain can also very easily affect magnetic properties, especially at the nanomagnetism level, or for very thin films

Figure 3 shows schematically the 6-fold degenerate sub-bands at the conduction band minimum of Si. Strain is typically introduced via growth on a lattice with different lattice constant. In the most interesting situations the strained layer is quite thin, and methods to determine strain quantitatively in these very thin films are desirable. Our aim was to show that we could determine strain in very thin layers. In both XRD and RS, the most widely used techniques for determining strain, measurements become difficult when the film becomes very thin. XAS can provide intermediate information, in that one can effectively observe the splitting of the conduction band degeneracies. By making a total electron yield measurement, one can create sensitivity to very thin films. The process is as follows: Synchrotron generated X rays with tunable energy, hν, excite electrons from shallow core levels (here the 2p level) of Si to empty conduction band states. The excited atoms relax predominantly by an Auger process, emitting an electron with an energy characteristic of the levels involved. The spectrum of the Auger electrons with x-ray energy as the variable reflects the convolution of the densities of states of the 2p core level and the conduction band. If the density of states (DOS) of the 2p core level is comparatively confined and its shape does not change with the strain, the spectrum provides an accurate picture of the density of states of the conduction band. The very shallow escape depth of Auger electrons at the energies involved in these XAS measurements (mean free path of the order of a few nm) enables measurement of energy level changes in very thin layers, so thin that quantum size effects are observable. The depth resolution is around 2-3 nm, thicknesses at which other techniques either fail or become extremely difficult.

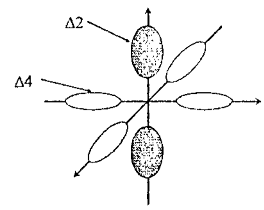


Figure 3. Si band structure: degenerate conduction band valleys.

Using this method, we have been able to determine strain in very thin layers and free-standing membranes quantitatively. We have been able to determine strain nonuniformity from broadening of the XAS spectra. Because the conduction band minimum valley splitting in Si depends very sensitively on strain, even very small strains are measurable. Figure 4 shows data from which we can extract the strain

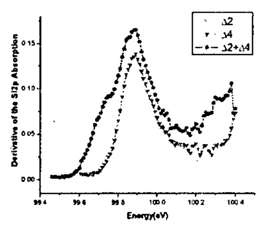


Figure 4. Derivative XAS spectra from strained Si. We extract the valley splitting from the peak positions, which in turn can be related to the strain.

Technology Transitions

We laid the groundwork for a collaboration with NIST (W.F. Egelhoff) on surfactant effects on the internal magnetic boundary, using our tools and materials from NIST. Unfortunately the grant ended before the collaboration became effective. We made initial measurements and a manuscript is being prepared.

George Celler of Soitec provides various types of SOI to us for our studies.

International Collaborations

There were no international collaborations on this project.