Spin Transport and Dynamics in Nanoscale Hybrid Structures
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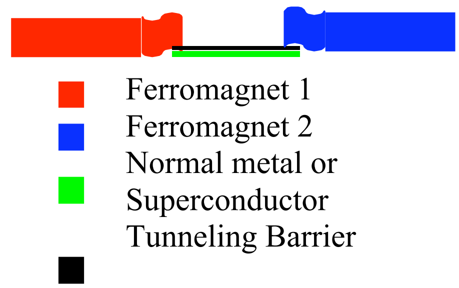
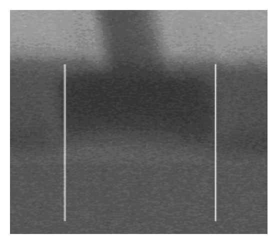
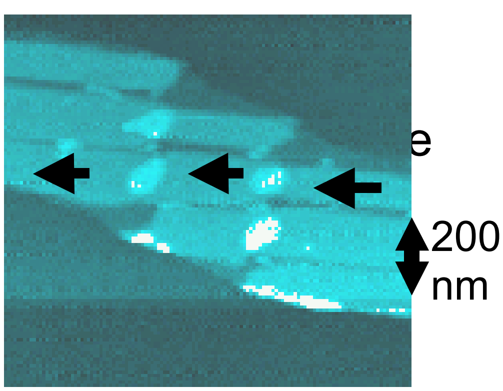
The objective of this project is to fabricate and characterize nanoscale hybrid tunnel-junction structures that will reveal new physical aspects of the *spin-dependent* quantum states and dynamic behavior of single electrons. Several interesting effects have been predicted for spin-dependent transport in ferromagnet (FM)/metal/ferromagnet and FM/superconductor/FM double junctions. One goal is experimentally to verify these theoretical predictions. The approach is to combine the recent advances in single-electron transistors and spin tunnel junctions, with the fabrication of hybrid junction devices using electron-beam lithography and shadow evaporation techniques. This work contributes to current research in the spintronics community and provides a more comprehensive understanding of the spin dynamics needed to develop innovative spin based nanoelectronic devices.



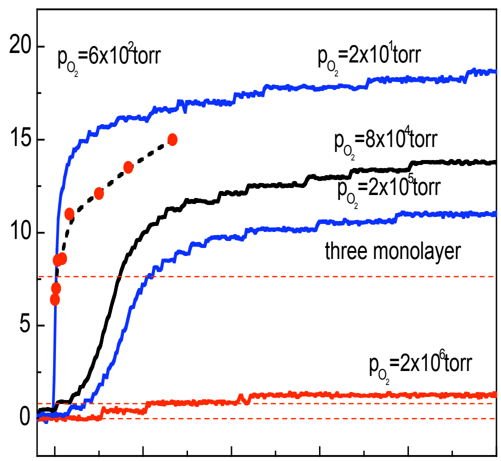
The key points for our device fabrication include: (1) fabricating large undercut masks using e-beam lithography for successful triple angle evaporation [the ratio between top line-width and undercut width needs to be at least 1:6], and (2) obtaining high quality oxide barriers between the ferromagnet and the center island. Good progress has been made on both of these tasks.

By exposing a bilayer resist with two different etching doses, we have successfully fabricated a resist mask with top linewidth of about 60 nm and an undercut of nearly 600 nm (see figure on the right). This mask set has been used to fabricate Fe/Al/Fe double-junction spin-tunnel devices (below, left). Results on these devices are not yet conclusive but one possible problem is the oxide barrier. In order to improve tunnel-barrier quality, we have studied the barrier oxidization process and the relation between the barrier thickness and spin polarization. We have gained expertise in growing ultra-smooth metal films and very thin oxide layers over the metal film using molecular beam epitaxy.



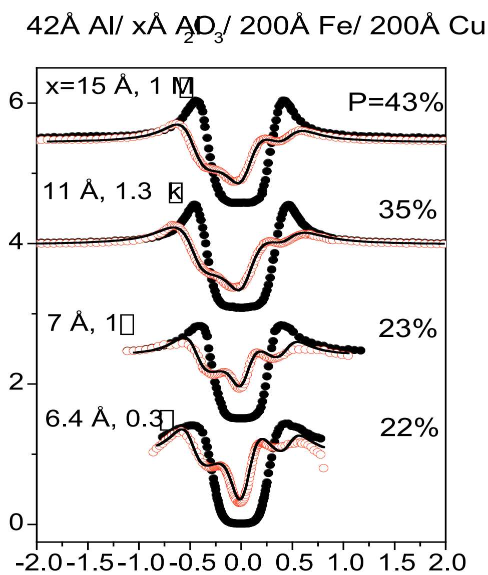


The figure at the top of the next page shows the dependence of the oxide thickness on time and oxygen partial pressure. Al is used as the center island in this sample. To measure the spin transport through the device, the barrier resistance should be in the range between 20 kΩ and 500 kΩ, corresponding to the oxide layer thickness of 5–7 Å. Al films grown at room temperature and at 77 K show different smoothness. The low-temperature-grown Al films are smooth with a roughness of 2-3 Å.



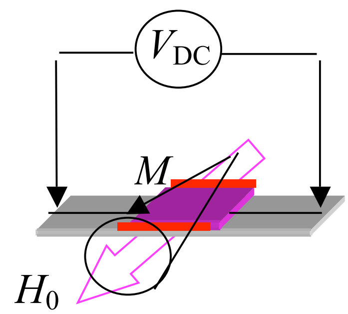
Our studies have shown that barrier thickness, which determines junction resistance, influence the spin polarization considerably (Fig. below). When the barrier resistance changes from 1 M□ to 0.3 □, the spin polarization drops from 43% to 22%. The black curve in the figure below indicates the conductance curve of superconducting Al when the external magnetic field is zero. In non-zero external magnetic fields, spin splitting of the density of states of Al occurs and the spin polarized electrons from Fe tunnel through the junction. The red curve in the figure is the conductance measured at 3.3 T. These advances in nanoscale shadow-mask-fabrication of double junction devices having superior barrier quality are important results of the program.

Another aspect of this project is the fabrication of magnetic tunneling junctions (MTJ) using half metallic materials. Half metallic materials are attractive because their high spin-polarization (100%), makes them promising candidates for tunnel junctions and spin injection. Epitaxial growth of Fe_3O_4 (magnetite) on single crystal MgO has been reported by many groups; it is predicted to be a half-metal. Fe_3O_4/MgO is known also to be a semi-hard magnetic material, however its low squareness renders it unfit as a pinned layer by itself. A highly conductive underlayer is required for applying Fe_3O_4 as an electrode in magnetic tunnel junctions to avoid non-uniform current distribution. We have successfully grown epitaxial Fe_3O_4 films using a V/Ru underlayer on an single-crystal MgO. This stack show relatively high squareness ratio (0.66) and H_c (550 Oe).

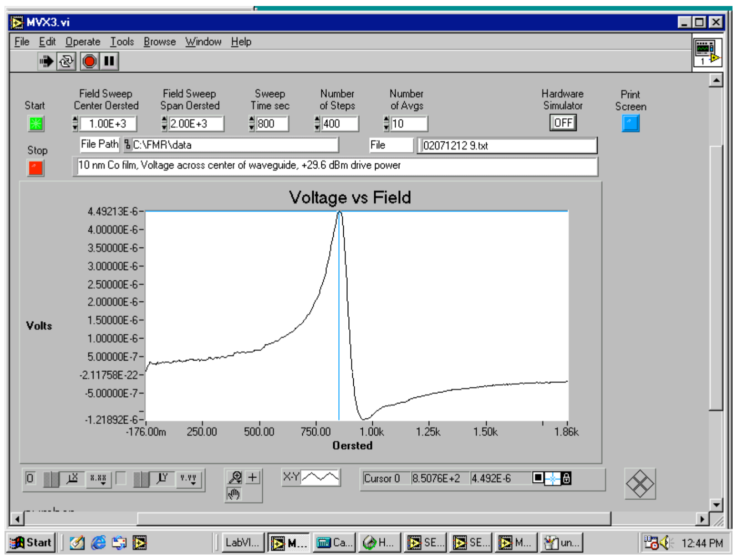


TMR of 12.6% to 14% and Resistance Area product (RA) of 3 to 3.5 k□ □□m^2 were achieved for almost all junctions. This value is one of the highest TMR ratios observed using an Fe_3O_4 electrode. RA product is almost same for different size junctions, which indicates that geometrical effect was hardly seen on this MTJ.

Our research program also calls for the dynamic characterization of spin



lifetime, relaxation and diffusion length when electrons tunnel from a ferromagnetic electrode to a non-magnetic island. The technique we utilize to address this problem is the measurement of DC effects associated with magnetic resonance (right). This technique affords a simple DC probe of electron spin polarization and relaxation time as a function of position in a thin film. We have designed and fabricated mask sets to measure the position dependence of the DC resonance signal accompanying magnetic resonance in films. Our FMR system has shown the uniform resonance in a variety of magnetic thin films having mm-scale lateral dimensions including several Ni and Ni-Fe layers 5 to 12 nm, and a 10-nm-thick Co film (shown below). We have made arrangements to have some e-beam-defined nanostructures fabricated at IBM for testing in our DC-effects FMR system. This method of characterizing spin dynamics is suitable for high resistivity, low magnetization films having small dimensions.



Collaborations: Our program has made good use of a number of collaborations that leverage the NSF support. The shadow masks and e-beam lithography were done at the Cornell Nanofabrication facility. JGL will be purchasing an e-beam lithography system for UCI with separate NSF support. This key acquisition will save considerable time and expense in sample fabrication. Our first double junction devices were grown at the Francis Bitter Magnet Lab at M.I.T. Films used to test the newly developed FMR system were grown in an M.I.T. departmental thin film fabrication facility run by Prof. Caroline Ross. We will soon be getting some e-beam lithography magnetic thin films (for next stage FMR testing) from Liesl Volk of IBM's Almaden Research Center.

Educational outreach: In addition to the four graduate students supported, or partially supported by this program, we make extensive use of undergraduate researchers, working, and in some cases publishing, with the graduate students. Further, Moodera's group hosts 4 to 5 local high school students with some NSF support.