New Trends in Magnetism, Magnetic Materials, and Their Applications

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Xe^+ Irradiation Increases Magnetoresistance in Sputtered Fe/Cr Superlattices

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Abstract

We have studied the magnetoresistance of sputtered Fe/Cr superlattices as a function of 500 keV Xe^+ irradiation in the fluence range of 1×10^{10} to 1×10^{15} Xe^+/cm^2. The results show that the giant magnetoresistance is enhanced for intermediate fluences and greatly suppressed for higher fluences. The suppression of the giant magnetoresistance is due to the destruction of the antiferromagnetic order, and the mechanism for the enhancement is under investigation.

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I. Introduction

Giant magnetoresistance (GMR) has been found in Fe/Cr superlattices where the adjacent layers of iron, which are antiferromagnetically coupled, can be brought into parallel alignment by an external magnetic field.[1] It has also been recognized that the presence of interface roughness makes a significant contribution to GMR: in sputtered Fe/Cr multilayers the GMR was found to increase substantially with increasing layer thickness fluctuations which gives rise to interfacial roughness.[2] The properties of sputter-deposited thin films depend strongly on the surface morphology that is in turn determined by the sputter-growth process. This also applies to ion-beam sputter etching, a widely used technique in surface science, which produces surfaces with topographies that depend on the sputtering conditions. On a macroscopic level (*i.e.*, length scales larger than one micron), ion sputtering is known to roughen surfaces, particularly metal surfaces where it results in such surface features as edges, corners, or peaks. However, from the viewpoint of GMR the nanometer scale is of most interest because the length scales of induced structural inhomogeneities must be comparable or preferably a fraction of the mean free path of electrons in the superlattice (which is typically a few nanometers) in order for irradiation to influence the electrical transport. Scanning tunneling microscopy measurements of graphite[3] and iron[4] sputtered by Ar have shown surface roughness on the scales down to $0.5 - 1$ nm as a result of ion bombardment. X-ray reflectivity measurements yielded roughening of Si by H and Ge by Xe on the same scale.[5] To investigate the nature of interface roughness effects on GMR ion irradiation can prove to be a useful tool. Moreover, irradiation appears to be a nice tool for "post-growth tailoring" GMR materials. In this work we report on structural, magnetic and magnetotransport measurements of ion beam irradiated Fe/Cr superlattices.

II. Experimental Details

The samples were prepared using dc magnetron sputtering (base pressure of 1×10^{-7} Torr) on ambient temperature Si[111] substrates (for details of the growth process see *e.g.*, Refs. 2, 6). The films were cut into, typically in-plane dimensions of 2.5×12 mm^2. The structure of these samples was characterized by high- and low-angle X-ray diffraction using a Rigaku rotating anode diffractometer with Cu-Kα radiation. The magnetic hysteretic loops were measured using a SQUID magnetometer and the magnetoresistance was measured with four terminal dc technique. Both in magnetic and magnetotransport measurements the external field was applied in plane of the film. For the transport measurements the field was also perpendicular to the current. Normal incidence irradiation (sample tilt angle is 0) was performed at room temperature in a vacuum of about 4×10^{-5} Pa with a beam of 500 keV Xe^+ ions rastered over 12 mm^2 area. The ion beam current was always kept below 0.6 μA/cm^2 and the samples were mounted using a heat conducting paste in order to avoid sample heating during irradiation. The irradiation parameter that was varied in this study was the fluence of particle radiation. The samples were characterized before and after bombardment using the same experimental parameters, although here we will give a preliminary report of our results.

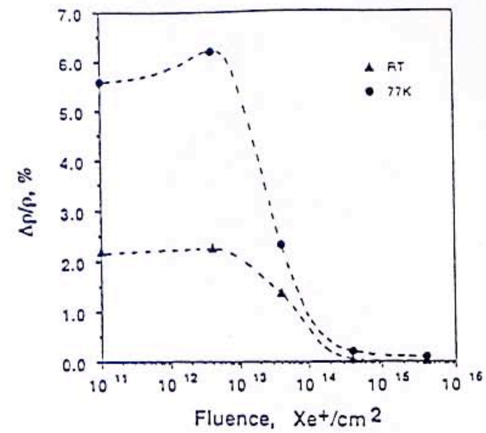

Figure 1. $\Delta\rho/\rho$ *vs.* 5000 KeV Xe^+ fluence for the first set of $[Fe(30\ \text{Å})/Cr(12\ \text{Å})]_{10}$ superlattices at room temper iture (triangles) and 77 K (circles).

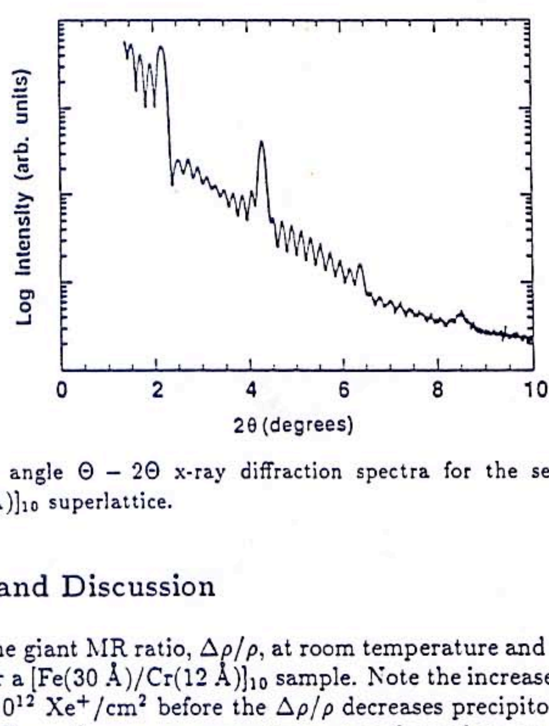

Figure 2. Low angle $\Theta - 2\Theta$ x-ray diffraction spectra for the second, unirradiated $[Fe(30\ \text{Å})/Cr(12\ \text{Å})]_{10}$ superlattice.

III. Results and Discussion

Figure 1 shows the giant MR ratio, $\Delta\rho/\rho$, at room temperature and 77 K as a function of Xe^+ fluence for a $[Fe(30\ \text{Å})/Cr(12\ \text{Å})]_{10}$ sample. Note the increase in $\Delta\rho/\rho$ observed at 77 K for 3×10^{12} Xe^+/cm^2 before the $\Delta\rho/\rho$ decreases precipitously to zero above 10^{13} Xe^+/cm^2. Since these measurements were performed on unpatterned samples it is difficult to ascertain weather the increase and consequent decrease in $\Delta\rho/\rho$ is caused by changes in the magnetoresistance $\Delta\rho$ or in the resistivity ρ. In order to investigate this issue, we have performed a series of ion damage studies on a second set of samples.

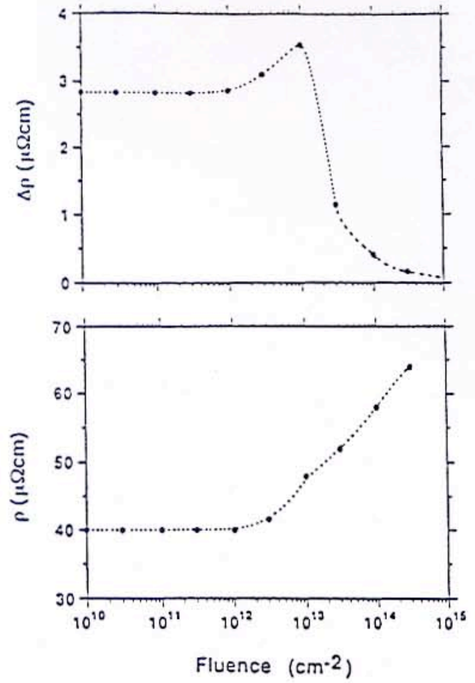

Figure 3. $\Delta\rho$ and ρ_s *vs.* Xe^+ fluence for the second $[Fe(30\ Å)/Cr(12\ Å)]_{10}$ superlattice.

Figure 2 shows the low angle x-ray diffraction for this second $[Fe(30\ Å)/Cr(12\ Å)]_{10}$ sample on a logarithmic scale. Notice the well developed Bragg peaks up to the fourth order and the presence of clear finite size peaks between the Bragg peaks. A semiquantitative interpretation of this data indicates that the sample has a periodicity of 42.0 Å, repeated 10 times. Further quantitative studies will be published elsewhere.

Figure 3 shows independent measurements taken at 77 K of the magnetoresistance, $\Delta\rho$, and the saturation resistivity, ρ, as a function of Xe^+ ion fluence. The magnetoresistance is defined as $\Delta\rho = \rho_0 - \rho_s$, where ρ_0 is the resistivity in zero field and ρ_s is the resistivity above the saturation field. As found ordinarily, the resistivity is initially flat, then increases substantially above $10^{12}\ Xe^+/cm^2$. Initially, $\Delta\rho$ is unchanged by the Xe^+ fluence, then increases about 25 % before decreasing to zero above a fluence of $10^{14}\ Xe^+/cm^2$. Since ρ_s increases as well in the region of enhancement of $\Delta\rho$, the proportional enhancement in $\Delta\rho/\rho$ is smaller, as observed in the first series of experiments (Fig. 1).

Three magnetization curves for as-grown (dashed line), irradiated with 1×10^{13} and $3\times10^{13}\ Xe^+/cm^2$ (solid lines) are shown in Fig. 4. The M *vs.* H curve of the as-grown sample looks typical of an antiferromagnetically (AF) ordered sample. A field of about 6 kG is needed to overcome the AF coupling and to saturate the magnetization of the sample. As the external field is decreased to zero, the antiferromagnetic coupling brings the magnetization back to about zero. The loop exhibits small remanence characteristic of conventional antiferromagnetism. When the fluence increases the magnetization loop becomes less and less sheared indicating that the AF ordering is

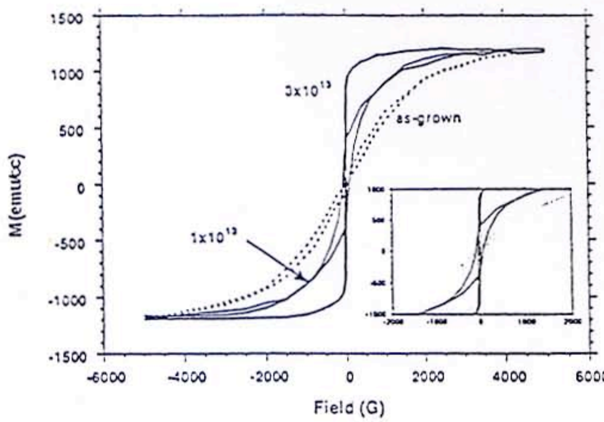

Figure 4. In-plane magnetization curves for the second [Fe(30 Å)/Cr(12 Å)]$_{10}$ samples. Shown above are the as-grown (dashed line), irradiated with 1×10^{13} and 3×10^{13} Xe^{+}/cm^2 (solid lines). Inset: region near the origin.

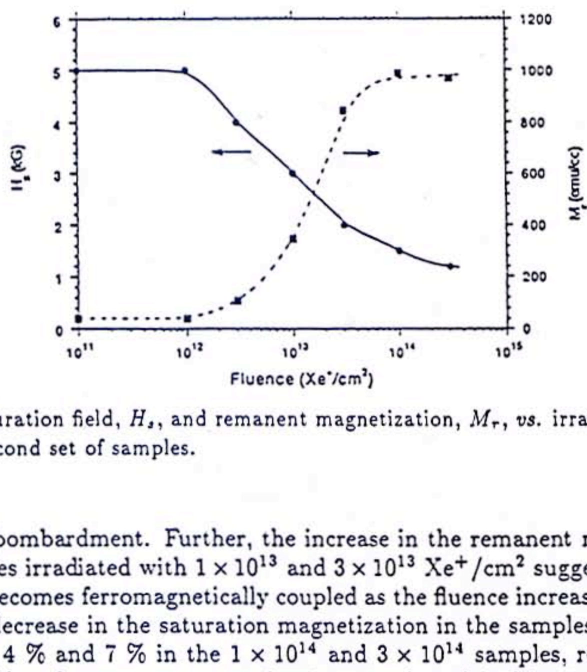

Figure 5. Saturation field, H_s, and remanent magnetization, M_r, *vs.* irradiation fluence at 77 K for the second set of samples.

destroyed by bombardment. Further, the increase in the remanent magnetization of the two samples irradiated with 1×10^{13} and 3×10^{13} Xe^{+}/cm^2 suggests that more of the material becomes ferromagnetically coupled as the fluence increases. We observed only a slight decrease in the saturation magnetization in the samples irradiated with high fluences, 4 % and 7 % in the 1×10^{14} and 3×10^{14} samples, respectively. The saturation field and remanent magnetization are plotted in Fig. 5 as a function of fluence.

Figure 4 shows that saturation magnetization is approximately 1200 emu/cc, about 70 % of the bulk value for Fe. This indicates that about 30 %, or 9 Å, of each iron layer is non-magnetic. As claimed for Fe/Nb superlattices[7] we presume that

4.5 Å of Fe at each interface is interdiffused with Cr to form a non-magnetic FeCr alloy (FeCr alloys are non-magnetic at 25 % Cr in Fe).[8] The small change in the saturation magnetization implies that the interdiffusion does not change significantly with irradiation in the investigated fluence range. Figure 5 shows the saturation field and the remanent magnetization as a function of the Xe^+ fluence. We observe that the remanent magnetization increases with irradiation, and the saturation field decreases. The remanence approaches the saturation magnetization at high fluences yielding an almost 90 % squareness of the magnetization loop for 3×10^{14} Xe^+/cm^2. This shows that as the fluence is increased, a larger amount of the material is coupled ferromagnetically and hence less of the sample AF. We have observed that when samples are roughened the remanent magnetization increases similarly,[2] and we are currently investigating the structure of the irradiated films. In conclusion, we have studied the magnetotransport and magnetization of sputtered Fe/Cr superlattices as a function of ion irradiation. The striking overall result of the work is that the change in the giant magnetoresistance with irradiation is not monotonic. Modest intensities of Xe^+ irradiation enhance GMR . The structure of the irradiated films, and the relationship between the structural changes and the changes in the magnetotransport are currently being investigated.

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