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Magnetotransport and exchange coupling in Fe/Cr multilayers: effects of annealing and ion irradiation

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Abstract

A comparative study of the effects of heat treatment, as well as Xe^+ ion irradiation on the structure, magnetotransport and magnetic properties of Fe/Cr multilayers exhibiting giant magnetoresistance (GMR) is presented. The experimental observations on the GMR are explained in terms of increasing roughness at the interfaces, and the consequent loss of antiferromagnetic (AF) coupling in the sample. We also discuss the role of interfacial as well as bulk scattering in the electronic transport of Fe/Cr multilayers.

It is widely accepted that giant magnetoresistance, GMR, originates from spin dependent scattering (SDS) of conduction electrons in antiferromagnetically coupled magnetic/nonmagnetic multilayers [1]. The character of the SDS relevant for GMR could arise from interfacial scattering [2] in addition to the bulk [3] characteristics of the multilayer system. For example in Fe/Cr interfacial scattering is significant while in permalloy SDS in the bulk contributes to the GMR. When bulk SDS dominates, the scattering ratio $\alpha = \lambda^{\uparrow}/\lambda^{\downarrow}$ ($\lambda^{\uparrow}$ and $\lambda^{\downarrow}$ are the mean free paths for majority and minority spin electrons, respectively) is different from unity everywhere in the ferromagnetic layers. On the other hand for systems with dominating interfacial SDS, $\alpha \neq 1$ only within the narrow region at the magnetic/nonmagnetic interface. In this case the electronic transport is determined by the combined effect of the electronic structure of the two metals, as well as by the nature of the interface. In Fe/Cr multilayers interfacial roughness was shown to play a significant role in enhancing GMR. MBE grown Fe/Cr (100) multilayers showed high sensitivity of the GMR to direct Fe-Cr alloying as well as heat treatment [4]. It has been shown for Fe/Cr (110) multilayers that by increasing roughness of the interfaces during sputtering process (e.g., by varying Ar pressure in the sputtering chamber) one can significantly enhance the GMR [6]. Almost twofold enhancement of the GMR was also reported for sputtered Fe/Cr (110) multilayers with Fe layers alloyed by Cr. In this paper we compare the results of heat treatment as against Xe^+ irradiation effects studied on the same Fe/Cr multilayered sample. The different nature of defects induced by annealing and ion bombardment has allowed us to separate the role of the interface and the bulk in the electronic transport in this system. Our results are consistent with spin-independent (saturation) resistivity which is weakly dependent on interfacial scattering, as well as spin-dependent resistivity (GMR) which is dominated by interfacial roughness.

The samples were prepared using dc magnetron sputtering (base pressure of 1×10^{-7} Torr) on ambient temperature Si[111] substrates. The multilayer structure was characterized by high and low-angle X-ray diffraction using a Rigaku rotating anode diffractometer with Cu-Kα radiation and showed a mix of (110) and (100) orientations. The in-plane magnetization was measured using a SQUID magnetometer and the magnetoresistance was measured using four terminal dc technique with the magnetic field perpendicular to the current. The same Fe/Cr sample was annealed in N_2 atmosphere at sequentially increasing temperatures and $R(H)$ and $M(H)$ curves were recorded after each annealing step. In each heat treatment at temperatures up to 450°C, the sample was isothermally annealed for 30 min, with a heating/cooling rate greater than 40 deg/min. Normal incidence irradiation was performed at room temperature in a vacuum of about 4×10^{-5} Pa with a beam of 500 keV Xe^+ ions rastered over 1.2×1.2 cm^2 area. The current was always kept below 0.6 $\mu A/cm^2$ and the samples were mounted using a heat conducting paste in order to avoid sample heating during irradiation. The

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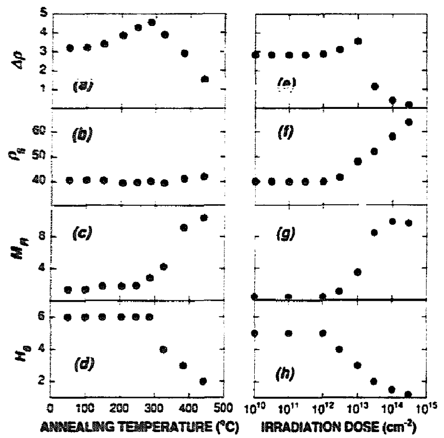

Fig. 1. Magnetoresistance, $\Delta\rho$ ($\mu\Omega$ cm), (a) and (e); saturation resistivity, ρ_S ($\mu\Omega$ cm), (b) and (f); remanent magnetization, M_R (10^2 emu/cc), (c) and (g); and saturation field, H_S (kG), (d) and (h) for $[Fe(30\ Å)/Cr(12\ Å)]_{10}$ versus annealing temperature and versus Xe^+ irradiation dose, respectively.

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.

Fig. 1a shows magnetoresistance measurements taken at 77 K as a function of annealing temperature. The magnetoresistance is defined as $\Delta\rho = \rho_0 - \rho_S$, where ρ_0 and ρ_S are the zero field and saturation resistivity, respectively. $\Delta\rho$ (GMR) first increases with increasing annealing temperature, goes through a peak at about 300°C, and then decreases for higher temperature anneals. The saturation resistivity, ρ_S (see Fig. 1b), however, does not change substantially and remains nearly constant in the range of annealing temperatures used in this study. The remanent magnetization, M_R, and the saturation field, H_S, are shown in Fig. 1c and d respectively. The sharp increase in the M_R and decrease in H_S at above 300°C anneal indicate that the strength of AF coupling is progressively reduced with annealing and more of the material becomes FM coupled. The drastic changes in the M_R and H_S can be well correlated with the decrease in $\Delta\rho$ at above 300°C, suggesting that the eventual reduction of the GMR is due to the loss of AF ordering in the sample.

Shown in Fig. 1e is the magnetoresistance, $\Delta\rho$, as a function of Xe^+ ion dose. $\Delta\rho$ first increases for the intermediate doses of irradiation and then decreases for higher doses. In contrast, the saturation resistivity increases monotonicaly with increasing ion fluence and shows no singularities at the fluence where the $\Delta\rho$ is maximum (Fig. 1f). As in the case with annealing, the M_R and H_S change monotonicaly with increasing irradiation dose (see Fig. 1g and h) and indicate a transition from AF to FM coupling between the Fe layers. Again, the loss of AF ordering appears to be responsible for the suppression of the GMR at above 10^{13} Xe^+/cm^{-2}. We observe no changes in the saturation magnetization on either annealing or irradiation, which indicates negligible interdiffusion for the annealing temperatures and irradiation doses used in these experiments.

The XRD data showed progressive loss of the multilayer structure as well as large changes of the interface microstructure with annealing and irradiation [7]. The predominant multilayer character remains unaffected even for the highest annealing temperatures and irradiation doses as evidenced by the presence of superlattice peaks in the low-angle X-ray data [7]. Increasing interfacial disorder (roughness and/or intermixing) would result in weaker AF coupling and larger portion of Fe layers coupled FM. This is consistent with the magnetic behavior observed in both the annealed and irradiated samples, as well as with the decrease in $\Delta\rho$ at higher annealing temperatures (irradiation doses). Moreover, increasing interfacial roughness would enhance the GMR as long as appreciable portion of the Fe layers is coupled AF. This qualitatively explains the nonmonotonic behavior of $\Delta\rho$ in both annealed and irradiated samples. However, whereas low temperature annealing affects mostly the interface between two metals, ion bombardment creates disorder both at the interfaces and in the bulk of the layers. Thus, the same nonmonotonic behavior of $\Delta\rho$ in the annealed and irradiated samples suggests that the SDS is of interfacial rather than bulk character. On the other hand, the low sensitivity of the saturation resistivity to annealing and its high sensitivity to irradiation imply that the spin-independent resistivity is weakly dependent on interfacial scattering and dominated by bulk disorder.

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