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Transport properties of sputtered Fe/Si multilayers

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Abstract

A relatively large GMR effect associated with antiferromagnetic (AFM) coupling in sputtered Fe/Si multilayers was observed and the dependence of transport properties on Si layer and Fe layer thickness and on the number of bilayers at room temperature and 77 K were studied. Our data suggests that the mechanism of AFM coupling and GMR effect in Fe/Si multilayers is the same as that in metal/metal systems. © 1999 Elsevier Science B.V. All rights reserved.

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Recently, Fe/Si multilayers have been reported to exhibit a peculiar magnetic coupling [1,2]. A negative magnetoresistance effect with two different temperature dependencies as a function of Si thickness was observed by Inomata et al., who considered that the magnetic coupling was mediated by thin spacers of a narrow gap semiconducting iron silicide [3]. However, some recent research gave an opposite opinion that the AFM coupling in Fe/Si multilayers is attributed to the formation of metallic silicides in the interlayer [1,2]. In addition, the magnitude of the MR ratio found by Inomata et al. is very small ($< 0.15\%$), and whether the MR effect was associated with the AFM coupling was also questioned [4]. Here, we report our observation of a larger GMR effect ($\Delta R/R \sim 1\%$) and present the detailed data of the dependencies of the resistivity and MR ratio on the Fe and Si layer thickness and on the numbers of bilayers of Fe/Si multilayers, which are not available in the literature. Our data suggest that the mechanism of AFM coupling and GMR effect in Fe/Si multilayers is the same as in the metallic system.

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Several series of Fe/Si multilayers were deposited on water-cooled glass substrates by RF magnetron sputtering technique from Fe and Si targets. The vacuum system had a base pressure 5×10^{-7} Torr. An argon gas pressure of 5 mTorr was maintained during deposition. The deposition rates of Fe and Si were controlled to be 0.09 and 0.06 nm/s, respectively. The layered structure was achieved by exposing alternatively the substrate to Fe or Si targets via a rotating substrate holder controlled by a computer. The structure was characterized by both low- and high-angle X-ray diffraction (XRD). In the low-angle XRD pattern, two (for $t_{Si} < 3$ nm) or four (for $t_{Si} > 3$ nm) Bragg peaks were observed as shown in Fig. 1. The modulation length of the multilayers derived from XRD is smaller than the designed value by about 1 nm, indicating that there is an interdiffusion between the Fe and Si layers. So, the sublayer thicknesses of Fe and Si in this paper are nominal. The coherence length is obtained from the full-width at half-maximum of Fe(0 1 1) diffraction peak by Scherrer formula as $\xi = 25$ nm for $t_{Si} < 3$ nm, and $\xi = 3.2$ nm for $t_{Si} > 3$ nm. This implies that the crystalline spacer for $t_{Si} < 3$ nm might change into a noncrystalline spacer when $t_{Si} > 3$ nm.

The in-plane hysteresis loop measurements of $[Fe(3\ nm)/Si(t_{Si})]_{30}$ multilayers with t_{Si} from 0.5 to 4 nm show an enhanced saturation field H_s and reduced

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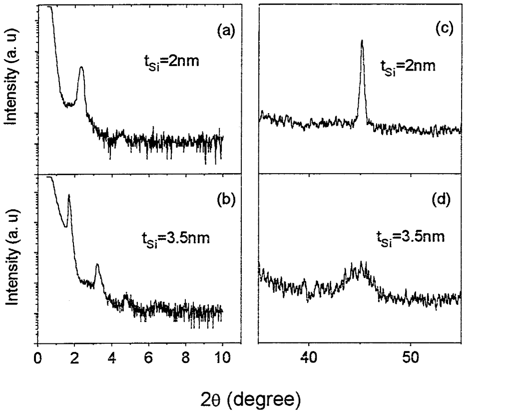

Fig. 1. Low angle and high angle X-ray diffraction patterns of $[\mathrm{Fe}(3\ \mathrm{nm})/\mathrm{Si}(t_{\mathrm{Si}})]_{30}$ multilayers with $t_{\mathrm{Si}} = 2$, and 3.5 nm, respectively.

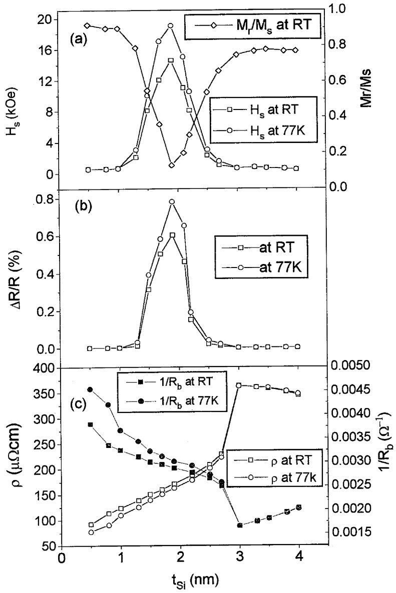

Fig. 2. The dependence on Si thickness of (a) saturation field H_s and in-plane remanence ratio M_r/M_s, (b) MR ratio $\Delta R/R$, (c) resistivity ρ in zero field and $1/R_b$ at RT and 77 K for the films of $[\mathrm{Fe}(3\ \mathrm{nm})/\mathrm{Si}(t_{\mathrm{Si}})]_{30}$ with $t_{\mathrm{Si}} = 0.5$–4 nm.

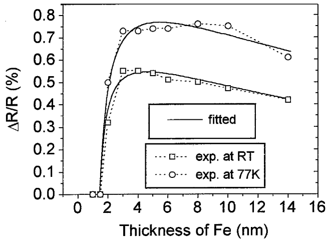

Fig. 3. The Fe layer thickness dependence of MR ratio at RT and 77 K for the films of $[\mathrm{Fe}(t_{\mathrm{Fe}})/\mathrm{Si}(1.9\ \mathrm{nm})]_{30}$ with $t_{\mathrm{Si}} =$ 1–14 nm.

remanence ratio M_r/M_s in a broad range with the extremes around $t_{\mathrm{Si}} = 1.9$ nm as shown in Fig. 2a, indicating AFM coupling, but no evidence of an additional AFM coupling peak for $t_{\mathrm{Si}} > 3$ nm. The AFM coupling is also identified by the measurements of the isotropic negative MR effect. The dependence of MR ratio on t_{Si} is similar to that of H_s as shown in Fig. 2b and both of them increase at 77 K. The increase of both H_s and MR ratio on cooling is incompatible with the speculation that the magnetic coupling across the Fe–Si spacers is mediated by the thermal excitation of charge carriers in the semiconducting spacers as suggested by several authors for their samples [3,5]. Fig. 2c shows the variation of the resistivity ρ of the multilayers in zero field and sheet conductance $1/R_b(=(t_{\mathrm{Si}}+t_{\mathrm{Fe}})/\rho$ [6]) of the bilayer versus nominal Si layer thickness at 77 K and RT. The rapid changes of ρ, $1/R_b$ and changes of XRD data at $t_{\mathrm{Si}} \approx 3$ nm can be understood by considering that in addition to the Fe–Si layer an α-Si layer appears in the spacer for $t_{\mathrm{Si}} \geqslant 3$ nm. The appearance of an α-Si layer in the spacers stops the increase of interdiffusion and results in the change of the slope in the figure on one hand, and prevents the AFM coupling on the other.

The dependencies of the transport properties on Fe layer thickness were studied for a second series of $[\mathrm{Fe}(t_{\mathrm{Fe}})/\mathrm{Si}(1.9\ \mathrm{nm})]_{30}$ multilayers with $t_{\mathrm{Fe}} = 0.5$–14 nm and $t_{\mathrm{Si}} = 1.9$ nm corresponding to the maximum AFM coupling. Fig. 3 shows the dependence of MR ratio on t_{Fe} at 77 K and RT. The shape of the MR versus t_{Fe} curve is similar to that in metal/metal systems with predominant bulk spin-dependent scattering and is fitted by a phenomenological formula of Eq. (1) in Ref. [7] for GMR. From the fitting the mean free path (MFP) of the spin-down electrons in the Fe layers is obtained as $\ell\downarrow = 15$ nm at 77 K and $\ell\downarrow = 13$ nm at RT. With decreasing t_{Fe}, the resistivity ρ increases probably due to an increase of interface scattering. For $t_{\mathrm{Fe}} < 2$ nm, AFM coupling, MR effect and Fe(1 1 0) diffraction peak in the XRD pattern disappear, the sign of the temperature coefficient of the resistivity (TCR) also changes from positive to negative probably due to the appearance of an α-Si layer in spacers and insufficient diffusion of Fe atoms into Si spacers for $t_{\mathrm{Fe}} < 2$ nm.

The dependence of MR ratio $\Delta\rho/\rho$ and MR, $\Delta\rho$, of $[\mathrm{Fe}(3\ \mathrm{nm})/\mathrm{Si}(1.9\ \mathrm{nm})]_N$ multilayers on the number of bilayers N ($N = 10$–60) were also studied. It was found that both $\Delta\rho/\rho$ and $\Delta\rho$ increase with increasing N and approaches to the saturation values above $N = 40$. The saturation values are $\Delta\rho/\rho \sim 1\%$, and $\Delta\rho \approx 2\ \mu\Omega$ cm, which are the largest values in our observations and in the literature for sputtered Fe/Si multilayers. It is well known that when the whole film thickness is small compared to the mean free path (MFP) in the multilayer, the

MR increases with N because the electrons may propagate across more sublayers within a conduction carrier MFP. However, the thicknesses of our films studied here (the smallest thickness is 40 nm for $N = 10$) are larger than the effective MFP of 13 nm at RT evaluated above. So, this argument may not be the main origin of the increase of MR ratio $\Delta\rho/\rho$ with increasing N and an additional origin may exist. The dependence of the saturation field H_s and $\Delta\rho$ on N show a similar behavior to that of the MR ratio. So the increase of the MR ratio and $\Delta\rho$ with N may be mainly related to the increase of AFM coupling strength as found in the previous work on this system [1,2].

In conclusion, a larger GMR effect associated with AFM coupling in sputtered Fe/Si multilayers was observed and the dependences of transport properties on Fe layer and Si layer thickness and bilayer numbers were studied. Our data suggest that the mechanisms of AFM coupling and GMR effect in our sputtered Fe/Si multilayers are the same as that in metal/metal systems.

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