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Magnetic and transport properties of Fe/Si multilayers with various iron thicknesses

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Resistivity, temperature coefficient of resistance and magnetization as functions of iron thickness have been studied in a series of magnetron sputtered Fe/Si multilayers with constant Si layer thickness. At the Fe/Si interfaces, a significant amount of deposited iron is transformed into nonmagnetic (0.5 nm) and ferromagnetic (up to 2 nm) nonuniform Fe–Si mixture with a gradient of Fe concentration. Finally, for iron thicknesses above 2.5 nm a *bcc*-Fe phase appears.

Key words: *thin films; magnetic multilayers; Hall effect*

1. Introduction

The Fe/Si multilayered system attracts a lot of attention because of the strong antiferromagnetic (AF) interlayer coupling [1–3] and due to potential application in integrated metal-semiconductor devices. Efforts have been made to clarify the origin of the interlayer interaction in the Fe/Si multilayers (Mls)[1–3]. It is well known that intermixing occurs at interfaces and leads to appearance of various structures similar to Fe–Si phases [1, 3] which may be responsible for the AF coupling. Dufour et al. [4] found that at the Fe/Si interface, a 1.8 nm thick mixture consisting of magnetic and nonmagnetic phases is formed. Kläsges et al. [5] found about 2 nm thick amorphous silicide layer with the composition close to Fe_3Si at the interfaces, and they showed that Fe/Si and Si/Fe interfaces are not symmetrical.

In our previous papers, we focused on the Si spacer properties [2, 3], whereas in this paper we follow the evolution of transport and magnetic phenomena as a function

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of Fe thickness (d_{Fe}). The observed changes of magnetic and transport properties are related to the formation of interfacial Fe–Si structures in Mls with different d_{Fe}.

2. Experimental

A series of [Fe(d_{Fe})/Si(1.1 nm)]$_{15}$ Mls, with constant surface area 3.5×6 mm^2 and iron thickness $0.25 \leq d_{Fe} \leq 4$ nm, have been deposited by magnetron sputtering onto oxidized Si wafers at room temperature (RT). Silicon layer thickness d_{Si} = 1.1 nm has been chosen to assure the maximum of antiferromagnetic coupling between the Fe layers [2]. Additionally, a 30 nm thick pure Fe reference sample has been prepared. Magnetic and transport properties have been investigated by the Hall effect, electrical resistance and magnetic moment measurements carried out in the temperature range 4.2–300 K.

3. Results and discussion

Based on the evolution of the magnetic and electron transport properties of the investigated Mls, shown in Figs. 1 and 2, the dependences can be arbitrarily divided into four regions discussed below.

For $d_{Fe} < 0.5$ nm (Fig. 1), the absence of magnetic moment is observed. It seems to be due to intermixing at the Fe/Si interfaces resulting in formation of nonmagnetic Fe–Si mixtures. The resultant mixture is Si-rich and characterised by high resistance and negative temperature coefficient of resistance (TCR) (Fig. 2). Its resistivity ρ drops drastically with the increase of Fe thickness within this range.

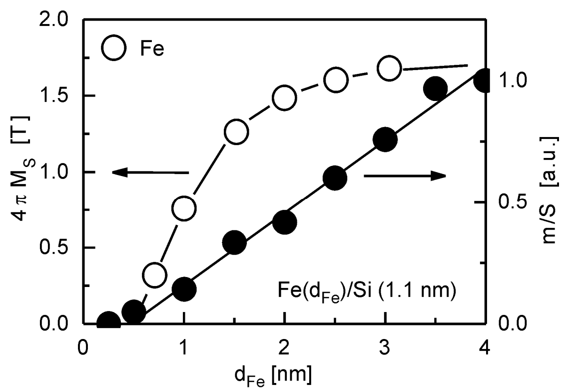

Fig. 1. Magnetic moment per surface area (m/S) and the $4\pi M_S$ values extracted from VSM and anomalous Hall effect, respectively, at room temperature as a function of Fe thickness d_{Fe}. The $4\pi M_S$ value of a Fe single layer sample is also shown

For $0.5 \leq d_{Fe} < 1$ nm, with increasing the amount of deposited Fe, the Fe–Si mixture is enriched with Fe. Therefore, for $d_{Fe} > 0.5$ nm, besides the dominant semiconducting layer consisted of Si-rich mixture, small metallic, ferromagnetic precipitations are formed, hence the magnetic moment appears. Thin metallic grains lower the ρ value but the effective transport properties are dominated by semiconducting matrix with negative TCR. Figure 3a displays temperature dependence of magnetic moment of the Ml with d_{Fe} = 0.7 nm measured at magnetic field 0.05 T. The magnetic moment, plotted as a function of $T^{3/2}$ (Fig. 3b), can be fitted with two straight lines. This means that for d_{Fe} = 0.7 nm two ferromagnetic phases, with the Curie temperatures T_C = 168 K and 393 K, are present. There exist no crystalline Fe–Si phases with such a low T_C [6]. However, similar T_C values have been observed in the case of amorphous alloys [7], thus the formation of amorphous Fe–Si structures with different Fe concentration at the interfaces cannot be excluded.

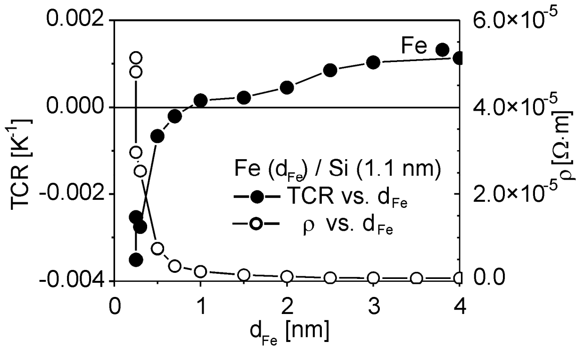

Fig. 2. Temperature coefficient of resistance TCR and resistivity ρ at 250 K as a function of Fe thickness

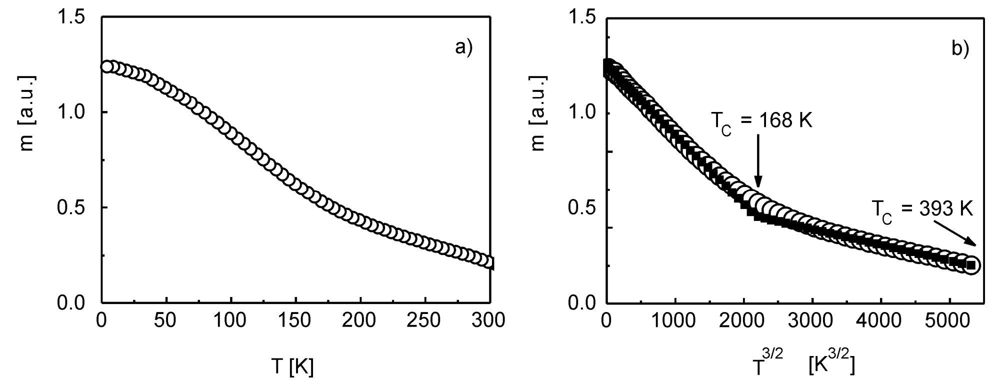

Fig. 3. Magnetic moment of Fe/Si Mls for d_{Fe} = 0.7 nm as a function of: a) T, b) $T^{3/2}$. See text for details

For 1 ≤ d_{Fe} < 2.5 nm, when the continuous metallic layer is formed, a transition from semiconducting to metallic behaviour occurs at about $d_{Fe} \approx 1$ nm. Further increase of the amount of deposited Fe results in an increase of $4\pi M_S$ extracted from anomalous Hall effect (Fig. 1) and positive TCR (Fig. 2) values. The $4\pi M_S$ shown in Fig. 1 is rather the effective magnetization, thus it can be influenced by the magnetic anisotropy (including surface anisotropy) and the AF coupling. The existence of ferromagnetic Fe–Si mixtures was confirmed by the presence of broad sextets in Mössbauer spectra with hyperfine field $H_{hf} \approx 29$ T [3].

Above $d_{Fe} \approx 2.5$ nm both TCR(d_{Fe}) and $4\pi M_S(d_{Fe})$ dependences flatten. Since measured $4\pi M_S$ is the average value of the *bcc*-Fe phase and several different ferromagnetic Fe–Si mixtures with reduced magnetizations (with respect to the *bcc*-Fe phase), the $4\pi M_S$ value of the investigated Mls does not reach the value of bulk Fe. For this d_{Fe} range, the presence of *bcc*-Fe phase (besides the Fe–Si mixtures) was previously indicated by our X-ray scattering and Mössbauer study [3].

Our results clearly show that the interfaces in the Fe/Si Mls are not sharp and a mixture with concentration gradient is formed. Its properties evolve, with the increase of Fe thickness, from nonferromagnetic semiconductor to ferromagnetic metal.

4. Conclusions

A significant amount of interfacial Fe–Si mixture, with nonuniform Fe concentration across the interface profile, has been found in the Fe/Si Mls. For thin iron layer ($d_{Fe} < 0.5$ nm) only nonmagnetic Fe–Si structures are present. Further increase of the iron thickness results in the appearance of ferromagnetic Fe–Si alloys with progressive increase of the $4\pi M_S$ value. The *bcc*-Fe phase appears just above $d_{Fe} \approx 2.5$ nm. Therefore the reduction of $4\pi M_S$ in respect to the bulk *bcc*-Fe value may be due to the averaging of magnetizations of different structures. However, the influence of the anisotropy and the AF coupling cannot be excluded.

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