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Temperature dependence of the magnetic interlayer coupling in Fe/Cr multilayers

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Abstract

Detailed SQUID magnetic measurements were performed in two series of $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}] \times 10$ multilayers, in the temperature range 5–300 K. These series were prepared by sputtering on different substrates: MgO(1 0 0) and Si(1 0 0). The interlayer magnetic coupling strength (J_{12}) was obtained from hysteresis cycles measured at each temperature. Our results show that J_{12} versus T behaves according to the equation $J_{12} = -J_{\mathrm{A}}(T/T_0)/\sinh(T/T_0)$ as predicted by the RKKY model of Bruno and Chappert. We have also observed that T_0 follows a linear dependence with the inverse of the Cr layer thickness ($T_0 \propto 1/t_{\mathrm{Cr}}$) as predicted in this model. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Multilayers; Exchange coupling

Since the discovery of oscillations in the exchange coupling strength between successive ferromagnetic layers (J_{12}) with respect to the non-magnetic spacer thickness [1], many important details of this interaction have been reported. It was found initially that this oscillatory behaviour exists in many magnetic multilayer structures with a large period of the order of 10 Å [2]. More accurate measurements of the interlayer coupling on extremely good samples have shown the presence of additional oscillations with a short period down to 2–3 monolayers [3–5]. Both the short- and long-period oscillations have been explained in terms of the modified RKKY model of Bruno and Chappert [6, 7].

The measurements of J_{12} are normally performed either at room or at low temperature ($T \sim 5$ K), and few studies have been focused on the intermediate temperature region. In order to deepen our understanding of the temperature dependence of the magnetic interlayer coupling, we have performed detailed magnetic measurements on Fe/Cr multilayers deposited by sputtering on different substrates (MgO, Si). The measurements were done in the temperature range 5–300 K, with a SQUID magnetometer.

The samples were deposited by sputtering over MgO(1 0 0) and Si(1 0 0) substrates, with Cr-layer thicknesses t = 10, 15, 17, 18, 19, 22, 37, 39 Å and t = 10, 16, 22, 39 Å, respectively. Details of the deposition technique were reported elsewhere [8].

Fig. 1a–Fig. 1d show magnetic hysteresis cycles measured at $T = 300$ K on the Fe/Cr multilayers deposited on Si substrates, and Fig. 1e–Fig. 1h show the ones measured on the multilayers deposited on MgO substrates. The corresponding saturation magnetization was 1300 and 1400 emu/cm^3, respectively. From the figures we can see that the saturation magnetic field decreases with increasing Cr layer thickness in both sets of samples, indicating a decrease of the interlayer coupling strength with increasing t_{Cr} in the Fe/Cr multilayers studied (see Eq. (1)). The magnetic remanence ratio ($M_{\mathrm{r}}/M_{\mathrm{s}}$) obtained from these hysteresis cycles is smaller than 0.5, indicating that J_{12} is predominantly antiferromagnetic in our samples, as shown in Fig. 2 for the samples deposited on Si. The high remanence ratio observed in the thicker Cr layer samples ($M_{\mathrm{r}}/M_{\mathrm{s}} \approx 0.77$; Fig. 2) indicates that for

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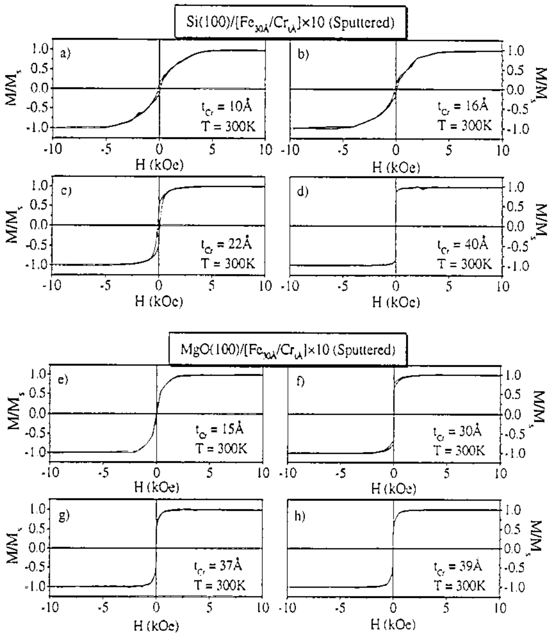

Fig. 1. Magnetic hysteresis cycles measured on the Fe/Cr multilayers studied, at $T = 300$ K. (a)–(d) Samples deposited on Si substrates, and (e)–(h) samples deposited on MgO substrates.

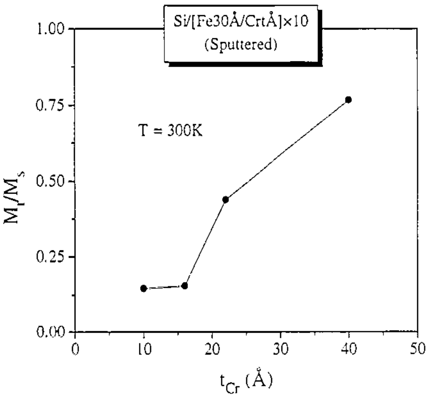

Fig. 2. Magnetic remanence ratio (M_r/M_s) obtained from the hysteresis cycles measured on the Fe/Cr multilayers deposited on Si.

these multilayers the antiferromagnetic coupling is weak or non-existent.

The interlayer magnetic coupling strength (J_{12}) can be obtained from the measured saturation magnetization (M_s) and saturation field (H_s), through the relation [9, 10]

$$J_{12} = -(\tfrac{1}{4} H_s M_s t_{Fe}). \qquad (1)$$

To interpret the temperature dependence of J_{12} we have used the RKKY model of Bruno and Chappert [6, 7]. The model ascribes this dependence to the rounding of the Fermi function with increasing temperature. Due to the discreteness of the studied samples we have used the leading order of J_{12} (large oscillation period), obtained through this model. So, according to it the interlayer magnetic coupling can be written as

$$J_{12} = -J_A (T/T_0)/\sinh(T/T_0), \qquad (2)$$

where $J_A = (J_0 C_0 / t_{Cr}^2) \sin(q^0 t_{Cr} + \Psi_0)$, and J_0 and C_0 are constants characteristic of each sample; ψ_0 is a phase related to the Fermi-surface topology; q^0 is a vector that connects the points on the Fermi surface with antiparallel velocities, originating oscillations of J_{12} versus t_{Cr} with a period Δ^0. The characteristic temperature T_0, in Eq. (2), is written as

$$T_0 = \hbar v_F^0 / 2\pi k_B t_{Cr}, \qquad (3)$$

where v_F^0 is the average of the antiparallel velocities that give Δ^0.

Fig. 3 shows the temperature dependence of the interlayer magnetic coupling, in the Fe/Cr multilayers studied, calculated using Eq. (1). Also shown in this figure are the corresponding fitting curves obtained with Eq. (2), indicating that the J_{12} versus T curves can be well described by the RKKY model of Bruno and Chappert. The results indicate that multilayers deposited on different substrates exhibit the same type of J_{12} versus T dependence, differing only on the J_A constant in Eq. (2). This is more evidenced by the similarity between the J_{12}/J_A versus T curves obtained on the samples MgO/

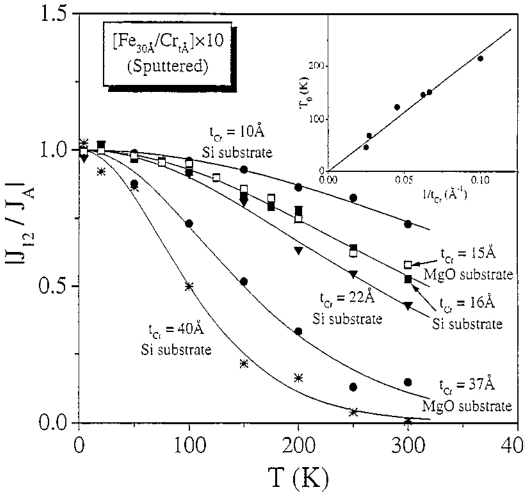

Fig. 3. Temperature dependence of the interlayer magnetic coupling (J_{12}) of the Fe/Cr multilayers studied. The lines are fitting curves obtained with the model of Bruno and Chappert (see text). In the inset is shown the linear fit to the T_0 versus $1/t_{Cr}$ points, indicating that T_0 is proportional to the inverse of the Cr layer thickness.

Table 1
Parameters obtained by fitting the curves of J_{12} versus T with the model of Bruno and Chappert [4]. T_0^{theor} was obtained from Ref. [11] (see text)

t_{Cr} (Å)	T_0 (K)	J_{A} (erg/cm^2)	T_0^{theor} (K)
10	215.35	0.5240	225
15	151.24	0.2820	150
16	146.37	0.2380	141
22	122.81	0.1650	102
37	68.871	0.0978	61
40	46.072	0.0972	56

$[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{15\,\text{Å}}] \times 10$ and $\mathrm{Si}/[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{16\,\text{Å}}] \times 10$ (different substrates, similar t_{Cr}) that can be described by a single fitting curve. The T_0 and J_{A} values given by the curve fitting here presented are displayed in Table 1. Also shown in this table are theoretical values of T_0 calculated with Eq. (3) using $v_{\mathrm{F}}^0 = 1.85 \times 10^7$ cm/s for the long period, $\Delta_0 = 13.3$ Å, referred in Ref. [11]. The T_0 experimental values shown in this table agree well with the theoretical predictions. Moreover, we have plotted the T_0 values, obtained from the fits to the J_{12} versus T curves, against $1/t_{\mathrm{Cr}}$ for the Fe/Cr multilayers studied, as shown in the inset of Fig. 3. The results can be well described by a straight line that goes through the origin. This indicates that $T_0 \propto 1/t_{\mathrm{Cr}}$ as predicted by the RKKY model of Bruno and Chappert (Eq. (3)). The slope of the linear fit to T_0 versus $1/t_{\mathrm{Cr}}$ shown in this figure is 2267 Å K, which is similar to the one predicted by theory (2251 Å K; from Ref. [11] and Eq. (3)).

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