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Abstract. – We present magnetization, torque and magnetoresistance measurements on (001)Fe/(001)Cr multilayers prepared by MBE. Our main results are: a) evidence of antiferromagnetic interlayer couplings, b) the observation of a huge magnetoresistance.

We have prepared (001)Fe/(001)Cr bcc superlattices by MBE on (001)GaAs substrates. The epitaxial relationships are determined by *in situ* RHEED and checked by X ray diffraction [1]. Auger sputter depth profiling and Scanning Transmission Electron Microscopy (Fig. 1) indicate that there is no significant intermixing at the interfaces [1]. The layer thicknesses range from 9 Å to 90 Å. We have performed magnetization (vibrating sample system), torque and magnetoresistance measurements on these multilayers.

We first present magnetization results on multilayers (ml) with a Cr thickness larger than 30 Å. At this thickness the interlayer coupling turns out to be negligible. As shown by figure 2, the easy axis is [100]. With H along the [110] hard axis M reaches its saturation value M_s at about 1 kG. The remanent magnetization along [110] is approximately $M_s/\sqrt{2}$, which is consistent with M at $\pi/4$ along [100] or [010]. M_s is generally in a range of ±15 % around M_s of bulk iron (it is hard to establish whether the scatter of the values of M_s arises from the uncertainty on the geometry of the samples or from some Cr contribution). By analysing the angular and field dependences

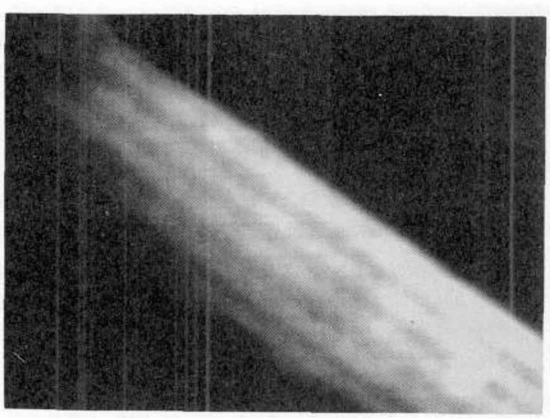

Fig. 1. – Cross section of a Fe60 Å / Cr60 Å ml obtained by Scanning Transmission Electron Microscopy.

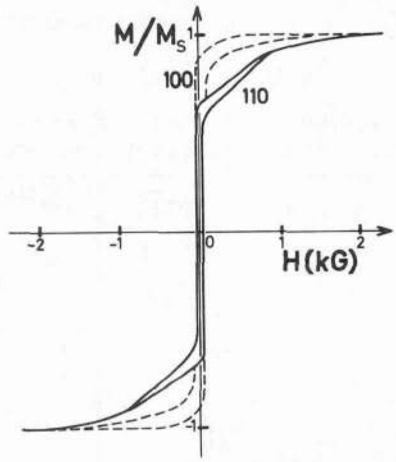

Fig. 2. – Hysteresis loop of a $(\text{Fe60 Å} / \text{Cr60 Å})_5$ multilayer at 77 K for an applied field along the [100] and [110] directions in the multilayer plane 5 is the number of bilayers.

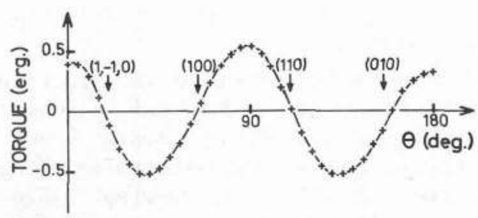

Fig. 3. – Torque *versus* field angle at 4.2 K for a $(\text{Fe60 Å} / \text{Cr60 Å})_5$ multilayer. The field (9 kG) rotates in the plane of the multilayer.

of torque curves with an applied field in the ml plane (Fig. 3), we derive the anisotropy constant K_1, $K_1 \approx 52 \times 10^4$ erg/cm^3 at 4.2 K, for the ml of figures 2, 3 (to be compared with $K_1 \approx 57.8 \times 10^4$ erg/cm^3 for bulk iron). We have also combined torque, Hall effect and ferromagnetic resonance to study the perpendicular anisotropy, as it will be reported elsewhere.

We proceed with results on ml with thin Cr layers. Figure 4 shows that for decreasing Cr thicknesses (below about 30 Å) the magnetization becomes harder to saturate (the tilt of the loop increases) and the remanent magnetization decreases to almost zero. This behavior can be accounted for by an antiferromagnetic (AF) exchange coupling between Fe layers through Cr. Such AF coupling have already been put forward to explain light scattering [2] and SPLEED [3] experiments on Fe/Cr/Fe sandwiches. To interpret our results in the simplest way, we assume a fixed magnetic moment ($= M_s t_{Fe}$ per surface unit if t_{Fe} is the thickness) and a coupling energy $J \cos\theta$ between two neighbour Fe layers (θ =angle between the magnetizations). With an applied field (see inset of Fig. 5), the total energy per layer and surface unit is written:

$$E = -J \cos 2\varphi - M_s t_{Fe} H \sin\varphi \qquad (1)$$

By minimizing E one derives $\sin\varphi$ and then the following expression of the magnetization along the field direction:

$$MM_s = M_s t_{Fe} H / 4J \qquad (2)$$

We show in figure 5 the values of J for $t_{Fe} = 30$ Å derived from the low field slopes of figure 4 (our results

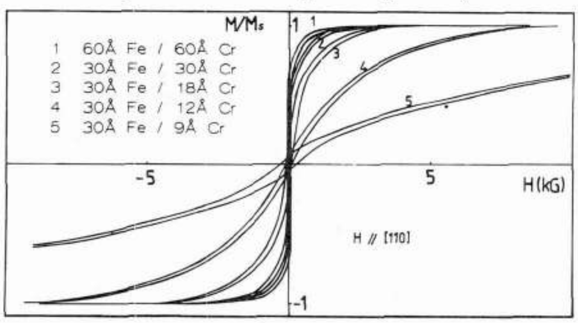

Fig. 4. – Hysteresis loops at 4.2 K with an applied field along [110] in the ml plane for several systems: 1) $(\text{Fe}60\ \text{Å} / \text{Cr}60\ \text{Å})_5$, 2) $(\text{Fe}30\ \text{Å} / \text{Cr}30\ \text{Å})_{10}$, 3) $(\text{Fe}30\ \text{Å} / \text{Cr}18\ \text{Å})_{30}$, 4) $(\text{Fe}30\ \text{Å} / \text{Cr}12\ \text{Å})_{10}$, 5) $(\text{Fe}30\ \text{Å} / \text{Cr}9\ \text{Å})_{40}$.

on multilayers with different t_{Fe} down to 12 Å lead to not very different values of J). J steeply increases as t_{Cr} decreases and an oscillatory behavior, as in Y/Gd [4], is unlikely. Equation (2) predicts a strictly linear dependence in H which is not observed in figure 4. The observed dependence can be accounted for more closely by assuming that the moments within the layers are more tilted towards H than the interface moments (and also by taking into account the anisotropy). The model leading to equation (2) is obviously too simple.

We finally summarize our magnetoresistance results. As shown in Figure 6, the variation of R follows that of the magnetization and saturates at about the same filed. The magnetoresistance is very large: in figure 5, R is deduced by about a factor of 2 at high fields; more generally $\Delta R / R$ is large for thin Cr layers. This huge magnetoresistance appears to arise from changes of the electron transmission through of Cr when the moments of the Fe adjacent layers are brought to be parallel.

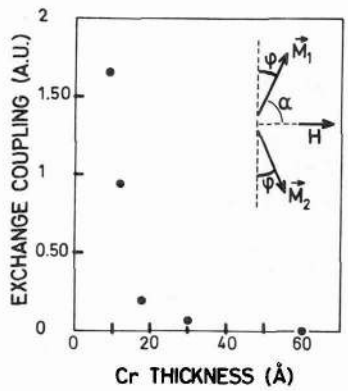

Fig. 5. – Interlayer coupling constant J for $t_{Fe} = 30$ Å *versus* Cr thickness. Inset: scheme for the magnetic moments of two coupled layers in a magnetic field.

In conclusion, the main results of our measurements are: a) clear evidence of antiferromagnetic interlayer couplings, b) the observation of a huge magnetoresistance (factor of 2).

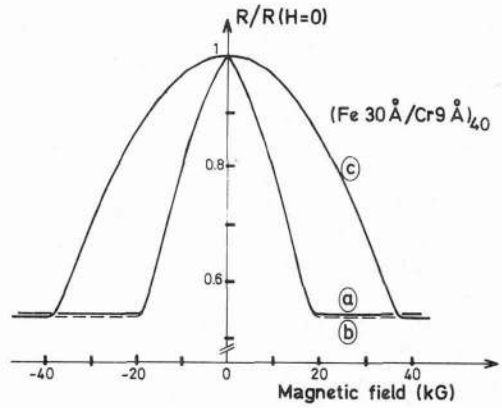

Fig. 6. – Magnetoresistance of a $(\text{Fe}_{30\ \text{Å}} / \text{Cr}_{90\ \text{Å}})_{40}$ multilayer. The current is along [110] and the field in the ml plane along the current direction (curve a), or in the ml plane perpendicularly to the current (curbe b) or perpendicular to the ml plane (curve c). There is a very small difference between the curves in increasing and decreasing field (hysteresis) that we have not represented on the figure. Yhe ml is covered by a 100 Å Ag protection layer. This means that the magnetoresistance of the ml alone is certainly still higher.

Acknowledgments

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