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# Oscillatory interlayer exchange and magnetoresistance in Fe/Cu multilayers

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We have studied the magnetic and magnetotransport properties of Fe/Cu multilayers prepared by sputtering. We find oscillations of the interlayer coupling as a function of the Cu thickness with the same long period as in Co/Cu multilayers (around 12.5 Å). The most striking result is that the oscillations in Fe/Cu and Co/Cu have almost exactly opposite phases. A large magnetoresistance of the spin-valve type is observed in the half periods with antiferromagnetic interlayer exchange. However, the magnetoresistance in Fe/Cu is definitely smaller than in Co/Cu.

In this paper we report on magnetoresistance and magnetization measurements on Fe/Cu multilayers prepared by sputtering. As in Co/Cu multilayers we have previously studied,[1] we find a long-period oscillation of the interlayer exchange as a function of the copper thickness and a large magnetoresistance (MR) in the thickness ranges where this exchange is antiferromagnetic.

There are now several examples of multilayered systems exhibiting an oscillatory interlayer exchange and a large magnetoresistance arising from the so-called spin-valve effect. Fe/Cr,[2-6] Co/Ru,[4] Co/Cr,[4] and Co/Cu (Ref. 1) are the best known systems. For the interlayer exchange, the most puzzling result is the long period of the exchange oscillations. Values between 12 and 21 Å are found, which is much longer than expected from the simple Ruderman-Kittel-Kasuya-Yosida (RKKY)-like models and have generated a large number of theoretical models.[7] An oscillatory behavior of the interlayer exchange, coupled with oscillations of the Kerr effect, has also been recently found by Bennet, Schwarzacher, and Egelhoff[8] in Fe fcc(001)/Cu/Fe fcc(001) sandwiches grown on Cu(100). Our present results on Fe/Cu multilayers prepared by sputtering confirm these oscillations. The period is practically equal to that found in Co/Cu, that is about 12.5 Å.[1] However, a puzzling and interesting result is that the oscillations in Co/Cu and Fe/Cu have opposite phases; in other words, the coupling between Fe layers is antiferromagnetic (AFM) in the thickness ranges where the coupling between Co layers is ferromagnetic (FM) and vice versa. The Fe/Cu system also exhibits a spin-valve effect in the AFM half periods but the magnetoresistance is smaller than in Co/Cu and does not exceed 12%.

Samples of 60×(15-Å Fe/$t_{Cu}$ Cu) multilayers have been deposited on Si(100) substrates in a UHV compatible sputtering system[9] at Michigan State University. A 50 Å buffer layer of Fe is first deposited on the substrate and the top layer is always a 50 Å layer of Cu. The experimental methods for the characterization of the samples, and the magnetic and magnetoresistance measurements have been described in our previous publication.[1] In addition we have performed extended x-ray-absorption fine-structure (EXAFS) measurements[10] at both the Fe and Cu $K$ edges using the facilities at the Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE) at Orsay. Preliminary results indicate that the structure of the Fe layers is clearly bcc. For the Cu layers, the structure is fcc above 20 Å, with a progressive improvement of the fcc order as the thickness of Cu increases. Below 20 Å the EXAFS oscillations suggest a more disordered structure which could be a mixing of bcc and fcc copper phases.

In Fig. 1 we show the MR of a 60×(15-Å Fe/15-Å Cu) sample at 4.2 K. The MR curves are very similar to those observed for Co/Cu.[1] The MR ratio (defined as the ratio of the total resistivity change $\Delta R$ to the resistivity at saturation $R_s$) amounts to 12% at 4.2 K for this multilayer.

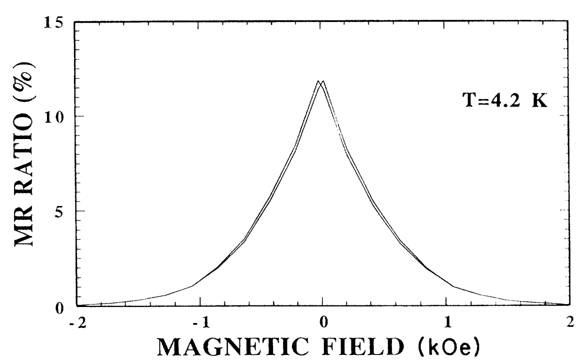


FIG. 1. Magnetoresistance of a 60×(15-Å Fe/15-Å Cu) multilayer at 4.2 K. The resistivity at zero field and at saturation are 27.8 and 24.8 $\mu\Omega$ cm, respectively. The magnetic field is applied in the plane of the multilayer along the current direction. For all the samples, the zero-field magnetization is in-plane.

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The saturation field $H_s$ is about 1.4 kOe. By analyzing $H_s$ as in Fe/Cr,[11] that is by relating $H_s$ to the interlayer coupling constant $J$ by $H_s = (4J/Mt_{Fe})$ where $M$ is the magnetization and $t_{Fe}$ is the thickness of the Fe layers, we find that $J$ is around 0.095 erg/cm$^2$. This is about eight times smaller than Fe/Cr with $t_{Cr} \simeq 15$ Å and we recall that a similar reduction factor with respect to Fe/Cr has also been found for Co/Cu.

The variation of the MR ratio as a function of the thickness of Cu for the samples with $t_{Fe} = 15$ Å is shown in Fig. 2. The MR oscillates from large to negligible or small values. As for Fe/Cr, Co/Ru, or Co/Cu,[1,4] this behavior can be ascribed to oscillations of the interlayer exchange with a succession of AFM and FM half periods.

The oscillations of the MR in Fe/Cu and Co/Cu multilayers can be compared in Fig. 3. The period is around 12.5 Å for both systems but the oscillations have almost exactly opposite phases: the maxima for Co/Cu coincides with the minima for Fe/Cu. We will discuss this very striking result below.

Concerning the amplitude of the MR, first we notice that it is definitely smaller in Fe/Cu (the scales for the MR of Fe/Cu and Co/Cu in Fig. 3 are different by a factor of 4.6). Leaving aside the differences in the amplitude and phase, the other features are practically the same. The first minimum (around 19 and 15 Å for Fe/Cu and Co/Cu, respectively) is nearly at zero, which means that the FM exchange at this thickness is strong enough to maintain an almost 100% FM arrangement of the magnetic layers during the magnetization reversal. This also implies that, at the first maximum (around 15 and 9 Å for Fe/Cu and Co/Cu, respectively), the AFM exchange is strong enough to induce an almost 100% AFM arrangement at low field and indicates that the first MR peak corresponds to approximately the full difference between the AFM and the FM resistivities. As the copper thickness increases and the interlayer exchange decreases, one expects a decrease of the maxima due to the variation of the ratio of the thickness to the mean free path,[12] and also to the progressive change from a 100% AFM arrangement to an almost random one at the magnetization reversal. On the other hand, the minima are expected to increase, the envelope of the minima joining the envelope of the maxima for negligible interlayer exchange when the arrangement of the magnetic layers is perfectly random at the magnetization reversal. This behavior is very well observed for Co/Cu in Fig. 3. In contrast, for Fe/Cu, we notice a slight upturn of the envelope of the maxima above approximately 30 Å. The "normally expected" progressive decrease seems to set in only at much larger thicknesses (Fig. 2). This anomaly of Fe/Cu could be due to the progressive improvement in the copper layer fcc structure that has been shown by EXAFS.

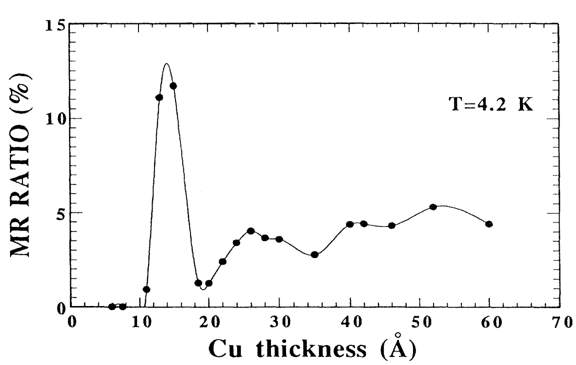


FIG. 2. Variation of the MR ratio as a function of the thickness of copper $t_{Cu}$ for $60\times(15\text{-Å Fe}/t_{Cu}\text{ Cu})$ multilayers. The solid line is a guide for the eye.

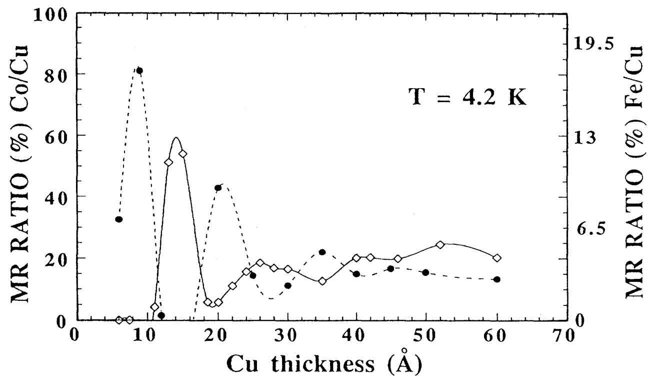


FIG. 3. Variation of the MR ratio as a function of the thickness of copper $t_{Cu}$ for $60\times(15\text{-Å Fe}/t_{Cu}\text{ Cu})$ (open symbols) and $30\times(15\text{-Å Co}/t_{Cu}\text{ Cu})$ (black dots) multilayers. The solid and the dashed lines are guides for the eye. Notice the different vertical scale for Fe/Cu and Co/Cu.

Another difference between Fe/Cu and Co/Cu is in the temperature dependence of the MR. In Co/Cu the temperature dependence is weak, with a typical value around 1.6 for the reduction of the MR ratio between 4.2 K and room temperature. The variation of the MR with temperature is much stronger in our Fe/Cu samples. We find a typical value of 5 for the reduction of the MR ratio between 4.2 K and room temperature. We shall present our data on the temperature dependence in more detail in a further publication.

We summarize and discuss now our main results on Fe/Cu.

(1) The interlayer coupling exhibits oscillations with the same long period ($\approx 12.5$ Å) that we have already observed in Co/Cu. The most striking result is the opposite phases of the oscillations in Fe/Cu and Co/Cu. This is a very clear result that the theoretical models of the interlayer exchange must now reproduce.

(2) The MR of Fe/Cu is definitely smaller than that of Co/Cu (a factor of 7). We propose the following explanation based on the different spin dependence expected for Cu impurities inside the Co or Fe layers. Co is a strong itinerant ferromagnetic metal. Its spin $\uparrow d$ band is full and if one neglects some *sp-d* hybridization, the $d\uparrow$ density of states (DOS) is zero at the Fermi level. At a Cu impurity site, because a Cu atom introduces only a weak perturbation potential, the $d\uparrow$ DOS at the Fermi level is also much smaller than the $d\downarrow$ DOS. Therefore we expect a much smaller $s \rightarrow d$ scattering for the spin $\uparrow$ direction (at least at low temperature where the spin-flip scattering is frozen) and a strongly spin dependent cross section for Cu

impurities in Co. In contrast, in Fe, the *d* DOS at the Fermi level is important for both spin directions and the spin dependence of the scattering by Cu impurities should be very much weaker than in Co (as a matter of fact the parameter $\alpha$ characteristic of the spin dependence of the scattering by impurities is never as large in Fe than in Co or Ni).[13] We, therefore, expect to have a smaller MR in Fe/Cu multilayers.

(3) The temperature dependence of the MR is definitely more pronounced in Fe/Cu than in Co/Cu. The reduction of the MR as the temperature increases is supposed to be due to increasing spin-flip scattering by electron-magnon collisions.[14] Again, as Co is a strong itinerant ferromagnetic metal, the $d\uparrow$ band is below the Fermi level, so that there is a gap for the excitation of spin waves. Such a gap does not exist for Fe. Also the coefficient $D$ of magnon dispersion curve ($E_q = Dq^2$) in Fe is smaller than in Co. It thus seems quite normal to find a faster increase of the electron scattering by spin waves and a faster reduction of the MR in Fe-based multilayers. We point out that the temperature dependence of the MR is also more pronounced in Fe/Cr than in Co/Cu.

In conclusion we emphasize that the Co/Cu and Fe/Cu multilayers systems should be of great interest to probe the theoretical models of the interlayer exchange and giant magnetoresistance. First, Cu has a particularly simple band structure and Fermi surface, so that the theoriticians probably cannot find a more simple case for the problem of the interlayer exchange. In addition, the dependence of the phase of the oscillations on the magnetic metal is a clear result that must be reproduced by the theoretical models. The very different amplitude of the MR in Co/Cu and Fe/Cu is also an interesting result to be explained by the theoretical models of the MR.

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