PHYSICAL REVIEW B VOLUME 45, NUMBER 5 1 FEBRUARY 1992-I

Antiferromagnetic exchange and magnetoresistance enhancement in Co-Re superlattices

P. P. Freitas
INESC, R. Alves Redol 9-3, 1000 Lisbon, Portugal;
Instituto Superior Técnico, R. Rovisco Pais, 1000 Lisbon, Portugal;
and CFMC–Instituto Nacional de Investigação Cientifica, Avenida Professor Gama Pinto, 1093 Lisbon, Portugal

L. V. Melo
INESC, R. Alves Redol 9-3, 1000 Lisbon, Portugal
and Instituto Superior Técnico, R. Rovisco Pais, 1000 Lisbon, Portugal

I. Trindade
INESC, R. Alves Redol 9-3, 1000 Lisbon, Portugal

M. From*
CFMC–Instituto Nacional de Investigação Cientifica, Avenida Professor Gama Pinto, 1093 Lisbon, Portugal

J. Ferreira and P. Monteiro
INESC, R. Alves Redol 9-3, 1000 Lisbon, Portugal

(Received 5 June 1991; revised manuscript received 21 August 1991)

Co-Re superlattices were prepared that show either antiferromagnetic or ferromagnetic coupling between the Co layers depending on the Re spacer thickness. Enhanced saturation magnetoresistance occurs for antiferromagnetically coupled layers. The saturation magnetoresistance decays exponentially with Re thickness but does not depend critically on the Co thickness.

Giant magnetoresistance effects in antiferromagnetically coupled transition metal magnetic superlattices have been discovered recently. Results have been reported for Fe-Cr,[1–4] Co-Ru,[4] Co-Cr,[4] and Co-Cu[5] superlattices.

In this paper we report magnetization and magnetoresistance studies of Co-Re superlattices that show antiferromagnetic coupling and enhanced saturation magnetoresistance for very thin Re spacer thicknesses.

The Co-Re superlattices were chosen bearing in mind the model proposed by Baibich *et al.*[1] for explaining the magnetoresistance of Fe-Cr superlattices and the results of Parkin, More, and Roche on Co-Ru and Co-Cr superlattices.[4] A semiclassical model involving spin-dependent interface scattering has been proposed.[1,6] This effect is related to spin-dependent scattering by magnetic impurities in transition metal ferromagnets. This leads to an unbalance between the spin-up and spin-down resistivities that is measured by the ratio $\alpha=\rho_\downarrow/\rho_\uparrow$. Cr in Fe, and Cr, Ru, and Re in Co form virtual bound state impurities in the respective Fe and Co matrices.[7] All have values of α which are smaller than unity and of the same order of magnitude. These elements have quite different room-temperature resistivity values, ranging from 7.4 $\mu\Omega$ cm in Ru to 12.9 $\mu\Omega$ cm in Cr and 18.6 $\mu\Omega$ cm in Re.[8] Since the magnetoresistance effect is supposed to depend on the nonmagnetic layer electron mean free path we expect those three systems to all have correlated results.

Co-Re superlattices were grown in a high-vacuum magnetron sputtering system with dc and rf magnetrons (Alcatel SCM 450). Total base pressure before deposition is 1×10^{-7} Torr, with a water vapor partial pressure of 5×10^{-8} Torr. The Co was deposited by rf magnetron sputtering at a rate of 0.4 to 0.5 Å/s while the Re was deposited by dc magnetron sputtering at rates of 0.4 Å/s. Deposition rates were monitored by *in situ* quartz crystal monitors. Glass and Si substrates were used and the Ar pressure during deposition was kept at 2.5 mTorr. Most samples were deposited at room temperature on water-cooled substrate holders. One group of samples with a Re spacer thickness of 5 Å was deposited onto substrates heated at a temperature varying from 100 to 300 °C. Co and Re absolute thicknesses were calibrated by Rutherford backscattering, profilometer, and x-ray diffraction on superlattices especially grown for this purpose. The three methods agreed with 10%. In this paper we report studies of superlattices with the following structure: glass/(150-Å Re)/$(\mathrm{Co}_{t_{\mathrm{Co}}}\mathrm{Re}_{t_{\mathrm{Re}}})_{16}$/(50-Å Re) where $t_{\mathrm{Co}}=20$ or 13 Å and t_{Re} varies from 3 to 30 Å by 1-Å steps and glass/(150-Å Re)/$(\mathrm{Co}_{t_{\mathrm{Co}}}\mathrm{Re}_5)_N$/(50-Å Re) with N varying from 1 to 16 and t_{Co} ranging from 6 to 30 Å. The films were deposited at a rate of four per pumpdown and a total of two series covering the total Re thickness range were prepared.

The structural characterization of the superlattices by x-ray and Rutherford backscattering will be described in detail elsewhere.[9] A brief summary of the results will be given here. The high quality of the superlattices can be checked by comparing the high-angle θ-2θ x-ray diffractogram with a theoretical simulation. In Fig. 1 we show results for two superlattices together with the simulated x-ray peak locations and intensities. First-, second-, and third-order satellites are observed with intensities close to those predicted which shows the coherence of the superlattice and the sharpness of the interfaces. Moreover, the superlattice periodicity and bilayer composition obtained from the experimental x-ray data agree within 5% with the nominal values. Results are shown for two superlattices prepared for periodicities of 67 and 65 Å, respectively. From the x-ray data the measured periodicity is 66.2 and 65.9 Å, respectively. We used a model developed by Carcia and Suna[10] for the x-ray simulation. The results indicate highly textured hcp structure with the c axis perpendicular to the plane of the samples. The growth direction is induced by the 150-Å-thick Re buffer.

Figures 2 and 3 show magnetization and resistance data versus in-plane magnetic field for a series of Co-Re superlattices with 16 bilayers, $t_{\mathrm{Co}}=20$ Å and t_{Re} ranging from 3 to 30 Å. With the exception of the results shown in the inset of Fig. 3 all measurements were taken at room temperature. All samples have in-plane magnetiza-

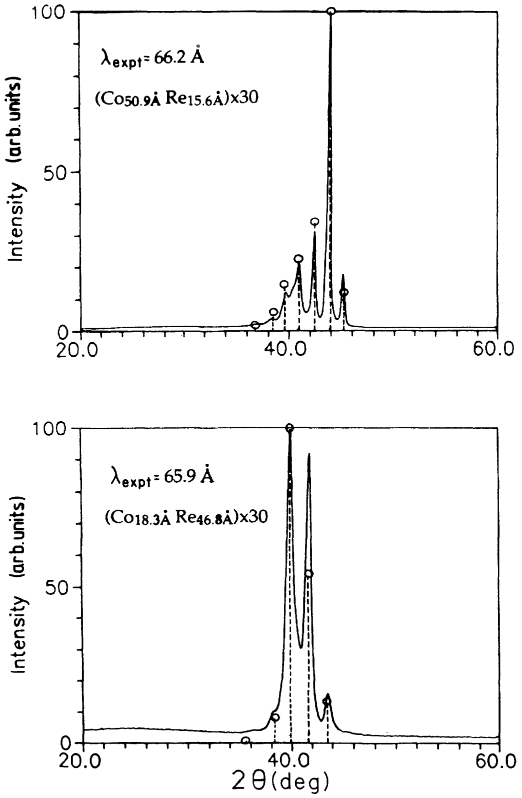

FIG. 1. X-ray diffractograms for two Co-Re superlattices with nominal periodicities of 67 and 65 Å. The vertical dashed lines culminated by open circles correspond to the position and intensities of the main peaks (002 and satellites) as predicted from simulation.

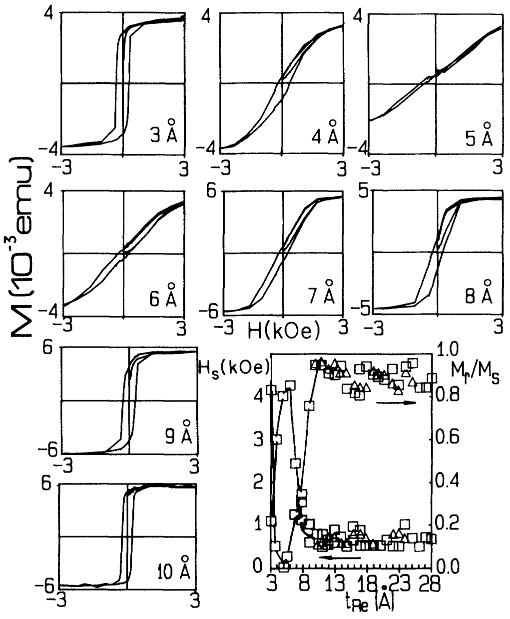

FIG. 2. Magnetization hysteresis cycles for Co-Re superlattices with Co thickness of 20 Å and Re thickness ranging from 3 to 10 Å. In the inset we show the dependence of the saturation field and the remanence on the Re thickness. Strong antiferromagnetic coupling occurs for t_{Re} less than 9 Å. The squares and triangles in the inset correspond to two different series of samples.

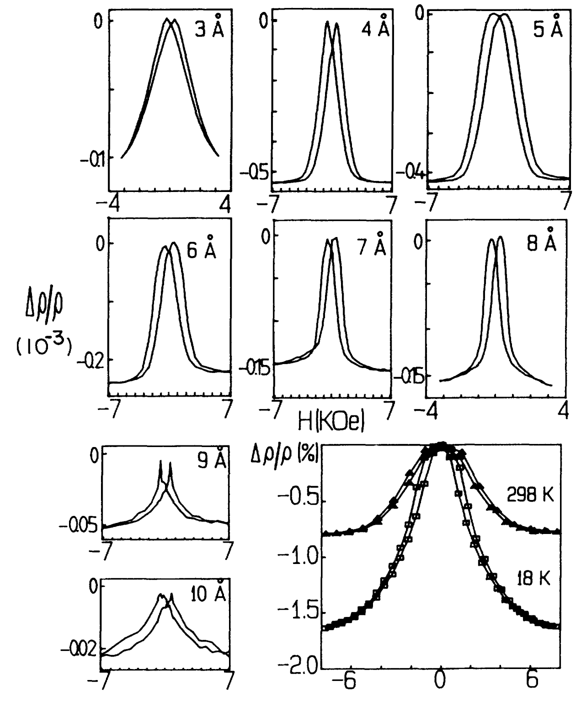

FIG. 3. Magnetoresistance data for Co-Re superlattices shown in Fig. 2. In the inset we show magnetoresistance data at 18 and 300 K for an antiferromagnetically coupled sample ($t_{\mathrm{Co}}=13$ Å, $t_{\mathrm{Re}}=6$ Å).

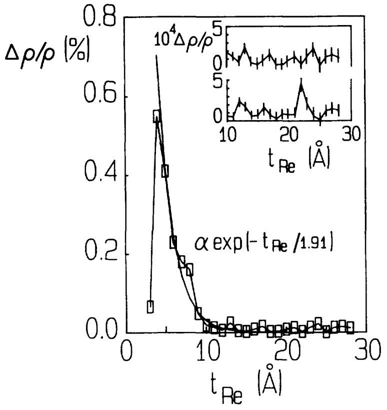

FIG. 4. Magnetoresistance versus Re spacer thickness. The inset shows a blow-up of the results for higher Re thicknesses. Notice exponential decrease of the magnetoresistance data versus Re thickness, and the occurrence of maximum saturation magnetoresistance when antiferromagnetic coupling is strongest.

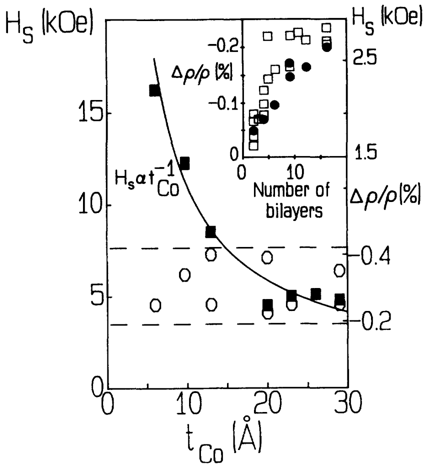

FIG. 5. Saturation field (solid squares) and magnetoresistance (open circles) versus Co thickness for antiferromagnetically coupled superlattices ($t_{\mathrm{Re}}=5$ Å). Notice that the magnetoresistance is essentially constant as t_{Co} varies while H_s varies as $1/t_{\mathrm{Co}}$. In the inset we show the dependence of the magnetoresistance (open squares) and the saturation field (solid circles) on the number of Co-Re bilayers.

tion with an average $4\pi M_s$ value of 18 200±1500 G. This is the bulk hcp Co value and holds for samples as thin as 13.5 Å Co corresponding to 6–7 atomic layers. The coupling between adjacent Co layers is antiferromagnetic for Re thicknesses below 9 Å. This can be seen in Fig. 2 where the hysteresis cycles get progressively more tilted and the remanence decreases to zero as the Re thickness decreases. For $t_{\mathrm{Re}}=5$ Å a field $H_s=0.43$ T is needed to overcome the antiferromagnetic coupling and saturate the magnetization at the bulk Co value. This saturation field reflects the strength of the interlayer antiferromagnetic coupling J, as $J=-(Mt_{\mathrm{Co}}H_s)/4$,[1] where M and t_{Co} are the magnetization and thickness of the Co layers. For the films shown in Fig. 2, J reaches -0.31 erg/cm^2 at 300 K. In the inset we show the dependence of the saturation field and remanence versus Re thickness. Notice the sharp decrease of H_s when the Re thickness changes from 5 to 10 Å and the antiferromagnetic coupling weakens. For $t_{\mathrm{Re}}>10$ Å the coupling can be either ferromagnetic or the Co layers can become effectively uncoupled. The magnetization and magnetoresistance data by themselves cannot provide this kind of information.

Regions with a slightly lower remanence can be observed around 16–17 Å and 22–23 Å of Re. This could indicate sample inhomogeneity with regions with ferromagnetic coupling or no coupling and regions with antiferromagnetic coupling. At this point these results can be compared with those obtained by Parkin for Co-Ru superlattices.[4] In both cases antiferromagnetic coupling is observed down to Re and Ru thicknesses of 2 atomic layers. Below this thickness the observed decrease in saturation fields may be caused by pinholes through the Re or Ru layers. The measured exchange coupling in Co-Ru superlattices is close to -3 erg/cm^2 while we measure values up to -0.35 erg/cm^2. In the case of Co-Ru, oscillations of the exchange coupling were clearly observed with a periodicity of 12 Å. This pattern cannot be seen in our Co-Re magnetization data.

We now turn to Fig. 3 where in-plane magnetoresistance data is shown (j⊥H). Notice the large magnetoresistance values found for Re spacings of 4–6 Å where antiferromagnetic coupling is stronger. When the antiferromagnetic coupling disappears the saturation magnetoresistance is 20 to 50 times smaller. In the inset we show results for a sample deposited at 170 °C and measured at 18 and 300 K. Notice that the magnetoresistance reaches 1.7% at 18 K and that it decreases by a factor of 2 at room temperature. Annealing treatments and substrate temperature during deposition are known to affect the magnetoresistance value[11] but will not be discussed here.

Figure 4 shows the detailed dependence of the magnetoresistance on the Re thickness. The solid line through the data corresponds to an exponential decrease with the Re thickness. This sharp decrease in magnetoresistance as Re thickness changes from 5 to 10 Å is mainly due to the decrease in the antiferromagnetic exchange coupling (see decrease in H_s in Fig. 2). In the inset we show a blow up of the magnetoresistance saturation values for higher Re thicknesses (data is shown separately for the two series of samples studied). Although a small wavelength oscillation is perceptible in both data sets this could be caused by scatter in the magnetoresistance of the magnetically identical sputtered thin films. A set of four identical samples were prepared with $t_{\mathrm{Re}}=22$ Å and we observed magnetoresistance values varying from -3×10^{-4} to $+1\times10^{-4}$. This prevents us from ascribing special physical meaning to the observed oscillations. Finally we notice that the low saturation magnetoresistance values obtained in this hcp system, are comparable to those found in hcp Co-Ru and Co-Cr systems and much lower than the giant values recently discovered in fcc Co-Cu.

In Fig. 5 we show the magnetoresistance and saturation field dependences on the Co thickness for a fixed Re spacer thickness equal to 5 Å (antiferromagnetically coupled samples). Consider first the magnetoresistance data (open circles). It can be seen that the data varies randomly between -2×10^{-3} and -4×10^{-3} for Co thicknesses ranging from 6.5 to 30 Å. Looking back at Fig. 4 we notice that this simply reflects an actual Re thickness varying between 5 and 6 Å, for samples nominally prepared for 5 Å of Re. Comparison of Figs. 4 and 5 for the magnetoresistance dependence on Re or Co thickness readily indicates that scattering processes across the Re spacer are responsible for the observed magnetoresistance effect with the Co thickness having a minor effect.

On the other hand, we observe that $H_s \propto 1/t_{\mathrm{Co}}$ for constant Re spacing equal to 5 Å (solid squares). This indicates that the antiferromagnetic exchange coupling between the Co layers is mainly dependent on the separation of the two magnetic layers.

In the inset we show the dependence of the magnetoresistance and the saturation field on the number of Co-Re bilayers, for $t_{\mathrm{Co}}=20$ Å and $t_{\mathrm{Re}}=5$ Å (antiferromagnetically coupled samples). This study was motivated by the theoretical work of Camley and Barnas[6] and the results obtained in Fe-Cr sandwiches and superlattices. Large increases of the magnetoresistance are expected when going from a single sandwich to a superlattice if the average electron mean-free path is much larger than the individual layer thickness. In our case this effect should not be prominent since Re is a high-resistivity material leading to average mean-free paths of a few bilayers only. The results in Fig. 5 show a magnetoresistance increase by a factor of 4 when going from a sandwich structure to a superlattice containing 16 bilayers. Half of this increase can be assigned to a factor of 2 decrease in the film resistivity as the total film thickness increases. We therefore conclude that the number of bilayers does not affect the magnetoresistance in the Co-Re superlattices to the same amount it does in Fe-Cr superlattices with much longer average mean-free paths. The saturation field is found to decrease by about 40% when going from a superlattice with 16 bilayers to a single bilayer. A similar study was recently reported by Parkin for Fe-Cr superlattices.[12]

In conclusion we have shown that Co-Re superlattices show antiferromagnetic coupling for ultrathin Re layer thicknesses. The sharp decrease of the magnetoresistance for Re thicknesses between 5 and 10 Å is mainly caused by the decrease in the strength of the antiferromagnetic coupling.

We thank T. S. Plaskett at IBM Yorktown Heights for x-ray work.

---

*Present address: Physics Department, Simon Fraser University, Vancouver, B.C., Canada.

[1] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 7472 (1988).

[2] G. Binasch, P. Grunberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989).

[3] J. J. Krebs, P. Lubitz, A. Chaikin, and G. A. Prinz, Phys. Rev. Lett. **63**, 1645 (1989).

[4] S. S. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[5] S. S. Parkin, R. Bhadra, and K. P. Roche, Phys. Rev. Lett. **66**, 2152 (1991).

[6] R. E. Camley and J. Barnas, Phys. Rev. Lett. **63**, 664 (1989).

[7] I. A. Campbell and A. Fert, in *Ferromagnetic-Materials*, edited by E. P. Wolfarth (North-Holland, Amsterdam, 1982), Vol. 3, p. 769.

[8] C. Kittel, *Introduction to Solid State Physics* (Wiley, New York, 1986), p. 144.

[9] L. V. Melo, I. Trindade, M. From, P. P. Freitas, N. Teixeira, M. F. da Silva, and J. C. Soares (unpublished).

[10] P. F. Carcia and A. Suna, J. Appl. Phys. **54**, 2000 (1983).

[11] F. Petroff, A. Barthelemy, A. Hamzic, A. Fert, P. Etienne, S. Lequiem, and G. Creuzet, J. Magn. Magn. Mater. (to be published).

[12] S. S. P. Parkin, A. Mansour, and G. P. Felcher, Appl. Phys. Lett. **58**, 1473 (1991).