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Magnetic multilayers of Fe/Au: role of the electron mean free path

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Abstract. The giant magnetoresistance (GMR) was measured for Fe/Au magnetic multilayers in both the CIP and CPP configurations, for a series of samples each having the same thickness for the Fe layers (10 Å) but a different thickness for the Au layers (in the range 20–50 Å). It was found that the GMR is only a few per cent in the CIP configuration, whereas the GMR ranges from 20 to 80% in the CPP configuration. We attribute this order-of-magnitude difference in the values of the GMR for the two configurations to the short electron mean free path, resulting from the relatively high resistivity of these multilayers. A short electron mean free path reduces sharply the value of the GMR in the CIP configuration, while leaving unchanged the value of the GMR in the CPP configuration.

1. Introduction

Since the discovery about ten years ago of the giant magnetoresistance (GMR) exhibited by magnetic multilayers [1], the intense investigation of this phenomenon continues unabated. One of the matters of recent interest is the comparison between the value of the GMR measured with the current in the plane of the layers (CIP configuration) and the value obtained when the current is perpendicular to the plane of the layers (CPP configuration). It is technically much simpler to measure the GMR in the CIP mode and most measurements of the GMR have used that configuration. However, the GMR has also been measured in the CPP configuration [2].

We here report the results of a comparison between the GMR measurements in the two configurations for a series of Fe/Au(111) magnetic multilayers, each having the same thickness for the Fe layers (10 Å) but a different thickness for the Au layers (in the range 20–50 Å). We found that the GMR is only a few per cent in the CIP configuration, whereas the GMR ranges from 20 to 80% in the CPP configuration. This striking difference between the values of the GMR for the CPP and the CIP configurations is the most important feature of these data. We attribute this order-of-magnitude difference in the values of the GMR for the two configurations to the relatively short electron mean free path for our samples, which is known [3, 4] to reduce sharply the value of the GMR in the CIP configuration, while leaving unchanged its value in the CPP configuration.

To support this interpretation, we grew another series of Fe/Au multilayers which had a lower resistivity, and hence a longer electron mean free path. For these lower-resistivity

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multilayers, the value of the GMR in the CIP configuration was 30–40% for the Au layer thicknesses that correspond to antiferromagnetic coupling. In other words, we found that for two series of Fe/Au multilayers, the magnitude of the GMR in the CIP configuration was very much smaller for the series of multilayers that had a shorter electron mean free path.

2. Experimental procedures

The Fe/Au multilayers were grown in our VG-80M MBE facility, using a base pressure of typically 4×10^{-11} mbar. The CIP samples were grown on sapphire($11\bar{2}0$) substrates using 30 Å of Nb and 20 Å of Au as buffer layers. This choice of substrate and buffer layers was found to produce epitaxial growth of the Fe/Au(111) multilayers, which were deposited at room temperature. Therefore, the full structure of the multilayers was as follows:

$$\mathrm{sapphire}(11\bar{2}0)/\mathrm{Nb}_{30}(110)\mathrm{bcc}/\mathrm{Au}_{20}(111)\mathrm{fcc}[\mathrm{Fe}_{10}(110)\mathrm{bcc}/\mathrm{Au}_t(111)\mathrm{fcc}]_N$$

where $N = 20$ bilayers, other subscripts refer to the thickness in Å and t ranges up to 50 Å.

The quality of each sample was continuously monitored by RHEED during the growth cycle. Details of growth conditions, including x-ray and LEED studies, have been reported previously [5]. Medium-energy-ion-scattering (MEIS) studies have also been carried out [6]. These confirm that the Fe grows as bcc(110) on fcc(111) Au, with a thin intermixed layer of somewhat less than two monolayers.

A sapphire substrate was used and the buffer layers were kept relatively thin for the CIP measurements. Previous workers [7], whose samples had a GaAs substrate, used a Au buffer as thick as 470 Å. Such a thick buffer significantly reduces the GMR by acting as a low-resistance shunt, leading to values for the GMR of only a few per cent for Fe/Au multilayers [7].

Our CPP measurements used the superconducting Nb electrode technique, developed in collaboration with Pratt and co-workers [2]. As in our previous CPP measurements [8, 9], the superconducting equipotential ensures that the current is perpendicular to the layers. We used a SQUID-based current comparator, working at 0.1% precision to measure changes in the sample resistance of order 0.1 nΩ. In order to avoid driving the Nb normal, the CPP measurements were performed at 4.2 K in magnetic fields below 0.5 T. Sapphire($11\bar{2}0$) substrates were again used but the Nb buffer layer was now 2000 Å thick.

Our Fe/Au(111) multilayers had a relatively high resistivity ($\rho \approx$ 15–20 $\mu\Omega$ cm) at 4.2 K because of interface roughness, as we determined from x-ray scattering. Therefore, for the lower-resistivity samples, we studied Fe/Au(100) multilayers grown on MgO(100). MEIS measurements [6] confirmed that the Fe grows as bcc(100) and the Au as fcc(100). Therefore, the full structure of these multilayers was as follows:

$$\mathrm{MgO}(100)/[\mathrm{Fe}_{10}(100)\mathrm{bcc}/\mathrm{Au}_t(100)\mathrm{fcc}]_N$$

where $N = 20$ bilayers. The lower resistivity ($\rho \approx$ 3–10 $\mu\Omega$ cm) of these multilayers can be attributed to electron channelling in the Au. It seems reasonable to assume that this difference in orientation between the two series of multilayers would alter the magnitude of the GMR, but would not be decisive in determining the presence or absence of the GMR. Even though the Fe/Au(111) multilayers were uncoupled, whereas the Fe/Au(100) multilayers were coupled, uncoupled multilayers also exhibit a substantial GMR.

3. CIP versus CPP configurations

The fundamental difference between the CIP and the CPP configurations can be understood in terms of the following semiclassical picture. The GMR is basically due to the electron trajectory passing through neighbouring magnetic layers and ‘sensing’ whether or not their magnetic moments are oriented parallel [3]. Therefore, for non-zero GMR, the electron has to reach at least one neighbouring magnetic layer. If the current flows *along* the layers (CIP configuration), then the electron will leave its present layer *only* if its mean free path is long enough. Hence, a short mean free path implies zero GMR. However, if the current flows perpendicular to the layers (CPP configuration), then the electron *must* drift through *all* the layers and will therefore sample the neighbouring magnetic layers regardless of the shortness of the mean free path.

One may assume that no spin-dependent scattering takes place in the spacer layer, which merely serves as a conduit through which the electron passes in its journey from one magnetic layer to another in the CIP configuration. Thus, the ‘electron mean free path’ refers to the distance between two scattering events occurring in *neighbouring magnetic layers*, either in the bulk or at the interfaces. However, since the electron traverses the spacer layer between these scattering events, the material properties of the spacer layer (Fermi velocity etc) are to be used in relating the resistivity to the electron mean free path.

4. Results

Figure 1 exhibits the magnetic-field dependence of the magnetoresistance in the CIP configuration for a typical sample ($t_{Au} = 27$ Å). We note that for small fields, the resistance decreases rapidly for the first 0.3 T, whereas the resistance decreases only very gradually for the next 6 T, which is still nowhere near saturation. This continuing gradual decrease in the resistance results from a well known thin-film effect [10]. Basically, as the magnetic field increases in a thin film, the electron tries to spiral around the field, thus altering its trajectory in a way that makes the electron a bit less likely to reach the surface of the film, thereby slightly reducing the electron–surface scattering resistivity. This small negative contribution to the magnetoresistance is seen in all thin films and multilayers, and does not concern us here. Therefore, we shall define the GMR as the value of the magnetoresistance at $B = 0.3$ T. The uncertainty introduced thereby in the GMR is quite small.

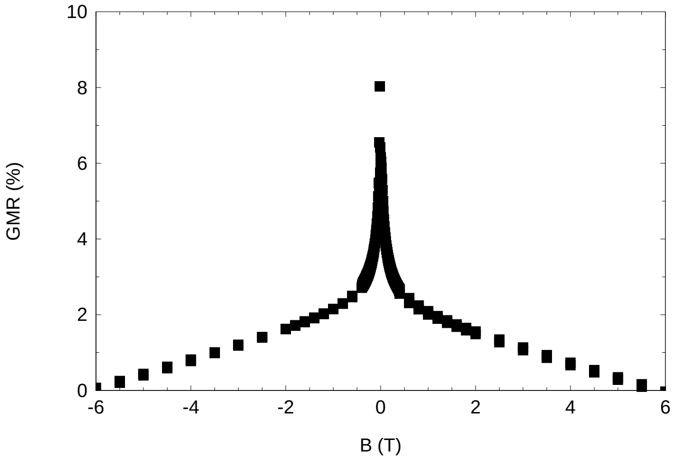

Figure 1. Magnetic-field dependence of the magnetoresistance for a typical Fe/Au multilayer ($t_{Au} = 27$ Å) in the CIP configuration.

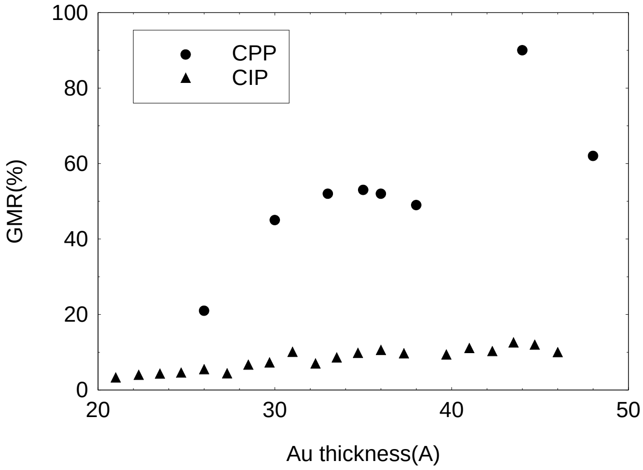

Figure 2. GMR as a function of the thickness of the Au layer for a series of Fe/Au multilayers in the CPP configuration (circles) and in the CIP configuration (triangles).

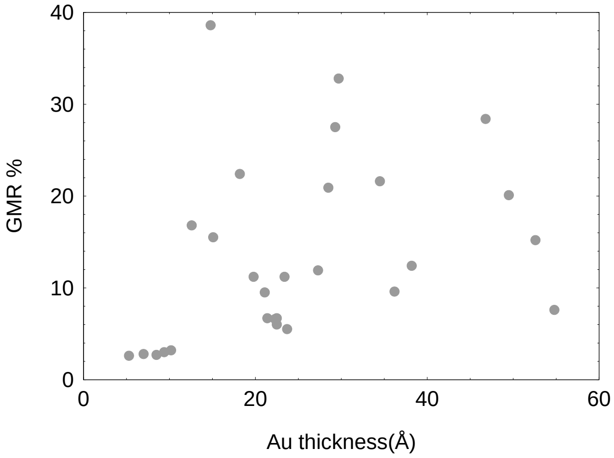

Figure 3. GMR as a function of the thickness of the Au layer for a series of low-resistance Fe/Au multilayers in the CIP configuration.

In figure 2, we present the GMR data for a series of Fe/Au(111) multilayers all of which have $t_{Fe} = 10$ Å, but with t_{Au} ranging from 20 to 50 Å. The circles and triangles represent the data measured at 4 K for the CPP configuration and the CIP configuration, respectively. It is seen that the values of the GMR are only a few per cent in the CIP configuration, whereas in the CPP configuration the GMR lies in the range 20–80%.

The absence of oscillations in the GMR data can be explained in the following way. For samples having Au layers thicker than 30 Å, the layers are uncoupled, as confirmed by the characteristic shape of the magnetization curve as a function of the magnetic field. Therefore, for these samples, no oscillations are present for the GMR, either in the CIP or in the CPP configurations. For samples having Au layers between 20 Å and 30 Å thick, the magnitude of the GMR for the CIP configuration is negligible, and hence no oscillations can be observed.

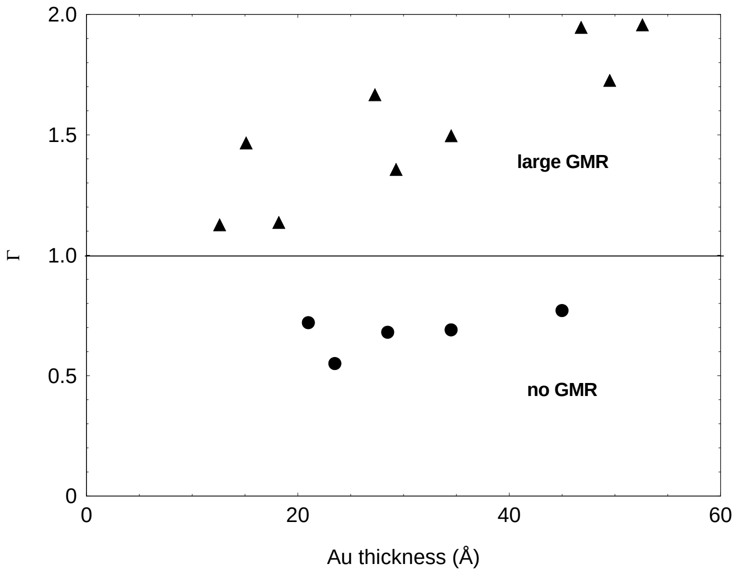

Figure 4. The ratio $\Gamma = \lambda/2t_{Au}$ as a function of the thickness of the Au layer, where λ is the electron mean free path and the GMR measurements were carried in the CIP configuration. The series of multilayers that exhibited a large GMR (full triangles) all correspond to $\Gamma > 1$ ('long' electron mean free path), whereas the series of multilayers that exhibited almost no GMR (full circles) all correspond to $\Gamma < 1$ ('short' electron mean free path).

For $t_{Au} < 20$ Å, we found that the GMR is negligible for both configurations, and therefore these data were not included in figure 2. To clarify why no GMR was observed for $t_{Au} < 20$ Å, we performed magnetization measurements on our samples. A dramatic drop in the remanent magnetization occurred for $t_{Au} < 20$ Å, whereas the remanent magnetization was independent of t_{Au} for thicker samples. These results indicate the presence of pinholes for samples having Au layers thinner than 20 Å, and their absence for samples having thicker Au layers. The magnetization data and the GMR data are thus consistent for both the CIP and the CPP configurations.

Our data for the GMR for the lower-resistivity multilayers—Fe/Au(100)—in the CIP configuration are given in figure 3. It is seen that the GMR is indeed large, reaching 30–40% for the values of t_{Au} that correspond to antiferromagnetic coupling.

5. Discussion

We are suggesting that the large difference between the CIP and the CPP values of the GMR for $t_{Au} > 20$ Å is due to the short electron mean free path λ, resulting from the relatively high resistivity of these multilayers. This interpretation is in quantitative agreement with the calculations of Edwards *et al* [4], who showed that the GMR is sharply reduced in the CIP configuration when the electron mean free path is less than about twice the thickness of the spacer layer.

In figure 4, we apply this criterion to our multilayers by plotting the ratio Γ of the mean free path to twice the thickness of the spacer layer: $\Gamma = \lambda/2t_{Au}$. The value of λ is readily obtained from ρ via the kinetic transport formula, using the material parameters of gold: λ (Å) $= 620/\rho$ ($\mu\Omega$ cm), where λ and ρ are given in the indicated units. Thus, for $\rho = 20$ $\mu\Omega$ cm, for example, $\lambda = 31$ Å, which is significantly shorter than $2t_{Au}$ for the multilayers shown in figure 2.

The circles in figure 4 represent the higher-resistivity multilayers for which only a very small GMR was found; for all these multilayers, it is seen that $\Gamma < 1$. The triangles represent the lower-resistivity multilayers for which a large GMR is obtained (GMR > 15%); for all these multilayers, it is seen that $\Gamma > 1$. The magnitude of the GMR in the CIP configuration is thus found to be strongly correlated to the electron mean free path.

In summary, a consistent picture emerges in which the length of the electron mean free path explains both the very different values for the GMR that we found for the same series of multilayers measured in the CIP and in the CPP configurations, as well as the very different values for the GMR found between our two series of multilayers both measured in the CIP configuration.

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References

[1] Baibich M N, Broto J M, Fert A, Nguyen Van Dau F, Petroff F, Etienne P, Creuzet G, Friederich A and Chazelas J 1988 *Phys. Rev. Lett.* **61** 2472

[2] Pratt W P Jr, Lee S-P, Slaughter J M, Loloee R, Schroeder P A and Bass J 1991 *Phys. Rev. Lett.* **66** 3060

[3] Mathon J 1991 *Contemp. Phys.* **32** 143

[4] Edwards D M, Mathon J and Muniz R B 1991 *IEEE Trans. Magn.* **27** 3548

[5] Xu J, Howson M A, Hucknall P, Hickey B J, Venkataraman R, Hammond C, Walker M J and Greig D 1997 *J. Appl. Phys.* **81** 3908

[6] Noakes T C Q, Bailey P, Hucknall P K, Donovan K and Howson M A 1998 *Phys. Rev.* B **58** 4934

[7] Sato H, Kobayashi Y, Aoki Y, Shintaku K, Hosoito N and Shinjo T 1993 *J. Phys. Soc. Japan* **62** 3380

[8] List N J, Pratt W P Jr, Howson M A, Xu J, Walker M J and Greig D 1995 *J. Magn. Magn. Mater.* **148** 342

[9] List N J, Pratt W P Jr, Howson M A, Xu J, Walker M J, Hickey B J and Greig D 1995 *Mater. Res. Soc. Symp. Proc.* vol 384 (Pittsburgh, PA: Materials Research Society) p 329

[10] Ziman J M 1960 *Electrons and Phonons* (Oxford: Clarendon) section 11.6