Electrical resistivity behavior of Fe/Cr multilayers deposited by different techniques (molecular-beam epitaxy, sputtering), on different substrates (MgO,Si)

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High-resolution electrical resistivity measurements ($\rho, d\rho/dT$) were performed in three series of $[Fe_{30Å}Cr_{tÅ}]$ multilayers in the temperature range 15–300 K, both at zero and under saturation magnetic field. The different series were prepared by MBE on MgO (100) substrates, by sputtering on MgO (100) substrates, and by sputtering on Si (100) substrates. In the temperature range $15\,K \lesssim T < 50\,K$ we always observe $\rho = \beta T^3$ where β is a sample-dependent constant, indicating the dominance of *phonon-assisted* interband (s-d) electron scattering ($\rho \propto T^3$ when $T \ll \Theta_{Debye}$). For the samples grown on MgO we observe that β *decreases* with t(Cr) whereas for the samples grown on Si, the coefficient β *increases* with t. For $T > 150$ K the resistivity attains the classical dependence with $\rho \propto T$ also predicted by this s-d model. In spite of these differences our results show that $\rho = \beta f(T)$ where $f(T)$ is the same function of temperature for all the different samples studied.
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INTRODUCTION

Previous coarse measurements of the electrical resistivity of Fe/Cr multilayers were analyzed in terms of electron–magnon scattering, giving an approximately quadratic dependence of $\rho(T)$ over the temperature range 20 K$<T<$100 K.[1] Also, it has been known for some time that giant magnetoresistance is very sensitive to film preparation conditions, mainly due to the dependence of the magnetic coupling on the quality of the multilayer modulation, crystallographic orientation, etc.[2,3] In order to deepen our understanding of these problems we have performed a detailed comparative study of the temperature dependence of the electrical resistivity (ρ) and its temperature derivative ($d\rho/dT$) on three sets of $[Fe_{30Å}/Cr_{tÅ}] \times 10$ multilayers deposited by different techniques (MBE, sputtering) over different substrates (MgO and Si). Our objective is to identify dominant electron scattering mechanisms by using detailed measurements of the temperature derivative of the electrical resistivity, and to reveal structural film differences arising from different growth conditions.

One series of samples was deposited by MBE over MgO (100) substrates, with Cr-layer thicknesses t=9, 18, 21, 39, and 57 Å. Another series was deposited by sputtering on MgO (100) substrates, with t=10, 15, 17, 18, 19, 22, 37, and 39 Å. The third series was deposited by sputtering over Si (100) substrates, with t=10, 16, 22, and 39 Å. Details of the deposition techniques were reported elsewhere.[4]

The electrical resistivity measurements were performed in the temperature range 15–300 K using the standard four-probe technique. Absolute values were obtained with the Van der Pauw method.

RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the intrinsic electrical resistivity $\rho_i = \rho - \rho_0$ (ρ_0 is the residual resistivity) in the temperature range 15$<T<$300 K, for the three sets of samples. Also shown is the corresponding $d\rho/dT$ temperature dependence for $T<$150 K. We distinguish two different types of behavior between the three sets of samples. In the samples deposited on MgO (by MBE and sputtering) the intrinsic resistivity and its temperature derivative decrease with increasing t(Cr) thickness whereas the reverse effect occurs in the multilayers deposited on Si.

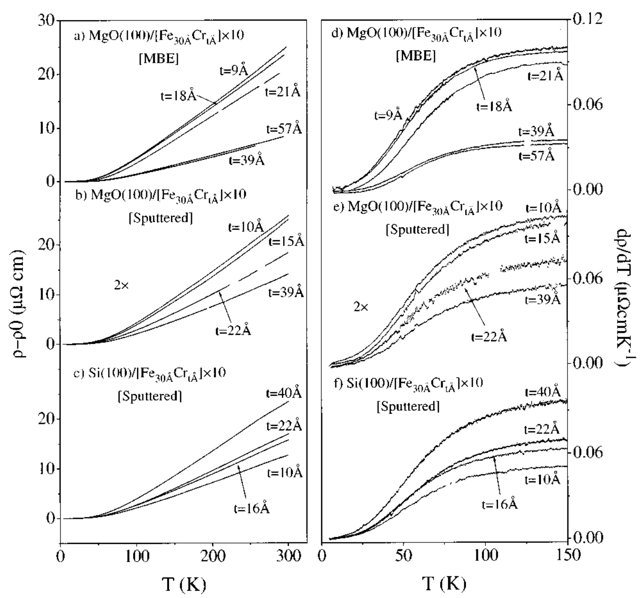

FIG. 1. Temperature dependence of the electrical resistivity of the three sets of Fe/Cr multilayers measured at H=0 Oe: (a) deposited by MBE on MgO substrates, (b) deposited by sputtering on MgO substrates, and (c) deposited by sputtering on Si substrates. Graphs (d), (e), and (f) show the corresponding $d\rho/dT$ curves. Results for sputtered samples on MgO are multiplied by 2 for clarity.

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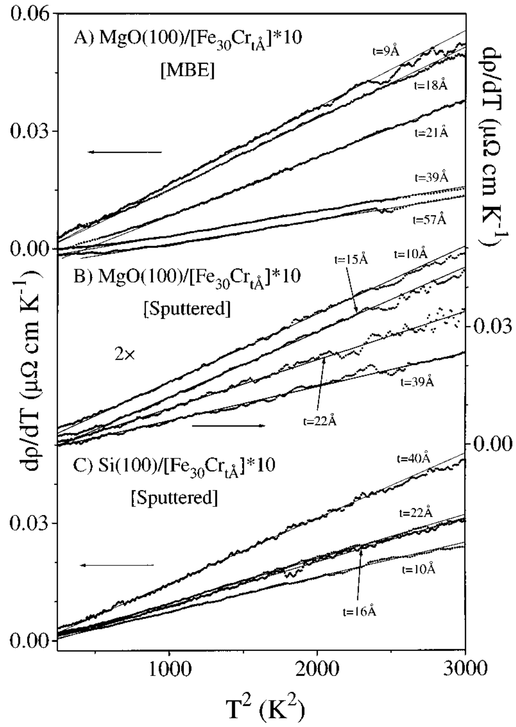

FIG. 2. Linear fits to the curves $d\rho/dT$ vs T^2 measured at $H=0$ Oe on all the Fe/Cr multilayers studied, in the temperature range ∼15–50 K.

In principle, in the temperature range reported here, electron–phonon (s-s), electron–magnon, and phonon-assisted interband (s-d) electron scattering may be operative.[5,6] It has been claimed that electron–magnon scattering, giving a T^2 dependence in ρ, is dominant in the temperature range 20–100 K.[1] Strictly this would lead to a linear temperature dependence in $d\rho/dT$, which is not supported by our $d\rho/dT$ data [Figs. 1(d)–1(f)].

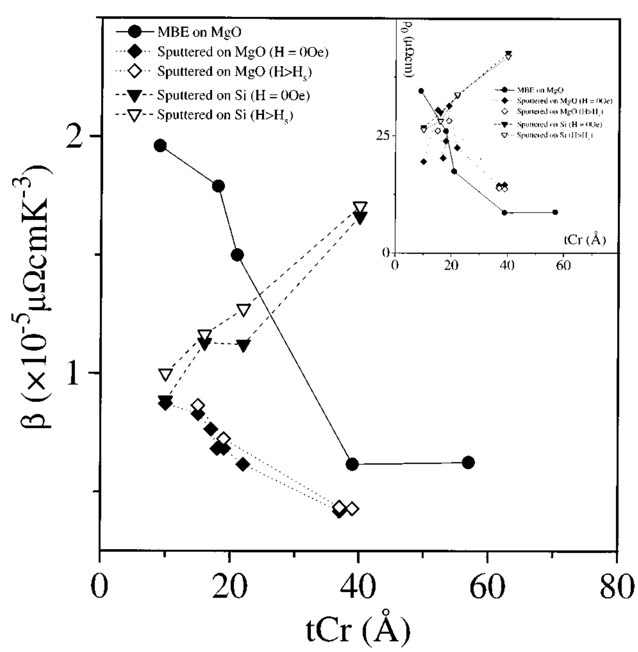

FIG. 3. Slope (β) of the linear fits to the curves $d\rho/dT$ vs T^2 obtained on all the Fe/Cr multilayers studied, both at zero and at saturation magnetic field. Inset is the residual resistivity ρ_0 vs t(Cr) for all the Fe/Cr samples studied here.

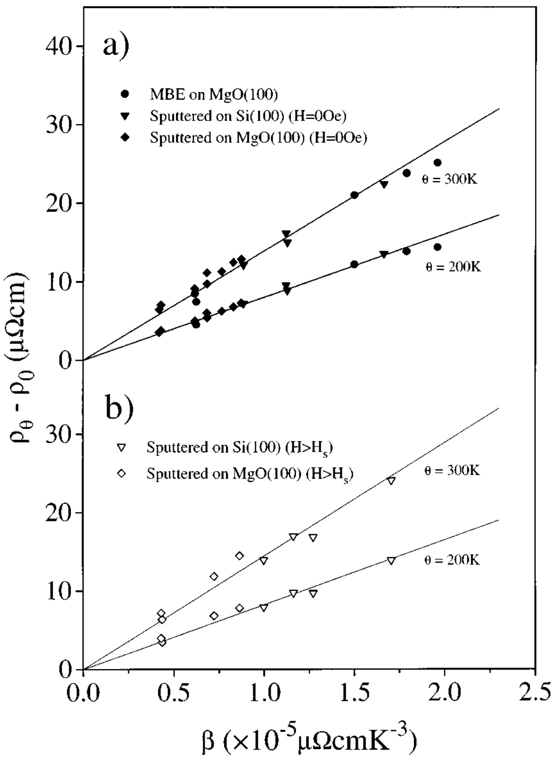

FIG. 4. Intrinsic resistivity measured at (a) zero and (b) saturation magnetic field vs β for the Fe/Cr multilayers studied. All the points for each temperature fall in the same line going through the origin; it indicates that $\rho=\beta f(T)$, where $f(T)$ is a universal function of temperature.

In fact, for 15 K$\lesssim T<$50 K we observe a T^2 dependence in $d\rho/dT$ for all the Fe/Cr multilayers studied, as shown in Fig. 2. This means that $\rho_i=\beta T^3$, suggesting the dominance of phonon-assisted interband s-d electron scattering[6] in that temperature range [$\rho_{sd}\propto$lattice specific heat$\propto(T/\Theta)^3$ when T is considerably less than the Debye temperature Θ;[5] $\Theta\sim450$ K in our case]. From the linear fits shown in Fig. 2 we have determined β for all the measured $Fe_{30Å}Cr_{tÅ}$ multilayers. The apparently small role played by electron–magnon scattering could be due to the fact that magnons cannot extend over the whole multilayer due to interface roughness and defects. The relative contribution of the spin-flip term, coming from collision with extended magnons, is then small as remarked earlier.[7]

For $T>50$ K the exponent n (in $\rho\sim T^n$) progressively decreases, reflecting the expected decay of lattice quantization effects and leading to the classical linear increase of the resistivity with temperature ($n=1$; $T\gtrsim150$ K in our case).

Besides zero-magnetic-field measurements, we have also performed ρ, $d\rho/dT$ measurements under magnetic saturation in the same temperature range. We observe a systematic decrease in the absolute resistivity due to the magnetoresistance effect, but the intrinsic resistivity $\rho_i(T)=\rho(T)-\rho_0$ again follows a $\rho_i=\beta T^3$ dependence in the temperature range ∼15–50 K, with slightly higher β values than in zero field.

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Figure 3 shows the dependence of β on the Cr-layer thickness, both for zero field and under magnetic saturation. For MgO-deposited multilayers β *decreases* with increasing Cr thickness, whereas for the samples deposited on Si the β coefficient *increases* with $t(\mathrm{Cr})$. The observed dependence of the residual resistivity on the Cr-layer thickness is shown in the inset of Fig. 3. Strikingly, the ρ_0 vs $t(\mathrm{Cr})$ dependence is similar to that of β vs $t(\mathrm{Cr})$, indicating a correlation between them.

By plotting the intrinsic resistivity ρ_i^k for different samples k, at any temperature, as a function of the corresponding β_k coefficient (obtained from the low temperature fits referred above), we find good straight lines through the origin, containing the experimental points from all the samples studied here, at that particular temperature (Fig. 4). This means that the intrinsic resistivity can be written as

$$\rho_i^k(T)=\beta_k f(T),$$

where $f(T)$ is a universal function of temperature, going as T^3 at low temperatures and as T at high temperatures. This suggests the dominance of a single physical mechanism in the electrical resistivity over the whole temperature range, $\sim$15–300 K, for all the Fe/Cr multilayers studied. This mechanism is here attributed to phonon-assisted interband s-d electron scattering. The slope of the linear fits to the ρ_i^k vs β_k shown in Fig. 4 is slightly higher for samples measured at saturation field than the corresponding one in the samples measured at zero magnetic field. This means that the function $f(T)$ is slightly different in both cases, which arises from the temperature dependence of $\Delta\rho=\rho(T,H=0)-\rho(T,H>H_{\mathrm{sat}})$. In our AF-coupled samples $\Delta\rho$ is proportional to T^2 at low temperatures, as expected for strong antiferromagnetic coupling as in Fe/Cr multilayers.[8]

ACKNOWLEDGMENTS

One of the authors (B.G.A.) acknowledges a Ph.D. grant from PRAXIS XXI, Portugal. This work has been performed under projects PRAXIS/3/3.1/FIS/21/94 and STRDA/C/CEN/522/92.

[1] J. E. Mattson, M. E. Brubaker, C. H. Sowers, M. Conover, Z. Qiu, and S. D. Bader, Phys. Rev. B **44**, 9378 (1991).
[2] D. H. Mosca, F. Petroff, A. Fert, P. A. Schroeder, W. P. Pratt, and R. Loloee, J. Magn. Magn. Mater. **94**, L1 (1991).
[3] S. S. P. Parkin, Z. G. Li, and D. J. Smith, Appl. Phys. Lett. **58**, 2710 (1991).
[4] J. M. Colino, I. K. Schuller, R. Schad, C. D. Potter, P. Belien, G. Verbanck, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. B **53**, 766 (1996).
[5] J. L. Duvail, A. Fert, L. G. Pereira, and D. K. Lottis, J. Appl. Phys. **75**, 7070 (1994).
[6] B. Loegel and F. Gautier, J. Phys. Chem. Solids **32**, 2723 (1971); S. D. Bader and F. Y. Fradin, *Superconductivity in d- and f-band Metals* (Plenum, New York, 1976), p. 567.
[7] S. Zhang and P. M. Levy, Phys. Rev. B **43**, 11048 (1991).
[8] Y. Saito, K. Inomata, S. Uji, T. Terashima, and H. Aoki, J. Phys. Soc. Jpn. **63**, 1263 (1994).

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