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s–d Electron scattering as a sensitive probe to study Fe/Cr multilayer structural differences (MBE/sputtered samples)

B.G. Almeida [a], J.B. Sousa [a,*], J. Colino [b], Y. Schuller [b], R. Schad [c,1], V.V. Moshchalkov [c], Y. Bruynseraede [c]

[a] IFIMUP, Faculdade de Ciências, Universidade do Porto, P-4150 Porto, Portugal
[b] Physics Department, University California–San Diego, La Jolla, CA 92093-0319, USA
[c] Laboratium Vaste-Stof-Fysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

Abstract

High resolution electrical resistivity measurements (ρ, $\mathrm{d}\rho/\mathrm{d}T$) were performed in two different series of $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]$ multilayers. One was prepared by MBE on a (100) MgO substrate and the other by sputtering on (100) Si. In the temperature range $18\ \mathrm{K} < T < 50\ \mathrm{K}$ we observe that $\rho = \beta T^3$ where β is a sample dependent constant. According to theory this indicates the dominance of *phonon-assisted* interband (s/d) electron scattering. For the MBE grown samples β *decreases* with t(Cr) whereas for the sputtered samples β *increases* with t. The observed variation of β provides a sensitive tool for comparison of structurally-related effects in MBE and sputtered multilayers.

1. Introduction

A detailed study of the temperature dependence of the electrical resistivity of two differently prepared sets of $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]_{10}$ multilayers (MBE and sputtered samples) is here reported using high resolution $\mathrm{d}\rho/\mathrm{d}T$ measurements taken in the temperature range 6–150 K.

The objective is to identify dominant electron scattering mechanisms and to use the temperature derivative of the electrical resistivity as a sensitive tool to reveal structural film differences arising from different growth conditions. In principle the main contributions to the electrical resistivity in the temperature range here reported, are electron–phonon (s–s), electron–magnon scattering and phonon-assisted interband (s–d) electron scattering [1].

One set of samples (A) was MBE epitaxially grown on (100) MgO substrates, with Cr thicknesses $t = 9$, 18, 21, 39 and 57 Å. The other set (B) was grown by sputtering on (100) Si substrates, with $t(\mathrm{Cr}) = 10$, 19, 22 and 40 Å.

The measurements of $\mathrm{d}\rho/\mathrm{d}T$ were done with a quasistatic four-probe technique, with the absolute resistivity values obtained using the Van der Pauw method.

2. Results and discussion

Fig. 1a shows the temperature derivative of the electrical resistivity for the A-set of multilayers (MBE-prepared), in the temperature range 6–150 K. We observe that for small Cr thicknesses ($t = 9$, 18, 21 Å) $\mathrm{d}\rho/\mathrm{d}T$ exhibits large values whereas in the thick-Cr samples it is about a factor 3 smaller.

For the B-set of Fe/Cr multilayers (sputtered samples), the $\mathrm{d}\rho/\mathrm{d}T$ data exhibits the reverse behaviour, with considerably *smaller* $\mathrm{d}\rho/\mathrm{d}T$ values in the thin Cr-layer samples.

For sputtered Fe/Cr multilayers (and based only on coarse $\rho(T)$ data [2]) it has been previously claimed that electron–magnon scattering (giving a T^2 dependence in ρ) is the dominant mechanism in the temperature range 20–100 K. If so one would expect a linear temperature dependence in $\mathrm{d}\rho/\mathrm{d}T$, which is not supported by our data (Fig. 1a,b). We observe instead several distinct $\rho(T)$ regimes within the 6–150 K range, which prevents the use of a single power data fit (T^n) to describe the whole curve.

(i) A dominant T^3 term occurs in $\rho(T)$ over the temperature range 18–50 K and *in all the measured samples*. This corresponds to a T^2 dependence in $\mathrm{d}\rho/\mathrm{d}T$, as clearly shown in the plots of Fig. 2a,b representing $\mathrm{d}\rho/\mathrm{d}T$ versus T^2.

This T^3 behaviour observed in $\mathrm{Fe}_{30\,\text{Å}}\mathrm{Cr}_{t\,\text{Å}}$ multilayers suggests the dominance of phonon-assisted interband s–d electron scattering. In fact one expects ρ_{sd} α lattice

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[*] Corresponding author. Fax: +351-2-608-2679.

[1] Present address: Research Institute for Materials, Katholieke Universiteit Nijmegen.

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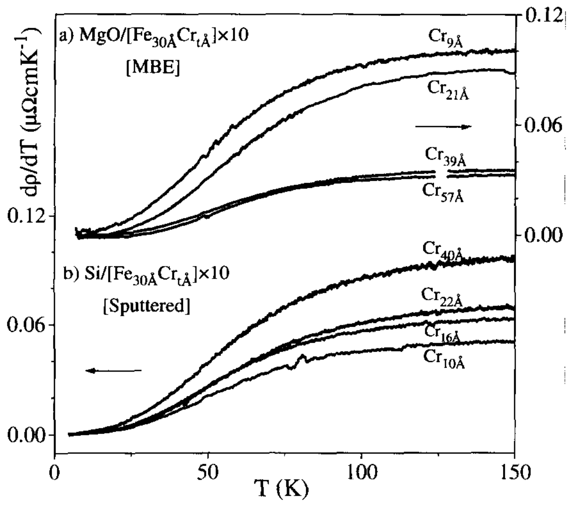

Fig. 1. Temperature derivative of the electrical resistivity, in the range 6–150 K, for: (a) $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]_{10}$ multilayers with $t = 9$, 21, 39 and 57 Å deposited by MBE on MgO and (b) $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]_{10}$ multilayers with $t = 10$, 19, 22 and 40 Å deposited by sputtering on Si.

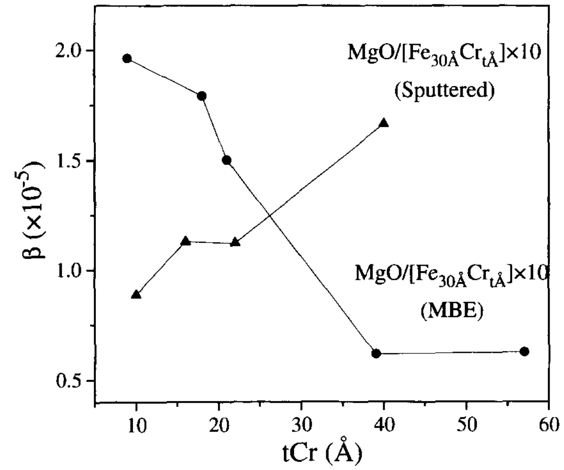

Fig. 3. Slopes (β) of the linear fits to the curves of $\mathrm{d}\rho/\mathrm{d}T$ versus T^2, for the MBE and sputtered samples, versus Cr-layer thickness.

specific heat $\propto (T/\Theta)^3$ when T is considerably less than the Debye temperature Θ [3], as in the present case ($\Theta \sim 450$ K). We then expect the dominance of lattice energy quantization effects. Putting $\rho_{\mathrm{sd}} = \beta T^3$ within such temperature range we have determined β for all the measured $\mathrm{Fe}_{30\,\text{Å}}\mathrm{Cr}_{t\,\text{Å}}$ multilayers.

Fig. 3 shows the dependence of β on the Cr-layer thickness. For the MBE samples β *decreases* with the Cr thickness (t), by a factor of 3.3 when t changes from 9 to 57 Å. For the sputtered samples β *increases* with t(Cr), by a factor of 1.9 when t changes from 10 to 40 Å.

(ii) For temperatures above ~ 50 K the exponent n (in $\rho \sim T^n$) progressively decreases, reflecting the expected decay in the vibrational lattice quantization effects. For temperatures ≤ 150 K we practically approach the classical regime characterized by a linear increase of the resistivity due to electron–phonon scattering ($n = 1$).

(iii) At temperatures below ~ 15 K, the $\rho(T)$ dependence gets more complex and we observe in some samples a faint minimum in the electrical resistivity.

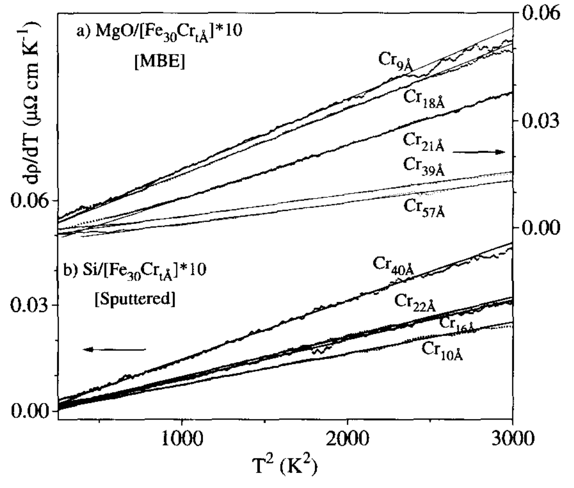

Fig. 2. Linear fit to the curves of $\mathrm{d}\rho/\mathrm{d}T$ versus T^2 in the temperature range 6–50 K, for: (a) $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]_{10}$ multilayers with $t = 9$, 18, 21, 39 and 57 Å deposited by MBE on MgO and (b) $[\mathrm{Fe}_{30\,\text{Å}}/\mathrm{Cr}_{t\,\text{Å}}]_{10}$ multilayers with $t = 10$, 19, 22 and 40 Å deposited by sputtering on Si.

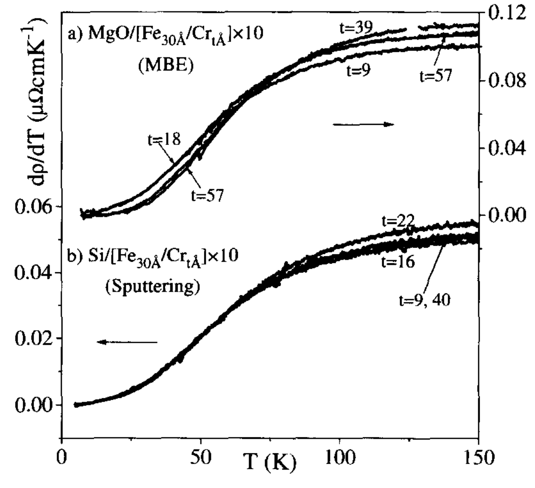

Fig. 4. Temperature derivative of the electrical resistivity in the range 6–150 K, with a scaling constant (α) for each sample: (a) $\alpha = \beta(9\,\text{Å})/\beta(t)$ for the Fe/Cr multilayers deposited by MBE on MgO and (b) $\alpha = \beta(10\,\text{Å})/\beta(t)$ for the ones deposited by sputtering on Si.

In spite of the different regimes observed in $\rho(T)$ (different n) and the large quantitative differences observed in $\mathrm{d}\rho/\mathrm{d}T$ among the different samples, it is remarkable that all the $\mathrm{d}\rho/\mathrm{d}T$ curves corresponding to multilayers grown by a particular method can be brought fairly close to each other over the the whole temperature range 6–150 K (see Fig. 4a for MBE samples; Fig. 4b for sputtered samples) through the use of a scaling constant (α) for each multilayer. In Fig. 4 we used $\alpha = \beta(9\,\text{Å})/\beta(t)$ for the MBE samples and $\alpha = \beta(10\,\text{Å})/\beta(t)$ for the sputtered ones. This suggests that the same s–d electron–phonon resistivity mechanism is dominant in both cases over that temperature range.

In summary, accurate $\mathrm{d}\rho/\mathrm{d}T$ measurements enable us to identify a dominant T^3 term in $\rho(T)$ (below ~ 50 K), indicating the importance of s–d electron scattering in Fe/Cr multilayers. We have shown that such measurements are very sensitive to the structure of each sample. A striking feature is an opposing Cr-thickness dependence of $\mathrm{d}\rho/\mathrm{d}T$ when measured in the MBE and sputtered samples. This could be useful to show structural differences occurring in multilayered thin films grown by different methods and/or deposited on different substrates.

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