Giant Magnetoresistance and Spin Valves I

Ming Mao, Chairman

Magnetic scattering in Fe–Cr multilayers in the ferromagnetic state at low temperatures

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We report here an interpretation of the electrical resistivity (ρ) below 15 K of two Fe–Cr multilayers (30 layers of 20 Å Fe/10 and 12 Å Cr) produced by Xe ion-beam sputter deposition. These multilayers have a negative giant magnetoresistance (GMR) of ~21% at 4.2 K and $H_{\mathrm{sat}} = 13$ kOe. Very high-resolution resistance measurements (better than 3 ppm) were made down to 2.3 K at every (100 ± 10) mK. Excellent results were obtained when the $\rho(T)$ data in the ferromagnetic state ($H = H_{\mathrm{sat}}$) were fitted to an equation containing the residual resistivity $[\rho(0)]$, electron–phonon interband $s-d$ scattering (Bloch–Wilson integral) and a magnetic BT^2 term, where B is proportional to $s-d$ interaction strength responsible for the electron–magnon $s-s$ scattering. The value of B is found to be typically $(9 \pm 2) \times 10^{-5}$ $\mu\Omega$ cm K^{-2} compared to the much smaller value of 1.5×10^{-5} $\mu\Omega$ cm K^{-2} for bulk crystalline Fe. The fits without the magnetic term are distinctly inferior as seen from their residuals plotted against T. However, the data in the antiferromagnetic state could be fitted very well with only the lattice term and $\rho(0)$. We have restricted our analysis to $T \leqslant 15$ K in order to avoid electron–magnon $s-d$ scattering which dominates above 20 K and is very difficult to estimate. Thus magnetic scattering in $3d$ metals are best interpreted at low temperatures even for these magnetic multilayers. [DOI: 10.1063/1.1555753]

I. INTRODUCTION

The electrical resistivity in $3d$ transition metals like Fe, Co, and Ni is given by (using Mathiessen's rule)

$$\rho(T) = \rho_0 + \rho_\ell + \rho_m, \tag{1}$$

where ρ_0 = residual resistivity due to the temperature-independent scattering of electrons from lattice defects and impurities. ρ_ℓ comes from the scattering of conduction electrons by lattice phonons and ρ_m from the spin waves produced by the magnetic spin system at finite temperatures. In $3d$ magnetic metals and alloys, the s and d bands overlap at the Fermi level. So for both lattice and magnetic scattering, conduction electrons might undergo $s-s$ (intraband) as well as $s-d$ (interband) transitions. The scattering of conduction electrons by lattice phonon gives the contribution

$$\rho_\ell = A\left(\frac{T}{\theta_D}\right)^n \int_0^{\theta_D/T} \frac{z^n dz}{(e^z - 1)(1 - e^{-z})}, \tag{2}$$

where θ_D = Debye temperature and $n = 3$ (Bloch–Wilson) for magnetic metals and alloys with large d-band density of states giving rise to electron–phonon scattering involving $s-d$ transitions.[1] The single band ($s-s$) electron–phonon scattering is described well by Eq. (2) with $n = 5$ (Block–Grüneissen) in simple metals and alloys.

In ferromagnetic metals, there is a distinct contribution to the electrical resistivity (ρ_m) arising from the exchange interaction between the conduction electrons (s) and the localized magnetic electrons ($3d$), commonly called $s-d$ interaction. Turov[2] calculated this spin-disorder resistivity using spin-wave treatment and found $\rho_m \sim T^2$ for $T \leqslant 10$ K. Kasuya[3] used a spin-wave description of the $s-d$ interaction (not $s-d$ scattering) and obtained

$$\rho_m = BT^2, \tag{3}$$

where B includes the strength of the $s-d$ interaction. Mannari,[4] using a different approach, got $\rho_m = 1.1 \times 10^{-5}$ T^2 $\mu\Omega$ cm for Ni in excellent agreement with the experimental results ($\rho_m = 1.4 \times 10^{-5}$ T^2 $\mu\Omega$ cm) of White and Woods[5] on Fe, Co, and Ni below 10 K. Kondorsky

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et al.[6] found that $\rho_m = 4\times10^{-5}$ T^2 $\mu\Omega$ cm continues till about 30 K. However, their samples were not as pure as those of Ref. 5.

It should be noted, however, that the aforementioned calculations of ρ_m considered only intraband $s-s$ electron–magnon scattering. Goodings[7] extended the aforementioned models to include contributions to the electrical resistivity from interband scattering of s electrons into d-band holes by magnons (ρ_{sd}). It was found that the contribution from the interband $s-d$ scattering is dominant above 20 K and is an order of magnitude larger than that from the intraband $s-s$ scattering. However, it is difficult to make a direct comparison with experiments because of the rather complicated temperature dependence of ρ_{sd}. Nevertheless, at lower temperatures ($<$20 K), ρ_{sd} is not effective and ρ_m is primarily given by Eq. (3), viz, $\rho_m \sim$ T^2. The latter is also supported by experiments[5] as mentioned earlier. Thus, the magnetic scattering in 3d metals and alloys is best interpreted at low temperatures.

We report here an interpretation of the electrical resistivity below 15 K of Fe–Cr multilayers with magnetic structures which depend strongly on external magnetic fields. These Fe–Cr multilayers show a negative GMR[8] of 21% at 4.2 K. GMR is attributed to the spin-dependent conduction properties of ferromagnetic metals. In zero field, the ferromagnetic (FM) iron layers are antiferromagnetically (AF) coupled through the Cr spacer layer giving rise to a large spin-dependent scattering and hence a high electrical resistance.[9] This antiferromagnetic coupling is ascribed to the indirect exchange interaction between the Fe layers through the oscillatory Ruderman–Kittel–Kasuya–Yosida interaction mediated by the conduction electrons. As the external field is turned on, the spins in different Fe layers align in the direction of the field producing a completely ferromagnetic (FM) arrangement beyond a field H_{sat}. Since the majority band electrons of bulk Fe have large conductivity, they produce a short-circuiting effect causing a drop in resistance and hence a negative GMR.

II. EXPERIMENTAL DETAILS AND RESULTS

The Fe–Cr multilayers of composition Si/Cr(50 Å)/[Fe(20 Å)/Cr(t Å)]X30/Cr[(50-t(Å)], where $t=10$ and 12 Å, were grown on Si substrates by ion-beam sputter deposition[8] technique. Electrical resistance was measured down to 2.3 K using the standard four-probe dc method with a resolution of 3 ppm. However, the resistivity values are accurate to only within 5%–10% due to uncertainties in the measurements of the sample dimensions. Resistance measurements were taken, using a home-made cryostat, at every 100 mK with a stability of $\sim$10 mK from 2.3 to 30 K in both the FM ($H=H_{\mathrm{sat}}$) and the AF ($H=0$) states. The magnetic field was provided by a Varian 15 in. (Model V-3800) electromagnet.

Figure 1 shows ρ versus T in a magnetic field of $H_{\mathrm{sat}} = 13$ kOe for two samples with $t=10$ and 12 Å (samples 1 and 2, respectively). The five different curves refer to samples from different lots and repeated runs (see Fig. 1 caption). They are shifted along the ρ-axis to bring them on the same plot. It is to be noted that ρ has increased by at most 1 part in 10^3 (0.04 $\mu\Omega$ cm in 42 $\mu\Omega$ cm) as T increased from 2.3 to 15 K. The high resolution of the data is evident from Fig. 1. The data were then fitted to Eq. (1) with ρ_ℓ and ρ_m given by Eqs. (2) and (3), respectively. At $H=H_{\mathrm{sat}}$, the Fe layers are ferromagnetically coupled and so the magnetic contribution ρ_m is expected to show up. Excellent fits, shown by the solid lines in Fig. 1, were obtained with typical values of $\chi^2 \sim 3\times10^{-11}$ (consistent with the experimental resolution of 3 in 10^6) and correlation coefficients $\sim$1.

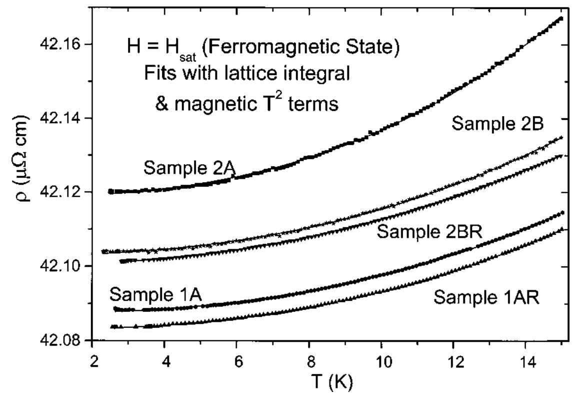

FIG. 1. Electrical resistivity (ρ) is plotted against temperature (T) to 15 K for two (five data sets) Fe–Cr multilayers in their FM state ($H=H_{\mathrm{sat}}$). The solid lines are the best fits to Eq. (1). Sample designations are: Sample 1A (lot A, first run), sample 1AR (lot A, second run), sample 2A (lot A, first run), sample 2B (lot B, first run), and sample 2BR (lot B, second run).

The coefficient of the magnetic term, $B=(7.0\pm0.2)\times10^{-5}$ $\mu\Omega$ cm K^{-2} for sample 1 and $(10.3\pm0.8)\times10^{-5}$ $\mu\Omega$ cm K^{-2} for sample 2 averaged over samples of different lots and repeated runs. The 30% lower value of B for sample 1 (Cr=10 Å) as compared to that for sample 2 (Cr=12 Å) falls outside the error of 5%–10% in ρ due to geometrical uncertainties. It is not clear why the values of B are different for the two samples where the thickness of Fe layers is the same (20 Å). However, the magnetic coupling between the Fe layers is different in the two samples due to the difference in Cr layer thickness. This may be the cause of the difference in the values of B. These values of B for the

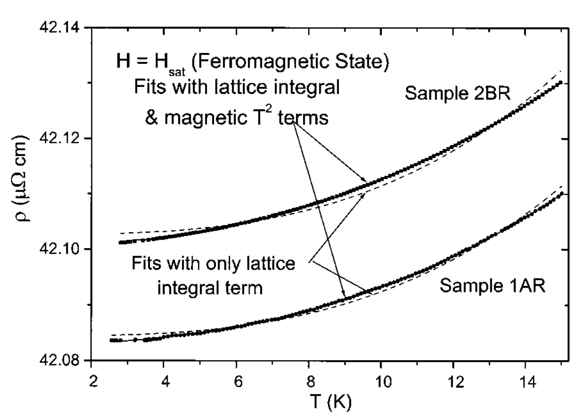

FIG. 2. ρ vs T for two Fe–Cr multilayers in their FM state ($H=H_{\mathrm{sat}}$). The solid lines show excellent fits to Eq. (1) with both the lattice integral and the magnetic T^2 terms whereas the fits (dashed lines) are poor with only the lattice integral term.

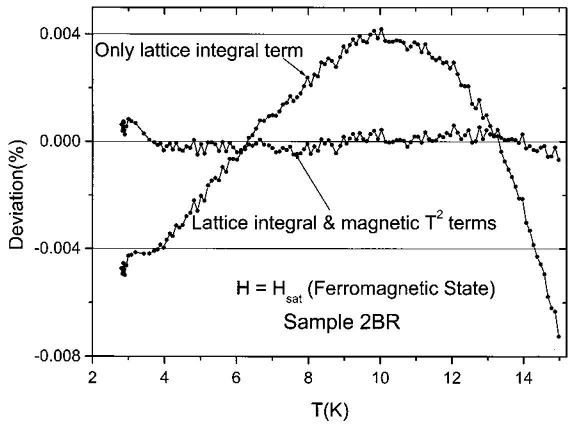

FIG. 3. Deviations (%) of the best-fitted curve from the actual data are plotted against T for sample 2BR in its FM state ($H=H_{sat}$) for fits with and without the magnetic term.

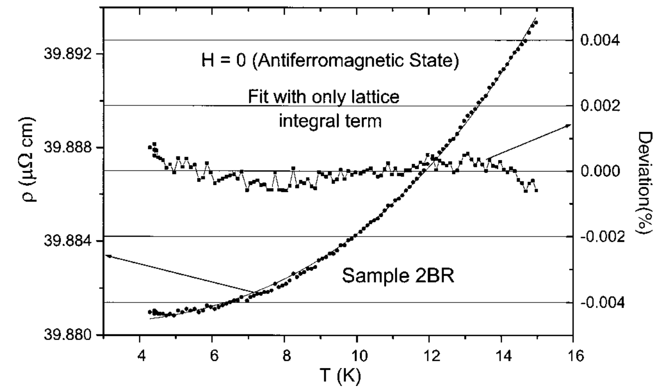

FIG. 4. $\rho(T)$ data (points) for sample 2BR in its AF state ($H=0$). The solid line is the best fit to Eq. (1) with only the lattice term. The fit is excellent with very small (3 ppm) and random deviation (right-hand side scale) proving the absence of the magnetic term in the AF state.

Fe–Cr multilayers are about six times larger than those for bulk crystalline Fe. They are approximately in the same ratio as their room-temperature resistivity [ρ(Fe)$\sim$10 $\mu\Omega$ cm and ρ(Fe–Cr)$\sim$60 $\mu\Omega$ cm]. It is instructive to see if the aforementioned data could be fitted to an equation involving only the residual resistivity and the lattice term, i.e., to Eq. (1) but without the magnetic T^2 term. Figure 2 shows, for both of the samples, fits with (solid lines) and without (dashed line) the magnetic term for comparison. Needless to say that the former fit is far better. Not only is the value of χ^2 higher by a factor of 50 to 100 for the fits without the magnetic term, the deviation of the best-fitted curve from the experimental one is large and systematic whereas it is much smaller and more importantly more random for the fit with the magnetic term. This is evident from Fig. 3 for sample 2BR. The average deviation for the fit with the magnetic term is only 0.0003% (almost equal to the experimental resolution). Moreover, it is random (crossing the x axis several times) whereas the deviation is systematic for the other fit. Thus, we get a convincing evidence for the magnetic T^2 term in these Fe–Cr multilayers in the ferromagnetic state ($H=H_{sat}$).

In the antiferromagnetic state ($H=0$), on the other hand, there should be hardly any magnetic contribution. The $\rho(T)$ data at $H=0$ for both the samples were fitted to Eq. (1) but without the magnetic term. Excellent fits were obtained, i.e., the lattice term was found to be adequate in explaining the temperature dependence of $\rho(T)$. χ^2 was $\sim 10^{-11}$, correlation coefficients of $\cong 1$ and the deviations were random. Figure 4 shows the data points, the fit (solid line) as well as the deviations without the magnetic term for sample 2BR for the AF ($H=0$) state. This is to be contrasted with the poor fits shown in Fig. 3 for the FM state ($H=H_{sat}$) when the magnetic term was not included. Thus, the necessity of the magnetic T^2 term *for only the FM state* is established from our low-temperature $\rho(T)$ measurements.

We also separate each term contributing to $\rho(T)$, viz., $\rho(0)$, ρ_ℓ and ρ_m for five different runs shown in Fig. 1. It is found that ρ_ℓ and ρ_m are indeed very small compared to $\rho(0)$. Moreover, $\rho_m > \rho_\ell$ even at 15 K for all the runs, i.e., the temperature dependent part of $\rho(T)$ is still dominated by the magnetic scattering. Also ρ_ℓ approaches ρ_m with the increase of temperature. The high resolution of our measurements allows us to separate the various contributions to $\rho(T)$ and draw the aforementioned conclusions.

To conclude, the temperature dependence of the electrical resistivity in ion-beam sputtered Fe–Cr multilayers showing GMR is interpreted till 15 K both in the ferromagnetic and the antiferromagnetic states. In the former, the electron–magnon s–s (intraband) scattering is found to be proportional to T^2 whereas in the latter state the electron–phonon s–d scattering alone describes $\rho(T)$ very well.

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