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THEORY OF THE NEGATIVE MAGNETORESISTANCE
IN MAGNETIC METALLIC MULTILAYERS*

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ABSTRACT

The Boltzmann equation is solved for a system consisting of alternating ferromagnetic - normal metallic layers. The in-plane conductance of the film is calculated for two configurations: successive ferromagnetic layers aligned (i) parallel and (ii) antiparallel to each other. The results explain the giant negative magnetoresistance encountered in these systems when an initial antiparallel arrangement is changed into a parallel configuration by application of an external magnetic field. The calculation depends on (A) geometric parameters (the thicknesses of the layers); (B) intrinsic metal parameters (number of conduction electrons, magnetization and effective masses in the layers); (C) bulk sample properties (conductivity relaxation times); and (D) interface scattering properties (diffuse scattering versus potential scattering at the interfaces). It is found that a large negative magnetoresistance requires, in general, considerable asymmetry in the interface scattering for the two spin orientations. All qualitative features of the experiments are reproduced. Quantitative agreement can be achieved with sensible values of the parameters. The effect can be conceptually explained based on considerations of phase-space availability for an electron of a given spin orientation as it travels through the multilayer sample in the various configurations and traverses the interfaces.

1. INTRODUCTION

Ferromagnetic-normal metallic superlattices and sandwiches [1,2] display a number of interesting properties, such as a varying interlayer magnetic coupling [3] and a negative, sometimes very large magnetoresistance (MR) effect [4-15]. Examples are (NiFe/Cu/NiFe), (NiFe/Ag/NiFe), (Fe/Cr)_n, (Co/Cu)_n, (Fe/Cu)_n, and (Co/Ru)_n, to name just a few. It has been found that the magnetic moment of each ferromagnetic layer is arranged with respect to that of the neighboring ferromagnetic layers either in a parallel fashion, or in an antiparallel one, depending on the thickness of the metal spacers and on the quality of the interfaces.

When the conditions are such that the consecutive moments are arranged antiparallel to each other, the application of an external magnetic field to the sample results in two effects: (1) the moments rearrange themselves into a completely parallel arrangement in fields of the order of 1 T; and (2) the sample decreases its resistance -- negative MR -- in all directions (in-plane in particular) by varying amounts which can be as small as a few percent, and as large as 55% (for Co/Cu at liquid Helium temperatures) [13]. A decrease by more than 20% is generally known as the *giant magnetoresistance effect* (GMR).

Even though the current knowledge of the MR effect is incomplete, one fact that has emerged is that spin-dependent interfacial scattering plays an important role. Experiments by Fullerton *et al.* [16] indicate that increased interfacial roughness enhances the GMR. Baumgart *et al.* [17] have found that ultrathin layers of elements (V, Mn, Ge, Ir, or Al) deposited at the Fe/Cr interface lead to changes in the MR which correlate with the ratio of spin-up and spin-down resistivities arising from spin-dependent impurity scattering of these elements when alloyed with Fe. This result is in agreement with the suggestion of Baibich *et al.* [4] that the spin-dependence of impurity scattering at the interfaces is related to that observed [18] in alloyed ferromagnetic metals such as Fe, Co, and Ni.

Further confirmation of the importance of the interface in the MR effect was provided by Barthélémy *et al.* [19] who point out that the experimental data they obtained for epitaxially

grown Fe(001)/Cr(001) multilayers seem to be in agreement with a variation of the MR of the form

$$\exp(-t_{Cr}/\lambda^*)$$

where t_{Cr} is the thickness of Cr layer and λ^* is a length of the order of the mean free path. Such a variation of the MR with layer thickness is expected from spin-dependent interface scattering.

It should be emphasized that it is important to distinguish between the concepts of spin-flip scattering and spin-dependent scattering. The first refers to an event in which, during scattering, an electron reverses its spin orientation; such a phenomenon is normally caused by spin-orbit effects and/or by scattering from impurities with a localized magnetic moment. Spin-flip scattering is neglected in this contribution. The second one refers to the fact that electrons with different spin orientations experience different potentials and have different phase-space distributions. Consequently they have very different scattering cross sections both in the bulk and at the interfaces. The latter is extremely relevant for the purposes of this study.

It is the aim of this contribution to present a model that incorporates spin-dependent interfacial scattering in a more realistic way. While the model presented here is similar in many respects to that of Camley and Barnaś [20,21] it does not suffer from the shortcomings in the description of interfacial scattering encountered there. Utilization of a more accurate description of the interface permits a study and separation of the various scattering mechanisms and their relevance in the MR effect.

The present model, an extension of the Fuchs-Sondheimer theory [22,23], uses a Stoner description [24] of the itinerant ferromagnetic layers: it introduces different potentials for majority and minority spins. Band-structure and electron-density effects are included only by means of a constant, metal- and spin-dependent potential, and an isotropic effective mass for each spin in each layer. The different potentials in neighboring layers results in coherent potential scattering (i.e., refraction) of electrons as they traverse the interface. It has been suggested [17] that this effect alone could account for the observed spin-dependent transport properties and the oscillatory effects with layer thickness [3]. Spin-dependent potentials are also responsible for different densities of states at the Fermi level, i.e., different available phase space for the two different spin orientations. The angular-dependent effects are treated by a quantum-mechanical matching of the electron wave functions at the interfaces. Impurity scattering at the interface and interfacial roughness are also a source of spin-dependent scattering, and they contribute to the present model through a spin-dependent function, in a way similar to that used by Camley and Barnaś.

The model predicts the dependence of the MR on the thickness of the layers, on the quality of the samples (mean free path) and on the quality (roughness) of the interfaces.

2. THE MODEL

The in-plane conductivity has been calculated for a multilayer structure consisting of alternating layers of a ferromagnet (F) of thickness d_F , and a spacer layer of thickness d_s . The coordinate system is chosen with the z axis perpendicular to the layers, and with complete isotropy in the (x,y) plane.

For a given structure the conductivity was calculated for both antiparallel alignment, denoted $\sigma_{\uparrow\downarrow}$, and for parallel alignment, denoted $\sigma_{\uparrow\uparrow}$, of the moments of successive F layers. In the antiparallel arrangement the structure repeats itself after four layers (.../ F \uparrow / s / F \downarrow / s / ...); in the parallel arrangement the period consists of two layers (.../ F \uparrow / s / ...). Application of a sufficiently large magnetic field to a sample in the antiparallel arrangement causes the magnetic moments to align parallel to one another. The magnetoresistance ($\Delta\rho / \rho$), is defined by

$$\frac{\Delta\rho}{\rho} \equiv \frac{\rho_{\uparrow\downarrow} - \rho_{\uparrow\uparrow}}{\rho_{\uparrow\downarrow}} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow}} \quad (1)$$

where $\rho_{\mu\nu} = (\sigma_{\mu\nu})^{-1}$. Note that this quantity varies between zero and one (or 0 and 100%)

whenever the resistance decreases upon the application of an external magnetic field.

The conductivity for both alignments is obtained by adding the contributions of the spin-up and the spin-down electrons, calculated separately. This is the two-current model [18], which provides a good description of electron transport in magnetic 3d metals. As mentioned above spin-flip processes, which mix the two currents, are neglected. It is known that their effect is small at low temperatures.

The electrons involved in transport are regarded as free electron-like with spherical Fermi surfaces. Within each layer the electrons move in a constant potential $V_{i\sigma}$ which depends on the particular layer i and the spin σ of the electron.

The electron distribution function within each layer i and for each spin σ is written in the form

$$f_{i\sigma}(v,z) = f_{i\sigma}^0(v) + g_{i\sigma}(v,z) \quad (2)$$

which is independent of x and y by symmetry. In (2), the first term $f_{i\sigma}^0(v)$ is the equilibrium distribution in the absence of an electric field and $g_{i\sigma}(v,z)$ is the deviation from that equilibrium in the presence of the electric field. For an electric field of magnitude E in the \hat{x} direction, the Boltzmann equation in the relaxation time approximation reduces to

$$\frac{\partial g_{i\sigma}}{\partial z} + \frac{g_{i\sigma}}{\tau_{i\sigma} v_z} = \frac{|e|E}{m_{i\sigma} v_z} \frac{\partial f_{i\sigma}^0}{\partial v_x} \quad (3)$$

where $\tau_{i\sigma}$ is the relaxation time in layer i for spin σ , and e is the charge of the electron. The second-order term, proportional to the product $(E \cdot g_{i\sigma})$, has been discarded since non-linear effects (deviations from Ohm's law) are neglected. The Lorentz-force term, proportional to $(\mathbf{v} \times \mathbf{H}/c)$, has also been dropped from the Boltzmann equation since it gives an effect which is orders of magnitude smaller than those considered here [20].

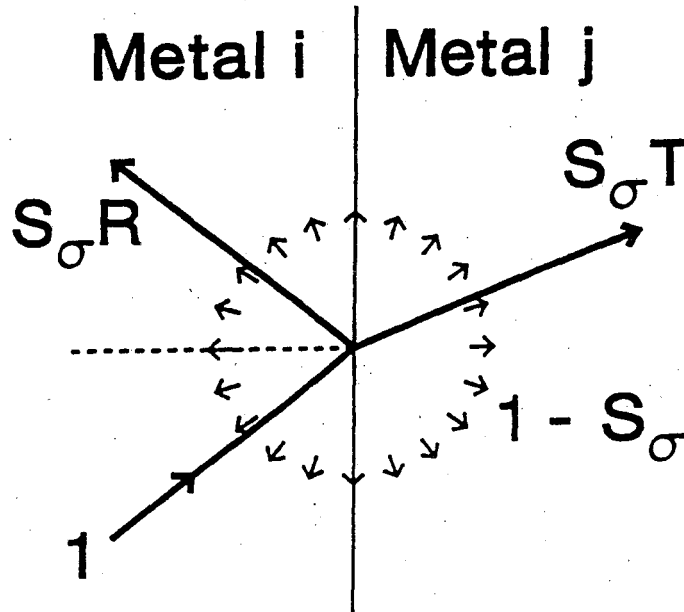


Figure 1. Schematic diagram of the scattering process at the metal-metal interface. The parameter S_σ defines the fraction controlled by the potentials; $S_\sigma R$ is the probability of specular scattering; $S_\sigma T$ is the probability of transmission (refraction) into the other metal.

Because of the boundary conditions it is useful to divide $g_{i\sigma}$ into two parts: $g_{i\sigma}^+(v,z)$ if $v_z \geq 0$ and $g_{i\sigma}^-(v,z)$ if $v_z < 0$. The boundary conditions for the potential (non-diffusive)

scattering at the (i, j) interface then take the form

$$\begin{aligned} g_{i\sigma}^- &= S_{ij;i;\sigma} R_{ij;\sigma} g_{i\sigma}^+ + S_{ji;i;\sigma} T_{ji;\sigma} g_{j\sigma}^- \\ g_{j\sigma}^+ &= S_{ji;j;\sigma} R_{ji;\sigma} g_{j\sigma}^- + S_{ij;j;\sigma} T_{ij;\sigma} g_{i\sigma}^+ \end{aligned} \quad (4)$$

Here $S_{ij;k;\sigma}$, which varies between zero and one, is a factor that indicates the degree of potential scattering at the interface (i, j) for an electron of spin σ arriving at the interface from the layer i and being scattered into the layer k . The scattering follows the reflection-refraction laws when all $S = 1$ and is completely diffusive when $S = 0$. The notation used for the transmission T and the reflection R coefficients is the following: $T_{ij;\sigma} \equiv$ probability for an electron of spin σ in layer i to be transmitted (refracted) into layer j ; $R_{ij;\sigma} \equiv$ probability for an electron of spin σ in layer i with a velocity directed towards layer j to be reflected back into layer i . The equations and boundary conditions, as written, satisfy all necessary conservation laws.

The functional dependence of the coefficients was determined [25] by matching the free electron-like (plane-wave) functions and their derivatives at each interface. The solution to this problem, which is identical to that encountered in optics for an interface between two media with different index of refraction, is shown schematically in figure 1.

The current density along the electric field in each layer i for electrons with spin σ is given by

$$J_{xi\sigma}(z) = -|e| \left[\frac{m_{i\sigma}}{h} \right]^3 \int v_x g_{i\sigma}(v, z) d^3v \quad (5)$$

where h is Planck's constant. The conductivity of the multilayer is obtained by averaging over the whole film

$$\sigma = \frac{1}{E d_{film}} \sum_i \sum_{\sigma=\uparrow, \downarrow} \int J_{xi\sigma}(z) dz$$

The MR, $(\Delta\rho / \rho)$, is found by calculating independently the conductivities σ_{\uparrow} and σ_{\downarrow} . The number of parameters necessary to characterize a structure is large. Associated with the electrons in the F layers are the minority (denoted using a small subscript m) and the majority (denoted using a capital subscript M) spins with effective masses m_m and m_M , relaxation times τ_m and τ_M , and potentials V_m and V_M . The spin-up and spin-down electrons in the spacer layer s move in a potential V_s with an effective mass m_s and relaxation time τ_s . At the interfaces, the functions $S_{ij;k;\sigma}$, which vary with angle of incidence, describe the interfacial scattering of the majority and the minority spins.

The values of the potentials are determined by treating all of the valence s and d electrons as being in a single free electron-like band with an isotropic effective mass. The effective mass is, in general, taken to be larger than the electron mass, since the d electrons, which contribute to the density of electrons, are in narrower bands than the free-electron-like s electrons. Within the F layers the bands for the minority and the majority spins are shifted by a k -independent exchange potential, yielding two different spin-dependent, constant potentials, V_m and V_M . The value of the exchange splitting is chosen so that the difference in the density of the majority and the minority electrons yields the net magnetic moment of the bulk ferromagnetic material.

3. RESULTS

The theory, as developed thus far, includes eleven parameters and eight angular functions:

- three effective masses m_M , m_m , and m_s ;
- three constant potentials V_M , V_m , and V_s ;
- three relaxation times τ_M , τ_m , and τ_s ;
- two thicknesses d_F , and d_s ;
- and eight interface scattering functions

$$S_{F,s:F,M}, S_{F,s:F,m}, S_{F,s;s,M}, S_{F,s;s,m}, S_{s,F;s,M}, S_{s,F;s,m}, S_{s,F:F,M}, \text{ and } S_{s,F:F,m}.$$

The results presented here include only the cases for which the *relaxation times* are identical $\tau \equiv \tau_m = \tau_M = \tau_s$. (The *mean free paths* of the minority and the majority spins within the F layers and for the spacer metal are still different, however, since the Fermi velocities are different.) The interfaces are treated in two different ways. In the first approach the angular dependence of the functions $S_{ij;k;\sigma}$ is neglected and the eight functions are replaced by two constants

$$\begin{aligned} S_{F,s;F;M} = S_{F,s;s;M} = S_{s,F;s;M} = S_{s,F;F;M} = S_M, \\ S_{F,s;F;m} = S_{F,s;s;m} = S_{s,F;s;m} = S_{s,F;F;m} = S_m, \end{aligned}$$

Now the system is defined by eleven constants.

In the second approach the different angular dependences in various $S_{ij;k;\sigma}$ are explicitly included.

Results are given for two different multilayer systems, $(\text{Fe/Cr})_n$ and $(\text{Fe/Cu})_n$. In these three metals the isotropic effective mass is assumed to be independent of the material and spin orientation with a value $m_M = m_m = m_s = 4.0 \times$ free-electron mass. With this effective mass the potentials, with respect to the Fermi energy E_F chosen to be at $E_F = 0$, are $V_M = -8.23 \text{ eV}$, $V_m = -5.73 \text{ eV}$ for Fe; $V_s = -5.77 \text{ eV}$ for Cr; $V_s = -8.54 \text{ eV}$ for Cu.

The parameters that remain to be specified for each case -- $(\text{Fe/Cr})_n$ and $(\text{Fe/Cu})_n$ -- in the constant- S approximation are altogether five: (A) two geometric parameters d_F and d_s ; (B) one relaxation time τ , which depends on bulk sample properties; and (C) two interface scattering parameters S_M , S_m (diffuse scattering versus potential scattering at the interfaces for the majority and the minority spins respectively).

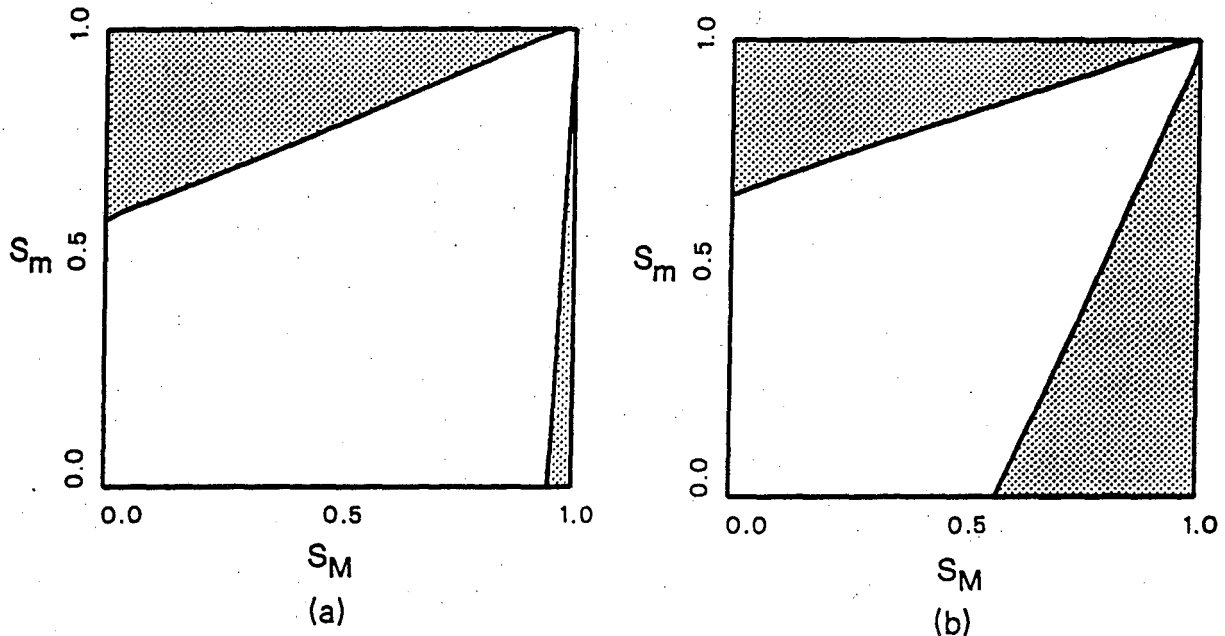


Figure 2. The region in the two-dimensional parameter space (S_M, S_m) where $(\Delta\rho / \rho) > 0.2$ for $d_F = 20 \text{ \AA}$, $d_s = 10 \text{ \AA}$, and $\tau = 5.0 \times 10^{-13} \text{ s}$. (a) Potential parameters corresponding to $(\text{Fe/Cr})_n$. (b) Potential parameters corresponding to $(\text{Fe/Cu})_n$.

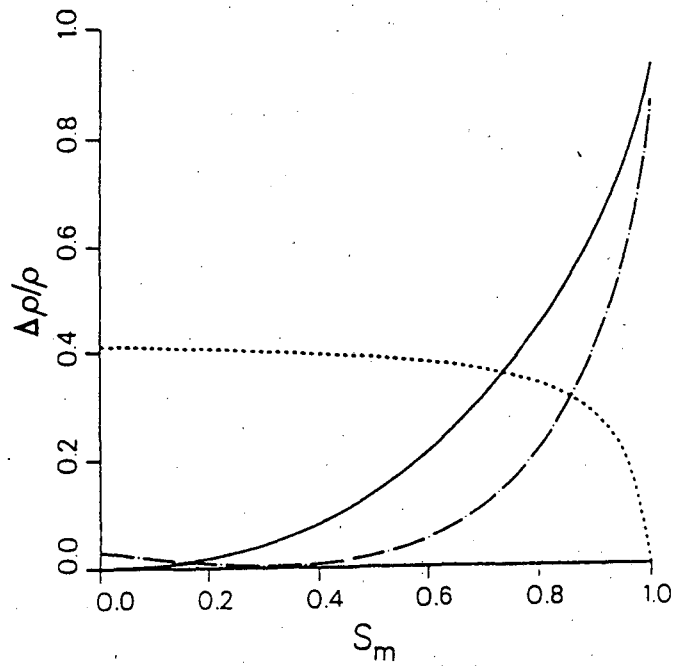


Figure 3. Variation of $(\Delta\rho/\rho)$ as a function of S_m for the parameters of $(\text{Fe/Cr})_n$, $\tau = 5.0 \times 10^{-13} \text{ s}$, $d_F = d_s = 10 \text{ \AA}$ and three values of S_M : (1) dashed curve $S_M = 1$; (2) chain dotted curve $S_M = 0.5$; and (3) solid curve $S_M = 0$.

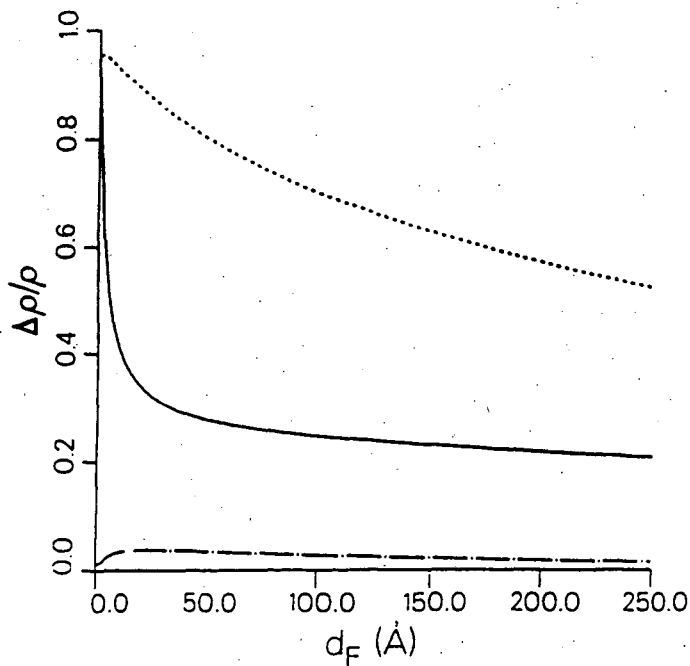


Figure 4. Variation of $(\Delta\rho/\rho)$ as a function of d_F for the parameters of $(\text{Fe/Cr})_n$, $d_s = 10 \text{ \AA}$, $\tau = 5.0 \times 10^{-13} \text{ s}$ and three different values of S_M and S_m : (1) chain dotted curve $S_M = S_m = 0.8$; (2) dashed curve $S_M = 0$, $S_m = 1$; and (3) solid curve $S_M = 1$, $S_m = 0$.

Even with these simplifications, the phenomena under consideration are complicated functions of the 5 variables, and the task of describing these dependencies is not simple. In general terms, and with exceptions, it is found that $(\Delta\rho / \rho)$ is a strong function of the interface parameters S_M and S_m , and a relatively weak function of the thicknesses and the mean free path. For example, as S_M and S_m independently vary between 0 and 1, the calculated $(\Delta\rho / \rho)$ varies between 0 and 92.7% for $(\text{Fe/Cr})_n$ and 0 and 94.4% for $(\text{Fe/Cu})_n$, when values of $d_F = 20.0 \text{ \AA}$; $d_s = 10.0 \text{ \AA}$ and $\tau = 5.0 \times 10^{-13} \text{ s}$ are chosen. Figure 2 shows the regions in the two-dimensional $(S_M - S_m)$ parameter space where $(\Delta\rho / \rho)$ is greater than 20% for these values of d_F , d_s , and τ . With this choice of τ , the mean free paths are: (i) 4,250 \AA for the majority-spin and 3,540 \AA for the minority-spin electrons in Fe; (ii) 3,560 \AA for electrons in Cr; and (iii) 4,330 \AA for electrons in Cu. These values correspond to all mean free paths which are orders of magnitude larger than the film thicknesses, i.e., the clean-film limit, where interface effects are supposed to be paramount.

Some of the interesting results of the calculations are illustrated in figures 2-6. It was found in general that:

(A) $(\Delta\rho / \rho)$ is in general small (only a few percent) when $S_M = S_m$, except [26] when both parameters are very close to 1 (see figures 2 and 3).

(B) $(\Delta\rho / \rho)$, as a function of d_F , exhibits a variety of behaviors which include (i) a monotonic decrease with increasing d_F ; and (ii) an initial increase followed by a decrease (a single maximum); in all cases the asymptotic value as $d_F \rightarrow \infty$ is zero (see figure 4).

(C) $(\Delta\rho / \rho)$, as a function of increasing d_s , exhibits either (i) a continuous monotonic decrease, or, most commonly, (ii) a single maximum at a value of d_s of the order of d_F ; the asymptotic value as $d_s \rightarrow \infty$ is also zero (see figure 5).

(D) $(\Delta\rho / \rho)$, as a function of the relaxation time τ , either (i) increases monotonically and saturates at a maximum value, or, most commonly, (ii) increases to a maximum, and then *very gradually* decreases (see figure 6).

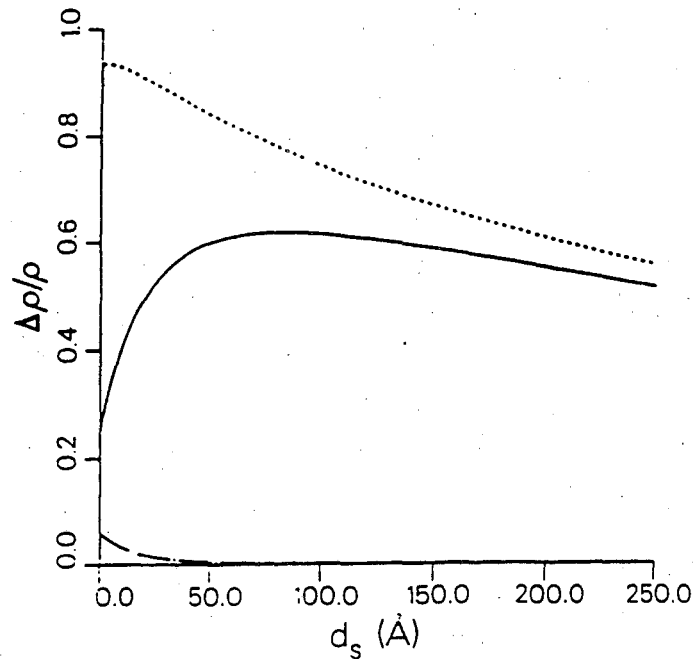


Figure 5. Variation of $(\Delta\rho / \rho)$ as a function of d_s for the parameters of $(\text{Fe/Cr})_n$, $d_F = 20 \text{ \AA}$, $\tau = 5.0 \times 10^{-13} \text{ s}$ and different values of S_M and S_m : (1) solid curve $S_M = 1$, $S_m = 0$; (2) dashed curve $S_M = 0$, $S_m = 1$; and (3) chain-dotted curve $S_M = S_m = 0.9$.

Figure 2 contains information on how, for specific values of d_F , d_s , and τ , the quality of the interfaces influences the MR. It is evident from the figure that the region of large MR is close either to the line $S_M = 1$, or to the line $S_m = 1$, and away from the line $S_M = S_m$. There is a very large asymmetry between S_M and S_m in $(\text{Fe/Cr})_n$, but considerably less so in $(\text{Fe/Cu})_n$.

A more realistic approach to the diffuse-versus-potential scattering at the interface requires a full angular dependence of the eight functions $S_{ij;k;\sigma}$. In general [27-30] the diffuse scattering is considerably larger for electrons impinging upon the interface in directions close to the normal. Grazing-angle electrons are less effectively scattered, and they tend to be almost completely internally reflected. A common (first-order) approximation to these functions [27-30] is

$$S_{ij;i;\sigma} = S_\sigma \exp \left[4\eta^2 (k_{i\sigma} \cos\Theta_i)^2 \right] ; \quad (6)$$

$$S_{ij;j;\sigma} = S_\sigma \exp \left[\eta^2 (k_{i\sigma} \cos\Theta_i - k_{j\sigma} \cos\Theta_j) \right] \quad (7)$$

Here η is a parameter which depends on the roughness of the interface as well as the strength and physical distribution of the scattering centers at the interface, $k_{i\sigma}$ is the magnitude of the k-vector at the Fermi sphere of the spin- σ electrons in layer i , and Θ_i is the angle between the electron velocity and the normal to the interface; S_σ is the overall diffuse scattering strength at grazing angle $\Theta = \pi/2$. It should be noted that the limit $\eta = 0$ reduces the approximation to the one previously discussed.

Figure 7 shows the influence of this angular dependence on the MR. As η increases, the MR in general decreases, except for the case in which S_M and S_m are very close in value; in the latter, the difference in k-vector between the two spins, and the non-vanishing η produce an asymmetry in the diffuse interface scattering between the spins, and thus increases the MR.

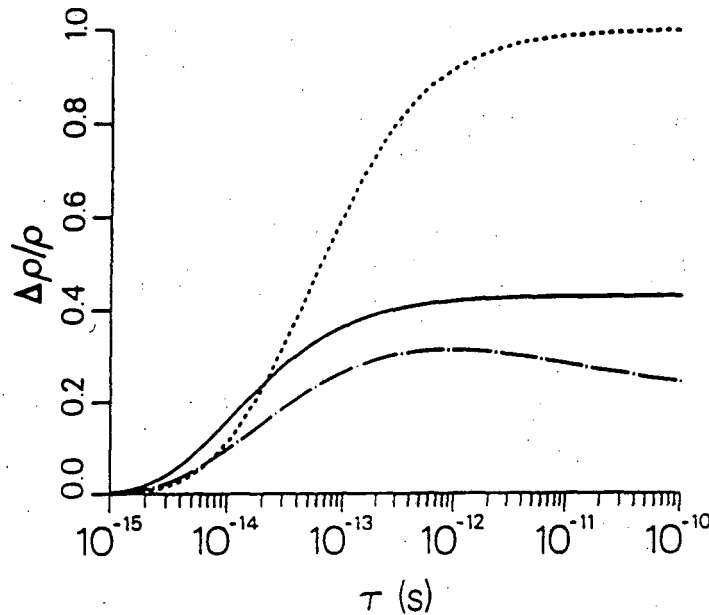


Figure 6. Variation of $(\Delta\rho / \rho)$ as a function of τ for the parameters of $(\text{Fe/Cr})_n$, $d_s = 10\text{\AA}$, $d_F = 20\text{\AA}$, and three different values of S_M and S_m : (1) chain dotted curve $S_M = 0$ and $S_m = 0.7$; (2) dashed curve $S_M = 0.5$ and $S_m = 1$; and (3) solid curve $S_M = 1$ and $S_m = 0$.

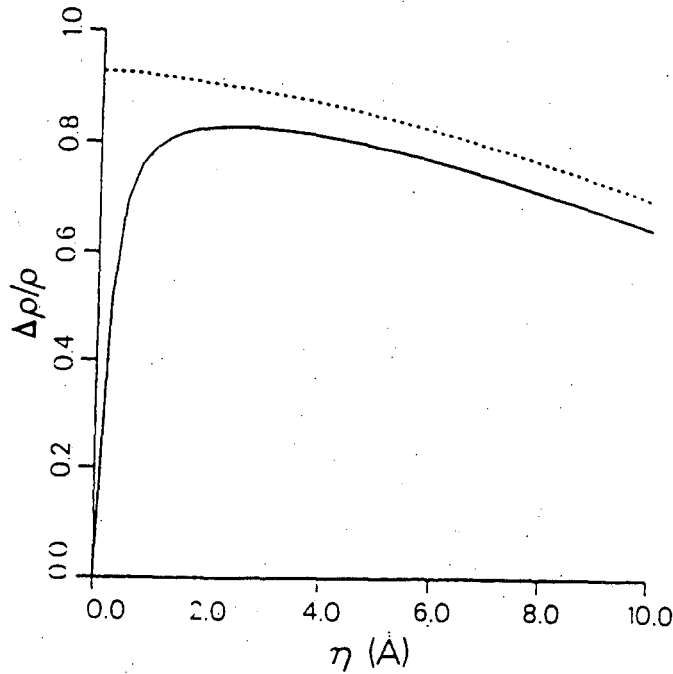


Figure 7. Variation of $(\Delta\rho / \rho)$ as a function of η for the parameters of $(\text{Fe/Cr})_n$, $d_r = 10 \text{ \AA}$, $d_F = 20 \text{ \AA}$ and two different values of S_σ in equations (6) and (7): (1) solid curve $S_M = S_m = 1$; and (2) dashed curve $S_M = 0$, $S_m = 1$.

4. DISCUSSION AND CONCLUSIONS

Figure 2(a) shows a marked asymmetry in the dependence of $(\Delta\rho / \rho)$ for $(\text{Fe/Cr})_n$ on S_M and S_m , i.e., the majority- and minority-spin interface scattering have a very different effect on the MR. For this system

$$|V_M| < |V_s| \approx |V_m|$$

By contrast, a large asymmetry is not present in $(\text{Fe/Cu})_n$, figure 2(b). Here

$$|V_s| \approx |V_M| < |V_m|$$

The difference in V_s has a large effect on the MR, as can be seen in plots of the in-plane current distribution across the layers [25]. In many cases when $(\Delta\rho / \rho)$ is very large, the current distribution responsible for the large value of $\sigma_{\uparrow\uparrow}$ is such that it is highly concentrated in one type of layer, either in the ferromagnet or in the spacer. This effect, which can be called *channeling*, appears frequently when there is a GMR. When the channeling is in the spacer layer it occurs *only when there is parallel alignment*. Channeling in the FM layers, on the other hand, occurs (in one type of F layer for each electron spin orientation) for both the parallel and the antiparallel configurations. From these considerations it is obvious that channeling in the spacer layer should be more intimately connected with a GMR. It should be emphasized that channeling is present when the potentials are different; GMR requires, in addition, asymmetric values of S_σ . Channeling and GMR are strongly correlated [31].

The experimentally observed values of MR in $(\text{Fe/Cr})_n$ and $(\text{Fe/Cu})_n$ multilayers can be matched by the calculation with a proper choice of the parameters. However, the model in its present form, which considers all of the valence s and d electrons as comprising a single band with a single isotropic effective mass, yields effective resistivities $\rho_{\uparrow\uparrow}$ and $\rho_{\uparrow\downarrow}$ which are about an order of magnitude smaller than those measured in multilayer structures. The effective resistivities are too small because the model has too many free-electron-like conduction electrons: eight in Fe, six in Cr, and eleven in Cu. Proper consideration must be taken of the fact that, in

these metals, *s* and *d* electrons contribute very differently to the transport properties. The narrow character of the *d*-bands has been accounted for in the single-band approach by a single, large, isotropic effective mass, four times larger than the free-electron mass. A better approach to the problem would be to include a realistic band structure with its 12 bands, wide and narrow, as well as the hybridization and spin polarization. Such a treatment would make the calculations much more involved.

Within the confines of a single-band model a simple, natural way to decrease the number of conduction electrons is by reducing the density of the electrons in each layer by a constant scaling factor, γ , independent of the material and the spin of the electron. It should be stressed that the introduction of such a scaling factor does not change the form of the results found above. The number of electrons and the magnetization decreases by a factor of γ . The resistivities $\rho_{\uparrow\uparrow}$ and $\rho_{\uparrow\downarrow}$ increase by a factor of about γ , and $(\Delta\rho / \rho)$ decreases by a factor of about γ^{-1} . A value of $\gamma = 8$ was chosen for making comparisons with experimental data. With this value the number of effective free-electron-like conduction electrons are: 1.00 in Fe, 0.75 in Cr, and 1.38 in Cu. Calculations were able to yield values of the MR and the resistivities, $\rho_{\uparrow\uparrow}$ and $\rho_{\uparrow\downarrow}$, similar to those measured experimentally.

Baibich *et al.* [4] found that a multilayer of $(\text{Fe } 30 \text{ \AA} / \text{Cr } 9 \text{ \AA})_{60}$, prepared by molecular beam epitaxy, had $(\Delta\rho / \rho) = 0.46$ and a absolute resistivity change of about $23 \mu\Omega \text{ cm}$. With $S_M = 0.23$, $S_m = 0.98$, $d_F = 30 \text{ \AA}$, $d_s = 9 \text{ \AA}$ and $\tau = 1 \times 10^{-13} \text{ s}$ values of $\rho_{\uparrow\uparrow} = 30.6 \mu\Omega \text{ cm}$ and $\rho_{\uparrow\downarrow} = 56.6 \mu\Omega \text{ cm}$ were calculated, which corresponds to $(\Delta\rho / \rho) = 0.46$ for the MR. Experimental values of ρ are between 20 and $80 \mu\Omega \text{ cm}$. With this choice of γ , τ , and effective mass (i.e., an effective mass of four times the electron mass), the bulk mean free paths are: 425 \AA for the majority-spin and 354 \AA for the minority-spin electrons in Fe; and 356 \AA for the electrons in Cr.

Pétroff *et al.* [14] report that a multilayer $(\text{Fe } 15 \text{ \AA} / \text{Cu } 15 \text{ \AA})_{60}$ made by sputtering, had the following characteristics: $\rho_{\uparrow\uparrow} = 24.8 \mu\Omega \text{ cm}$, $\rho_{\uparrow\downarrow} = 27.8 \mu\Omega \text{ cm}$, and $(\Delta\rho / \rho) = 0.108$. With $S_m = 0.71$, $S_M = 0.92$, $d_F = d_s = 15 \text{ \AA}$ and $\tau = 1 \times 10^{-13} \text{ s}$ values of $\rho_{\uparrow\uparrow} = 25.2 \mu\Omega \text{ cm}$ and $\rho_{\uparrow\downarrow} = 28.3 \mu\Omega \text{ cm}$ were calculated, which correspond to $(\Delta\rho / \rho) = 0.11$. Here the bulk mean free paths are: 425 \AA for the majority-spin and 354 \AA for the minority-spin electrons in Fe; and 433 \AA for the electrons in Cu.

As clearly seen above, a large MR requires, in general, a large difference in interface scattering for the different spins. When $S_M = S_m$ the MR is found to be not more than a few percent. Therefore a large MR cannot be explained as being caused solely by different densities of electrons with different spins, which vary from layer to layer. What is required is a spin imbalance *and* a spin-dependent scattering mechanism at the interface, i.e., $S_M \neq S_m$. When such a spin-dependent scattering mechanism exists, for example when magnetic impurities are present at the interfaces, the MR is profoundly influenced by spatial variations in the density of electron spins. This is the main cause of the GMR effect in ferromagnetic multilayers.

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