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# THEORY OF TUNNELING MAGNETORESISTANCE

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Rigorous theory of the tunneling magnetoresistance (TMR) based on the real-space Kubo formula and fully realistic tight-binding bands fitted to an *ab initio* band structure is described. It is first applied to calculate the TMR of two Co electrodes separated by a vacuum gap. The calculated TMR ratio reaches $\approx$65% in the tunneling regime but can be as high as 280% in the metallic regime when the vacuum gap is of the order of the Co interatomic distance (abrupt domain wall). It is also shown that the spin polarization $P$ of the tunneling current is negative in the metallic regime but becomes positive $P \approx 35\%$ in the tunneling regime. Calculation of the tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction is also described. The calculated optimistic TMR ratio is in excess of 1000% for an MgO barrier of $\approx$20 atomic planes and the spin polarization of the tunneling current is positive for all MgO thicknesses. It is also found that spin-dependent tunneling in an Fe/MgO/Fe(001) junction is not entirely determined by states at the $\Gamma$ point ($\boldsymbol{k}_{\parallel}$=0) even for MgO thicknesses as large as $\approx$20 atomic planes. Finally, it is demonstrated that the TMR ratio calculated from the Kubo formula remains nonzero when one of the Co electrodes is covered with a copper layer. It is shown that non-zero TMR is due to quantum well states in the Cu layer which do not participate in transport. Since these only occur in the down-spin channel, their loss from transport creates a spin asymmetry of electrons tunneling from a Cu interlayer, i.e. non-zero TMR. Numerical modeling is used to show that diffuse scattering from a random distribution of impurities in the barrier may cause quantum well states to evolve into propagating states, in which case the spin asymmetry of the nonmagnetic layer is lost and with it the TMR.

*Keywords:* Theory of tunneling magnetoresistance; Real-space Kubo formula; Tight-binding bands

The conductance $\Gamma(H_s)$ of a tunnel junction with two ferromagnetic electrodes whose magnetic moments are aligned parallel in an applied saturating field $H_s$ is much higher than its conductance $\Gamma(0)$ in zero field when the moments are antiparallel (Miyazaki and Tezuka, 1995; Moodera *et al.*, 1995; Li *et al.*, 1998). The effect is called tunneling magnetoresistance (TMR) and the relative change in the resistance of the junction, i.e. the so called 'optimistic' magnetoresistance ratio

$$R_{TMR} = \frac{\Gamma(0)^{-1} - \Gamma(H_s)^{-1}}{\Gamma(H_s)^{-1}} \tag{1}$$

can be as high as 60%. The traditional explanation of the TMR effect is based on the assumption that electrons tunneling from a ferromagnet are spin-polarized and their polarization $P$ is given in terms of the spin-dependent density of states $D^{\sigma}$ of

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the ferromagnet by $P = [D^{\uparrow}(E_F) - D^{\downarrow}(E_F)]/[D^{\uparrow}(E_F) + D^{\downarrow}(E_F)]$. Since the classical theory of tunneling (Merservey and Tedrow, 1994) states that the junction conductance is proportional to the product of the densities of states of the left and right electrodes, it is easy to show that the TMR ratio (1) can be written in terms of the spin polarizations $P_L$, $P_R$ of the left and right electrodes

$$R_{TMR} = \frac{2P_L P_R}{1 - P_L P_R}. \tag{2}$$

This is the well-known Julliere's formula (Julliere, 1975). Although the Julliere's formula is quite successful in predicting the TMR ratios from the observed values (Merservey and Tedrow, 1994) of the spin polarization of electrons tunneling from Fe, Ni and Co into a superconductor, it suffers from several fundamental defects. First of all, it has been known for long time that the polarization of the tunneling current predicted from the total density of states (DOS) of the ferromagnetic electrodes has the wrong sign. One would expect from the DOS that the tunneling current from Fe, Co, and Ni should be dominated by down-spin (minority) electrons since their density of states at $E_F$ is high. In fact, the observed $P$ has just the opposite sign.

The second problem is that the properties of the insulating barrier are not included in the Julliere's formula, i.e., the polarization of the tunneling current is assumed to be just the property of the ferromagnetic electrodes.

The third problem that has come to light only recently is that the Julliere's formula when applied to a tunneling junction with a thin nonmagnetic metallic interlayer, such as Cu, inserted between one of the ferromagnetic electrodes and the insulating barrier fails to explain the observed (Parkin, 2002) nonzero TMR ratio. In fact, since the density of states of the Cu layer adjacent to the barrier is spin independent, $P_{Cu} = 0$ and, therefore, it follows from Eq. (2) that $R_{TMR} = 0$, which contradicts the experiment (Parkin, 2002).

The three problems we have identified call into question the validity of the whole classical theory of tunneling based on the density of states of the ferromagnetic electrodes. We shall examine the reasons for the failure of the DOS approach using the rigorous real-space Kubo formula (Lee and Fisher, 1981; Mathon *et al.*, 1997a). The Kubo formula is exact in the linear response regime (low bias limit).

To obtain clear-cut answers, we consider tunneling between cobalt electrodes across a vacuum gap and coherent tunneling in an epitaxial Fe/MgO/Fe junction. In the case of a junction with a metallic nonmagnetic interlayer, tunneling takes place from a cobalt electrode covered with an overlayer of $N$ atomic planes of copper across a vacuum gap into another cobalt electrode. The geometry of the junctions we consider is shown in Fig. 1. Initially, we assume that the electrodes are perfect so that the electron wave vector

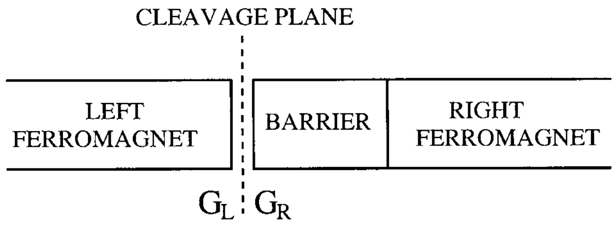


FIGURE 1 Schematic picture of a magnetic tunneling junction.

parallel to the layers $\boldsymbol{k}_{\|}$ is conserved in tunneling. This restriction will be relaxed later. In contrast to the junction with an amorphous $Al_2O_3$ barrier used in most experiments, tunneling across a vacuum gap or in an epitaxial Fe/MgO/Fe junction has the great advantage that the real-space Kubo formula (Lee and Fisher, 1981; Mathon *et al.*, 1997a) can be evaluated without any approximations for a fully realistic band structure of all the components of the junction. The results we obtain are, therefore, exact.

We use a tight-binding parametrization of an *ab initio* band structure of Co and Cu for vacuum tunneling and of Fe and MgO for the epitaxial Fe/MgO/Fe junction (for details, see Mathon *et al.*, 1997a; Mathon and Umerski, 2001). The total conductance of the junction $\Gamma^{\sigma}$ in a spin channel $\sigma$ is expressed (Mathon, 1997) in terms of the one-electron Green's functions $G_L^{\sigma}(E_F, \boldsymbol{k}_{\|})$, $G_R^{\sigma}(E_F, \boldsymbol{k}_{\|})$ at the left and right surfaces of the junction cut by a cleavage plane into two independent parts (Fig. 1)

$$\Gamma^{\sigma} = \frac{4e^2}{h} \sum_{\boldsymbol{k}_{\|}} Tr\,[T_{\sigma}\ \mathrm{Im}\ G_R^{\sigma}(E_F, \boldsymbol{k}_{\|})][T_{\sigma}^{+}\ \mathrm{Im}\ G_L^{\sigma}(E_F, \boldsymbol{k}_{\|})]. \tag{3}$$

The summation in Eq. (3) is over the two-dimensional Brillouin zone and the trace is over the orbital indices corresponding to s, p, d-orbitals. Since we use a multiorbital band structure, $G^{\sigma}$ and $T_{\sigma}$ are matrices whose size depends on the number of orbitals. The matrix $T_{\sigma}$ is given by

$$T_{\sigma} = t(\boldsymbol{k}_{\|})[I - G_R^{\sigma}(E_F, \boldsymbol{k}_{\|})t^{+}(\boldsymbol{k}_{\|})G_L^{\sigma}(E_F, \boldsymbol{k}_{\|})t(\boldsymbol{k}_{\|})]^{-1}, \tag{4}$$

where $I$ is a unit matrix in the orbital space and $t(\boldsymbol{k}_{\|})$ is the matrix of tight-binding hopping integrals connecting atomic orbitals in the right surface of the cut junction to atomic orbitals in the left surface.

The Kubo formula (3) has a simple physical interpretation. First of all, since we operate in the linear-response regime, the current is proportional to the conductance and, therefore, Eq. (3) gives effectively the tunneling current. The quantities $\mathrm{Im}\ G_{L(R)}^{\sigma}(E_F, \boldsymbol{k}_{\|})$ are (up to a factor $1/\pi$) one-dimensional densities of states of the left (right) surfaces of the cut junction in the channel $(\boldsymbol{k}_{\|}, \sigma)$ and the matrix $T_{\sigma}$ can be regarded as an effective tunneling matrix. Since we assume coherent tunneling (perfect electrodes) the current flows in independent $(\boldsymbol{k}_{\|}, \sigma)$ channels which means that all the channels contribute additively to the total current and, hence, the sum over $\boldsymbol{k}_{\|}$ in Eq. (3).

With this interpretation, the Kubo formula (3) resembles superficially the Julliere's formula. However, in contrast to the classical theory of tunneling, the Kubo formula (3) does not assume separation of the tunneling junction into two independent left and right parts. Although the Green's functions $G_L^{\sigma}$ and $G_R^{\sigma}$ are for disconnected left and right surfaces, the mutual interaction of the two surfaces is described exactly through the matrix $T_{\sigma}$ defined by Eq. (4). It will be seen that this interaction is essential for correct treatment of the tunneling junction with a nonmagnetic metallic interlayer (Mathon and Umerski, 1999).

Since the full interaction between the left and right surfaces is contained in Eq. (3), it applies not only to tunneling but also to metallic conduction. In the case of a metallic sample, one has to make sure that the resistance of the electrodes is much lower than the resistance of the sample (which is automatically satisfied for a tunneling junction). This can be achieved experimentally in the 'pillar' geometry shown schematically in

Fig. 2. The 'sample' in Fig. 2 is the narrow region (pillar). It should be noted that calculations made in the slab geometry (Fig. 1) apply directly to the pillar geometry (Fig. 2) provided the constriction is adiabatic, i.e. the cross section of the structure decreases gradually rather than abruptly.

We first apply the Kubo formula (3) to calculate the magnetoresistance (MR) ratio for two cobalt electrodes in direct (metallic) contact (Fig. 2). We then break the contact by introducing a vacuum gap between the left and right electrodes. This allows us to investigate how the MR evolves from the ballistic current-perpendicular-to-plane magnetoresistance (CPP GMR) for a metallic system to tunneling magnetoresistance. In calculating the MR we assume that the magnetization in the left electrode points up and that in the right electrode can point either up or down. The MR in the unbroken (metallic) contact is, therefore, due to a completely abrupt domain wall (the orientation of the magnetization changes by $180^\circ$ from one atomic plane to the next). Following Harrison (Harrison, 1979; Mathon, 1997) we model tunneling across vacuum gap (broken contact) by turning off gradually the hopping matrix $t(\boldsymbol{k}_{\|})$ across the gap. As discussed in Mathon (1997), hopping between s, p, d-orbitals scales differently with the distance between the electrodes (width of the vacuum gap). This has the consequence that tunneling between d-orbitals is rapidly suppressed owing to their weak overlap across the gap. In the case of an MgO barrier discussed later, suppression of d-type tunneling is due to the fact that there are no d-orbitals present in the barrier. Given that only the s–s interaction survives in the tunneling regime, it is appropriate to use it as a measure of the width of the vacuum gap between the Co electrodes. It is, therefore, convenient to introduce a dimensionless reduced s–s hopping parameter $0 \leq t \leq 1$ by $t = t_{ss\sigma}^{\mathrm{gap}}/t_{ss\sigma}^{\mathrm{bulk}}$, where $t_{ss\sigma}^{\mathrm{bulk}}$ is the bulk s–s hopping in Co and $t_{ss\sigma}^{\mathrm{gap}}$ is the hopping across the vacuum gap.

The dependence of the TMR ratio, determined from Eq. (3), on the reciprocal of the reduced hopping parameter $1/t$ is shown in Fig. 3. It can be seen that the TMR ratio drops very rapidly from its metallic value of 280% for the abrupt domain wall ($t = 1$) to about 40% and then remains almost constant in the tunneling regime reaching about 65% for $t = 0.1$. The rapid initial decrease of the MR ratio occurs because, in the metallic limit $t \approx 1$, a significant proportion of the current in Co is carried by d electrons that are highly spin-polarized. This explains a large MR ratio in the metallic regime (abrupt domain wall). In the tunneling regime, the current is carried only by s–p electrons which are weakly spin-polarized and, hence, the TMR ratio is much

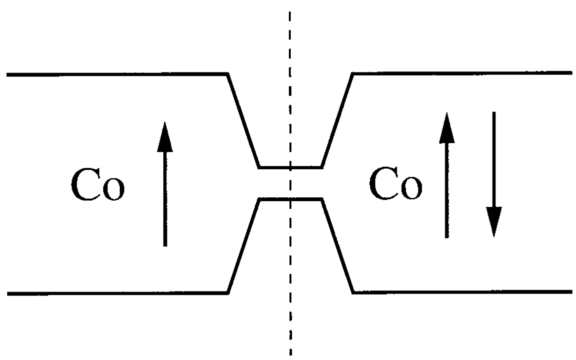


FIGURE 2 Schematic picture of a metallic contact in the pillar geometry. Arrows indicate the orientation of the magnetization.

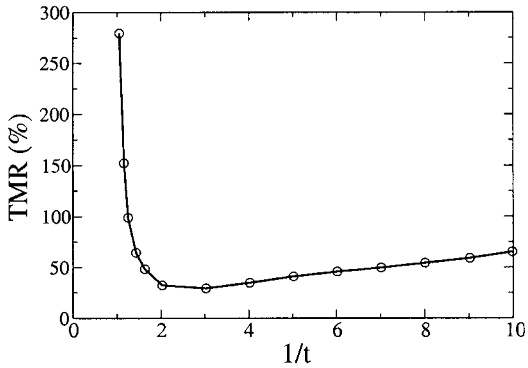


FIGURE 3 Dependence of the tunneling magnetoresistance of a Co(001) junction on the reciprocal of the reduced s–s hopping between the Co electrodes.

smaller. The switching from d-type to s–p type conduction, which occurs as one moves from the metallic to the tunneling regime, has also important implications for the sign of the polarization of the tunneling current which can be easily determined from Eq. (3). It should be noted that the correct definition of the spin polarization is not in terms of the densities of states, as assumed in the Julliere's formula, but in terms of the partial tunneling currents carried by $\uparrow$ and $\downarrow$ spin electrons. In the linear-response regime, $P_{L(R)}$ is, therefore, given by

$$P_{L(R)} = \frac{\Gamma^{\uparrow}_{L(R)} - \Gamma^{\downarrow}_{L(R)}}{\Gamma^{\uparrow}_{L(R)} + \Gamma^{\downarrow}_{L(R)}}, \tag{5}$$

where $\Gamma^{\sigma}_{L(R)}$ gives the current of electrons of spin $\sigma$ tunneling from the left (right) ferromagnet through a barrier (vacuum gap) into a suitable detector of spin-polarized current. In practice, the detector is usually a superconducting aluminum electrode. We stress that the spin polarization of the tunneling current is not just a property of the ferromagnetic electrode (as is assumed in the Julliere's formula) but is instead the joint property of the electrode and the barrier.

The dependence of the spin polarization $P$ of the Co junction on the width of the vacuum gap (reciprocal hopping $1/t$) obtained from Eqs. (3) and (5) is shown in Fig. 4. For a small vacuum gap of the order of the lattice constant ($1/t \approx 1$), the conductance is dominated by d-electrons and $P$ has the 'wrong' sign $P < 0$ consistent with the total DOS argument of the classical theory of tunneling (Merservey and Tedrow, 1994). However, there is a rapid crossover to $P > 0$ as the width of the gap increases. It can be seen from Fig. 4 that the calculated $P$ for Co not only has the correct sign in the tunneling regime $1/t \gg 1$ but its magnitude 30–40% is in excellent agreement with the observed (Merservey and Tedrow, 1994) $P \approx 35\%$. The crossover from negative to positive $P$ occurs because the overlap of d-orbitals decreases with increasing gap much faster than that of s-orbitals and it is, therefore, s electrons that determine the conductance in the tunneling regime.

We now turn to spin-dependent tunneling between two Fe(001) electrodes separated by an MgO barrier (Mathon and Umerski, 2001). It is known experimentally (Kanaji *et al.*, 1976) that thin epitaxial bcc Fe(001) films grow pseudomorphically on rocksalt MgO(001) substrate so that the Fe atoms sit above the O ions. The Fe lattice is,

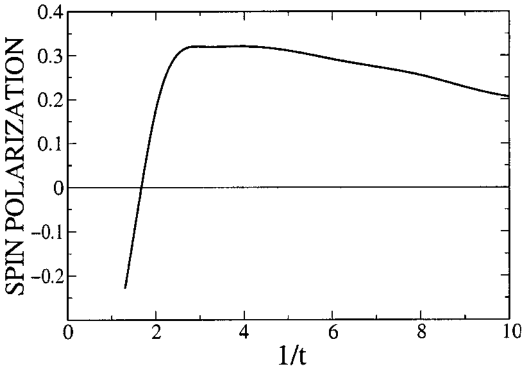


FIGURE 4 Dependence of the spin polarization of electrons tunneling between two cobalt electrodes across a vacuum gap on the reciprocal of the reduced s–s electron hopping between the Co electrodes (width of the gap).

therefore, rotated by 45° relative to the MgO lattice. There is only a small lattice mismatch of about 3.5% between the Fe–Fe and O–O in-plane distances. Based on these results, we neglect the small lattice mismatch between Fe and MgO and assume that the whole Fe/MgO/Fe(001) junction grows epitaxially. We describe the band structure of the electrodes by tight-binding bands fitted to the *ab initio* band structure of bcc Fe (Papaconstantopoulos, 1986) and that of the barrier by tight-binding bands fitted to the band structure of bulk MgO (Lee and Wong, 1978). Since the whole structure is epitaxial, momentum parallel to the junction is conserved and, therefore, our Kubo formula (3) is directly applicable to the Fe/MgO/Fe (001) junction. The TMR is calculated by the same method as for the vacuum cobalt junction. For convenience, we shall use the (pessimistic) TMR ratio $R_{TMR} = (\Gamma(H_s) - \Gamma(0))/\Gamma(H_s)$ to characterize the TMR of the Fe/MgO/Fe junction. The dependence of $R_{TMR}$ on the thickness of the MgO barrier is shown in Fig. 5(a). The majority-spin $\Gamma^{\uparrow}_{FM}$ and minority-spin $\Gamma^{\downarrow}_{FM}$ conductances in the ferromagnetic configuration of the junction and the conductance $\Gamma_{AF}$ of electrons of either spin in the antiferromagnetic configuration are plotted against the MgO thickness on a logarithmic scale in Fig. 5(b). The TMR ratio oscillates initially with MgO thickness but after about 7 atomic planes of MgO stabilizes and increases only slowly reaching a very high value of 0.92 for 20 atomic planes of MgO. This corresponds to the optimistic ratio of some 1200%. The behavior of the individual conductances is more informative. Firstly, it is clear from Fig. 5(b) that the majority-spin conductance is always higher than the minority-spin conductance. It follows that the calculated spin polarization of the tunneling current is positive, as found experimentally for junctions based on $Al_2O_3$ barrier. It is also clear that after some ten atomic planes of MgO the junction reaches an asymptotic regime with all the conductances decreasing exponentially with MgO thickness. However, the slope of $\Gamma^{\uparrow}_{FM}$ is somewhat smaller than that of $\Gamma^{\downarrow}_{FM}$ and $\Gamma_{AF}$, which explains why the TMR ratio increases with MgO thickness. Different rates of decrease of the conductances $\Gamma^{\uparrow}_{FM}$, $\Gamma^{\downarrow}_{FM}$ and $\Gamma_{AF}$ are due to the fact that tunneling through MgO is not dominated by $\boldsymbol{k}_{\parallel} = 0$ (the $\Gamma$ point) even for thicknesses of MgO as large as 20 atomic planes.

Our calculated dependence of the TMR ratio on the MgO thickness demonstrates clearly a failure of the classical Julliere's formula (2) which predicts a constant TMR ratio independent of the barrier thickness. The reason why the TMR depends on the

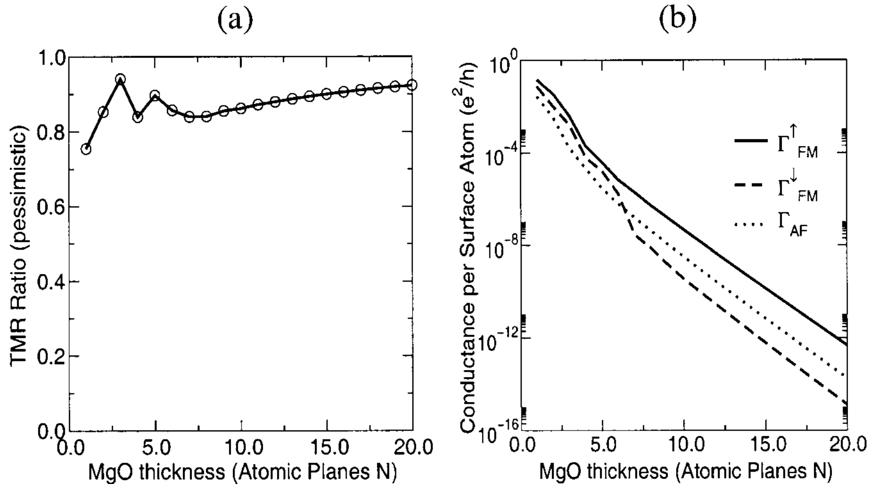


FIGURE 5 (a) Dependence of the pessimistic TMR ratio $R_{TMR}$ of an Fe/MgO/Fe(001) junction on MgO thickness; (b) Dependences of the total conductances $\Gamma^{\uparrow}_{\mathrm{FM}}$, $\Gamma^{\downarrow}_{\mathrm{FM}}$, and $\Gamma_{\mathrm{AF}}$ on MgO thickness.

barrier thickness is that the conductances in the individual spin channels $\Gamma^{\uparrow}_{FM}$, $\Gamma^{\downarrow}_{FM}$ and $\Gamma_{AF}$ are determined by details of the matching of the wave functions of tunneling electrons across the whole junction. The wave function matching is treated exactly by the Kubo formula but ignored completely in the classical theory of tunneling (Merservey, and Tedrow, 1994; Julliere, 1975).

Finally, we shall use the Kubo formula (3) to demonstrate that TMR of a Co junction with a vacuum gap remains nonzero when one of the Co electrodes is covered with a Cu layer. This is yet another example of a system for which the exact matching of the wave functions of tunneling electrons across the whole junction is vital.

The dependence of the TMR ratio obtained by numerical evaluation of the Kubo formula (3) on the thickness of the Cu overlayer is shown in Fig. 6. The calculation is for (111) orientation of the layers and vacuum gap characterized by reduced hopping $t = 0.1$. In contrast to the Julliere's formula (2), the TMR determined from the Kubo formula (3) is nonzero and oscillates as a function of Cu thickness due to quantum interference of electrons on the Cu interlayer. It is interesting that for a small Cu thickness (two monolayers) the TMR ratio becomes negative. A negative TMR with a very thin gold interlayer has been observed by Moodera *et al.* (1999).

The physical explanation of a nonzero TMR is that the Cu layer acts as a spin filter. Since the Fermi surfaces of Cu and of the majority-spin electrons in Co are very similar (the Co majority d band lies below $E_F$), majority-spin electrons cross easily the Co–Cu interface and participate in tunneling as if there were no intervening Cu layer. On the other hand, there is a poor match between the Cu bands and the minority-spin bands in Co, which results in formation of down-spin quantum well states in the Cu overlayer (Mathon *et al.*, 1997b; Segovia *et al.*, 1996). Since the quantum well states are localized in the Cu layer they do not contribute to transport of charge in the down-spin channel, which gives rise to a spin asymmetry (nonzero polarization $P$) of the tunneling current and, hence, nonzero TMR.

The apparent paradox that the Julliere's formula predicts zero TMR but the Kubo formula gives a nonzero TMR can now be easily resolved. Since the down-spin

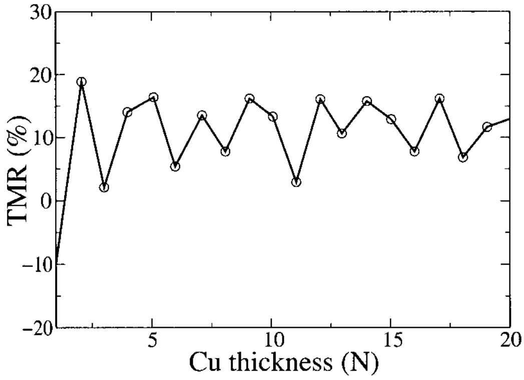


FIGURE 6 Dependence of the tunneling magnetoresistance of a vacuum cobalt junction with a copper interlayer on the thickness of the copper layer.

quantum well states in the Cu layer contribute to the ordinary DOS they are, incorrectly, counted in the Julliere's formula (2) as contributing to the tunneling current. The total DOS of down-spin electrons, which is made up of propagating and quantum well states, is equal to the DOS of up-spin states which are all propagating. There is, therefore, no spin asymmetry in the DOS of the Cu overlayer and, hence, the Julliere's formula gives zero TMR. On the other hand, the Kubo formula excludes automatically all the quantum well states. Since these only occur in the down-spin channel, their loss from transport creates a spin asymmetry of electrons tunneling from a Cu overlayer, i.e., nonzero TMR.

It is clear that for a nonzero TMR effect to occur, one needs a strong scattering at the ferromagnet–nonmagnet interface in one of the spin channels and weak scattering in the other spin channel. These are the same conditions as those required for a large GMR in the corresponding ferromagnet–nonmagnet multilayer. It is, therefore, clear that Co–Cu is a particularly good combination but, for example, an Al interlayer should not lead to any sizable TMR since GMR for an Al spacer is very small. This is in agreement with the observation (see, e.g. Moodera, 1999) that an Al interlayer kills the TMR very effectively.

To observe a nonzero TMR, quantum-well states in one of the spin channels need to be well defined. This is the case when the effect of impurities is negligible (ballistic transport across the whole junction) and scattering at the ferromagnet–nonmagnet interface is specular. Scattering from impurities or/and diffuse scattering at the ferromagnet–nonmagnet interface may allow quantum well states to evolve into propagating states, in which case the spin asymmetry of electrons tunneling from the nonmagnetic interlayer may be lost (and with it the TMR effect). The fact that the calculated TMR shown in Fig. 6 is nondecaying as a function of Cu thickness is due to our neglect of impurity–interfacial scattering.

To investigate qualitatively the effect of diffuse scattering on the quantum well states, we have used a one-band model of the tunneling junction with a random distribution of impurities in the barrier. Since $\boldsymbol{k}_{\parallel}$ is no longer conserved we had to use a large in-plane supercell geometry to simulate disorder in the barrier. We also checked our supercell results using the coherent potential approximation (CPA) with vertex corrections. The supercell method allows us to evaluate the Kubo formula without any

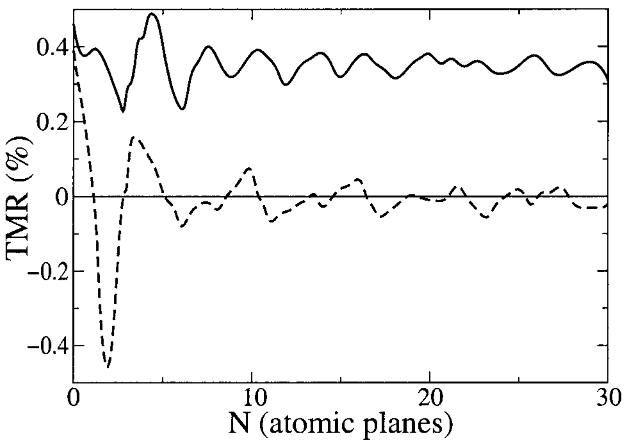


FIGURE 7 Dependence of the TMR ratio for a junction with a nonmagnetic metallic interlayer on the interlayer thickness N. Solid curve is for a perfect junction; broken curve for a junction with random impurities in the barrier.

approximations for a realistic model of disorder. The results of our supercell calculations are in excellent agreement with the CPA calculations for the same model of disorder. The price to pay is a simplified band structure – one band model – and a junction with a relatively small cross section (supercell size). Figure 7 shows the TMR ratio as a function of the thickness of a nonmagnetic metallic interlayer for a junction with (broken curve) and without disorder (solid curve). It can be seen that disorder suppresses the average TMR but, rather surprisingly, large oscillations about zero of the TMR as a function of the nonmagnetic spacer thickness are not washed out by the disorder. This is clearly due to the fact that quantum interference in the metallic spacer is not strongly affected by disorder in the barrier. The oscillation period is given by the spacer Fermi surface wave vector expected from the theory of the ballistic magnetoresistance (Mathon *et al.*, 1995) for a metallic junction. The second oscillation period due to a cutoff of the conductance also predicted for the metallic junction (Mathon *et al.*, 1995) is suppressed in a tunneling junction since only the wave vector $\boldsymbol{k}_{\parallel} = 0$ contributes to the tunneling conductance. The results shown in Fig. 7 are for a barrier of five atomic planes, i.e., the amount of disorder is relatively large. For a thinner barrier with disorder (1–3 atomic planes), the average TMR remains nonzero.

Quantum oscillations of the tunneling magnetoresistance predicted theoretically (Mathon and Umerski, 1999) have recently been observed for a tunneling junction with an amorphous $Al_2O_3$ barrier but with a Co–Cu electrode grown epitaxially. Detailed explanation of such oscillations in a junction with a disordered barrier will be given elsewhere (Itoh, 2002).

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