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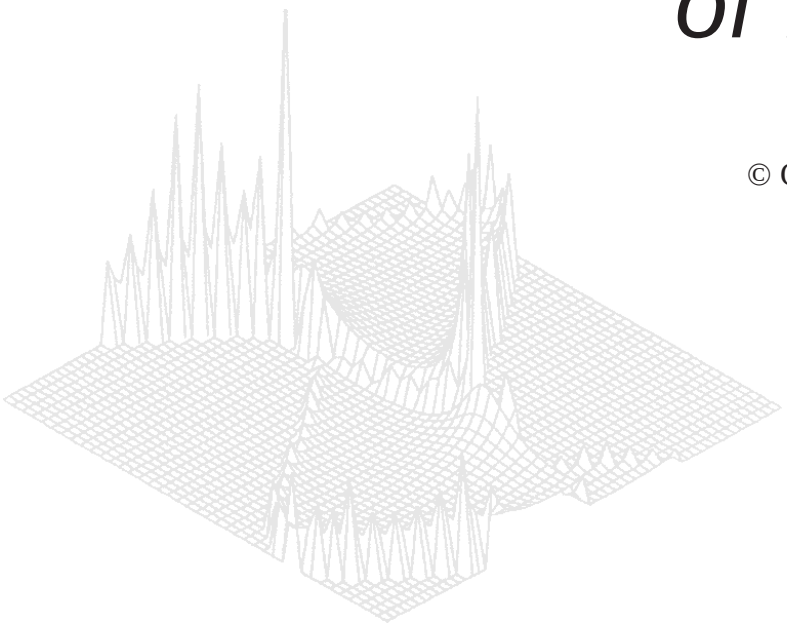

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Interlayer Exchange Coupling: Doping, Interface States and Domain Wall Resonance*

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Abstract

Possible interface effects are examined theoretically for oscillatory exchange coupling between ferromagnetic metal films separated by a nonmagnetic spacer film. It is argued that the exchange coupling is sensitive to aspects of the magnetic film's electronic structure, and evidence from magnetic film doping experiments is described. Possible effects of interface electronic states are also explored. Finally, a suggestion for a new type of domain wall resonance experiment is made that could provide unique measures of local values of the exchange coupling strength.

1. Introduction

Fifteen years ago, a class of magnetic interactions was discovered in metallic multilayers that is mediated by conduction electrons in a nonmagnetic spacer between two ferromagnetic metals (Grünberg *et al.* 1986; Parkin 1991). These kind of interactions are RKKY-like in the sense that oscillations are induced in the spacer film electron distribution by the ferromagnetic interfaces (Yosida and Okiji 1965; Bruno and Chappert 1991). The lowest energy configuration of the electron system depends on the relative orientation of the ferromagnets, resulting in an effective exchange coupling between the ferromagnetic films (Edwards *et al.* 1991). The exchange coupling is particularly sensitive to the thickness of the spacer, and to a large extent seems to be controlled by spin dependent confinement effects within the spacer.

The sign of the coupling, which indicates parallel or anti-parallel alignment, varies with the thickness of the spacer film and oscillates in a manner very similar to de Haas–van Alphen oscillations. Indeed, the earliest explanations of the effect proposed that the period of oscillation is determined by stationary points on the Fermi surface. As noted by Stiles (1993), a careful examination of the Fermi surfaces for several nonmagnetic spacer films suggests a variety of oscillation periods that have not yet been observed in experiment. The origin of these discrepancies is thought to be with imperfections and inhomogeneities in the interface region.

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Progress has been made toward understanding selected systems using fully self-consistent band structure calculations, although there are great difficulties arising from the required computational accuracy (Ortega and Himpsel 1992; Herman and Schrieffer 1992). Progress has also been made using various approximations for the true band structure of the multilayer with good results (Shi *et al.* 1994; Barnas 1994; Stoeffler and Gautier 1991). Because of the difficulties inherent in the calculations for real materials, much of the most careful work has been limited to accurate descriptions of the spacer layer. Questions still remain about the effects of the magnetic film band structure and the interface region.

This paper contains considerations of these questions based on a tight binding phenomenology. Dependence of the coupling on magnetic film thickness and composition are discussed, with particular regard to recent experimental evidence. Finally, a new type of experiment is proposed based on a domain wall resonance that could, in principle, provide accurate local measures of interlayer coupling.

2. Theory of Interlayer Exchange

The essential physics of the coupling can be readily expressed within a tight binding approximation (Edwards *et al.* 1991; Barnas 1994; Stoeffler and Gautier 1991). This is particularly useful for addressing questions concerning the role of imperfections at the interface and the influence of the magnetic film band structure on the interlayer coupling. The calculations described here are used to illustrate how the phase, magnitude and oscillation period of the coupling depend on band structure parameters of the magnetic and interface components of the multilayer.

Before discussing the theoretical model, it is useful first to describe the mechanism from an intuitive point of view first put forward by Edwards *et al.* (1991). Suppose the multilayer is thought of as containing a simple electron gas and that the different films are distinguished by the potential experienced by the electrons. The ferromagnetic films have separate potentials for each spin, whereas the spacer does not. The potential seen by spin-up and spin-down electrons in the multilayer thus depends on the relative orientation of the ferromagnetic films. The above picture is sketched in Fig. 1 for an antiparallel configuration of the ferromagnet films (films 1 and 3). Comparison of the total electronic energies for parallel and antiparallel film magnetisations provides a measure of the interlayer exchange energy. It turns out that for thick ferromagnet films, the electronic states mostly confined in the spacer (film 2) determine whether parallel or antiparallel alignment is favoured.

Comparison of the energies for the two ferromagnet configurations as a function of spacer thickness further shows an oscillatory behaviour. The coupling changes sign with a periodicity determined by the cut-off wavevector (the Fermi wavevector) associated with the electron energies. The amplitude of the coupling typically obeys a relation of the form $\sin(d_{\mathrm{s}}/P+\phi)/{d_{\mathrm{s}}}^2$, where d_{s} is the spacer thickness, P the period and ϕ an initial phase.

The theory presented here is an extension of the tight binding model of Edwards *et al.* (1991) to allow the hopping parameter and potential to vary within a film. The calculation is not done self-consistently, and the justification for the use of this phenomenology is in the ability to adjust various parameters independently in order to discover their effect on the coupling. The parameters

have clear physical interpretations, allowing for generalisation of the results to a variety of systems.

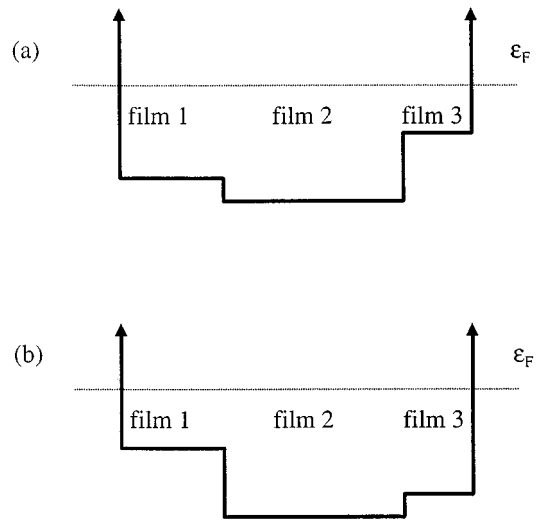

Fig. 1. Schematic representation of the quantum well origin for interlayer exchange coupling. In (a) a potential of spin-up electrons is shown for a multilayer with antiparallel ferromagnetic films. In (b), a potential of spin-down electrons is shown for the same configuration.

A simple cubic structure is considered for simplicity and the geometry is defined with the index m indicating the position of each atomic layer in the direction normal to the film. There are N_1 magnetic layers in the first film, N_2 nonmagnetic layers in the second film, and N_3 magnetic layers in the third film. For most of the discussion, only one band of orbitals is considered.

A Bloch form for directions in the film plane is used to represent the electron wavefunctions. The amplitude of the wave in layer m is defined as A_m and solutions in each region are assumed to have forms such as

$$A_m = C_m^+ \mathrm{e}^{\mathrm{i}q_\sigma am} + c_m^- \mathrm{e}^{\mathrm{i}q_\sigma am} \tag{1}$$

for $1 \leq m \leq N_1$ (in the first film). The wavevector is spin dependent in the magnetic layers and the spin index is σ. In the magnetic films it is denoted by q_σ and in the spacer it is defined as simply q. The lattice constant is a. Solutions in the other films are constructed in an analogous manner to equation (1).

The energies ϵ are found by solving:

$$\sum_{m'} A_{m'} \{[\epsilon - E_{\sigma m} + 2\gamma_m \epsilon_{||}]\delta_{mm'} + \gamma_{mm'}\} = 0\,, \tag{2}$$

where

$$\epsilon_{||} = \cos(k_x a) + \cos(k_z a) \tag{3}$$

and where γ_m is the hopping integral in layer $m, \gamma_{mm'}$ is the hopping integral between adjacent layers, and $E_{\sigma m}$ is the spin dependent potential.

The E and γ are assumed to be the same everywhere within a particular film except possibly at the surfaces and interfaces. Far from the interfaces, relations between q and energy ϵ can be determined for solutions in each individual film through equation (2).

For the interface and surface layers, equation (2) provides a set of six coupled equations with six unknown coefficients. Solving, one arrives at an implicit dispersion relation for $q(\epsilon)$:

$$\Gamma_1\Gamma_2\Gamma_3 - \gamma_i^2[G_1\Gamma_3 + G_3\Gamma_1]G_2 - \gamma_i^4 G_1 G_3 \sin[qa(N_2-1)] = 0\,, \tag{4}$$

$$\begin{aligned}\Gamma_1 = {} & [E_\sigma - E_{\sigma\nu} - 2\gamma_\sigma\cos(q_\sigma a)][E_\sigma - E_{\sigma i} - 2\gamma_\sigma\cos(q_\sigma a)]\sin[q_\sigma a(N_1-1)] \\ & + 2\gamma_\sigma[E_\sigma - \tfrac{1}{2}(E_{\sigma\nu} + E_{\sigma i}) - 2\gamma_\sigma\cos(q_\sigma a)]\sin[q_\sigma a(N_1-2)] \\ & + \gamma_\sigma^2\sin[q_\sigma a(N_1-3)]\,,\end{aligned} \tag{5}$$

where

$$G_1 = [E_\sigma - E_{\sigma\nu} - 2\gamma_\sigma\cos(q_\sigma a)]\sin[q_\sigma a(N_1-1)] + \gamma_\sigma\sin[q_\sigma a(N_1-2)]\,. \tag{6}$$

Expressions for Γ_3 and G_3 are obtained from (5) and (6) by substituting N_3 for N_1. Similarly, expressions for Γ_2 and G_2 are obtained by substituting N_2 for N_1, E_s and γ_s for E_σ and γ_σ, and by replacing $E_{\sigma i}$ and $E_{\sigma\nu}$ with E_i.

At zero temperature an expression for the magnetic coupling J is

$$J = \Omega_{\mathrm{FM}} - \Omega_{\mathrm{AF}}\,, \tag{7}$$

where the total energy Ω for a given configuration is defined as

$$\Omega = \sum_{\substack{n,\sigma \\ k_x,k_z}} [\epsilon_{n,\sigma}(k_x,k_z) - \epsilon_{\mathrm{f}}]\,\theta[\epsilon_{\mathrm{f}} - \epsilon_{n,\sigma}(k_x,k_z)]\,. \tag{8}$$

In (8) θ is the step function and the potential is chosen to represent either parallel (FM) or antiparallel (AF) configurations.

(2a) Thickness Dependencies

As noted by Edwards *et al.* (1991), the energy differences are very small and require great accuracy in the sums over the two-dimensional Brillouin zone. In order to reduce the number of points needed for the zero temperature J, the sums in (4) were performed by dividing the two-dimensional Brillouin zone into triangles. A two-dimensional density of states for each level n was then calculated using a linear approximation for the electron energies in each triangular region. Convergence to four significant digits was obtained using a number of k points on the order of 10^5. Finite temperature results are simpler to achieve and are not done using this triangle scheme, because summing over the distribution of occupied levels eliminates the sharp cutoff at the Fermi energy responsible for the slow convergence.

As noted at the beginning of this section, the individual energy states of the parallel and antiparallel configurations nearly cancel in the sum of (4). For thick magnetic films the non-cancelling energies are dominated by the density of states of the spin-down electrons confined to the nonmagnetic film. This is especially apparent at energies near where the band edges have a maximum density of states at the boundaries of the two-dimensional Brillouin zone.

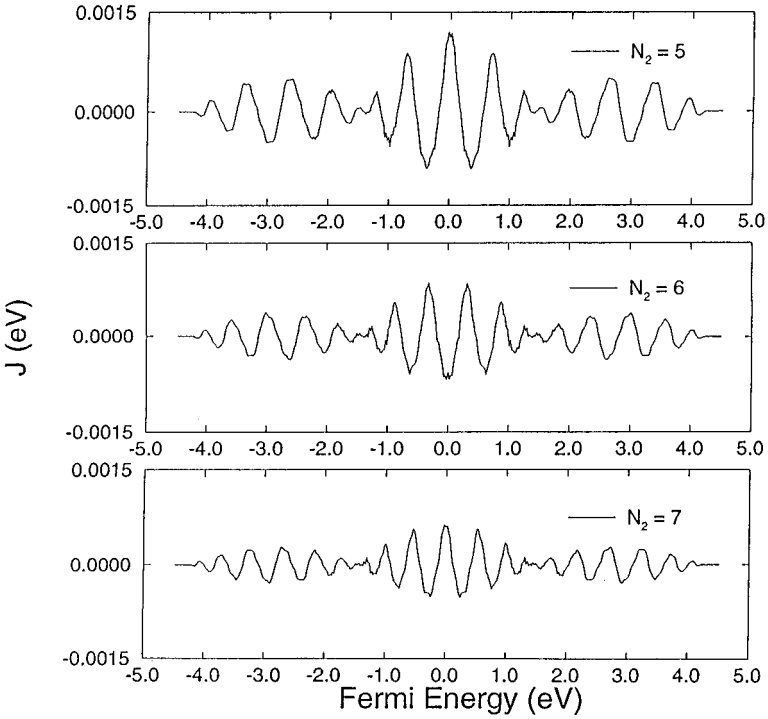

Fig. 2. Interlayer exchange J as a function of Fermi energy for three nonmagnetic film thicknesses N_2. The number of oscillations in J corresponds to the number N_2 of spacer layers. The value of J at a constant ϵ_F thus oscillates with N_2.

Oscillatory behaviour and phase shifts can be described simply by calculating J as a function of Fermi energy for different spacer thicknesses. An example is given in Fig. 2 where a structure of $N_1 = N_3 = 30$ and $N_2 = 5$ is assumed with $\gamma = 7 \cdot 2$ eV in the ferromagnetic films and spacer. The potential of the spacer is set equal to the potential of the lowest magnetic spin band for purposes of illustration. Additionally, a large exchange splitting of 100 eV in each ferromagnet was chosen, so that the lowest energy states are electron levels corresponding to electrons confined inside the nonmagnetic film. Interface and surface potentials are set equal to those inside the films and the interface overlap integrals are set equal to the geometrical mean of the different film values. Surface and interface states do not appear for this choice of parameters.

For the simple cubic geometry, the electron states in the spacer form discrete levels inside bands of thickness $4\gamma_s$ and total width $12\gamma_s$. The number of levels in this band is equal to the number of atomic layers in the nonmagnetic film.

There is a direct correspondence between the zeros of J and where an energy level intersects the Brillouin zone boundary near ϵ_{f}. This is due to the large density of states at these points.

The periodicity of J with respect to N_2 follows directly. The addition of an atomic layer to the nonmagnetic film increases the number of levels in the band and increases the number of oscillations in $J(\epsilon_{\mathrm{f}})$. Since the energy levels are constrained to lie inside a band, however, the rate of change of J with respect to film thickness is also a function of the Fermi energy. The slowest variations, and hence the longest periods, occur near energies where the levels at the edges of the band intersect the Brillouin zone boundary.

A simple argument shows that the oscillation period must be inversely proportional to the Fermi wavevector q_{f}. For a film with N_2 layers, q_{f} is defined as $\pi S/(N_2+1)$, where S is determined by the location of ϵ_{f} relative to the band edge. The period P of the coupling is then defined as the minimum number of layers needed so that $J(N_2) = J(P+N_2)$. This gives the condition

$$\frac{S}{N_2+1} = \frac{S+1}{N_2+1+P} \tag{9}$$

and results in $P = \pi/q_{\mathrm{f}}$. This is in agreement with the results of Edwards *et al.* (1991) and is equivalent to determining the period by measuring the spanning wavevector in the direction normal to the film at a stationary point on the Fermi surface.

It is useful to note that the existence of the exchange coupling is due to hybridisation between energy states associated with the uncoupled films brought about by interface hopping integrals. The degree to which the bands overlap depends on the relative potential energies of the electrons, the amount of exchange splitting in the magnetic bands, and the magnitude of γ_i.

A fundamental point is that the dependence on γ_i is significant regardless of the thickness of the magnetic films. This is illustrated in Fig. 3*a* where $J(\epsilon_{\mathrm{f}})$ is shown for two different values of γ_i. Here $\gamma_{\mathrm{f}} = 3\cdot 6$ eV in the ferromagnetic films and $\gamma_{\mathrm{s}} = 7\cdot 2$ eV in the spacer. The exchange splitting is still 100 eV in the magnetic films as in Fig. 2, and the majority spin band is aligned with the spacer band.

The strength of the coupling decreases as expected with decreasing γ_i, but there are also changes in the sign of the coupling at many Fermi energies due to the effects of hybridisation. By controlling the degree of hybridisation, γ_i has a large influence phase and periodicity of J with respect to film thicknesses in addition to controlling the magnitude of J.

The influence of the magnetic band structure on J is even more pronounced when the exchange splitting is reduced. This is illustrated in Fig. 3*b* where the potentials are $E_{\mathrm{s}} = 0$, $E_{\downarrow} = 1\cdot 87$ eV and $E_{\uparrow} = 0\cdot 85$ eV corresponding to an exchange splitting in the magnetic films of $1\cdot 02$ eV. This choice of potentials also places the centre of the magnetic majority band above the centre of the nonmagnetic band. As a result, J is very small for energies below the centre of the nonmagnetic band.

An interesting possibility for non-oscillatory coupling can occur when ϵ_{f} is just *above* the nonmagnetic band. Electrons in the magnetic films can still tunnel

into the nonmagnetic film and, provided that the film is thin enough, contribute to a magnetic coupling between the magnetic films.

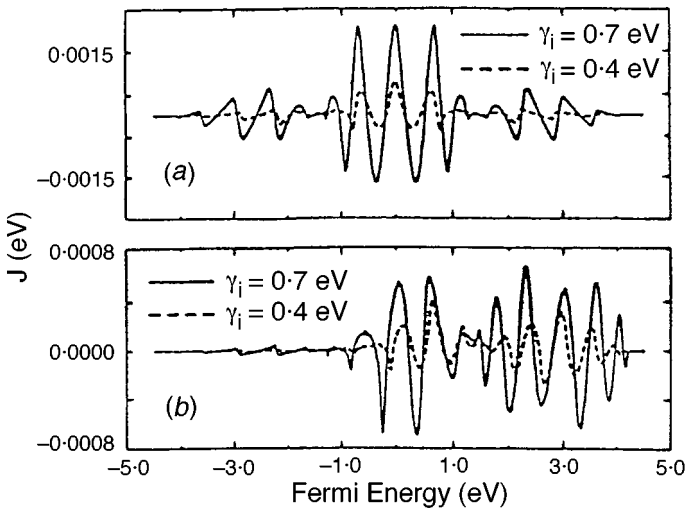

Fig. 3. Interlayer exchange J as a function of ϵ_f for two values of γ_i. In (a) the overlap integrals and potentials of the spacer and majority spin states are the same as in Fig. 2. The bandwidths are different in (b) with $\gamma_m = 0{\cdot}36$ eV and $\gamma_s = 0{\cdot}7$ eV, and an exchange splitting of $1{\cdot}02$ eV is assumed for the potentials of the majority and minority bands in the magnets (roughly representing a Co/Ru/Co trilayer).

A very thin magnetic film means that changes in the number of magnetic layers will have large effects on the density of electronic states in the magnetic bands. This leads to oscillations in the magnitude of J around a nonzero value as the number of magnetic layers is increased. The period of oscillation depends on the position of the magnetic bands relative to ϵ_{f}. For example, the oscillation period of J with respect to N_3 is short when ϵ_{f} is above the spin-up band and increases as ϵ_{f} is decreased below this value. The period again decreases as ϵ_{f} approaches the bottom of the spin-up band.

(2b) Doping the Magnetic Films

The above discussion illustrates how magnetic film band structure parameters and thickness affect the exchange coupling. One consequence was that the initial phase of the coupling could be sensitive to the magnetic film bandwidth and relative potential. One way to modify this in an experiment is to introduce different valence impurities into the magnetic film. Screening of the impurities by the magnetic film can introduce low lying states that serve, in a rough sense, to change the relative height of the potential step encountered by electrons crossing the interface between the spacer and magnetic films.

This argument was put on a firmer footing by studying large supercell band structure calculations for hexagonal Co with a fraction of Co atoms substituted with Ag (Ebels *et al.* 1998*a*, 1998*b*). The calculation method was a self-consistent linear muffin-tin orbital technique in an atomic sphere approximation. The resulting

density of states showed that for concentrations of Ag less than 12%, the Fermi surface was unperturbed but a significant number of additional states appeared at the bottom of the Co s-band.

At 12% concentration, this corresponded to a $0\cdot4$ eV lowering of the Co s-band relative to the d-band. In order to examine the effect of such a shift on J, a two-band tight binding model similar to that described was constructed where one band respresented s electrons and the second band represented one set of d orbitals. The results showed that such a shift could significantly change the initial phase of the coupling through sd hybridisation.

Experimental evidence for this effect was sought by constructing $\mathrm{Co/Ru/Co_{1-x}M_x}$ and $\mathrm{Co_{1-x}Ag_x/Cu/Co_{1-x}Ag_x}$ multilayers where M = Ag, Au, Ru or Cu. A phase shift was observed in all cases. The Ag series in particular was studied as a function of concentration x, and displayed a 180° change in phase at a Ag concentration of 3%, and a complete 360° change in phase at a Ag concentration of 8% (Ounadjela *et al.* 1997).

(2c) Interface States

So far the interface potentials and overlap integrals were chosen so as to supress the formation of electronic states outside the bulk bands (Cooper and Bennett 1970; Kalkstein and Soven 1971). Changes in these parameters relative to their values in the bulk of the films can result in the formation of states localised to the interfaces with energies that fall outside the bulk bands.

Existence conditions can be obtained in the following manner. An expansion of (4) to first order in q reveals that up to four states localised to the magnetic film/spacer interface can exist outside the bulk bands. Approximate existence conditions for the interface state can be derived by expanding (4) about q and $q_\sigma = 0$ in the limit $N_1 = N_3 \gg 1$. For simplicity it is assumed that $E_{\sigma i} = E_{\sigma\nu} = E_i$. To first order in q and q_σ, and with $qaN_2 \ll 1$, one obtains the condition

$$R^2(N_2 - 1) - 2R[N_2(1 + r) - r] + N_2(1 + 2r) + 1 = 0\,. \tag{10}$$

The interface states depend on the parameters

$$R = \gamma_i^2/\gamma_\sigma\gamma_\mathrm{s}\,, \tag{11}$$

$$r = (E_i - E_\mathrm{s})/\gamma_\mathrm{s}\,. \tag{12}$$

Interface states can exist if (1) $r = 0$ and $R \geq (N_2 \pm 1)/(N_2 - 1)$ and (2) $R < 1$ and $r \leq (R - 1)$ when $N_2 \gg 1$.

The nature of the interface modes is found by examining the corresponding A_m. Two modes can exist above the band and are formed by the antibonding modes. They represent symmetric and antisymmetric solutions with respect to the midplane of the trilayer structure. Two interface modes can also exist below the band. These are the corresponding symmetric and antisymmetric solutions formed by bonding modes.

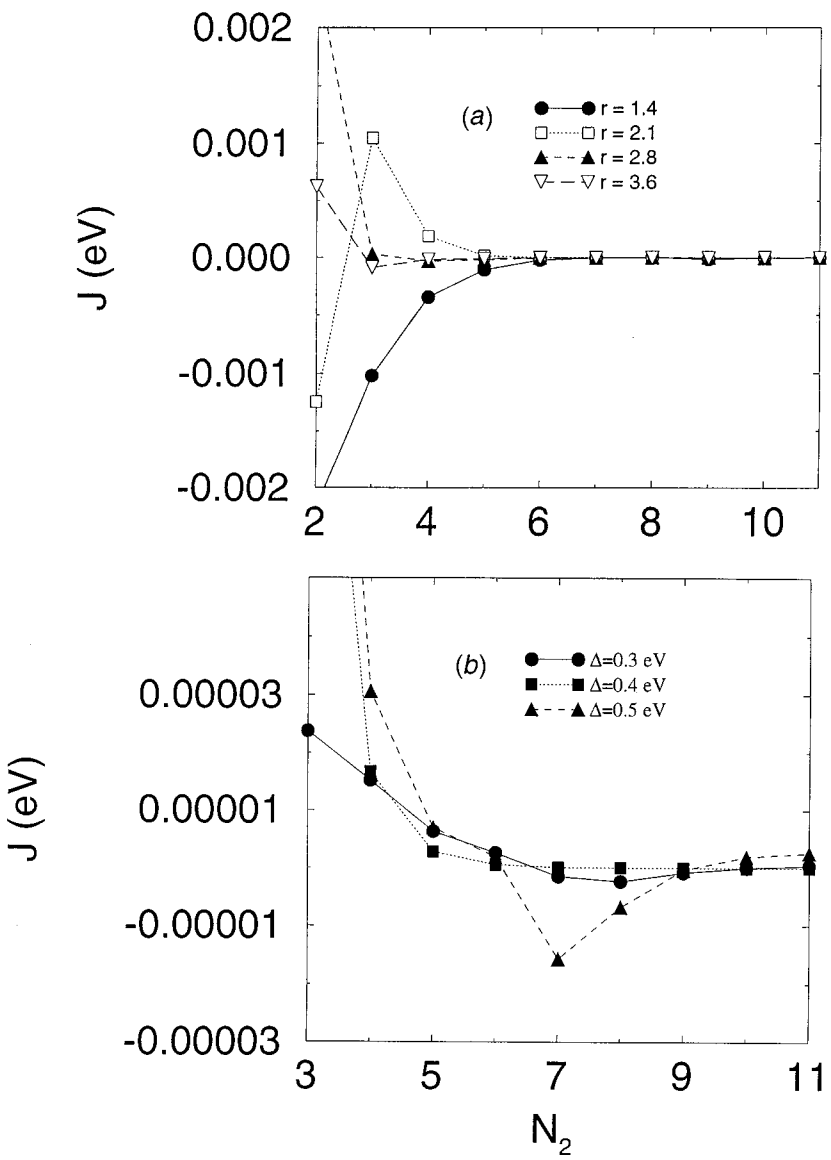

Fig. 4. Interlayer exchange J as a function of N_2 with interface states. In (a) J is shown for four values of r. The Fermi energy is near the top of the nonmagnetic film band. Interface states appear for $r > 1{\cdot}5$ and cause J to change sign. In (b), the parameters are as in Fig. 3b, but with $R = 0{\cdot}9$ and different values of a potential barrier in the first spacer layer at the interfaces.

The effect of interface states on J can be understood by their location with respect to the Fermi energy. By creating states outside the bulk bands, the bandwidth is effectively increased as far as J is concerned. This changes the behaviour of J with respect to N_2 and can lead to changes in the initial phase

and even oscillation period. In some cases, multiple periods can appear as the shape of the Fermi surface is altered and new stationary points appear. Examples are shown in Fig. 4 where J is plotted as a function of N_2. In (a) the nonmagnetic bandwidth is $2\cdot8$ eV and $\epsilon_{\mathrm{f}} = 1\cdot35$ eV which is $0\cdot5$ eV below the nonmagnetic band limit. Here J is shown for different values of r. As r increases, the energies of the interface states also increase and contribute more strongly to J. For $r > 1\cdot5$, additional interface states appear above the nonmagnetic film band and cause J to change sign. In (b), the effect of a potential barrier located at the interface is shown. The parameters are the same as in Fig. 3b except that $R = 0\cdot9$ and $\epsilon_{\mathrm{f}} = 1\cdot75$ eV. The barrier is a small change in the potential of the interface spacer layer measured relative to the spacer potential inside the film. Here J is very large for small N_2 but falls off quickly with increasing spacer thickness.

3. Domain Wall Resonance

As described earlier, exchange coupling across interfaces in magnetic multilayers can exist and have large effects on the overall magnetic properties of a structure. The presence of domains in a multilayer suggests an additional interesting effect: coupling of domain walls and oscillations via interlayer exchange (Stamps *et al.* 1997). The coupled wall oscillations are analogous to breathing wall vibrations in isolated films (Slonczewski 1984; Braun and Brodbeck 1993).

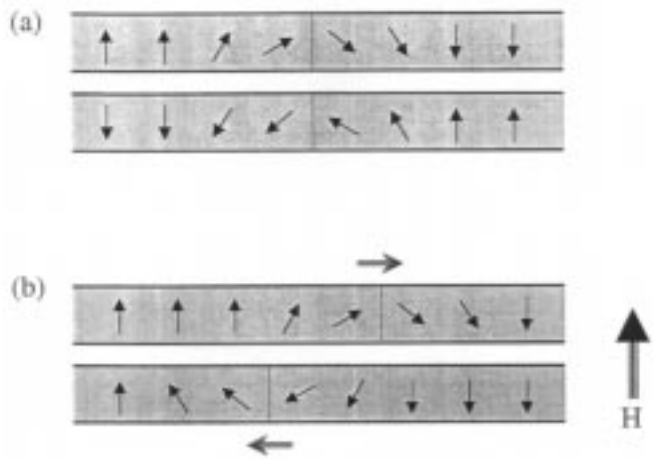

Fig. 5. A schematic illustration of domain wall correlations in antiferromagnetically coupled multilayers. The dotted line in each film separates domains and the lowest energy configuration is for the walls to exist on top of one another as in (a). Application of a field in (b) causes one domain to grow at the expense of another and displaces the walls relative to one another.

A detailed discussion has been presented by Stamps *et al.* (1997), and only an outline is presented here. The essential idea is indicated schematically in Fig. 5. Domains in two antiparallel coupled films are shown for (a) an equilibrium case and (b) a non-equilibrium case. A single domain wall exists in each film, separating regions of uniform magnetisation. At equilibrium, the energy of the

configuration is least when the two walls are positioned directly above one another since this allows exact antiparallel alignment between spins from separate films.

Walls in ferromagnets have a finite width and a slight displacement of the walls from equilibrium results in effective restoring forces. The restoring forces originate with the interlayer exchange since this opposes the displacement. The resulting dynamics is that of a simple coupled oscillator, wherein the walls can oscillate in phase and out of phase with one another.

A quantitative description of the dynamics can be had from the free energy for the system. Neél walls are assumed and the films are supposed thin enough that there is no curling of the magnetisation near the surfaces. The films lie in xy planes and the magnetisation far from the walls aligned along the z-axis. The free energy of the coupled film system is given by

$$\begin{aligned} E = & \int \left\{ A\left[\left(\frac{\mathrm{d}\theta_1}{\mathrm{d}x}\right)^2 + \left(\frac{\mathrm{d}\theta_2}{\mathrm{d}x}\right)^2\right] + K[\sin^2\theta_1 + \sin^2\theta_2]\right\}\mathrm{d}x \\ & + 2\pi M^2 \int [\sin^2\theta_1 \sin^2\phi_1 + \sin^2\theta_2 \sin^2\phi_2 \mathrm{d}x \\ & + J \int \{\sin\theta_1 \cos\phi_1 \sin\theta_2 \cos\phi_2 \\ & + \sin\theta_1 \sin\phi_1 \sin\theta_2 \sin\phi_2 + \cos\theta_1 \cos\theta_2\}\mathrm{d}x \\ & - Mh \int [\cos\theta_1 + \cos\theta_2]\mathrm{d}x\,. \end{aligned} \tag{13}$$

The subscripts indicate which film the magnetisation belongs to, while θ and ϕ are angles describing the orientation of the magnetisation at a position x along the film. The intrafilm exchange is A, J is the interfilm exchange, and K is a uniaxial anisotropy with easy axis in the z direction.

Solutions describing domain walls are assumed in each film. The strategy is to assume trial solutions corresponding to the uncoupled film case and use the wall width as a variational parameter to find the minimum energy of the coupled wall system under the assumption that $J \ll A$. The trial solutions are of the form $\cos\theta = \tanh(x/\Delta)$, which are the usual forms for simple walls. The domain wall width Δ is used as the variational parameter.

For small displacements from equilibrium, the interlayer exchange introduces a term into the domain wall energy of the form

$$J\Delta\{2\Psi_1\Psi_2 + [(\Psi_1)^2 + (\Psi_2)^2]\} + J(x_1 - x_2)^2/\Delta\,. \tag{14}$$

This quadratic potential leads to a restoring force linear in the displacement and proportional to the interlayer coupling J. Two modes of oscillation are possible: one wherein the walls oscillate in-phase and one with the walls oscillating out-of-phase. These modes are labelled acoustic and optic in analogy to simple elastic waves in a diatomic crystal. The frequencies can then be calculated from equations of motion constructed from the domain wall energy σ (Malozemoff

and Slonczewski 1979). In the presence of a small static applied field h, the frequencies for the acoustic ω_{a} and optic ω_{o} modes are

$$(\omega_{\mathrm{a}}/\gamma)^2 = (Mh^2/3J)(H_{\mathrm{e}} + 4\pi M)\,, \tag{15}$$

$$(\omega_{\mathrm{o}}/\gamma)^2 = 4\pi M(H_{\mathrm{e}} + Mh^2/3J)\,, \tag{16}$$

where $H_{\mathrm{e}} = 2J/M$. The equilibrium separation of the walls depends on h and increases the frequencies of both modes. The linear dependence on field of the acoustic mode in contrast to the optic mode is interesting and could help with experimental identification.

These kind of coupled domain wall resonances would give very local information about J on length scales comparable to domain wall widths, but observations have not yet been made experimentally. Evidence for high frequency domain wall resonances has recently been reported, however, for thin metallic ferromagnetic Co films using ferromagnetic resonance on films with narrow stripe domain patterns (Ebels *et al.* 1998*a*, 1998*b*).

4. Summary and Conclusions

Interlayer magnetic coupling has been discussed in terms of how the magnetic films and interface regions affect the coupling using a tight binding phenomenology. The magnetic film thickness and composition were shown to have subtle effects on the magnitude and phase of the coupling. Experiments performed by adding dopants to the magnetic films revealed phase shifts that may be associated with the appearance of low lying electronic states in the magnets.

Potential steps and/or large hopping integrals at the spacer–magnetic film interfaces were examined in the framework of a tight binding phenomenology, and may result in electronic interface states. The existence of these states depends strongly on the spacer film thickness, and local values of overlap integrals and effective potential at the interfaces. Interface states at the Fermi level can have a large impact on the coupling, to the extent even of suppressing oscillations altogether. Other effects include phase shifts and additional periodicities in the coupling. The sensitivity of aspects of the coupling to details of the electronic environment at the interface and in the magnetic films suggests that interlayer coupling may be useful as a probe of the magnetic film electronic structure.

A new type of experiment is proposed based on a domain wall resonance peculiar to exchange coupled multilayers. Domain walls in coupled films will be correlated, and can be self-pinning in the sense that they will possess a minimum energy configuration due to the coupling energy. Small displacements from equilibrium result in harmonic oscillations with a frequency that provides a direct measure of the strength of the coupling. An attractive aspect is that the oscillations require wall overlap. Wall widths in common metallic ferromagnets such as Co or Fe are of the order of 100 Å, and would thus provide a local measure of the exchange coupling. The wall oscillation frequencies would be of the order of 1–10 GHz for multilayers consisting of materials such as Fe.

Finally, it is worth noting that the theoretical considerations leading to a description of the resonance can be readily generalised and applied to a number of coupled systems capable of supporting domain boundary walls.

Acknowledgments

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