Exchange coupling between two magnetic films separated by an antiferromagnetic spacer

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An expression for the interaction strength between two magnetic films separated by an insulating antiferromagnet spacer has been derived as a function of temperature and thickness. We consider the mechanism wherein the magnetic interaction between the ferromagnetic layers is mediated by the intervening antiferromagnetic insulator via the Suhl–Nakamura (SN) interaction. The interaction energy per unit area, σ_{SN}, is derived as $\sigma_{\mathrm{SN}}=\frac{1}{8}(J_C^2/J_{\mathrm{AF}})(\delta/a)\exp(-t/\delta)$. Here, J_{AF} is the magnetic coupling constant between nearest-neighbor antiferromagnetic spins in the spacer, J_C is the effective coupling constant (which is greatly reduced from the Heisenberg exchange constant), between the spins in the ferromagnetic film and the nearest-neighbor spins in the antiferromagnetic spacer, t is the separation of the two ferromagnetic plates, and δ is the width of an antiferromagnetic domain wall. This mechanism is the antiferromagnetic analog of the Ruderman–Kittel oscillatory coupling between two magnetic films separated by a normal metal. [S0021-8979(99)67608-3]

The interaction between two ferromagnetic layers separated by an intervening *metallic*, nonmagnetic layer has been found to be oscillatory in nature, both decaying and alternating in sign with increasing separation. This has its origin in the oscillatory Ruderman–Kittel[1] interaction, which couples two spins embedded in a metallic matrix. Integrating this interaction over all spins in the ferromagnetic layers yields an oscillatory coupling between the layers. The resulting quasiperiodic dependence on layer separation of the intralayer coupling has been observed many times.

In an analogous fashion, we will derive the interaction between two magnetic layers separated by an *insulating* antiferromagnet utilizing the monotonically decaying, nonoscillatory Suhl–Nakamura[2] (SN) interaction, which describes the coupling between two spins, S_i and S_j, embedded in an *antiferromagnetic* matrix. These spins are exchange coupled to the matrix, and separated from each other by a distance R

$$H_{ij}=(J_C^2/32\pi J_{\mathrm{AF}})\left(\frac{a}{R}\right)\exp[-R/a(H_A/H_E)^{1/2}]\times(S_i^+S_j^-+S_j^+S_i^-). \qquad (1)$$

Here, J_C is the effective coupling constant describing the interaction between the embedded spins and the spins which comprise the antiferromagnetic sublattices. When considering interfacial ferromagnetic spins, J_C is greatly reduced from the nearest-neighbor Heisenberg exchange constant due to the relatively strong coupling between other *ferromagnetic* spins, and to the existence of roughness and/or interfacial antiferromagnetic walls at the interface.[3,4] The remaining parameters of the theory, J_{AF}, H_E, H_A, and a, are, respectively, the antiferromagnetic exchange constant, the antiferromagnetic exchange field, the antiferromagnetic anisotropy field, and the lattice constant of the antiferromagnet. In order to obtain a formula for the interaction between the two opposing ferromagnetic layers from the SN formula, we need only integrate the interaction described by Eq. (1) over the spins in the opposing ferromagnetic monolayers.

Slonczewski[5] has previously proposed a quite different mechanism involving a helical spin interaction which couples the two opposing films through an intervening antiferromagnet domain wall. In the current article we describe a further possible explanation which is based on quantum aspects of the distortion induced in the antiferromagnetic spin system by its exchange coupling to the two ferromagnetic films. Under certain conditions, the quantum interaction can yield coupling coefficients which are comparable to the helical interaction.

In the following derivation, we shall treat the ground state of the ferromagnet as the Neél state, a state in which the two magnetic sublattices are oppositely directed. Only subsequently, shall we indicate that the actual ground state configuration contains antiferromagnetic domain walls. The question now is how the presence of these static walls alters the SN interaction. Winter[6] has already provided an answer to this question by calculating the spin-spin coupling within a wall, using the excitation spectrum of the wall. He finds that the new interaction is of the SN form, but is larger by a factor $(K/K')^{1/2}$, where (K/K') is the ratio of the bulk anisotropy to the apparent wall anisotropy. In the theory, below, we shall utilize the simple bulk anisotropy. The user may replace H_A the bulk anisotropy field with $H_{A'}$, the wall anisotropy field, if necessary. The calculation of $H_{A'}$ is discussed in Winter's article.

The easy axis of the antiferromagnet is assumed aligned along the z axis. The interaction H_{ij} between a spin S_i which resides on the surface of a ferromagnetic layer and an adjacent spin s_j which is part of the antiferromagnetic matrix, is given by

$$H_{ij}=J_C\mathbf{S}_i\cdot\mathbf{s}_j, \qquad (2)$$

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where J_C is the effective coupling constant between spins on the ferromagnetic film and spins on the antiferromagnetic layer which lies directly beneath. From Eq. (1) the interaction between two spins coupled to the antiferromagnetic lattice and separated by a distance R, is governed by the SN range function $F(R)$, which is given (for large R) by the expression

$$F(R)=\frac{a}{R}\exp\left(-\frac{R}{\delta}\right), \tag{3}$$

where $\delta=a(H_E/H_A)^{1/2}$. To obtain the Suhl–Nakamura coupling energy between the two ferromagnetic layers as a function of the antiferromagnetic spacer thickness t, we must sum over the spins by integrating Eq. (1) over the surface area of the ferromagnetic layers, and dividing by the spin density per unit area, a^2. This yields

$$\sigma_{1,2}=\frac{1}{8}\left(\frac{J_C^2}{J_{\mathrm{AF}}}\right)\frac{\delta}{a}\exp\left(\frac{-t}{\delta}\right)(\sigma_1^x\sigma_2^x+\sigma_1^y\sigma_2^y). \tag{4}$$

Here, $\sigma_1^{x,y}$ and $\sigma_2^{x,y}$ are the components of the spin density (per unit area) in the plane of the film 1 and 2, respectively. The parameter, δ, is actually the width of a domain wall in an antiferromagnet and is seen to determine the range of the magnon-mediated interaction. t is the thickness of the antiferromagnetic spacer.

The coupling energy $\sigma_{1,2}$ between two ferromagnets (separated by an antiferromagnetic spacer) is conventionally expressed as

$$\sigma_{1,2}=J_{\mathrm{SN}}\sigma_1\cdot\sigma_2, \tag{5}$$

where we have defined J_{SN} to be the Suhl–Nakamura exchange coupling parameter between the two ferromagnetic sheets; σ_1 and σ_2 are the vector spin *densities* of the ferromagnetic layers (which are constrained to lie within their respective planes). Combining Eqs. (4) and (5), we obtain the following expression for the magnon-mediated exchange parameter of two magnetic layers embedded in an antiferromagnet and spaced apart a distance t

$$J_{\mathrm{SN}}=\frac{1}{8}\left(\frac{J_C^2}{J_{\mathrm{AF}}}\right)\frac{\delta}{a}\exp\left(\frac{-t}{\delta}\right). \tag{6}$$

Equation (6) is the primary conclusion of this article.[7]

We now address the frequently asked question, ''What happens when the ferromagnets couple to opposite sublattices?'' The simple answer is that this situation will simply not occur when materials are chosen with good exchange-bias properties. In that case, the antiferromagnet sublattice immediately adjacent to each ferromagnetic film is forced to align along the magnetization of the contiguous ferromagnet as the sample is cooled through the Neél temperature. This happens at both interfaces, and the bulk antiferromagnet accommodates itself, if necessary, by the formation of a domain wall. Following the usual argument, we can assume that this antiferromagnetic spin configuration, with the end-spins aligned parallel to the ferromagnetic spins and the bulk of the antiferromagnet accommodating by a magnetization reversal (a domain wall) remains frozen at lower temperatures. As shown by Mauri *et al.*,[4] the gain in energy due to wall formation is offset many times by the loss of interfacial exchange energy. This results in a reduction of the effective exchange energy by nearly 2 orders of magnitude, yielding $J_C\sim J_{\mathrm{AF}}/100$. In a simple bilayer, when the applied magnetic field is reversed, the antiferromagnet retains its configuration, giving rise to a shifted hysteresis loop. In a trilayer, two coupled, shifted loops can be anticipated. However, this assumption of a completely frozen antiferromagnet cannot be strictly true, since many exchange-bias materials show evidence[8] of mobile antiferromagnetic walls, even at very low temperatures. When the interface is rough, domain walls form laterally[3] with a residual nonzero interfacial spin density, which again produces a ferromagnetic but greatly reduced interfacial exchange interaction at both interfaces.

Recently, Suhl and Schuller[9] (SS) have calculated the exchange-bias field, H_{ex}, (which we designate as $H_{\mathrm{ex}}^{\mathrm{SS}}$) induced by the emission and reabsorption of magnetic excitations by a single, thin magnetic layer in contact with an antiferromagnet. The present article, on the other hand, utilizes similar techniques to calculate the energy, J_C, coupling *two* thin magnetic films separated by an antiferromagnetic layer. The two calculations are alike: our article utilizes virtual magnons which propagate across the antiferromagnet, while SS utilize virtual magnons which couple ferromagnetic spins on the same side of the antiferromagnetic spacer. Suhl and Schuller obtain for the exchange-anisotropy field $H_{\mathrm{ex}}^{\mathrm{SS}}=2J_C^2/(J_{\mathrm{AF}}M_Ft_F)$. Expressing the coupling energy between the two ferromagnetic layers, Eqs. (5) and (6), as an effective magnetic field between the two layers, $H_{1,2}$, and re-expressing it in terms of $H_{\mathrm{ex}}^{\mathrm{SS}}$, we obtain

$$H_{1,2}=H_{\mathrm{ex}}^{\mathrm{SS}}(\delta/16a)\exp(-t/\delta). \tag{7}$$

Assuming, then, that both the ''coupling field'' and the exchange-bias field are caused by the virtual magnon interaction,[10] it should prove possible to observe the former with reasonable ratios of t/δ by, e.g., ferromagnetic resonance.

The coupling coefficient depends primarily on two parameters: the width of the domain wall $\delta=a\pi(H_E/H_A)^{1/2}$ and the AF–F interfacial exchange parameter J_C. The magnitude of δ and J_C, will be discussed using a generic antiferromagnet, typical of several used in exchange-biased bilayers (such as NiO, CoO, or $Mn_{50}Fe_{50}$). Some values for the Neél temperature T_N, the exchange field H_E, and the anisotropy field H_A of these materials have been published by Lax and Button[11] and by Chikazumi.[12] Here, we will follow Malozemoff's[3] direction, and choose a typical ratio of exchange-to-anisotropy to be $\pi(H_E/H_A)^{1/2}\sim 100$. It follows that $\delta=100a$.

With *M(T)* as the temperature dependence of the sublattice magnetization, the mean field approximation combined with the single-ion approximation yield the following temperature dependencies: $H_E\propto M(T)$ and $H_A\propto[M(T)]^2$. For the temperature dependence of M, we choose as an approximation, $M(T)\propto(1-T/T_N)^{1/2}$ [rather than the more accurate function $M(T)\propto B_S(T/T_N)$, where B_S is the Brillouin function and T_N is the Neél temperature]. Using these approximations, the temperature-dependent domain wall width for NiO is given by

$$\delta(T)=100\pi a/(1-T/T_N)^{1/4}. \quad (8)$$

The domain wall is of the order of several hundred lattice constants and is nearly temperature independent, except quite near the Neél temperature.

We can now estimate the strength of this interaction strength, and compare it with the domain wall coupling theory of Slonczewski.[5] As an example, we choose to consider a slab of antiferromagnet whose thickness is 100 lattice constants placed between two layers of a ferromagnetic metal (e.g., permalloy). As previously explained,[3,4] the roughness of the F–AF interface is believed to be responsible for a drastic reduction of the coupling constant between the ferromagnetic film and the antiferromagnetic spacer by about two orders of magnitude from the antiferromagnetic exchange constant. If we choose $J_C=J_{\mathrm{AF}}/100$ as a representative number, and use the values for our generic antiferromagnet, we obtain as an estimate of the Suhl–Nakamura interaction coefficient

$$J_{\mathrm{SN}}\sim J_{\mathrm{AF}}/(250). \quad (9)$$

The domain wall coupling mechanism of Slonczewski predicts a coupling constant $J_{\mathrm{DW}}\sim J_{\mathrm{AF}}/(2N)$, where N is the number of lattice constants in the antiferromagnetic slab. For our example, we obtain

$$J_{\mathrm{DW}}\sim J_{\mathrm{AF}}/(200). \quad (10)$$

(In truth, J_{DW} is considerably smaller than this estimate owing to the very weak coupling of the end spins to the ferromagnets.) For the width of the ferromagnetic spacer we have chosen, the two mechanisms are predicted to be comparable in magnitude. For thinner antiferromagnetic spacers, the Slonczewski domain-wall mechanism will dominate.

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