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Journal of Magnetism and Magnetic Materials 310 (2007) e759–e761

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Non-collinear magnetic junction mediated by Rashba interaction

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Abstract

We study the non-collinear exchange coupling across the trilayer magnetic junction composed of an intermediate layer with Rashba interaction and two sandwiching ferromagnetic ones. To compute the mediated exchange coupling between the ferromagnetic layers, one needs to go beyond the single-particle argument and numerically integrates over contributions from the whole Fermi surface. We found interesting competition between the oscillatory Ruderman–Kittel–Kasuya–Yosida and the non-collinear spiral interactions. Surprisingly, the Fermi surface topology determines which type of magnetic interaction becomes dominant. Finally, we also discuss potential applications for the non-collinear exchange coupling across the junction.

PACS: 71.70.Ej; 73.23.−b; 79.60.Jv; 85.70.Kh

Keywords: Spintronics; Magnetic junction; Rashba interaction

The central theme of spintronics is how to manipulate the extra spin degrees of freedom in condensed matter systems [1–5], in contrast to the traditional electronic devices where only the charge part is utilized. One of the classic examples, which merges charge and spin sectors together in a single device, is the spin field effect transistor (SFET) proposed by Datta and Das [6] more than a decade ago. It was suggested that the Rashba interaction, whose strength can be controlled by the gate voltage, causes the spins of the itinerant carriers to precess and thus can be used to modulate the transport currents.

Compared with the intense attentions on the transport properties, it is less explored how the spin–orbit interaction will reshape our understanding in the more conventional F/N/F trilayer magnetic junction (TMJ) [7], as shown in Fig. 1. The TMJ we study here consists of a pinned ferromagnet on the left and an unpinned one on the right, with the intermediate layer made of semiconductors (such as GaAs) with significant Rashba interaction. Integrating out the itinerant carriers in the intermediate Rashba layer numerically, we can compute the mediated non-collinear exchange coupling. Interestingly, it goes from the oscillatory Ruderman–Kittel–Kasuya–Yosida (RKKY) type to the spiral regime, as we crank up the Rashba interaction. It is rather remarkable that this crossover coincides with the Liftshitz transition for the Fermi surface topology. In addition, the TMJ we propose here may have potential applications to build a non-collinear magnetic junction controlled by the electric field.

We start with integrating out the itinerant carriers in the 2D electron gas described by the Rashba Hamiltonian,

$$H = \int d^2r \Psi^\dagger \left[\frac{k^2}{2m^*}\mathbf{1} + \gamma_R(k_y\sigma^x - k_x\sigma^y)\right]\Psi, \qquad (1)$$

where γ_R is the strength of the Rashba interaction and $\Psi^\dagger, \Psi$ are the two-component spinors of the creation/annhilation operators for itinerant carriers. The eigenstates carry definite momentum k and chirality $\lambda = (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{s}}) \cdot \hat{\boldsymbol{z}} = \pm 1$, where the hat denotes the unit vector [6]. After integrating out the itinerant carriers [7], the exchange coupling between the ferromagnetic layers is

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doi:10.1016/j.jmmm.2006.10.805

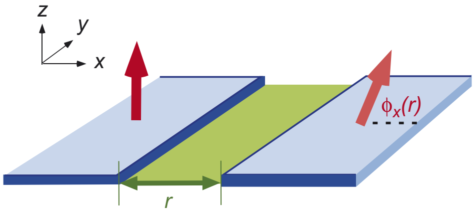

Fig. 1. Schematic plot for the trilayer magnetic junction where $\phi_x(r)$ is the non-collinear angle between the ferromagnets.

proportionally to the spin susceptibility tensor,

$$\chi_{ij}(\mathbf{r}) = \int_0^\infty \mathrm{d}t \langle\langle i[\sigma^i(\mathbf{r},t), \sigma^j(0,0)]\rangle\rangle\, \mathrm{e}^{-\eta t}. \tag{2}$$

Here $\sigma^i(\mathbf{r},t) = \sum_{\alpha\beta}\psi^\dagger_\alpha(\mathbf{r},t)\sigma^i_{\alpha\beta}\psi_\beta(\mathbf{r},t)$ is the spin density operator for the itinerant carriers. Besides, $\langle\langle\ldots\rangle\rangle \equiv \mathrm{tr}[\mathrm{e}^{-\beta H}\ldots]$ represents the thermal average at finite temperature and η is the spin relaxation rate. By utilizing the rotational SO(2), parity P_y (or equivalently P_x), and time reversal symmetries, the susceptibility tensor can be shown to take the following form:

$$\chi_{ij}(r,\theta) = \begin{bmatrix} g_0 + g_2\cos 2\theta & g_2 \sin 2\theta & g_1 \cos\theta \\ g_2 \sin 2\theta & g_0 - g_2 \cos 2\theta & g_1 \sin\theta \\ -g_1 \cos\theta & -g_1 \sin\theta & h_0 \end{bmatrix}. \tag{3}$$

The symmetry arguments are powerful in reducing the numerical task down to evaluation of four real scalar functions, $g_0(r)$, $g_1(r)$, $g_2(r)$ and $h_0(r)$.

Suppose the ferromagnet on the left of the TMJ is aligned along the z-axis, we are interested in the mediated non-collinear exchange coupling proportional to $\chi_{iz}(r,\theta=0)$, where r is the width of intermediate layer. Since $\chi_{yz}(r,0)=0$, the induced moment is captured by the spiral angle $\phi_x(r) = \tan^{-1}[\chi_{zz}(r,0)/\chi_{xz}(r,0)]$, as shown in Fig. 1. Taking parameters from realistic materials [8], we choose the spin splitting $\Delta_\mathrm{R} \equiv 2k_\mathrm{F}\gamma_\mathrm{R} = 5\,\mathrm{meV}$ and the Fermi energy $\varepsilon_\mathrm{F} = 60\,\mathrm{meV}$. Or equivalently, it corresponds to the Rashba coupling $\gamma_\mathrm{R} = 8.91\times10^{-12}\,\mathrm{eV\,m}$ and the carrier density $n_\mathrm{2D} = 1.25\times10^{12}\,\mathrm{cm}^{-2}$. Thus, it falls into the weak Rashba regime (the Fermi surface is illustrated in Fig. 2), characterized by the dimensionless parameter $k_\mathrm{R}/k_\mathrm{F} = 0.042 \ll 1$, where $k_\mathrm{R} = 2m^*\gamma_\mathrm{R}$ and k_F is the Fermi momentum in the absence of Rashba splitting. From Fig. 2, it is clear that the non-collinear angle between the ferromagnets $\phi_x(r)$ shows RKKY-like oscillations with the gradual upswing trend due to the Rashba interaction. The numerical results, drastically different from the spin-precession argument in Datta-Das SFET, demonstrate the importance of the quantum interferences from all patches of the Fermi surface.

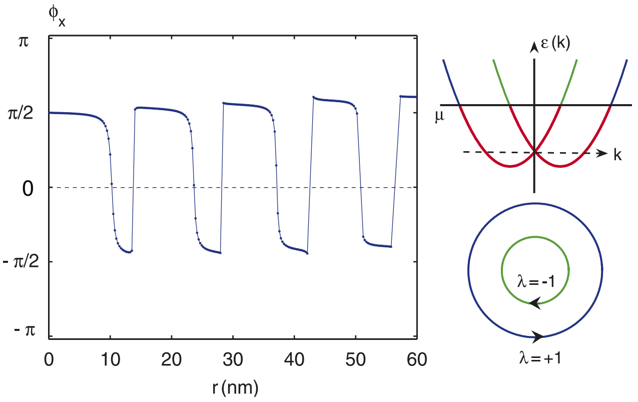

Fig. 2. The spiral angle in weak Rashba regime with $k_\mathrm{R}/k_\mathrm{F} = 0.042$ at $T = 30\,\mathrm{K}$. The Fermi surfaces consist of two concentric circles with *opposite* chiralities, where μ denotes the chemical potential. The smooth minus π-jumps originate from the opposite tendency of angle evolution of the Rashba spiral and RKKY effect.

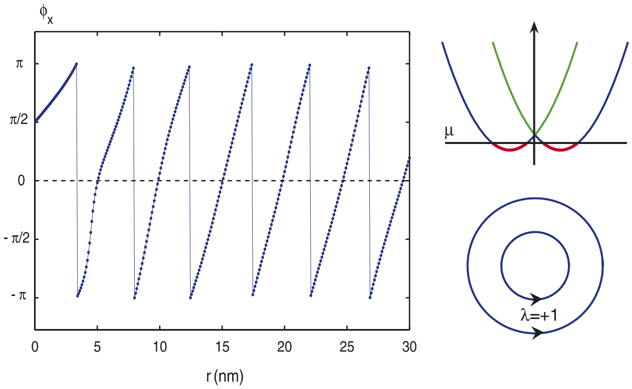

Fig. 3. The spiral angle in the strong Rashba regime where $k_\mathrm{R}/k_\mathrm{F} = 2.6$ and $T = 30\,\mathrm{K}$. The Fermi surface topology changes to two concentric circles with the *same* chirality.

By increasing Rashba coupling to $k_\mathrm{R}/k_\mathrm{F} = 2.6$, the Fermi surface topology changes with only one chirality present (shown in Fig. 3). In this regime, our numerical results demonstrate robust spiral structure with minor oscillatory ripples. It is rather amazing that the change of Fermi surface topology swings the magnetic property from the RKKY dominated to the spiral. Note that the trends of $\phi_x(r)$ at and after the transition $k_\mathrm{R}/k_\mathrm{F} \geqslant 1$ are similar with strong spiraling backbone as seen in Fig. 3. We give a rough estimate for the critical density to enter this spiral regime. With $\gamma_\mathrm{R} = 8.91\times10^{-12}\,\mathrm{eV\,m}$ fixed, one needs to reduce the density below $n_\mathrm{2D} \sim 2.18\times10^9\,\mathrm{cm}^{-2}$.

It is worth emphasizing that the robust spiral exchange in our numerics should not be confused with the spin precession from the single-particle argument. Due to the time-reversal symmetry in the Rashba Hamiltonian, the quantum interferences between the Kramers-degenerate patches of the Fermi surface are *always* present. Thus, so are the RKKY oscillations. The puzzle is why the spiral interaction, when only one chirality is present, always takes the leading role, rendering the RKKY into minor ripples on the spiral backbone. At the point of writing, we do not have a simple physical interpretation for the interesting transition driven by the change of Fermi surface topology.

We acknowledges the grant supports from the National Science Council in Taiwan through NSC 94-2112-M-007-031(HHL) and NSC 94-2112-M-009-025 (CHC).

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