Spin-interference device

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We propose a spin-interference device which works even without any ferromagnetic electrodes and any external magnetic field. The interference can be expected in the Aharonov–Bohm (AB) ring with a *uniform* spin-orbit interaction, which causes the phase difference between the spin wave functions traveling in the clockwise and anticlockwise direction. The gate electrode, which covers the whole area of the AB ring, can control the spin-orbit interaction, and therefore, the interference. A large conductance modulation effect can be expected due to the spin interference. © *1999 American Institute of Physics.* [S0003-6951(99)03031-4]

Much attention has been focused on spin related transport in semiconductor systems. One attractive device application using spins of electrons is the so-called spin field effect transistor (spin FET) which was proposed by Datta and Das.[1] The key idea of this device is that the precession of the spins of carriers injected by the ferromagnetic injector electrode depends on a spin-orbit interaction α of the channel. The modulation of current can be expected by controlling the alignment of the carrier's spin with respect to the magnetization vector in the collector ferromagnetic electrode. Recently it has been shown that the spin-orbit interaction α can be controlled by the gate voltage in InGaAs-based two dimensional electron gas (2DEG)[2,3] and GaAs two dimensional hole gas (2DHG)[4] systems. These results show that the Rashba spin-orbit interaction[5,6] is a dominant mechanism for the spin splitting in these semiconductor systems.

Large efforts have been dedicated to demonstrate spin injection from ferromagnetic contacts into semiconductors. However, the modulation in the conductance of the spin-FET structure has been very small so far.[7] The problem of the spin FET is that the 2DEG is very sensitive to the perpendicular component of the stray field from the ferromagnetic electrodes.[8,9]

In this letter, we propose a spin-interference device which works without any ferromagnetic electrodes and any external magnetic field. We calculate the phases which are acquired by the spin wave functions during a cyclic evolution in an Aharonov–Bohm (AB) ring in the presence of Rashba spin-orbit interaction and Zeeman coupling. It is shown that a large conductance modulation can be expected due to the interference of spin wave functions.

The electron Hamiltonian H in a one dimensional ring in the presence of Zeeman coupling and spin-orbit interaction is given by

$$H=\frac{1}{2m}(-i\hbar\boldsymbol{\nabla}-e\mathbf{A})^2+\frac{e\hbar}{4m^2c^2}\hat{\sigma}\cdot\mathbf{E}\times(-i\hbar\boldsymbol{\nabla}-e\mathbf{A})+\frac{ge\hbar}{4mc}\cdot\hat{\sigma}\cdot\mathbf{B}, \tag{1}$$

where A is the vector potential and the σ's are the Dirac spin matrices. We can rewrite this Hamiltonian in cylindrical coordinates as

$$H=\frac{\hbar\omega_0}{2}\left(-i\frac{\partial}{\partial\phi}+\frac{\Phi}{\Phi_0}\right)^2+\frac{\alpha}{a}\sigma_r\left(-i\frac{\partial}{\partial\phi}+\frac{\Phi}{\Phi_0}\right)+\frac{\hbar\omega_B}{2}\sigma_z, \tag{2}$$

where a is the radius of the AB ring, and we introduce the following parameters:

$$\omega_0=\frac{\hbar}{ma^2},\quad \omega_B=\frac{geB_z}{2mc},\quad \alpha=\frac{e\hbar^2E_z}{4m^2c^2},\quad \Phi_0=\frac{h}{e}.$$

By substituting the Dirac matrices for the spin operators and then diagonalizing this 2×2 matrix, we can find four eigenfunctions of the Hamiltonian. They are given by

$$\begin{aligned}
\Psi_\uparrow^+(\phi)&=\exp[in\phi]\begin{bmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{bmatrix},\\
\Psi_\uparrow^-(\phi)&=\exp[-in\phi]\begin{bmatrix}\cos\frac{\theta}{2}\\ -\sin\frac{\theta}{2}e^{i\phi}\end{bmatrix},\\
\Psi_\downarrow^+(\phi)&=\exp[in\phi]\begin{bmatrix}\sin\frac{\theta}{2}e^{-i\phi}\\ -\cos\frac{\theta}{2}\end{bmatrix},\\
\Psi_\downarrow^-(\phi)&=\exp[-in\phi]\begin{bmatrix}-\sin\frac{\theta}{2}e^{-i\phi}\\ -\cos\frac{\theta}{2}\end{bmatrix},
\end{aligned} \tag{3}$$

where the arrow stands for the spin direction and the plus/minus sign for the travel direction. Figure 1 gives an overview of the spin direction of the clockwise and anticlockwise traveling electronic waves. It is natural to have eigenfunctions like Eq. (3) from the definition of the spin directions in Fig. 1. The effective magnetic field B_{eff} due to the spin-orbit interaction is perpendicular to the momentum direction

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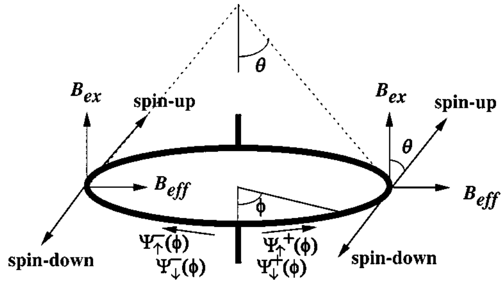

FIG. 1. Overview of the spin directions of the clockwise and anticlockwise traveling electronic waves.

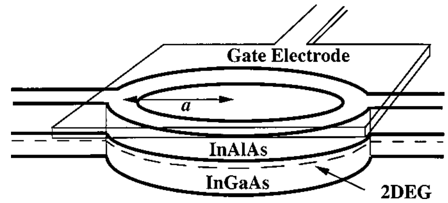

FIG. 2. Schematic structure of a spin-interference device. The channel has a strong spin-orbit interaction. The AB-ring area is covered with the gate electrode which controls the spin-orbit interaction.

and the electric field induced by the asymmetric quantum well profile. The spin tilt angle θ is given by $\tan\theta = \langle H_{\mathrm{s.o.}}\rangle / \langle H_{\mathrm{Zeeman}}\rangle$.

Notice that we have defined n in Eqs. (3) to be positive, in order to get the right sign of the expectation value of the velocity. By using these eigenfunctions we can deduce the expectation value of the energy. The expectation value of the energy will depend on the spin direction μ and travel direction λ, and is given by

$$\begin{aligned}\langle E\rangle_\mu^\lambda = &\frac{\hbar\omega_0}{2}\left(n_\mu^\lambda + \lambda\frac{\Phi}{\Phi_0} + \lambda\mu\frac{1}{2}(1-\cos\theta)\right)^2 \\ &+\mu\frac{\alpha}{a}\left(n_\mu^\lambda + \lambda\frac{\Phi}{\Phi_0} + \lambda\mu\frac{1}{2}(1-\cos\theta)\right)\sin\theta \\ &+\mu\frac{\hbar\omega_B}{2}\cos\theta. \end{aligned}\tag{4}$$

Here we can easily identify the first term as being the kinetic energy, the second term as being the spin-orbit energy, and the last term as being the Zeeman energy, respectively.

When we impose that the energy of the electrons is independent of spin- and travel direction and should be equal to the Fermi energy, we can deduce the difference in quantum numbers n_μ^λ by using Eq. (4). Therefore, the phase difference between the spin-up waves traveling in opposite directions after half a revolution can be obtained as

$$\begin{aligned}\Delta\varphi_{\Psi_\uparrow^+ - \Psi_\uparrow^-} &= \int (k_\uparrow^+ - k_\uparrow^-)\cdot dr \\ &= \pi a \Delta k_\uparrow^\lambda = \pi\Delta n_\uparrow^\lambda = -2\pi\frac{\Phi}{\Phi_0} - \pi(1-\cos\theta).\end{aligned}\tag{5}$$

In a completely analogous way we find for the phase difference between spin-down waves

$$\Delta\varphi_{\Psi_\downarrow^+ - \Psi_\downarrow^-} = -2\pi\frac{\Phi}{\Phi_0} + \pi(1-\cos\theta).\tag{6}$$

For the phase difference between waves of opposite spin and travel direction we get

$$\begin{aligned}\Delta\varphi_{\Psi_\uparrow^+ - \Psi_\downarrow^-} &= \pi(n_\uparrow^+ - n_\downarrow^-) = -2\pi\frac{\Phi}{\Phi_0} - 2\pi a\frac{m^*\alpha}{\hbar^2}\sin\theta, \\ \Delta\varphi_{\Psi_\downarrow^+ - \Psi_\uparrow^-} &= -2\pi\frac{\Phi}{\Phi_0} + 2\pi a\frac{m^*\alpha}{\hbar^2}\sin\theta.\end{aligned}\tag{7}$$

Equations (7) are only valid if the spin-orbit energy is much larger than the Zeeman energy, i.e., when we apply a small magnetic field. In Eq. (5), we can identify the first term as being the Aharonov–Bohm (AB) phase, and the second term as being the Aharonov-Anandan phase, which is equal to the Berry phase in the adiabatic limit. In expression (7), we also identify the AB phase as well as the dynamical part of the Aharonov–Casher (AC) phase. The Berry phase[10] and the AC dynamical phase[11] of the AB ring in the presence of the Rashba spin-orbit interaction were obtained in different ways. The present calculation clearly shows that the Berry phase is important in an interference between equal spin waves, and the AC dynamical phase in an interference between opposite spin waves. It is also clear from Fig. 1 that opposite spin waves traveling in the same direction are orthogonal, but that spin-up and spin-down waves traveling in different directions are not orthogonal. From our calculation, the origin of the AC dynamical phase is due to the difference in precession direction of the spin between the upper and lower branch of the ring.

In a weak magnetic field limit $B=0$, $\langle H_{\mathrm{Zeeman}}\rangle = 0$ therefore $\theta=\pi/2$, the phase difference between waves of equal spin now goes to π, and the phase difference between opposite spin waves becomes exactly the dynamical AC phase. Notice further that in the case of $B=0$, the spinors of equal spin states traveling in opposite directions become orthogonal, whereas the spinors of opposite spin state are parallel.

As the first order approximation, we can describe the conductance of the ring as

$$G = \frac{2e^2}{h}\sum_n T_n = \frac{e^2}{h}\left|\sum_{\mu,\lambda}\Psi_\mu^\lambda\right|^2.\tag{8}$$

Thus, we have to calculate 16 inner products, some of which will vanish because of spinor-orthogonality condition. Here we see that the phase difference between opposite spin states play an important role, and the conductance modulation in one dimensional ring can be given by

$$G = \frac{e^2}{h}\left[1+\cos\left(2\pi a\frac{\alpha m^*}{\hbar^2}\right)\right].\tag{9}$$

Figure 2 shows a spin-interference device which we propose. The gate which controls the spin-orbit interaction α covers the whole area of the AB ring. Note that Datta and Das[1] pointed out a possibility of spin interference due to the weak antilocalization effect[12] such as an AB ring with *different* spin-orbit interaction strengths in the two branches. However, the present calculation shows that a spin-interference effect can be expected in the AB ring with a *uniform* spin-orbit interaction. The dynamical phases acquired in the upper and lower branch are not the same but of opposite sign, and are not cancelled out at the outgoing lead. It is interesting to note that the obtained dynamical phase is the same expression as in the case of the spin FET. The origin of the phase difference in both cases is related to the spin precession.

In the case of the spin-FET device, the spin-polarized electrons injected from the ferromagnetic electrode contribute the conductance modulation. The spin polarization rate in the conventional ferromagnetic material is not 100%; several times 10% has been reported from the superconductor/insulator/ferromagnetic tunneling experiments.[13] On the other hand, all carriers contribute to the spin interference in this proposed device.

So far we discussed the one dimensional AB ring where the channel consists of a single mode. Here we emphasize that this spin-interference device with multi modes works as well, because the phase difference of the spin waves is independent of the wave vector of the modes in upper and lower branches. Usually electron quantum interference devices[14] have to be a single mode in order to obtain larger modulation, because the difference in wave vector from one mode to another causes a different phase shift which smears the interference effect. An important advantage of this proposed spin-interference device is that the current modulation is not washed out even when multiple modes are involved.

In this device, the gate voltage changes the spin-orbit interaction as well as the carrier concentration, and therefore the wavelength of the electrons. If we make the upper and lower branch of the ring of equal length, the interference effect due to the change in wavelength will be cancelled out. Another way to pick up only the spin-interference effect is to put a back gate which cancels the carrier concentration change. The combination of front and back gate can only control the asymmetry of the quantum well, therefore, the spin-orbit interaction. According to the experimental data[2] of the spin-orbit interaction $\alpha = 0.65 - 1.05 \times 10^{-11}\,\mathrm{eV\,m}$, the change in the phase difference is $\Delta\varphi = 4.6\pi - 7.4\pi$ in an AB ring with 0.3 μm radius, and therefore, a large conductance modulation is possible.

In summary, we propose a spin-interference device which does not have any ferromagnetic electrodes. The interference can be expected in the AB ring with a *uniform* spin-orbit interaction, which causes the phase difference in the spin wave functions. The gate electrode, which covers the whole area of the AB ring, controls the spin-orbit interaction, and therefore, the interference. The advantage of this proposed spin-interference device is that conductance modulation is not washed out even in the presence of multiple modes.

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