Rashba spin precession in a magnetic field

Jun Wang,[1,2] H. B. Sun,[1] and D. Y. Xing[2]
[1]*Center of Quantum Computing Technology and School of Physical Sciences, University of Queensland, Brisbane Qld 4072, Australia*
[2]*National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China*
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Spin precession due to Rashba spin-orbit coupling in a two-dimension electron gas is the basis for the spin field effect transistor, in which the overall perfect spin-polarized current modulation could be acquired. There is a prerequisite, however, that a strong transverse confinement potential should be imposed on the electron gas or the width of the confined quantum well must be narrow. We propose relieving this rather strict limitation by applying an external magnetic field perpendicular to the plane of the electron gas because the effect of the magnetic field on the conductance of the system is equivalent to the enhancement of the lateral confining potential. Our results show that the applied magnetic field has little effect on the spin precession length or period although in this case Rashba spin-orbit coupling could lead to a Zeeman-type spin splitting of the energy band.

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Spin-polarized electron transport in microstructures has attracted considerable attention since last decade, fueled by the possibility of producing efficient photoemitters with a high degree of polarization of the electron beam (spin light-emitting diode), creating spin-based memory device and utilizing the properties of spin coherence for quantum computation and communication. In the spintronics (spin-based electronics) field, both degree of freedom of spin and charge are exploited, even spin could entirely replace the electric charge to carry information. This is the basis for a new generation of electric devices.[1]

The spin-polarized field effect transistor (SFET) proposed by Datta and Das[2] is one of the most attractive spintronic devices for it may switch faster than the traditional transistor since it can avoid redistributing charges during operation. The idea is based on Rashba spin-orbit (RSO) coupling[3] in two-dimensional electron gas (2DEG). It results in spin precession as electrons move along a heterostructure and can be controlled by an external electric field. This novel spintronic device has three requirements: (1) long spin-relaxation time in 2DEG; (2) gate voltage control of RSO coupling, and (3) high spin injection efficiency. At present, the first two conditions have been basically satisfied in experiments.[4,5] It appears to be very difficult, however, to achieve an efficient injection of spin-polarized carriers from a ferromagnetic metal into 2DEG, and a great deal of work has been dedicated to this challenge.[6–11]

Apart from the three requirements above for an SFET, in fact, there is another basic limitation to the ultimate implementation of SFET, i.e., in order to restrict the angular distribution of electrons in a 2DEG,[2] a strong enough transverse confining potential must be imposed on the 2DEG or the width of the confined quantum well must be very narrow. The RSO interaction in the 2DEG comes from the inversion asymmetry of the structure and can be expressed as[3] $\mathcal{H}_R = (\alpha/\hbar)(\boldsymbol{\sigma}\times\mathbf{p})$, where $\boldsymbol{\sigma}$ is Pauli matrix, α is the RSO coupling constant proportional to the external electric field **E**, and **p** is the momentum operator. The term $\mathcal{H}_R$ itself can lift the degeneracy of spin space but not lead to a Zeeman-type split of energy band, because the time inversion symmetry of system remains unchangeable under this RSO interaction. When an electron propagates, however, the RSO coupling can result in spin precession of electronic current along its propagating way due to the interference of two spin-splitting electronic waves. To ensure the perfect spin modulation of electric current in SFET, the energy gap between two neighboring subbands due to the lateral confining potential, which is generally assumed to have reflection symmetry, must be much larger than the intersubband mixing from RSO coupling,[2,12] i.e., $\langle n|\mathcal{H}_R|n+1\rangle/(\varepsilon_{n+1}-\varepsilon_n)\ll 1$ with n being the index of subband. Therefore, the subband energy dispersion from RSO keeps linear k dependence. It has been argued[12] that in the hard-wall confining potential, the width of the quantum well must satisfy $W\ll\hbar^2/\alpha m$ with m being the effective mass of electrons. From this, one can see that the RSO coupling constant α modulated by an external electric field is strongly limited by the width W of transverse confined potential well.

In this paper, we propose to employ an external magnetic field to relieve the limitation to a strong transverse confining potential or the narrow well width. The Landau level will form in the magnetic field so that the energy gap of intersubbands could be enlarged and the RSO coupling constant α could be modulated in a larger range, in which the perfect spin-current modulation could not be destroyed. The magnetic field effect is equivalent to the enhancement of the confining potential or the reduction of the effective width of the quantum wire. However, does it introduce another factor to destroy the spin precession? To answer this question is another motive of this paper that investigates the interplay between the RSO coupling and the external magnetic field. Our numerical results show that the RSO coupling in magnetic field will lead to spin split of the subband spectrum like Zeeman effect, while the spin precession from RSO coupling keeps almost invariable such as its length or period.

The model we adopted is a two-terminal device that a quasi-one-dimensional quantum wire with RSO coupling is connected by two ideal leads. This device is subjected to a magnetic field perpendicular to the two-dimensional plane (xy plane, it is assumed that x is the current direction of the device). Considering the real condition in experiment, the magnetic field applied to the RSO coupling region is assumed inhomogeneous and being tuned adiabatically on and off as in Ref. 13. After discreting procedure, a type of tight-binding Hamiltonian including the RSO coupling on a square lattice is obtained in absence of magnetic field,[12]

$$\mathcal{H}=\sum_{lm\sigma} \varepsilon_{lm\sigma}C^{\dagger}_{lm\sigma}C_{lm\sigma}-t\sum_{lm\sigma}\{C^{\dagger}_{l+1,m\sigma}C_{lm\sigma}+C^{\dagger}_{l,m+1,\sigma}C_{lm\sigma}+\text{H.c}\}-t_{so}\sum_{lm\sigma\sigma'}\{C^{\dagger}_{l+1,m,\sigma'}(i\sigma_y)_{\sigma\sigma'}C_{lm\sigma}-C^{\dagger}_{l,m+1,\sigma'}(i\sigma_x)_{\sigma\sigma'}C_{lm\sigma}+\text{H.c.}\}, \quad (1)$$

where $C^{\dagger}_{lm\sigma}(C_{lm\sigma})$ is the creation (annihilation) operator of electron at site (lm) with spin σ and $\varepsilon_{lm\sigma}=4t$ is the site-energy, $t=\hbar^2/2ma^2$ is the hopping energy, a is the lattice constant, and $t_{so}=\alpha/2a$ is the RSO coupling strength. Here we focus on the case of an impurity-free quantum wire with RSO coupling. The generalization to the case including impurities is straightforward.[14] In our following calculation, all energy is normalized by the hoping energy $t(t=1)$. When the magnetic field $\mathbf{B}(0,0,1)$ is introduced, it could be incorporated into the nearest-neighbor hopping energy by the Peierl's phase factor such as

$$T_{lm,lm+1}=t\exp(i\hbar\omega_c l/2t)=(T_{lm+1,lm})^{\star};T_{lm,l+1,m}=(T_{l+1m,lm})^{\star}=t, \quad (2)$$

where $\omega_c=eB/mc$ is the cyclotron frequency. We choose vector potential $\mathbf{A}(By,0,0)$ and keep the transitional symmetry of system along the x direction (electric current direction). In magnetic field, RSO coupling Hamiltonian is reexpressed as $\mathcal{H}_R=(\alpha/\hbar)\boldsymbol{\sigma}\times(\mathbf{p}+e\mathbf{A}/c)$ so that t_{so} has a similar modification. The spin-quantum axis is chosen along z direction. The Zeeman effect from the external magnetic field is not included here.

In the ballistic transport, the conductance of structure is given by Landauer-Buttiker formula $G^{\sigma}=(e^2/h)T^{\sigma}$ and T^{σ} is the multichannel transmission coefficient of electron with spin σ. Based upon the nonequilibrium Green function formalism,[15] the following result for spin-resolved conductance is obtained[14]

$$G^{\sigma\sigma'}=\frac{e^2}{h}\text{Tr}[\Gamma^{\sigma}_{L}G^{\sigma\sigma'}_{r}\Gamma^{\sigma'}_{R}G^{\sigma'\sigma}_{a}], \quad (3)$$

where $\Gamma_{L(R)}=i[\Sigma^{r}_{L(R)}-\Sigma^{a}_{L(R)}]$, $\Sigma^{r}_{L(R)}=(\Sigma^{a}_{L(R)})^{\star}$ is the self energy from the left (right) lead, $G_{r(a)}$ is the retarded (advanced) Green function of the structure, and the lead effect is incorporated into the self energy of green function $G_{r(a)}$. The trace is over the spatial degrees of freedom. The Green function above is computed by the well-known recursive Green function method[16,17] and the conductance is evaluated at the Fermi energy. Our following discussion is based on the assumption that only spin-up polarized electrons are injected from the left lead into RSO region (where the spin precession of incident electron is induced) and collected in the right lead.

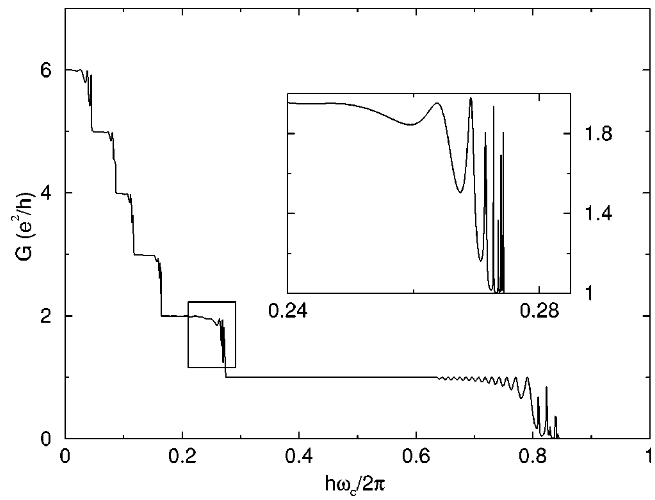

FIG. 1. The conductance of quantum wire as a function of magnetic field $\hbar\omega_c$ in absence of RSO coupling $t_{so}=0$. The inset enlarges the points just above the threshold of the second transmitted mode.

We have chosen the lattice size a much smaller than the Fermi wavelength λ_F $(\lambda_F=10a)$ so that our model can simulate a continuum system. The width and the length of the quantum wire are taken as $N_y a=30a$ and $N_x a=60a$, respectively. The calculated results of the conductance are plotted in Fig. 1 as a function of the external magnetic field in the absence of RSO interaction. It appears that the conductance is quantized and decreases with magnetic field. At $\hbar w_c=0$, there are 6 modes (subbands) at the Fermi energy $(E_F=0.4t)$ contributing to the conductance. When $\hbar w_c\neq 0$, all subbands are elevated and the energy gap of intersubbands increases due to the formation of Landau level as shown in Fig. 2 (more detailed later). The transmitted modes below E_F thus becomes less and the conductance is quantized and decreases with $\mathbf{B}$. Basically, when $\hbar w_c>2E_F$, there is no transmitted mode contributing to conductance and it decreases to zero. The conductance quantization induced by magnetic field resembles that found in quantum point contact, in which the number of modes at E_F will change in discrete steps by constricting continuously its width.[18] In other word, the magnetic field effect on the conductance of a quantum wire is equivalent to the reduction of its effective width or enhancement of the confining potential because a strong transverse potential will also lead to decrease of the number of modes at E_F.[19]

Apart from the quantization of conductance in Fig. 1, another character, the oscillation of conductance is also found in our results. This oscillation is referred to as the Aharonov-Bohm (AB) effect[20,21] and originates from the edge state[22] in a magnetic field. Due to the multireflection of electrons in quantum wire before they escape to the collector, the right-going channel and left-going channel form a loop resulting from the perpendicular magnetic field so that the quantum interference will lead to AB effect as that in a mesoscopic ring. The oscillation periodicity is related to the wave vector of the transmitted mode and the length of the multireflection region. Consequently, the oscillation becomes apparent just

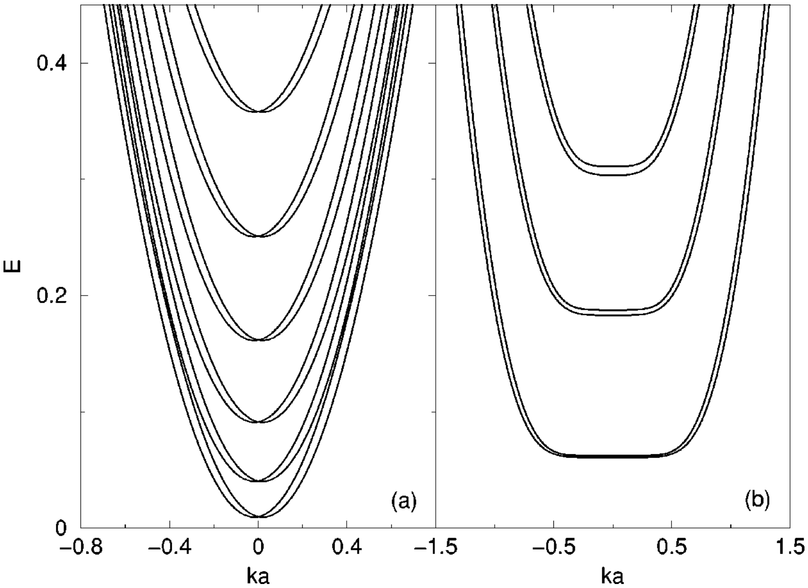

FIG. 2. The subband energy spectrum with RSO coupling strength $t_{so}=0.02$; (a) no magnetic field $\hbar\omega_c=0$ and (b) $\hbar\omega_c=0.24$.

above the threshold of every transmitted mode where the wave vector turns out to be smaller.

The subband energy spectrum is plotted in Fig. 2 at the presence of RSO coupling. Since the contribution to conductance of those evanescent modes could be neglected, only these modes at E_F are shown. When there is no magnetic field $\mathbf{B}=0$ in Fig. 2(a), the spectra seem to be simple parabolic due to a weak RSO coupling $t_{so}=0.02t$ used in our calculation.[19] The degeneracy of spin space is lifted by the RSO coupling, however, it does not resemble Zeeman effect that leads to split of the energy band, and here the spin degeneracy at $k=0$ still exists. When the intersubband mixing from RSO coupling is neglected, the spin-resolved eigenvalues are approximately at every subband $\varepsilon_{\pm}(k)=\varepsilon_n+\hbar^2k^2/2m\pm\alpha k$, $\pm$ denotes two spin-splitting bands due to the RSO coupling and not the eigenstates of $\boldsymbol{\sigma}_z$ yet. Once $\mathbf{B}\neq 0$, the Landau levels form in the system and this is the reason of the platform appearing at the bottom of subbands (near $k=0$) as shown in Fig. 2(b). Both the subbands and their energy difference are enhanced in comparison with Fig. 2(a) when the external magnetic field increases, moreover, the gap of intersubbands is basically equivalent to $\hbar w_c$. It is interesting to note that the RSO coupling will lead to a Zeeman-type energy-band split under $\mathbf{B}\neq 0$. In an ideal 2DEG under a magnetic field, the plane waves of eigenstates have no group velocity, $\partial\varepsilon/\partial k=0$, and the RSO modification has no relation with wave vector k. At this moment, the difference of the two spin eigenvalues is $\Delta\varepsilon=(2\alpha\sqrt{2m}/\hbar)\sqrt{\hbar w_c(n+1)}$, here n denotes the Landau level. Thus the RSO spin-splitting strength is related to the energy level index n and the magnetic field $\mathbf{B}$.

The effect of an external magnetic field is equivalent to the enhancement of the transverse confining potential on a quantum wire, which results in an enlargement of the intersubband energy gap so that the perfect spin-polarized current modulation can be kept in a larger α parameter region. In Fig. 3, two spin-splitted conductances are presented as the RSO coupling strength t_{so} varies. At $\mathbf{B}=0$, the conductance modulation is quickly and clearly weakened by the intersubband mixing that increases with RSO coupling; otherwise, as $\mathbf{B}$ increases, the subband mixing from RSO coupling could be neglected compared to the intersubband energy gap, and the perfect spin modulation of conductance would remain in a larger RSO coupling range as shown in Fig. 3(b), where

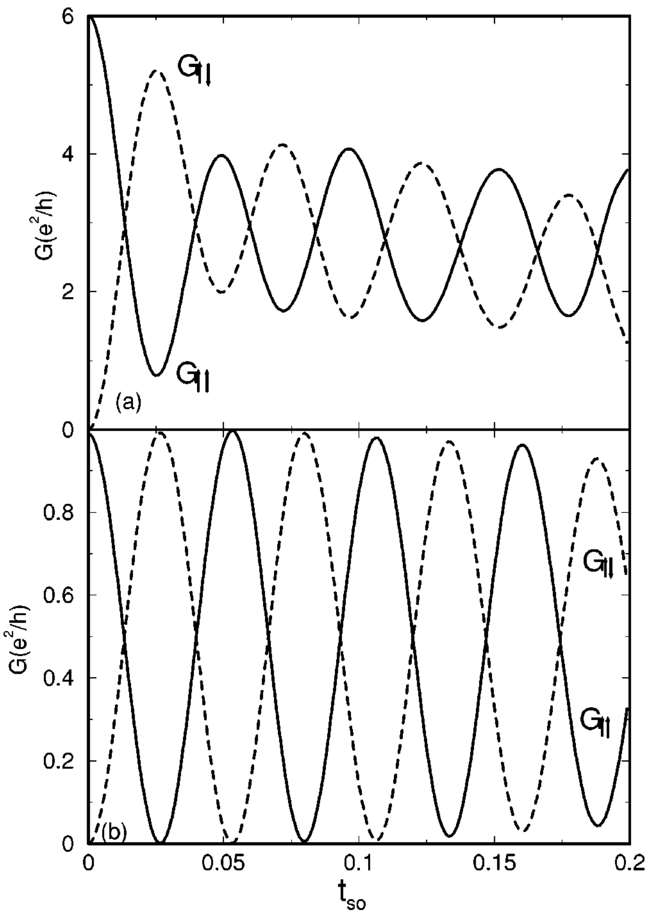

FIG. 3. The spin modulation of conductance vs RSO coupling strength t_{so}; the solid line and dash line represent $G^{\uparrow\uparrow}$ and $G^{\uparrow\downarrow}$, respectively. (a) $\hbar\omega_c=0$ and (b) $\hbar\omega_c=0.40$.

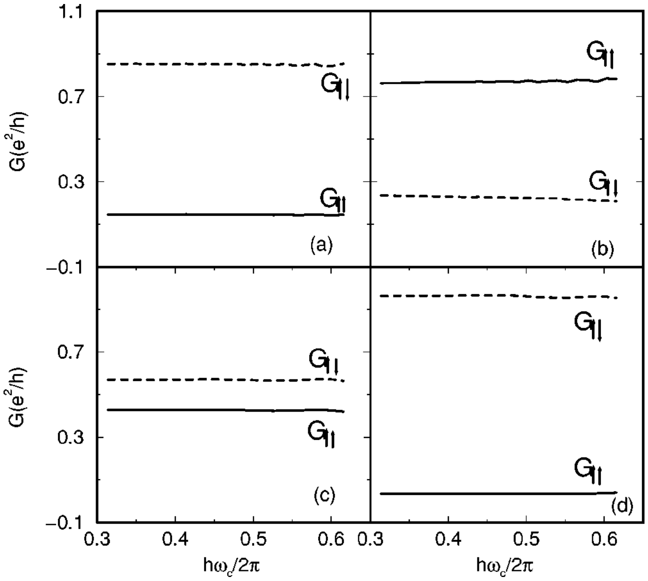

FIG. 4. The spin-resolved conductance in different RSO coupling constants t_{so} and the lengths of quantum wire N_x; the solid line and dash line are same as in Fig. 3. (a) $t_{so}=0.02$, $N_x=60$; (b) $t_{so}=0.04$, $N_x=60$; (c) $t_{so}=0.02$, $N_x=40$, $t_{so}=0.04$, $N_x=40$.

only one transmitted mode contributing to conductance is chosen to be plotted as a result of the magnetic field effect. This oscillation of conductance originates from the interference of two RSO spin-splitted electronic waves in one subband. The oscillation period can be determined by the accumulated phase difference $\Delta\theta=2t_{so}^{*}N_x$, here $N_x a$ is the length of RSO interaction region. For instance, $N_x=60$ is chosen in our calculation and the oscillation period is estimated $T_{t_{s0}}=0.512$. The RSO coupling is the basic principle for the operation of an SFET. One can control the output spin polarization of the SFET by tuning the RSO coupling constant via an external electric field. In a real device, it is also required that spin dephasing length should be much longer than device size to avoid spin mixing. While in order to avoid the distraction of spin modulation at the collector by the intersubband mixing, an external magnetic field may be an alternative as discussed above.

Another point to be noted is that even $\mathbf{B}\neq 0$, the oscillation period from RSO coupling is still independent of the energy of injected electrons and the magnetic field, i.e., two spin-resolved conductances are mainly determined by the RSO coupling constant α and the length of RSO region $N_x a$, when the number of mode at E_F is fixed. In Fig. 4, we plot the conductances as a function of magnetic field at different α and N_x. It is shown that the conductance $G^{\uparrow}$ and $G^{\downarrow}$ keep almost unvaried as the magnetic field **B** varies. This case is similar to that they are independent of the energy of injected electrons at a weak RSO coupling region unless the different transmitted modes at Fermi energy are involved (not shown) when the energy of injected electrons varies.[12]

In summary, we have investigated the ballistic transport of a quasi-one-dimensional quantum wire considering the RSO interaction under an external magnetic field. We find that the perfect spin modulation of the conductance due to the RSO coupling would not be destroyed in the large coupling constant region because the RSO coupling between different transmitted modes is negligible compared with their energy difference. We conclude that our proposal of applying a magnetic field to the system can be a proper alternative to the prerequisite of the narrow width of the quantum wire or the strong transverse confining potential for the functional operation of a spin field effect transistor.

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