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Tunable energy bands and spin filtering in two-dimensional superlattices with spin-orbit interaction

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We theoretically investigate the electronic energy bands and spin filtering tuned by Rashba spin-orbit coupling (SOC) and magnetic field in two-dimensional superlattices (2DSLs), where the square rods of quantum barriers, matrix, and wells are imposed periodically. It is shown that electronic energy spectra form a band structure and the energy levels are split up by the Rashba SOC. Correspondingly, the electrical conductance presents a "band-gap" structure against the electron energy. With manipulating the strength of SOC, the conductance in the "band" is enhanced for the spin-up electrons, while it is reduced for the spin-down electrons. Interestingly, by introducing a magnetic modulation, conductance curves for spin-up and spin-down electrons are translated in the different directions. As a result, high spin polarization is observed, and fully spin-polarized conductance is achieved in this 2DSL. Furthermore, the electronic wavefunctions have been obtained, which presents a clear picture of spin filtering. Our investigations achieve potential applications in spin quantum devices and spin filters. © *2012 American Institute of Physics*. [doi:10.1063/1.3684715]

Recently, much attention has been paid to generating and manipulating spin-polarized current in semiconductor devices for the purposes of spintronics.[1,2] Considering the electronic transport in semiconductors, it is essential to take into account the impact of the spin-orbit coupling (SOC) on the dynamics of carriers and especially on their spin.[3] The strength of the Rashba SOC depends on the materials and the confinement fields via a gate voltage applied on the semiconductor.[4] Up to now, more and more studies of transport properties in a two-dimensional electron gas (2DEG) with SOC have been reported.[5,6] For example, Khodas *et al.*[7] demonstrated that electrons will split into two spin-polarized beams when passing through the lateral interface between two regions with different strengths of the spin-orbit interactions in 2DEG. The spin double refraction and the negative refraction of spintronics have also been investigated by including SOC.[8] These researches provide a significant method to achieve spin beam splitters or spatially separating spin filters, which are important for spin injection.

On the other hand, the problem of electrons subject to perpendicular magnetic field and two-dimensional periodical potential remains actual.[9] It is found that the quantum states in this system can be influenced by the magnetic field and periodical potential. Other studies demonstrate that the conductance in two-dimensional arrays can be significantly modulated by the SOC, even at high temperature and strong dephasing.[10,11] In this work, we theoretically investigate the electronic energy bands and spin filtering in two-dimensional superlattices (2DSLs), where the square rods of quantum barriers, matrix, and wells are imposed periodically. By manipulating the strength of SOC or the magnetic potential, high spin polarization is observed and fully spin-polarized conductance can be achieved in this 2DSL. The investigations achieve potential applications in spin quantum devices and spin filters.

We consider a 2DSL confined in the x-y plane with a uniform magnetic field $\boldsymbol{H}$ along the z-axis (as shown in Fig. 1). In the potential wells, the confining electric field in the z direction results in the Rashba SOC.[3,4] Then, the Hamiltonian of the system can be written as

$$H = \frac{p_x^2 + [p_y + eA_y]^2}{2m(x,y)} + V(x,y) + \frac{\alpha}{\hbar}[\sigma_x(p_y + eA_y) - \sigma_y p_x]f(x,y) + \Delta\sigma_z,$$

where $\sigma_i (i = x, y, z)$ is the Pauli matrix, and α is the spin-orbit Rashba parameter. Δ indicates the strength of the Zeeman-type potential, and A_y represents the y-component of the magnetic vector potential given, in the Landau gauge, by $A = [0, A_y, 0]$. The function $f(x,y)$ equals to 1 and 0 in the

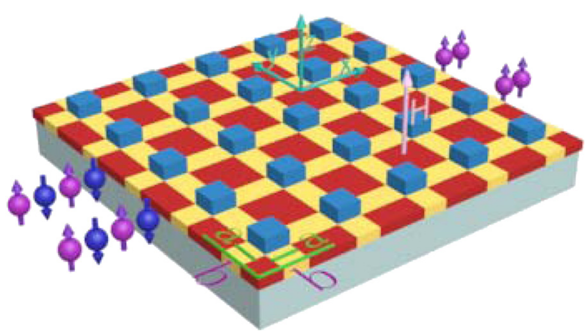

FIG. 1. (Color online) The schematic configuration for the 2DSL with the electron transport along the x-axis.

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regions with and without SOC, respectively. We have performed calculations based on the $Al_dGa_{(1-d)}As$ superlattice with $d = 0.6$, 0.3, and 0 in the potential barrier, matrix, and well, respectively. The effective mass and the conduction band bottom level can be expressed by[12] $m(x,y) = m_0(0.067 + 0.083d)$ and $V(x,y) = 0.944d - 0.283$, respectively. Here, m_0 is a free electron mass and the effective potential in eV.

Notice that the wave function of the system can be described as $\psi_\pm = \frac{e^{i(k_x x + k_y y)}}{\sqrt{2}}\begin{pmatrix} 1 \\ \pm i e^{i\theta}\end{pmatrix}$ $(\theta = \arctan(k_y/k_x))$ when the magnetic field is zero. Actually, the time-reversal symmetry will be broken when the magnetic field is introduced,[13] which can influence the transport property of electrons. Once the spinor-valued wave functions are determined, the spin-dependent charge density distribution can be achieved by $|\psi_\pm|^2$. Based on the Landauer Büttiker formula,[14] the conductance for oppositely spin-polarized electrons can be achieved by $G_\uparrow = (e^2/h)(T_{\uparrow\uparrow} + T_{\downarrow\uparrow})$ and $G_\downarrow = (e^2/h)(T_{\downarrow\downarrow} + T_{\uparrow\downarrow})$ respectively. $T_{\uparrow\uparrow}$ and $T_{\downarrow\uparrow}$ are defined as the transmission coefficients for electrons in the outgoing spin-up state with the incident spin-up state and spin-down state and $T_{\downarrow\downarrow}$ and $T_{\uparrow\downarrow}$ for electrons in the outgoing spin-down state with the incident spin-up and spin-down state, respectively. Then the spin polarization can be expressed as $P = (G_\downarrow - G_\uparrow)/(G_\downarrow + G_\uparrow)$.

We have calculated the electron eigenenergies by using finite-element methodology. Figures 2(a)–2(d) show the energy levels along the path $\Gamma - X - M - \Gamma$, which connects the respective critical points in the Brillouin zone (BZ) of 2DSL with the side length a = 5 nm and b = 15 nm and different α. It is found that the electron eigenenergies form a band structure and the energy levels are split up, due to the Rashba SOC. The degree of separation is enhanced with increasing the strength of SOC α (see the dotted boxes in Fig. 2). However, the spin degeneracy is not lifted both at the border and the center of BZ. This feature comes from the fact that the energy gaps are opened up at the border of BZ when a periodic potential $V(x,y)$ is included. Meanwhile, the group velocities, which are proportional to the gradient of energy curves in the reciprocal space, are zero at the border and the center of the BZ. Nevertheless, the group velocities are nonzero in BZ beside its border and center, which brings about the spin-split of energy bands. Therefore, the spin-split energy band is formed in the 2DSL, which can lead to electron transport that is very sensitive to electron spin.

It is worthwhile to study the conductance for the purpose of application. Figures 3(a)–3(d) show the conductance against the electron energy in the 2DSL. There are several interesting features. First, due to the band structure of the electronic energy spectra, there is a conductance "band-gap" structure against the electron energy. Second, the conductance curves are separated when the Rashba SOC is included. As shown in Figs. 3(a)–3(b), the conductance for one kind of spin-polarized electron is enhanced, while the other one is reduced in the "band". It should be noted that the conductance "bands" both for spin-up and spin-down electrons are overlapped. By increasing α, the separation of conductance curves is enlarged. Then, spin-

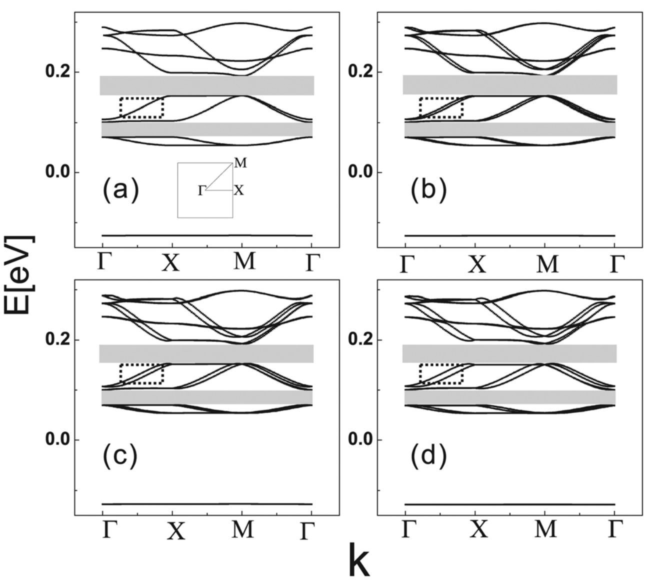

FIG. 2. The energy spectra along the path $\Gamma - X - M - \Gamma$, which connects the respective critical points in the BZ (see the inset in (a)) with different α: (a) $\alpha = 0$ a.u. (1 a.u. $= 1 \times 10^{-11}$ eV.m); (b) $\alpha = 3$ a.u.; (c) $\alpha = 5$ a.u.; and (d) $\alpha = 7$ a.u.

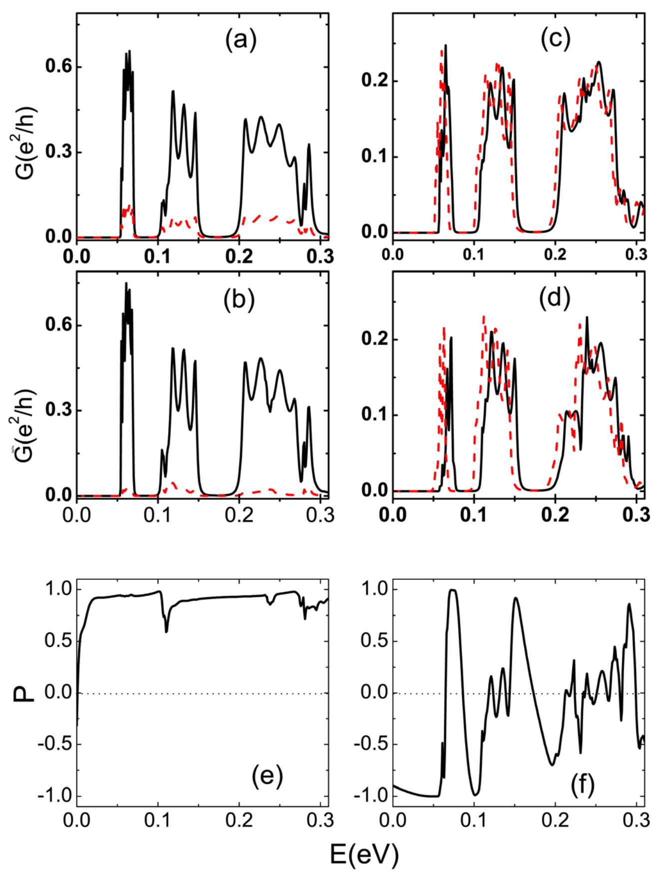

FIG. 3. (Color online) (a) and (b) present the spin-dependent conductance against the electron energy with $\Delta = 0$ and different α: (a) $\alpha = 2$ a.u. and (b) $\alpha = 5$ a.u. The black solid and red dashed lines correspond to spin-up and spin-down electrons, respectively. (c) and (d) show the spin-dependent conductance vs E with $\alpha = 0$ a.u. and different Δ: (c) $\Delta = 3$ MeV and (d) $\Delta = 5$ MeV. (e) and (f) plot the spin-polarization against E corresponding to (b) and (d), respectively.

polarized conductance can be obtained. Third, the conductance curves for spin-up and spin-down electrons are translated in the different directions by introducing a magnetic modulation. As shown in Figs. 3(c)– 3(d), the electronic "band-gaps" for spin-up and spin-down electrons do not coincide with each other when the magnetic potential is involved. At some regions of electron energy, the "gap" of spin-up electrons can correspond to the "band" of spin-down electrons, while, at other regions of electron energy, the "band" of spin-up electrons can overlap with the "gap" of spin-down electrons. By increasing the magnetic potential, the curves for spin-up and spin-down electrons become farther away from each other. Then, fully spin-polarized conductance can be obtained. Consequently, it is possible to use the 2DSL to perform as spin filtering by manipulating the SOC or magnetic field.

The spin polarization has been calculated against the electron energy (Figs. 3(e)–3(f)). Obviously, the spin polarization is high when $\alpha = 5$ a.u. and $\Delta = 0$, and it mainly lies at above the zero line (Fig. 3(e)). However, the spin polarization can be changed alternatively from positive to negative when the electron energy is varied with $\Delta = 5\,\mathrm{MeV}$ and $\alpha = 0$ (Fig. 3(f)). This feature originates from the difference of bandgap structures between spin-up and spin-down electrons (Fig. 3(d)). Interestingly, the absolute value of spin polarization can reach 1.0 at some electron energies. Thereafter, the absolute value of spin polarization can be changed rapidly from zero to one or from one to zero by modulating the electron energy. This feature provides a way to improve the spin polarization and may have potential applications in the designing of spin switches.

In order to understand the behavior of spin-up and spin-down electrons clearly, we have studied the spin-dependent electronic charge distributions in the 2DSL. Figures 4(a)–4(b) present the spin-dependent charge distributions when $\Delta = 0$ and $\alpha = 5$ a.u. with $E = 0.135$ eV. Obviously, strong electronic charge distribution of the spin-up electron is observed in the whole 2D space (as shown in Fig. 4(a)), which corresponds to the extended state. Differing from the spin-up state, some maxima of wave envelop for spin-down electrons located at the input side and the electronic charge distribution decays exponentially, i.e., localized state (as shown in Fig. 4(b)). On the other hand, Figs. 4(c)–4(f) illustrate the spin-dependent electronic charge distributions when $\Delta = 5\,\mathrm{MeV}$ and $\alpha = 0$ at different electron energy $E_1 = 0.107$ eV and $E_2 = 0.15$ eV. For the spin-up electron at E_1, the electronic charge distribution is localized (Fig. 4(c)), while, for the spin-down electrons, the charge distribution electrons extend in the whole 2D space (Fig. 4(d)). Meanwhile, the extended state for spin-up electrons (Fig. 4(e)) and localized states for spin-down electrons (Fig. 4(f)) can be observed at E_2. As discussed above, there is a large (zero) conductance for spin-down (spin-up) electrons and a zero (large) conductance for spin-up (spin-down) electrons in the 2DSL at E_1 (E_2) (Fig. 3(d)). The spin-dependent electronic charge distributions demonstrate a clear picture of the spin filtering for tunneling electrons. This implies that the spin-polarized conductance can be modulated by the SOC, magnetic field, and the microstructure, which may be applied in spin-based quantum devices and semiconductor spintronics.

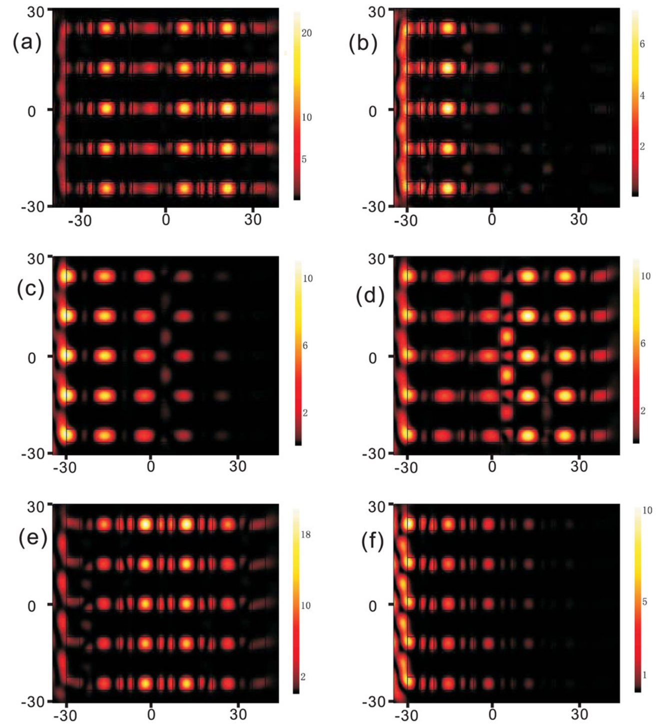

FIG. 4. (Color online) The spin-dependent electronic charge distributions in the 2DSL. (a), (c), and (e) spin-up electron; (b), (d), and (f) spin-down electron.

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