Ideal switching effect in periodic spin–orbit coupling structures

2007 J. Phys.: Condens. Matter 19 446209

(http://iopscience.iop.org/0953-8984/19/44/446209)

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **19** (2007) 446209 (8pp) doi:10.1088/0953-8984/19/44/446209

Ideal switching effect in periodic spin–orbit coupling structures

S J Gong and Z Q Yang[1]

Surface Physics Laboratory (National Key Laboratory), Fudan University, Shanghai 200433, People's Republic of China

E-mail: zyang@fudan.edu.cn

Received 2 August 2007, in final form 28 September 2007
Published 16 October 2007
Online at stacks.iop.org/JPhysCM/19/446209

Abstract

An ideal switching effect is discovered in a semiconductor nanowire with a spatially periodic Rashba structure. Bistable 'ON' and 'OFF' states can be realized by tuning the gate voltage applied on the Rashba regions. The energy range and position of 'OFF' states can be manipulated effectively by varying the strength of the spin–orbit coupling (SOC) and the unit length of the periodic structure, respectively. The switching effect of the nanowire is found to be tolerant of small random fluctuations of SOC strength in the periodic structure. The ideal switching effect might be applicable in future nanoelectronic devices.

1. Introduction

Spin freedom of electrons in semiconductors can be manipulated efficiently through the mechanism of spin–orbit coupling (SOC) [1–3], which has been confirmed in experiments [4]. Among the several types of SOC in semiconductors, Rashba SOC [3], which results from asymmetric electric confinement in nanostructures, is the most attractive because its strength can be tuned easily by an external gate voltage [5, 6]. Various spintronic devices, such as the spin filter [7], spin valve [8], and spin-field-effect transistor [9, 10], have been brought forward in two-dimensional electron gases with Rashba interactions. Since no external magnetic field is required to realize the control of the spin of electrons, all-electrical fabrication of practical devices has been expected in such kinds of system [11, 12].

Recently, a switching effect of electronic flow in spin-field-effect transistors has been proposed based on Rashba and/or Dresselhaus SOCs [13–15]. Jiang *et al* [14] and Gong *et al* [15] investigated the electronic flow in a one-dimensional electron gas sandwiched between two electrodes. The transmission coefficient of electrons in the drain electrode can be varied from 1 to 0 by tuning the SOC strength. However, in both schemes, the behavior of the switching effect is strongly dependent on the height of the scattering potentials at the interfaces between the

[1] Author to whom any correspondence should be addressed.

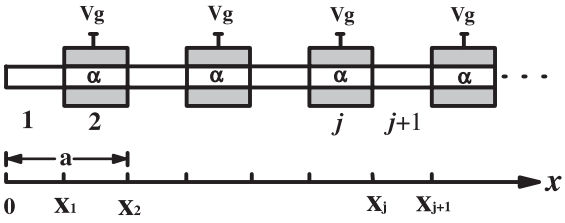

Figure 1. Schematic diagram of the switch device: a one-dimensional quantum wire along the x direction with periodic Rashba structure.

sample and the electrodes. With a high interfacial barrier, the 'ON' state of the switch cannot work effectively: the total transmission peak is too sharp to gain a stable 'ON' state. While with a relatively low barrier, the 'OFF' state cannot be absolutely reached: there is usually considerable leakage in the 'OFF' state even if the SOC strength is tuned to the maximum value permitted in current experiments [5, 6]. And the barrier height cannot be controlled effectively by experimental means. All these factors reduce the feasibility of practical application of the switching schemes.

In the present work, an ideal switching effect is found in a one-dimensional semiconductor quantum wire with a spatially periodic Rashba structure, where SOC and non-SOC segments connect in series alternately. The principle of the effect can be rationalized by the transport properties of the electrons in the wire. When an appropriate magnitude of Rashba strength is provided, an energy gap can be formed near the boundaries of the Brillouin zone due to the periodic Rashba potential. This causes the incident electrons with energies in the gap to be totally reflected. If the Rashba strength is tuned to be smaller than a critical value, all the incident electrons can be transmitted. Therefore, a stable 'rectangle-type' switching effect can be obtained by controlling the Rashba SOC. Further investigation shows that the ideal switching behavior survives from small fluctuations of the Rashba strength in the periodic structure.

2. Models and analysis

The geometry we consider is a narrow two-dimensional electron gas (2DEG) strip with a periodic Rashba structure along the x direction, as illustrated in figure 1. Since the electrons are confined in both y and z directions, a one-dimensional model[2] can be employed in the calculation. Each periodic unit consists of one non-SOC segment and one SOC segment with the same length of $a/2$ (a is set at 24 nm in the following calculations except the case in figure 2(b)). The symbol of V_g in the figure expresses the applied gate voltage to control the Rashba strength. The gate electrodes are laid on the plane of the 2DEG. Note that in our model the SOC and non-SOC segments are composed of the same semiconductor material. Therefore, if gate voltage is removed (i.e. the Rashba SOC is neglected), all the segments unite into a homogeneous structure. In the calculation, an electron wave is injected from the left to the right along the x direction.

The Hamiltonian in the SOC segment can be written as [3]

$$H = \frac{p_x^2}{2m^*} - \frac{\alpha}{\hbar}\sigma_y p_x, \tag{1}$$

[2] For example, the model can describe well a quasi-1DEG system with width less than 20 nm, since the first confinement energy of the geometry is found to be higher than 20 meV and the Fermi energy of a semiconductor 2DEG is generally about or below 20 meV.

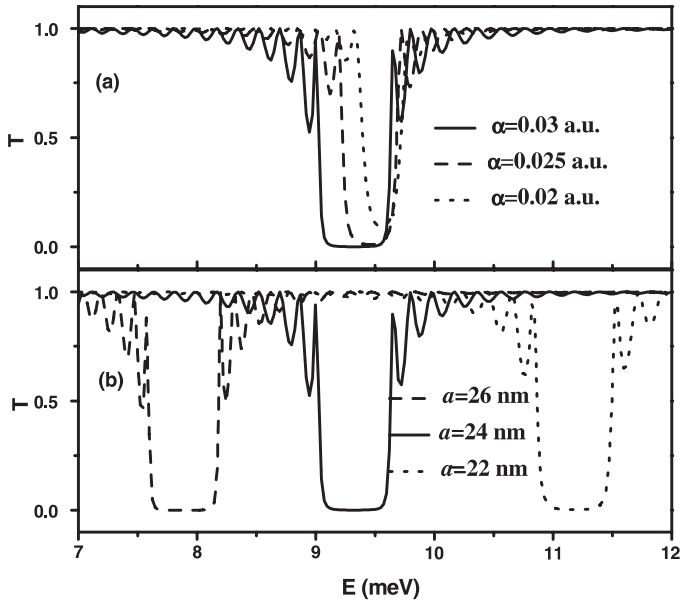

Figure 2. (a) Transmission coefficient as a function of incident energy of electrons at different Rashba strengths. (b) Transmission coefficient as a function of incident energy with different lengths of unit cell. The Rashba strength is taken as $\alpha = 0.03$ au.

where the effective mass of electrons m^* is set as $0.067\ m_e$ (m_e is the mass of the free electron), σ_y is the Pauli spin operator, and p_x is the x-component of the momentum operator. The parameter α describes the SOC strength. To determine the final transmission coefficient after propagating through the whole quantum wire, we need to consider the transmission process of an electron with energy E through one unit, and obtain the transfer matrix. To provide a clear illustration, we label the segments in series: $1, 2, \ldots, j, j+1 \ldots$, as shown in figure 1. Even j stands for SOC segments, and the wavefunction in it can be expressed as $\psi_j = a_j e^{ik^+x}|\uparrow\rangle + b_j e^{-ik^-x}|\uparrow\rangle + c_j e^{ik^-x}|\downarrow\rangle + d_j e^{-ik^+x}|\downarrow\rangle$, where $k^+ = \left(\alpha + \sqrt{\alpha^2 + \frac{2\hbar^2 E}{m^*}}\right)\frac{m^*}{\hbar^2}$, $k^- = \left(-\alpha + \sqrt{\alpha^2 + \frac{2\hbar^2 E}{m^*}}\right)\frac{m^*}{\hbar^2}$. The notations $|\uparrow\rangle$ and $|\downarrow\rangle$ express the eigenspinor states $\binom{1}{i}$ and $\binom{1}{-i}$, respectively. Similarly, odd j stands for the non-SOC segments, where the wavefunction can be written in the same form as an SOC segment with, however, different wavevectors: $k^+ = k^- = k_0$ ($k_0 = \sqrt{\frac{2m^*E}{\hbar^2}}$).

Using boundary conditions at the interfaces of non-SOC/SOC, i.e. the continuous conditions of wavefunctions and conservation ones of the current [8, 16, 17], we can get the following transfer matrix for the wavefunctions at $j = 2$ and 1 segments:

$$\begin{pmatrix} a_2 \\ b_2 \\ c_2 \\ d_2 \end{pmatrix} = L_2^{-1}(x_1) q_2^{-1} q_1 L_1(x_1) \begin{pmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \end{pmatrix}, \tag{2}$$

where

$$L_1(x_1) = \begin{pmatrix} e^{ik^+x_1} & 0 & 0 & 0 \\ 0 & e^{-ik^-x_1} & 0 & 0 \\ 0 & 0 & e^{ik^-x_1} & 0 \\ 0 & 0 & 0 & e^{-ik^+x_1} \end{pmatrix},$$

$$q_1 = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ \frac{\hbar k^+}{m^*} & -\frac{\hbar k^-}{m^*} & 0 & 0 \\ 0 & 0 & \frac{\hbar k^-}{m^*} & -\frac{\hbar k^+}{m^*} \end{pmatrix},$$

$$q_2 = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ \frac{\hbar k^0}{m^*} - \frac{\alpha}{\hbar} & -\frac{\hbar k^0}{m^*} - \frac{\alpha}{\hbar} & 0 & 0 \\ 0 & 0 & \frac{\hbar k^0}{m^*} + \frac{\alpha}{\hbar} & -\frac{\hbar k^0}{m^*} + \frac{\alpha}{\hbar} \end{pmatrix},$$

$$L_2(x_1) = \begin{pmatrix} \mathrm{e}^{\mathrm{i}k^0 x_1} & 0 & 0 & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}k^0 x_1} & 0 & 0 \\ 0 & 0 & \mathrm{e}^{\mathrm{i}k^0 x_1} & 0 \\ 0 & 0 & 0 & \mathrm{e}^{-\mathrm{i}k^0 x_1} \end{pmatrix}.$$

Note that $L_1(x_1)$ and $L_2(x_1)$ are related to the coordinates, while q_1 and q_2 are not. The transfer matrix for the wavefunction in the jth segment can be deduced as $M_j = L_j^{-1}(x_{j-1})q_j^{-1}q_{j-1}L_{j-1}(x_{j-1})\cdots L_3^{-1}(x_2)q_3^{-1}q_2L_2(x_2)\cdot L_2^{-1}(x_1)q_2^{-1}q_1L_1(x_1)$, from which the coefficients $\binom{a_j}{b_j}{c_j}{d_j}$ in the jth segment can be expressed as

$$\begin{pmatrix} a_j \\ b_j \\ c_j \\ d_j \end{pmatrix} = M_j \begin{pmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \end{pmatrix}. \tag{3}$$

From equation (3), the transmitted wavefunction in the jth segment can be obtained if the incident wavefunction is known. The total transmission coefficient (T) consisting of spin-up and -down states in the jth segment is then calculated. In the switch scheme, '$T = 1$' and '0' correspond to ideal 'ON' and 'OFF' states of the outgoing wave, respectively.

In order to understand the switching effect well, we calculate the band structure of the periodic structure by using the plane wave method. The wavefunction can be expressed as: $\psi = \psi_{1k}(x)\binom{1}{0} + \psi_{2k}(x)\binom{0}{1}$, where $\psi_{1k}(x)$ and $\psi_{2k}(x)$ are expanded in plane waves: $\psi_{1k}(x) = \frac{1}{\sqrt{L}}\sum_{K_n} C_{1k}(K_n)\mathrm{e}^{\mathrm{i}(K_n+k)x}$, $\psi_{2k}(x) = \frac{1}{\sqrt{L}}\sum_{K_n} C_{2k}(K_n)\mathrm{e}^{\mathrm{i}(K_n+k)x}$, where L is the total length of the nanowire, K_n is the reciprocal lattice vector, $K_n = n\frac{2\pi}{a}$. The Rashba interaction is modulated periodically along the x direction (see figure 1), and expanded as $\alpha(K_n) = \frac{1}{a}\int_{x_1}^{x_2} \alpha \mathrm{e}^{-\mathrm{i}K_n x}\,\mathrm{d}x$. Solving the schrödinger equation in reciprocal space, we get two coupling equations:

$$\sum_{K_n}\left(\frac{\hbar^2(K_n+k)^2}{2m^*} - E_k\right)C_{1k}(K_n)\delta(K_n - K_m) - \frac{\mathrm{i}}{2}\sum_{K_n}(K_m + K_n + 2k)\alpha_0(K_m - K_n)C_{2k}(K_n) = 0, \tag{4}$$

$$\sum_{K_n}\left(\frac{\hbar^2(K_n+k)^2}{2m^*} - E_k\right)C_{2k}(K_n)\delta(K_n - K_m) + \frac{\mathrm{i}}{2}\sum_{K_n}(K_m + K_n + 2k)\alpha(K_m - K_n)C_{1k}(K_n) = 0. \tag{5}$$

For each K_m, there are two equations like the above. If the total number of plane waves used is N, there will be $2N$ coupling equations, corresponding to $2N$ coefficients

$\{C_{1k}(K_m), C_{2k}(K_m), m = 1, N\}$. The eigenvalues at each k point can be solved by diagonalizing the secular equation.

3. Results and discussion

The transmission coefficients as a function of the incident energy of electrons at different Rashba strengths are shown in figure 2(a). Note that the total transmission coefficient is independent of the incoming spin state, as has been pointed out in previous work [18]. The striking feature in the figure is the appearance of energy gaps, within which the transmission coefficient $T = 0$. When the Rashba strength $\alpha = 0.03$ au (1 au $= 1.44 \times 10^{-9}$ eVm), the width of the gap is about 0.5 meV (roughly from 9.1 to 9.6 meV). That means the incident electrons with energies in this range will be reflected totally by the periodic structure. The width of the gap is found to be sensitively dependent on the Rashba strength. It is clear that the gap becomes larger with the increase of the Rashba strength. In addition, the gap is also related to the number of repeated periodic units in the structure (the number of repeats is set at 100 in the calculation for the periodic structure). At the same Rashba strength, the gap width will increase with the increase in the number of the periodic units until it reaches a saturated value. A larger number of units and a stronger α are expected to produce a wider gap. In the practical case, an appropriate α value and number of units may be chosen.

To realize the switching effect, we hope that the Fermi energy of the incident electrons is located within the energy gap, so that electrons cannot transmit through the quantum wire. This state then corresponds to the 'OFF' state of a switch. In figure 2(b), we fix the SOC strength $\alpha = 0.03$ au, and give our attention to the gap position under different lengths of the unit cell. It can be seen that the gap shifts toward the lower energy region with increase in a, which can be rationalized by the properties of the band structure (in the following). Therefore, by selecting appropriate lengths of a, the position of the energy gap can be modulated according to the position of the Fermi energy.

From figure 2(a), we also find that only when the incident energy of the electrons is within the energy gap, Rashba SOC makes the decisive contribution to the transmission coefficient. Beyond the gap, the contribution of the Rashba SOC is negligible ($T \simeq 1$). The oscillations of transmission varying from $T = 1$ to 0 as the energy approaches the position of the energy gap can be ascribed to the SOC/non-SOC interfaces [19] in the periodic structure. To clearly illustrate the contribution of the Rashba SOC, we plot the dependence of transmission coefficient on the Rashba strength in figure 3(a), in which the incident energies are given as 9.2, 9.3, and 9.4 meV. All of the energies are located in the transmission gap shown by the solid curve in figure 2(a). Obviously, we obtain a binary 'rectangle-type' transmission behavior with values of 1 and 0 by tuning the Rashba strength continuously. For a given energy (for example, $E = 9.3$ meV), we can find a critical value α_c (α_c corresponds to the peak in the solid curve). When $\alpha < \alpha_c$, a nearly total transmission is achieved, corresponding to the 'ON' state. When $\alpha > \alpha_c$, no electrons can be transmitted, corresponding to the 'OFF' state. It is found that a small incident energy corresponds to large α_c, which can be illustrated by the trends of T as a function of E at different Rashba strengths shown in figure 2(a). In reality, the incident energies of the electrons may range from E_1 to E_2 (suppose $E_1 < E_2$), we need to find α_{c1} (corresponding to E_1) and α_{c2} (corresponding to E_2). When $\alpha > \alpha_{c1}$, the switch is 'OFF', when $\alpha < \alpha_{c2}$, the switch is 'ON'.

To gain a deeper insight into the properties of the switch, we investigate the band structure of the one-dimensional system with periodic Rashba potential. Figure 3(b) shows the band structures without ($\alpha = 0$) and with Rashba SOC ($\alpha = 0.03$ au), respectively. Comparing

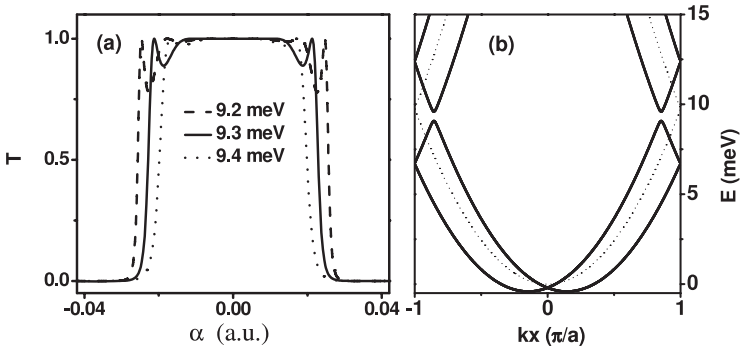

Figure 3. (a) Transmission coefficient as a function of the Rashba strength with different incident energies. (b) Band structures of one-dimensional quantum wires. Dotted curve: no Rashba interaction, solid curve: Rashba strength $\alpha = 0.03$ au.

the solid curve and the dotted one, we find that due to the Rashba spin–orbit interaction, the degenerate band structure splits into two subbands: one is for spin-up and the other for spin-down. Here we emphasize the energy gap near the boundaries of the Brillouin zone. With the same parameters as in the case of the solid curve in figure 2(a), the gap width in figure 3(b) is also about 0.5 meV from 9.1 to 9.6 meV. There is, in fact, a difference in the geometries between figures 3(b) and 2(a). For the band structure calculation, the one-dimensional system is infinitely long, while the switch structure is a quantum wire with finite length. The fact that figures 3(b) and 2(a) produce almost the same gap demonstrates that the length of the periodic Rashba structure in figure 2(a) is long enough to be equivalent to the infinite one. With weak Rashba strength, the difference between the two structures can be observed. In figure 2(a), when Rashba strength is decreased to 0.02 au, the energy gap is smeared out. If we increase the number of the periodic unit cell, the gap will be opened.

In a practical case, the SOC strength may not change abruptly at the SOC/non-SOC interfaces. Due to boundary effects, there is usually leakage of electric field outside the gate electrodes and the SOC strength may experience a smooth change from the full value to zero. The switching effect is, however, essentially from the controllable periodic structure. To illustrate this main feature, we employ a sinusoidal function $\alpha(x) = \alpha_0(\mathrm{Sin}(2\pi x/a) + 1)/2$ to approximately simulate the smooth change of the SOC strength possibly appearing in practical cases. The schematic diagram of the smooth SOC distribution as a function of position is shown in figure 4(a) (solid curve). For comparison, the 'abrupt' case is also given in figure 4(a) (dashed curve). The obtained transmission coefficients[3] are displayed in figure 4(b), in which the solid curve is the numerical result of the 'smooth' model, and the dash curve of the 'abrupt' one. The calculation parameters chosen are the same for the two models; for example, the periodic length $a = 24$ nm and the amplitude of the SOC strength is 0.03 au. In figure 4(b), it is obvious that for the 'smooth' model there is still an energy interval within which the electrons cannot be transmitted. Based on this energy gap, an ideal switching effect can be obtained by tuning the SOC strength for the 'smooth' case. The width of the energy interval for the 'smooth' case is slightly narrower than that for the 'abrupt' case, which will only slightly affect the switching behaviour in quantity. Therefore, it can be inferred that the switching effect is robust even when the leakage effect is considered. We also calculate the band structure (not shown) for

[3] The transmission coefficient for the 'smooth' model is calculated by using discrete lattice model with the help of the Green's function method, which has been introduced in detail in [20].

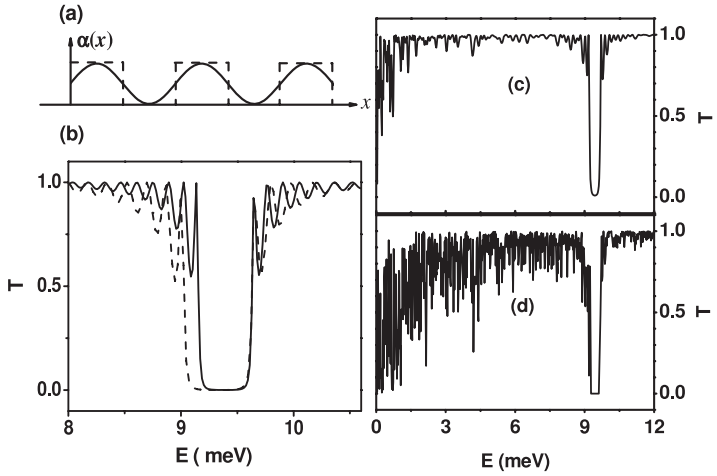

Figure 4. (a) Schematic diagram of the continuous change of SOC strength as a function of x (solid curve) and the abrupt change (dashed curve). (b) The transmission coefficients as a function of the incident energy. The dashed curve shows the result of the 'abrupt' case and the solid curve shows the result of the 'smooth' case. The amplitude for the SOC strength $\alpha_0 = 0.03$ au and the periodic length $a = 24$ nm. (c) Transmission coefficient versus the incident energy in a disordered structure. The number of units in the structure is 100. (d) The same as in (c) but with the number of units being 1000.

this 'smooth' case and the obtained energy gap is consistent with the result shown by the solid curve in figure 4(b).

Another point to be considered is that we usually cannot get a perfect periodic structure, for example α_j may fluctuate from its set value. Here we consider a disordered SOC structure, i.e. the Rashba strengths in SOC segments are randomly given, and investigate its switching effect. Figure 4(c) shows the case in which Rashba strengths randomly fluctuate from 0.02 to 0.03 au. Comparing figure 4(c) with the dashed curve of figure 2(a), whose Rashba strength is set at 0.025 au (the average value of 0.02 and 0.03 au), it is found that the energy gaps in the two cases show little difference. Therefore, it can be inferred that the switching effect we obtained is tolerant of such disorder. In addition, to our knowledge, in a one-dimensional system the presence of disorder will induce localized states of electrons, which is a critical difference between periodic and disordered systems. Therefore, the 'OFF' state may be achieved due to the localized states in an ideal disordered system. For example, if the number of periodic units in the structure increases from 100 in figure 4(c) to 1000 in figure 4(d), the small dips in the energy region of 2.0–8.0 meV will become deeper. Some gaps may form with the further increase of the length of the structure.

4. Conclusions

A perfect switching effect of electronic flow is found in a one-dimensional nanowire with spatially periodic Rashba spin–orbit coupling. A stable 'rectangle-type' switching effect is obtained by controlling the Rashba SOC strength. The leakage of electric field outside of gate electrodes may only slightly influence the effect in quantity. The switching effect also behaves well even if the fluctuations in the Rashba strengths destroy the periodic structure to some extent.

Acknowledgments

The authors are grateful to Professor Rui-Bao Tao at Fudan University for very helpful discussion. This work was supported by the National Natural Science Foundation of China with grant no. 10674027, the Grand Foundation of Shanghai Science and Technology (05DJ14003), PCSIRT, and 973 project under grant no. 2006CB921300.

References

[1] Luttinger J M 1956 *Phys. Rev.* **102** 1030
[2] Dresselhaus G 1955 *Phys. Rev.* **100** 580
[3] Bychkov Y A and Rashba E I 1984 *J. Phys. C: Solid State Phys.* **17** 6039
[4] Stern N P, Ghosh S, Xiang G, Zhu M, Samarth N and Awschalom D D 2006 *Phys. Rev. Lett.* **97** 126603
Wunderlich J, Kaestner B, Sinova J and Jungwirth T 2005 *Phys. Rev. Lett.* **94** 047204
Kato Y K, Myers R C, Gossard A C and Awschalom D D 2004 *Science* **306** 1910
[5] Nitta J, Akazaki T, Takayanagi H and Enoki T 1997 *Phys. Rev. Lett.* **78** 1335
[6] Engels G, Lange J, Schäpers Th and Lüth H 1997 *Phys. Rev.* B **55** R1958
[7] Kago T, Nitta J, Takayanagi H and Datta S 2002 *Phys. Rev. Lett.* **88** 126601
[8] Matsuyama T, Hu C-M, Grundler D, Meier G and Merkt U 2002 *Phys. Rev.* B **65** 155322
[9] Datta S and Das B 1990 *Appl. Phys. Lett.* **56** 665
[10] Egues J C, Burkard G and Loss D 2003 *Appl. Phys. Lett.* **82** 2658
Egues J C, Burkard G, Saraga D S, Schliemann J and Loss D 2005 *Phys. Rev.* B **72** 235326
[11] Popescu A E and Ionicioiu R 2004 *Phys. Rev.* B **69** 245422
[12] Stepanenko D and Bonesteel N E 2004 *Phys. Rev. Lett.* **93** 140501
[13] Wang X F, Vasilopoulos P and Peeters F M 2002 *Phys. Rev.* B **65** 165217
[14] Jiang K M, Zheng Z M, Wang B G and Xing D Y 2006 *Appl. Phys. Lett.* **89** 012105
[15] Gong S J and Yang Z Q 2007 *Phys. Lett.* A **367** 369
[16] Zülicke U and Schroll C 2002 *Phys. Rev. Lett.* **88** 029701
[17] Sun Q-F and Xie X C 2005 *Phys. Rev.* B **71** 155321
[18] Molnár B, Vasilopoulos P and Peeters F M 2005 *Phys. Rev.* B **72** 075330
[19] Reynoso A, Usaj G and Balseiro C A 2006 *Phys. Rev.* B **73** 115342
[20] Datta S 1995 *Electronic Transport in Mesoscopic System* (New York: Cambridge University Press)