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Electron spin filtering in all-semiconductor tunneling structures

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Abstract

In this work we briefly review the present day perspectives for exploiting conventional non-magnetic semiconductor nano-technology to design high speed spin-filter devices. In recent theoretical investigations a high spin polarization has been predicted for the ballistic tunneling current in semiconductor single- and double-barrier asymmetric tunnel structures of III–V semiconductors with strong Rashba spin–orbit coupling. We show in this paper that the polarization in the tunneling can probability be sufficiently increased for producing realistic single-barrier structures by including of the Dresselhaus term into consideration.

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Keywords: Nano-structures; Spin–orbit interaction; Tunneling

Recently a new branch of electronics, so-called spintronics, became a focus of interest (see for instance [1, 2]). For this reason the electronic spin polarization (filtering) in solid-state systems has attracted considerable attention. Many possible structures were investigated for achieving high level electronic spin filtering and injection. Most of them consist of magnetic material elements (see [1–5] for references). But in principle one can use the all-semiconductor approach utilizing multi-layered nano-systems to generate and detect the electron spin polarization [6]. The semiconductor approach has the advantage of being compatible with conventional semiconductor technology. From this point of view the most important property of semiconductors to be utilized in all semiconductor

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spintronic nano-devices is the spin–orbit (SO) interaction [7–9]. The control of spin in semiconductors together with modern semiconductor technology can guarantee the future of the spintronics and result in valuable commercial interest.

The SO interaction comes from a relativistic correction to the electronic non-relativistic Hamiltonian and manifests the lack of inversion symmetry in semiconductor compounds. In the bulk of III–V and II–VI semiconductor materials the SO interaction lifts the spin degeneracy of the conduction states in the center of the Brillouin zone [7]. This part of the SO interaction is called of bulk inversion asymmetry (BIA) type and it is represented by the effective Dresselhaus Hamiltonian. Macroscopic effective electric fields in semiconductor nano-structures result in structural inversion asymmetry (SIA) and a linear (in the electron wavevector $\mathbf{k}$) term (or of Rashba type) of the SO interaction [8, 9]. Ample experimental evidence in recent years shows that the SO interaction becomes easy to detect in semiconductor heterostructures by measurements of the Shubnikov–de Haas oscillations [10], weak antilocalization [11], and electronic Raman scattering [12].

It has been found out recently that the Rashba spin–orbit coupling in conventional III–V semiconductor tunnel barrier structures can lead to the spin-dependent tunneling phenomenon [13–15]. The spin-polarization ratio in tunneling structures is defined as

$$P(E_z, \mathbf{k}) = \frac{T_+(E_z, \mathbf{k}) - T_-(E_z, \mathbf{k})}{T_+(E_z, \mathbf{k}) + T_-(E_z, \mathbf{k})}, \tag{1}$$

where $T_\pm(E_z, \mathbf{k})$ is the spin-up (spin-down) tunneling probability and E_z is the part of the electronic energy which corresponds to the motion perpendicular to the barrier (z-axis), and $\mathbf{k} = (k_x, k_y)$ is the component of the electronic wavevector parallel to the barrier. In resonant tunnel heterostructures (due to the strict resonant tunnel conditions) the spin-dependent asymmetry in the tunneling probability can gain a higher level. In symmetric structures with the exceptional Rashba interaction included we need to apply an external perpendicular electric field F_z to generate asymmetry of the tunneling probability. At the same time in asymmetric structures a difference between T_+ and T_- exists with zero external electric field and it is possible to reverse the polarization by means of adjusting the strength of the external electric field F_z.

The calculation results show considerable influence of the SO interaction on the tunneling transmission characteristics at zero external magnetic field and the dependence can be controlled by an external electric field. In addition the SO interaction can provide a big difference (a few orders of magnitude) between tunneling times of electrons of different spin polarizations without additional magnetic fields [16]. The polarization of the electronic current can gain about 40% for moderate electric fields.

The Dresselhaus coupling term can also lead to a dependence of the tunneling probability on the spin orientation even for symmetrical barrier structures [17]. Results from different authors suggest that the spin–orbit filtering for all-semiconductor tunnel devices can reach almost 100% polarization for more sophisticated designs of the devices [18, 19]. Recent investigations have shown that completely planar or linear designs of the tunnel transistors can be achieved with present day technology [20]. Such a design should have much better efficiency in spin filtering.

In this paper we further investigate the spin-dependent tunneling probability for realistic symmetric tunneling structures, with consideration of both the Rashba and

Dresselhaus couplings. Our calculation is performed for realistic semiconductor structures on the basis of the effective electronic one-band Hamiltonian, energy- and position-dependent electron effective mass approximation, and spin-dependent Ben Daniel–Duke boundary conditions. We consider the spin-dependent Hamiltonian for a single-barrier structure, which can be written as follows [13, 17, 21, 22]:

$$\hat{H} = \hat{H}_0 + \hat{H}_D + \hat{H}_R, \tag{2}$$

where

$$\hat{H}_0 = -\frac{\hbar^2}{2}\frac{\mathrm{d}}{\mathrm{d}z}\frac{1}{m(E,z)}\frac{\mathrm{d}}{\mathrm{d}z} + \frac{\hbar^2 k^2}{2m(E,z)} + E_c(z) + V(z),$$

and

$$\frac{1}{m(E,z)} = \frac{2P^2}{3\hbar^2}\left[\frac{2}{E - E_c(z) + E_g(z) + V(z)} + \frac{1}{E - E_c(z) + E_g(z) + \Delta(z) + V(z)}\right],$$

represents the energy- and position-dependent reciprocal effective mass. $E_c(z)$, $E_g(z)$, and $\Delta(z)$ stand for the position-dependent conduction-band edge, the band gap, and the spin–orbit splitting in the valence band, $V(z) = -eF_z z$ is the potential energy due to the external electric field in the barrier region (e is the electronic charge), and P is the momentum matrix element. In Eq. (2) the Rashba and Dresselhaus terms (when the kinetic energy of electrons is substantially smaller than the barrier height V_0) are correspondingly [13, 17, 21]

$$\hat{H}_R = (\hat{\sigma}_x k_y - \hat{\sigma}_y k_x) \cdot \frac{\mathrm{d}\beta(E,z)}{\mathrm{d}z},$$

and

$$\hat{H}_D = \gamma(\hat{\sigma}_x k_x - \hat{\sigma}_y k_y)\frac{\mathrm{d}^2}{\mathrm{d}z^2},$$

where $\hat{\boldsymbol{\sigma}} = \{\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z\}$ is the vector of the Pauli matrices,

$$\beta(E,z) = \frac{P^2}{3}\left[\frac{1}{E - E_c(z) + E_g(z) + V(z)} - \frac{1}{E - E_c(z) + E_g(z) + \Delta(z) + V(z)}\right]$$

is the Rashba spin-coupling parameter, and γ is a material constant.

The wavefunction of the electron can be written in the form

$$\Phi_{\pm}(x,y,z) = \chi_{\pm}\Psi_{\pm}(z)\exp[i(k_x x + k_y y)]$$

where $\chi_{\pm}$ are spinors, which correspond to electron spin states of opposite spin directions, and $\Psi_{\pm}$ satisfies the spin-dependent Ben Daniel–Duke boundary conditions in each

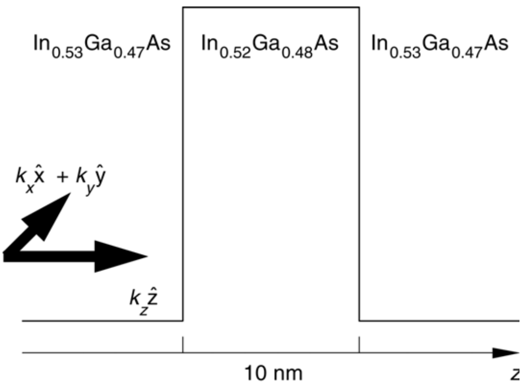

Fig. 1. A sketch of a realistic $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ symmetric single-barrier structure of width 10 nm.

interface of the structure:

$$\begin{cases} \Psi_{\pm}(z) \\ \left\{\left[\frac{\hbar^2}{2m} + \gamma(\hat{\sigma}_x k_x - \hat{\sigma}_y k_y)\right]\frac{\mathrm{d}}{\mathrm{d}z} + \beta(\hat{\sigma}_x k_y - \hat{\sigma}_y k_x)\right\} \Psi_{\pm}(z) \end{cases}$$
$$\Rightarrow \text{continuous at the boundary.}$$

The standard solutions of the Schrödinger equation with the Hamiltonian (2) and the spin-dependent boundary conditions above allow us to calculate the spin-dependent tunneling probability and polarization ratio (1) for symmetric single-barrier tunneling structures [13, 23], as we demonstrate in Fig. 1. In Fig. 2 we present results of our calculation for a realistic $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ symmetric single-barrier structure of width 10 nm. The band structure parameters are chosen as follows: for $In_{0.53}Ga_{0.47}As$ $E_g = 0.937$ eV, $\Delta = 0.361$ eV, $m^*/m_0 = 0.04368$, $\gamma = 76.89$ eV A^3; for $In_{0.52}Al_{0.48}As$ $E_g = 1.289$ eV, $\Delta = 0.332$ eV, $m^*/m_0 = 0.0840$, $\gamma = 73.36$ eV A^3; band offset $V_0 = 0.278$ eV [24, 25]. Parameters for compound materials are calculated according to a linear interpolation formula. The polarization is quite significant even without an electric field (symmetric structure, only the Dresselhaus coupling is included). An additional possibility for manipulating the polarization ratio arises when an external electric field is applied (the Rashba term included). Fig. 2(b) and (c) show how one can manipulate with the polarization by means of the field.

To briefly conclude, in this paper we demonstrate that the transmission tunneling probability for a realistic symmetric single-barrier structure can gain a well-recognizable spin dependence for a not too large in-plane wavevector of the tunneling electrons. In addition, one can control the magnitude of the polarization ratio by means of an external electric field. The effect described can provide a basis for more advanced spin-filtering techniques at zero magnetic field. Our calculation results show that the interplay between the BIA and SIA interactions makes the spin-filtering processes richer and more controllable.

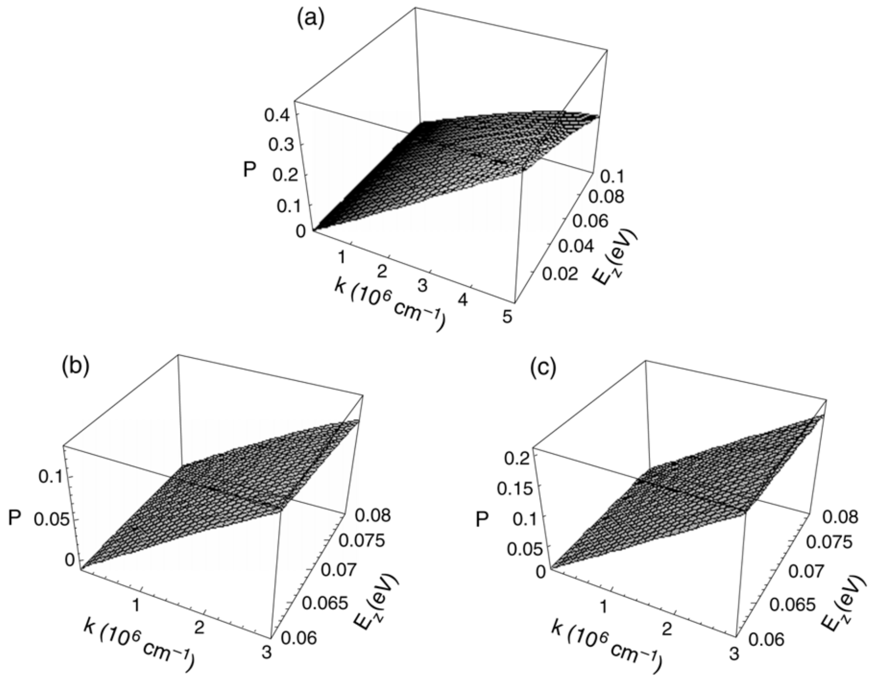

Fig. 2. (a) The polarization ratio for a $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ symmetric single-barrier structure without an external electric field; (b) the polarization ratio for the same structure with the external electric field $F_z = +5 \times 10^4$ V cm^{-1}; (c) the polarization ratio for the same structure with the external electric field $F_z = -5 \times 10^4$ V cm^{-1}.

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