# Spin-dependent electronic tunneling at zero magnetic field

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The spin-dependent tunneling phenomenon in symmetric and asymmetric semiconductor heterostructures at zero magnetic field is studied theoretically on the base of a single conduction band and spin-dependent boundary conditions approach. It is shown that the spin-orbit splitting in the dispersion relation for the electrons in $A_{\rm III}B_{\rm V}$ semiconductor quantum-tunneling structures can provide a dependence of the tunneling transmission probability on the electron's spin polarization. The dependence is calculated and discussed for different kinds of tunnel heterostructures. [S0163-1829(98)04548-2]

The spin-dependent electron quantum confinement and dynamics in $A_{\rm III}$-$B_{\rm V}$ semiconductor heterostructures at zero magnetic field call attention during recent years from theoretical[1–4] and experimental[5–10] points of view. In heterostructures with sharp changes in electronic band parameters at interfaces or with external electric field, the spin-orbit interaction provides coupling between spatial motion in plane parallel to the heterointerfaces and the electron's spin. The spin-orbit splitting of the electron conduction band at zero magnetic field is a consequence of the coupling. That is a well-known phenomenon dealing with the fundamental physical characteristics of the heterostructures.[11–14] Recent theoretical and experimental investigations demonstrated the existence of such effect in asymmetric quantum well structures. Experimentally, the spin-orbit splitting for electrons confined in the heterostructures has been studied by Raman scattering[5–7] and Shubnikov–de Haas oscillation.[8–10] From a practical point of view, the application of the spin-orbit splitting effect in quantum electronic devices can lead to a new generation of ultrafast spin-dependent electronics.[3] A potential advantage of the devices is that the spin-dependent processes can be easily controlled by an external voltage. Therefore, a detailed analysis to clarify and to evaluate the effect magnitude is greatly desired.

In this paper, we pay attention to another type of the spin-dependent phenomena in the semiconductor heterostructures—quantum tunneling. Advances in modern epitaxial growth technologies such as molecular-beam epitaxy and metal-organic chemical-vapor deposition technology provide us an opportunity to construct two-dimensional barrier heterostructures in which the material parameters can be changed with a wide range and controlled with a considerable accuracy. We can discuss possible influence of the spin-orbit splitting on the transmission probability for models of the quantum tunneling structures with realistic parameters. The tunneling coupling in double quantum wells[15] and tunneling transmission processes through barrier between the wells those consider the electron's in-plane motion[16] are also fields of possible the spin-orbit splitting effect investigation and implementations.

We calculate the tunneling transmission probability for heterostructures with space-dependent electron's effective mass and spin-orbit coupling parameters. The dependence leads to the mass and spin-dependent boundary conditions.[3,17,21,18] Since we expect considerable effect with narrow gap $A_{\rm III}$-$B_{\rm V}$ semiconductors (where the spin-orbit splitting effect is strong), it is important to take into account nonparabolicity for the electron's dispersion relation.[3] In our calculation, we use the well-known approximation for energy and space dependencies of the electronic effective mass.[3,17,21] For the spin-dependent tunneling process we obtained a dependence of the transmission probability on in-plane electron's wave vector. The dependence consists of two parts: the known dependence originated from space-dependent electron's effective mass,[18] and a new one originated from the electronic wave function's spin-dependent boundary conditions.[3] Each of them is a result of the band-edge discontinuity at the heterostructure interfaces. It will be demonstrated that the consideration of spin in tunneling processes can considerably change energy and in-plane wave-vector dependencies of the transmission probability in tunnel structures.

The variation of the band-structure parameters for the single barrier tunneling structure to be discussed is shown in Fig. 1. To describe the spin-dependent tunneling in the heterostructure we use the approximate effective Hamiltonian in the form proposed in Ref. 3. Layers of the structure are perpendicular to $z$ axis, in-plane electron's wave vector is $k$ [if $k$ is put along an arbitrary $x$ direction, the spin polarization is set along the $y$ axis in the layer plane $\rho=(x,y)$]. In this paper, we discuss the influence of discontinuity of effective mass and spin-orbit coupling parameters on tunneling processes. The influence from additional external electric field is not discussed here. With the above-mentioned assumptions, the total wave function of the electron $\Phi_\sigma(z,\rho)$ can be presented as

 

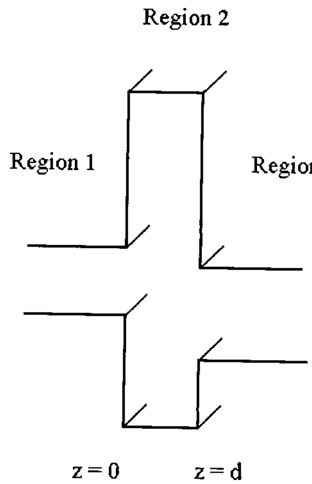


FIG. 1. Variation of the semiconductors band parameters in tunneling heterostructures; $z$–the normal to the barrier direction.

$$\Phi_{\sigma}(z,\rho)=\Psi_{j\sigma}(z)\exp(i\mathbf{k}\cdot\rho),$$

where $\Psi_{j\sigma}(z)$ satisfies the $z$ component of the Schrödinger equation in the $j$th region,

$$H_j\Psi_{j\sigma}(z)=E\Psi_{j\sigma}(z), \quad (1)$$

with the effective one-electronic zone Hamiltonian

$$H_j=-\frac{\hbar^2}{2m_j(E)}\frac{d^2}{dz^2}+\frac{\hbar^2k^2}{2m_j(E)}+E_{jc}, \quad (2)$$

In Eqs. (1) and (2) $m_j(E)$ presents electronic effective mass in nonparabolic approximation

$$\frac{1}{m_j(E)}=\frac{P^2}{\hbar^2}\left[\frac{2}{E-E_{jc}+E_{jg}}+\frac{1}{E-E_{jc}+E_{jg}+\Delta_j}\right], \quad (3)$$

$E$ denotes the total electron energy in the conduction band, $E_{jc}$, $E_{jg}$, and $\Delta_j$ stand correspondingly the conduction-band edge, the main band gap, and the spin-orbit splitting in the $j$th region ($E_{1c}=0$, conventionally in our calculation). We suppose, that the matrix element $P$ does not depend on $z$.[17]

The spin-dependent boundary conditions for $\Psi_{j\sigma}(z)$ at the interface plane $z=z_j$ between $j$ and $j+1$ regions have been introduced in Ref. 3,

$$\frac{1}{m_j(E)}\left\{\frac{d}{dz}\ln[\Psi_{j\sigma}(z)]\right\}_{z=z_j}-\frac{1}{m_{j+1}(E)}\left\{\frac{d}{dz}\ln[\Psi_{j+1\sigma}(z)]\right\}_{z=z_j}=\frac{2\sigma k[\beta_{j+1}(E)-\beta_j(E)]}{\hbar^2},$$

$$\Psi_{j\sigma}(z_j)-\Psi_{j+1\sigma}(z_j)=0, \quad (4)$$

where

$$\beta_j(E)=\frac{P^2}{2}\left[\frac{1}{E-E_{jc}+E_{jg}}-\frac{1}{E-E_{jc}+E_{jg}+\Delta_j}\right] \quad (5)$$

is a position and energy-dependent electronic spin-coupling parameter and $\sigma=\pm1$ refers to the spin polarization.

The transmission probability $T_{\sigma}(E,\mathbf{k})$ is calculated by the standard quantum mechanics procedure for a rectangular barrier structure with the boundary conditions (4) and is given by

$$T_{\sigma}(E_z,k)=\frac{4q^2k_1k_3m_2^2}{m_1m_3(f_1^2+f_2^2)}, \quad (6)$$

where

$$f_1(E_z,k)=qs_{31}\cosh\left(\frac{qd}{\hbar}\right)-\left(q^2-k_1k_3\frac{m_2^2}{m_1m_3}+s_{21}s_{32}\right)\sinh\left(\frac{qd}{\hbar}\right),$$

$$f_2(E_z,k)=q\left(k_1\frac{m_2}{m_1}+k_3\frac{m_2}{m_3}\right)\cosh\left(\frac{qd}{\hbar}\right)-m_2\left(k_1\frac{s_{32}}{m_1}+k_3\frac{s_{21}}{m_3}\right)\sinh\left(\frac{qd}{\hbar}\right),$$

$d$ is the thickness of the barrier, $q(E_z,k)=\sqrt{2m_2(E_{2c}-E_z)+\hbar^2(1-m_2/m_1)k^2}$, $k_j(E_z,k)=\sqrt{2m_j(E_z-E_{jc})-\hbar^2(1-m_j/m_1)k^2}$, and $s_{ij}(E_z,k)=2\sigma km_2(\beta_i-\beta_j)$ (here we discuss the tunneling regime for the electron, when $q^2\geqslant0$ and $k_3^2\geqslant0$). $E_z$ is longitudinal component of the total energy in the first region

$$E_z=E-\frac{\hbar^2k^2}{2m_1(E,k)}. \quad (7)$$

Using (2) in Eq. (7), we find dependence $E(E_z,k)$ and, through that, $m_j(E_z,k)$ ($j=2,3$) and $\beta_j(E_z,k)$ dependencies, when $j=1,2,3$. We can notice, that the expressions (6) generalizes the approach of Ref. 18 for asymmetric rectangular tunneling structures.

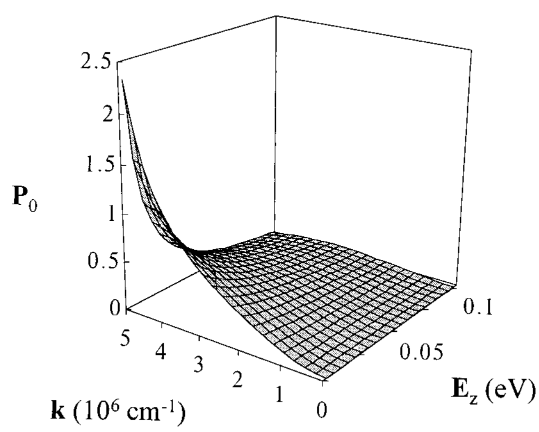


FIG. 2. Relative difference between the transmission tunneling probability with accounting of spin in boundary conditions and without that. The InSb-CdTe-InSb symmetric barrier structure parameters are obtained from Refs. 20 and 21: $E_{2c}=0.35$ eV, $E_{3c}=0.0$ eV, $E_{1g}=E_{3g}=0.235$ eV, $E_{2g}=1.59$ eV, $\Delta_1=\Delta_3=0.81$ eV, $\Delta_2=0.8$ eV, $m_1(0)=m_3(0)=0.0135m_0$, $m_2(0)=0.11m_0$ ($m_0$ is the free-electron's mass), $d=20$ Å.

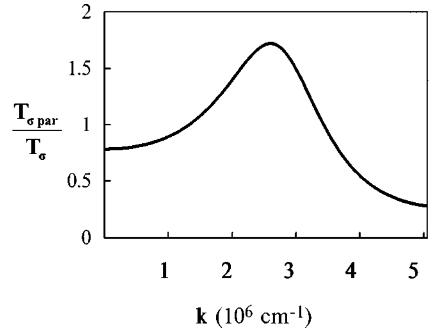


FIG. 3. Relative magnitude of the spin-dependent transmission tunneling probability for the structure of Fig. 2 within parabolic approximation ($T_{\sigma \mathrm{par}}$) and with accounting of nonparabolicity ($T_\sigma$). $E_z = 0.01$ eV.

It is clear from Eq. (6) that for symmetric tunnel barrier structures (when $m_1 = m_3$, $E_{3c} = 0$, $k_1 = k_3$, $s_{21} = s_{32}$, and $s_{31} = 0$) the transmission probability does not depend on the electron's spin direction, but still is different from the traditional description for electrons without consideration of the electron spin. At the same time, expression (6) describes the coupling effect of the wave-vector components.[18] We use this expression to investigate the spin dependence of the tunneling transmission probability for electrons tunneling through different kinds of barrier structures.

For symmetric tunnel barrier structures a relative difference between results with consideration of spin ($T_\sigma$) and without that ($T_0$) can be evaluated by the following expression

$$\mathbf{P}_0(E_z, k) = \frac{T_\sigma(E_z, k) - T_0(E_z, k)}{T_0(E_z, k)}. \qquad (8)$$

To clarify the difference quantitatively, we show in Fig. 2 $\mathbf{P}_0(E_z, k)$ calculated for the structure with parameters of InSb-CdTe-InSb.[2,19,20] The difference is well pronounced for large $k$-vector magnitude. We show in comparison in Fig. 3 relative magnitude of the transmission probabilities calculated (for the same structure as in Fig. 2) with the nonparabolic approximation and with the parabolic one. From Fig. 3 it is clear that using of the parabolic approximation (as it was done in Ref. 18) leads to overestimation of the effect's magnitude. It demonstrates again that for narrow gap semiconductors with relatively strong spin-orbit interaction it is very important to involve the nonparabolic dispersion relation to describe the spin-dependent phenomena.[2] All calculations presented below (as in Fig. 2 also), therefore, consider the nonparabolic approximation for all involved semiconductor materials.

For asymmetric tunnel structures we can expect a difference between $T_+(E_z, k)$ and $T_-(E_z, k)$ for the electron with the same $E_z$ and $k$. To evaluate the electron spin-polarization effect in the tunneling process it is useful to calculate ''coefficient of the polarization efficiency'' (CPE) as follows:

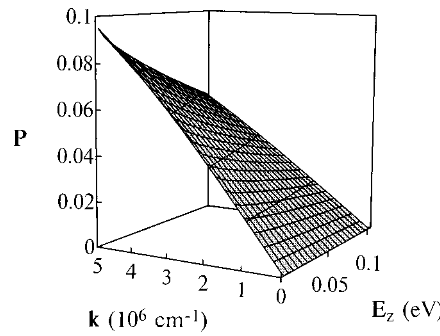


FIG. 4. Relative difference between transmission probability for electrons with ''spin up'' and ''spin down'' for asymmetric InP-$Al_{0.48}In_{0.52}As$-$Ga_{0.47}In_{0.53}As$ barrier structure. The heterostructure parameters are from Ref. 18: $E_{2c} = 0.252$ eV, $E_{3c} = -0.252$ eV, $E_{1g} = 1.424$ eV, $E_{2g} = 1.508$ eV, $E_{3g} = 0.813$ eV, $\Delta_1 = 0.11$ eV, $\Delta_2 = 0.33$ eV, $\Delta_3 = 0.361$, $m_1(0) = 0.077 m_0$, $m_2(0) = 0.075 m_0$, $m_3(0) = 0.041 m_0$, $d = 20$ Å.

$$\mathbf{P}(E_z, k) = \frac{T_+(E_z, k) - T_-(E_z, k)}{T_+(E_z, k) + T_-(E_z, k)}. \qquad (9)$$

It should be notified that, according to the boundary conditions (2), CPE demonstrates the well-understood property,

$$\mathbf{P}(E_z, k) = -\mathbf{P}(E_z, -k).$$

We calculate the effect's magnitude for an asymmetric structure with sharp discontinuity in the spin-orbit coupling parameters as in InP-$Al_xIn_{1-x}As$-$Ga_xIn_{1-x}As$ heterostructure.[21] In Fig. 4 a result of the calculations is presented. The effect is quite significant and probably can be proposed to experimental investigation. We can expect also increasing of the CPE for tunnel structures with additional asymmetry produced by external electric field.

In short conclusion, we demonstrate in this paper that the tunneling transmission probability for single barrier structures can have recognizable spin dependence with well-pronounced magnitude of the dependence for not too large in-plane wave vector of tunneling electrons. The dependence is strong for unstrained heterostructures with sharp discontinuity of the band-edge parameters, and can provide in asymmetric structures the spin polarization effect in the tunneling process. We can expect an opportunity to optimize conditions of the effect's existence especially for resonant tunneling systems. The described effect can be a base of development of spin-dependent fast tunneling electronic devices.

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