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Spin-dependent delay time in electronic resonant tunneling at zero magnetic field

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Abstract

The dependence of the phase tunneling time on electronic spin polarization in symmetric and asymmetric double-barrier semiconductor heterostructures is studied theoretically. The effective one-band Hamiltonian approximation and spin-dependent boundary conditions are used for theoretical investigation of the electron spin influence on the delay time in tunneling processes. It is shown that the spin–orbit splitting in the dispersion relation for the electrons can provide a dependence of the delay time on the electron spin polarization without additional magnetic field. This dependence can be controlled by an external electric field and can be very pronounced for realistic double-barrier semiconductor heterostructures.

Keywords: A. Quantum wells; A. Semiconductors; D. Spin–orbit effects; D. Tunneling

An understanding of the time aspects of tunneling processes is of much significance [1–3]. Apart from a theoretical interest [1,3], this understanding is of importance because of increasing attention on miniaturizing tunnel semiconductor devices [4]. Although in recent years the tunneling time of an electron through double-barrier resonant heterostructures (DBRH) has been studied extensively, the concept of the tunneling time is still not as clear as it is desired [1]. In fact, tunneling time is a basic characteristic that determines the dynamic range of tunneling devices. There are several quantities used in description of the tunneling process with the dimensions of time. These time characteristics have been introduced by different authors to describe different aspects of electron dynamics [5–9]. Additional complexity arises with some recent publications that demonstrated position-dependent effective mass and parallel (to interfaces) motion dependence of the tunneling process [10–16]. Since the miniature tunnel semiconductor devices typically have position-dependent effective electron mass, the parallel (in-plane) motion of the electron can provide additional specific effects [15,16].

In this article we call attention to another consequence for the tunneling time theory that originates from the electron parallel motion in DBRH. It is well known that there is a spin–orbit coupling between in-plane electron motion and the electron spin polarization [17–20]. The coupling causes spin-splitting in the electronic energy band in asymmetric heterostructures or heterostructures with an external electric field [21–24]. Recently, it has been found that this effect is also strong in tunnel barrier structures and can lead to spin-dependent tunnel coefficients [25–27]. There are two contributions to the spin-splitting effect that can be distinguished, which play different roles: band-edge discontinuity at the structure interfaces and additional electrostatic potential. The former brings about the spin-dependent boundary conditions to the tunnel problem and the latter gives a spin-dependent term in the effective mass Hamiltonian [21–24]. Both of them form different tunneling resonance conditions for different spin polarizations of tunneling electrons and lead to a spin-splitting of the resonance level in the asymmetric DBRH well [26,27]. The spin-split levels correspond to different electronic spin polarizations and obviously have different characteristic times of the electron tunnel process. We will show below that the spin–orbit coupling can lead to significant differences in tunneling

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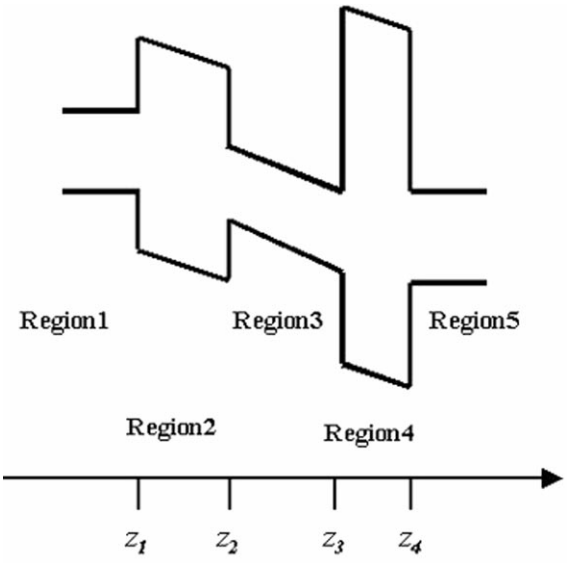

Fig. 1. Variation of the semiconductor-band parameters in DBRH with external electric field.

times for different electron spin polarizations at zero magnetic field.

In this investigation we use the "stationary phase approach" to the tunneling time definition introduced by Bohm [5]. It is a well-understood and widely used definition that actually deals with the phase delay time. The delay time can be described as the energy derivative of the phase Θ of the structure transmission amplitude

$$\tau = \hbar \frac{\partial \Theta}{\partial E_z}, \tag{1}$$

where E_z denotes the longitudinal (corresponding to a motion along the perpendicular direction to the heterostructure interface) component of the electron's total energy.

We describe here a DBRH with variations of the band structure parameters with an external electric field, as shown in Fig. 1. Layers of the structure are perpendicular to the z-axis, the 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). In the structure we have two sources for the k-vector dependence of the transmission coefficient: through position-dependent energy band parameters (as in Refs. [10–15]), and through the coupling between in-plane electron motion and the electron's spin polarization produced by the external electric field. The last one can lead to the spin polarization dependence in symmetric DBRH (sDBRH). The former leads to the spin-dependent boundary conditions and manifests the spin-splitting effect when the DBRH is asymmetric (aDBRH), even without an additional electric field [23,26,27]. We use the effective quasi-one-dimensional one-electronic-zone Hamiltonian [23] within the envelope function approximation for the total wave function of the electron $\Phi_\sigma(z, \rho)$ and can present the function as

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

where $\Psi_{j\sigma}(z)$ satisfies the z-component of the Schrödinger equation in the jth region and $\sigma = \pm 1$ refers to the spin polarization. The mass and spin-dependent boundary conditions for $\Psi_{j\sigma}(z)$ at an interface plane $z = z_j$ between j and $j+1$ regions have been introduced in Ref. [23]

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

$$\Psi_{j\sigma}(z_j) - \Psi_{j+1\sigma}(z_j) = 0, \tag{2}$$

where

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

is position- and energy-dependent electronic effective mass in nonparabolic approximation and

$$\beta(E,z) = \frac{P^2}{2}\left[\frac{1}{E - E_c(z) + E_g(z) + V(z)} - \frac{1}{E - E_c(z) + E_g(z) + \Delta(z) + V(z)}\right] \tag{4}$$

is position- and energy-dependent electronic spin-coupling parameters. In Eqs. (2) and (3), E denotes the total electron energy in the conduction band, $V(z) = -eFz$ is the external electric potential (F—the electric field, e—the electron's charge). The matrix element P is assumed to be z-independent [28]; $E_c(z)$, $E_g(z)$, and $\Delta(z)$ stand correspondingly for z-dependencies of the conduction-band-edge, the main band gap, and the spin–orbit splitting profiles.

The most attractive material system for the spin-splitting effects in DBRH preferably should contain a component of narrow-band semiconductors [17,18,21]. It worth noticing that the parabolic approximation in the electron motion description can lead to incorrect results for this case [22,25]. Therefore, in our calculations we use values below the nonparabolic approximation (2) for the electronic dispersion relations in all materials of the structures.

To obtain the structure tunneling transmission amplitude, we use the transfer matrix method [29] with the boundary conditions above Eq. (2) as was described in Ref. [26]. The potential profile in the DBRH consists of five regions and the total transfer matrix, which matches regions 5 and 1, can be written as

$$M_\sigma = \prod_{j=1}^{4} M_\sigma^j \tag{5}$$

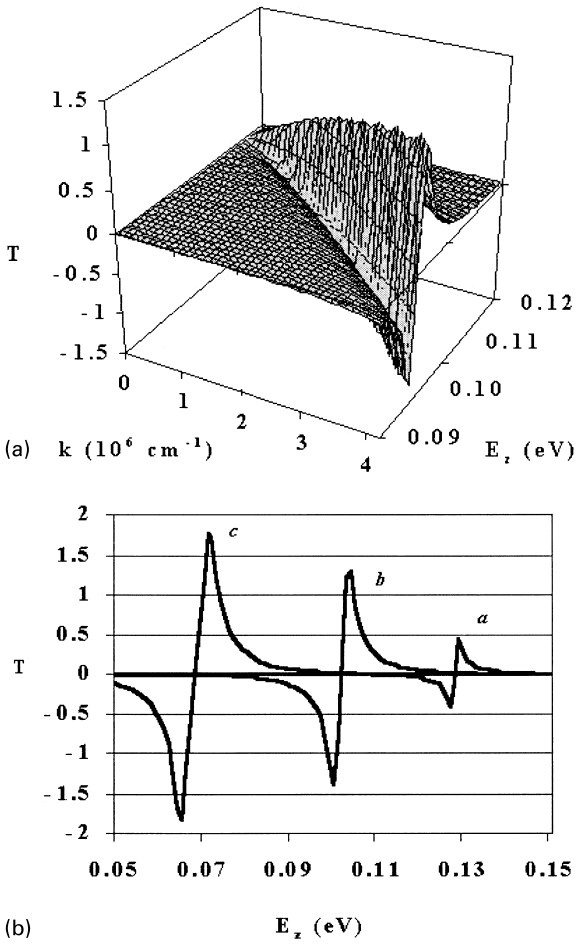

Fig. 2. Ratio between the delay time for different polarization of the electron spin in sDBRH with parameters of InAs–GaAs–InAs–GaAs–InAs (parameters are obtained from Ref. [30]): $E_{2c} = E_{4c} = 0.792$ eV, $E_{3c} = E_{5c} = 0.0$ eV, $E_{1g} = E_{3g} = E_{5g} = 0.418$ eV, $E_{2g} = E_{4g} = 1.52$ eV, $\Delta_1 = \Delta_3 = \Delta_5 = 0.38$ eV, $\Delta_2 = \Delta_4 = 0.341$ eV, $m_1(0) = m_3(0) = m_5(0) = 0.023m_0$, $m_2(0) = m_4(0) = 0.067m_0$ (m_0—the free electron's mass), $z_2 - z_1 = z_5 - z_4 = 30$ Å, $z_3 - z_2 = 60$ Å. (a) **T** plot in E_z–k plane for external electric field $F = 5 \times 10^4$ V cm^{-1}; (b) $\mathbf{T}(E_z, k = 4 \times 10^6\ \text{cm}^{-1})$ intersections of the three-dimensional plots. Curves a–c correspond, respectively, to the cases $F = 2 \times 10^4$, 5×10^4, and 1×10^5 V cm^{-1}.

In Eq. (4) M_σ^j is the transfer matrix that matches regions j and $j+1$. The structure transmission amplitude is equal to $(M_{\sigma 11})^{-1}$ and we can finally write

$$\tau_\sigma(E_z, k) = -\hbar \frac{\partial \arg(M_{\sigma 11})}{\partial E_z}, \tag{6}$$

which is the equation we use to calculate the spin-dependent delay time of the double-barrier structures.

The delay time is a function of the two variables E_z and k. The function normally demonstrates a sharp peak for one defined polarization of the electron spin [8]. Consequently, in the E_z–k plane we have two overlapping peaks for two polarizations [26,27]. From the point of view of possible applications, it is interesting to clarify a difference between the tunneling times for electrons with identical energy and wave vectors and different spin polarizations. Because the peaks have very sharp dependencies in the E_z–k plane [8,26,27], to get a quantitative filling about possible difference of the delay time for electrons with different spin polarizations, it is useful to calculate and present a logarithmic ratio of the times with spin-up ($\tau_\uparrow$) and spin-down ($\tau_\downarrow$) polarization

$$\mathbf{T}(E_z, k) = \log_{10} \frac{\tau_\uparrow}{\tau_\downarrow} \tag{7}$$

First, we consider an sDBRH composed of two identical InAs–GaAs–InAs barriers (parameters of materials are from Refs. [28,30]). The thickness of the GaAs barriers is chosen as $z_2 - z_1 = z_5 - z_4 = 30$ Å, and InAs well width is $z_2 - z_3 = 60$ Å. For this structure, the spin-splitting effect in the tunneling processes comes only when we apply the external electric field. The three-dimensional plot of $\mathbf{T}(E_z, k)$ in Fig. 2(a) presents two sharp peaks, one positive and one negative (corresponding to the spin-split resonance levels [26,27]), where the tunneling delay time is strongly dependent on the spin polarization. The difference increases with increase of the k vector and the external electric field magnitude. This is demonstrated in Fig. 2(b). Curves a–c in Fig. 2(b) correspond to different values of the external electric field, when $k = 4 \times 10^6$ cm^{-1}. Absolute values of the time for the described sDBRH lie between 10^{-12} and 10^{-15} s. It should be noticed that the ratio between the delay times can gain a few orders in magnitude.

The delay time (near resonance energy in the E_z–k plane) presents the halfwidth of the resonance peak for the tunneling probability $\Gamma_\sigma \approx 2\hbar/\tau_\sigma(E_z^\sigma(k))$, $E_z^\sigma(k)$ is the resonance peak position in E_z–k plane [8]. Our results show that conditions of the electrons "trapped" in resonant two-dimensional states inside the well can depend strongly on the electron spin polarization. The decay time of the states (or the time spent by an electron in the well) becomes also different for the electrons with different spin polarizations. We can control the difference by the external electric field. These facts could be a base for experimental investigations and practical applications of the effect.

In Fig. 3(a), we have shown results of the $\mathbf{T}(E_z, k)$ calculation for an aDBRH with electronic-band parameters of InAs–GaAs–InAs–AlAs–InAs [30]. The thicknesses of GaAs and AlAs barriers are 35 and 15 Å, respectively, and InAs well width is 60 Å. For this structure we have a big polarization effect even without any external electric field. The effect is originated from the built-in asymmetry of the structure [22,23]. Additional external electric field can increase, suppress, and even reverse the effect as shown in Fig. 3(b). Curve d in the insert to Fig. 3(b) demonstrates the last situation. We can conclude that involving the aDBRH extends the range of opportunities to control the

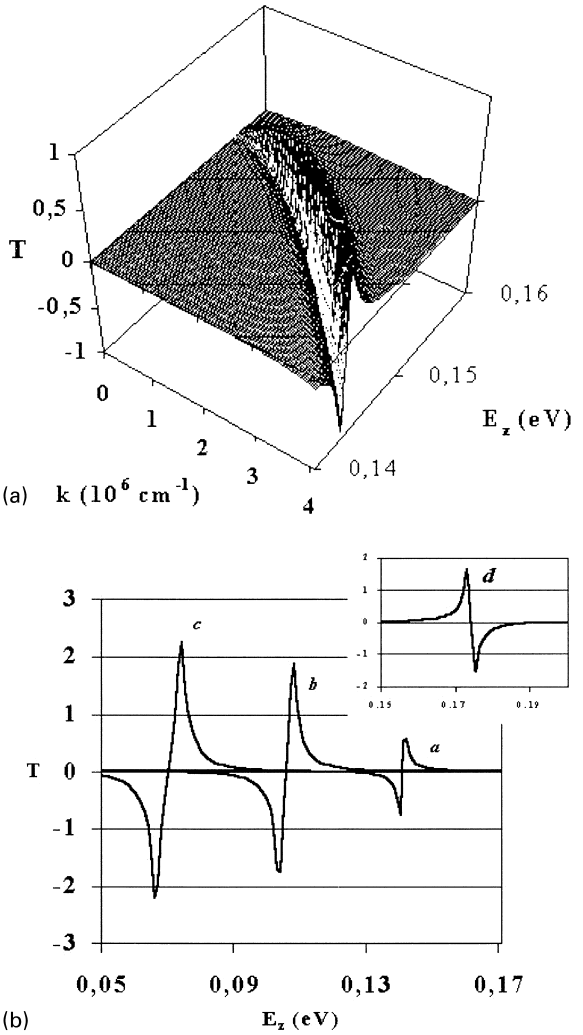

Fig. 3. Ratio between the delay time for different polarizations of the electron spin in aDBRH with parameters of InAs–GaAs–InAs–AlAs–InAs (parameters are obtained from Ref. [30]): $E_{2c} = 0.792$ eV, $E_{4c} = 1.86$ eV, $E_{3c} = E_{5c} = 0.0$ eV, $E_{1g} = E_{3g} = E_{5g} = 0.418$ eV, $E_{2g} = 1.52$ eV, $E_{4g} = 3.13$ eV, $\Delta_1 = \Delta_3 = \Delta_5 = 0.38$ eV, $\Delta_2 = 0.341$ eV, $\Delta_4 = 0.28$ eV, $m_1(0) = m_3(0) = m_5(0) = 0.23m_0$, $m_2(0) = 0.067m_0$, $m_4(0) = 0.15m_0$, $z_2 - z_1 = 30$ Å, $z_3 - z_2 = 60$ Å, $z_4 - z_3 = 15$ Å. (a) Three-dimensional plot for the structure without external electric field. (b) $\mathbf{T}(E_z, k = 4\times10^6\ \mathrm{cm}^{-1})$ intersections of three-dimensional plots. Curves *a*–*c* correspond, respectively, to the cases $F = 0$, 5×10^4, and 1×10^5 V cm^{-1}. Insert (*d* curve) corresponds to the case of reverse external electric field $F = -5\times10^4$ V cm^{-1}.

effect and could be more attractive from the practical point of view.

In conclusion, we have presented a study of the spin-dependent tunneling phase time (delay time) in the double-barrier heterostructures at zero magnetic field. The spin-dependent tunneling resonance conditions lead to the spin-splitting of the resonance level in the asymmetric DBRH well and to different characteristic times for different spin polarizations of the tunneling electrons. The effective one-band Hamiltonian approximation with the spin-dependent boundary conditions was employed to describe and evaluate the effect of spin-dependent tunneling in symmetric and asymmetric tunnel heterostructures. The calculated results show considerable influence of the spin-splitting effect on the resonant delay time. The dependence can be controlled by an external electric field. This effect may potentially become a physical base for a new generation of fast spin-polarizing tunneling devices.

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