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Effect of negative electric field on spin-dependent tunneling in double barrier semiconductor heterostructures

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ABSTRACT

The effect of negative electric field on spin-dependent tunneling in double barrier heterostructures of III–V semiconductor is theoretically investigated. The transfer matrix approach is used by considering Dresselhaus and induced-Rashba effect to calculate the barrier transparency and polarization efficiency. Cent percent polarization efficiency can be achieved for the negative electric field by increasing the width of the potential barrier. The separation between spin-up and spin-down resonances are evaluated. The separation between spin resonances and tunneling lifetime of electrons are observed for various negative electric fields as well as for various barrier widths. The linear variation of spin separation and tunneling lifetime of electrons are observed as a function of negative electric field.

1. Introduction

The electron spin, not the electron charge, carries the information and that causes the positive changes in the electronic device applications in terms of speed and data storage which are based on Dresselhaus spin–orbit interaction (SOI) and Rashba SOI. For this reason, theoretical and experimental progress in semiconductors has become forefront now [1–11]. The spin of an electron can be manipulated in the low dimensional semiconductor heterostructures by external electric or magnetic field [12,13].

Bin wang et al. investigated the spin polarization induced by an external electric field in a hybrid magnetic-electric barrier and they pointed out that the electric barrier can greatly suppress the current density and affect the degree of spin polarization [14]. Wan Li et al. reported the Dresselhaus spin–orbit coupling effect on dwell time of electrons tunneling through double-barrier structures. Their results indicate that structural asymmetry and external electric fields can affect the dwell time of electrons [15]. Dong Kwon Kim et al. analyzed the electric field induced strong mixing between e1–hh1 and e1–hh2 excitons in asymmetric double quantum wells [16]. Marko Eric et al. studied the spin-dependent dwell times of electron tunneling through double and triple-barrier structures. They mentioned the difference of dwell times of electrons with opposite spin orientations depends on structural parameters, electric field and in-plane wave vector [17]. Trinath Sahu et al. analyzed the effect of electric field on low temperature multi-subband electron mobility in a coupled $Ga_{0.5}In_{0.5}P/GaAs$ quantum well structure. They showed that the reversing electric field a large change in mobility was obtained due to the asymmetric nature of the interface roughness scattering potential [18]. Yamagishi et al. have reported the tunneling rates for spin-up and spin-down electrons for a GaAs quantum dot in an in-plane magnetic fields. An extremely small current is observed with the spin and energy dependences of the tunneling rates [11].

In this present work, we reported the effect of negative electric field on the spin-dependent tunneling in non-magnetic strained double barrier system such as InAs/GaAs/InAs/GaAs/InAs. The paper is arranged as follows: In Section 2, theoretical formalism is given. Spin and electric field dependent Hamiltonian and Airy function based Eigen functions are considered. By applying the boundary conditions, interface matrix at each interface and hence the transfer matrix are formed. Transfer matrix approach is employed to calculate the barrier transparency, energy separation between spin-up and spin-down components, polarization efficiency and tunneling lifetime in the heterostructures within the envelope function approximation and Kane model for the bulk. In

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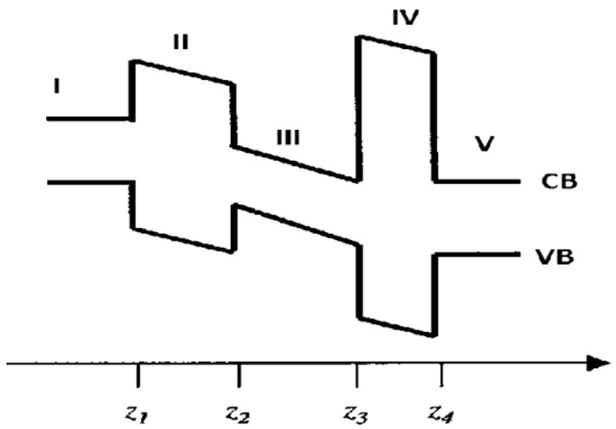

Fig. 1. The potential profile of double barrier hetero structure under external electric field.

Section 3, results and discussions are presented followed by conclusion.

2. Formalism

We consider the transmission of electrons with the initial wave vector $\vec{k}(k_\parallel, k_z)$ through a double barrier structure grown along z $\parallel$[001] as shown in Fig. 1.

The electron motion is described by the quasi-one dimensional Hamiltonian is given by,

$$H = \frac{-\hbar^2}{2}\frac{d}{dz}\frac{1}{m(E,z)}\frac{d}{dz} + \frac{\hbar^2 k_\parallel^2}{2m(E,z)} + E_c(z) + V(z) + H_D + H_R \tag{1}$$

where $m(E_z, k_\parallel)$ is the effective mass of the electron due to the external electric field, V(z) is the potential due to the external electric field, $E_c(z)$ is the conduction band edge, H_D is the Dresselhaus Hamiltonian and H_R is the Rashba Hamiltonian.

The potential due to the external electric field is given by,

$$V(z) = -eFz \tag{2}$$

The electric field and position dependent effective mass of an electron is given by,

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

The Dresselhaus and Rashba Hamiltonian are diagonalized by the spinor,

$$\chi_\sigma = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -\sigma e^{-i\phi} \end{pmatrix} \tag{4}$$

$$k_5\left(E_z, k_\parallel\right) = \sqrt{\frac{2m_5^*\left(E_z, k_\parallel\right)\left(E_z - E_{5c} + eFd - \frac{\hbar^2}{2m_5(E,z)}\left[1 - \frac{m_5(E,z)}{m_1(E,z)}\right]k_\parallel^2\right)}{\hbar^2}}$$

Table 1
Parameters used in calculations [20–22].

Parameters	InAs	GaAs
Effective mass of an electron	0.023 m_0	0.067 m_0
Spin-orbit splitting	380 meV	341 meV
Conduction band edge	0 meV	792 meV
Band gap	418 meV	1520 meV
Dresselhaus spin–orbit splitting	130 eV Å^3	24 eV Å^3

Here σ represents the spin-up and spin-down states, P is the momentum matrix element, E_g is the main band gap and Δ is the spin–orbit splitting. The diagonalized spin–orbit interaction due to the combined effect of Dresselhaus and Rashba spin interactions on the spin dependent tunnelling through a double barrier is described by [16],

$$H_{j\sigma} = -\frac{\hbar^2}{2m_j(E,z)\left[1 + \frac{\sigma 2\gamma m_j(E,z)k_p}{\hbar^2}\right]^{-1}}\frac{d^2}{dz^2} + \frac{\hbar^2 k_\parallel^2}{2m_j(E,z)} + E_{jc} - \frac{\sigma d\beta(E,z)}{dz}k_\parallel + V(z) \tag{5}$$

where

$$\beta(E,z) = \frac{P^2}{2}\left[\frac{1}{E - E_c(z) + E_g(z) + V(z)} - \frac{1}{E + \Delta(z) - E_c(z) + E_g(z) + V(z)}\right] \tag{6}$$

For regions I–V, the eigen function is given by [19].

$$\begin{aligned} u_{1\sigma}(z) &= a_{1\sigma}e^{+ik_1 z} + b_{1\sigma}e^{-ik_1 z} \\ u_{2\sigma}(z) &= a_{2\sigma}Bi(Z_{2\sigma}) + b_{2\sigma}Ai(Z_{2\sigma}) \\ u_{3\sigma}(z) &= a_{3\sigma}Bi(Z_{3\sigma}) + b_{3\sigma}Ai(Z_{3\sigma}) \\ u_{4\sigma}(z) &= a_{4\sigma}Bi(Z_{4\sigma}) + b_{4\sigma}Ai(Z_{4\sigma}) \\ u_{5\sigma}(z) &= a_{5\sigma}e^{+ik_5 z} + b_{5\sigma}e^{-ik_5 z} \end{aligned} \tag{7}$$

where

$$k_1\left(E_z, k_\parallel\right) = \sqrt{\frac{2m_1^*\left(E_z, k_\parallel\right)E_z}{\hbar^2}},$$

$$Z_{j\sigma}(E,z) = \left[\frac{2em_j^*\left(E_z, k_\parallel\right)|F|}{\hbar^2}\right]^{1/3}\left[\frac{A_{j\sigma}(E,z) - zeF}{e|F|}\right],$$

$$A_{j\sigma}(E,z) = E_{jc} - E_z + \frac{\hbar^2 k_\parallel^2}{2m_j(E,z)}\left[1 - \frac{m_j(E,z)}{m_1(E,z)}\right] - (\sigma\alpha_j k_p - z_1)eF$$