IOP Conf. Series: Materials Science and Engineering **214** (2017) 012037 doi:10.1088/1757-899X/214/1/012037

Influence of Incident Angle of Electron on Transmittance and Tunneling Current in Heterostructures with Bias Voltage by Considering Spin Polarization Effect

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Abstract. In this work, an analytical expression is presented of electron transmittance through a potential barrier by applying a bias voltage with spin polarization consideration. A zinc-blende material was employed for the barrier in the heterostructure to calculate the transmittance, which depends on the spin states indicated as “up” and “down”. The obtained transmittance was then employed to compute the tunneling current. It was shown that the transmittances are different for each state and asymmetric with incident angle. The polarization is positive for a positive incident angle of and negative for a negative incident angle. It was also shown that the tunneling current did not reach its highest value at an incident angle of 0° (z-direction).

1. Introduction

It is known that the electron-tunneling phenomenon depends on spin polarization. It has received great attention in the study of charge transport in heterostructures due to its application in spintronic devices [1-3]. Since the invention of diluted magnetic semiconductors (DMS) by Ohno many researchers have reported that spin polarization in semiconductor heterostructures can be achieved by using a ferromagmetic semiconductor material [4-6]. On the other hand, Voskoboynikov et al. have proposed that the Rashba spin-orbit coupling can cause a non-magnetic semiconductor material to become a spin filter [7-9]. Furthermore, by using only nonmagnetic materials that exploit the unique characteristics of bulk inversion asymmetry in (110)-oriented semiconductor heterostructures, a spin transistor can be obtained, as proposed by Hall et al. [10-11]. Perel et al. have reported that spin polarization is dependent on the electron tunneling through a zinc-blende semiconductor. Moreover, the current interface enhancement in the case of a thin barrier that arises due to the Dresselhaus effect occurring in the zinc-blende [12]. Previously, Suryamas et al. have calculated the transmittance of electron tunneling through a nanometer-thick zinc-blende semiconductor square barrier with spin consideration. However, they did not consider the effect of bias voltage applied to the barrier in calculating the tunneling current [13, 14].

In this paper, we report our study on electron tunneling through a potential barrier with spin polarization consideration by applying a bias voltage to the barrier (called a trapezoidal barrier) following the method from Ref. [13]. The electron transmittance, which depends on spin orientation, was obtained by combining the Dresselhaus term to the Hamiltonian and solving the Schrödinger equation. The obtained transmittance was then utilized to calculate the tunneling current. The effect of the incident angle of the electron on the transmittance and tunneling current are discussed thoroughly.

2. Theoretical Model

Figure 1 depicts the potential profile of heterostructures with a voltage applied to the barrier. We consider that the material in Region 1 is the same as that in Region 3. The zinc-blende semiconductor in Region 2 acts as a potential barrier with width and height d and Φ_0, respectively. The potential profile is expressed as:

$$V(z)=\begin{cases} 0 & z<0 \\ \Phi_0 - e\dfrac{V_b}{d}z & 0\le z<d \\ -eV_b & z\ge d. \end{cases} \tag{1}$$

where V_b is the oxide voltage and e is the electronic charge.

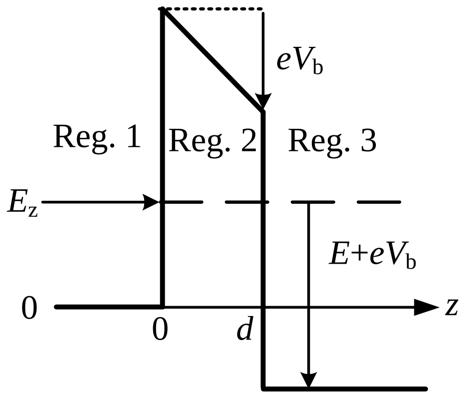

Figure 1. Potential profile of heterostructures with bias voltage applied to the barrier.

The electron tunnels through the potential barrier from the Regions 1 to 3 with initial wave propagation vector are given by

$$\vec{k} = k_\rho \hat{\rho} + k_z \hat{z} \tag{2}$$

where k_ρ and k_z are the momentum in parallel and normal directions, respectively. $\hat{\rho}$ and $\hat{z}$ are the unit vectors in parallel and normal directions to the interfaces between two regions, respectively. Furthermore, the incident angle, θ, is expressed as:

$$\theta = Arc\tan(k_\rho / k_z) \tag{3}$$

An electron in a semiconductor heterostructure with spin polarization is described by the Hamiltonian equation, which is given by:

$$H\Psi = E\Psi \tag{4}$$

where E is the total electron energy and Ψ is the electron wavefunction. H is the Hamiltonian, which is composed of H_O for the heterostructure without spin polarization and H_D for considering the spin polarization (Dresselhauss term), which is given by [15]:

$$H_D = \gamma(\alpha_x k_x - \alpha_y k_y)(\partial^2 / \partial z^2) \tag{5}$$

where γ is the Dresselhauss constant and α_i are the Pauli matrices.
By solving the Schrödinger equation and using the boundary condition at each interface [16] it is easy to find the transmission coefficient, which is expressed as:

$$t_\pm = -2i\frac{k_{1\pm}\delta_{1\pm}}{m_1}\exp(-ik_{3\pm}d)\times\left\{\left(\frac{2eV_b}{m_2{}^2\hbar^2 d}\right)^{\frac{1}{3}}\delta_{2\pm} + i\left(\frac{k_{1\pm}\delta_{3\pm}k_{3\pm}\delta_{4\pm}}{m_1m_3}\right) - \left(\frac{k_{1\pm}k_{3\pm}}{m_1m_3}\right)\left(\frac{2eV_b}{m_2{}^2\hbar^2 d}\right)^{-\frac{1}{3}}\delta_{5\pm}\right\} \tag{6}$$

with

$$k_{1\pm} = \left(\frac{2m_1E_{z\pm}}{\hbar^2}\right)^{\frac{1}{2}}\left(1\pm\frac{2\gamma m_1k_\rho}{\hbar^2}\right)^{-\frac{1}{2}}, \tag{7}$$

$$k_{3\pm} = \left(\frac{2m_1}{\hbar^2}(E_z + eV_b)\right)^{\frac{1}{2}}, \tag{8}$$

$$\eta_\pm(z) = \left(\frac{2m_2eV_b}{\hbar^2 d}(E_z + eV_b)\right)^{\frac{1}{3}}\left\{(\Phi_0 - E_z)\frac{d}{eV_b} - z\right\}, \tag{9}$$

$$\delta_{1\pm} = Ai'(\eta(d))Bi(\eta(d)) - Ai(\eta(d))Bi'(\eta(d)), \tag{10}$$

$$\delta_{2\pm} = Ai'(\eta(d))Bi'(\eta(0)) - Ai'(\eta(0))Bi'(\eta(d)), \tag{11}$$

$$\delta_{3\pm} = Ai(\eta(0))Bi'(\eta(d)) - Ai'(\eta(d))Bi(\eta(0)), \tag{12}$$

$$\delta_{4\pm} = Ai(\eta(d))Bi'(\eta(0)) - Ai'(\eta(0))Bi(\eta(d)), \tag{13}$$

$$\delta_{5\pm} = Ai(\eta(0))Bi(\eta(d)) - Ai(\eta(d))Bi'(\eta(0)). \tag{14}$$

The transmittance is then obtained as follows:

$$T_\pm = t_\pm{}^* t_\pm, \tag{15}$$

where $t_\pm{}^*$ is the conjugate of $t_\pm$.

The polarization of spin P is written as:

$$P = \frac{|t_+|^2 - |t_-|^2}{|t_+|^2 + |t_-|^2}\times 100\%. \tag{16}$$

Furthermore, the tunneling current is calculated by using the following equation [17]:

$$J_z = \frac{em_1kT}{2\pi^2\hbar^3}\times\int_0^\infty T(E_z)\ln\left\{\frac{(1+\exp[(E_F - E_z)/kT])}{1+\exp[(E_F - E_z - eV_b)/kT]}\right\}dE_z, \tag{17}$$

where k is the Boltzmann constant, T is the temperature, E_F is the Fermi energy of metal, and $T(E_z) = T_+(E_z) - T_-(E_z)$ is the total transmittance. The tunneling current in Equation (17) is easily evaluated by using the Gauss-Laguerre Quadrature method [18].

3. Calculated Results and Discussion

In order to study the effects of the electron incident angle, we use metal/GaSb/metal structures. The following parameters were used to calculate the electron transmittance and tunneling current: $\gamma_1 = 0$, $\gamma_2 = 187$ eV/Å3, $\Phi_0 = 0.2$ eV, $E = 0.1$ eV, $V_b = 0.1$ V. Since the Dresselhauss constant, γ, in Region 1 is the same as that in Region 3, the wave vectors are also the same.

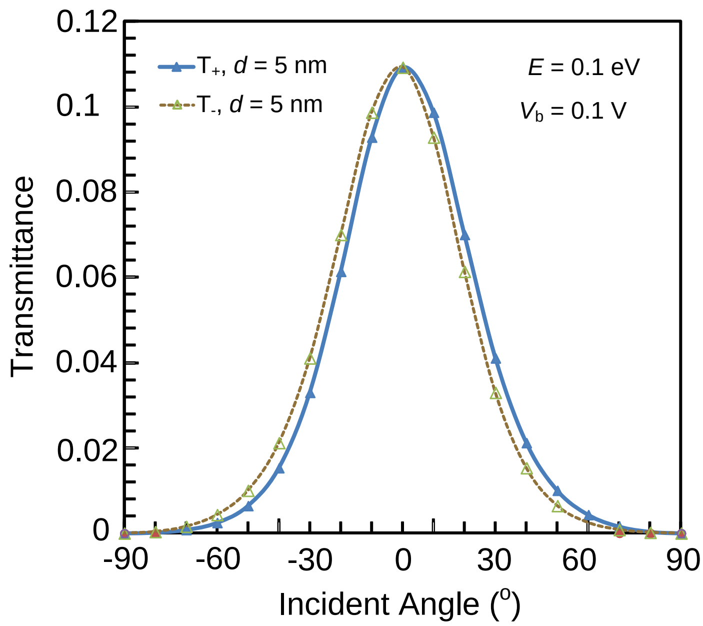

Figure 2. Transmittance versus incident angle of electron with barrier width at 5 nm.

Figure 2 illustrates the electron transmittance as a function of the electron incident angle with the barrier width at 5 nm. The transmittance had the highest value at an incident angle, θ, of about +5° and -5° for spin "up" and "down" polarization respectively. It decreased as the incident angle increased. The result is the same as that obtained without considering the bias voltage [13, 14] in which the transmittance for each state is not the same and asymmetric with the incident angle because of the bulk inversion asymmetry properties of the zinc-blende.

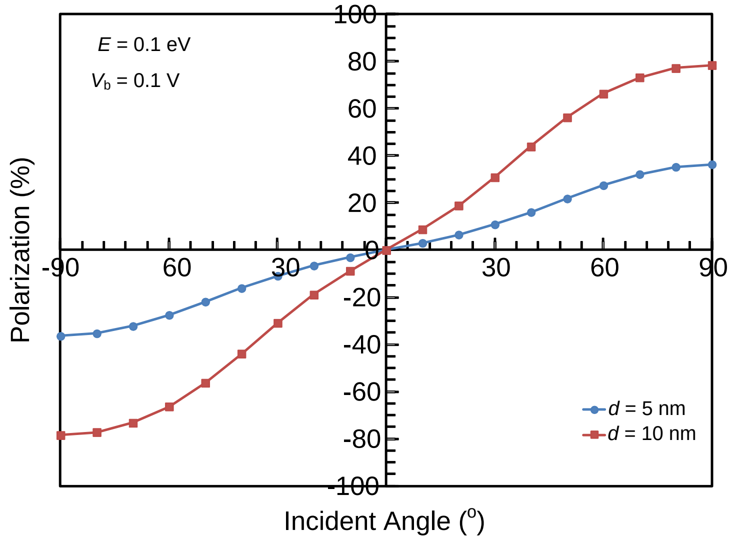

Figure 3. Transmittance versus incident angle of electron with barrier width at 5 nm.

The effect of incident angle on polarization is shown in Figure 3. It can be seen that the polarization increases as the incident angle of electron increases and has zero value at an incident angle of 0° (normal direction). It is also shown that the polarization gives a negative value for $\theta < 0^{o}$ and a positive value for $\theta > 0^{o}$ because the negative and positive states are dominant for $\theta < 0^{o}$ and $\theta > 0^{o}$, respectively. Moreover, the polarization shows the highest value at an incident angle in the parallel direction.

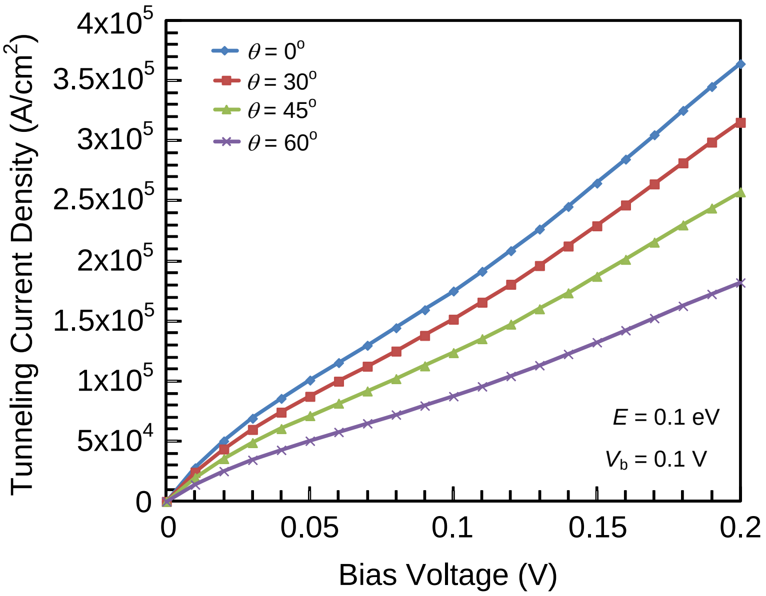

Figure 4. Tunneling current as a function of bias voltage for a variety of incident angles of the electron.

The electron tunneling current in metal/GaSb/metal heterostructures as a function of the oxide voltage for a variety of electron incident angles is displayed in Figure 4. It can be seen that as the incident angle decreases, the tunneling current increases and reaches the highest value at an incident angle of 0°. However, the variation of the incident angle is not significant for an oxide voltage less than 0.01 V. It can also be seen that the tunneling current increases with increasing bias voltage.

4. Conclusions

The electron transmittance and tunneling current in metal/GaSb/metal heterostructures with bias voltage under spin polarization consideration were calculated by taking into account the Dresselhauss term. A zinc-blende material for the barrier in the heterostructure was employed to calculate the transmittance. The transmittance was evaluated for "up" and "down" states. It was found that the transmittance for each state is different and asymmetric with the incident angle. It was also shown that the polarization was optimum at the incident angle in the parallel direction. On the other hand, the tunneling current reached its highest value at an incident angle in the normal direction.

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Acknowledgments

This research was supported by "Riset Desentralisasi" Research Grants in the fiscal year of 2017.