Transmittance and Tunneling Current through a Trapezoidal Barrier under Spin Polarization Consideration

F A Noor*, E Nabila, H Mardianti, T I Ariani and Khairurrijal

Physics of Electronic Materials Research Division, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung 40132, Indonesia

*fatimah@fi.itb.ac.id

Abstract. The transmittance and tunneling current in heterostructures under spin polarization consideration were studied by employing a zinc-blended structure for the heterostructures. An electron tunnels through a potential barrier by applying a bias voltage to the barrier, which is called the trapezoidal potential barrier. In order to study the transmittance, an Airy wave function approach was employed to find the transmittance. The obtained transmittance was then utilized to compute the tunneling current by using a Gauss quadrature method. It was shown that the transmittances were asymmetric with the incident angle of the electron. It was also shown that the tunneling currents increased as the bias voltage increased.

Introduction

It was known that spin-polarized electron transport in semiconductors attracts great attention due to its application in spintronic devices [1-3]. The development is focused on the possibility and methods of spin injection into semiconductors [4]. In order to obtain the desired spin orientation, spin-polarized carriers from magnetic materials are injected [4]. However, the conductivity mismatch of the metal-semiconductor structure is a general difficulty for electrical injection of ferromagnetic semiconductors, as reported by Schmidt et al. [4-5]. On the other hand, a spin transistor can also be achieved by using only nonmagnetic materials that exploit the unique characteristics of bulk inversion asymmetry in (110)-oriented semiconductor heterostructures, as reported by Hall et al. [6-7]. Furthermore, Voskoboynikov et al. have proposed that a non-magnetic semiconductor material can be produced by Rashba spin-orbit coupling due to the Dresselhaus effect occurring in zinc-blende [8-10].

Several methods have been proposed to study the tunneling current in heterostructures under spin polarization [11-13]. Suryamas et al. have studied the tunneling process in a heterostructure with a zinc-blende semiconductor under spin polarization consideration [14-15]. However, they did not consider the effect of bias voltage on the heterostructure. In this research, we studied the electron transmittance and tunneling current through a nanometer-thick zinc-blende semiconductor with spin consideration by considering the bias voltage applied to the barrier (called the trapezoidal barrier). The transmittance was derived by considering the Dresselhaus effect and solving the Schrödinger equation. The effects of the electron’s incident angle and bias voltage were investigated.

Theoretical Model
The potential profile of the heterostructures when applying a bias voltage to the barrier is depicted in Fig. 1. Here, \( V_0 \) is the barrier height, \( d \) is the barrier width, \( e \) is the electronic charge, \( V_b \) is the bias voltage, and \( E \) is the energy. We consider an electron tunneling through a zinc-blende semiconductor; in this study, GaSb was used. The potential profile is therefore expressed as:

\[
V(z) = \begin{cases} 
0 & \text{if } z < 0 \\
V_0 - eV_b \frac{z}{d} & \text{if } 0 \leq z < d \\
-eV_b & \text{if } z \geq d.
\end{cases}
\]  

(1)

![Figure 1. Potential profile of heterostructures under a bias voltage applied to the barrier.](image)

The model begins from the Hamiltonian equation, which describes an electron in a material as given by:

\[
H \Psi = E \Psi
\]  

(2)

where \( E \) is the total electron energy, \( \Psi \) is the electron wave function, and \( H \) is the Hamiltonian. The Hamiltonian, \( H \), is composed of \( H_0 \) for the heterostructure without spin polarization and \( H_D \) for considering the spin polarization (Dresselhauss term) and is written as \( H = H_0 + H_D \). Here \( H_D \) is expressed by [16]:

\[
H_D = \gamma \left( \alpha_x k_x - \alpha_y k_y \right) \left( \frac{\partial^2}{\partial z^2} \right)
\]  

(3)

where \( \alpha_i \) are Pauli matrices \( (i \in \{x, y\}) \) and \( \gamma \) is a Dresselhauss constant.

By solving the Schrödinger equation and applying the boundary condition at \( z = 0 \) and \( z = d \) [17], it is easy to find the formulation of the transmission coefficient, \( f \). The formulation is [18]

\[
f_{\pm} = -2i \frac{k_\pm \delta_{\pm}}{m_1} \exp(-ik_\pm d) \times \left\{ \frac{2eV_b}{m_2^2 \eta^2 d} \right\}^{\frac{1}{3}} \delta_{2\pm} + i \left( \frac{k_\pm \delta_{3\pm}}{m_1 m_3} \right) - \left( \frac{k_\pm \delta_{4\pm}}{m_1 m_3} \right) \left( \frac{2eV_b}{m_2^2 \eta^2 d} \right)^{\frac{1}{3}} \delta_{5\pm} \right\}.
\]  

(4)

Here,

\[
k_{\pm} = \left( \frac{2m_1 E_{z\pm}}{\eta^2} \right)^{\frac{1}{2}} \left( 1 \pm \frac{2m_1 k_{1\pm}}{\eta^2} \right)^{\frac{1}{2}},
\]  

(5)
\[ k_{3\pm} = \left( \frac{2m_1}{\eta^2} (E_z + eV_b) \right)^{\frac{1}{2}}, \]

\[ \eta_{\pm}(z) = \left( \frac{2m_2 eV_b}{\eta^2 d} (E_z + eV_b) \right)^{\frac{1}{2}} \left( \Phi_0 - E_z \right)^{\frac{1}{2}} \left( \frac{d}{eV_b} - \frac{d}{\eta} \right), \]

\[ \delta_{1\pm} = A_i^- (\eta(d)) B_i^- (\eta(d)) - A_i (\eta(d)) B_i^- (\eta(d)), \]

\[ \delta_{2\pm} = A_i^- (\eta(0)) B_i^- (\eta(0)) - A_i (\eta(0)) B_i^- (\eta(0)), \]

\[ \delta_{3\pm} = A_i (\eta(0)) B_i^- (\eta(d)) - A_i^- (\eta(d)) B_i^- (\eta(d)), \]

\[ \delta_{4\pm} = A_i (\eta(d)) B_i^- (\eta(0)) - A_i^- (\eta(0)) B_i^- (\eta(d)), \]

\[ \delta_{5\pm} = A_i (\eta(0)) B_i^- (\eta(0)) - A_i^- (\eta(0)) B_i^- (\eta(0)). \]

From Eq. (4), we can obtain the transmittance as follows:

\[ T_{\pm} = f_{\pm}^* f_{\pm}, \]

where the signs ‘+’ and ‘−’ denote spin up and spin down, respectively. \( f_{\pm}^* \) is the conjugate of \( f_{\pm} \).

Finally, the tunneling current is computed by using the following equation [19]:

\[ J_z = \frac{e m k T}{2 \pi^2 \eta^3} \left[ T(E_z) \ln \left( \frac{1 + \exp \left( (E_F - E_z)/kT \right)}{1 + \exp \left( (E_F - E_z - eV_b)/kT \right)} \right) \right] dE_z, \]

where \( k \) is the Boltzmann constant, \( T \) is the temperature, \( E_F \) is the Fermi energy of metal, and \( T(E_z) = T_{\pm} (E_z) - T_{\mp} (E_z) \) is the total transmittance. The tunneling current in Equation (14) is easily evaluated by using the Gauss-Laguerre Quadrature method [20].

**Calculated Results and Discussion**

![Figure 2. The transmittance depends on the incident angle of the electron.](image-url)
The transmittances and tunneling currents for electrons in metal/GaSb/metal structures can be calculated on the basis of Equations (13) and (14). The parameters in this study were: \( \gamma_1 = 0, \gamma_2 = 187 \) eV/Å³, \( V_0 = 0.2 \) eV, \( E = 0.1 \) eV, \( d = 10 \) nm. Figure 2 presents electron transmittance versus incident angle of the electron for a barrier width and bias voltage of 10 nm and 0.1 V, respectively. The transmittances show the highest value at an incident angle of 0° (z-direction) for a spin up and spin down polarization respectively. This gives the same results as the calculation without considering the bias voltage [14-15], in which the transmittance for each state is quasi-symmetric with the incident angle of the electron because of the bulk inversion asymmetry properties of the zinc-blende.

![Figure 3. Electron tunneling current dependence on bias voltage.](image)

The bias voltage dependence of the transmittance in metal/GaSb/metal heterostructures for a spin up and spin down states is depicted in Figure 3. It can be seen that as the bias voltage increased, the tunneling current increased for both states. However, the tunneling current for electron spin up was larger than that for electron spin down. This means that the electron spin up state is more dominant than the spin down one.

**Conclusions**

The electron transmittance and tunneling current through metal/GaSb/metal heterostructures have been calculated by taking into account the spin polarization. The transmittance and tunneling current were evaluated for the up and down states. It was shown that the transmittances are quasi-symmetric with the incident angle of the electron. It was also shown that the tunneling current increased as the bias voltage increased. Moreover, the tunneling current for the spin-up state was larger than that for the spin down one.

**Acknowledgments**

This research was supported by *Riset Desentralisasi* research grants for the fiscal year of 2017.

**References**

[1] Zutic I, Fabian J, Das Sarma S 2004 *Rev. Mod. Phys.* 76 323.
[2] Fabian J, Matos-Abiague A, Ertler C, Stano P, Zutic I 2007 *Acta Phys. Slov.* 57 566.
[3] Lu J W, Chen E, Kabir M, Stan, M R, Wolf S A 2016 *Int. Mater. Rev.* 61 456.
[4] Perel V I, Tarasenko S A, Yassievich I N 2003 *Phys. Rev. B* 67 201304.
[5] Schmidt G, Ferrand D, Molenkamp L W, Filip A T, and Wees J 2000 *Phys. Rev. B* 62 R4790.
[6] Hall K C, Lau W H, Gundogdu K, Flatte M E 2003 *Appl. Phys. Lett.* 83 2937.
[7] Flatte M E, Byers J M, Lau W H 2002 *Spin Dynamics in Semiconductors* *Semiconductor
Spintronics and Quantum Computation (Berlin: Springer-Verlag).

[8] Voskoboynikov A, Liu S S, Lee C P 1998 Phys. Rev. B 58 15397.
[9] Boda A, Boyacioglu B, Erkaslan U, Chatterjee A 2016 Physica B Condens Matter 498 43.
[10] Tutunculer H, Koc R, Olgar E 2004 J. Phys. A 37 11431.
[11] Dakhlaoui H, Jaziri S 2005 Physica B 355 401.
[12] Lebedeva N, Kuivalainen P 2003 J. Appl. Phys. 93 9845.
[13] Michaeli K, Varade V, Naaman R, Waldeck D H 2017 J. Phys : Condens Matter 29 103002.
[14] Suryamas A B, Abdullah M, Khairurrijal 2006 Indonesian J. Phys. 17 43.
[15] Suryamas A B, Abdullah M, Khairurrijal 2006 Transmittance Coefficient of Electron Tunneling through a Nanometer Thick Square Barrier with Spin Polarization Consideration International Conference on Mathematics and Natural Sciences (ICMNS) (Bandung, 29-30 November 2006) pp. 941.
[16] Dresselhauss G 1955 Phys. Rev. 100 580.
[17] BenDaniel D J, Duke C B 1966 Phys. Rev. 152 683.
[18] Noor F A, Nabila E, Sustini E, Khairurrijal 2016 Influence of Incident Angle of Electron on Transmittance and Tunneling Current in Heterostructures with Bias Voltage by Considering Spin Polarization Effect 2nd Material Research Society of Indonesia (MRS-id) Meeting (Bandung, 24-26 October 2016) published in IOP Conf. Series: Materials Science and Engineering 214 (2017) 012037
[19] Noor F A, Abdullah M, Sukirno, Khairurrijal, Ohta A, Miyazaki S 2010 J. Appl. Phys. 108 093711.
[20] De Vries P L 1993 A first course in computational physics (New York: John Wiley & Sons).