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Modelling of Tunnelling Current through a Trapezoidal Potential Barrier by Using Exponential Wavefunction Approach

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Abstract

A tunnelling current through a trapezoidal barrier potential has been modelled. The transmittance is determined using the exponential wavefunction approach method. Furthermore, the transmittance is used to calculate the tunnelling current density by applying the Gauss-Laguerre quadrature method. The simulation results show the increasing bias voltage causes the raising tunnelling current, and an increase of temperature is proportional to the tunnelling current.

Keywords: tunnelling current, exponential wavefunction, Gauss-Laguerre quadrature

INTRODUCTION

The tunnelling effect is a quantum phenomenon studied many times because this effect gives many benefits, especially in electronic device development. The tunnelling effect is closely related to transmittance through barrier potential [1]. There are several methods to calculate the transmittance, such as transfer matrix method (TMM), airy wavefunction, WKB and exponential wavefunction.

Some researchers have simulated Tunnelling current; some of them are tunnelling current simulation through trapezoidal barrier potential using TMM [2] and the exponential wavefunction approach [3]. In 2015, Peng Zang modelled the tunnelling effect of the metal-insulator-metal (MIM) system, the benefits of the structure are for developing capacitor [5] and diode [6]. In this work, the simulation in a trapezoidal barrier potential using exponential wavefunction for MIM structure and the Gauss-Laguerre method is used to determine the tunnelling current density.

THEORETICAL MODEL

Fig. 1 shows the potential profile of trapezoidal barrier potential with width Z and height V_0.

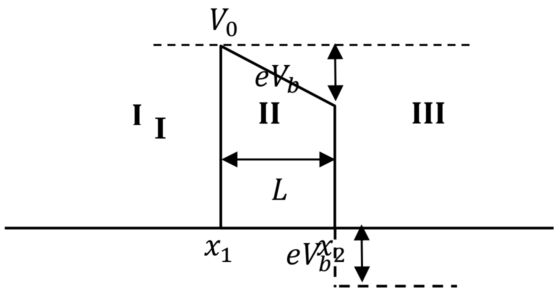

Fig. 1 Potential profile of trapezoidal barrier potential.

The potential barrier can be expressed as follows:

$$V(x) = \qquad \begin{matrix} x < x_1 \\ x_1 \le x < x_2 \end{matrix}$$

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$$\begin{cases} 0, \\ V_0 - \frac{eV_b}{x_2}x, \\ -eV_b, \qquad x \geq x_2 \end{cases}$$

The exponential wavefunction approach could be used to calculate the transmission coefficients through the potential barrier. The wavefunction solutions of each region are written as [3]:

$$\varphi(x) = \begin{cases} Ae^{ik_1x} + Be^{-ik_2x}, & for\ region\ I \\ Ce^{\int_0^x k_2(x')dx'} + De^{-\int_0^x k_2(x')dx'}, & for\ region\ II \\ Ee^{ik_3x}, & for\ region\ III \end{cases} \quad (1)$$

with,

$$k_1 = \sqrt{\frac{2m_1E_x}{\hbar^2}}, \quad (2)$$

$$k_2 = \sqrt{\frac{2m_2E_x}{\hbar^2}\left(V_0 - \frac{eV_b}{L}x\right)}, \quad (3)$$

$$k_3 = \sqrt{\frac{2m_1E_x}{\hbar^2}(E_x + eV_b)}. \quad (4)$$

The transmission coefficient of the system could be expressed as:

$$\left(\frac{E}{A}\right) = 2k_1\left(\frac{k_2(L)}{k_2(0)}\right)e^{-ik_3L}\frac{\left[\left(k_3 + \left(k_1\frac{k_2(L)}{k_2(0)}\right)\right)\cosh(a)\right] + i\left[\left(\frac{m_2k_1k_3}{m_1k_2(0)} - \frac{m_1k_2(d)}{m_2}\right)\sinh(a)\right]}{\left[\left(k_3 + \left(k_1\frac{k_2(L)}{k_2(0)}\right)\right)\cosh(a)\right]^2 + \left[\left(\frac{m_2k_1k_3}{m_1k_2(0)} - \frac{m_1k_2(d)}{m_2}\right)\sinh(a)\right]^2} \quad (5)$$

with,

$$a = \int_0^L k_2x\,dx, \quad (6)$$

$$a = \sqrt{\frac{2m_2}{\hbar^2}}\frac{2L}{3eV_b}\left((V_0 - E_x)^{\frac{3}{2}} - (V_0 - E_x - eV_b)^{\frac{3}{2}}\right). \quad (7)$$

The tunnelling current density for this system is determined by:

$$J_x = \frac{emk_BT}{2\pi^2\hbar^3}\int_0^\infty T(E_x)\ln\left\{\frac{1 + \exp\left[\frac{E_F - E_x}{k_BT}\right]}{1 + \exp\left[\frac{E_F - E_x - eV_b}{k_BT}\right]}\right\}dE_x \quad (8)$$

k_B is Boltzmann constant, T is temperature, $\hbar$ is Planck reduced constant, and E_F is Fermi energy [2].

The equation (8) contains infinity integral, and it could be solved using a numerical method, Gauss-Laguerre quadrature [7]:

$$\int_0^\infty e^{-x}f(x) \approx \sum_{j=1}^{n} w_jf(x_j) \quad (9)$$

with w_j is weight, and x_j is associated with polynomial $L_n(x) = \frac{e^xd^n}{dx^n}(e^{-x}x^n)$.

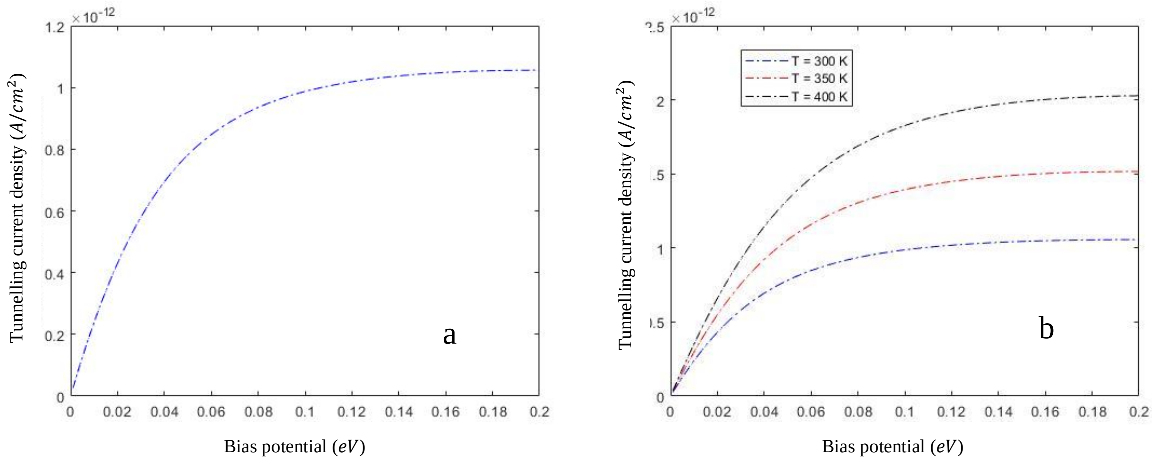

Fig. 2 (a) Tunnelling current density vs bias potential (b) Tunnelling current density in various temperature.

RESULTS AND DISCUSSION

Modelling of tunnelling current in a system with a height of the potential is 0.8, width 5 nm, and the Fermi energy is 0 eV is illustrated in Fig. 2a. It shows an increase tunnelling current when bias potential eV_b is increased. This phenomenon happened because the electron could pass the barrier quickly caused the bias voltage.

The value of tunnelling current density depends on temperature. Fig. 2(b) shows that when increased the temperature, the tunnelling current density went to a higher value in the same bias potential. It means, higher temperature makes higher tunnelling current density.

CONCLUSION

In conclusion, by the results, the bias potential proportional to tunnelling current density. Additionally, higher temperature will make higher tunnelling current density in the same bias potential value.

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