Tunneling Current of Electron in Armchair Graphene Nanoribbon Bipolar Transistor Model Using Transfer Matrix Method

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Abstract. The tunneling current of n-p-n bipolar junction transistor AGNR-based is modeled with semi-numerical method. The exponential solution from Schrödinger equation is used and solved analytically. The potential profile of n-p-n BJT divided into several segments in the numerical method. Then, the solved analytical result is used in the numerical method to compute the electron transmittance. Transfer Matrix Method (TMM) is the numerical method used to compute the electron transmittance. From the calculated transmittance the tunneling current can be computed by using Landauer formula with aid of Gauss-Legendre Quadrature (GLQ). Next, the tunneling current is computed with several change of variables which are base-emitter voltage (V_{BE}), base-collector voltage (V_{BC}), temperature and the AGNR's width. The computed tunneling current shows that the larger value of applied voltage for both V_{BE} and V_{BC} results in larger value of tunneling current. At the lower temperature, the current is larger. The computed tunneling current shows that at wider width of AGNR, the current is also larger. This is due to the decreased band-gap energy (E_g) because of the wider width of AGNR.

1. Introduction

Graphene is a 2D crystal layer arranged in honeycomb lattice structure constructed from carbon atoms. Graphene known to be one of the strongest material [1], transparent [2], conducting [3] and bendable [4]. Graphene can be made into graphene nanoribbon (GNR). Based on its edge-shape and width, graphene can be metallic or semiconducting [5, 6]. Zigzag graphene nanoribbon (ZGNR) has metal properties while armchair graphene nanoribbon (AGNR) can be metal or semiconductor. Graphene-based electronic devices are promising for future application.

The characteristic of n-p-n bipolar junction transistor based on silicon [7] and graphene material was modeled [8,9]. The device is made of p-type and n-type semiconductor. In the graphene-based n-p-n bipolar junction transistor, the p-type and n-type semiconductor can be made with doping a Boron and Nitrogen atoms [10] or electrostatically engineered [11]. Several approaches for computing tunneling current of AGNR-based devices has been done such as with Airy-wave function approach [9] and WKB approach [12]. A better tunneling current behavior was shown using TMM approach than most existing models [13,14].

In this paper, we study the tunneling current in the n-p-n bipolar transistor based on AGNR by solving the Schrödinger equation. By employing TMM and Landauer formula, we calculate the tunneling

current. The computed tunneling current will be discussed in detail for its effect on voltage, temperature and AGNR width.

2. Theoretical Approach

AGNR width is determined by the number of atoms that make up the whole width illustrated by figure 1. The AGNR width is computed using equation (1) [15]

$$w = (N-1)\frac{\sqrt{3}}{2}a_{cc} \tag{1}$$

Wherein a_{cc} is the C-C bond length. AGNR is semiconducting for $N = 3p + 1$ and metallic for $N = 3p$, where p is integer [16]. The band structure of AGNR is given by [17]:

$$E = s\hbar v_f \sqrt{k_z^2 + k_n^2} \tag{2}$$

Wherein $s = +1$ and $s = -1$ represent conduction band and valence band respectively, $\hbar$ is reduced Planck constant, v_f is the Fermi velocity, k_z is the electron momentum along GNR axis, $k_n = n\pi/3w$ is the electron transverse momentum which is quantized by the ribbon width and $n = \pm1, \pm2, \pm3, ...$ Band gap energy can be derived from Eq. (2), where $E_g = E_V - E_C$ assuming the material is isotropic and E_g is depend on v_f and w.
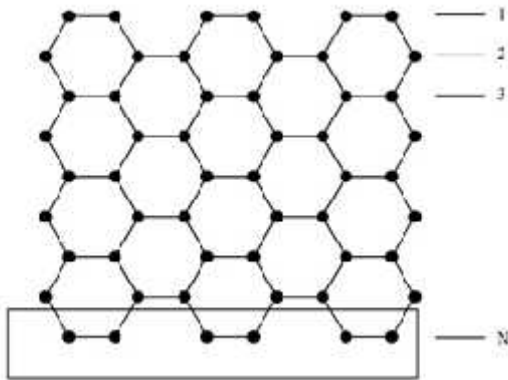
$$E_g = \frac{2f\hbar v_f}{3w} \tag{3}$$

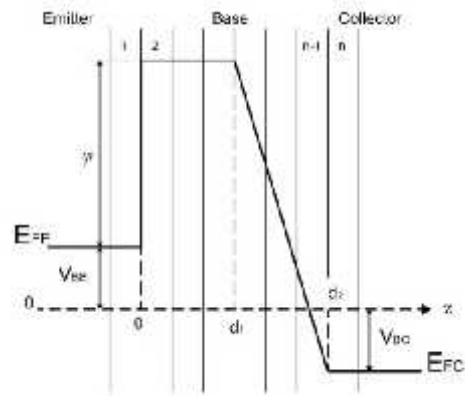**Figure 1.** The AGNR and its width formed by N atoms

Figure 2. Segments of n-p-n BJT potential profile

Analytical expression of the transmittance is derived by using exponential solution of the time independent Schrödinger equation and by applying boundary condition of the potential profile depicted in figure 2. The tunneling current can be computed by applying the computed transmittance using Landauer formula in equation (4) [12].

$$I = \frac{2g_v e}{h}\int_0^{eV}[f_V(E) - f_C(E)]T(E)dE \tag{4}$$

Wherein g_v is the degeneration of GNR ($g_v = 1$ for GNR) and $T(E)$ is the transmittance. The $f_V(E)$ and $f_C(E)$ are the Fermi-Dirac distribution functions for electrons in the valence and conduction band showed in equation (5) and equation (6).

$$f_V(E) = \left(1 + \exp\left[\frac{E - eV_b}{k_BT}\right]\right)^{-1} \tag{5}$$

$$f_V(E) = \left(1 + \exp\left[\frac{E}{k_B T}\right]\right)^{-1} \tag{6}$$

Wherein k_B is the Boltzmann constant and T is the temperature.

3. Results and Discussion

The computed tunneling current as a function of base-emitter voltage (V_{BE}) for various base-collector voltages (V_{BC}) depicted in figure 3. The AGNR length as base in the BJT device is 10 nm, the AGNR index is $N = 22$ ($w \approx 2.58\ nm$) and $T = 300\ K$. It shows that the tunneling current is proportional to the V_{BE} and also increasing with V_{BC}. The tunneling current is obtained in forward-active mode. The results are consistent with the previous computed tunneling current using different approach on various junction voltages [8,9].
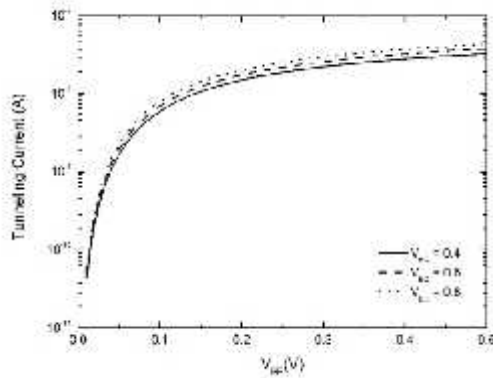

Figure 3. The computed tunneling current as a function of V_{BE} for various V_{BC}
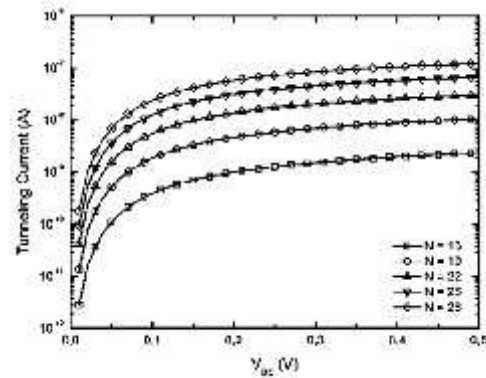

Figure 4. The computed tunneling current as a function of V_{BE} for various N

Figure 4 shows the computed tunneling current as the function of V_{BE} for various N index with $T = 300\ K$ and $V_{BC} = 0.3\ V$. The N index affects the AGNR width and its E_g. As N increases, the width is wider and the E_g value decreases. The tunneling current is increasing for larger AGNR index. This result is consistent with previous computed tunneling current model on the effects of AGNR index [8].
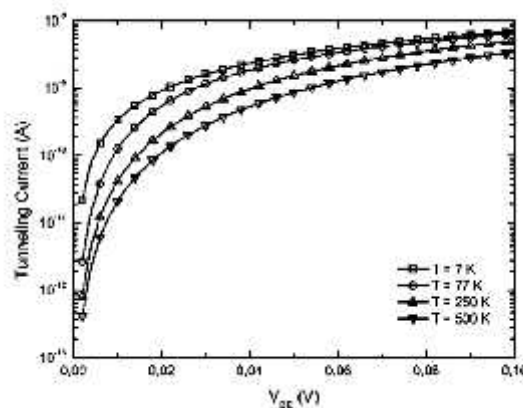

Figure 5. The computed tunneling current as the function of V_{BE} for various T

Figure 5 shows the computed tunneling current as the function of V_{BE} for various T with $N = 22$ ($w \approx 2.58\ nm$) and $V_{BC} = 0\ V$. It shows that as the temperature is increasing, the tunneling current is decreasing. This is due to the thermal resistivity of device that linearly with temperature. The result is relatively close compared with computed tunneling current using different approach [9]. The compared results are showed in figure 6.
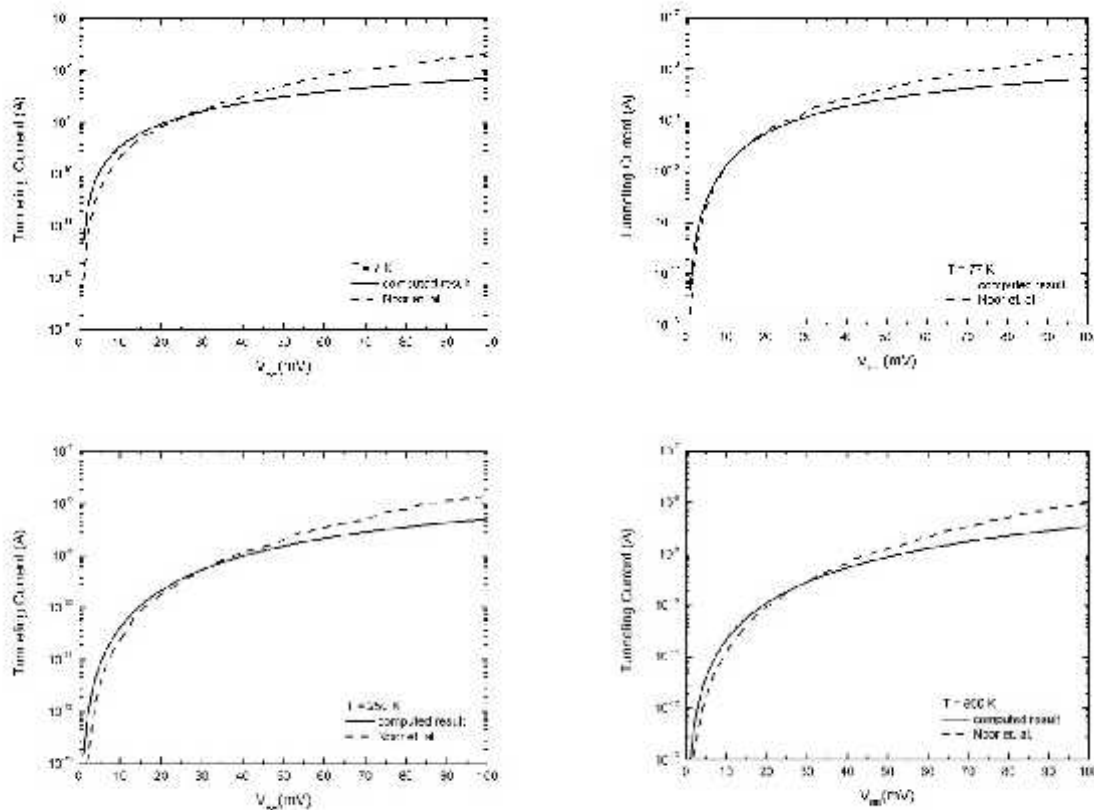

Figure 6. Comparison of computed tunneling currents with different approach

Conclusion

We have studied the tunneling current in an n-p-n bipolar transistor based on AGNR. The electron transmittance is computed using TMM, then the obtained transmittance is used to compute the tunneling current by using Ladauer formula. It is found that the tunneling current increases with base-emitter voltage and base-collector voltage in the forward-active mode. It is also obtained that for larger N index of AGNR the tunneling current is increasing. The tunneling current decreases as the temperature increases.

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