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Modelling of Drain Current in Tunnelling Field-Effect Transistor Based on Strained Armchair Graphene Nanoribbons

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Abstract. A tunnelling field-effect transistor (TFET) based armchair graphenenanoribbons (AGNRs) with variation of uniaxial strain has been modeled. Bandgap of strained AGNR estimated by an extended tight binding method is applied to obtain electrical characteristics of a TFET under the quantum capacitance limit device approximation. Furthermore, the electron transmittance is calculated by utilizing the WKB (Wentzel–Kramers–Brillouin) approach. The obtained transmittance is then used to calculate the drain current by employing the Landauer formula. The results show that strain parameter has significant effect on the current. In other words, the electrical characteristics of AGNR TFET can be tuned by the strain of AGNR.

1. Introduction

Since discovered in 2004, graphene has a great interest as an alternative material for future nanoelectronic device because it has high electron and hole motilities, high thermal stability, and massless of electron [1,2]. Although graphene has a zero bandgap, it can be changed into one-dimensional electronic system by making its width is much smaller than its length which is known as graphene nanoribbons (GNRs) [1,3]. GNRs are known to have two types based on the edge shape, they are armchair GNRs and zigzag GNRs. AGNRs have semiconductor or metal characteristics depending on their width while ZGNRs have metal characteristics for all widths [1]. It was known that the bandgap of AGNRs can be altered by manipulating their geometry and width. Besides that, the bandgap also can be changed by applying a strain to the lattice of AGNRs [4,5]. Because of those, AGNRs are preferable to be applied in nanoelectronic devices including tunneling field effect transistor (TFET) [6-8].

In this paper, we report the study on the strained AGNRs by using the extended tight binding method in which the atom position is not only considering in the nearest neighbor atom but also beyond the nearest neighbor atom. The strain applied to the AGNRs is considered in the x- direction.
The transmittance and tunneling current through the strained potential barrier of AGNRs in TFET are also studied by employing the WKB approach and Landauer formula, respectively. The effects of strain to the energy band gap, transmittance, and tunneling/drain current will be discussed thoroughly.

2. Theoretical Approach

Figure 1 illustrates the lattice crystal and atomic position of AGNR. Under the extended tight binding model, the Hamiltonian and energy dispersion relation are described by [1]

\[
H = \begin{pmatrix}
E_o & tf(k) \\
-\text{t}f^*(k) & E_o
\end{pmatrix},
\]

(1)

\[
E(k) = E_o \pm t|f(k)|,
\]

(2)

in which \(E_o\) is the initial energy of electron and \(t\) is the overlapping electron parameter which has a magnitude of 2.76 eV. The geometry factor \(f(k)\) is defined by [1]

\[
f(K + p) \approx \sum_{m_i} e^{i \kappa m_i} (1 - i p m_i),
\]

(3)

where \(K = \frac{4\pi}{3\sqrt{3}a}\) is the meeting point of conduction and valence bands, \(p\) is the slight shift position of \(K\) point, and \(m_i\) is the atom position.

Figure 1. Lattice structure and atomic position of AGNR

The atom positions of \(m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8,\) and \(m_9\) after applying the strain to the AGNRs are

\[
m_1 = a(1 + \xi_x) e_y, \quad m_2 = \frac{\sqrt{3}}{2} a(1 + \xi_x) e_x - \frac{1}{\sqrt{3}} (1 + \xi_y) e_y, \quad m_3 = \frac{\sqrt{3}}{2} a(-1 + \xi_x) e_x + \frac{1}{\sqrt{3}} (1 + \xi_y) e_y,
\]

\[
m_4 = \frac{\sqrt{3}}{2} a(1 + \xi_x) e_x + \frac{3}{\sqrt{3}} (1 + \xi_y) e_y, \quad m_5 = \frac{\sqrt{3}}{2} a(1 + \xi_x) e_x + \frac{3}{\sqrt{3}} (1 + \xi_y) e_y, \quad m_6 = \sqrt{3} a(1 + \xi_x) e_x,
\]

\[
m_7 = \frac{\sqrt{3}}{2} a(-1 + \xi_x) e_x + \frac{3}{\sqrt{3}} (1 + \xi_y) e_y, \quad m_8 = -\sqrt{3} a(1 + \xi_x) e_x, \quad m_9 = \frac{\sqrt{3}}{2} a(-1 + \xi_x) e_x + \frac{3}{\sqrt{3}} (1 + \xi_y) e_y,
\]

respectively. Here \(a\) is the distance between two atoms, and \(\xi_x\) and \(\xi_y\) are the strains in the \(x\) and \(y\) directions, respectively. The relation between \(\xi_x\) and \(\xi_y\) is described by Poisson ratio, \(\nu = -\xi_y/\xi_x\), which has a magnitude of 0.186 [4]. By substituting the atom positions into equation (3) and equation (2), the bandgap of AGNR can be written as follows:
$$E = \pm \left( \frac{3at}{2} \left( 1 + \varepsilon_x \right)^{\frac{1}{2}} + (1 + \varepsilon_y)^{\frac{1}{2}} p_y + E_M \right),$$

where (+) and (-) indicate the conduction and valence bands, respectively, and \( p_x \) and \( p_y \) are the wave number in the x- and y- directions, respectively. The first term in equation (4) describes the energy dispersion relation using the position of nearest neighbor atoms, while the term of \( E_M \) illustrates the energy dispersion relation using the position of beyond the nearest neighbor atoms. Noting that AGNRs sheet is limited only in the x-axis, the wave number in the x-direction is defined as

$$p_x = \frac{1}{1 + \varepsilon_x} \left[ \frac{\pi n}{W_{ac} + \sqrt{3}a} + \frac{4\pi}{3\sqrt{3}a} \right]$$

where \( W_{ac} \) is the AGNR width.

Figure 2 displays the schematic diagram of AGNR TFET device. The source, channel, and drain are the AGNR doped to be p+, p, and n+, respectively [9]. The potential profile for the strained AGNR TFET was calculated by following reference [9]. The electronic characteristic of TFET is considered under quantum capacitance limit device [10].

![Figure 2. A schematic diagram of AGNR TFET.](image)

![Figure 3. The energy band diagram of AGNR in (a) off-state and (b) on-state.](image)

Figures 3(a) and 3(b) present an energy band diagram of AGNR TFET under quantum capacitance limit device in off- and on-conditions, respectively. By applying the gate voltage to the TFET (on-condition), the valence band of source region is higher than the conduction band of channel so that the electrons in the source region tunnel through the depletion region toward the channel region as depicted in figure 3(b). In this case, the depletion region acts as a triangular potential barrier, and the process is known as Zener tunneling [11].

The transmittance of electron passing through triangular potential barrier are calculated by utilizing WKB approximation following the method in reference [9]. The obtained transmittance was then employed to calculate the tunneling/drain current by using the Landauer formula given in reference [11].

3. Results and Discussion

Figures 4(a) and 4(b) present the energy diagram of AGNRs by applying strains to the AGNRs when off- and on-state conditions, respectively. The AGNRs width is taken to be 10 nm. It is shown that the
The energy diagram is changed due to uniaxial strain for both conditions. The energy gap gets wider as the strain increases. It occurs because the lattice structure and atom position are altered by the strain so that the energy gap also changes [4,5].

![Energy Diagram](image)

**Figure 4.** The energy diagram of AGNRs for various strains in the off-(a) and on-(b) states.

The transmittance as a function of gate voltage in the variety of strains is demonstrated in figure 5(a). The AGNRs width, \( W \), and oxide thickness, \( t_{ox} \), are 10 nm and 1 nm, respectively. It is seen that the transmittance decreases as the strain increases. It happens because the potential barrier becomes higher when the strain is applied to the AGNRs so that the electrons becomes more difficult to tunnel through the barrier.

![Transmittance](image)

**Figure 5.** (a) The transmittance versus gate voltage for various strains. (b) The drain current as a function of gate voltage for different strains

Figure 5(b) shows the dependence of the drain current on the gate voltage for different strains. It is taken that the drain voltage, \( V_{DS} \), oxide thickness, \( t_{ox} \), and temperature, \( T \), are 0.05 V, 1 nm, 300 K, respectively. It is shown that the drain current is inversely proportional to the strain. Its bandgap increases as the strain applied to AGNR increases. The transmittance is reduced so that the tunneling current also decreases. The result indicates that the drain current is affected by the strain.

**4. Conclusions**

We have studied the effects of the strain to the drain current in TFET AGNR. It is shown that the energy gap gets wider with the increase of the strain. As the applied strain to AGNRs increases, the transmittance decreases, so that the drain current is also reduced. These results imply that the electronic properties of TFET AGNR can be tuned by the strain of AGNR.
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