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# Current-Voltage Characteristic of Schottky-Barrier CNTFET Considering Resonant Transmission

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***Abstract*-In this paper previous works on calculating the output current of SBCNFET are reviewed and a new three capacitance model for estimating potential profile along the channel is proposed. Furthermore the transmission coefficient through the channel has studied and some new formulas considering the electron coherency in the channel are suggested. Electron coherency will results in resonant transmission and by taking this effect into account the source drain current is obtained by Solving Poisson and Schrödinger equations self consistently.**

***Index terms*- SBCNFET, Resonant Transmission, Three capacitor model.**

## I. Introduction

From discovery of first carbon nanotube field effect transistor (CNFET) in 1998 [1,2], it has been the most promising successor to today's MOSFETs. From basic underlying physics, the CNFETs are divided in two main types: conventional CNFETs (C-CNFET) and Schottky-barrier CNFETs (SBCNFET) [3]. In C-CNFETs the two ends of CNT channel are highly doped so the metal contacts are Ohmic. In SBCNFETs on the hand, the source and the drain metal contacts are directly connected to the intrinsic nanotube channel and make two Schottky contacts.

The main advantage of C-CNFET over the SBCNFETs is its higher output current, but the SBCNFETs are the most common structure in practice for two following reasons:

I. Doping of CNTs is so difficult and common doping techniques aren't applicable to CNTs [3].
II. In SBCNFET different types of operation are achievable simply by tuning the height of the Schottky barriers. Bipolar conduction i.e. hole and electron conduction, and ambipolar operation are achievable. The latter means that one SBCNFET may acts as a PMOS or an NMOS simply by adjusting the gate voltage [3].

In this paper, after a brief review of the previous works, we will introduce a new analytical model for estimating channel potential profile as a function of gate-source and drain-source voltages. Moreover, we will introduce an analytical formulation for the resonant transmission through the channel for the first time and verify it by a physics based simulation.

The paper is organized as follows: The current CNFET theories will be reviewed briefly in section 2. Section 3 presents our analytical formulations. Section 4 presents simulation results and section 5 the conclusions.

## II. Existing SBCNFET theories

In open literatures there are two different approaches in modeling an SBCNFET. In the first approach [4], the potential of some point at the beginning of the channel is related to the gate and drain voltages via two capacitances. Those capacitors, i.e. $C_{ins}$ and $C_D$, are connected between that point and the gate and the drain contacts respectively (See figure 1).

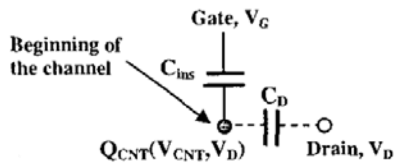


Fig. 1. Schematic of the double capacitance model.

In the second approach [5] the total channel charge is related to the voltage of a point at the middle of the tube via a single capacitor. In this approach the channel charge is calculated by summing the right and left going electrons.

In the first approach the current is assumed to be limited mainly by the amount of injected charges from the source contact so, the main assumption is that any injected carrier will traverse the overall channel without any reflection from the drain contact. In the second approach the main stress is on the amount of existing charges in the channel which is calculated from addition of forward and backward traveling waves and therefore the most important issue is the existence of reflected waves from the drain side barrier. These two approaches will result in same current only if there is no energy barrier at the drain and it happens when $V_{DS}$ is large enough.

The second model is more complete than the first one because it considers the reflected waves but it lacks a clear way for calculating potential at the midpoint of the channel.

We have combined these two approaches and proposed a new model which has three capacitances (see figure 2).

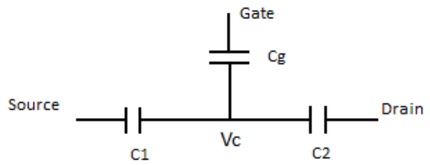


Fig. 2. Triple capacitances model for calculating channel potential profile

### III. Three Capacitance model

The new approach has two features. i. introducing a straight forward way for calculating potential profile. ii. Modifying the existing formulas for calculating overall channel transmission coefficient. We will consider these two features in more details below.

*A. Calculating potential profile*

With respect to figure (2) the voltage at the common node of capacitors could be written as:

$$V_C = \frac{C_2}{C_1+C_2+C_g} V_{DS} + \frac{C_g}{C_1+C_2+C_g} V_{GS} + \frac{Q_{CNT}}{C_1+C_2+C_g} \quad (1)$$

To calculate voltage profile, we consider C; the common node, as a sliding point. Figure (3) shows the voltage of C point as a function of $1/C_1$. The voltage profile at low $V_{DS}$ has always a U shape. To calculate the bottom point of the profile in order of separating the source/drain-channel barriers, C should be at a point with the following property:

$$\frac{dV_C}{dC_1} = \frac{dV_C}{dC_2} = 0 \quad (2)$$

The correct value of $C_1$ can be deduced from figure (3).

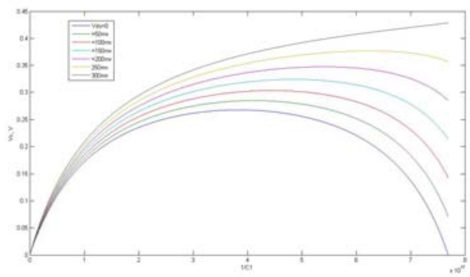

Fig. 3. The value of $V_C$ as a function of $1/C_1$ at $V_{GS}$=0.5 and various $V_{DS}$ from 0 to 300mV ($C_C$=1.3aF and $C_g$=6aF).

Figure (4) shows the desired $C_1$ as function of $V_{DS}$. Now note that $C_1$ & $C_2$ capacitances are inversely proportional to the distance between C point and source/drain and using this, we may construct a relation between the equivalent circuit shown in figure (3) and the voltage profile along the channel of SBCNFET.

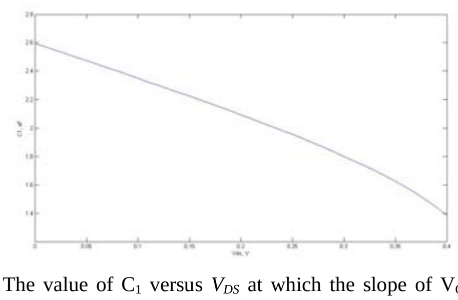

Fig. 4. The value of $C_1$ versus $V_{DS}$ at which the slope of $V_C$ is zero with respect to $C_1$ at $V_{GS} = 0.5$ ($C_C$=1.3aF and $C_g$=6aF).

From figure (4) one can see that $C_1$ becomes smaller when $V_{DS}$ gets larger which means that the C point which was located at the midpoint of the channel at first (for low $V_{DS}$ ) will gradually move towards the drain contact when $V_{DS}$ gets larger.

Having the values of the circuit elements and the above mentioned concept, the potential profile can be approximated. Generally this profile is a continuum, hence may be described by a polynomial and in the simplest case a second order one. So we write:

$$E(x) = \alpha x^2 + \beta x + \gamma$$
$$E(0)=0$$
$$E(L)=-qV_{DS}$$
$$\frac{\partial E}{\partial x}(L_C)=0$$
$$\Rightarrow \quad \alpha = \frac{qV_{DS}}{L^2\left(2\frac{C_C}{C_1}-1\right)}$$
$$\& \quad \beta = \frac{-2qV_{DS}L_C}{L^2\left(2\frac{C_C}{C_1}-1\right)}$$

Where $E(.)$ is the energy profile, $C_C$ is series equivalent of $C_1$ and $C_2$, $L$ is the channel length of SBCNFET and $L_C$ is the distance of C point from the source contact.

Figure (5) shows the potential profile for fixed $V_{GS}$ and various $V_{DS}$ and figure (6) shows potential profile for fixed $V_{DS}$ and various $V_{GS}$.
Having potential profile we can calculate the transmission coefficient of the source and the drain potential barriers using WKB approximation [6].

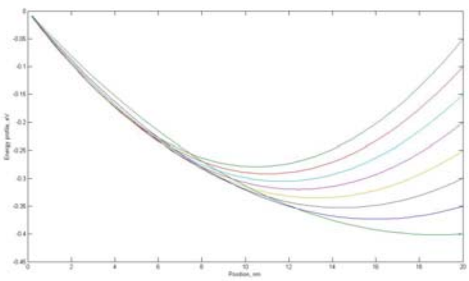

Fig. 5. The conduction band edge, $E_C$, versus position for $V_{GS} = 0.5$ and various $V_{DS}$ from 50mV (highest curve) to 400mV (lowest curve). The capacitances were equal to: $C_C$=1.3aF and $C_g$=3aF.

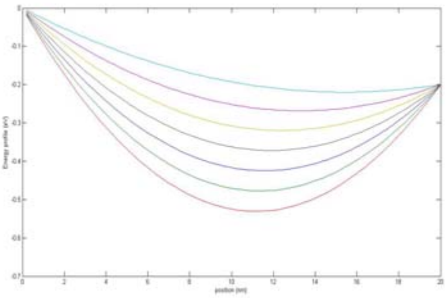

Fig. 6. The conduction band edge, $E_C$, versus position for $V_{DS} = 0.2$ and various $V_{GS}$ from 0.4V (highest curve) to 1V (lowest curve). The capacitances were equal to: $C_C$=1.3aF and $C_g$=6aF.

*B. Overall channel transmission coefficient*

Now we focus on the transmission coefficients of the source, $T_S$ and the drain, $T_D$ which were introduced in second approach [7], [5]. Therein, these two quantities were assumed to be real quantities and the right going and left going electron densities ( $f^+$ and $f^-$ ) were based on them and calculated as follow:

$$f^+ = \frac{T_S f_S + T_D f_D - T_S T_D f_D}{1-(T_S-1)(T_D-1)} \tag{3}$$

$$f^- = \frac{T_S f_S + T_D f_D - T_S T_D f_S}{1-(T_S-1)(T_D-1)} \frac{1}{2} \tag{4}$$

We have modified these formulas. In fact the source and the drain transmission coefficient, i.e. $t_S$ and $t_D$, are complex quantities with both magnitude and phase. They are related to the previous quantities [5,7] by following relations:

$$T_S = |t_S|^2 \quad \& \quad T_D = |t_D|^2 \tag{5}$$

With respect to the RTD's (Resonant Tunneling Diode) theories which there is two potential barriers at the both sides of a well as exist in SBCNFET [8], $f^+$ and $f^-$ must be computed from equations below:

$$f^{+} = \frac{f_s|t_s|^2}{|1-r_d r_s e^{-2ikL}|^2} + \frac{f_d|t_d|^2|r_s|^2}{|1-r_d r_s e^{-2ikL}|^2} \quad (6)$$

$$f^{-} = \frac{f_s|t_s|^2|r_d|^2}{|1-r_d r_s e^{-2ikL}|^2} + \frac{f_d|t_d|^2}{|1-r_d r_s e^{-2ikL}|^2} \quad (7)$$

Which $r_s$ and $r_d$ are reflection coefficients from the source and drain barriers respectively and L is channel length of SBCNFET. In this formula each of the right and left going waves has two terms which come from drain and source carrier densities (i.e. $f_s$ and $f_d$). These two terms are added together in a normal fashion because the source and the drain electrons are not phase dependent. On the other hand, the contributions from $f_s$ are strongly phase coherent so we must consider their phase relation and they must not simply be added together. In other words, the contributions from $f_s$ (and $f_d$) to $f^+$ and $f^-$ will add together for some energies and subtract from each other for some others. This fact is the base of what has been called resonant transmission through the double-barrier structures. In this model the overall transmission coefficient is calculated from [8]:

$$t = \frac{1}{t_s t_d e^{-ikL} + r_s r_d e^{+ikL}} \quad (8)$$

As we see the overall transmission coefficient depends on $t_S$ and $t_D$ hence, in spite of existence of two opaque potential barriers, could be quite high for some energies. Assessing validity of these results, we have performed a simulation. In the next session we discuss the simulation results and show how the results verify our work.

## IV. Simulation

To verify the above models we have performed a simulation. Our simulation is based on self consistent solution of Schrödinger and Poisson equations as follows:

$$\frac{-h^2}{2m}\left(\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2}\right) + U\psi = E\psi$$

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = -\frac{\rho}{\varepsilon}$$

Our simulated device was a coaxial gate Schottky barrier CNFET with following characteristics [5]:

Tube diameter: $R_t = 0.63\text{nm}$ ; nanotube band gap: $E_g = 0.62$ eV , tube length: $L_t = 20$ nm , gate oxide thickness: $t_{ins} = 2.5$ nm , and insulator electrical permittivity: $\varepsilon_{ins} = 25$. The source and drain work functions were taken to be 4.5 eV and the nanotube electron affinity was 4.2 eV.

In the rest of the paper we have shown simulation results. Figure (7) shows voltage profile of the channel for $V_{DS} = 0.1$ and $V_{GS} = 0.4$ . A polynomial is fitted to the simulated profile. As we see there is acceptable correspondence between the simulated and fitted curves. The ripples in the simulation curve originated from the charges in the channel which we have not considered in our analytical model.

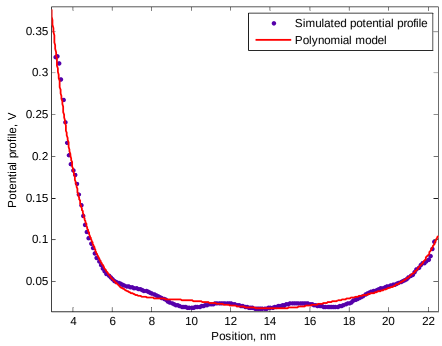


Fig. 7. Conduction band edge of the described SBCNFET at $V_{gs}=0.4$ and $V_{ds}=0.1$ (blue curve) and fitted curve (red curve).

Figure (8) shows the overall transmission coefficient. We see that the overall transmission coefficient has peaks and valleys and it is periodic with respect to the energy.

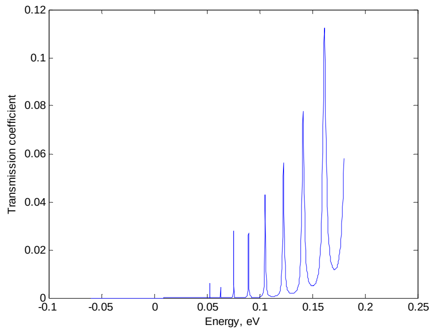


Fig. 8. Electron transmission coefficient in the described SBCNFET at $V_{gs}$=0.4 and $V_{ds}$=0.1. We see it has a periodic nature with peaks and valleys.

The current now could be calculated as follows:

$$I = \int_{E_C}^{\infty} \frac{\hbar k}{m^*}.|t|^2 .g(E).f(E) \quad dE \tag{9}$$

Where k is wave vector on the contact and equals to $\frac{\sqrt{2mE}}{\hbar}$ , $|t|^2$ the overall transmission coefficient given by (8), and g(E) and f(E) are one dimensional density of states of carbon nanotube and Fermi-Dirac distribution function respectively. Figure (9) shows I-V characteristics of simulated device for various $V_{GS}$ . The ripples seen on the curves are originated from resonant transmission through the channel. It is important to note that among of the terms in (9), $|t|^2$ is the only part that depends on the bias and as illustrated in figure (8) for each bias has some peaks. When the bias varies these peaks and valleys move across the integration zone and cause the ripples on the I-V curves. The distance between two ripples firmly depends on channel length so that in long channels becomes very small. This is the reason why the ripples haven't been reported yet in practice. Devices which have been realized in practice so far are too larger than the 20nm length CNFET, we have simulated in this paper.

## V. Conclusion

Previous two models that one of them calculates the beginning of the channel potential using a double capacitance model and the other calculates the midpoint of the channel potential by a single capacitance model were investigated. The positive and negative aspects of each model discussed. Then, a three capacitance model proposed and by means of it, the potential profile of the channel extracted analytically. Next the channel transmission coefficient of previous models investigated and showed that they are incorrect. Correct relations for transmission coefficients and right/left going wave densities were suggested. Validity of new models and relations assessed by means of solving Poisson and Schrödinger equations self consistently.

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