The Impact of Varying Temperature on Performance of Carbon Nanotube Field-Effect Transistors
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Abstract: In this paper the impact of varying the temperature on performance of carbon nanotube field-effect transistors (CNTFETs) is investigated and presented by developing a two-dimensional (2-D) full quantum simulation. The simulations have been performed by the self-consistent solution of 2-D Poisson–Schrödinger equations, within the nonequilibrium Green’s function (NEGF) formalism. The effects of varying the temperature are investigated in terms of on current, off current, on–off current ratio, drain conductance, transconductance characteristics, and subthreshold swing. Simulation results show that by increasing the temperature, the on and off current increase, but the increase in off current is much more than that of on current which results in lower on-off current ratio. Also the drain conductance and subthreshold swing increase by increasing the temperature. The results can be used for design considerations in CNTFETs.

Key-Words: CNTFET, Temperature, NEGF, subthreshold swing, on-off current ratio, drain conductance.

1 Introduction
Scaling MOSFETs to their limits is a key challenge faced by the semiconductor industry. Carbon nanotubes (CNTs) [1,2] due to their excellent electrical properties are considered as promising building blocks for nanoelectronic devices and they have received great attention since their first discovery by Ijima [3]. Their extraordinary electronic and optical properties destine them to play a major role in molecular electronics. In particular, electronic transport properties of single-wall CNTs have attracted considerable experimental and theoretical interest [4-9]. For example, CNT field effect transistors (CNTFETs) have generated considerable interest in the past few years because of their quasi ideal electronic properties and have recently reached a high level of performance [10-13].

Transistor devices made of semiconductor single wall carbon nanotubes (SWCNT’s) [2] can be considered as simple silicon MOS field effect transistors with the silicon material replaced by the carbon nanotube structures. These devices are one of the current leading technologies to replace MOSFETs [14-16].

The temperature could play key role in the CNTFET performance and changes its characteristics. Hence, the CNTFET performance has to be predicted in different temperatures. In this paper by varying temperature the attributes of these devices have been investigated. These attributes of CNTFETs in different temperatures have been investigated using two dimensional (2-D) quantum simulations. The simulations have been done by the self consistent solution of 2-D Poisson Schrödinger formalism [17]. The effects of varying temperature are investigated in terms of on current, off current, on–off current ratio, transconductance characteristics, drain conductance, and subthreshold swing.

2 CNTFET Structure
In this paper we use a CNTFET with the structure that has been shown in Fig. 1. We consider a zigzag (13,0) CNT that has a 1 nm diameter and is embedded in cylindrical gate insulator of HfO₂. The thickness of insulator is 2 nm and its dielectric constant is 16 [18]. The length and doping concentration of source and drain regions are 20 nm and 10⁷ cm⁻¹, respectively. The channel is intrinsic with the length of 20 nm and there is no overlap between source (drain) and gate.
3 Simulation Method

The simulation has been done by the self-consistent solution of 2-D Poisson– Schrödinger equation, within nonequilibrium Green’s function (NEGF) formalism. The NEGF method provides a sound approach for the simulation of the nanoscale system out of equilibrium. We must solve Poisson and transport equations. Poisson equation simulates gate control on channel and transport equation simulates charge transfer between source and drain. The Poisson equation is solved to obtain the electrostatic potential in the nanotube channel. By solving the Schrödinger equation within the NEGF method, the density of states and the charge of the surface of the CNT are obtained. By using the calculated charge and solving the Poisson equation the new electrostatic potential can be obtained. The iteration between Poisson and Schrödinger equations continues until the self-consistency is achieved.

It is convenient to solve Poisson’s equations in cylindrical coordinates. Since the potential and charge are invariant around the nanotube, the Poisson equation is essentially a 2-D problem along the tube (z-direction) and the radial direction (r-direction) as Poisson equation is written as[19, 20]:

\[
\frac{\partial^2 u_j(r, z)}{\partial r^2} + \frac{1}{r} \frac{\partial u_j(r, z)}{\partial r} + \frac{\partial^2 u_j(r, z)}{\partial z^2} = -\frac{q}{\varepsilon} \rho(r, z)
\]

where \(u_j(r, z)\) is the electrostatic potential, \(\partial\) is the dielectric constant and \(\rho(r, z)\) is the net charge density distribution which includes dopant density as well. The net charge distribution \(\rho(r, z)\) is given by:

\[
\rho(r = r_{CNT}, z_j) = p(z_j) - n(z_j) + N_{D}^{+} - N_{A}^{-}
\]

\[
\rho(r \neq r_{CNT}, z) = 0
\]

where \(r_{CNT}\) is CNT radius, \(N_{D}^{+}\) and \(N_{A}^{-}\) are the ionized donor and acceptor concentrations, respectively. Then the computed electrostatic potential is used as the input for the Schrödinger equation that is solved by using NEGF formalism.

The retarded Green’s function is computed by the following equation [5]:

\[
G_{r}(E) = [(E + i\eta)I - H - \sum_{S} - \sum_{D}]^{-1}
\]

For an \((n,0)\) zigzag CNT with quantum number \(q\), the Hamiltonian matrix for the sub-band is given by equation (4). Where \(b_{2q} = 2t\cos(q\pi/n)\), \(t=3\ ev\) is the nearest neighbor hoping parameter, and \(N\) is the total number of carbon rings along the device. Here, the diagonal element \(U_j\) correspond to the on-site electrostatic potential along the tube surface obtained by solving the Poisson equation.

We have considered a self energy for semi-infinite leads as boundary conditions. In these conditions we can consider that CNT is connected to infinitely long CNTs at its end. All in entries of source self energy function \((\Sigma_{S})\) are zero except for the \((1, 1)\) element [21]:

\[
\sum_{(1,1)} = \frac{(E-U_{S})^2 + b_{2q}^2 + (E-U_{D})^2 + b_{2q}^2 - 4(E-U_{S})y^2}{2(E-U_{D})}
\]

Similarly, \(\Sigma_{D}\) has only its \((N, N)\) element nonzero, and it is given by an equation similar to above equation with \(U_{1}\) replaced by \(U_{N}\).

After solving the Poisson equation and obtaining the electrostatic potential in the nanotube channel, this potential is used as input of transport equation. Self-consistency is achieved by iteration between Poisson and transport equation. The current is calculated by:

\[
I = \frac{2q}{h} \int T(E)[F(E - E_{FS}) - F(E - E_{FD})]dE
\]

This equation is Landau–Buttiker formula. In this formula \(T(E)\) is transmission coefficient, \(E_{FS}\) and \(E_{FD}\) are source and drain Fermi level respectively, \(q\) is the electron charge, and \(h\) is Planck constant. \(T(E)\) is calculated from the following equation:

\[
T(E) = trace(G_{r}G_{p}G^{\dagger})
\]

where \(G\) is Green’s function, \(\Gamma_{S(D)}\) is the energy level broadening due to source (drain) contact and is calculated from below equation:

\[
\Gamma_{S(D)} = i\left(\sum_{S(D)} e^{\gamma_{S(D)}} - \sum_{S(D)} e^{\gamma_{S(D)}}\right)
\]

In this paper, the results are obtained from this simulation method.
4 Results and Discussion

For investigating the impact of temperature on CNTs, we have changed the temperature from T=250˚K to 500˚K and we have simulated the transistor behavior in this temperature interval. Fig. 2 shows the output characteristic of the transistor in T=250˚K and T=500˚K. It can be seen from the figure that the drain current in saturation region for higher temperature in low gate source voltage is higher than lower temperature. But for higher gate source voltages the difference between higher and lower temperature in saturation current region decreases. When the transistor is in on-state before saturation, the drain current is decreased by increase in temperature from 250˚K to 500˚K.

The transconductance characteristic of CNTFET is shown in Fig. 3 in two different temperatures at V_{DS}=50 mV and V_{DS}=0.8 V. The results of this figure confirm the result of figure 2.

Fig. 4 (a) shows on-state current versus temperature at V_{GS}=0.8 V and V_{DS}=0.8 V. The on-current increases when temperature increases. The slope of this increase is approximately a constant slope. Off current variation by temperature is illustrated in Fig. 4 (b) at V_{GS}=0 V and V_{DS}=0.8 V bias conditions. The off-current in T=500˚K is 150 times higher than T=250˚K.

By using the Fig. 4 (a) and 4 (b), the on-off current ratio versus temperature is plotted in Fig. 4. By increasing the temperature the on-off current ratio decreases. It is apparent from the figure that the I_{on}/I_{off} ratio of 1.1×10^5 at 250˚K reaches to 650.4 at 500˚K which shows the harmful effects of temperature in the current drive of the device in spite of increase in on current by temperature. This ratio for T=500˚K is 169 times lower than T=250˚K. This decrease is more noticeable between 250 and 310˚K. After 310˚K the reduction slope will be decreased and after 410˚K the on-off current ratio is approximately constant. The results imply that by increasing the temperature, the gate control on channel decreases so the on-off current ratio decreases.
The subthreshold swing is a key parameter for transistor miniaturization. A small subthreshold swing (S) is desired for low threshold voltage and low power operation FETs that scaled down to small sizes. The variation of subthreshold swing (\(S=\Delta V_{GS}/\Delta \log(I_D)\)) versus temperature for the CNTFET with 20 nm gate length is shown if Fig. 5. It can be seen that the subthreshold swing increases with increment in off current. The subthreshold swing is approximately increases by 4.35 mV in each temperature decade in \(V_{GS}=0.25\) V and \(V_{DS}=0.8\) V bias conditions.

Drain conductance \((g_d)\) depends on the drain current in on state. So, increase in on current results in increase in drain conductance. The dependence of drain conductance on temperature is shown in Fig. 6. It is evident from the figure that the drain conductance changes with temperature and its value becomes higher by increase in temperature, approximately. The gate and drain voltages are set at 0.8 V.

5 Conclusion

In this paper we have investigated the attributes of carbon nanotube field-effect transistors (CNTFETs) by varying the temperature using two-dimensional (2-D) quantum simulation. We explain the effect of varying temperature on CNTFET performance in terms of on current, off current, on–off current ratio, transconductance, drain conductance characteristics, and subthreshold swing. Our results show that the increase in temperature results in higher subthreshold swing and lower on-off current ratio. Our results can be used for design considerations in these devices.

References:


