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Novel attributes and design considerations of source and drain regions in carbon nanotube transistors

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ABSTRACT

Source and drain regions are inseparable sections of carbon nanotube field effect transistor (CNTFET) whose parameters are effective for CNTFET performance. For the first time in this paper, design considerations of source and drain regions are presented by developing a two-dimensional (2-D) full quantum simulation. The simulations have been done by the self-consistent solution of 2-D Poisson–Schrödinger equations, within the nonequilibrium Green's function (NEGF) formalism. The effects of varying the source and drain parameters are investigated in terms of on–off current ratio, transconductance characteristics, drain conductance, and subthreshold swing. Simulation results demonstrate that we could improve the CNTFET performance with proper selection of the source and drain parameters.

1. Introduction

Silicon based MOSFET technology will eventually reach its limit. In order to continue improving the density and performance of electronic products, new devices are explored. Carbon nanotubes (CNTs) are among the promising candidates for future electron device applications because of their excellent electrical properties [1–3]. Their excellent properties, for which they have been proposed as potential alternatives to CMOS devices, are their capability of ballistic transport with exceptionally high mobility, direct bandgaps, symmetric bands, superior high conductance and current carrying capability in a nanoscale channel [4–6].

Parameters of source and drain regions could play important role in the CNT field effect transistor (CNTFET) performance. Hence, the CNTFET performance may improve with optimization of source and drain parameters. Therefore, for the first time in this paper, we have investigated novel attributes and design considerations of source and drain parameters in CNTFETs using two-dimensional (2-D) quantum simulation. The simulations have been done by the self-consistent solution of 2-D Poisson–Schrödinger equations, within the nonequilibrium Green's function (NEGF) formalism [7,8]. Also, the effects of varying the source and drain parameters are investigated in terms of on–off current ratio (I_{on}/I_{off}), transconductance characteristics, drain conductance, and subthreshold swing using the two-dimensional simulation.

In this work, we explain features of CNTFET structure in two sections. First, we investigate the performance of CNTFET with varying of source and drain doping densities in terms of I_{on}/I_{off} ratio, transconductance characteristics, drain conductance and subthreshold swing. Second, we explain the effect of the source and drain lengths variations in the performance of CNTFET.

2. CNTFET structure

A schematic view of coaxially CNTFET is shown in Fig. 1. We consider a (13, 0) CNT with a diameter of $\sim$1 nm that is embedded in cylindrical gate insulator of HfO_2 with thickness of 2 nm (t_{ox}=2 nm) and dielectric constant of 16 [9]. The channel is intrinsic and its length is 20 nm (L_{ch}=20 nm).

The typical values of source and drain lengths (L_S and L_D) are chosen 20 nm. Also, the typical doping densities of source and drain regions (N_D and N_S) are identical and equal to 1×10^7 cm^{-1}.

3. Simulation method

For simulation of a transistor behavior, we must solve transport and Poisson equations. Poisson equation simulates gate control on channel and transport equation simulates charge transport between source and drain. For a given charge density, the Poisson equation is solved to obtain the electrostatic potential in the nanotube channel. For the coaxially gated CNTFET, it is convenient to solve Poisson's equation in cylindrical coordinates [8]. Since the potential and charge density are invariant around the nanotube, the Poisson equation is essentially a 2-D problem

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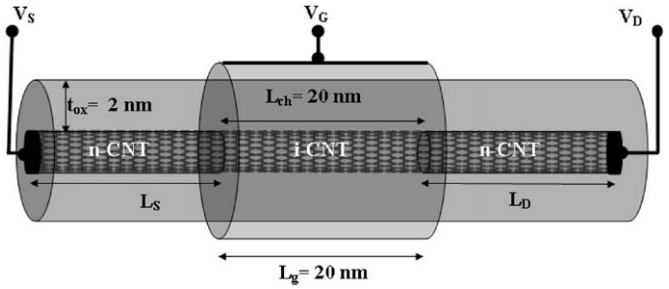

Fig. 1. Schematic view of CNTFET structure with coaxial gate.

along the tube (z-direction) and the radial direction (r-direction) as Poisson's equation is written as

$$\nabla^2 U_j(r,z) = -\frac{q}{\varepsilon}\rho(r,z_j) \tag{1}$$

where $U_j(r,z)$ is the electrostatic potential, ε is the dielectric constant, and $\rho(r,z_j)$ is the net charge density [10,11].

Then the computed electrostatic potential is used as the input for the transport equation. The transport equation (Schrödinger equation) is solved by using the NEGF formalism. The retarded Green's function for the device in matrix form is computed as

$$G(E) = [(E+i\eta^+)I - H - \Sigma_S - \Sigma_D]^{-1} \tag{2}$$

where Σ_S and Σ_D are the self-energies of the source and drain, respectively, η^+ is an infinitesimal positive value, E is the energy, I is the identity matrix, and H is the Hamiltonian of the CNT. As can be seen in Eq. (2), the transport is assumed here to be completely ballistic [12,13].

The device Hamiltonian used in this work is based on the atomistic nearest neighbor p_z-orbital tight-binding approximation. The cylindrical geometry of the device, which is shown in Fig. 1, ensures symmetry in the angular direction, thus drastically simplifying the mode-space treatment of electron transport. The Hamiltonian matrix for the subbands with angular quantum number q in an $(n,0)$ zigzag CNT is then given by

$$H = \begin{bmatrix} U_1 & b_{2q} & & & & \\ b_{2q} & U_2 & t & & 0 & \\ & t & U_3 & b_{2q} & & \\ & & & \ddots & & \\ & 0 & & t & U_{N-1} & b_{2q} \\ & & & & b_{2q} & U_N \end{bmatrix}_{N\times N} \tag{3}$$

where $b_{2q}=2t\cos(\pi q/n)$, $t \approx 3$ eV is the nearest neighbor hopping parameter, and N is the total number of carbon rings along the device. Here, the diagonal elements U_j correspond to the on-site electrostatic potential along the tube surface obtained by solving the Poisson equation [14].

The source self-energy function Σ_S has all its entries zero except for the $(1,1)$ element:

$$\Sigma_S(1,1) = \frac{(E-U_1)^2 + t^2 + b_{2q}^2 \pm \sqrt{\left[(E-U_1)^2 + t^2 + b_{2q}^2\right]^2 - 4(E-U_1)^2 t^2}}{2(E-U_1)} \tag{4}$$

Similarly, Σ_D has only its (N,N) element nonzero, and it is given by an equation similar to Eq. (4) with U_1 replaced by U_N. The charge density calculated with green function (G) solution as the source (drain) local-density-of-states (LDOS) is $D_{S(D)}=G\Gamma_{S(D)}G^+$, where $\Gamma_{S(D)} = i(\Sigma_{S(D)} - \Sigma_{S(D)}^+)$ is the energy level broadening due to the source (drain) contact. The charge density within the device is computed by integrating the LDOS:

$$Q(z) = (-q)\int_{-\infty}^{+\infty} dE\,\mathrm{sgn}[E-E(z)] + \{D_S(E,z)f(\mathrm{sgn}[E-E_N(z)](E-E_{FS})) + D_D(E,z)f(\mathrm{sgn}[E-E_N(z)](E-E_{FD}))\} \tag{5}$$

where q is the electron charge, sgn(E) is the sign function, $E_{FS,\ FD}$ is the source (drain) Fermi level, and $D_{S,\ D}(E,z)$ is the local density of states due to the source (drain) contact, which is computed by the NEGF method. The charge neutrality level $E_N(z)$ is at the middle of the bandgap because the conduction and valence bands of the CNT are symmetric [15,16].

For a given charge density, the Poisson equation is solved to obtain the electrostatic potential in the nanotube channel. Next, the computed potential profile is used as the input for the transport equation, and an improved estimate for the charge density is obtained. The iteration between the Poisson equation and the transport equation continues until self-consistency is achieved. Then current is calculated by the Landaur–Buttiker formula,

$$I = \frac{2q}{h}\int T(E)[F(E-E_{FS}) - F(E-E_{FD})]dE \tag{6}$$

where the transmission coefficient is $T(E)=trace(\Gamma_S G \Gamma_D G^+)$ in the NEGF simulations, q is the electron charge, and h is the Planck constant. In this paper results are obtained from this simulation method.

4. Results and discussions

To best study the optimization of source and drain parameters, this section is divided into two parts. First, effects of source and drain doping densities explain the CNTFET performance. In the second part, we investigate the effects of source and drain lengths.

4.1. Source and drain doping densities

In this part, the lengths of source and drain regions are identical and fixed at 20 nm while the source/drain doping densities (N_S, N_D) are varied for investigating the design optimization in terms of the I_{on}/I_{off} ratio, transconductance characteristics, drain conductance and subthreshold swing.

Fig. 2 shows transconductance characteristics for the CNTFET structure for different values of source and drain doping densities in V_{DS}=0.8 V. It can be seen from the figure that the characteristic is in the best case for $N_D=N_S=1.8\times10^7$ cm^{-1} condition due to high on current (I_{on}) and low off current (I_{off}).

The dependence of on current, off current, and I_{on}/I_{off} ratio on the source and drain doping densities is shown in Fig. 3. The drain voltage is set at 0.8 V. It is evident from Fig. 3(a) that I_{on} increases with increase in source and drain doping densities and then almost stabilises.

In a fixed gate voltage, the fixed channel density is due to electrostatic effects of gate voltage. When source and drain densities are more than the fixed channel density, the channel density is not limited. But the channel density is limited to source and drain densities when source and drain densities are lower than the fixed channel density and therefore the on current decreases.

Also as can be seen from Fig. 3(b), I_{off} almost fixes with increase in source and drain doping densities and then increases. I_{off} increases due to increment of the channel density in high source and drain densities.

It is worth noting that the on–off current ratio in its maximum value is almost 1090 times of its minimum value. Therefore, the source/drain doping densities have an important impact on I_{on}/I_{off} and we must choose their values carefully.

Fig. 4 shows output characteristics of the CNTFET structure for different source and drain doping densities in V_{GS}=0.8 V. It is