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Tunneling CNTFETs

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Abstract Based on the non-equilibrium Green's function formalism we numerically studied gate-controlled tunneling carbon nanotube field-effect transistors. The effect of doping concentration on the performance of the device has been investigated. We show that an asymmetric doping profile can improve the $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio of the device improves.

Keywords Non-equilibrium Green's function · Band to band tunneling · Carbon nanotube transistors

1 Introduction

Exceptional electronic and mechanical properties together with a nanoscale diameter make carbon nanotubes (CNTs) candidates for nanoscale field effect transistors (FETs). High performance CNTFETs were achieved recently [1, 2]. Metallic contacts can be directly connected to the gate-controlled CNT channel [1]. To reduce the parasitic capacitance the spacing between the gate-source and the gate-drain contacts can be increased. The extension region can be of n or p-type leading to n/i/n or p/i/p devices. Unlike conventional semiconductors in which doping is introduced by implantation, doping of CNTs requires controlling the electrostatics of the CNT environment by additional gates [2], molecules [3], or metal ions [4]. The gate controls the thermionic emission current, therefore a sub-threshold slope of about 64 mV/dec can be achieved [2]. Aggressively scaled devices of this type suffer from charge pile-up in the channel [5, 6], which deteriorates the off-current substantially and ultimately limits the achievable $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio [5]. To overcome this obstacle a gate-controlled tunneling device (T-CNTFET) is proposed. In this type of device either a p/i/n or n/i/p doping profile can be used (Fig. 1). The gate voltage modulates the band to band tunneling current. T-CNTFETs benefit from a steep inverse sub-threshold slope and a better controlled off-current. In T-CNTFETs, if the potential difference between the gate and drain contact increases, there will be a strong band-bending near the drain contact. As a result the band to band tunneling current increases, leading to a decrease of $I_{\mathrm{on}}/I_{\mathrm{off}}$. We numerically studied the effect of doping profile on the performance of T-CNTFETs. Simulation results indicate that by using an asymmetric doping profile the parasitic current is suppressed.

2 Approach

Due to quantum confinement along the tube circumference, the wave functions of carriers are bound around the CNT and can propagate along the tube axis. Assuming that the potential profile does not vary around the circumference of the CNT, sub-bands can be decoupled [7]. We assume bias conditions in which the first sub-band contributes mostly to the total current. In the mode-space approach [7] the retarded Green's function, G^R, for each sub-band can be written as [8]:

$$G^R = \left[EI - H - \Sigma_s^R - \Sigma_d^R\right]^{-1} \tag{1}$$

where $\Sigma_{s,d}^R$ is the self-energy due to the coupling of the device to the source and drain contacts. $\Sigma_{s,d}^R$ is zero except at the boundaries. A recursive Green's function method is used for solving (1). In (1) an effective mass Hamiltonian is

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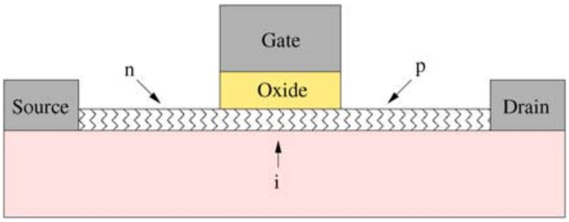

Fig. 1 T-CNTFET device with n/i/p doping profile

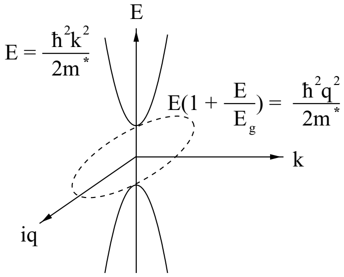

Fig. 2 The complex dispersion relation connecting the conduction and the valence bands [6]

assumed which is discretized using finite differences.

$$H = \begin{pmatrix} U_1 + 2t & -t & 0 & 0 & 0 & 0 & 0 \\ -t & U_2 + 2t & -t & 0 & 0 & 0 & 0 \\ 0 & \bullet & \bullet & \bullet & 0 & 0 & 0 \\ 0 & 0 & 0 & \bullet & \bullet & \bullet & 0 \\ 0 & 0 & 0 & 0 & -t & U_{n-1} + 2t & -t \\ 0 & 0 & 0 & 0 & 0 & -t & U_n + 2t \end{pmatrix} \tag{2}$$

Here U_j is the potential energy at the point j, $t = \hbar^2/(2m^* a^2)$, and a is the grid spacing. In [9,10] the validity of the effective mass has been discussed in detail. To consider strong band to band tunneling in T-CNTFETs it is essential to use an appropriate band structure [6, 11]. One has to assume an energy dependent effective mass inside the band-gap, $t(\epsilon) = \hbar^2/(2m^*(1 + \epsilon/E_g)a^2)$, see Fig. 2. All our calculations assume a CNT with a diameter of $d_{\mathrm{CNT}} = 1.6$ nm corresponding to a band-gap of $E_g = 0.6$ eV.

The carrier concentration can be calculated as:

$$n = \int G^R \Gamma_s [G^R]^\dagger f_s dE + \int G^R \Gamma_d [G^R]^\dagger f_d dE \tag{3}$$

where $\Gamma_{s,d}$ is the broadening due to contacts and is given by $\Gamma_{s,d} = i(\Sigma_{s,d} - \Sigma^\dagger_{s,d})$. Carriers are treated as a sheet charge distributed over the surface of the CNT [12]. The coupled system of transport and Poisson equations is solved iteratively. Details are presented in [13]. Finally the current density is given by (4).

$$I = \frac{4q}{h} \int TC(E)(f_S - f_D) dE \tag{4}$$

where the transmission coefficient of carriers through the device is given by $TC(E) = \mathrm{Tr}\{\Gamma_s G^R \Gamma_d [G^R]^\dagger\}$.

3 Simulation results

The operation of the device can be well understood by considering the spectrum of electron density along the device (Fig. 3). At high negative gate voltages, due to strong band bending near the source contact, band to band tunneling contributes significantly to the total current. By increasing the gate voltage to positive values the band bending near the source contact decreases, and as a result band to band tunneling decreases. On the other hand, the increase of the gate voltage results in a strong band to band tunneling near the drain contact. As a result the total current increases in the off-regime which has a detrimental effect on the device performance (Fig. 4(a)). For the considered device the doping concentrations at the source and drain sides are assumed to be equal. Decreasing the doping of the drain side, the band

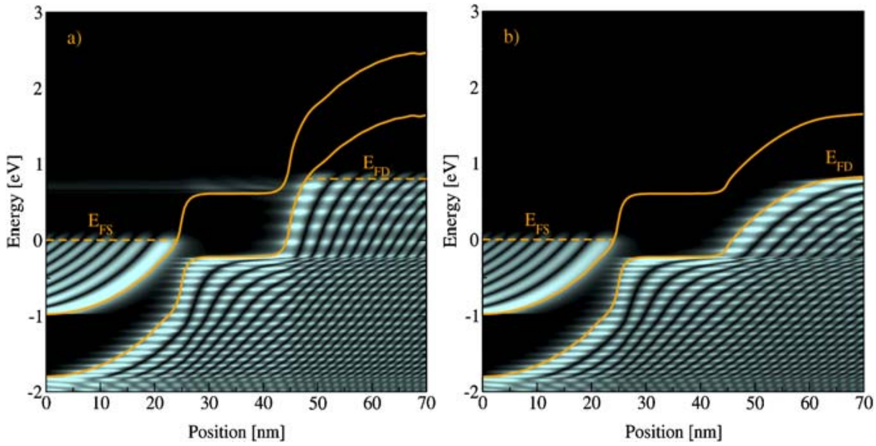

Fig. 3 The distribution of electrons along the device with (a) symmetric and (b) asymmetric doping profile

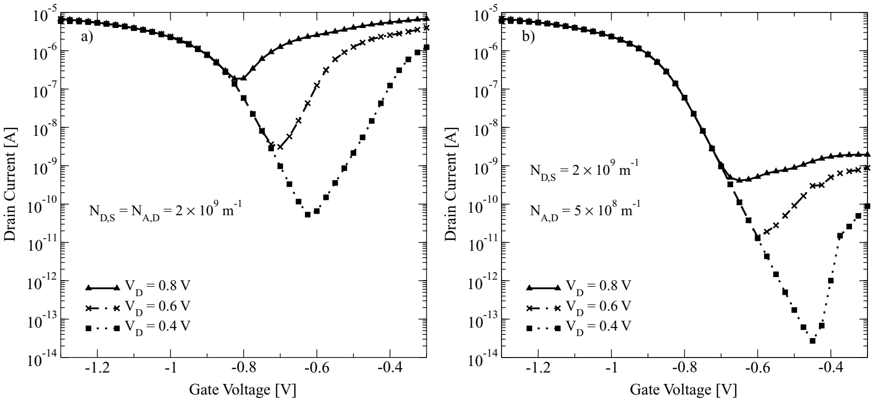

Fig. 4 The transfer characteristics of the device with (a) symmetric and (b) asymmetric doping profile

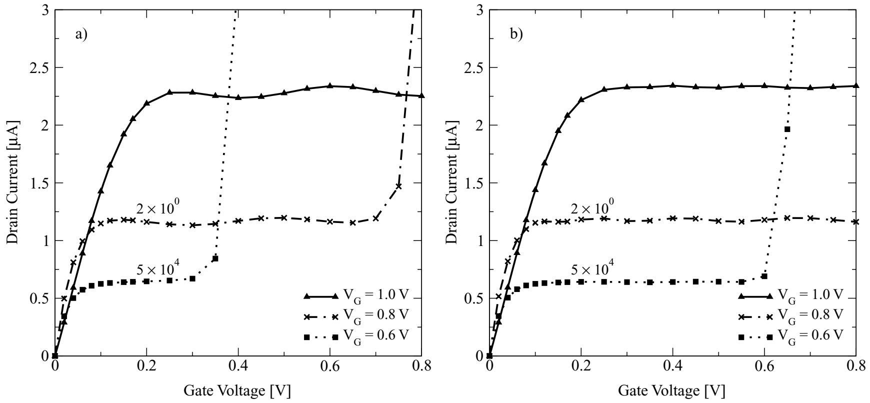

Fig. 5 The output characteristics of the device with (a) symmetric and (b) asymmetric doping profile

bending decreases for the same gate voltage (Fig. 3(b)) and the band to band tunneling current near the drain contact decreases considerably (Fig. 4(b)).

The parasitic current exists also in the on regime. Fig. 5(a) shows that if the drain voltage becomes much higher than the gate voltage the parasitic current increases. By using an asymmetric doping profile, the parasitic current in the on-regime is suppressed (Fig. 5(b)). For the device with symmetric doping we assumed that the donor and acceptor concentrations at the source and drain contacts are $N_{D,s} = N_{A,d} = 2 \times 10^9$ and for the device with asymmetric doping profile $N_{D,s} = 2 \times 10^9$ and $N_{A,d} = 5 \times 10^8$.

4 Conclusion

We performed a numerical investigation of a Tunneling CNT-FET. Due to strong quantum effects including band to band tunneling, the NEGF formalism along with an elaborate band structure gives a suitable model for the analysis of these devices. Simulation results suggest that an asymmetric doping profile reduces the parasitic carrier injection and increases the $I_{\mathrm{on}}/I_{\mathrm{off}}$ ratio by several orders of magnitude.

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