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Nanometer-Scaled Contacts in CNTFETs

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Abstract: The evolution of Si-based nanoelectronics over the past two decades is remarkably well described by Moore's Law. It has been realized for some time now that fundamental physical limits must exist for developing CNTFET (Carbon-Nano-Tube-Field-Effect-Transistors) devices. However, for CNTFETs with asymmetric contacts, such as source contact - CNT – drain contact and CNT/Si (100) contacts, especially for CNT-based schottky diodes, the two different contacts play different roles in determining the device performance. We use the electrostatic charge balance in the entire SWCNT (Single-Walled-CNT) channel and two contacts. The obtained results interpret puzzling findings from several CNT schottky transistors with asymmetric source and drain contacts.

Key words: CNTFET · Nanoscale Contacts · Channel and Band bending

INTRODUCTION

One device most widely used is silicon-based integrated circuits is the MOSFET (Metal-Oxide-Semiconductor-Field-Effect-Transistors). However, the success of the device attributes to several technologically important factors. First, silicon can be thermally oxidized to produce a stable oxide which is an excellent insulator. Second, the surface-state density at the silicon-oxide interface is sufficiently low to ensure reproducibility. Third, being planner, the structure is amenable to large-scale integration. However, some issues such as boron diffusion through the ultra thin, increased leakage current and limit the use of ultra thin silicon for the next CMOS devices. Some researchers believe that the next nano transistor generations will be designed based CNT elements, called CNTFET. This is because CNTs have been called the "wonder material of the 21st century, the building blocks for silicon circuits [1-3]". While it is debatable whether the contacts and shorter channel length respect to fermi wavelength confirm this grant prediction.

The use of CNT for electronic applications within the last decade extolling the virtues of electronic components based on silicon substrate characteristic. During this lapse of time, a whole new field of research, CNTFET with SWCNT- channel, has developed. However, a major step still has to be taken to make an electrical contact between SWCNT-channel and source (and or drain) of CNTFET.

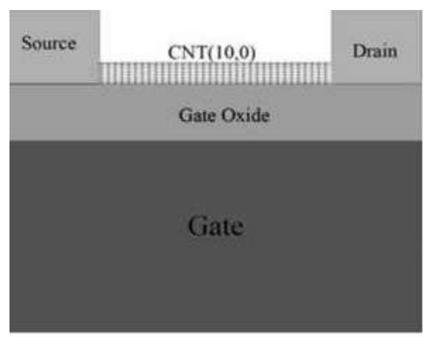

Fig. 1: Schematic view of a CNTFET

Much progress has been made over the past few years in the investigation of carrier transport properties in channel connected to two electrodes. We have studied analytically the stated contacts and their effects on the SWCNT potential as a future channel of CNTFET.

Theory: Figure 1 illustrates the device structure of a CNTFET with the source-, drain-, Si- SWCNT channel contacts.

In fact, the source and drain electrodes can be fabricated either before or after placing the CNT, but better contacts have been observed experimentally in the latter case [4-7]. By looking at Fig. 2, a qualitative representation of the conduction and valence band profiles in a p-type CNTFET (hole transport) for two values of the gate voltage, V_G , is obtained. There are three distinguished regions; region (1) represents

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(a) Off state (b) On state

Fig. 2: Schematic picture of the transistor bands, off state $V_G<V_{th}$ and (b) on state $V_G > V_{th}$.

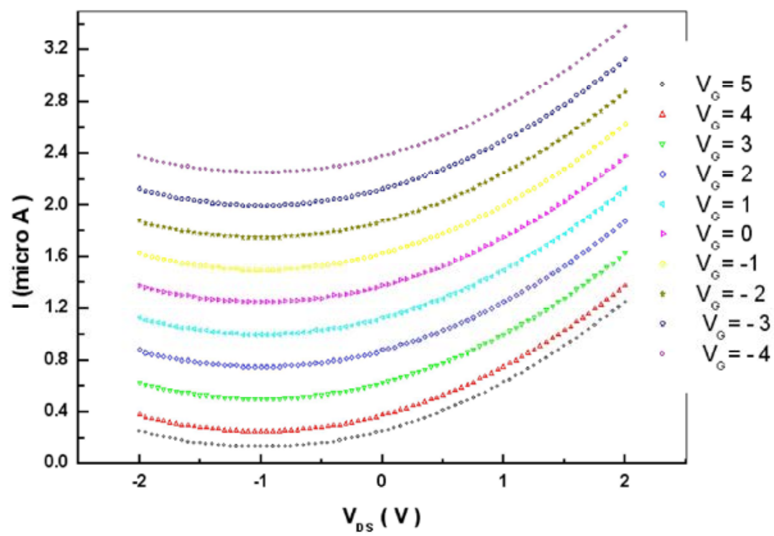

Fig. 3: Current versus drain – source voltage

segment of SWCNT located near the emitting (source) electrode (Schottky barrier region). Region (2), the central part of the SWCNT, which can be so short and causes Q-point scattering. Region (3) similar to region (1) represents segment of SWCNT located near the collecting (drain) electrode (Schottky barrier region).

It is obviously the value of the gate voltage (V_G) respect to the threshold voltage (V_{th}), if $V_G < V_{th}$, the current I_d between the emitter and collector is blocked by the barrier in the region (1), whilst for $V_G > V_{th}$, the effect of the voltage applied between the source and drain can be understood from the below discussions. Before going in more details, let us say that in the $V_G< V_{th}$ case, the barrier width can be modulated by the gate, but also by the field between the emitter and the collector. Furthermore, the bulk part of the SWCNT plays no role whatever in controlling the off-state current. This hypothesis has been confirmed by studies of the contact and transport properties in the CNTFET. The analytical calculation result, output characteristics is shown in Figure 3.

DISCUSSIONS AND CONCLUSIONS

The potential drop across the contacts is seen in Figure 2. We introduce some needed parameters in where V_{ng}, χ, E_f is the nano gap potential, the SWCNT electron affinity, the energy Fermi level, respectively. The surface band bending, the depletion width at the source and drain are shown as Φ_{bb}, Φ_{dw}, W_{source}, W_{drain}, respectively. The charge neutrality condition is given by [8 -10].

$$q_1 + q_2 + q_3 = 0 \qquad (1)$$

Where q_i is the charge in the region of I, as shown in Figure 2. On the other hand,

$$V_{ng} = \Phi_{bb} + \Phi_{dw} - \chi - \chi_m \quad (2)$$

Here, the charge supplied by the SWCNT is found viz.

$$q_2 = \pm\sqrt{2\varepsilon_{SWCNT}|\phi_S| N_{Contacts}} \quad (3)$$

We assume the semiconducting type of SWCNT and suppose the Fermi- Diract distribution function given by

$$F(Ei) = \frac{1}{1 + e^{-(Eg/2 - \phi_{CNT} - E_f)/KT}}$$

And (4)

$$N = \frac{N_{\text{intrinsic}}}{1 + e^{-(E_{g/2} - \phi_{CNT} - E_f)/KT}}$$

Where k is the Boltzmann constant, T is absolute temperature, Φ_{CNT} is CNT work function and N_i is the intrinsic carrier density in the SWCNT. But the point is the gate modulation which shifts the Fermi level from E_f to $E_f = E_{f0} - \eta V_G$, the gate efficiency ç measures how much gate voltage can more the SWCNT Fermi level. And Ef0 is the Fermi level position at $V_G = 0$. Some researchers found the gate efficiency equal to 0.1 [2, 11 -13].

The main aim of the present work is the rate of tunnel events at the SWCNT channel-source and SWCNT channel-drain contacts, for this purpose, we consider the Fermi golden rule as

$$\Gamma_{i\to f}(\Delta F) = \frac{2\pi}{\hbar} |T_{ki,kf}|^2 \, d(E_i - E_f - \Delta F),\ \Delta F = F_f - F_1 \quad (5)$$

The difference between the initial and final energies of the tunnel carrier. E_i respectively, includes the free energy variation it generates; the total tunnel currant rate can be obtained with transition from occurred states at region (1) to unoccupied states of region (2). Similarly this event can be occurred from region (2) to region (3) in Fig. 2. Therefore, it yields to.

$$\Gamma(\Delta F) = \frac{2\pi}{\hbar} \sum_i \sum_f |T_{ki,kf}|^2 f(E_i)\,[1 - f(E_i)]\, d(E_i - E_f - \Delta F) \quad (6)$$

By using time-dependent Schrodinger equation (and small perturbation, H_1) and series of orthonormal eigenfunctions, it become to

$$i\hbar \frac{dc_{m(t)}}{dt} = \sum_n c_n(t) \int ?_{m*}\, H_1\, ?_n\, e^{it(\omega_m - \omega_n)} \quad (7)$$

Where the wave function of carrier through the contacts are given by

$$? = \sum_n C_n(t)\, ?_n e^{-iwnt}$$

$$H_{mm} = \int ?^*_{m}\, H_1\, ?_n d^3r$$

Setting $\omega_{mn} = \omega_m - \omega_n$, $H_{mn} = \int \psi^*_m H_1 \psi_n d^3r$ and $C_m(0)=1$, $C_n(0)=0$, $C_m(t)=1$, we then deduce the occupation probability of state n as follow

$$|C_n(t)|^2 = \frac{4|H_{mn}|^2 t^2}{\hbar^2} \cdot \frac{Sin\left(\frac{\omega_{mn}t}{2}\right)}{\left(\frac{\omega_{mn}t}{2}\right)^2} \quad (8)$$

$$C_n(t) = -\frac{i}{\hbar}\int_0^t H_{mn} e^{i\omega_{mn}t} = \frac{H_{mn}}{\hbar\omega_{mn}}\left(1 - e^{i\omega_{mn}t}\right) \quad (9)$$

Eq. 7 tends to a Dirac δ-function for large enough t, where the scattering process has ended to

$$\frac{Sin^2\left(\frac{w_{mn}t}{2}\right)}{\left(\frac{w_{mn}t}{2}\right)^2} \quad (10)$$

In addition, the number of carriers (electrons and or holes), N, in an energy interval dE is obtained by density of states, D(E), in where,

$$\Gamma(\Delta F) = \frac{2\pi}{\hbar}|T|^2 \int_{E_{c,i}}^{\infty} dE_i \int_{E_{c,f}}^{\infty} dE_f \quad (11)$$

$$D(E_i)\, D(E_i)\, f(E_i)[1 - f(E_f)]d(E_i - E_f - \Delta F$$

Where $E_{c,i}$, $E_{c,f}$ are the conduction band edge from the carriers tunnel from region i towards f.

Likewise $D_{i,f}$ is the density of states of the left and right side's barrier the contacts.
Therefore,

$$\Gamma(\Delta F) = \frac{2\pi}{\hbar}|T|^2 D_i D_f \int f(E)\,[1 - f(E - \Delta F)]\, dt \quad (12)$$

Where E_c= Max ($E_{c,i}$, $E_{c,f}$) and thus the single-carrier tunnel effect at each contact is equal to;

$$\Gamma(\Delta F) = -\frac{\Delta F.2\pi e^2 \left| T \right|^2 D_i D_f}{e^2 \hbar \left(1 - e^{\frac{\Delta F}{KT}}\right)} \quad (13)$$

Eq. 13 indicates that the probability of a carrier transfer entailing an increase in the Helmohltz energy is very low.

We can conclude that the tunneling and leakage current will only be large at contacts if the charge in free energy is lower energy. We suggest that SWCNT can be used as a good channel of the next CNTFET devise if the charge in free energy can be positive.

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