PHYSICS-BASED COMPACT MODEL FOR SCHOTTKY BARRIER CARBON NANOTUBE FET

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Introduction:

For not highly doped or undoped source/drain regions, CNTFET Schottky barriers (**SB**) are formed between the metal contacts and the semiconducting carbon nanotube at source/drain (S/D). Under these conditions, the source and drain current is affected by tunnelling mechanisms through these barriers. By changing the gate voltage (figure 1), energy bands are shifted which modulates the SB transmission function and subsequently the transistor current. In this work, we focus on the self-consistent analytical modeling of SB-CNFET. Self-consistent means that the effect of the injected charge (current) in the channel on the band bending and consequently on the drain current is taken into account. In section II, the physics-based analytical model for the channel charge in the SB-CNTFET is presented. Section III gives the drain-source current formulation and finally, a comparison between the Current-Voltage characteristics of the SB model and a MOS-like simulated CNTFET is performed.

Formulation of the intrinsic nanotube charge:

In the SB-CNTFET, the linear charge density n_{CNT} results from the product of the Fermi-Dirac (FD) distribution *f(E)* times the density of states *g(E)* times the source-drain transmission function $T_T(E)$. This later describes the transparency of the SB at the source/CNT or CNT/Drain interfaces, over the carrier energy range:

$$n_{CNT} = e\int_{E_0}^{+\infty} \frac{g(E)}{2} \times T_T(E) \times \left[f(E-\mu_S) + f(E-\mu_D) \right] dE \qquad (1)$$

with E_0 being the mid-gap energy of the intrinsic region. The integral (1) has no direct analytical solution. Hence, an approximation of the transmission function is proposed in this work according to the assumption published in [1]. This approximation consists in solving analytically the 1D modified Poisson equation for the channel potential which leads to calculate an effective SB height. Hence, considering the approximations on the effective SB height and assuming a 1D density of states relation, the linear density of charge in the source writes as:

$$n_{CNT,S} = eD_0 \int_0^{+\infty} \frac{1}{\sqrt{E + \Phi_{SB}^{eff} - sbbd_{[p]}}} \times \frac{1}{1 + \exp\left(\frac{E + \Phi_{SB}^{eff} - eV}{k_B T} \right)} dE \qquad (2)$$

Since this integral has no analytical solution over the whole potential V and carrier energy E ranges, partial solutions have been considered according to the Fermi distribution and the density of state relative variation.

Partial analytical solutions calculation

At low gate bias conditions, the FD distribution is considered as an exponential function in the energy range of interest which leads to the following analytical solution of the integral [2].

$n_1 = eD_0 \sqrt{\pi k_B T} \exp\frac{eV - sbbd_{[p]}}{k_B T} \left(1 - Erf\left(\sqrt{\frac{\Phi_{SB}^{eff} - sbbd_{[p]}}{k_B T}} \right) \right)$, where Erf(x) is the error function.

At high bias, an additional energy bound Δ is required to solve (2) in order to separate the energy range where the FD distribution is nearly constant and the energy range where the FD distribution behaves as an exponential function. Then, the linear charge density is written:

$$n_2 = eD_0 \left[\int_{\Phi_{SB}^{eff}}^{\Delta} g(E) f(E) dE + \int_{\Delta}^{+\infty} g(E) f(E) dE \right]$$

i) Low energy: For an energy range from Φ_{SB}^{eff} to Δ, the FD distribution variation evolves weakly compared with *g(E)*. Thus, it can be expanded in a Taylor series around $E=sbbd_{[p]}$ and the linear density of charge becomes:

$$n_{2a} = 2eD_0 \times \left[\sqrt{\Phi_{SB}^{eff} - sbbd_{[p]}} \left(a_0 + \frac{a_1}{3}\left(\Phi_{SB}^{eff} + sbbd_{[p]}\right)\right) + \sqrt{\Delta + \Phi_{SB}^{eff} - sbbd_{[p]}} \left(a_0 - \frac{1}{3} a_1 \left(sbbd - \Phi_{SB}^{eff} - \Delta \right)\right)\right]$$

ii) High energy: For an energy range from Δ to $+\infty$, *g(E)* is considered as constant and equal to *g(Δ)* and the exponential approximation is used for the Fermi distribution. The analytical expression of the linear density of charge is then straightforwardly obtained as:

$$n_{2b} = eD_0 \frac{\alpha}{\sqrt{\Delta + \Phi_{SB}^{eff} - sbbd_{[p]}}} k_B T \exp\left(- \frac{\Delta + \Phi_{SB}^{eff} - sbbd_{[p]}}{k_B T} \right)$$

Finally, for model convergence issues, a smoothing function, f_{SMO} is used to obtain a complete solution [3]. Figure 2 shows the good agreement between the complete analytical charge model result and the numerical solution over a wide range of the SB height and gate voltage.

Formulation of the drain current:

The current through the structure is calculated by means of the Landauer–Buttiker formula assuming a one dimensional ballistic channel in between the SB. Hence, after integration over energy and for all the energy sub-bands, the drain-source current is expressed as [4]:

$$I = \frac{4ek_B T}{h} \sum_{p=1}^{+\infty} \left[\ln\left(1 + \exp\frac{eV_S + \Phi_{SB}^{eff} - sbbd_{[p]}}{k_B T} \right) - \ln\left(1 + \exp\frac{eV_D + \Phi_{SB}^{eff} - sbbd_{[p]}}{k_B T} \right) \right]$$

where the calculation of sbbd[p] is consistent with the general expression of energy dispersion. Figure 3 shows the IV-characteristics of the SB-CNTFET model (Φ_{SB}=0.5eV) in comparison with simulation results for a MOS like CNTFET according to drain voltage: (i) SB's limit by a factor of 2 the drain-to-source current and (ii) shift the gate threshold voltage. Further developments are in progress to evaluate SB's impact on dynamic performances.

Conclusion

An analytical physics based compact model for Schottky barrier CNTFET has been developed and implemented in a SPICE like simulation environment. It has been shown the SB affect strongly the I(V) characteristics of the transistor. Small signal simulation will be performed to benchmark SB-CNTFET with respect high frequency performance.

References:

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Figures:

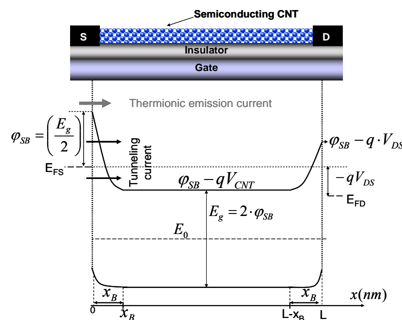

Fig 1. SB-CNTFET structure in back gate configuration with first conduction and valence sub-energy band profiles for $V_{GS}>V_{DS}$

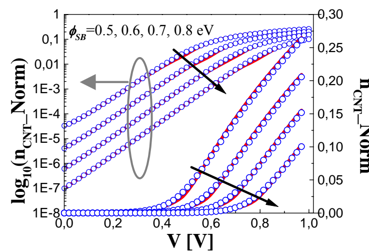

Fig 2. Linear channel charge density [normalized by $eD_0=8e/(3\pi bV_{pp\Pi})$] at 300K, as a function of the potential V for different Φ_{SB}. Dots are numerical calculation and lines are analytical solution.

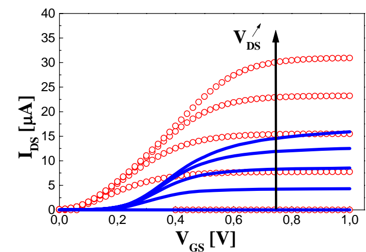

Fig 3. I_{DS} as a function of the V_{GS} bias for 5 drain biases ranging from 0 to 0.2V by a step of 25mV. Dots are for MOS-like CNTFET and lines are for SB-CNTFET analytical model with Φ_{SB}=0.5eV.