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Analysis of Carrier Transport in Carbon Nanotube FET Devices

E. Ungersboeck[a], A.Gehring[a], H. Kosina[a], S. Selberherr[a],
B. H. Cheong[b], and W. B. Choi[b]

[a]Institute for Microelectronics, TU Vienna, Gusshausstrasse 27–29, A-1040 Vienna, Austria
[b]Samsung Advanced Institute of Technology, P.O. Box 111, Suwon 440-600, Korea

Ungersboeck@iue.tuwien.ac.at

We discuss models to describe the carrier transport in axial and lateral type carbon nanotube field effect transistors (CNT-FET). Operation is controlled by the electric field from the gate contact, which can lead to strong band bending allowing carriers to tunnel through the interface barrier. The simulated output and transfer characteristics show reasonable agreement with experimental data for both lateral and axial CNT-FET devices.

I. INTRODUCTION

Carbon nanotubes represent a promising alternative to conventional MOSFET structures to allow further downscaling of memory devices. Experiments and theory have shown that the tubes can either exhibit metallic or semiconducting behavior. Their electrical properties can rival, or even exceed, those of the best metals or semiconductors known. The electrical behavior is a consequence of the electronic band structure which depends on the exact position of the carbon atoms forming the tube. Semiconducting nanotubes can be used as active elements in field-effect transistor (FET) designs. While early devices showed poor device characteristics, improvements were achieved by using thinner dielectric films [1].

Two different device structures are commonly considered for future CNT-FET devices (see Fig. 1). While devices with laterally aligned tubes provide better gate-tube coupling, the manufacturability challenges are still significant. Transistors with axially aligned carbon nanotubes are more suitable for large-scale integration.

Recently models to describe the transport through carbon nanotubes have been developed [2]. It was shown that CNT-FETs act as unconventional Schottky barrier transistors. Transistor action is achieved by varying the contact resistance rather than the channel conductance. Transport through the nanotube is ballistic, so the current predominately depends on energy barriers between the source and drain contacts. Since the shape of this barrier and hence the operation of the transistor depends crucially on the device geometry, device simulation becomes necessary to predict device performance.

II. SIMULATION

We used the general-purpose device simulator MINIMOS-NT [5] to acquire the potential profile of lateral and axial CNT-FET devices.

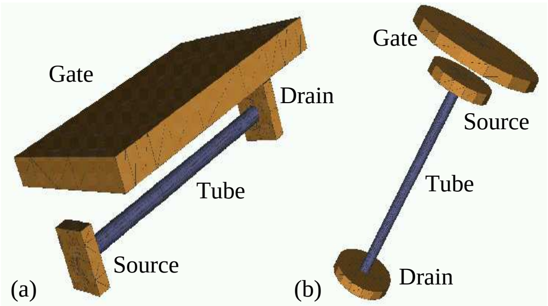

Fig. 1: The lateral (a) and axial (b) carbon nanotube transistor structures.

Since measured characteristics of most CNT-FETs resemble those of conventional p-type FETs we concentrate on hole transport and the valence band edge in the nanotube. However, the method is suited for electron transport as well. For sample simulations a band gap of $0.6\,\mathrm{eV}$ and undoped tubes have been assumed. The tube is covered in $\mathrm{HfO_2}$ and connected to Al source and drain contacts. Fig. 2 shows the resulting valence band edge along the tube for the lateral and for the axial device at $V_\mathrm{DS} = 0\,\mathrm{V}$.

In the case of lateral CNT-FETs the gate field heavily influences the valence band. Modulating the gate voltage, the valence band can be shifted upwards towards the Fermi level of the source and drain electrodes. This effectively reduces the energy barrier for holes. At moderate gate voltages the carriers have to surmount a large energy barrier. Tunneling current is small and thermionic emission prevails. Increasing the gate voltage leads to a reduction of the energy barrier till tunneling dominates over thermionic emission. The threshold voltage V_th of the device can be defined as the gate voltage necessary to shift the valence band up so that the tunneling current exceeds thermionic emission. Hence, for lateral devices, the output characteristics is characterized by three distinct regions: an exponential region where thermionic emission dominates over tunneling, a linear region where tunneling prevails and the drain barrier decreases, and a saturation regime with a constant current. A model for the tunneling current using the WKB method and a non-parabolic dispersion relation [3] of nanotubes was developed and implemented in MINIMOS-NT.

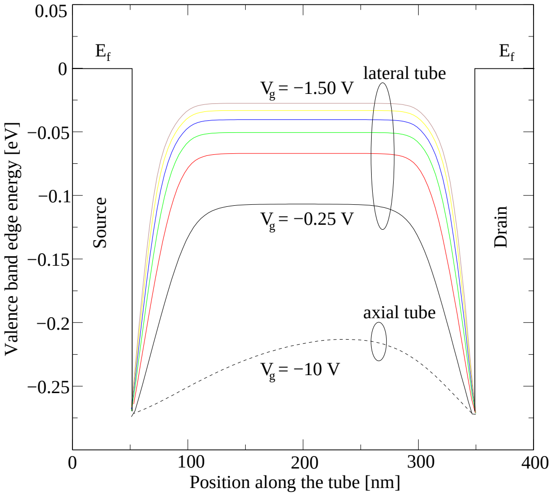

Fig. 2: The valence band edge in a lateral CNT-FET at different gate voltages. The dashed line shows the band profile of an axial CNT-FET at $V_\mathrm{g} = -10\,\mathrm{V}$.

In axial devices the gate field is screened to a large extent by the underlying source contact. Even when applying relatively high gate voltages the effect on the barrier between source and drain is weak. The charge carriers have to surmount a potential barrier with two peaks at the contacts which is almost constant throughout the carbon nanotube (see Fig. 2). In this sense the threshold for tunneling is never reached and thermionic emission will dominate at all voltages. This results in output characteristics which resemble those of conventional Schottky barrier transistors.

Within the thermionic emission theory the current density can be written as

$$J = C \exp\left(-\frac{q\Phi_\mathrm{B}}{\mathrm{k_B}T\gamma}\right) \cdot \left[\exp\left(\frac{qV_\mathrm{DS}}{\mathrm{k_B}T\gamma}\right) - 1\right],$$

where $C = 4\pi m_\mathrm{eff} q {\mathrm{k_B}}^2 T^2/\mathrm{h}^3$. The parameter γ has been introduced to describe the exponential slope of the IV-characteristics. To get a model which only depends on the gate-source and drain-source voltages, the values of Φ_B and γ

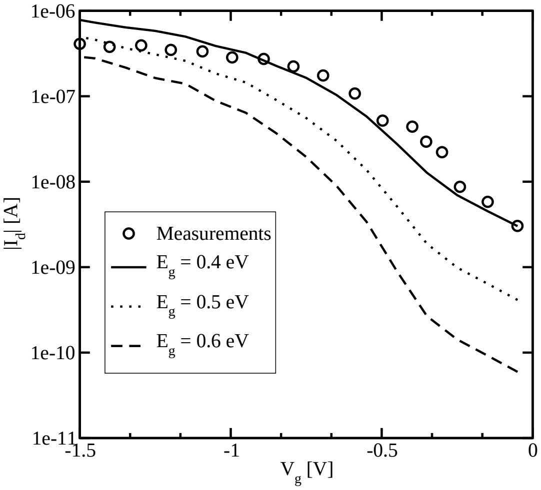

Fig. 3: Experimental data [2] and simulation results for a lateral CNT-FET. Increasing the tube radius reduces the band gap and thus decreases the threshold voltage.

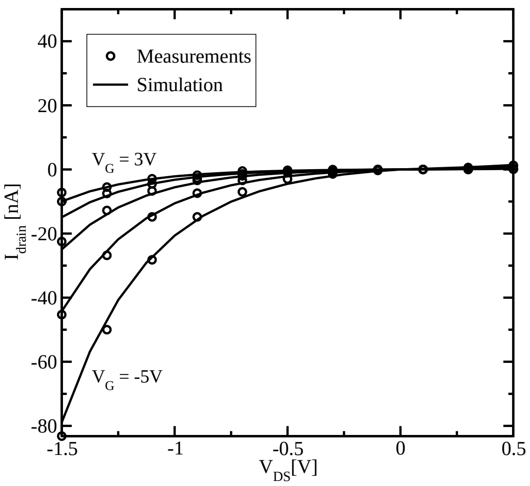

Fig. 4: Output characteristics of an axial multi-wall CNT-FET at 4.2 K compared to simulations assuming thermionic emission.

have been fitted to measurement results. Φ_B can be understood as the barrier height the electrons have to overcome.

III. RESULTS AND CONCLUSION

A lateral CNT-FET with a $20\,\mathrm{nm}$ HfO$_2$ layer (ε_r = 11) between the gate and the carbon nanotube and a source drain separation of $300\,\mathrm{nm}$ has been simulated. The single-wall carbon nanotube has a radius of $0.7\,\mathrm{nm}$ and a bandgap of $0.6\,\mathrm{eV}$. The subthreshold characteristics of this device for a drain voltage of $V_\mathrm{DS} = -1.2\,\mathrm{V}$ is shown in Fig. 3. The experimental data [2] show reasonable agreement with the simulation results for $\mathrm{E_g} = 0.4\ \mathrm{eV}$.

Furthermore, for the simulation of axial CNT-FETs a modified thermionic emission model was developed. Simulations are compared to measurements of a highly defective multi-wall carbon tube with a diameter of approximately 20 nm, covered by SiO$_2$ and attached to source and drain contacts. The measured band gap of this device was 0.6 eV. Good agreement to experimental data [4] is found for a wide range of gate voltages (see Fig. 4).

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