Carbon Nanotube Field-effect Transistors: AC Performance Capabilities.

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ABSTRACT

The AC performance capabilities of Schottky-barrier carbon nanotube field-effect transistors are examined via simulations using a self-consistent Schrödinger-Poisson solver. It is shown that good high-frequency performance demands use of a small-bandgap nanotube, whereas good digital-switching performance can be achieved with larger-bandgap tubes. For typical transistor geometries it is shown that the inter-electrode capacitance makes a large contribution to the total capacitance, and must be reduced if exceptional AC performance is to be attained.

1. Introduction

Much is known about the DC capabilities of carbon nanotube field-effect transistors [1,2,3], and devices with high ON currents and large ON/OFF current ratios have already been fabricated [4]. By contrast, the AC capabilities of CNFETs are just starting to be examined. Measurement techniques for recording the small-signal performance of these miniscule transistors are being developed [5], but we must presently look to simulations in order to obtain some idea of the high-frequency capability of CNFETs [6,16]. This is also true for assessing the large-signal switching performance of CNFETs [4,7,8,9]. AC performance metrics, such as unity-gain frequencies and device discharge times, can be obtained by making appropriate use of DC simulation results from custom Schrödinger-Poisson solvers [10], as we describe in this paper.

2. Models

For small-signal modeling, numerical differentiation of the charge and drain current can be performed to produce values for the circuit components which constitute the traditional FET equivalent circuit [11], as illustrated in Fig. 1. This circuit is particularly germane to CNFETs as the substrate in these devices is not electrically significant. From this circuit, expressions for the extrapolated, high-frequency, figures-of-merit f_T and f_{max} may be derived, and, after making appropriate approximations, cast into compact forms, which should prove useful for guiding device design [13], *e.g.*,

$$\frac{1}{2\pi f_T} = \frac{(C_{gs} + C_{gd})}{g_m}\left[1 + g_{ds}(R_s + R_d)\right] + (R_s + R_d)C_{gd} \quad .... \quad (1)$$

$$f_{\max} = \frac{1}{4\pi C_{gd}}\sqrt{\frac{g_m}{(2R_g + R_d)(1 + g_m R_d)}} \quad .... \quad (2)$$

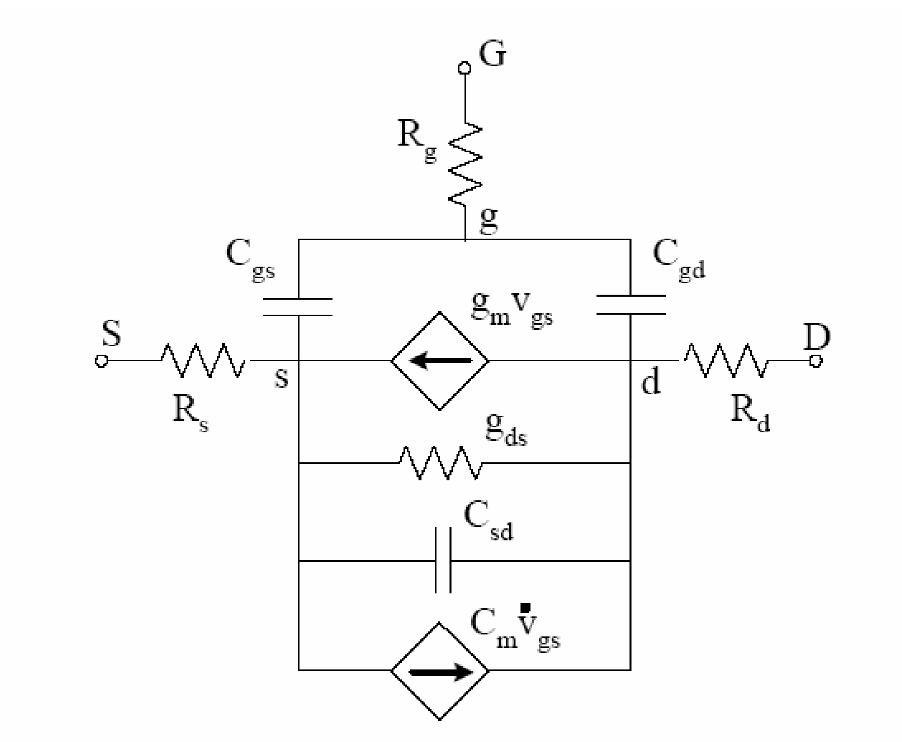

Figure 1. Small-signal equivalent circuit [12].

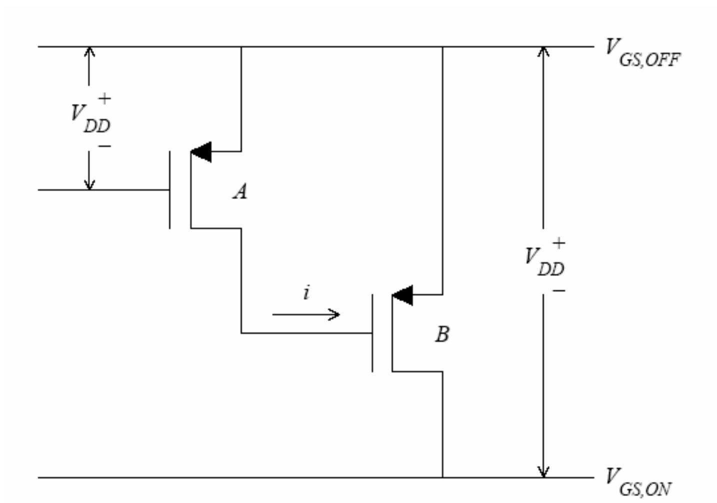

Figure 2. Effective switching circuit for estimation of large-signal properties [9].

The circuit for large-signal simulations of the CNFET discharge time, henceforth called the switching time [7], is shown in Fig. 2. It is based on a method that, in essence, estimates the time taken for a constant gate capacitance C_G of a single CNFET (transistor B, the load), charged to a voltage V_{DD}, to be discharged through another CNFET (transistor A, the driver) at a constant current I_{ON}, where the latter is evaluated for the driver transistor at drain- and gate-source voltages equal in magnitude to V_{DD}. Thus, the switching time is given by:

$$\tau = \frac{C_{G,ON}^{B} V_{DD}}{\left| I_{ON}^{A} \right|} \quad .... \quad (3)$$

The method has merit not only because all parameters can be computed from a DC simulation performed at a single V_{DD}, but also because the discrepancies involved in using constant values for the discharge current and the gate capacitance may tend to compensate each other [9].

3. Results and Discussion

We present results for Schottky-barrier CNFETs with nanotubes of length 25-60 nm, and with Pd source and drain contacts. An example of the oscillatory nature of the quantum capacitance of CNFETs is shown in Fig. 3. The peaks in capacitance arise, on application of a gate bias, when the quasi-bound states in the nanotube become populated: this occurs when the quasi-bound-state energy levels cross the source or drain Fermi level [14]. An example of this is shown in Fig. 4.

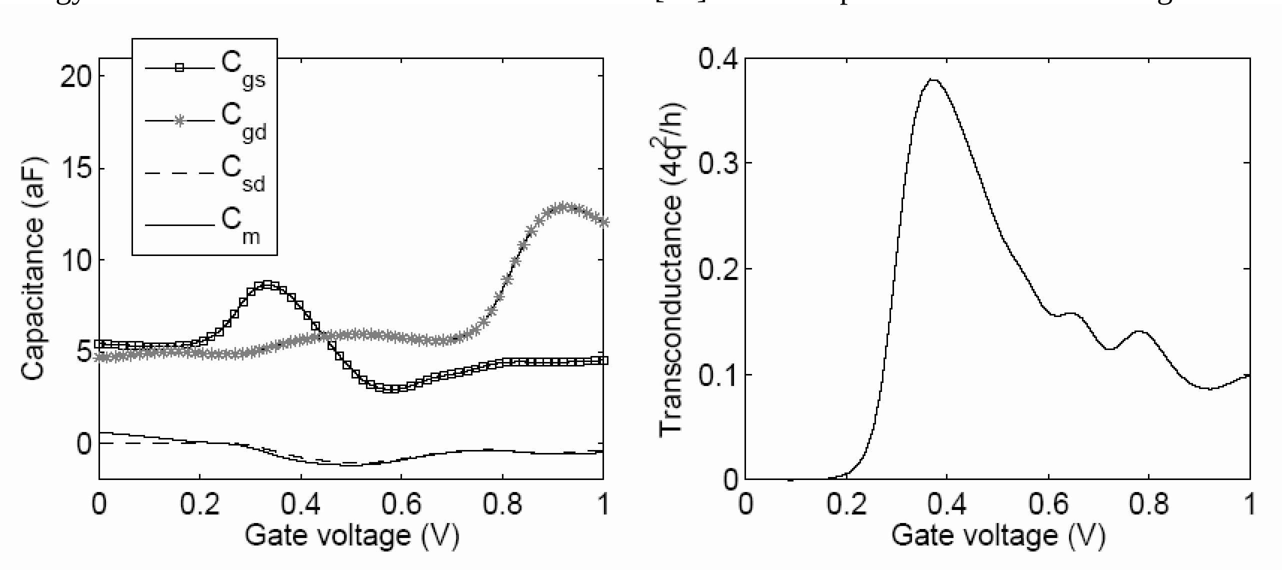

Figure 3. Capacitances and transconductance for a coaxial transistor with a (16,0) tube, of length 30nm, and with an insulator of thickness 2.5nm and relative permittivity 25 [12].

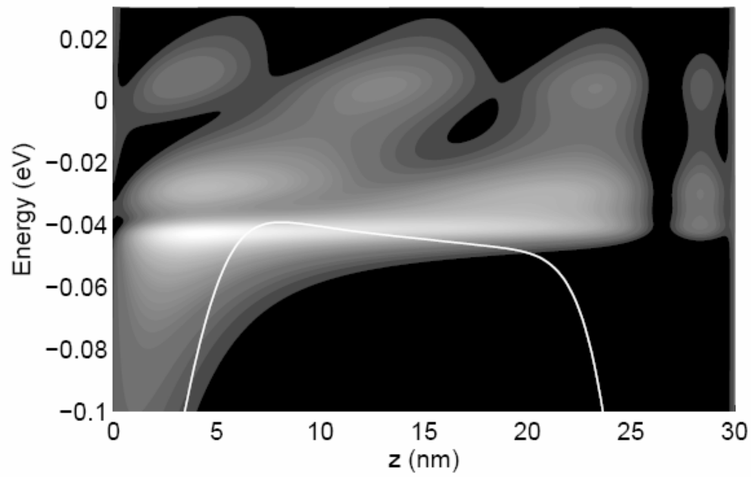

Figure 4. Charge density at a gate-source bias of 0.38V for the device listed in the caption to Fig. 3. Bright patches indicate higher charge density. The conduction band edge is shown, and the energy values are referenced to the Fermi energy [12].

Since the charge accumulation in the quasi-bound states affects the amount of band bending in the channel, the transconductance g_m also exhibits peaks, as shown in Fig. 3. The latter feature translates to peaks in f_T and f_{max}, as shown in Fig. 5. This strong correlation with g_m indicates that small-bandgap nanotubes, for which g_m can be high due to the hole Schottky-barrier height becoming negative [15], are advantageous for small-signal applications [13]. Fig. 5 also illustrates the importance of keeping the parasitic resistances low.

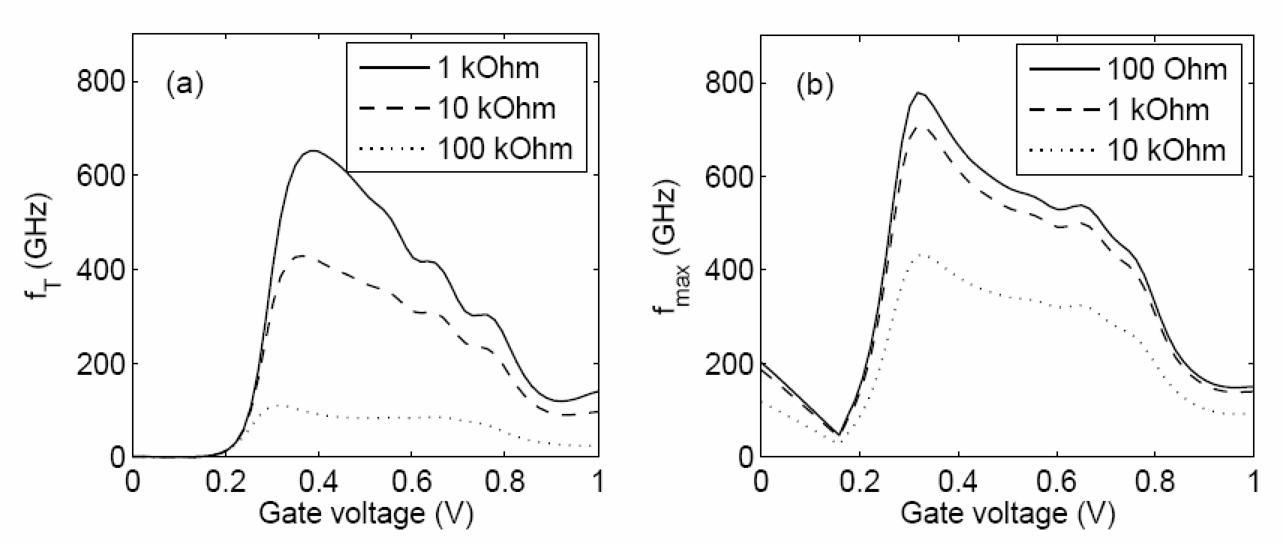

Figure 5. Extrapolated figures of merit at V_{GS}=V_{DS}=0.5V for the device listed in the caption to Fig. 3. In (a) the parameter is the contact resistance, while in (b) the parameter is the gate resistance, and the contact resistances are 10kOhm [12].

Equations (1) and (2) provide a useful design guide for CNFETs intended for high-frequency applications. Obviously, reducing C_{gd} would be helpful because of its domination of the output admittance. Equation (2) indicates that, for obtaining high f_{max}, C_{gd} is a more important parameter than g_m. One way to trade-off g_m against C_{gd} would be to increase the insulator thickness. Ways to reduce C_{gd} directly would be to shorten the drain contact, and to increase the gate-drain contact separation. The beneficial effect to a CNFET with a small-bandgap nanotube of making these changes is illustrated in Fig. 6, where the peak value of f_{max} is raised by about 15% to 580 GHz [13].

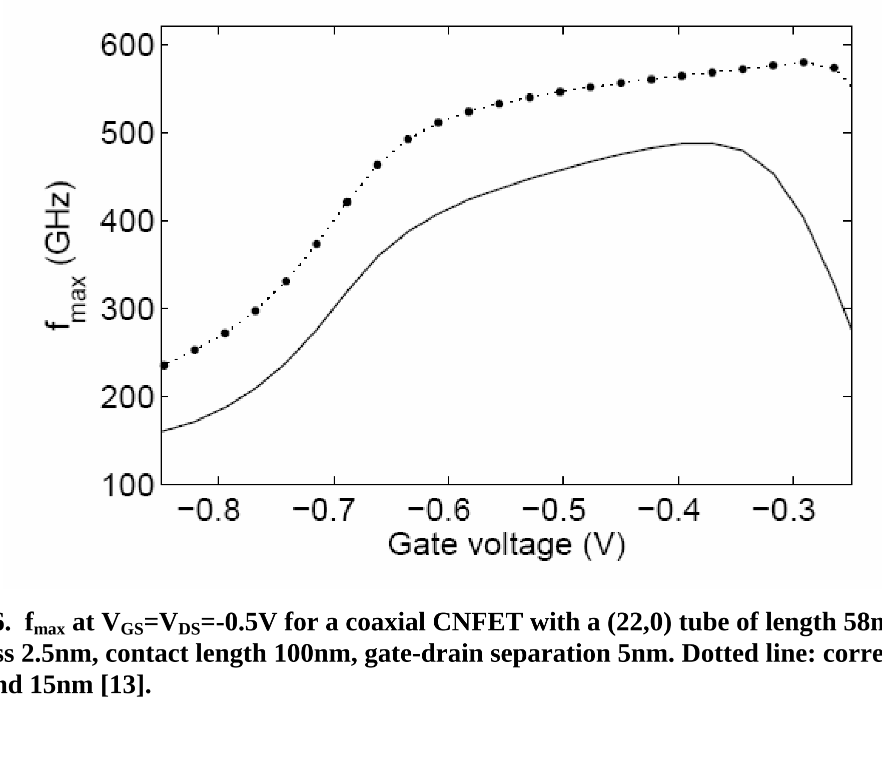

Figure 6. f_{max} at V_{GS}=V_{DS}=-0.5V for a coaxial CNFET with a (22,0) tube of length 58nm. Solid line: insulator thickness 2.5nm, contact length 100nm, gate-drain separation 5nm. Dotted line: corresponding values are 8nm, 30nm and 15nm [13].

However, the Schottky barrier height for the source and drain contacts increases with tube bandgap [15], so the ON current is lower than in smaller diameter tubes. The consequence of this for large-signal applications is that τ is larger (see Fig. 7). One way to preserve a high ON-OFF current ratio and yet reduce τ, would be to use a CNFET with a large bandgap tube and improve the ON-current by more tightly coupling, electrostatically, the gate to the channel, *i.e.*, by reducing the insulator thickness [9]. The beneficial effect of doing this is clear from Fig. 7. Note that the results shown in this figure are for the extrinsic switching time, *i.e.*, when the inter-electrode capacitances have been included together with the quantum capacitance. It is imperative to include the inter-electrode capacitance because the naturally small size of CNFETs inevitably places the electrodes very close together. When this capacitance is neglected, as is often done [7,8], it leads to switching times that are optimistic by one or more orders of magnitude [9].

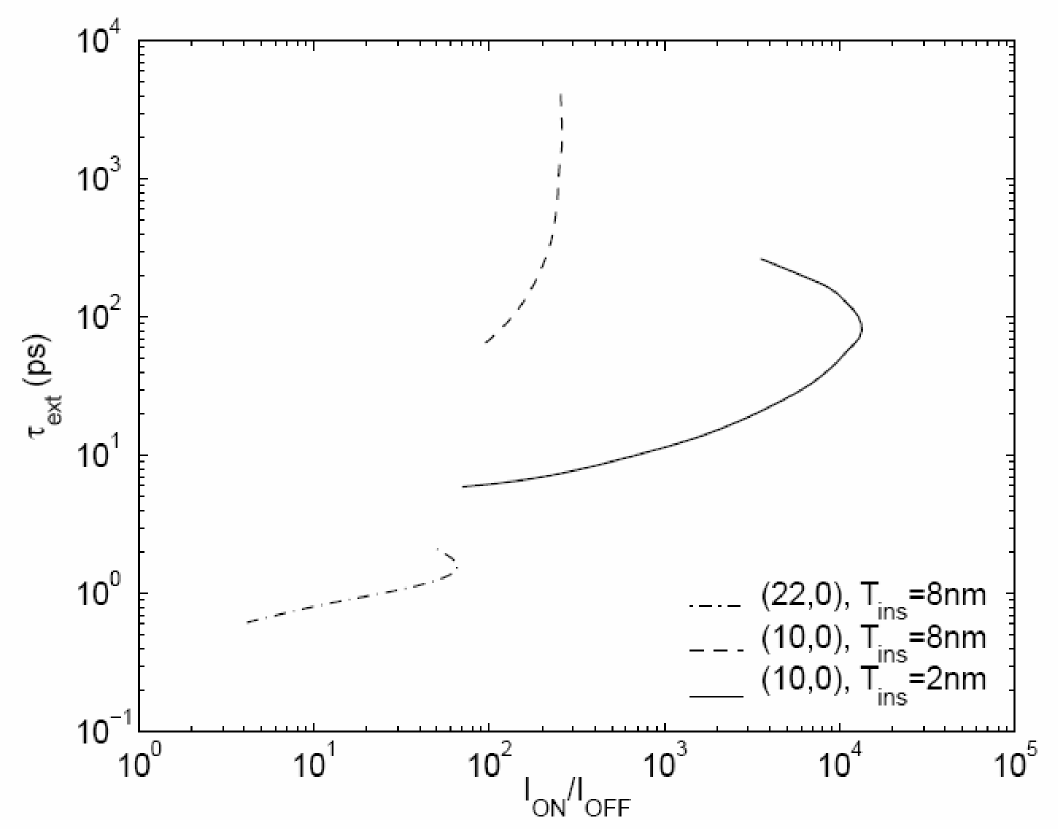

Figure 7. Extrinsic switching time and ON/OFF ratio at V_{DS}=-0.5V for planar CNFETs with a tube length of 28nm and an insulator of relative permittivity 16. The tube chirality and insulator thickness (nm) are, respectively: dot-dash - (22,0), 8; dashed- (10,0), 8; solid- (10,0), 2 [9].

Conclusions

From this study of the AC performance of Schottky-barrier carbon nanotube FETs, it can be concluded that: devices intended for small-signal, high-frequency applications should employ small-bandgap nanotubes; and devices intended for large-signal switching applications should use larger bandgap nanotubes. In both cases, inter-electrode capacitance is important, but high performance, in the form of near-terahertz unity-gain frequencies and near-picosecond switching times, appears possible.

Acknowledgement

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