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High Frequency Response in Carbon Nanotube Field-Effect Transistors

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Abstract

We report electrical measurements of the RF response of carbon nanotube field-effect transistors (CNFETs). The very low current drive of CNFETs makes conventional high frequency measurements difficult. To overcome this problem, we have used a novel approach to easily measure the response up to 250 MHz in non-optimized experimental conditions. We observe a clear response of our CNFETs with no deterioration in signal up to at least 250 MHz, which is the limit for our present configuration.

Index Terms

carbon nanotube, field-effect transistor, high frequency response

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I. Introduction

There has been much recent interest in carbon nanotube transistors for future electronic applications due to their smallness and unique electrical properties. While a number of recent experiments have clearly shown their potential in terms of DC performance [1], [2], a necessary step in the evaluation of CNFETs is the verification of their anticipated high-frequency behavior. Previous measurements have only gone up to a few hundred Hertz [3], [4] because the very low drive current of most CNFETs inhibits conventional high frequency measurements. Here, we report for the first time measurements on individual nanotube transistors, up to 250MHz, using a novel method that is particularly amenable to the low drive currents of CNFETs.

II. Experimental Procedure

To fabricate nanotube transistors, we start with a p-type Si wafer covered by a uniform silicon dioxide layer of 100 nm thickness with small windows ($\sim 30\mu\mathrm{m}^2$) where the oxide thickness is reduced to $t_{ox} = 5$nm. Then laser ablation tubes with an average diameter of $t_{si} = 1.4$ nm are spun onto this substrate. Figure 1(a) is a schematic of our device layout. Contact pads reside on the thick oxide, while the active device element - the nanotube channel - is located on top of the thinned gate dielectric area. The silicon substrate acts as a gate in our experiments. Source and drain contacts are made from titanium with a source/drain separation of L = 300 nm. Details of the sample fabrication can be found elsewhere [5]. Since the gate oxide is thin, our CNFETs operate with both gate-to-source voltage V_{gs} and drain-to-source voltage V_{ds} of the same order of ~ 1V.

Because nanotube FETs only tend to reach on-currents of order 1 μA for single tube transistors, they yield only very tiny signals into the 50 Ω impedances of conventional high frequency measurement equipment, making it very hard to separate signal from noise. The approach we have used to circumvent this difficulty (see Fig. 1(b)) is to apply RF to one terminal (the source), and then observe the average DC response at the other terminal, the drain. In general, when an AC signal is applied to a nonlinear device, some degree of rectification occurs, resulting in an average DC signal. This DC response can be measured to high accuracy, even at low current levels, making it very compatible with nanotube current drive levels. Capacitive coupling of the RF signal between source and drain does not interfere with this measurement because it is linear and does not generate any average DC current. Note that since the gate voltage V_{gs} is kept at the same voltage as the drain V_{ds}, as they are both swept together, the CNFET is basically being biased as a diode. Our approach may be extendable to obtain more information on the gain by integrating a nonlinear load along with the CNFET and then monitoring the average DC response of the load, but this has not been investigated.

Figure 2 shows the average current I_d measured on the drain of a CNFET as a function of applied bias (V_{bias} = V_{gs} = V_{ds}) for various levels of RF drive amplitude V_{RF} at a fairly low frequency (1 MHz). Measurement sweeps were repeated five times for each V_{RF} condition, with actual runs displayed to illustrate the intrinsic current variation for this device. The observed noise level is typical for state-of-the art nanotube transistors [6]. Different from conventional MOSFETs, carbon nanotube transistors of this diameter have been found to function as Schottky barrier devices [7], [8]. Current injection occurs by thermal assisted tunneling through a barrier at the metal/nanotube interface. While not completely understood at the moment it is likely that traps impact current flow during this tunneling process giving rise to the observed noise.

As can be seen, the current in the subthreshold region[1] increases substantially as the RF amplitude increases, as expected, since the exponential nonlinearity is strongest there. To explain it in words, the oscillating source potential causes the device to vary between 'off' in the subthreshold region (when the gate-to-source voltage is sufficiently positive for this p-type device), and 'on' in the other direction. The on-current, being exponentially larger, greatly outweighs the off current, giving rise to an increase in average current at any given gate voltage.

To reach high frequencies in our experimental setup it is important to calibrate the RF amplitude that reaches the sample, since the pad capacitance will damp the incoming RF signal for frequencies approaching the GHz regime. For this particular sample the capacitance of the double-pad source was 11.2 pF, because of the conducting substrate, which leads to a time constant of ~ 560 ps for a ~ 50 Ohm coaxial signal source, and thus the input corner frequency is ~ 300 MHz, above which significant attenuation occurs.) We found that we could calibrate the RF amplitude by using the exponential Fowler-Nordheim tunneling current I_{FN} that flows through our gate oxide at high voltage. As explained above, the non-linearity of I_{FN} as a function of applied bias is the key component in this approach. Using a different test-site on the same wafer, with exactly the same pad configuration as the CNFETs of interest, but with no nanotube

[1]Note that since V_{ds} is varied together with V_{gs}, the curves are not exactly the same as the usual subthreshold characteristics in which V_{ds} is held constant.

present, we biased the MIS diode formed by the $\sim 6\mu\mathrm{m}^2$ source contact, the 5 nm oxide, and the substrate, so that the substrate was in accumulation. Under this condition the transit time of a tunneling hole is estimated to be less than 10 fs, [9] making the frequency response of the tunneling current much higher than what can be measured in our setup, thus making it suitable for calibration. We measured the $\mathrm{I_{FN}}$ curve at biases between 5 and 7 V, and used the 1 MHz response curve (for which there was no RF signal loss to the sample) as a standard against which to calibrate the drive amplitude needed at higher frequencies to achieve the same response.

III. Experimental Results

Using the amplitude calibrations, we measured the RF response of a CNFET at frequencies from 1MHz up to 250MHz, adjusting the drive amplitude so that $\mathrm{V_{RF}}$=515 mV at the CNFET source, for each frequency. As can be seen in Fig. 3, there is no change in frequency response over this entire frequency range. This indicates that the internal frequency response for any carrier concentration of the nanotube must still be much higher than we have been able to measure, since the rectification response should diminish when we approach the intrinsic speed similar to the behavior shown in Fig. 2 for decreasing $\mathrm{V_{RF}}$. Since the carrier velocity is around 10^8cm/s in nanotubes and ballistic transport over a few hundred nanometers has been experimentally confirmed [10] this intrinsic speed is expected to correspond to a maximum frequency of ~ 500GHz for L =300nm. At frequencies well above this switching speed, the current and charge in the CNFET would not have time to respond significantly to the RF, the CNFET would behave like a linear resistor-inductor-capacitor network, and there would be no net DC shift.

It is a relatively simple matter to compute the expected IV curve shifts due to the applied RF, since the expected current is given by

$$\langle \mathrm{I_d} \rangle = \frac{1}{2\pi}\int_0^{2\pi} d\varphi\ \mathrm{I_d}\left(\mathrm{V_{bias}} + \mathrm{V_{RF}} \cdot \sin\varphi\right) \qquad (1)$$

where I_{d} is the drain current as a function of bias, V_{bias} = $\mathrm{V_{gs}}$ = $\mathrm{V_{ds}}$ is the applied DC bias, and V_{RF} is the magnitude of the RF voltage. The expected $\langle \mathrm{I_d} \rangle$ versus $\mathrm{V_{bias}}$ curves have been computed numerically using a phenomenological curve-fit to the $\mathrm{V_{RF}} = 0$ case and the measured $\mathrm{V_{RF}}$ values. These curves are the solid lines in Fig. 2, and show generally excellent agreement, supporting the consistency of our measurement.

IV. CONCLUSION

We have shown for the first time that carbon nanotube FETs have a frequency response well in excess of 250MHz, and we have introduced a relatively simple measurement technique for exploring the frequency response of these devices even though they have relatively weak current drive. With improvements in the experimental setup and reduction of parasitic capacitances, it should be possible to use this technique up to 10's of GHz, where more interesting frequency response may come into play.

V. ACKNOWLEDGEMENT

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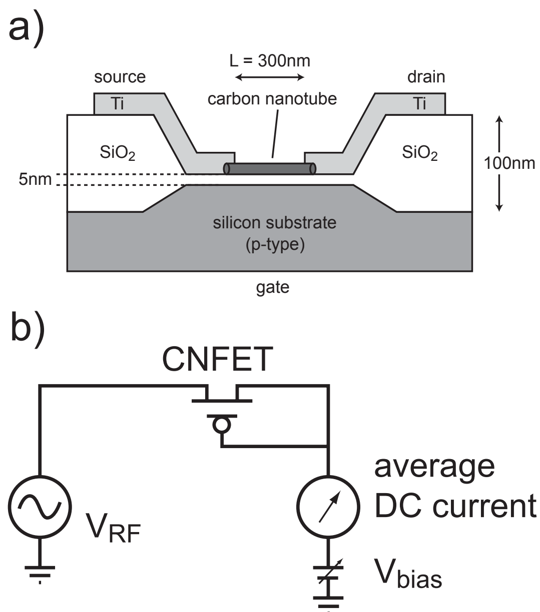

Fig. 1 a) Device layout for our back gated CNFET. b) Circuit diagram of measurement setup. The RF signal source is HP ESG1000A, the drain current is measured and biases are applied with an HP4156C, and wires are a combination of coax and triax.

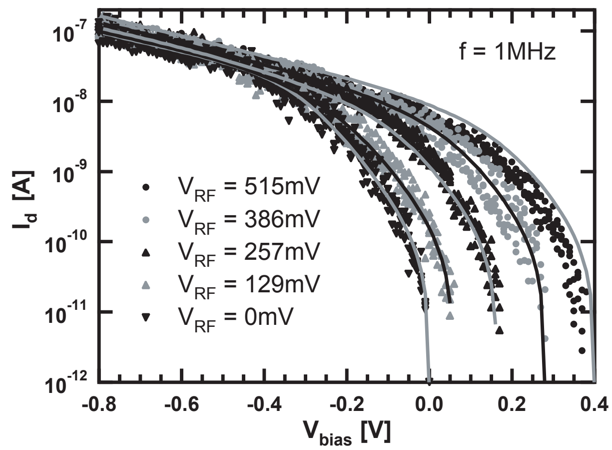

Fig. 2. Plot of I_d versus V_{bias} for different amplitudes of RF, showing the expected monotonic stretch in positive V_{bias} -direction with increase in RF amplitude. V_{RF} is the peak amplitude RF signal applied to the source. The solid lines are the theoretically expected variations, based on the measured variations, based on the measured static nonlinear IV curve.

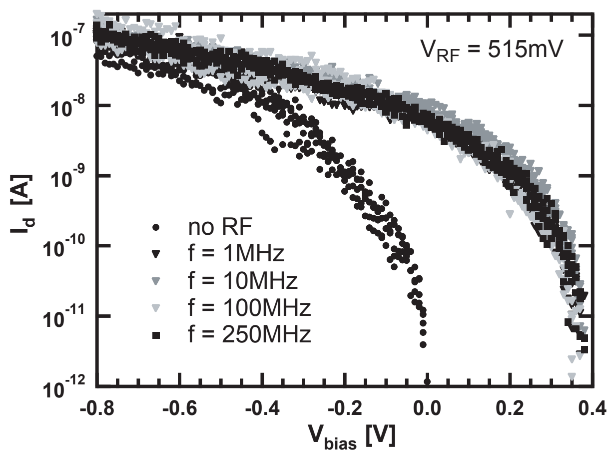

Fig. 3. Plot of I_d versus V_{gs} for different frequencies, showing the frequency independence out to 250MHz. RF signal amplitude is 515mV.