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Advances in Carbon Nanotube Devices and Circuits

Yu-Ming Lin, Zhihong Chen, Joerg Appenzeller, Paul M. Solomon and Phaedon Avouris

IBM T. J. Watson Research Center
Yorktown Heights, NY 10598, USA
E-mail: yming@us.ibm.com

1. Introduction

Carbon nanotubes (CNs) are excellent realizations of one-dimensional quantum wires. With a diameter less than a couple nanometers and an essentially unlimited length, carbon nanotubes offer an attractive platform for nanoelectronic devices and circuits. Of particular interest is their potential for high-speed and low-power logic applications owing to their excellent electrical properties such as the ballistic transport, high carrier velocity, and the ultra-thin body. Here we first review some of the important aspects of the transport behaviors in carbon nanotube field-effect transistors (CNFETs), and demonstrate a compact, CMOS-type, 5-stage ring oscillator circuit built on one individual carbon nanotube.

2. Carbon Nanotube Field-Effect Transistor

The regular CNFET consists of an undoped semiconducting CN channel in direct contact with source/drain (S/D) metal electrodes and a gate overlapping the entire channel region to ensure proper switching of the device. This configuration gives rise to a unique one-dimensional Schottky barrier (SB) type switching mechanism, which is very different from that of a conventional MOSFET. Figure 1 shows the characteristics of a CNFET with a gate dielectric of 10nm SiO_2. The CNFET exhibits ambipolar transport characteristics, where the device is switched on for sufficiently negative or positive gate voltages. At negative gate voltages, holes are injected from the source contact through the SB into the valance band of the CN, resulting in the p-branch that shows little drain voltage dependence. When the gate voltage is increased, the conduction band moves downwards and enables the electron injection from the drain contact, resulting in the n-branch and a drain voltage dependent off-state. Due to the SB switching mechanism, an inverse subthreshold slope larger than 60mV/dec is usually observed in this type of CNFETs.

In principle, having the Schottky barrier contacts is disadvantageous because they lead to lower currents and the ambipolar behavior. Much progress in improving the switching characteristics of CNFETs has been made by optimizing the contacts and/or the device geometry. The SB height is influenced by the band gap of the CN, which is inversely proportional to the CN diameter, and the contact metal work function. Their impact on the device on-currents has been carefully examined in Ref. [1]. For instance, by choosing a large work function metal, e.g. Pd, and a larger diameter CN, highly transparent SBs with negative barrier heights can be obtained to achieve high on-current for the p-branch. To address the issue of ambipolar characteristics, more sophisticated device structures have been proposed and fabricated to enable the bulk-channel switching similar to that in a conventional MOSFET [2]. In these improved CNFET designs, nanotube S/D extensions are doped by either a charge transfer mechanism or by electrostatic fields, whereas the gate electrode controls the undoped nanotube segment. Unipolar transistor characteristics with an inverse subthreshold slope close to 60 mV/dec have been realized in these n/i/n or p/i/p CNFETs.

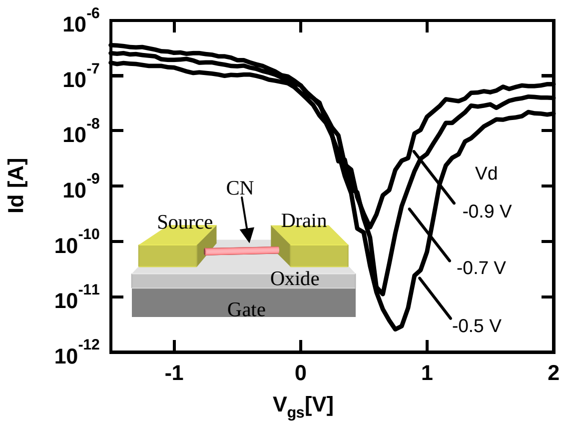

Fig. 1 Subthreshold characteristics of a CNFET. The inset shows the schematics of the device layout.

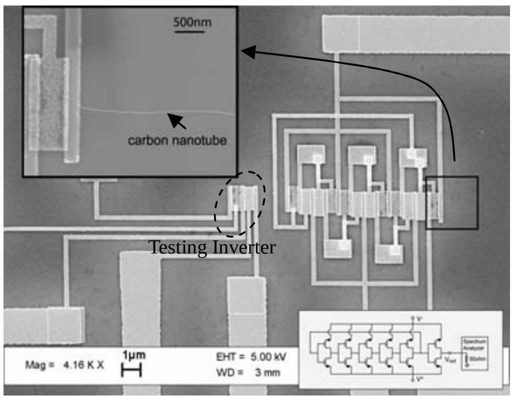

Fig. 2 SEM of a 5-stage CMOS-type CN ring oscillator, followed by a read-out inverter stage and an independent test inverter on the same nanotube. The inset is the zoom-in that shows the actual nanotube underneath of the contacts and the gate dielectric.

3. CMOS Inverter and Ring Oscillator

The ambipolar characteristics in a regular CNFET, albeit undesirable for most applications, can be engineered by controlling the metal gate work function to offer the n- and p-type transistors required for a CMOS circuit. As shown in Fig. 2, we fabricated a 5-stage CMOS ring oscillator entirely built on one single wall carbon nanotube [3]. The nanotube was CVD grown with ~2 nm diameter. Palladium source/drain contacts were defined on top of the nanotube, followed by the deposition of an Al_2O_3 gate dielectric and metal gate on top of each transistor channel. The 5-stage CMOS ring oscillator consists of 5 inverters, each formed with a pair of p- and n-FETs, connected in series. The circuit layout is designed such that the same type FETs from contiguous inverter stages share the same source/drain contacts, which makes the circuit rather compact. An additional CMOS inverter stage right next to the ring oscillator is used to buffer the output to a spectrum analyzer. One separate inverter stage is fabricated on the same nanotube to probe the electrical properties of the nanotube such that the ideal parameter set for the ring oscillator measurement can be obtained.

The CMOS scheme on a single carbon nanotube is realized by using different work function metal gates, i.e. palladium (Pd) for the p-FET and aluminum (Al) for the n-FET. In addition to these metal gates, the highly doped silicon substrate can be used to adjust both the p-type and n-type FETs' threshold voltages simultaneously. Fig. 3 shows inverter characteristics measured at 3 different silicon back-gate voltages, V_{bg}. We found that negative V_{bg} shifts the V_{th} for both p-type and n-type FETs to positive values. The highest inverter gain of ~9 is obtained at V_{bg} = -6V.

We use a spectrum analyzer to analyze the output of the ring oscillator as a function of the supply voltage, V_{dd}, as shown in Fig. 4. The ring oscillator operation frequency increases with increasing V_{dd}, and at V_{dd}=1.04V, the oscillation frequency is 72 Mhz. The small signal heights, ranging from 34μV to 390μV for different V_{dd}, result from the mismatch between the ~1MΩ output impedance of the ring oscillator circuit and the 50Ω input impedance of the spectrum analyzer.

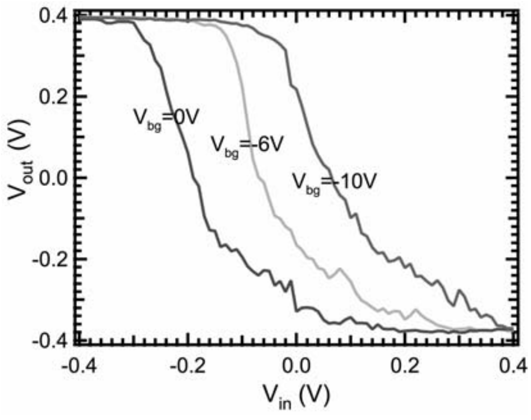

Fig. 3 the CMOS inverter characteristics as a function of Si back gate voltage, at $V_{Si\text{-}gate}$=-6V, the inverter gain is 9.

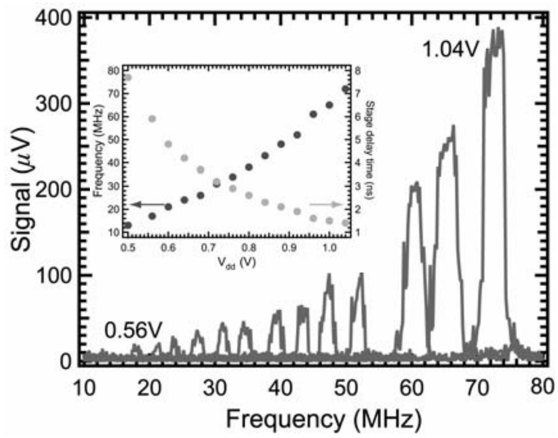

Fig.4 Single carbon nanotube ring oscillator frequency spectra as a function of supply voltage, V_{dd}. V_{dd} ranges from 0.56V to 1.04V from the left to the right, in 0.04V step. Inset: Ring oscillator resonance frequency (left axis) and the corresponding stage delay time (right axis) as a function of V_{dd}.

The inset of Fig. 4 shows the resonance frequency of the ring oscillator and the corresponding stage delay time as a function of the supply voltage V_{dd}. At V_{dd}=1.04V, the ring oscillator operates at a stage delay time of 1.4ns. While this stage delay is dominated by the parasitic capacitance associated with the overlapping between contacts rather than the intrinsic capacitance of nanotube channel, this is to our knowledge the fastest stage delay measured for a ring oscillator built on any nanostructure including nanowires thus far.

4. Conclusions

We have demonstrated a ring oscillator built entirely on a single molecule. While this frequency response is still far from the predicted THz performance of carbon nanotubes, these results established an essential step towards all-nanotube based nanoelectronics.

References

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