A 500 MHz carbon nanotube transistor oscillator

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Operation of a carbon nanotube field effect transistor (FET) oscillator at a record frequency of 500 MHz is described. The FET was fabricated using a large parallel array of single-walled nanotubes grown by chemical vapor deposition on ST-quartz substrates. Matching of the gate capacitance with a series inductor enabled greater than unity net oscillator loop gain to be achieved at 500 MHz. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2988824]

Carbon nanotube (CNT) field effect transistors (FETs) promise operation at microwave frequencies and beyond with highly linear gain and low power dissipation.[1] However, because of their high impedance, FETs comprising single nanotubes cannot be measured directly at microwave frequencies with conventional 50 Ω test equipment such as a network analyzer.[2–4] CNT FET impedance has been reduced by operating many nanotubes in parallel,[5–12] and while significant progress has been made, multigigahertz broadband gain in a 50 Ω circuit has yet to be reported. Progress toward this end and construction of an amplitude modulation transistor radio using only multitube CNT FETs as active components have been published recently.[13] Here we describe the fabrication of a multitube CNT transistor and its operation in an oscillator configuration at 500 MHz. This frequency of oscillation is ten times higher than previously reported for a CNT ring oscillator.[14] The ring oscillator comprised several single nanotube CNT FETs in cascade and provided an indication of the digital speed of the transistors. In contrast, the oscillator described here used one multitube transistor operating in a 50 Ω circuit and dissipating more than 10 mW of power. This result verifies the achievement of power gain at 500 MHz in a 50 Ω circuit. Oscillators are key building blocks in all radio frequency (rf) receiver and transmitter systems.

The FET device was based on the massive parallel nanotube array techniques[9–11] and was nominally identical to the devices described recently.[13] The dense arrays of single-walled nanotubes (SWNTs) were grown by chemical vapor deposition on single crystal quartz substrates. The average density of the tubes was ~5 SWNT/μm with the local density as high as ~25 SWNT/μm. The average length of the tubes was around 100 μm. The device used split source and common drain electrodes with the gate electrode in a double finger configuration[13] as shown in Fig. 2 (center). The total gate width (W) was 300 μm and the gate length (L_g) was 4 μm. The parasitic capacitances were reduced by lowering the overlap of gate and S/D electrodes. Double layer gate dielectric consisting of HfO_2 (≈10 nm), formed by atomic layer deposition, and benzocyclobutene (≈20 nm) spin cast on the SWNTs was used. The capacitance of the bilayer dielectric is $(C_g) \approx 160$ nF/cm^2. The field effect mobility of the device calculated using parallel plate capacitance for V_{ds} between −0.5 and −2 V is 150–200 cm^2/Vs. This value was comparable to our previous reports of similar devices with similar channel lengths.[10,11] The on/off ratio, on the other hand, was somewhat lower. This device showed predominately p-channel behavior with $g_m \approx 2.7$ mS at a drain bias of −2 V and gate bias of −0.4 V (Fig. 1). This corresponded to an average transconductance/nanotube of ~1.8 μS. The average on-current per nanotube was estimated to be ~5 μA. Approximately one-third of the SWNTs in the channel were metallic, which resulted in a low ratio of on and off currents. The metallic SWNTs also limited the available $g_m R_0$ to ≤2. From Fig. 1, the measured $g_m R_0 \approx 1.15$. Elimination of metallic nanotubes is a topic of current interest, and based on a simple model that assumes that the conductance of a metallic CNT and the transconductance of a semiconducting CNT are equal, $g_m R_0 \approx (1-\gamma)/\gamma$, where γ is the fraction of metallic CNTs in the array. Thus the fraction of metallic SWNTs must be reduced below ~8% to realize $g_m R_0 > 10$ necessary for 20 dB of broadband gain. Digital applications require significantly lower fractions of metallic SWNTs.

Large numbers of isolated SWNTs provide large values of transconductance without sacrificing the intrinsic performance of the tubes. This high transconductance with small parasitic capacitance leads to devices with good performance in the rf range. Although the gate-drain capacitance (C_{gd}) has not been calculated from the device geometry, the measured C_{gd} was ≈0.25 pF. The dependence of maximum gain on

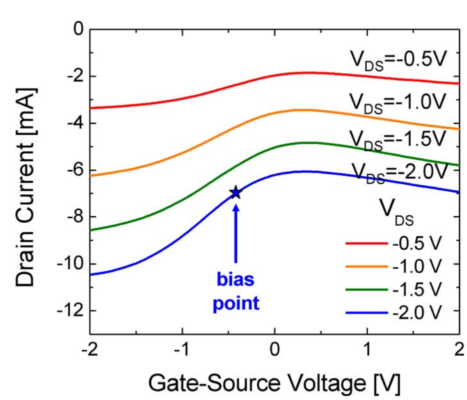

FIG. 1. (Color online) Measured CNT FET drain current with gate-source voltage with the drain source voltage as a parameter. The device operating point for the oscillator test was $V_{gs}=0.4$ V and $V_{ds}=-2.0$ V.

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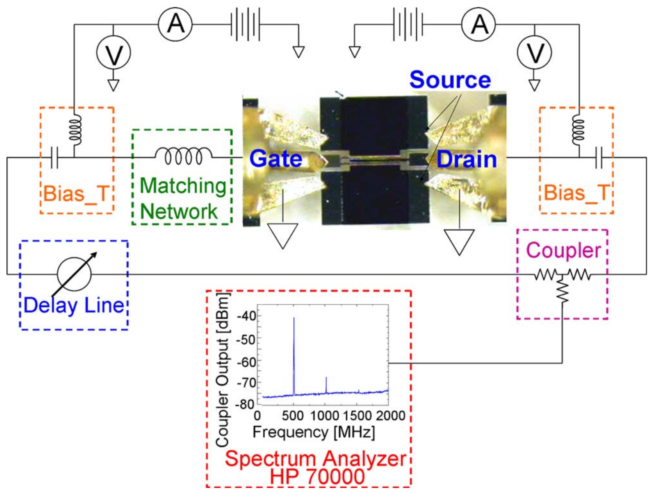

FIG. 2. (Color online) Circuit schematic for the SWNT based 500 MHz oscillator. The SWNT FET is shown in the center of the figure and consists of a split source with two gate electrodes and a common drain. The gate is 300 μm wide with a gate length of 4 μm. The FET electrodes are contacted by coplanar probes. Bandpass gain at 500 MHz was provided by the matching network and the loop phase shift was set by the coaxial delay line. The coupling loss of the output coupler was 20 dB.

frequency derived from two port *S*-parameter data for identical devices at frequencies between 10 MHz and 10 GHz, indicating a unity power gain (f_{max}) of 1 GHz, and additional details of the rf device measurements were given previously.[13]

A schematic of the measurement system for an oscillator where the gain was provided by the CNT FET described above is shown in Fig. 2. A series inductor at the gate of the FET enabled impedance matching. The inductor combined with the C_{gd} to form a resonator, stepping up the voltage on the input to the gate. The inductor, estimated at 2 nH, was a short length of high impedance transmission line. In principle, the oscillation frequency is roughly set by the inductor/gate-capacitance resonant frequency, which provides maximum gain at that frequency, and is accurately adjusted to the desired frequency by the variable coaxial delay line, which sets the loop phase shift to $2n\pi$ radians. However, in practice the conditions for oscillation were more complicated because the output of the CNT amplifier was not purely 50 Ω resistive and its complex impedance was presented to the resonator circuit by transformation through an arbitrary length of coaxial line that formed the feedback path. Figure 3 shows the oscillator output as a function of frequency with the fundamental output at 500 MHz and harmonic outputs at 1000 and 1500 MHz. The measured power at the 500 MHz fundamental was −40 dBm corresponding to a −20 dBm signal

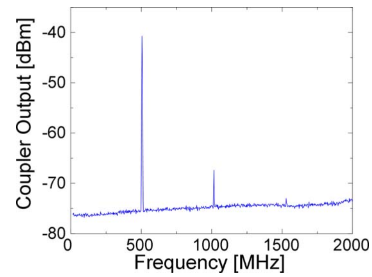

FIG. 3. (Color online) CNT FET oscillator output power as a function of frequency measured on an HP 70000 Spectrum Analyzer.

level at the drain output of the FET. The relatively low output power compared to the FET dissipation of ~11.5 dBm was due to the presence of metallic nanotubes that increase the FET power dissipation without contributing to the gain and prevent effective impedance matching of the FET drain output.

The results presented here provide confirmation that CNT FETs can provide power gain in a 50 Ω circuit at uhf frequencies. Rapid progress toward broadband gain at microwave and millimeter-wave frequencies is expected as device processing techniques are optimized for short gate length devices and metallic tubes are eliminated.

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