A 500 MHz carbon nanotube transistor oscillator

A. A. Pesetski,1 J. E. Baumgardner,1 S. V. Krishnaswamy,1 H. Zhang,1 J. D. Adam,1,a) C. Kocabas,2 T. Banks,2 and J. A. Rogers2

1Northrop Grumman Electronics Systems, 1212 Winterson Road, Linthicum, Maryland 21090, USA
2University of Illinois, Urbana-Champaign, Illinois 61801, USA

(Received 23 June 2008; accepted 4 September 2008; published online 23 September 2008)

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 at 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 transistor operating in a 50 Ω circuit has yet to be reported. Progress toward this end and construction of an amplitude modulation transistor radio using only multitone CNT FETs as active components have been published recently.13 Here we describe the fabrication of a multitone 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 multitone 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 techniques6–11 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 gate electrodes with the gate electrode in a double finger configuration13 as shown in Fig. 2 (center). The total gate width (W) was 300 μm and the gate length (Lg) was 4 μm. The parasitic capacitances were reduced by lowering the overlap of gate and S/D electrodes. Double layer gate dielectric consisting of HfO2 (~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 (Cg) = 160 nF/cm2. The field effect mobility of the device calculated using parallel plate capacitance for Vds between −0.5 and −2 V is 150–200 cm2/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 gms = 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 gmsR0 to ~2. From Fig. 1, the measured gmsR0 = ~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, gmsR0 = (1 − γ)/γ, where γ is the fraction of metallic CNTs in the array. Thus the fraction of metallic SWNTs must be reduced below ~8% to realize gmsR0 > 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 (Cgd) has not been calculated from the device geometry, the measured Cgd was ~0.25 pF. The dependence of maximum gain on the device calculated using parallel plate capacitance for Vds was ~200 cm2/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 gms = 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 gmsR0 to ~2. From Fig. 1, the measured gmsR0 = ~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, gmsR0 = (1 − γ)/γ, where γ is the fraction of metallic CNTs in the array. Thus the fraction of metallic SWNTs must be reduced below ~8% to realize gmsR0 > 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 (Cgd) has not been calculated from the device geometry, the measured Cgd was ~0.25 pF. The dependence of maximum gain on the device calculated using parallel plate capacitance for Vds was ~200 cm2/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 gms = 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 gmsR0 to ~2. From Fig. 1, the measured gmsR0 = ~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, gmsR0 = (1 − γ)/γ, where γ is the fraction of metallic CNTs in the array. Thus the fraction of metallic SWNTs must be reduced below ~8% to realize gmsR0 > 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 (Cgd) has not been calculated from the device geometry, the measured Cgd 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 Vgs=0.4 V and Vds=−2.0 V.
A 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 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.