Mixing at 50 GHz using a single-walled carbon nanotube transistor

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We have probed the electrical properties of top-gated single-walled carbon nanotube transistors at frequencies up to 50 GHz by using the device as a microwave mixer. We find that the amplitude of the mixing signal decays as a function of frequency with a characteristic time constant that is limited by the setup. Despite the setup-limited cutoff frequency of ~10 GHz, we show that the devices still operate faster than 50 GHz. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2103391]

Semiconducting carbon nanotubes have been shown to have very high mobilities, high transconductances, and long mean free paths.[1–6] As a result, they offer promise as very high-frequency transistors. A short single-walled carbon nanotube operating in the ballistic regime and at the quantum capacitance limit is theoretically expected to provide gain at frequencies above a terahertz.[7] Recent experiments have provided initial progress towards this goal, but high-frequency measurements are challenging since the signal levels are small. Direct measurements of switching speeds have only been performed to 100 MHz.[8] Li *et al.*[9] showed that a nanotube could be operated as a transistor at 2.6 GHz using a resonant circuit, but the electrical properties could only be studied at the resonant frequency. More recently, Huo *et al.*[10] studied the scattering properties from a transmission line terminated with nanotubes at frequencies up to 12 GHz.

An alternative way to explore the high-frequency properties of a transistor is to operate it as a mixer or rectifier.[11] Due to the gate-induced nonlinear current-voltage curve of a transistor, an ac signal applied to the source is rectified and produces a dc output current.[12,13] When an ac voltage is applied to the source, a small-signal approximation reveals a dc current resulting from frequency mixing with magnitude

$$I_{\text{mix}} = -\frac{1}{4}\frac{\partial G}{\partial V_g}(V_s^{\text{ac}})^2, \tag{1}$$

where $\partial G/\partial V_g$ is the derivative of the conductance G relative to the gate voltage V_g, and the amplitude of the ac signal is V_s^{ac}. Equation (1) holds at frequencies below that dictated by the *RC* time constant of the transistor.

Appenzeller *et al.*[12] demonstrated the nanotube mixing up to 580 MHz, limited by the capacitance of the pads of the device. Sazonova *et al.*[14] used electromechanical mixing in suspended nanotubes to detect their vibrations in a similar frequency range. In the current work, we create devices with smaller input capacitance and probe the high-frequency response of single-walled nanotubes up to 50 GHz. We find, up to the highest frequencies measured, that operation is limited by the setup, not the device, except very near turnoff, when the high resistance of the nanotube begins to play an important role.

A schematic of the device used in these experiments is shown in Fig. 1(b). The nanotubes were grown by chemical vapor deposition (typically single walled with diameter 2–3 nm)[15] on a high-resistivity Si substrate (HR-Si, 12–39 kΩ cm) with a 1 μm thermal silicon dioxide layer. The nanotubes were contacted with 50-nm-thick Pd.[4] For probing, pads were made with a 5 nm Cr adhesion layer, 50 nm Au, and 10 nm Au–Pd alloy. Evaporation of 10 nm of evaporated silicon dioxide for the gate insulator[16] was followed by evaporation of 50 nm Al for the top gate electrode. The source-drain contact gap was ~3 μm and the extension of the top gate over the nanotube was ~2 μm. The top gate produced a small overlap (~100 nm) over the source electrode.

The experimental setup for the high-frequency measurements is depicted in Fig. 1(a). The experiment was performed at room temperature in a full-wafer (4 in.), six-arm probe station (Desert Cryogenics), with interface for two custom-made microwave probes (GGB Industries). The top gate was dc biased independently from the source. A bias-tee was used at the source to provide independent dc and ac source-drain bias (voltage is applied to the *source*), and only 2.4 mm connectors were used. The dc bias on the source was set to zero during the experiments. The electrical probe used for the source was a high-frequency ground-signal-ground probe, and the ac source spans from 10 MHz to 50 GHz.

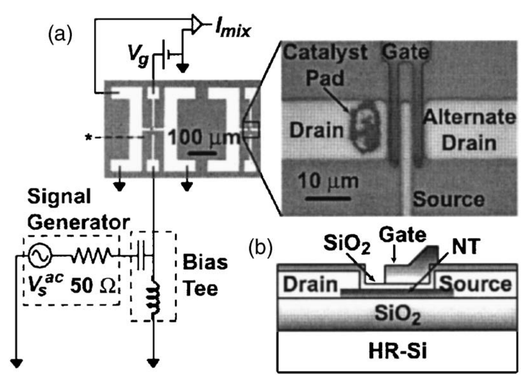

FIG. 1. (a) Optical micrograph of nanotube device along with circuit schematic. The backgate voltage applied to the substrate is not shown. A high-frequency probe delivers the ac signal V_s^{ac} to the source electrode while simultaneously grounding the drain electrodes. The mixing current I_{mix} was detected as a function of frequency and of the gate voltage V_g. The ground line was cut along the dashed line (*) to separate the drain from ground. An alternate drain is available in case a long nanotube grows across the junction. (b) Schematic cross section of device, layers not to scale. The oxide thicknesses are 10 nm for the top gate and 1 μm for the back gate. The top gate has a slight overlap with the source contact. Catalyst pad not shown.

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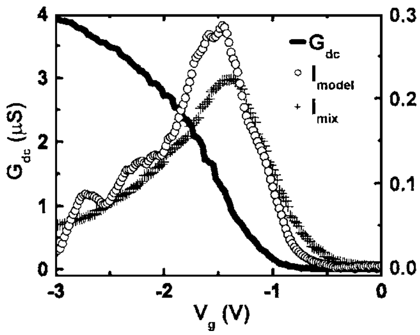

FIG. 2. Conductance G_{dc} (left axis) and mixing current (right axis) vs gate voltage for a semiconducting device. G_{dc} was measured at dc source-drain bias of 10 mV, and I_{mix} at 10 MHz for $V_s^{ac,rms}=400$ mV. In open circles is the numerical derivative of G_{dc} scaled by the prefactor of Eq. (1). The predicted amplitude of the mixing peak is ~1.5 times larger than the experimental value.

Measurements were performed in vacuum to minimize hysteresis in the gate voltage threshold.[17]

The conductance G_{dc} vs V_g for a semiconducting device is shown in Fig. 2, for a dc source-drain bias of 10 mV. Figure 2 also shows dc mixing current I_{mix} vs V_g at a frequency of 10 MHz and $V_{ac}=400$ mV. The peak in I_{mix} correlates with the position of the peak in $\partial G_{dc}/\partial V_g$. Over 60 devices were measured, including both large- and small-band gap semiconductors, and all displayed low-frequency mixing with similar relation to $\partial G_{dc}/\partial V_g$.

We plot in Fig. 3 the mixing amplitude near the peak in $\partial G_{dc}/\partial V_g$ against the V_s^{ac} at a variety of frequencies, plotted on a log scale. At frequencies above ~2 GHz, the overall amplitude decreases with frequency. The straight lines indicate that the response follows a power law in V_s^{ac} with an exponent in the range 1.9–2.2.

The main experimental results are well described by the mixing expression, Eq. (1), taking into account the frequency response of the measurement circuit. At low frequencies, we multiply the derivative of G_{dc} by the prefactor in Eq. (1) to theoretically predict I_{mix}. The result is within a factor of 1.5 of the data (see Fig. 2). This factor is always between 1 and 2 for all the devices studied and is likely due to coupling losses. The origin of the sample-dependent discrepancies is not known. The response also varies with the square of the ac voltage, as predicted by Eq. (1).

At high frequencies, we expect the external circuit and/or the nanotube device itself to limit the effective voltage seen by the mixer. The simplest model for either is that

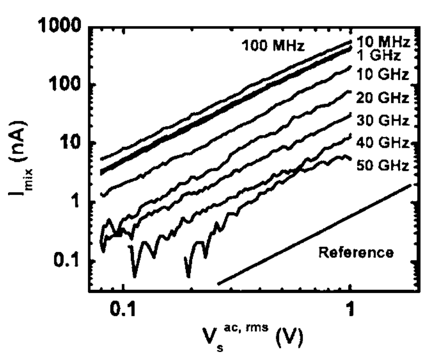

FIG. 3. Mixing current I_{mix} vs $V_s^{ac,rms}$, for a gate voltage near the peak of I_{mix} in Fig. 2. Amplitude at 10 MHz and 1 GHz approximately overlap. The ideal power-law line of 2 is shown for reference.

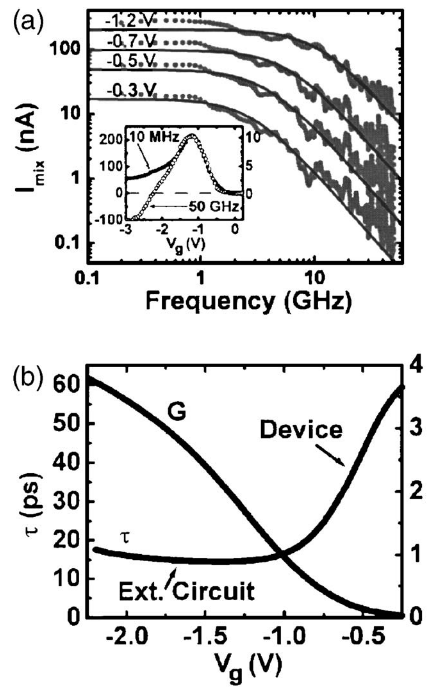

FIG. 4. Damping of mixing current I_{mix} as a function of frequency. (a) Current vs frequency at selected gate voltages, for $V_s^{ac,rms}=400$ mV. Black lines correspond to the numerical fit assuming a first-order low-pass filter. Cutoff frequency decreases from ~10 GHz at $V_g=-1.2$ V to ~3 GHz at $V_g=-0.3$ V. Inset: mixing signal at 10 MHz and 50 GHz, currents in nA. (b) Time constant τ plotted against gate voltage. τ is roughly constant in the conductive state (see plot of conductance G) due to the external circuit. As the device turns off (positive gate voltage), τ increases. The plot for G was taken with the same gate voltage threshold as the frequency plot in (a), which drifted slightly relative to the data in Fig. 2.

of a low-pass *RC* filter with a time constant τ. We start with the expression for voltage gain of a low-pass filter

$$\frac{I_{mix}(\omega)}{I_{mix}(\omega \to 0)} = \left| \frac{V_{out}}{V_{in}} \right|^2 = \frac{1}{1+(\omega\tau)^2}, \tag{2}$$

where V_{out}/V_{in} is the voltage gain. This equation predicts damping at high frequencies with a slope of 20 dB/dec for voltage.

In Fig. 4(a), we fit this expression to the data[18] at different V_g's and extract the time constant τ at different gate voltages. We plot it versus gate voltage (and conductance) in Fig. 4(b). The time τ is ~15 ps and is roughly constant while the device is conducting, but it increases when the resistance of the device becomes greater than ~1 MΩ.

All of the time constants measured for all nanotubes near the peak in $\partial G/\partial V_g$ were found to be in the 5–20 ps range, independent of their resistances (devices with on-state resistance as little as 5 kΩ to as high as ~1 MΩ). It was also unchanged when the back gate was used to change the conductance of the portion of the nanotube not covered by the top gate. Since this time constant is nearly independent of the device properties, we attribute it to a time constant τ_{ext} associated with the external circuit (measurement probes plus pads).

Despite the attenuation due to the measurement circuit, the inset of Fig. 4(a) shows that, even at 50 GHz, the mixing signal is nearly identical in shape to the signal at 10 MHz. This means that the nanotube device *still operates as a mixer at* 50 GHz. Note, however, that this does not imply the circuit is operating with gain at this frequency. If we estimate the RC time constant of the device, we obtain an expected corner frequency $f_c=(2\pi RC)^{-1}\sim 6$ GHz, where we used $R\sim 250$ kΩ for the on-state resistance and $C_g\sim 10^{-16}$ F[1] for the gate-tube capacitance.

When the device becomes highly resistive, the time constant of mixing changes dramatically with increasing gate voltage. We attribute this to the intrinsic rolloff of the device due to the high resistance of the tube and the capacitance of the tube to the gate. For $R\sim 1$ MΩ, this gives $RC\sim 100$ ps. This is in order-of-magnitude agreement with our observations—the RC time of the device dominates as the device resistance approaches the megaohm scale. A more quantitative model would require taking into account the distributed nature of the mixing along the nanotube length and the spatial variations in the threshold voltage.[19,20]

In the inset of Fig. 4(a), I_{mix} is negative for $V_g<-2$ V at high frequencies. We attribute this to mixing caused by the Schottky barriers at the contacts.[21] In the on-state, their nonlinear I-V properties lead to mixing which at high frequencies dominates over the transistor mixing described by Eq. (1).

In conclusion, we have demonstrated that single-walled carbon nanotube transistors can operate as mixers at frequencies up to 50 GHz. Eliminating parasitic capacitances from the setup should allow the devices to operate at even higher frequencies and explore their true high-frequency limits.

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