Carbon Nanotube GHz Nano-Resonator

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Abstract — We present the first microwave measurements of the dynamical impedance of an individual, electrically contacted single walled carbon nanotube. Both semiconducting and metallic nanotubes are measured. Using a semiconducting nanotube, we construct an LC nano-resonator at 2 GHz. The Q of the nano-resonator can be tuned by varying the back-gate voltage on the nanotube. In contrast, the Q of a resonator fabricated with a metallic nanotube is insensitive to the back-gate voltage. This represents the first step towards passive microwave signal processing components based on carbon nanotubes.

Index Terms — Nanotechnology, Resonators, Tuning Circuits.

I. INTRODUCTION

At dc, it is known that electrons can move without scattering over many microns inside a carbon nanotube[1]. The dynamical properties of nanotubes may be quite different than the dc properties, due to the quantum nature of electrons confined to one dimension. The dynamical electrical properties of carbon nanotubes is technologically relevant for both active and passive devices made from carbon nanotubes, including nanotube transistors, nanotube interconnects, and, as we show in this paper, resonators.

We recently analyzed, from a theoretical point of view, the microwave electrical properties of nanotubes in some detail [2,3]. In this paper, we present the first *measurements* of the electrical properties of single walled nanotubes at GHz frequencies, and use this to construct a tunable GHz resonator. Recently a multi-walled nanotube based RF single electron transistor was reported [4]. This is a preliminary report for a conference paper; a more detailed report and analysis, considering how a carbon nanotube device performs as a transistor at high frequencies and the relationship to the Landauer-Buttiker formalism of quantized conduction, is forthcoming[5].

II. DEVICE FABRICATION

A. Nanotube Growth

The nanotubes were grown from lithographically patterned nanoparticle catalyst sites using CVD[6]. The nanotube growth procedure and recipes are described in detail in reference[7].
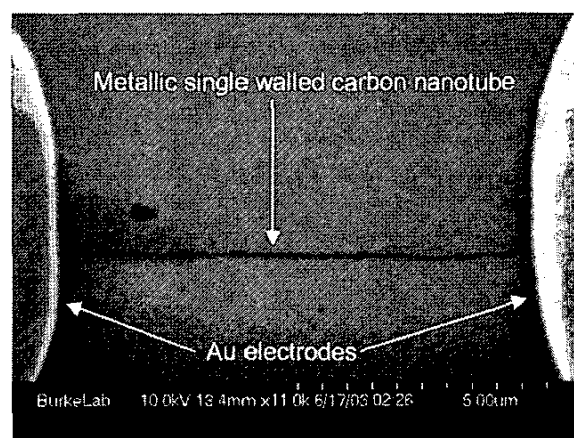

Fig. 1. SEM image of the metallic single walled carbon nanotube used in these studies.

B. Electrical Contact

Electrical contact was achieved with evaporate Ti/Au electrodes using optical lithography. An SEM was used to locate the nanotubes before the electrical contact, and the catalyst pattern was used to align the contacts to the nanotubes. The metallic nanotube was annealed at 600 C in Ar for 5 minutes; the semiconducting nanotube was not annealed. The electrode pattern consisted of a ~ 1 mm by ~ 1 mm contact pad.

C. Device Characterization

SEM images of two nanotube devices grown are shown in Figs. 1 and 2. Both devices were fabricated simultaneously on the same wafer and were only separated by cleaving after the fabrication process. This means they were both grown in the same growth run, the metallization was evaporated onto both samples in the same metallization procedure, etc. The diameter of nanotubes grown under similar conditions in our lab was less than 1.5 nm as measured with an AFM, which leads us to conclude that the nanotubes shown are single walled nanotubes.
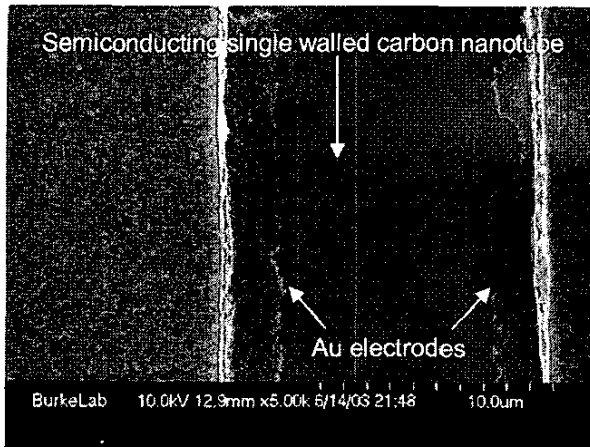
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Fig. 2. SEM image of the semiconducting single walled carbon nanotube used in these studies.

III. LC RESONATOR DESIGN

The microwave reflection coefficient (S_{11}) was measured off of an LC resonator fabricated out of the nanotube mounted to a test fixture. The wire bonds used to connect the device served as the inductor, and the on-chip capacitance to ground served as the capacitor. We performed measurements at room temperature and at 4 K. At room temperature, the substrate losses were severe. Therefore, only the 4 K data will be presented in this paper.

A. Test Fixture

A microstrip launcher was used to connect an SMA cable to a 1 cm length of Cu microstrip on a 0.5 mm thick Duroid substrate. The test fixture used was characterized extensively in reference[8]. There, it was shown to provide resonance free performance up to 40 GHz. For the measurements at 4 K, a 1 m long UT-141 cable was used to insert the test fixture directly into a liquid He storage dewar.

B. Device Mounting

The Si wafer with the nanotube devices was cleaved into 2 x 2 mm pieces, and abutted to the end of the microstrip. The plane of the microstrip and the surface of the Si wafer were at the same height above the brass test fixture. Because the substrate was used as a gate and the test fixture was grounded, we used a thin piece of Cu tape on the back side of the substrate to provide electrical contact to the substrate but to insulate the substrate from ground.

To contact the sample electrically, 25 μm diameter gold wires of length ~ 2 cm were soldered from the end of the

microstrip to one of the electrical contact pads, and from the other electrical contact pad to the ground plane. These provided the inductors which formed approximately 10 nH of inductance in series with the nanotube. When we measured the same sample mounted with In solder (which has very little inductance) instead of wire bonds, the resonance dip in S_{11} (see below) disappeared, thus verifying that the Au wires served as inductors. The excess capacitance to ground from the electrical contact pads is estimated to be ~ 0.1 pF from the geometry.
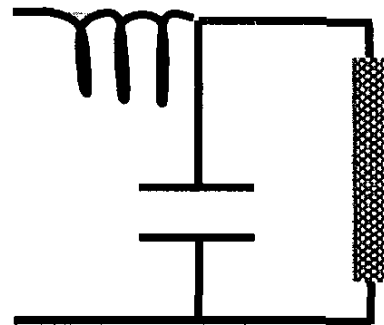

Fig. 3. Equivalent circuit for the resonator.

C. Equivalent Circuit

The LC resonator equivalent circuit is shown in Fig. 3. We measured S_{11} off of this resonator using a control sample with the same electrode pattern as the nanotube device (but no nanotube), and found there is an additional radiation resistance due to losses into free space of ~ 10 kΩ (not shown in Fig. 3). This issue will be further quantified in future work on optimized resonators.

A critical issue is how the nanotube contacts the Au electrically. At dc, the theoretical lower limit for the nanotube resistance is $h/4e^2 = 6.2$ kΩ. At ac, the theory is much more complicated[2]. For the nanotubes we present in this work, the nanotube extended under the Au contact pads by at least 5 μm. Thus, even though the dc contact resistance is high (~ 1 MΩ, see below), there may be an additional capacitive electrical contact to the nanotube, if the evaporated Au does not destroy the nanotube. Indeed, other SEM images (not shown) indicate the nanotube is still intact under the Au electrodes.

III. SEMICONDUCTING NANOTUBE RESONATOR

A. Resonator Performance

In Fig. 4 we show the measured S_{11} vs. frequency for the semiconducting nanotube based resonator. A clear resonance is visible at 2.6 GHz. By applying a voltage of 10 V_{pp} to the substrate, we are able to consistently change the measured value of S_{11} on resonance with high reproducibility, as shown in the inset. This clearly demonstrates tunability of a microwave resonator with a single walled carbon nanotube.
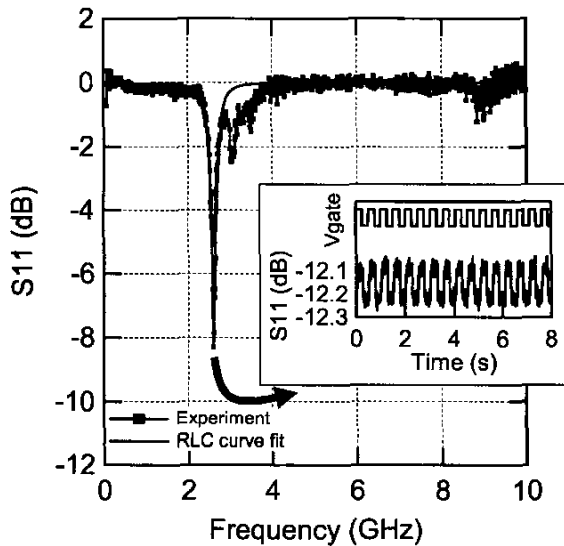

Fig. 4. Measured S_{11} for semiconducting nanotube resonator. The time domain measurement is exactly on resonance, where as the frequency domain measurement missed the resonance frequency due to the finite point density.

B. Semiconducting Nanotube DC Electrical Properties

The semiconducting nanotube had a room temperature resistance of 300 kΩ, and behaved as a p-type device when using the substrate as a back-gate, consistent with previously measured results[1]. Because the nanotube could be gated at room temperature, we have characterized it as a semiconducting nanotube.

At 4 K, the dc performance is more complicated. We plot in Fig. 5 the low-bias conductance vs. back-gate voltage. The complicated structure is probably due to a combination of Coulomb-blockade[9] (single electron transistor) effects and quantum interference of the electron wave functions[10]. The inset shows the nanotube I-V curve, which shows a gap at the origin. Complicating the issue is the fact that the semiconducting nanotube is not

straight (see Fig. 2), and so may behave as a series of quantum dots at 4 K.
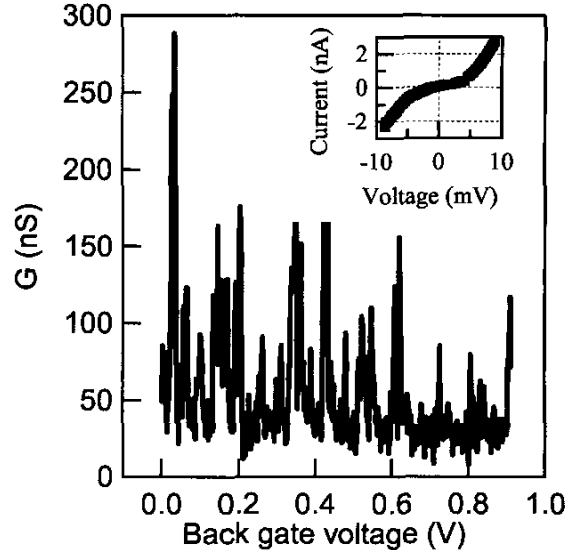

Fig. 5. DC electrical properties of semiconducting nanotube.

III. METALLIC NANOTUBE RESONATOR

A. Resonator performance

In Fig. 6 we show the measured S_{11} vs. frequency for the metallic nanotube based resonator. A clear resonance is visible at 4 GHz. In contrast to the semiconducting nanotube resonator, a voltage of 10 V_{pp} applied to the substrate does not change the S_{11} within the noise limits of 0.01 dB. If we model the nanotube as shown in Fig. 3 as a pure resistor, a 3 parameter fit to the measured S_{11} data give a value of L = 14 nH, C = 0.1 pF, and R = 1.7 kΩ. The fitted curve is shown in Fig. 6. The resistance is lower than the radiation resistance, indicating that the nanotube ac resistance is indeed 1.7 kΩ.
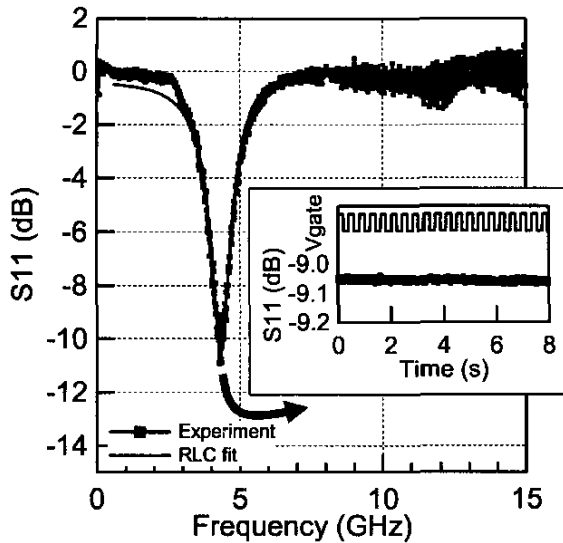
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Fig. 6. Measured S_{11} for metallic nanotube resonator.

B. Metallic nanotube dc electrical properties

The metallic nanotube had a room temperature resistance of 80 kΩ; this did not vary appreciably (less than 1%) with a back-gate voltage. Because the nanotube could not be gated at room temperature, we have characterized it as a metallic nanotube. We plot in Fig. 7 the conductance vs. gate voltage at 4 K, where it is seen that the nanotube conductance is independent of gate voltage. The I-V curve (also shown in Fig. 7) is linear. Thus, neither the dc nor ac properties of the metallic nanotube depend on the back-gate voltage. In this sense, the dc and ac electrical properties are consistent. However, the dc and ac electrical resistance are different. Further experiments are underway to clarify this relationship between the dc and ac electrical properties.
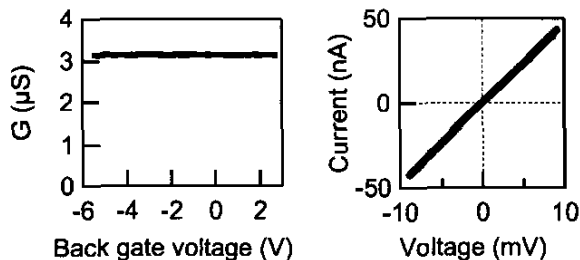

Fig. 7. DC electrical properties of metallic nanotube.

VII. CONCLUSION

In conclusion, we have measured for the first time the nanotube dynamical impedance and showed that, for semiconducting nanotubes, it changes with back-gate voltage. We have constructed a GHz nanotube resonator. This work marks the beginnings of the application of nanotechnology to microwave technology, circuits and systems.

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