ORAL SESSION n°3

« Novel Devices & Technologies for THz »

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Chaired by :

Dr. Wojtek Knap & Dr. Peter Siegel

Microwave Detection and Mixing in Metallic Single Wall Carbon Nanotubes and Potential for a New Terahertz Detector

K.S. Yngvesson, F. Rodriguez-Morales, R. Zannoni, J. Nicholson, M. Fischetti and J. Appenzeller

Abstract— **This paper reports measurements of microwave (up to 4.5 GHz) detection in metallic single-walled carbon nanotubes. The measured voltage responsivity was found to be 114 V/W at 77K and 9,000 V/W at 4.2K. We also demonstrated heterodyne detection at 1 GHz. Above 1.3 GHz the detector response falls off by 12 dB/ octave. The detection mechanism can be explained based on standard microwave detector theory and the nonlinearity of the DC IV-curve, the so-called "zero-bias anomaly". We discuss the possible causes of this nonlinearity. While the frequency response is limited by circuit parasitics in this measurement, we discuss evidence that indicates that the intrinsic effect is much faster and that applications of carbon nanotubes as terahertz detectors are feasible.**

Index Terms—**terahertz detectors, single wall carbon nanotubes, microwave detectors, contact resistance.**

I. INTRODUCTION

The availability of Single Wall Carbon Nanotubes (SWNTs) has stimulated considerable recent exploration of different ideas for use of SWNTs in new electronic devices [1]. SWNTs have different electronic band structures depending on their chirality, and can be either metallic or semiconducting [2]. Much of the research so far has been concentrated on the semiconducting version of SWNTs (s-SWNTs), in particular with the prospect of developing a high-performance Carbon Nanotube Field Effect Transistor (CN-FET) [3], [4]. Other applications that have been proposed are to detectors for microwave or terahertz frequencies. Schottky barriers exist at the contacts of semiconducting SWNTs [5], [6], and were fabricated and analyzed for use as terahertz detectors by Manohara *et al.* [7]. Experimental results were recently published by Rosenblatt *et al.* [8] demonstrating detection of microwaves up to 50 GHz, as well as by Pesetski *et al.* [9] who measured heterodyne detection with flat frequency-dependence up to 23 GHz. These references [7]-[9] all used the s-SWNT-FET configuration. Metallic SWNTs (m-SWNTs) also have considerable potential for detector applications, and one of us (KSY) recently proposed a very fast terahertz detector based on the hot electron bolometric (HEB) effect [10],[11]. In the present paper we report experimental results for a device using an m-SWNT that detects microwaves in the low GHz range, based on a traditional IV-curve nonlinearity at 77 K, and that shows much enhanced direct detection responsivity at 4 K. The device described here operates both as a direct (DC output) detector and as a heterodyne detector (difference frequency output up to at least 200 MHz). In this paper we will discuss the experimental results and interpret these in terms of the detection mechanisms involved. We also discuss the potential of this type of detector for application at terahertz frequencies.

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II. EXPERIMENTAL RESULTS

A. Experimental Procedures

SWNTs used in our study were grown using laser ablation [12]. CNTs with diameters between 0.6 nm and 1.5 nm were spun from solution onto a p+-doped silicon substrate covered with 100 nm of silicon oxide. Contact strips of width 350nm were made with 20 nm of Ti followed by 100 nm of Au, and were connected to 80μm x 80μm contact pads. The length of the tubes between contacts is known to be in the range of 300nm to 500nm. The silicon chip was placed in a small copper enclosure (with a metallic cover) to isolate it from external radiation, see Figure 1. The contact pads were connected by wire bonds to (1) a microstrip transmission line that was in turn connected to a standard coaxial connector installed in the side of the enclosure; and (2) the ground plane of the enclosure. The silicon substrate was left electrically insulated in order to minimize parasitic reactances. The assembly was placed in a liquid helium vacuum dewar and pumped to a good vacuum for at least one day in order to remove most of the surface contaminations on the CNT. A well shielded stainless steel coaxial cable makes the sample accessible from the outside of the dewar. We used a programmable DC power supply (Keithley) to provide a voltage source bias to the device through the coaxial cable. The DC supply also measured the DC voltage and current, and these were read by a computer for further processing. Microwave sources (Agilent) were also fed to the coaxial cable, and different sources (DC and microwave) were separated through the use of commercial bias tees.

B. I-V-Curves

It is well-known that Ti/Au contacts yield a contact resistance that is usually quite high and strongly dependent on the nanotube diameter [13]-[15]. The devices used in our study had contact resistances that were in the range of a few hundred kΩ to a few MΩ. It is also known that the

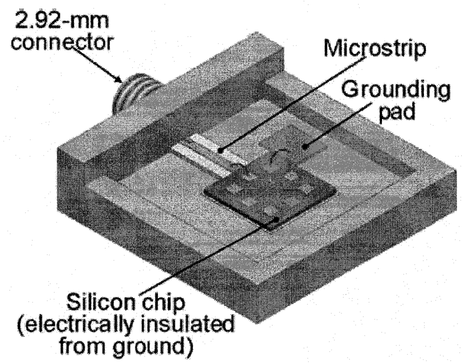


Figure 1. The experimental fixture used in this work.

conductance of such CNTs shows a "zero-bias anomaly" [16], i.e. the differential conductance (dI/dV) plotted as a function of bias voltage (V) shows a dip at low values of V with a width of about +/- 400 mV [17]. This presents a nonlinearity in the IV-curve (Figure 2) that we exploited for microwave detection. Similar IV-curves were obtained for devices fabricated at IBM and at UMass/Amherst, but the results presented here are for devices fabricated at IBM.

The zero-bias anomaly "dip" is also evident from the additional plot of dI/dV in Figure 2. This dip deepens as the temperature is decreased (the curves shown in Figure 2 were taken at 77K). At larger voltages the IV-curve shows a linear dependence between current and bias with a slight decrease in dI/dV for the highest voltage range. Except for the zero-bias anomaly, the IV-curve can thus be assumed to be due to a (roughly) constant contact resistance, that is almost independent of the temperature. Evidence from other metallic CNTs [18] indicates that the electrons have mean free paths of about 1μm; thus in our tubes they travel ballistically from contact to contact. The zero-bias anomaly is usually ascribed to the very strong electron-electron Coulomb interactions in one-dimensional conductors that necessitates treating the electrons as a collective, plasmon-like, medium known as a "Luttinger liquid" ("LL"). Tunneling from the contacts into the LL is suppressed at low temperatures, which explains why the conductance approaches zero. It has been suggested that the behavior of the conductance in the entire temperature range from 4 K to 300 K can be better explained as being due to a combination of effects, the LL effect, and that of interfacial barriers at the contacts [15]. The LL effect is expected to be important only in the lowest temperature range. As made clear in the paper mentioned above [15], a complete understanding of the contacts between the one-dimensional m-SWNTs and a 3-D metal is not yet available.

As microwaves were applied to the SWNT at 77K, we recorded a change in the device DC current (ΔI), and plotted this versus DC bias voltage (Figure 3 (a)). This recording was done by measuring the voltage across a series resistance with a lock-in amplifier, while square wave modulating the microwave source. The DC power supply was still configured as a voltage source. The microwave reflection coefficient (S11) was also measured with an automatic network analyzer, see Figure 4. This particular recording was obtained for a CNT with resistance of a few MΩ, but similar results were obtained for in total three samples. A resonance is seen at about 1.28

C. Microwave Measurements

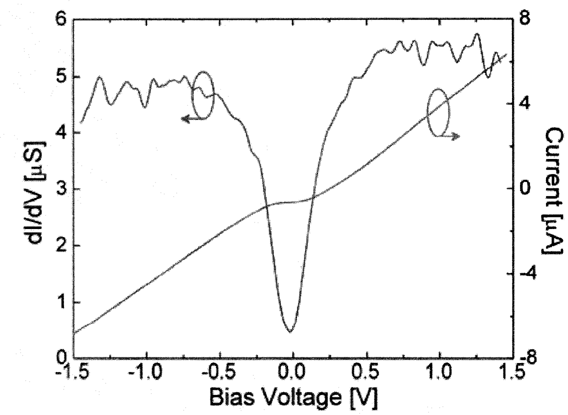
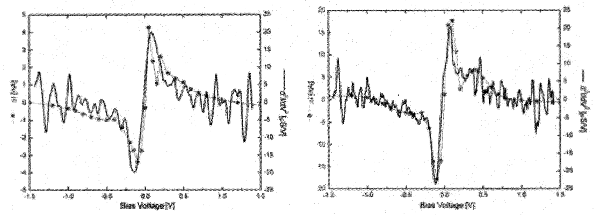


Figure 2. Measured IV-curve for a SWNT at 77 K (right scale); dI/dV based on the IV-curve (left scale).

GHz, which we interpret as being due to the combined effect of the bond wires, the contact pads and the connecting strips, situated on top of the oxide and the doped silicon chip. The equivalent circuit shown in the inset of Figure 4 was used to produce a good fit to the magnitude of S11, as shown in Figure 4. For this fit we used the full S11 data, including the real and imaginary parts (not shown explicitly). We also used the model to predict the measured detected change in current versus frequency, plotted in Figure 4 for two different microwave power levels. The detected signal is essentially independent of frequency below the resonance, indicating that the effect of any parasitic reactance is negligible at frequencies below about 900 MHz. Above the resonance frequency, the response falls off by 12 dB per octave, in good agreement with the model. The highest frequency at which we detected the signal was 4.5 GHz, limited by the sensitivity of our measurement system. Given that s-SWNTs detected microwaves up to 23GHz and 50GHz, respectively [7]-[9] it is reasonable to assume that the detection effect we report here for m-SWNTs will extend to similarly high frequencies, once parasitic effects have been minimized.

At 77 K, the detected DC current change (ΔI) depends linearly on the microwave power (a "square law detector") up to a power of about 0.02 mW; the detected current change then decreases smoothly after passing a maximum at about 1 mW, see Figure 5. The linear current responsivity at low MW powers was found to be $S_I = \Delta I/P_{MW} = 455$ μA/W, based on the measured output power at the microwave source (P_{MW}). The bias voltage dependence at 4K also follows that of d^2I/dV^2 as shown in Figure 3(b). As the microwave power was increased from that used in Figure 3(b), the detector response increased in a series of discontinuous steps, that occurred at a reproducible set of MW power levels. Further investigation of the device behavior at 4K is required to clarify these phenomena, and will be covered in a future paper.



(a) (b)

Figure 3. Detected DC current change (ΔI; points connected with line segments) due to microwave signal at 900 MHz, compared with d^2I/dV^2 (fulldrawn), at (a) input power -20dBm, T=77K; (b) input power -30dBm, T=4K.

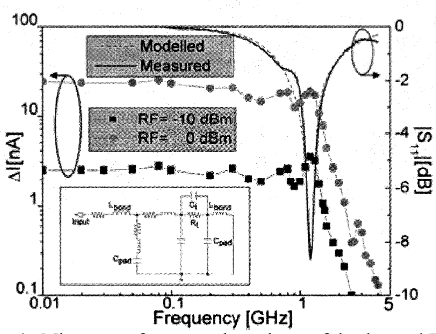


Figure 4. Microwave frequency dependence of the detected DC current change (at two power levels; left scale) and the magnitude of the reflection coefficient S11 (right scale; dB units), compared with the data predicted from the circuit model. Inset: Circuit model.

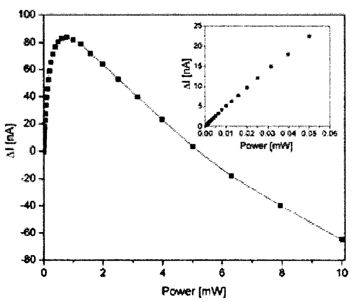


Figure 5. The DC current change (ΔI) at negative peak of Figure 3(a), as a function of microwave power. Temperature: 77K. Inset: expanded view of the part of this figure corresponding to the lowest power range.

The current responsivity can be converted to a voltage responsivity (S_V) by multiplying with the device resistance, 250 kΩ, yielding S_V = 114 V/W at 77K. At 4K the measured voltage responsivity was 9,000 V/W at low MW power levels. Higher resistance CNTs have lower values for S_I, roughly in inverse proportion to the resistance, and therefore have about the same S_V. Using standard small-signal microwave detector theory [20] we can calculate the current responsivity from the following expression:

$$\Delta I = (1/4)*(d^2I/dV^2)*V_{MW}^2 \qquad (1)$$

Here, V_{MW} is the peak microwave voltage. The factor d^2I/dV^2 was calculated from the measured IV-curve, and is compared with ΔI in Figure 3 (a) and (b). The small oscillations in the plot of d^2I/dV^2 are an artifact of the measurement method caused by the finite steps produced by the voltage source. The linear dependence of ΔI on MW power in the small-signal regime, as shown in the inset of Figure 4, indicates that Eq. (1) applies. Further, the bias voltage dependence of ΔI at 77K agrees well with that of d^2I/dV^2 (Figure 3). For a microwave power of 10 μW we use Eq. (1) to estimate ΔI in the range 5nA to 20nA, depending on the detailed assumptions made about the values of the equivalent circuit elements in Figure 4. The measured value is 5nA, and this quantitative agreement within expected error bars gives further strong support to the interpretation that the detector operates as a standard microwave detector with a response that can be predicted from its IV-curve. For higher microwave powers, the small signal approximation becomes invalid, and the response becomes nonlinear, as is clear from Figure 5. We note that since the transport in the m-SWNT is ballistic, the entire nonlinearity of the detector is due to the contact resistance.

We next demonstrated *heterodyne* detection in the same SWNT by connecting it to two microwave sources with different microwave frequencies f_1 (designated as the "Local oscillator, LO") and f_2 ("RF or signal frequency"), while measuring the output power (or voltage) at the difference frequency (IF), (| f_1-f_2 |). The IF power seen on a spectrum analyzer (inset in Figure 6) was essentially independent of the IF frequency up to 200 MHz. Detecting a higher IF was not possible due to the properties of the bias tees used. The detected IF voltage response versus DC bias voltage at 77K and 4K, respectively, is shown in Figure 6.

For the data plotted in Figure 6 we used a more sensitive method of detecting the IF on a lock-in amplifier. The reference voltage for the lock-in amplifier was created by employing a separate commercial microwave mixer to mix f_1 and f_2, see e.g. Sazonova et al. [20]. Typical frequency combinations used were f_1 and f_2 near 1 GHz, with an IF of 50 kHz. Again, parasitic circuit elements on the chip decreased the mixer efficiency for f_1 and f_2 above 1 GHz. As for the direct detection case, the response follows d^2I/dV^2 when the bias voltage is varied. This indicates that the heterodyne detection mechanism is attributable to the IV-curve using standard mixer theory.

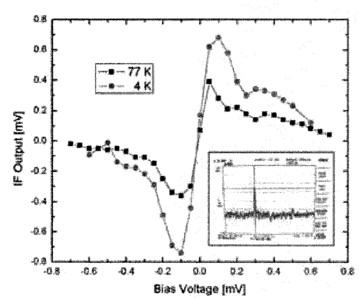


Figure 6. IF output voltage of the detector at 77K (black) and 4K (red) in the heterodyne mode.

We estimate a total mixer conversion loss at 77K to a 50Ω IF amplifier of 95dB, much of which is due to the high mismatch loss (60 dB total) to a device with 250 kΩ resistance. Lower resistance SWNTs [16],[18] would show lower mismatch loss as mixers. Note, however, that the higher resistance SWNTs show very good performance as *direct* detectors.

III. DISCUSSION

We now want to further discuss some of the implications of our experimental data. We have shown that sensitive detection of microwaves is possible in an m-SWNT. The detector response follows standard microwave detector theory, based on the zero-bias anomaly (ZBA) nonlinearity in the IV-curve. The origin of the ZBA has been much discussed, and this discussion is still ongoing. Especially interesting is to understand how the character of the electron transport changes as the temperature and the bias voltage are changed. The Luttinger liquid (LL) theory has been invoked to explain the ZBA, with the main experimental evidence for this theory being provided by the power-law dependence of the conductance on eV/kT [19]. Further microwave detector studies would be useful for exploring this problem. The fact that the microwave detection response is well predicted by the DC IV-curve indicates that whatever effect that causes the ZBA, it operates at speeds up to at least 4.5 GHz. This frequency limit is presently set only by the parasitics of the circuit, not the SWNT. It would be of great interest to extend the studies of coupling high frequency fields to SWNTs from the gigahertz range to the terahertz range in order to explore the intrinsic speed of the SWNT. Resonances in the LL are predicted to occur at frequencies in the terahertz range for the length of SWNTs studied here [23], but the losses under these conditions are not well known. Another paper at this conference [24] reports measurements up to 50 GHz of a frequency-dependent loss in non-contacted SWNTs, so this issue needs further exploration. The contact resistance is also predicted to be shunted by the contact capacitance at these high frequencies. We propose that terahertz detection may occur based on three different potential mechanisms:

1) Electrons tunnel into the LL plasmon medium ($Z_0 \sim 10$ kΩ [23]) which is heated and changes its resistance creating an HEB type effect. This mechanism requires operation in the lower temperature range (up to 10-20 K). The nonlinearity would now be located in the SWNT itself, not in the contacts as in the experiments described above. Tuning the frequency should provide a means of directly probing the LL medium, which has so far been mainly studied by more indirect methods.

2) Tunneling is fast enough that the electron current follows the THz frequency voltage similar to what happens in the 1 GHz device we have demonstrated; detection would then occur due to the nonlinear contact resistance. The maximum frequency for operation in this mode would be determined by the RC time-constant. The relevant capacitance values are very low, so operation up to THz frequencies should be feasible for SWNTs in the lower resistance range (e.g. parallel CNTs; see the discussion of the parallel case of Schottky diodes [7]).

3) Lower resistance SWNTs show nonlinear IV-curves at higher voltages (above 0.2 V) due to the onset of optical phonon emission [16],[18]. These should allow operation in the HEB mode, as proposed earlier [10],[11].

In conclusion, it appears very promising to extend the present study toward exploration of potential terahertz detectors based on m-SWNTs. Both direct and heterodyne detectors may be considered. The impedance matching may be easier at terahertz frequencies where the contact resistance is partly shunted by the contact capacitance.

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