Microwave and Terahertz Detection in Bundles of Single-Wall Carbon Nanotubes

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***Abstract*—We present new data on microwave detection in bundles of carbon nanotubes (CNTs). In particular, we derive a circuit model based on ANA measurements. We also demonstrate the first terahertz detection (up to 2.54 THz) in bundles of CNTs that were deposited through dielectrophoresis across the smallest gap in log-periodic antennas. Data are given that support the hypothesis that the detection process is bolometric at THz frequencies. Future extensions are planned that will employ suspended CNTs and explore heterodyne detection. Finally, we have performed unique ab initio simulations of CNTs with the aim of comparing these with the experimental data.**

I. INTRODUCTION AND BACKGROUND

We have earlier reported the experimental detection of microwaves [1] and of terahertz radiation [2] in single wall carbon nanotubes (SWNTs). In this paper we give further results on both microwave and terahertz detection in bundles of such tubes and relate these to models for the detection processes. One can infer from our results and that of others that there is no intrinsic frequency limitation of the SWNTs as high frequency detectors, up to 50 GHz. It is therefore of interest to explore if SWNTs can also detect frequencies up to the terahertz range. Terahertz detection in SWNTs can potentially lead to very wide band heterodyne detectors that may be useful in future terahertz imaging applications.

II. RESULTS

For the present work we have fabricated bundles containing m-SWNT devices by the Dielectrophoresis (DEP) method. The SWNTs were placed across the smallest gap in the lithographically fabricated structures shown in Figure 1.

Figure 1. Microwave CPW (left) and terahertz LPA (right) structures for coupling to the CNTs.

We first performed microwave probe measurements on CNTs contacted to CPWs (Figure 1, left) on sapphire or silicon on sapphire substrates. We obtained larger direct detector responsivities at 300 K (up to about 1,000 V/W) compared with our previous work [1] and also measured a detector response that was essentially independent of frequency up to 20 GHz, the highest frequency of our source, see Figure 2.

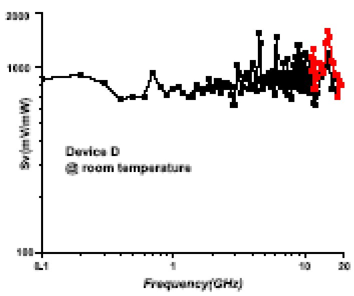

Figure 2. Microwave responsivity versus frequency for one of the SWNT devices.

We also measured the S-parameter S11 of the same devices with a microwave Automatic Network Analyzer. We fit the S11 data to a model in which we assume that there were effectively 50 parallel metallic SWNTs (m-SWNTs) across the CPW gap. Each m-SWNT tube is assumed to be modeled by the equivalent circuit introduced and analyzed by P. Burke [3] and good fits to the measured S11 data were obtained up to 26 GHz for most of the devices when we added capacitances parallel to each contact resistance. As in [1] we find that the detection can be predicted from the IV-curves similar to a standard microwave diode. Another result was that the contact capacitance was found to be in the range 4 fF to 40 fF.

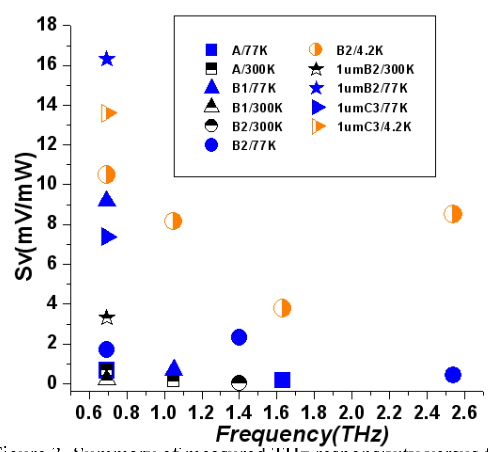

Figure 3. Summary of measured THz responsivity versus frequency.

We also performed terahertz measurements on devices coupled to log-periodic antennas (LPAs) (Figure 1, right). Two

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different LPAs were used, with gaps of about 8 µm ('LPA1') and 1 µm ('LPA2'), respectively. The CNTs were quasi-optically coupled through a silicon lens, and the terahertz source was a gas laser. We obtained experimental detections of terahertz radiation at five frequencies from 0.69 THz to 2.54 THz with measured voltage responsivities shown in Figure 3.

The variation of the responsivity with bias voltage is consistent with a bolometric detection process in the m-SWNTs, and not the diode type process we see at microwaves. In order to explore this, we measured IV-curves at a number of temperatures and from these derived the factor b = (1/R)*dR/dT in the standard equation for a bolometer:

$$S_V = \Delta V/P_{THz} = \frac{I_0 * R * b}{[G_{th} + i\omega C_h]}(V/W) \qquad (1)$$

Here, G_{th} is the heat conductance from the bolometer to the heat sink, and C_h is the total heat capacity of the bolometer. We fit the measured responsivity data to Eq. (1) while allowing G_{th} to vary until we found the optimum fit. Good fits were obtained for all cases tested, and Figure 4 shows two examples of these. This figure also shows that the diode model is unable to produce a good fit. We note that Itkis et al. [4] also obtained a good fit to a bolometer model for a near IR detector. That detector utilized CNT films, however, with much larger area, and a thickness of 80 nm. It thus had a much larger heat capacity, and consequently much longer thermal time constant. Crucially, the films were suspended above the substrate.

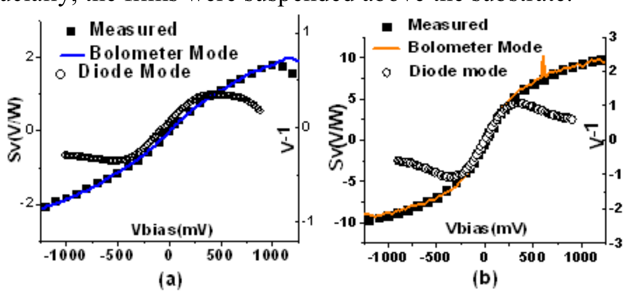

Figure 4. Best fits of Eq. (1) ('bolometer model') to the measured curves of S_V versus bias voltage. We also show predictions based on the diode model [1].. (a) a laser frequency of 1.395 THz at 77 K and (b) a laser frequency of 0.694 THz at 4.2 K;

The devices show promise for operation well above 4.2 K. The maximum responsivity at present is about 17 V/W (not correcting for about 3-4 dB optical losses) but reference to [4] indicates how this may be increased by perhaps two orders of magnitude in the future by suspending the SWNTs across the antenna gap without touching the substrate. Based on the microwave measurements, we believe that the large contact resistance is almost completely bypassed by the contact capacitance at THz. This fact, and the use of parallel tubes placed by the DEP substantially improves the matching of the SWNTs to the 100 Ω antenna impedance. Devices coupled to the log-periodic antenna with the 1 µm gap (LPA2) show larger responsivities at a given temperature, as shown in Figure 3. This is also expected from the bolometer model. The decrease of the responsivity with temperature is quite slow up to about 50 K, and S_V is down by a factor of two at about 25 K. Thus there is good promise for operation well above 4.2 K.

In order to obtain the different component characteristics presented in the equivalent circuit model, we aim to go beyond the current state-of-art capabilities for simulating CNTs by developing large-scale *ab-initio* atomistic approaches. Our proposed atomistic Density Functional Theory (DFT) and Kohn-Sham equation approach has the potential to clear up our understanding of many experimental issues, and to offer the high degree of reliability and accuracy needed to characterize the following macroscopic quantities: kinetic inductance, contact resistance and contact capacitance, quantum capacitance and CNT resistance. To give a perspective of the computational time required by our proposed atomistic-based simulation, only a few minutes of CPU time are needed to obtain electronic properties (electron density, potential, etc.) of long nanotubes which is orders of magnitude faster than any other existing *ab-initio* techniques. An example of the results obtained so far is shown in Figure 5.

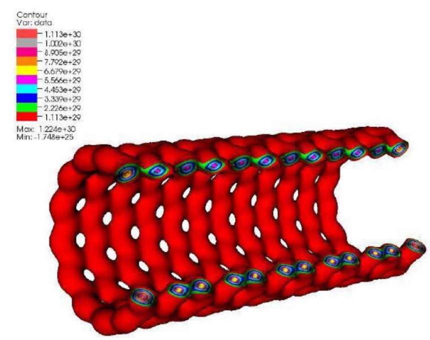

Figure 5. Electron density in CNT calculated using real-space pseudopotentials.

Future work on the new THz detector will concentrate on improved fabrication and simulation methods for m-SWNT devices, optimizing the device coupling, and demonstration of heterodyne detection.

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