

Asymmetric devices based on carbon nanotubes as detectors of sub-THz radiation

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Abstract. Demand for efficient terahertz (THz) radiation detectors resulted in intensive study of the asymmetric carbon nanostructures as a possible solution for that problem. In this work, we systematically investigate the response of asymmetric carbon nanodevices to sub-terahertz radiation using different sensing elements: from dense carbon nanotube (CNT) network to individual CNT. We conclude that the detectors based on individual CNTs both semiconducting and quasi-metallic demonstrate much stronger response in sub-THz region than detectors based on disordered CNT networks at room temperature. We also demonstrate the possibility of using asymmetric detectors based on CNT for imaging in the THz range at room temperature. Further optimization of the device configuration may result in appearance of novel terahertz radiation detectors.

1. Introduction

Terahertz (THz) radiation is used in applications ranging from security to medicine. However, sensitive room-temperature detection of terahertz radiation is notoriously difficult. The use of nano-scale objects is a promising route for obtaining cost-effective solutions for new THz detectors. One particular route is the use of carbon nanomaterials: single-wall carbon nanotubes (SWCNTs) and graphene and it already brought very encouraging results even at room temperature [1-7].

This work is a continuation of the author's investigation of the response of asymmetric devices based on CNTs to THz radiation [6-7]. It was previously shown that under certain conditions such devices demonstrate strong response to terahertz radiation even at room temperature. Analysis of the experimental data shows that the response contains two components. The first is the thermal reflecting different increase in temperature in the areas of the nanotube/metal interfaces. The second is the response due to the non-linearity of the current-voltage characteristic of the device at zero bias. Here, we systematically investigate the response of asymmetric carbon nanodevices to sub-THz radiation using different sensing element in order to determine the optimal morphology of it.

2. Experimental

The schematic device configuration is illustrated in Figure 1 (a). Our devices are made in a configuration of a field-effect transistor. The conduction channel between source and drain electrodes is formed by CNT networks of different density: disordered CNT networks, consisting of a mixture of



the single-wall semiconducting CNTs (sm-CNTs) and quasi-metallic CNTs (qm-CNTs) of the p-type (Figure 1 (c)) or individual CNTs (Figure 1 (b)) both semiconducting and quasi-metallic. The carbon nanotubes are grown by a CVD method on Si/SiO₂ substrates using methane as a carbon feedstock. Room temperature resistivity of the silicon substrate is 10 Ω·cm and is high enough to use it as a backgate. The devices are coupled to the radiation with a logarithmic spiral antenna which also serves for DC contacts. The devices are fabricated in such way that the contact material is different for source and drain electrodes: vanadium and gold (Figure 1 (a)).

The experimental set-up is shown on Figure 1 (d). The sub-THz radiation was provided by a multiplier chain based on Schottky diodes allowing to measure spectral characteristics in the region from 140 GHz to 220 GHz. The DC voltage signal appearing at the asymmetric structures under the radiation was measured using lock-in amplifier. In all measurements gold electrode was grounded. The gate voltage between the silicon substrate and the electrode was supplied by the source - meter Keithley 2600.

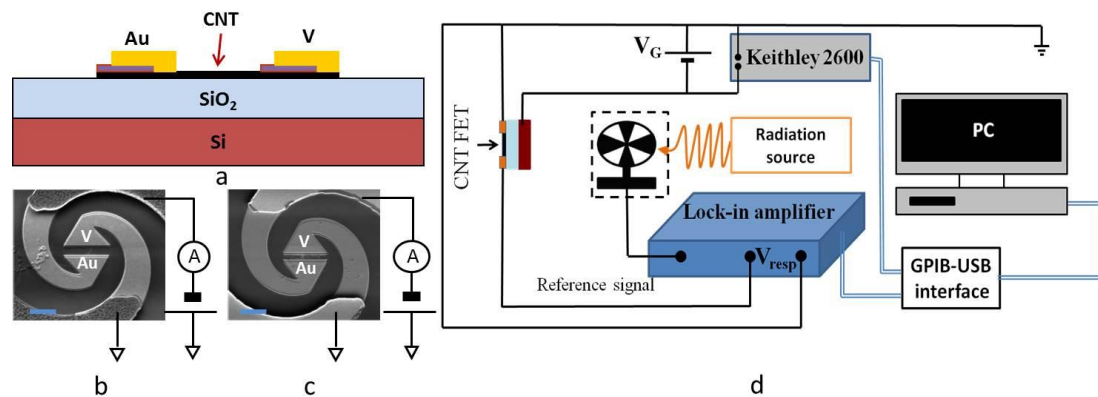


Figure 1. (a): Device configuration: schematic representation of the sensing element of the device illustrating the current path between gold and vanadium electrodes; (b-c): SEM images of the devices based on individual CNT (b) and disordered CNT networks (c). Scale bars are 5 μm; (d): the schematic representation of the experimental setup

3. Results and discussion

The transfer characteristics of our devices are shown on figure 2. As seen on Figure 2 (a), in the case of semiconductor CNT conductivity of the device is suppressed when gate voltage is positive. This is because that the Fermi level is in the band gap. When we apply negative voltage on the gate the Fermi level moves in the valence band and the conductivity of the device increases. Note that the conductivity of quasi-metallic CNTs is almost insensitive to the gate voltage (Figure 2 (b)). The asymmetry of the transistor characteristics is due to the fact that we use the different metals for source and drain electrodes. In the case of disordered CNT network ON/OFF ratio is about 2.4:1 (Figure 2 (c)), which corresponds to the ratio of average number of semiconductor nanotubes in the array to the amount of metal [8].

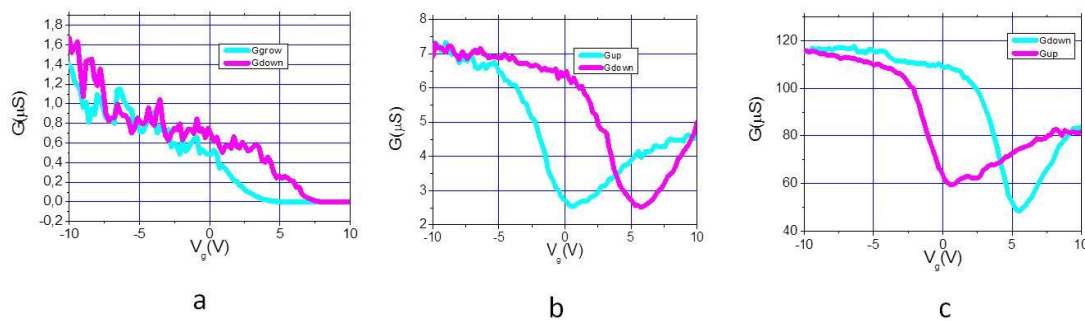


Figure 2. The transfer characteristics of the devices based on individual sm-CNT (a), individual qm-CNT (b) , mixed CNT network (c)

As it was shown in our previous works the asymmetry incorporated into our devices should result in DC voltage response to incident radiation at room temperature [6-7]. There are two effects that in turn may lead to observed DC voltage response to incident radiation at room temperature. One is related to the nonlinearity of the IV curve – so called diode type response. Second, the thermal effect is related to the temperature gradient building up across the devices under the action of the radiation and resulting thermal electromotive force [7]. In order to illustrate the contribution of this effect into the response we measured the gate voltage dependence of the response voltage in case of disordered CNT film (see Figure 3). We compare the observed signal with the gate voltage dependence of the Seebeck coefficient calculated using the Mott formula [9]:

$$S \equiv \frac{\Delta V}{\Delta T} = - \frac{\pi^2 k_B^2 T}{3 |e|} \frac{1}{G} \frac{dG}{dE} \bigg|_{E_F} = - \frac{\pi^2 k_B^2 T}{3 |e|} \frac{1}{G} \frac{dG}{dV_G} \frac{dV_G}{dE} \bigg|_{E_F} \quad (1)$$

where k_B is the Boltzmann constant and e is the electron charge. We use the measured $G(V_G)$ curves to calculate the $S(V_G)$ dependence using the formula (1).

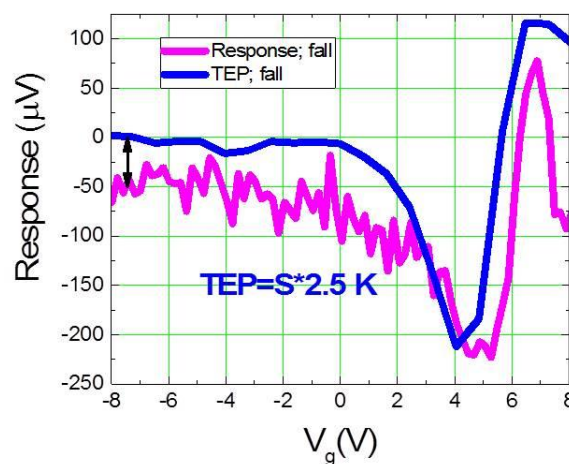


Figure 3. Room temperature response of device based on disordered CNT network as a function of gate voltage (magenta) compared to the TEP (blue) calculated using Eq. (1).

The most important feature of the calculated $S(VG)$ dependence is that it tends to zero as the gate voltage goes to more negative values. Same should apply to the thermoelectric power (TEP) across the device. At the same time the measured response is not going to zero at negative gate voltages. This additional component of response (so called diode response [7]) should be almost the same at negative gate voltage for a given type of sensing element. This operating mode of the detector is the most promising from a practical point of view. In particular, the operation of the detectors at the same gate voltage is necessary to unite them in a matrix to create imaging systems. In this regard, we compared the response of our devices at negative gate voltage.

Figure 4 shows the spectral response of our devices to sub-THz radiation in the region from 140 GHz to 220 GHz. As we can see the detectors based on individual CNTs both semiconducting and quasi-metallic demonstrate much stronger response in sub-THz region than detectors based on disordered CNT networks. The weaker response of the network is most probably to extra scattering in the channel introduced by the CNT crossing points. At the same the shape of spectrum does not depend on sensitive element and is determined by characteristics of antenna. The explanation of this dependence is beyond the scope of this work and is the subject of further study. The response time of the devices is determined by device resistance and geometric capacitance between the electrodes and the gate [6], indicating that the detectors based on CNT networks should be faster due to the higher conductivity. The presence of a large number of CNTs in the conduction channel should lead to a more stable operation of the detector.

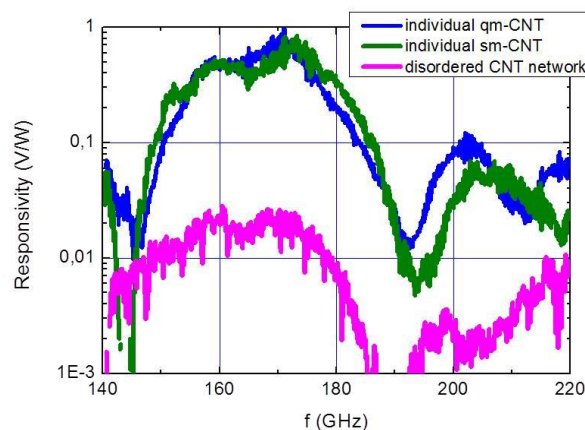


Figure 4. The spectral response of the devices with different numbers of CNTs in the channel at negative gate voltage

In order to demonstrate prospects of the use of the asymmetric carbon nanostructures as room temperature THz detectors we make a THz image of object hidden in carton box (Figure 5). The visualized object is placed inside carton box and fixed on the motorized translation stage allowing to move automatically in horizontal and vertical direction. The radiation source and the detector are fixedly mounted, so that the radiation is focused on the detector by a lens system. The carton box with the object inside it moves so that the entire surface of the box is scanned by radiation. Figure 5 (c) shows the resulting THz image of the hidden object.

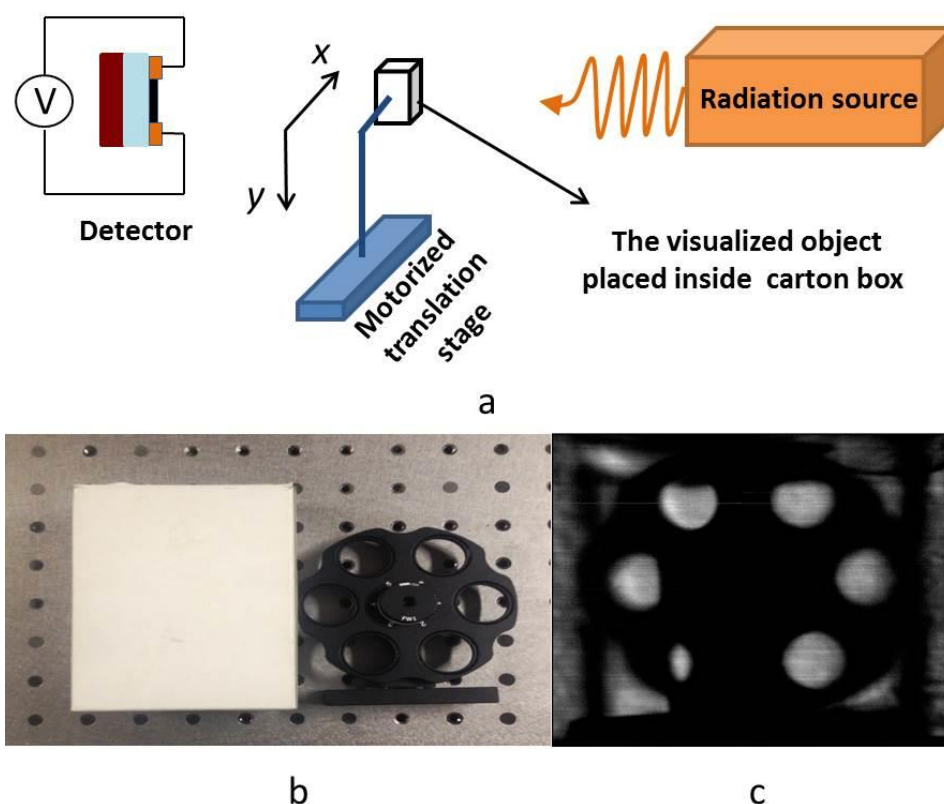


Figure 5. The schematic representation of the experimental setup for THz imaging (a). Optical (b) and THz (c) image of the rotator placed inside carton box

4. Conclusion

We conclude that the detectors based on individual CNTs both semiconducting and quasi-metallic demonstrate much stronger response in sub-THz region than detectors based on disordered CNT networks at room temperature. We also demonstrate the possibility of using asymmetric detectors based on CNT for imaging in the THz range at room temperature. Further improvement of the network morphology, e.g. aligning the CNTs along the same direction will make it possible to make a detector that is as sensitive as one based on an individual CNT, but with better stability.

Acknowledgments

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