Carbon nanotube based terahertz radiation detectors

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Abstract. In this paper, we study terahertz detectors based on single quasimetallic carbon nanotubes (CNT) with asymmetric contacts and different metal pairs. We demonstrate that, depending on the contact metallization of the device, various detection mechanisms are manifested.

1. Introduction

Individual single-walled nanotubes (SWNT) have unusual electronic and optical properties, which makes them a promising material for the development of optoelectronic devices in the terahertz region. In the last decade, the field of terahertz technologies has been actively developing, and recently several types of detectors based on individual tubes and network capable of operating effectively in the frequency range up to 2.5 THz were demonstrated both at room [1] and at helium temperatures [2]. One of the approaches is to use asymmetric metallization for observation of photovoltaic response [3]. The demonstrated detectors were fabricated as field-effect transistors (FET) with asymmetric metallization of contacts. In our earlier works we employed vanadium and gold as two metals with different work functions. As gold has a work function of 5.1 eV, which is larger than that of CNT (4.7 eV) and vanadium has work function (4.1 eV) smaller than that of CNT this configuration leads to formation of a p-n junction in the device channel due to contact doping. This p-n junction can work as a rectifying element leading to photovoltaic response to incident radiation [4]. At the same time different metals provide different contact resistance and different Joule heating is released at the contacts so that the temperature gradient is maintained through the channel resulting in a DC voltage signal due to thermoelectric effect.

In order to avoid the ambiguity in interpreting the results we fabricated devices similar to those reported previously but replaced vanadium with nickel that has almost the same work function as gold so no p-n junction is expected in the channel leaving thermoelectric effect as the only mechanism explaining the observed DC voltage signal as the device is exposed to the radiation.

2. Experimental

Single carbon nanotubes were grown by a CVD method using bimetallic suspension of Fe(NO₃)₃·9H₂O and MoO₂(acac)₂ with alumina (Al₂O₃) nanoparticles in isopropanol as a catalyst [5]. The growth of CNTs was carried out on boron doped silicon substrates coated with 500 nm thermally grown SiO₂. The doping level of the substrate at the same time is such that the silicon substrate remains transparent to radiation in a given frequency range. After the growth of the CNTs, the substrate is investigated using SEM. Subsequently, metal electrodes are formed to chosen CNTs using e-beam evaporation and lift-off. 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 (Fig. 1a, b) [3]. For this study we fabricated two sets of samples. In both sets, we used 80 nm gold on the side of the drain. And for the source we used vanadium 40 nm thick in one set and nickel (also 40 nm) in the other. Length of the nanotube between the electrodes is about 1 micron.

![Device configurations](image)

**Figure 1.** Device configurations a) Schematics view of a CNT contacted b) SEM image of a typical device

The measurement setup we are using here is similar to that described in detail in [6, 7]. Our devices are coupled to the radiation with a logarithmic spiral antenna. A choice of the antenna was determined by simplicity of its fabrication and its wideband characteristics for terahertz frequency range. THz range stands for the region of 0.1 - 3 THz. A device chip with dimensions 4x4 mm$^2$ was fixed on a flat surface of a silicon lens, placed inside the cryostat, equipped with high density polyethylene window. A Zytex-106 cold infrared filter was mounted on the radiation shield to cut off the 300 K background.

The sensing element of the device, the individual CNT inside the antenna, is located in the focus of the lens, enabling good coupling to the incident electromagnetic radiation. The power incident on the cryostat window is measured by a Golay cell. The terahertz radiation is provided by backward wave oscillators (BWO) with frequency ranges of 120 – 140 GHz, 250 – 450 GHz and 630 – 660 GHz.

![Transfer characteristics](image)

**Figure 2.** Transfer characteristics of device with V/Au (a) and Ni/Au (b). Insert Band diagrams of the corresponding devices.
For this work we selected similar devices for both types based on so called quasi-metallic CNT (qm-CNTs) [4], that have a curvature-induced band gap in a few meV range. Such devices have a small dip on the conductance vs gate voltage dependence (see Figure 2). Since we use metals with different work functions, the Fermi levels at the interface Au/CNT and Ni/CNT will be shifted to the valence band. In this case, the Fermi levels at the V/CNT interface will be shifted to the conduction band. The band diagrams shown on the inserts of Figure 2a and 2b. Graphs of conductivity versus gate voltage confirm the formation of a barrier at the vanadium – CNT interface [8, 9].

After selecting suitable devices, we characterized their response to radiation of different frequencies at room temperature (Fig. 3). The maximum radiation power reaching the lens was set to 50 µW for all frequencies. Response of both types of devices to radiation room temperature is illustrated in the Figure 3.

**Figure 3.** Responsivity of device with V/Au (a) and Ni/Au (b) for 300K.

### 3. Result and discussion

To understand the mechanisms of the demonstrated detection, we cooled our samples to 77 K and measured them again gate voltage dependence of the response to the radiation with a frequency of 129 GHz with a power of 32 µV, while the sample is not displaced by the current. The Fig. 4a shows data for V/Au device, while the Fig. 4b shows the data for Ni/Au device. In both graphs the response is compared to calculated FET-factor defined as \( \frac{dG}{dV_g} / G \). It allows for verification of the assumption that for devices with Ni/Au contacts only the thermoelectric effect will manifest itself since the Seebeck coefficient is described by the formula

\[
S = -\frac{\pi^2 k_B^2 T}{3|e|} \frac{1}{G} \frac{dG}{dV_g} \frac{dV_g}{dE} \sim \frac{1}{G} \frac{dG}{dV_g} \quad (1)
\]

The calculated FET-factor defined as \( F = \frac{dG}{dV_g} / G \) is shown in Figure 4 in red. Comparing the measured signal with the calculated FET factor values, we obtained a good agreement in case of the samples with Ni / Au contacts. On our view this is an evidence of the thermoelectric origin of the photoresponse of this type of devices. The deviation of the curves manifested for samples with V/Au can be explained by the presence of an additional response mechanism.
An additional mechanism for samples with V / Au is related to the nonlinearity of the I-V curves (the so-called diode mechanism). The reason for its occurrence is the p-n junction formed on the V/CNT interface due to the difference in the work function. The diode response is calculated by the formula

\[ S_V = -\frac{R}{4} \frac{d^2 I}{d^2 V} Z_A \]  

where \( Z_A \) is the antenna impedance equal to 100 Ohms, \( R \) is the resistance of the sample. The experimental values usually exceed the calculated ones, but the approximation describes well the obtained values of the volt-watt sensitivity [9].

The study of samples with nickel contacts in the temperature range from 300 to 4K, showed that during cooling the bolometric response mechanism contributes significantly [10].

4. Conclusion

The sensitivity for samples with different pairs of contacts is comparable in magnitude. Despite the fact that we are observing different detection mechanisms, both types of devices can be successfully applied.

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Figure 4. Responsivity of device with V/Au (a) and Ni/Au (b) for 77K.
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