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IOP Conf. Series: Journal of Physics: Conf. Series **1092** (2018) 012039 doi:10.1088/1742-6596/1092/1/012039

Towards to the development of THz detectors based on carbon nanostructures

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Abstract. Demand for efficient terahertz radiation detectors resulted in intensive study of the carbon nanostructures as possible solution for that problem. In this work we investigate the response to sub-terahertz radiation of detectors with sensor elements based on CVD graphene as well as its derivatives – carbon nanotubes (CNTs). The devices are made in configuration of field effect transistors (FET) with asymmetric source and drain (vanadium and gold) contacts and operate as lateral Schottky diodes. We show that at 300K semiconducting CNTs show better performance up to 300GHz with responsivity up to 100V/W, while quasi-metallic CNTs are shown to operate up to 2.5THz. At 300 K graphene detector exhibit the room-temperature responsivity from R = 15 V/W at f= 129 GHz to R = 3 V/W at f = 450 GHz. We find that at low temperatures (77K) the graphene lateral Schottky diodes responsivity rises with the increasing frequency of the incident sub-THz radiation. We interpret this result as a manifestation of a plasmonic effect in the devices with the relatively long plasmonic wavelengths. The obtained data allows for determination of the most promising directions of development of the technology of nanocarbon structures for the detection of THz radiation.

1. Introduction

Increase in the sensitivity of the THz radiation detectors range can be achieved by reducing the size of the sensor element. Graphene is an almost ideal material for creating nanoscale structures for this purpose. One of the major advantages of graphene is its high carrier mobility and the associated large coherence length, so that the band structure is determined by the size quantization and can be controlled via the geometry of the structure [1].

Several successful configurations of detectors of THz radiation on the basis of graphene and nanotubes have been proposed recently [2-5]. Further improvement of this type of device is not possible without better understanding of the mechanisms that determine the magnitude of the response to radiation.

In this paper we present the results of our systematic studies of different configurations of detectors with sensor elements based on graphene as well as its derivatives – carbon nanotubes (CNTs) and graphene nanotubes (GNRs). The asymmetry means that different metals are used to contact the channel.

Detection of the radiation takes place through the rectification: due to asymmetry of the IV curve mean current under harmonically changing voltage is not zero. In case of a CNT rectification takes place due to transport through a Schottky barrier at V contact directly related to the nanotube's bandgap. In case of graphene the situation is more complicated. Transport of carriers through the p-n junction depends on the angle between the normal to the junction and the carrier momentum. For normally incident electrons there is no energy barrier and they shunt the nonlinear transport. At the same time current of the non-normally incident electrons is non-linear function of the applied voltage. This scenario is evidenced by the temperature dependence of the response of our structures to the radiation.

At room temperature our results show that semiconducting CNT (s-CNT) devices are preferable for frequencies up to 300GHz (cut off about 500 GHz), while quasi-metallic -CNT devices can be used as broad band detectors operating at frequencies up to at least 2.5 THz. At 300 K graphene detector exhibit the room-temperature responsivity from R = 15 V/W at f= 129 GHz to R = 3 V/W at f = 450 GHz.

At low temperatures (77K) we fan that graphene lateral Schottky diodes responsivity rises with the increasing frequency of the incident sub-THz radiation. We interpret this result as a manifestation of a plasmonic effect in the devices with the relatively long plasmonic wavelengths.

2. Experimental

For our experiments we fabricated asymmetric structures in configuration of field effect transistors (FET) with channel based on graphene or CNTs. The structures consist of a single layer graphene (SLG) or individual CNT on the SiO_2 substrate with moderately conducting silicon bottom layer (room temperature resistivity of 10 Ω·cm). The latter plays the role of the back gate. The source and drain contacts were made from different metals (vanadium and gold) and connected to the logarithmic spiral electrodes serving as an antenna coupling the incident radiation to the device (Fig. 1). The single layer graphene and single walled carbon nanotubes (SWNTs) used in our experiments as a FET channel were synthesized by chemical vapor deposition (CVD) . Detailed description of device fabrication and configuration is presented in our previous works [4-5].

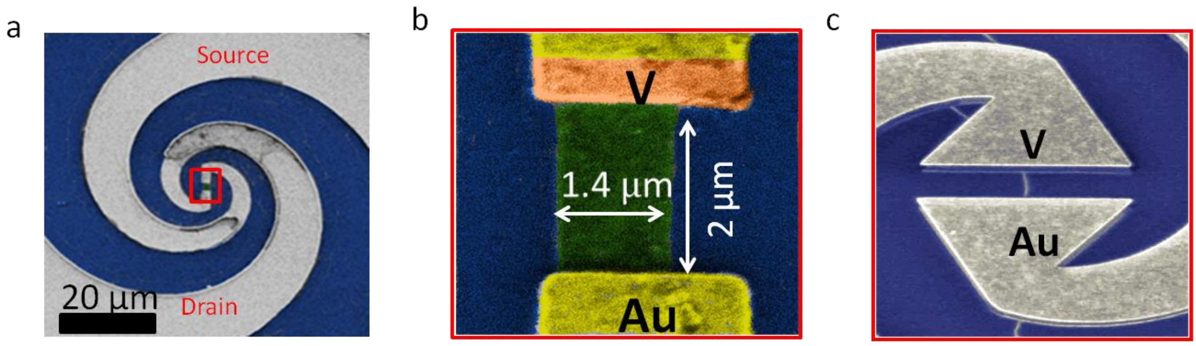

Figure 1. (a): Electron image of the device coupled to the radiation with a logarithmic spiral antenna. The red rectangle marks the transistor channel area; (b) Electron image of the device channel formed by graphene; (c): Electron image of the device channel formed by CNT

The terahertz radiation is provided by two backward wave oscillators (BWO) and laser. The power incident on the cryostat window is measured by a Golay cell. The first BWO is used as a source of radiation with a frequency of 129 GHz (Maximum power is 1mW). The second BWO is used for frequency range 265-450 GHz. Its maximum power was found to be about 400 µW. We also used a gas discharge laser operating on a 2.5 THz H_2O line. Its maximum output power is 200 µW.

First, we measured DC transport characteristics of our devices. Figure 2 (a-b) shows conductance of CNT devices as a function of gate voltage. The $G(V_G)$ curve shown on the Fig. 2(a) is typical for a semiconducting CNT (s-CNT). The transistor curve G(VG) on Fig. 2(b) is typical for a device with conductance channel formed with a quasi-metallic CNT (m-CNT)[4]. We note that the ON state conductance of m-CNT devices is much larger than that of s-CNT devices. This can be explained if we consider the Schottky barrier formed at the vanadium electrode that has the work function less than that of the CNT. The width of this barrier at the Fermi level is proportional to the nanotube's band gap. Thus the G(VG) curves confirm the existence of a Schottky barrier at the vanadium-CNT interface. In case of graphene (fig.2 (c)) device resistance in all cases goes up as the gate voltage is swept from -10 to10 V indicating p-doping of the graphene channel.

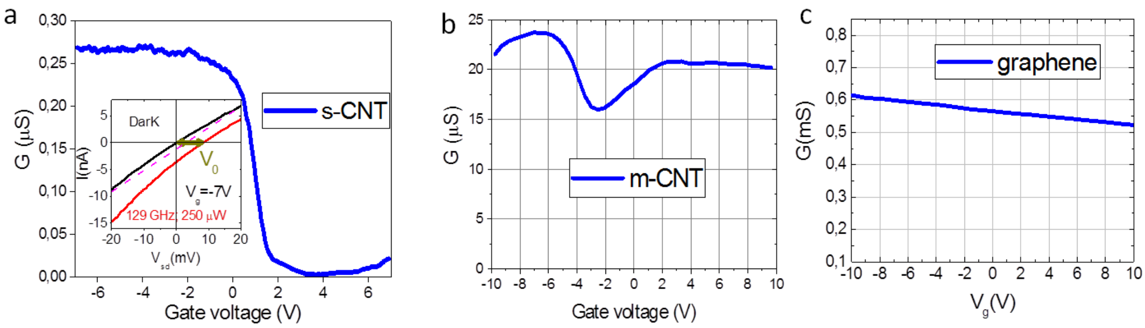

Figure 2. Transfer characteristics of semiconducting (a) , quasi-metallic (b) nanotubes and graphene (c) measured at room temperature

First, we characterize the room temperature response of our devices to radiation at the frequency of 129 GHz. For this we measured the devices IV curves with and without radiation. For all types of the devices under the radiation with a power P = 250 μW the IV curves shift to the right along the voltage axes, that clearly indicates the appearance of a DC voltage induced by the radiation equal to V_0, which we further refer to as response voltage V_{RESP}. The typical IV-curve of the s-CNT device measured at negative gate voltage with and without radiation is shown in the Figure 2.

Next, we measure the gate dependence of the response voltage $V_{RESP}(V_G)$ for all types of the devices. The results for CNT device are displayed in Fig. 3, with the responsivity defined as V_{RESP}/P, where P is a power incident on the device. Detection of the radiation takes place through combination of two mechanisms: photothermoelectric effect arises from nonuniform temperature distribution in FET channel rectification due Schottky barrier at V contact directly related to the nanotube's bandgap [4]. Figure 3 shows comparison of Seebeck coefficient (which is proportional to $G^{-1}*(dG/dV_G)$) and measured response. At negative and positive voltages measured signal isn't zero (opposite Seebeck coefficient), indicating additional contribution of diode response.

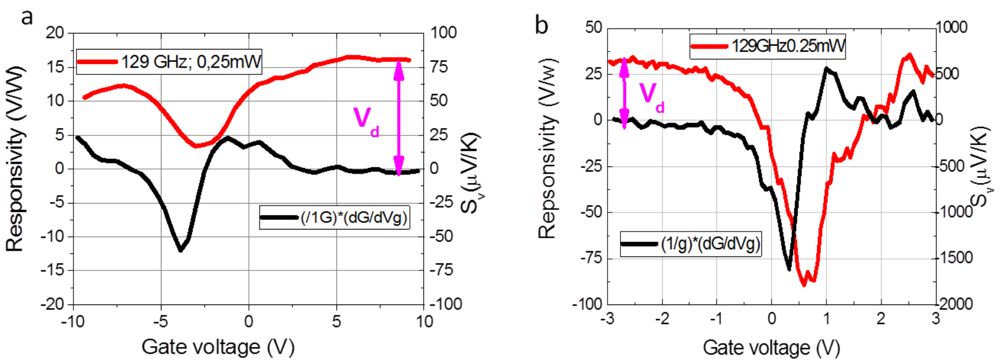

Figure 3. Seebeck coefficient and measured response as function of gate voltage for m-CNT (a) and s-CNT (b) devices.

Next measure CNT device response at different frequencies up to 2.5 THz. At room temperature our results show that semiconducting CNT (s-CNT) devices are preferable for frequencies up to 300GHz (cut off about 500 GHz), while quasi-metallic -CNT devices can be used as broad band detectors operating at frequencies up to at least 2.5 THz.

The results for graphene device are displayed in Fig. 4. As seen from the data, graphene device responsivity at 300 K and 77K is practically independent of the gate voltage. Figure 4(b) shows responsivity of graphene device at different frequencies. As seen from Fig. 4(b), at room temperature the responsivity decreases as the frequency is increased. While at 77 K the responsivity increases as the frequency increases within the range from 129 GHz to 450 GHz.

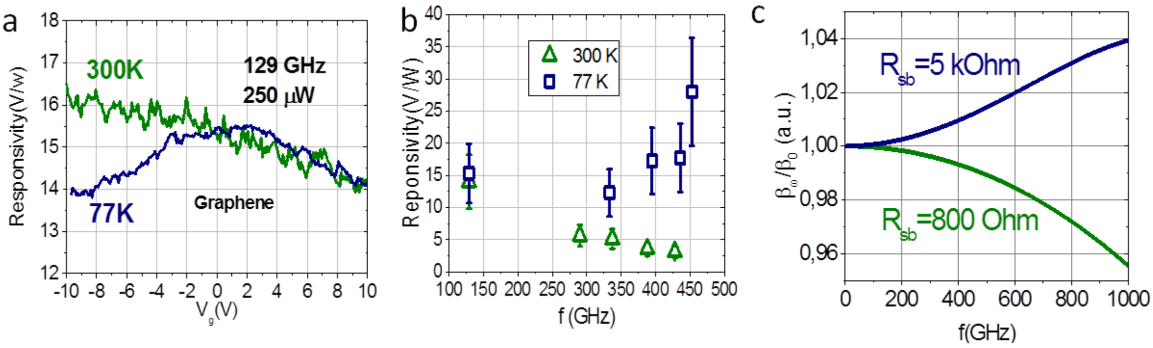

Figure 4. (a):Responsivity of graphene device as a function of gate voltage measured at 300K and 77K; (b): Responsivity of the graphene devices as a function of the radiation frequency measured at 300K and 77K; (c): Calculated frequency dependence of the rectified current normalized at its value at zero frequency [5].

The most important feature observed in our experiments is the qualitative change of the frequency dependence of the device responsivity upon a decrease of the temperature from 300 K to 77 K. To interpret obtained results we consider rectification on barrier formed on graphene/Vanadium interface for non-normally incident electrons and rake in account excitation of plasmons [5].

3. Summary

We show that at 300K semiconducting CNTs show better performance up to 300GHz with responsivity up to 100V/W, while quasi-metallic CNTs are shown to operate up to 2.5THz. At 300 K graphene detector exhibit the room-temperature responsivity from R = 15 V/W at f= 129 GHz to R = 3 V/W at f = 450 GHz. The minimum noise equivalent power, NEP, at 300K of our devices was nW/Hz$^{-0.5}$, which in order of magnitude corresponds to commercially available THz cameras [6].

We find that at low temperatures (77K) the graphene lateral Schottky diodes responsivity rises with the increasing frequency of the incident sub-THz radiation. We interpret this result as a manifestation of a plasmonic effect in the devices with the relatively long plasmonic wavelengths.

4. Acknowledgments

The research has been carried out with the support of the Russian Science Foundation (project No. 17-72-30036).

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