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Sub-terahertz radiation detection using graphene noise thermometry method

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Abstract. In this paper we investigate a novel approach to inventing graphene-based sub-terahertz bolometers using noise thermometry. Graphene is a unique material for detecting radiation in the sub-terahertz (0.1–1 THz) and terahertz (1–10 THz) ranges due to its record low electron heat capacity and weak electron-phonon coupling. This results in sufficient heating of graphene electron system under terahertz radiation. The main challenge in the realization of graphene terahertz detectors arises due to weak graphene resistance dependence on temperature. Here, we solve this problem by measuring noise spectral density in graphene devices using lock-in amplifier technique under radiation of 0.13 THz. The measured thermal noise is directly dependent on electron temperature and can be used as detector signal as well as probe of electron temperature under sub-terahertz radiation. The obtained experimental data can be used to optimize modern graphene terahertz detectors and develop new ones.

Keywords: graphene, THz detectors, bolometers, noise thermometry

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Детектирование суб-терагерцового излучения методом шумовой термометрии в графене

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Аннотация. В этой статье мы исследуем новый подход к созданию суб-терагерцовых болометров на основе графена с использованием шумовой термометрии. Графен

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является уникальным материалом для детектирования излучения в субтерагерцовом (0,1–1 ТГц) и терагерцовый (1–10 ТГц) диапазонах благодаря его рекордно низкой электронной теплоемкости и слабой электрон-фононной связи. Это приводит к достаточному нагреву электронной системы графена под действием терагерцового излучения. Основная проблема при реализации графеновых терагерцовых детекторов возникает из-за слабой зависимости сопротивления графена от температуры. Здесь мы решаем эту проблему путем измерения спектральной плотности шума в графеновых устройствах с использованием метода блокировки усилителя. Измеренный тепловой шум напрямую зависит от температуры электронов и может быть использован в качестве сигнала детектора, а также для измерения температуры электронов при суб-терагерцовом излучении. Полученные экспериментальные данные могут быть использованы для оптимизации современных графеновых терагерцовых детекторов и разработки новых.

Ключевые слова: графен, ТГц-детекторы, болометры, шумовая термометрия

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Introduction

Recently terahertz range (THz) of Electromagnetic (EM) spectrum has been of great interest due to a wide spectrum of potential applications: medical diagnostics, nondestructive testing, security systems, and data transmission [1]. These and many other applications require fast, sensitive THz detectors that can be easily integrated in arrays.

Graphene is a unique material for detecting radiation in the terahertz range [2]. Firstly, it has a gapless structure and absorbs electromagnetic radiation in a wide range of frequencies. Secondly, graphene has a record low electron heat capacity and weak electron-phonon coupling. This in turn leads to a strong heating of its electronic subsystem under the influence of incident electromagnetic radiation [3] presenting a unique platform for the development of sensitive bolometers based on graphene [4]. The main challenge in the realization of graphene terahertz detectors arises due to weak graphene resistance dependence on temperature [5]. To achieve strong response one can artificially increase weak temperature dependence of the graphene resistance by embedding defects, nanostructuring, or opening a band gap in bilayer graphene [4]. This, in turn, leads to a decrease in the operation speed of the detector.

Here we explore a novel approach to inventing graphene-based THz bolometers using noise thermometry [6]. The heating of electrons caused by the absorption of radiation of 0.13 THz frequency is detected by measuring noise spectral density in graphene devices using lock-in amplifier technique. The potential advantages of this approach include high sensitivity up to single photon detection at low temperatures [7], as well as the ability to easily multiplex detector signals, which allows the creation of detector arrays.

Device fabrication

Our detectors are three-electrode devices in which the graphene acts as a conduction channel and has a gate electrode to control the concentration of charge carriers in the device (Fig. 1, *a*). Note that the aim of this work is not to develop and optimize a new type of THz detector, but only to demonstrate the possibility of detecting sub-THz radiation using the noise thermometry method. Therefore, we chose the simplest device configuration for fabrication (inset to Fig. 1, *b*), in which the electrodes are in the form of strips and are not optimally matched to the incident radiation.

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Our detectors are fabricated as follows. At the first stage, metallic marks are formed by standard methods of photolithography and electron-beam sputtering. Then the graphene is synthesized by the Chemical vapor deposition (CVD) method and transferred to a silicon substrate [8]. This method of graphene synthesis by chemical vapor deposition is one of the most efficient and economical ways of graphene production. It allows to increase the area of the substrate, covered by the graphene, and make several experimental samples at once.

Next, contact electrodes are formed using electron lithography and electron-beam evaporation of V/Au film (3/100 nm). In a subsequent step we form the graphene channel with dimensions of 0.6·2 μm^2 using lithography and plasma etching in O_2. Finally, 100 nm dielectric film of Al_2O_3 and V/Au gate electrode are made by electron lithography and electron-beam evaporation. Optical micrograph of fabricated device is presented in Fig. 1, *b* inset.

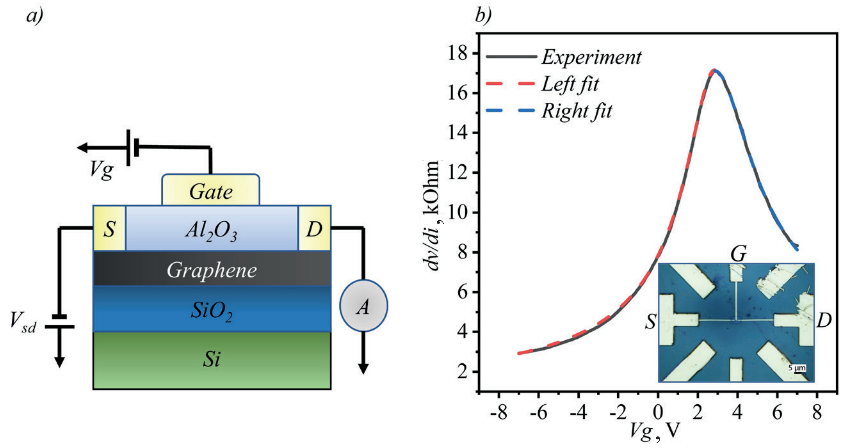

Fig. 1. Schematics of a top-gated graphene-based field effect transistor (*a*). Experimental measurements of two-terminal resistance as a function of *Vg*. Measured at T = 300 K (black curve) along with modeling results according to [8]. Red dashed line for p-side of graphene transistor, blue dashed line for n-side of graphene transistor. Inset: An optical micrograph of our device. Scale bar is 10 μm (*b*)

Experiment and discussion

After device fabrication the transport characteristics of graphene were measured. Fig. 1, *b* shows a two-terminal resistance *R* as a function of top gate voltage *Vg* measured at T = 300 K. At room temperature (RT) *R* exhibits a peak of 17 kOhm located around *Vg* = 2.5 V corresponding to the charge neutrality point (CNP) and falls with increasing *Vg*. The RT field effect mobility μ, extracted from the slope of *R*(*Vg*) dependence according to the method described in [9], of our graphene device was 1500 cm^{2}V^{-1}s^{-1} which is typical for graphene on $Si0_2$ substrate. According to the obtained data we can say that the devices are based on high quality CVD graphene.

Photoresponse measurements were performed in a variable temperature optical cryostat allowing the coupling of the device under study to electromagnetic radiation via a polyethylene window. The sub-THz radiation was generated backward wave oscillator with frequency of 129 GHz. Detailed description of the experimental technique is presented in reference [10]. Fig. 2, *a* shows the results of the RT measurements of photovoltage as a function of *Vg*. Dependence of photovoltage forms S-shape: finite photovoltage is observed at all experimentally accessible *V* except CNP where the sign of the photoresponse changes in agreement with ambipolar transport in graphene. This behavior of graphene THz photodetectors is well known and can be explained in terms of photothermal effect with a small contribution of overdamped plasma wave rectification [11]. To prove the thermal origin of the photovoltage, we measured noise spectral density of graphene device.

Noise spectral density of graphene was measured at room temperature in the region of white noise under two conditions: without radiation and under sub-THz radiation. We used a backward-wave oscillator with frequency of 129 GHz as sub-THz source. The measurements were performed using the standard built-in noise measurement functions of the Lock-in sr830 synchronous amplifier at 90 kHz. To prove the thermal origin of measured noise we calibrated lock-in amplifier, using resistors of known value. Fig. 2, *b* inset shows comparison of measured noise spectral density of the resistors with Johnson–Nyquist noise $(4KTR)^{0.5}$, where K is Boltzmann constant. We see good agreement between theory and experiment at low resistance values, so we measured graphene noise at minimum resistance at *V*g = -7V. The experiment revealed that the noise spectral density of graphene device increases markedly in the presence of sub-THz radiation. Since the Johnson-Nyquist noise dominates in graphene devices at zero bias conditions in the white noise region [12] we attributed this behavior to the changes in electron temperature of graphene under sub-THz radiation. At this stage our technique does not allow us to quantitatively estimate electron temperature in graphene under the influence of sub-THz radiation; however, even not in the optimal configuration, the magnitude of the signal allows us to hope that this method is suitable for estimating the electron temperature of graphene devices after additional calibration of the setup. To date, the best graphene THz photodetectors demonstrating commercially attractive characteristics, operate based on the photo-thermoelectric effect, which directly depends on the heating value of the electronic system [12]. The technique used in this work may further allow direct measurement of the electron temperature in graphene and help optimize the performance of graphene photodetectors operating on the electron heating effect.

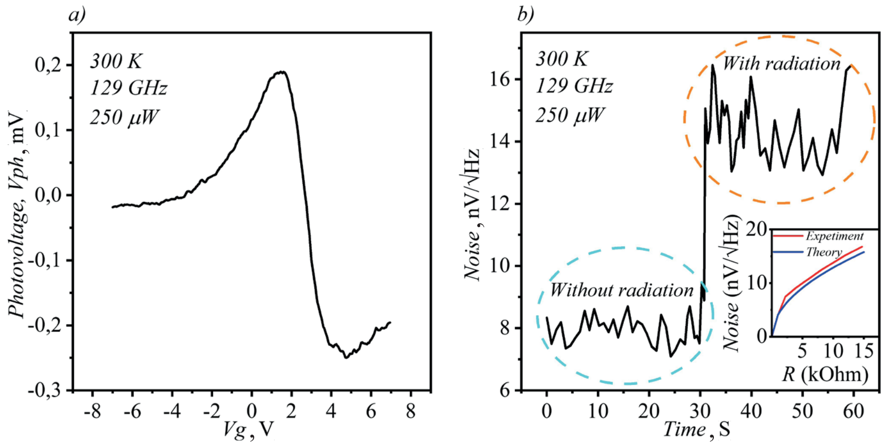

Fig. 2. Photovoltage as a function of *V*g measured at 250 μW power of incoming 130 GHz radiation (*a*). Noise spectral density measured with and without of incoming 130 GHz radiation at *V*g = -7V. Inset: Noise spectral density of set of resistors (1, 2, 4, 8, 16 kOhm) measured at frequency of 90 kHz by lock in amplifier (red curve). Calculated values of spectral density of the same set of resistors according to the thermal noise (*b*)

Conclusion

In conclusion, we demonstrate the detection of sub-THz radiation using graphene noise thermometry. The measured noise is dependent on electron temperature and can be used as detector signal as well as probe of electron temperature under terahertz radiation. The obtained data can be used to optimize existing graphene THz and sub-THz detectors based on the electron heating effect, for example, photo-thermoelectric detectors [12], as well as develop new ones.

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