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Johnson noise thermometry of CVD graphene bolometers

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Abstract. Graphene, due to its record low electron heat capacity and weak electron-phonon coupling at low temperatures, is considered as a promising material for creating terahertz hot electron bolometers. The main challenge to the development of such devices is the weak dependence of graphene resistance on temperature. Here we demonstrate measurement system based on Johnson noise thermometry to directly measure electron temperature in graphene. We measure thermal conductance due to electron-phonon coupling at bath temperature 4,2 K. Our graphene is synthesized by chemical vapor deposition (CVD) method and transferred to Si/SiO_2 substrate. The electron–phonon thermal conductance has a temperature power law of T^4 which is typical for highly disordered graphene. We estimate the sensitivity of CVD graphene based bolometer with Johnson noise readout. The internal noise equivalent power (NEP) is determined by thermodynamic fluctuations and is equal to 3 fW/Hz$^{0.5}$. The sensitivity of the detector is limited by the read out noise and is equal to 267 pW/Hz$^{0.5}$. The low internal NEP together with potential fast response time makes CVD graphene to be promising material in the area of bolometry.

Keywords: graphene, THz detectors, bolometers, noise thermometry

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Шумовая термометрия болометров на основе графена, синтезированного методом химического осаждения из газовой фазы

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Аннотация. Графен, обладая рекордно низкой электронной теплоемкостью и слабой электрон-фононной связью при низких температурах, представляет собой многообещающий материал для разработки терагерцовых болометров на основе горячих электронов. Основной проблемой является слабая зависимость сопротивления графена от температуры. В данной работе мы демонстрируем использование метода шумовой термометрии Джонсона-Найквиста для прямого измерения температуры электронов в графене. Мы исследуем теплопроводность, обусловленную электрон-фононным взаимодействием, при температуре 4,2 K. Графеновая пленка была синтезирована методом химического осаждения из газовой фазы (CVD) и перенесена на подложку кремния, покрытую термическим оксидом SiO_2. Результаты исследования показали, что электрон-фононная теплопроводность имеет степенную зависимость от температуры T^4, что характерно для сильно разупорядоченного графена. Мы оценили внутреннюю эквивалентную мощность шума (ЭМШ) детектора, которая определяется термодинамическими флуктуациями и равна 3 фВт/Гц$^{0.5}$. Чувствительность детектора ограничена шумом схемы считывания сигнала и равна 267 пВт/Гц$^{0.5}$. Низкое значение внутренней ЭМШ вместе с потенциально быстрым временем отклика делает CVD-графен перспективным материалом в области болометрии.

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

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Introduction

Currently, the terahertz (THz) range of the electromagnetic spectrum is of great interest due to a wide range of potential applications: medical diagnostics, non-destructive testing, security systems and data transmission [1]. These and many other applications require fast and sensitive THz detectors that can be easily combined into matrices. Graphene is a unique material for detection of THz radiation in the terahertz range due to its record-low electron heat capacity and weak electron-phonon coupling. This leads to a strong heating of the graphene electronic system under terahertz radiation. The main problem in the implementation of graphene terahertz detectors arises from the weak dependence of graphene resistance on temperature [2]. To measure the temperature of electron gas in graphene under electromagnetic radiation, various signal readout systems have been developed: noise thermometry method [3], Josephson junctions [4] and photo-thermoelectric method [5]. In addition, sensitive infrared [6] and microwave [4] bolometers based on graphene have been demonstrated. However, most of the works presented in the literature to date investigate thermal transport in high-quality graphene encapsulated in boron nitride [7], as well as exfoliated graphene on a $Si0_2$ substrate [3], which are difficult to apply in practice.

In this paper, we present a study of the thermal transport of graphene synthesized chemical vapor deposition (CVD) method to develop THz bolometers. We measure thermal conductance due to electron-phonon coupling at bath temperature 4.2 K and estimate intrinsic performance limits of CVD graphene bolometers. The value of thermal conductance G is $G = 6.7$ nW/K which leads to internal noise equivalent power limited by thermodynamic fluctuations of 3 fW/$Hz^{0.5}$. The sensitivity of the detector is limited by the readout noise and is equal to 267 pW/$Hz^{0.5}$.

Results and Discussion

Our samples are field-effect transistors in which graphene acts as a conduction channel (Fig. 1, *a*). We have fabricated our devices based on graphene synthesized using chemical vapor deposition (CVD), which is the most industrially viable method for producing graphene. The detailed description of device fabrication is presented in [8].

The transport properties of the manufactured devices were characterized at 4.2 K (Fig 1, *b*). Following [9] we estimated field mobility, residual concentration of charge carriers, as well as concentration dependence on applied gate voltage of the CVD graphene-based device. The field mobility was 650 $cm^2V^{-1}s^{-1}$ in our case. We note that the field mobility gives us a lower bound on the mobility estimation and strongly depends on the contact resistance.

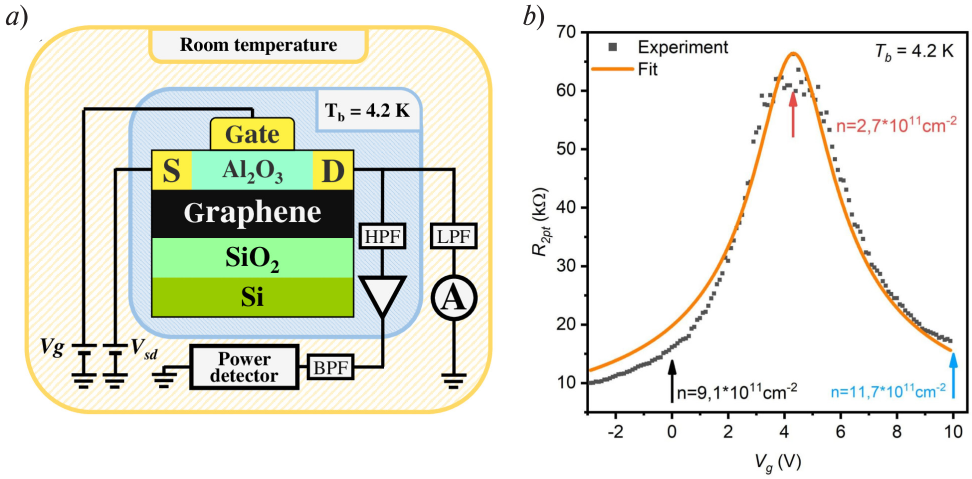

Fig. 1. Schematic of the device and Johnson noise thermometry scheme (*a*).
Typical dependence of two-point resistance on gate voltage: the dots are the experimental data, the orange curve is a fitting curve according to [9]. Measured at $T = 4.2$ K. The arrows illustrate the values of charge carrier concentration at which the measurements were made using the noise thermometry method (*b*)

The temperature of the graphene electron system was measured as a function of applied DC current and concentration of charge carriers. The values of the charge carrier concentration at which the measurements were carried out are marked with arrows in Fig. 1, *b*. For noise thermometry we measure the current noise spectral density S_I in the current-biased regime and determine the noise temperature as $T_N = S_I\,(dV/dI)/4k_B$ (Fig. 2, *a*). A detailed description of the experimental technique is presented in [10]. The length of our samples ($L = 2$ μm) is chosen to be much longer than the electron-phonon length l_{e-ph} in CVD graphene, which allows us to ignore electron heat diffusion into contacts. The configuration also leads to practically uniformity of T_e along the length L and, as a consequence, $T_N = T_e$ [11].

Fig. 2, *a* demonstrates the dependence of electron temperature on applied DC current at different concentrations. We see strong heating of electron gas in graphene: the maximum temperature of the electron gas was about 30 K with a current of 30 μA.

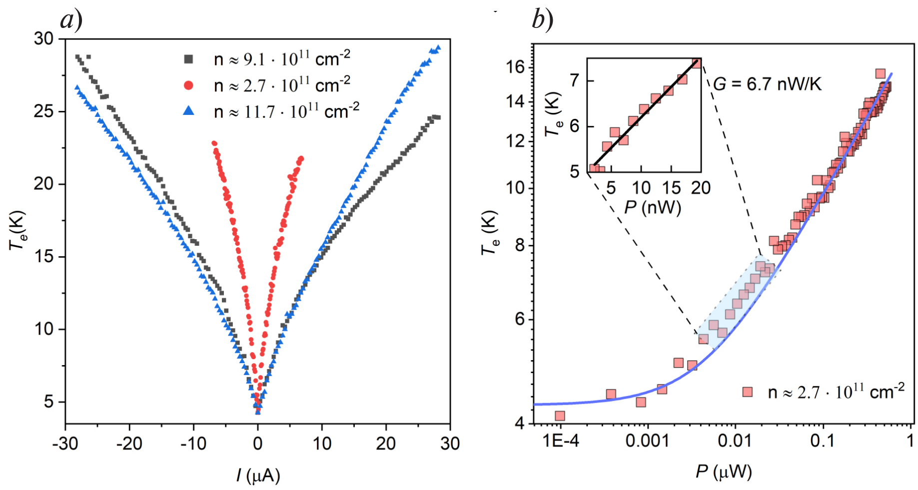

Fig. 2. Electron temperature T_e as a function of applied DC current at different carrier concentrations (*a*). Electron temperature T_e as a function of absorbed Joule heating power *P*. Solid blue line is the best fitting curve. Fitting parameters: $\delta = 4$ and $\Sigma = 0.5$ $Wm^{-2}K^{-\delta}$. Inset: The slope in the quasi-linear-response regime near zero *P* is the inverse of $G = P/(T_e - T_b)$ (black curve)

Next, we explore the dependence of the electron gas temperature T_e on the absorbed Joule heating power *P* (Fig. 2, *b*). $T_e(P)$ dependence transitions from a linear to a sublinear dependence with increased *P*. Following a standard analysis [3], we fitted the experimental data with the linear $P = G(T_e - T_b)$ dependence, where *G* is the thermal conductance describing the total heat escape from graphene to the bath, and obtained $G = 6.7$ nW/K (black line in inset to Fig. 2, *b*). This value agrees with previous experiments conducted using Johnson noise thermometry in the linear regime. Next, we fitted the nonlinear part of $T_e(P)$ dependence. There are two main mechanisms of heat dissipation in graphene devices: through electron diffusion and dissipation into the lattice via electron-phonon (e-ph) coupling [11]. We ignore the diffusion mechanism due to device geometry ($l_{e-ph} << L$). The dissipation into the lattice via e-ph coupling is described by power law $P = \Sigma A(T_e^{\delta} - T_b^{\delta})$, where *A* is the graphene area, Σ-electron photon coupling constant, T_b is the bath temperature, δ varies from 3 to 4 depending on temperature, concentration, device geometry and cleanliness. Theory predicts that $\delta = 4$ for electron coupling to phonons in pristine graphene at low temperatures. Weakly disordered graphene with $k_F l \gg 1$, where k_F is the Fermi wavevector and *l* is the electron mean free path, admits the possibility of $\delta = 3$ [11]. Blue line on Fig. 2, *b* shows the best fitting curve with fitting parameters $\delta = 4$ and $\Sigma = 0.5$ $Wm^{-2}K^{-n}$, which differ from the expected theoretical ones for weakly disordered graphene. Such power-law dependence with $\delta = 4$ was previously experimentally reported for highly disordered graphene in which $k_F l < 1$ [12]. These conditions are met in our sample. This indicates that there is a need to extend the theory of electron-phonon coupling in weakly disordered graphene to the strongly disordered limit. Finally, we calculate the noise equivalent power (NEP) of our detectors. There are two main sources of noise in the bolometers [13]. The first is due to intrinsic energy fluctuations in the device $NEP_{TF} = (4K_b T^2 G)^{0.5} = 3$ fW/Hz$^{0.5}$. The second source of noise is the accuracy limit with which one can measure the temperature of a device using Johnson-noise thermometry and can be calculated using the Dicke radiometer formula $NEP_{JN} = (T_e + T_{readout})G/(2B)^{0.5} = 267$ pW/Hz$^{0.5}$, where $T_{readout} = 50$ K is the readout noise temperature associated with amplifier noise, $B = 1$ MHz is the the readout bandwidth of measurement setup. The sensitivity of the detector is limited by the readout system which is determined by amplifier noise and bandwidth of measurement system.

Conclusion

We study thermal properties of CVD graphene on SiO_2 substrate using Johnson noise thermometry. We show that electron-phonon thermal conductance has a temperature power law of T^4 which is not typical for a disordered limit at low temperatures. This indicates that there is a need to extend the theory of electron-phonon coupling in weakly disordered graphene to the strongly disordered limit. We estimate the sensitivity of CVD graphene based bolometer with Johnson noise read out. The internal noise equivalent power determined by thermodynamic fluctuations is equal to 3 $fW/Hz^{0.5}$. The sensitivity of the detector is limited by the readout noise and is equal to 267 $pW/Hz^{0.5}$. Further improvement of readout system by extending of broadband characteristics based on low-noise amplifiers can lead to NEP reduction by 2 orders of magnitude. The intere nal low NEP together with potential fast response time [6] and ease of fabrication makes CVD graphene to be promising material in the area of sensitive THz bolometry.

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