Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: K A Baryshnikov *et al* 2020 *J. Phys.: Conf. Ser.* **1482** 012039

Terahertz photoconductivity enhancement in graphene in magnetic fields

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Abstract. The terahertz photoconductivity of epitaxial graphene grown on a SiC substrate is studied in magnetic fields. Under a magnetic field applied perpendicular to the sample's plane, a strong increase in the photoconductivity signal was detected due to suppression of electron-electron scattering. The photoconductivity mechanism based on the heating of electrons by terahertz radiation explains the experimental results.

1. Introduction

The studies of terahertz photoconductivity in graphene are of a particular interest due to the small effective mass and high mobility of electrons [1]. It was believed that graphene is suitable for creating bolometric devices, since electrons are easily heated by absorption of light due to the low heat capacity of 2DEG, and an increase in the electron temperature should lead to a change in the resistance of the sample [2]. However, it was turned out that the carrier mobility in graphene weakly depends on temperature. Therefore, heating by the light leads to a slight change in sample's resistance, but the bolometric signal is usually weak. Sufficiently strong bolometric signal was possible to register in samples with strong disorder [3] and in samples made in the form of a meander with a large ratio of length to width [4] only. In both cases, the bolometric effect was studied in the absence of magnetic field.

The main feature observed in graphene and graphene-like materials (with linear dispersion for electrons and holes) in magnetic fields is the non-equidistant character of energies between Landau levels. Graphene shows a square-root magnetic field dependence for Landau levels, which reads as $E_n = sign(n)v\sqrt{2e\hbar B|n|}$ in SI [5], where $v \approx 10^6$ m/s is the effective velocity of Dirac electrons in graphene, e is the absolute value of the electron charge, $\hbar$ is the Planck constant, and B is the magnitude of the magnetic field applied perpendicular to the graphene plane. It is interesting that the numeration of Landau levels in graphene runs all integers $n = 0, \pm 1, \pm 2, \ldots$, whereas for ordinary materials with a quadratic law of dispersion, Landau levels are numerated for only positive integers (for a certain electron energy band). The non-equidistance of energy levels can affect the relaxation of photoexcited carriers in graphene [6].

2. Experiment

The experiments were carried out on graphene structures obtained by sublimation on the Si surface of a 4H-SiC substrate by thermal decomposition in an argon atmosphere. Using laser lithography, the samples were patterned in the shape of a meander, as shown in figure 1(a). The measurements were carried out on two samples with a width of $W = 25$ μm and a length of $L = 15$ mm, so that the ratio $L/W = 600$. Each sample has several Ti/Au 5/50 nm contacts, which were made by electron evaporation. After fabricating the structures in the form of a meander, the surface of the samples was sequentially coated with PMMA and ZEP520A polymer films to change the carrier concentration upon irradiation of the samples with ultraviolet radiation. Before exposure, the electron concentration in graphene was $5 \cdot 10^{11}$ cm^{-2}. After exposure, the concentration decreased to $2.7 \cdot 10^{11}$ cm^{-2}.

A pulsed molecular laser [7,8] with optical pumping by a TEA-CO_2 [9] laser operated at wavelengths of 280, 148, and 90 μm, which correspond to frequencies of 1.1, 2.0, and 3.3 THz, was used as a source of terahertz radiation. The photoconductivity signal was measured under normal incidence of terahertz radiation. An external magnetic field up to 5.5 T was applied normally to the surface of the sample and parallel to the propagation of radiation. All measurements were carried out at the temperature of liquid helium $T = 4.2$ K.

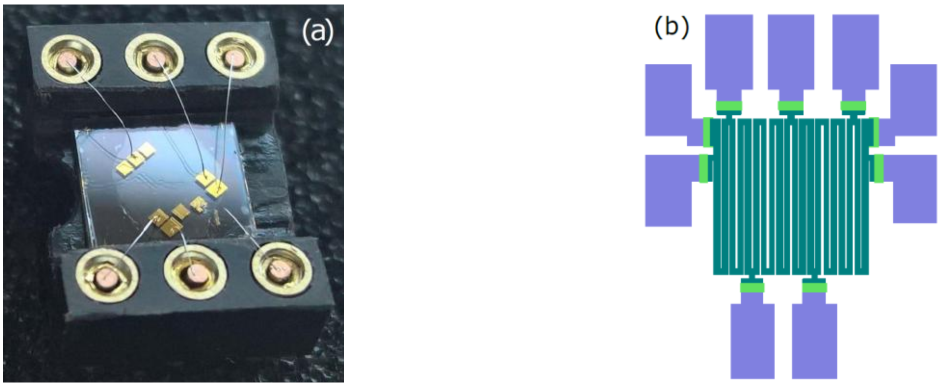

Figure 1. (a) Picture of the sample; (b) Shape of the sample in the form of a meander in which the strip width is 25 μm and the total length is 15 mm.

3. Results and discussion

Figure 2(a) shows the dependence of the photoresponse on the magnetic field for a wavelength of 148 μm. There are two parts of it. Initially, the signal intensity practically does not change with the increase in the magnetic field from 0 up to 2 T. With a further increase in the magnetic field above 2 T, a linear growth of the signal is observed. When the magnetic field changes from 2 T to 5 T, the signal amplitude increases by more than 4 times. These results were obtained for a carrier concentration of $n = 5 \cdot 10^{11}$ cm^{-2}. Similar dependences are observed for all measured wavelengths, bias currents, and concentrations, see figures 2(b), 2(c), and 2(d). The smaller the concentration of carriers, the lower the magnitude of the magnetic field above which the growth of the signal begins. This follows from a comparison of the results presented in figures 2(a) and 2(c). For the carrier concentration $n = 2.7 \cdot 10^{11}$ cm^{-2}, the signal growth begins from fields of about 1T that could be seen from figure 2. In figure 2(c), the results of similar measurements are presented for a larger bias current. The bias current does not affect the magnitude of the magnetic field, above which the increase in photoconductivity begins, but it affects the amplitude of the photoconductivity. With an increase in current from 1.5 μA to 1.9 μA, the photoconductivity amplitude at low fields decreases from 2 mV to 0.5 mV.

Let us turn to a discussion of mechanisms for the photoresponse in graphene under the action of terahertz radiation. Generally, photoconductivity can be associated either with a change in the number of carriers in the sample under the transitions induced by light, or with a bolometric effect if heating of the electron gas by radiation absorption leads to a change in the carrier mobility. Since the Fermi energy in our samples is much higher than the energy of terahertz photons, vertical optical transitions between the valence and conduction bands are forbidden. The observed photoconductivity signal is associated with the heating of electrons by terahertz radiation. This is evidenced by the strong temperature dependence of the resistance for the samples, previously studied in zero magnetic field [4]. The experimental results can be described using a simple model of the bolometric mechanism for photoconductivity. After emission absorption, the electron system heats up to some effective temperature $T_e = T_L + \Delta T_e$, which exceeds the equilibrium temperature (lattice temperature) by $\Delta T_e = P\tau / C_e$.

Here P is the light energy absorption rate per unit area, C_e is the specific heat of the electron gas per unit area, and τ is the relaxation (scattering) time of photoexcited carriers. The magnitude of the photoresponse can be represented as $\Delta V = I_{dc}\Delta R_{xx} = I_{dc}\frac{L}{W}\Delta\rho_{xx} = I_{dc}\frac{L}{W}\frac{\partial\rho_{xx}}{\partial T_L}\Delta T_e$, where $\Delta R_{xx} = \frac{\partial R_{xx}}{\partial T_L}\Delta T_e$ is the resistance change under illumination. Here $\frac{\partial\rho_{xx}}{\partial T_L}$ is the temperature coefficient of the resistivity. The magnitude of the photoresponse signal depends on the bias current I_{dc} and is proportional to the ratio of the sample length L to its width W.

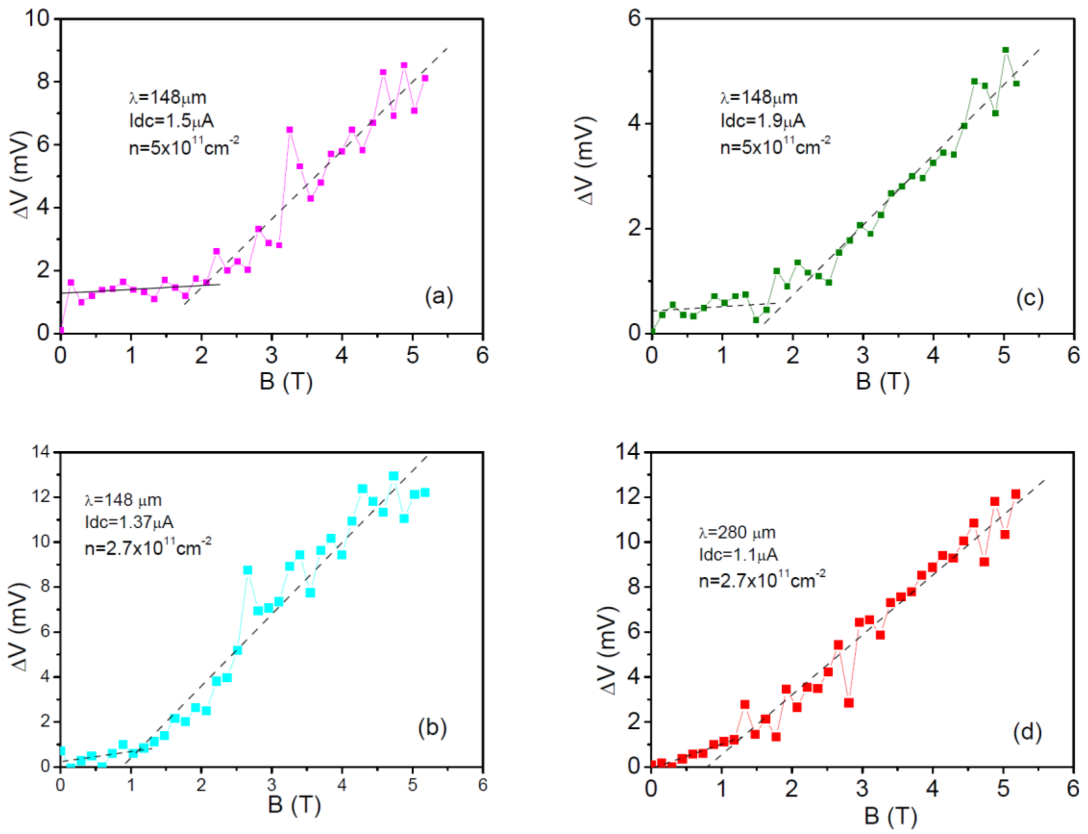

Figure 2. Dependences of the amplitude of the photoconductivity signal ΔV on the magnetic field for different electron concentrations (a) and (b), bias currents (a) and (c), and different wavelengths of the incident radiation (b) and (d).

Since the heating of the electron gas and, accordingly, the photoconductivity signal are proportional to the magnitude of the scattering time, the electron scattering mechanisms determine the magnitude of the photoconductivity. The relaxation of hot carriers in graphene has been studied in numerous papers both in zero magnetic field [10] and in the presence of a magnetic field [6]. It has been found that the electron-electron interaction dominates in graphene, and the main mechanism for relaxation of hot carriers is the relaxation due to electron-electron scattering. In magnetic fields, an increase in the relaxation time is observed, which is explained by suppression of electron-electron scattering due to the unequal distance between Landau levels in graphene [6]. A significant effect on the value of photoconductivity is clearly seen in figure 2 starting from the critical value of the magnetic field. The lower the electron concentration, the weaker the magnetic fields that provide an increase in the photoconductivity signal. At high electron concentrations the energy of transitions between appropriate Landau levels is small compared to the lower carrier concentration case due to the non-equidistance of Landau levels in graphene. Therefore, in this case, stronger magnetic fields are required to split the Landau levels in energy and to achieve a certain distance between the levels necessary for scattering suppression. The distance between Landau levels is equal to several millielectronvolts under the conditions of our measurements (radiation with a frequency of 1-3 THz and magnetic fields up to 5 T [11]), which is comparable with the broadening of Landau levels. Therefore, there is no quantization of Landau levels (they overlap), but the density of states is modulated, leading to a decrease in the efficiency of electron-electron scattering in magnetic fields. Previously, in the study of the kinetics of relaxation in applying pump-probe, an increase in the relaxation time was observed due to suppression of electron-electron scattering in graphene in the absence of Landau levels quantization [6]. The effect of the magnetic field on the value of photoconductivity can also be associated with magnetoresistance as far as the resistance of the sample decreases when the magnetic field is increased. In this case, the temperature coefficient of resistivity can also change. Apparently, this effect is insignificant in comparison with the effect of suppressing electron-electron scattering, since the first effect cannot explain the appearance of critical magnetic fields at which the photoconductivity growth starts.

In general, electrons can be heated not only by the absorption of radiation but also by the bias current through the sample. The electronic system heating by different bias currents results in different photoconductivities being observed. As can be seen in figures 2(a) and 2(c), the photoconductivity in low magnetic fields decreases significantly with increasing current from 1.5 μA to 1.9 μA. This effect can be explained by the fact that the photoconductivity $\Delta V = I_{dc}\frac{L}{W}\frac{\partial \rho_{xx}}{\partial T_L}\Delta T_e$ depends not only on the terahertz radiation induced by electron gas heating resulting in ΔT_e but also on the joule heating by the bias current. The latter decreases the temperature coefficient $\frac{\partial \rho_{xx}}{\partial T_L}$. At strong bias currents, the joule heating becomes stronger than the terahertz heating, reducing the sensitivity of the electronic system to heating induced by terahertz radiation. This unambiguously indicates the bolometric mechanism of the terahertz photoconductivity.

4. Conclusions

Terahertz photoconductivity has been studied in magnetic fields in epitaxial graphene grown on SiC substrates. The dependence of the photoresponse signal on the magnetic field has been measured for different values of electron concentration, bias current, and terahertz radiation intensity. The photoconductivity mechanism based on the heating of electrons by terahertz radiation explains the experimental results. A strong increase in the photoconductivity signal at magnetic fields was detected due to suppression of electron-electron scattering.

Acknowledgements
This work was partially supported by grants from the Russian Foundation for Basic Research (project 18-02-00498), the FLAG-ERA program (project DeMeGRaS, project GA501/16-1 of the DFG) and Foundation for Polish Science (IRA Program, grant MAB/2018/9, CENTERA).

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