APPLIED PHYSICS LETTERS **103**, 173114 (2013)

The effect of a transverse magnetic field on 1/*f* noise in graphene

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(Received 23 August 2013; accepted 10 October 2013; published online 25 October 2013)

The low frequency 1/*f* noise in graphene devices was studied in a transverse magnetic field of up to $B = 14$ T at temperatures $T = 80$ K and $T = 285$ K. The examined devices revealed a large *physical* magnetoresistance typical for graphene. At low magnetic fields ($B < 2$ T), the level of 1/*f* noise decreases with the magnetic field at both temperatures. The details of the 1/*f* noise response to the magnetic field depend on the gate voltage. However, in the high magnetic fields ($B > 2$ T), a strong increase of the noise level was observed for all gate biases. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4826644]

Most of graphene sensing, microwave and terahertz applications[1–4] require low levels of the low frequency noise. Low frequency noise measurements also allow one to study impurities and defects in semiconductor structures and to diagnose the quality and reliability of electronic devices. The importance of the subject led to a large number of publications on the low frequency (1/*f*) noise in a single-layer graphene (SLG) and multi-layer graphene.[3,5–12]

The nature of the 1/*f* noise in graphene is still unknown. Typical values of the 1/f noise in graphene are on the order of or even somewhat smaller than in good quality Si MOSFETs.[5] However, in contrast to MOSFETs, the gate voltage dependence of the 1/*f* noise in graphene[5,6] does not follow the prediction of the McWhorter model.[13] In accordance with this model, the 1/*f* noise appears as a result of the capture and release of the charge carriers by the traps in the gate dielectric.[13] In some cases, the charges, trapped in the dielectric, can cause additional mobility fluctuations of the carriers in the MOSFET channel.[14] The nature of the 1/f noise has also been established for Si, GaAs, and metals. In bulk Si and GaAs, the 1/*f* noise is due to the fluctuations of the occupancy of the density of states tails near the conduction and valence bands.[15] In metals, the 1/*f* noise is due to the mobility fluctuations.[16,17]

Recent measurements of noise in graphene after electron beam irradiation revealed unusual decrease of the noise with the increase of the irradiation dose.[11] As shown in Refs. 7 and 11, the mobility fluctuation model[17,18] can qualitatively explain both the gate voltage dependence of the noise and noise reduction as a result of electron irradiation.

A possible way for gaining understanding of the nature of the low frequency noise is the measurement of the effect of the transverse magnetic field on the noise characteristics. In this letter, we report the results of such measurements for single-layer graphene at 80 K and 285 K in the magnetic field of up to 14 T.

The SLG flakes with characteristic dimension of ~10 μm were produced by mechanical exfoliation of Kish graphite and placed on a Si substrate with 300 nm SiO_2. The SLG flakes were identified by a combination of optical microscopy and Raman spectroscopy. The latter was also used to monitor the sample quality by measuring the D to G peak intensity ratio.[21] The source and drain contacts [(Cr (5 nm)/Au (80 nm)] defined the conducting graphene channel of $L = 390$ nm in length and $d = 530$ nm in width on a larger graphene flake. The doped Si substrate served as a gate. The samples were bonded and placed into the helium cryostat with 14 T superconducting coil.

The samples had the mobility within the range $\mu_0 = 400–600$ cm^2/Vs estimated using the following expression:

$$\mu_{eff} = \frac{L_g}{R_{eff} C_g (V_{GS} - V_D) W}, \tag{1}$$

where $R_{eff} = \frac{R_{ds}}{1-\sigma_0 R_{ds}}$ (with the contact resistance, R_c, set to zero), R_{ds} is the drain-source resistance, σ_0 is the conductivity in the Dirac point, V_D is the Dirac voltage ($V_D \sim -7$ V for the sample under study), C_g is the gate capacitance, and V_{gs} is the gate-source bias. The contact resistance, R_c, was estimated using the procedure outlined in Ref. 5 and was found to be ~0.01R_{ds} for all gate voltages. The noise measurements were performed using conventional instrumentation with the source grounded and drain voltage $V_d = 4$ mV. In all cases, the noise spectral density within the frequency range from 1 to 100 Hz was close to $\sim 1/f^{\gamma}$ with $\gamma \approx 0.95–1.05$ depending on temperature and gate voltage. The absence of Lorentzian bulges indicated the absence of a defined time constant in the spectra.

The transport phenomena in the magnetic field are usually studied either in the Hall or Corbino disc configurations. In the

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Corbino disc configuration, the Hall voltage does not exist, and the magnetic field leads to the so-called *geometrical* magnetoresistance. The same geometrical magnetoresistance is observed in a rectangular sample with $d/L > 3$.[19] In weak magnetic fields $\mu_0 B \leq 1$, the geometrical magnetoresistance is $\Delta\rho/\rho_0 = (\mu_0 B)^2$. Here, μ_0 is the mobility in the zero magnetic field, ρ is the resistivity, and B is the magnetic field. For the sample under investigation, $d/L = 1.36$, and geometrical magnetoresistance should be smaller than that for the Corbino disk.[19] As shown below, the contribution of the geometrical magnetoresistance in our graphene samples is negligible.

Figure 1 shows the relative magnetoresistance $\Delta R_{ds}/R_{ds0}$ as a function of the magnetic field at $T = 85$ K and $T = 285$ K in relatively low and high magnetic fields, respectively (Here, R_{ds0} is the drain to source resistance at $B = 0$).

The absolute value of the magnetoresistance is comparable with that observed in Ref. 22 for the samples with $\mu_0 = 1860\,\mathrm{cm^2/Vs}$ at $T = 330$ K. It is somewhat smaller than the magnetoresistance of SLG with the mobility ~6200 $\mathrm{cm^2/Vs}$ at $T = 2.9$ K.[23] Dashed lines in Figs. 1(a) and 1(b) show the maximum *geometrical* magnetoresistance calculated as $\Delta\rho/\rho_0 = (\mu_0 B)^2$ for $\mu_0 = 500\,\mathrm{cm^2/Vs}$. As seen, even maximum *geometrical* magnetoresistance is much smaller than that observed experimentally and the measured magnetoresistance is almost entirely is the physical magnetoresistance.

Figure 2 shows the dependences of the relative spectral noise density, S_I/I^2, on the drain current fluctuations in the magnetic field for the sample with the magnetoresistance shown in Figure 1. The amplitude of noise normalized to the area at 285 K and $B = 0$ is $S_I/I^2 \times L \times d \approx 6.6 \times 10^{-9}\,\mu\mathrm{m^2/Hz}$, which is of the same value or even smaller than that found for the graphene of higher mobility at T = 300 K.[5]

In relatively low magnetic fields (see Figures 2(a) and 2(c)), the noise decreases with the increasing magnetic field for both temperatures. The dependence of the magnetic field B_{min}, corresponding to the noise minimum, on the gate voltage and temperature is complex. At 80 K and $V_g = 0$, the minimum is attained at $B_{\mathrm{min}} \approx 2$ T. Increasing the gate voltage initially results in a decrease of B_{min}, which reaches the value of 0.63 T at $V_g = 4.3$ V. A further increase of the gate voltage leads to the increase in B_{min}. However, it remains smaller than the B_{min} value at $V_g = 0$. At T = 285 K, B_{min} is the same for $V_g = 0$ and for $V_g = 6.3$ V, while at $V_g = 12$ V, $B_{min} = 1.1$ T is higher than at $V_g = 0$.

The dependence of noise on the magnetic field resulted from *geometrical magnetoresistance* is given by[20]

$$S_I \sim \left(\frac{\delta\mu}{\mu}\right)^2 = \left[\frac{1-(\kappa\mu_0 B)^2}{1+(\kappa\mu_0 B)^2}\right]^2 \left(\frac{\delta\mu_0}{\mu_0}\right)^2. \qquad (2)$$

Here $\kappa < 1$ is the geometric factor, which is equal to unity for the Corbino disc configuration. As seen from Eq. (2), at $\kappa\mu_0 B = 1$, the current fluctuations are predicted to be equal to zero independently of the value of the mobility μ_0.

The dashed lines in Figs. 2(a) and 2(b) show the trend predicted by Eq. (2). As seen, both in low and high magnetic fields, this dependence is completely different from that observed experimentally. In a week magnetic field of $B = 1$ T, where experimental noise spectral density S_I/I^2 is close to its minimum and for $\mu_0 = 500\,\mathrm{cm^2/Vs}$, Eq. (2) predicts the decrease of the noise only by ~−0.04 dB. Meanwhile, the observed noise reduction is (0.3–1.3) dB. For the entire range of the magnetic fields studied, Eq. (2) predicts the decrease of the noise since $\mu_0 B < 1$ even at B = 14 T. However, at high fields $B > 2$ T, the measured spectral noise density increases significantly with

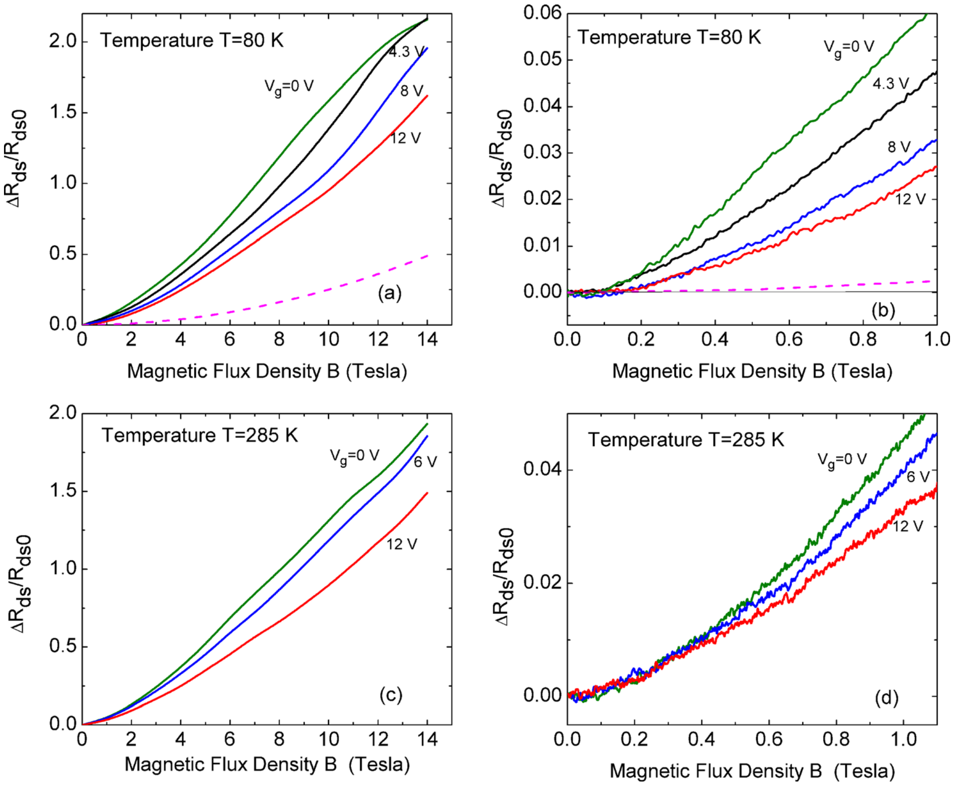

FIG. 1. Relative magnetoresistance of graphene transistor in transverse magnetic field for $T = 80$ K (a) and (b) and for $T = 285$ K (c) and (d) in strong (a) and (c) and low (b) and (d) magnetic fields. The Dirac voltage is $V_D = -7$ V in this device. Dashed lines show estimated geometrical magnetoresistance $\Delta\rho/\rho_0 = (\mu_0 B)^2$.

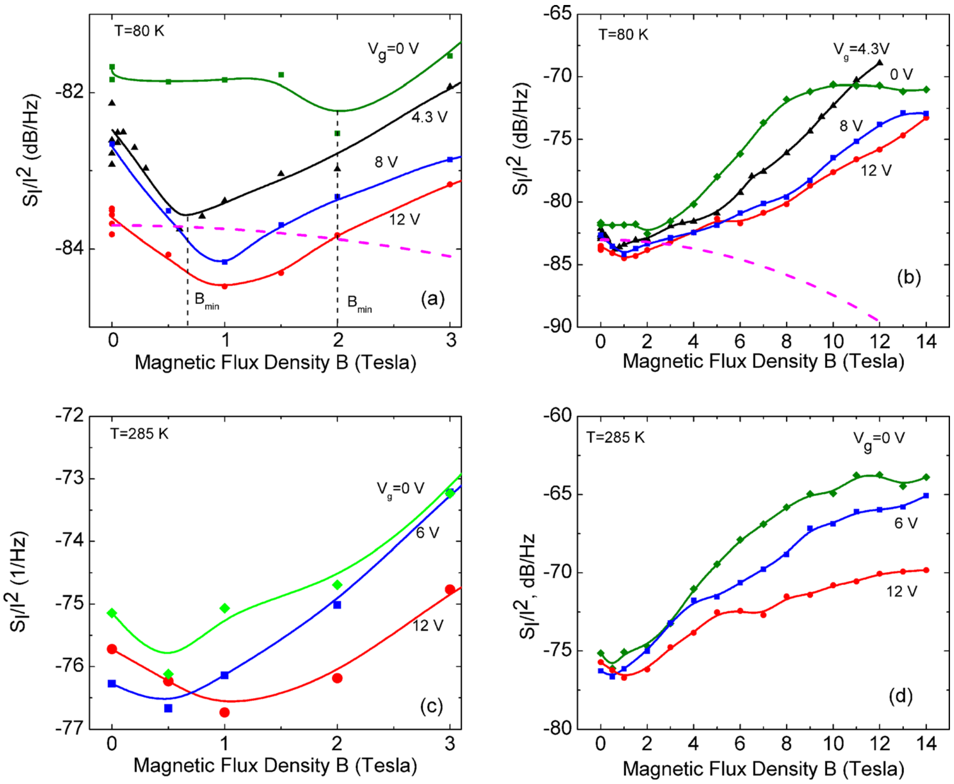

FIG. 2. Noise spectral density S_I/I^2 versus transverse magnetic field at $f = 1$ Hz for $T = 80$ K (a) and (b) and $T = 285$ K (c) and (d) for different gate voltages in the weak (a) and (c) and strong (b) and (d) magnetic fields. Dashed line shows the trend predicted by Eq. (2).The values of B_{min} are indicated for $V_g = 0$ V and $V_g = 4.3$ V (a).

increasing magnetic field. The noise amplitude at $B = 14$ T is at least one order of magnitude higher than that at $B = 0$. Therefore, we conclude that *physical* (not *geometrical*) mechanisms are responsible for the magnetoresistance in graphene and for the observed noise dependence on the magnetic field.

Non-monotonic dependence and strong increase of noise in high magnetic fields make graphene very different from what is observed in other electronics systems. In particular, GaAs samples[20,22–24] and GaN/AlGaN transistors[25,26] exhibit an absence of or a weak dependence of noise on the magnetic field, consistent with the number of carriers fluctuations as an origin of noise in these materials. The scattering mechanisms and magnetoresistance in graphene are still under discussion.[27–29] The obtained magnetic field dependence of 1/*f* noise in graphene may provide additional information for better understanding of the carrier transport mechanisms and 1/*f* noise itself.

In conclusion, the 1/f noise in a single layer graphene has been studied at temperatures 80 and 285 K in the magnetic fields of up to 14 T. The samples revealed strong *physical* magnetoresistance typical for graphene devices. The noise measurements indicated a complex and unique non-monotonic dependence of 1/*f* noise on the magnetic field and gate voltage in graphene that has never been observed before. The reported magnetic field dependence of noise in graphene confirms unconventional nature of noise and scattering mechanisms in graphene.

The work at RPI was supported by the Army Research Laboratory under CRA "Alliance for Multiscale Modeling for an Energy Efficient Army" and by the US-French initiative "PUF." At the Ioffe Institute, the work was supported by the Russian Foundation for Basic Research (Grant No. 11-02-00013). The work at UCR was supported, in part, by the Semiconductor Research Corporation (SRC) and Defense Advanced Research Project Agency (DARPA) through STARnet Center for Function Accelerated nanoMaterial Engineering (FAME), and by the National Science Foundation (NSF) Projects EECS-1124733 and EECS-1102074.

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