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Ultra low $1/f$ noise in suspended bilayer graphene

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We have studied $1/f$ noise power S_f in suspended bilayer graphene devices. Around the Dirac point, we observe ultra low noise amplitude on the order of $f * S_f / I_b^2 = 10^{-9}$. The low frequency noise level is barely sensitive to intrinsic carrier density, but temperature and external doping are found to influence the noise power. In our current-annealed samples, the $1/f$ noise is dominated by resistance fluctuations at the contacts. Temperature dependence of the $1/f$ noise suggests the presence of trap states in the contact regions, with a nearly exponential distribution function displaying a characteristic energy of 0.12 eV. At 80 K, the noise displays an air pressure sensitivity that corresponds to ~ 0.3 ppm gas detection sensitivity; this indicates the potential of suspended graphene as a platform for gas sensing applications. © 2015 AIP Publishing LLC.

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Graphene is truly a remarkable two-dimensional material with highly tunable charge density and ultra high intrinsic mobility. Due to these unique properties, graphene provides a niche platform for future high performance rf devices in conjunction with conventional CMOS technology. However, the charge carrier density and mobility of graphene are prone to both external and internal perturbations that lead to frequency dependent low frequency noise, i.e., $1/f$ noise, and frequency independent noise, i.e., shot noise. The external perturbations can originate, for example, from substrate roughness, ripples in graphene, gas adsorbate, and metal to graphene contact, and internal perturbations from phonons, edge dislocations, edge effects, etc.^{1,2} The $1/f$ noise not only hampers low frequency measurements but it is also up-converted to high frequency inducing phase noise in high frequency measurements. Thus, the understanding of the low frequency noise in graphene is important for its rf applications as well.

However, a comprehensive model for low frequency noise in graphene based devices is still missing. The major source of low frequency noise in on-substrate graphene devices is attributed to charge trap fluctuations in the substrate's oxide. These fluctuations modulate the charge density and mobility in the graphene flake.^{3–6} These could be reduced by passivation of the oxide layer or by suspending the graphene flakes. Zhang *et al.* observed reduced noise in a suspended single layer graphene device in comparison to on-substrate graphene devices.⁷ The low frequency noise level in on-substrate devices can also be reduced by using bilayer graphene instead of monolayer graphene, as demonstrated by Lin and Avouris.⁶ This reduced noise in bilayer graphene devices is due to its unique band structure and charge distribution between the two layers.⁸

Our experiment is motivated by Zhang *et al.*⁷ and Lin and Avouris.⁶ We have studied the low frequency noise in suspended bilayer graphene devices and found lower $1/f$ noise level in our devices in comparison to similar suspended carbon devices. The origin of low frequency noise in suspended bilayer graphene devices is pinned to the contact

region where the fluctuation in the contact resistance influences the transmission eigenvalues through the whole sample.^{9–11}

All the devices investigated here are suspended bilayer graphene fabricated using two different methods: LOR-technique and HF technique. In both techniques, a part of the graphene flakes exfoliated on LOR(500 nm)/SiO₂(285 nm)/Si(P⁺⁺) and SiO₂(285 nm)/Si (P⁺⁺) were suspended either with e-beam irradiation of LOR or by wet etching of SiO₂.^{12,13} Prior to suspension of bilayer graphene, flakes were optically identified and characterized using Raman spectroscopy. The top metal contacts (5 nm Cr/60 nm Au) were patterned using standard e-beam lithography and e-beam evaporation techniques. After the low temperature noise and conductance measurements, the device size and contact area were characterized using optical and SEM imaging. The SEM image of our device S3 is shown in the inset of Figure 1.

Following the initial characterization, the samples were cooled down to $T = 10$ mK using a dry dilution refrigerator for electrical measurements. The electrical measurements were conducted through low frequency lines with 1 MHz low-pass filters. Prior to dc and noise characterization, all devices were current annealed in a cryogenic vacuum. Afterwards, the samples were characterized by lock-in conductance measurements as a function of applied gate voltage. A reference sinusoidal signal of voltage 0.5 mV and frequency of 17.777 Hz was used for the charge carrier modulation on top of gate modulation produced by the dc gate V_g sweep. The applied gate voltage was converted into charge carrier density using $n = (V_g - V_D)C_g/e$, where C_g is the gate capacitance obtained using a parallel plate capacitor model. The mobility μ was determined by $\mu = (\sigma - \sigma_0)/ne$, where minimum conductance σ_0 corresponds to the measured maximum resistance. Main sample characteristics are listed in Table I.

The low frequency noise measurements were carried out using a voltage bias scheme with a dc bias up to 100 mV. The current was amplified with a transimpedance amplifier

FIG. 1. (a) Current fluctuations measured on sample S4 with current of $0.9 \text{ nA} < I_b < 1.6 \text{ } \mu\text{A}$ for $V_g = 4.5 \text{ V}$. The low frequency noise spectra are of $1/f$ type for all current bias values. Here, noise spikes at 50 Hz, 60 Hz, and their harmonics are removed. (b) Noise power for gate voltages $V_g = -8.5 \text{ V}$ ($\square$), -4.5 V ($\circ$), and 8.5 V ($\star$). The SEM image of a typical device is shown as an inset. Bilayer graphene (marked with dashed line) was suspended using contact leads (S-D). P-doped Si was used as back gate to modulate charge carrier density.

(SR570, gain 10^5) and measured with a voltmeter and its corresponding fluctuations were measured using an SRS 785 FFT analyzer. For $1/f$ noise measurement, spectra consisting of 800 FFT points in frequency a span of 250 mHz–200 Hz were averaged for 200 s. The average corner frequency of $1/f$ noise measured on our devices was found to be above 10 kHz. The low frequency data presented here were measured at 10 Hz and normalized by the measured current. The low frequency measurements were performed in an electrically shielded environment.

Our devices exhibited ultra low $1/f$ noise level compared to all reported suspended graphene based devices of similar size. The low frequency noise measurement with respect to

TABLE I. Characteristics of our suspended bilayer samples: dimensions of samples (length L and width W), contact area (A_c), contact resistance (R_c), the resistance and the gate voltage at the Dirac point (R_D and V_D), mobility (μ) measured at $V_g = 10 \text{ V}$, the gate capacitance calculated using the parallel plate capacitor model (C_g), normalized $1/f$ noise, and the fabrication method.

	L μm	W μm	A_c μm^2	R_c $\text{k}\Omega$	R_D $\text{k}\Omega$	V_D V	C_g $\frac{\text{nF}}{\text{cm}^2}$	μ $\frac{\text{cm}^2}{\text{Vs}}$	$f * S_I / I_b^2$	Method
S1	0.43	0.51	0.8	1.5	5.8	-0.3	4.7	3500	1×10^{-8}	HF
S2	0.63	1.15	1.3	0.6	3.8	0.7	3.3	5300	7×10^{-9}	LOR
S3	1.18	3.13	6.3	0.5	3.0	0.35	3.3	5100	6×10^{-10}	LOR
S4 ^a	2.10	2.10	5.5	3.5	13.0	4.26	1.6	6400	8×10^{-9}	LOR

^aS4 measured at 4.2 K.

bias current is shown in Figure 1. The low frequency noise power shows quadratic dependence with respect to bias current. For bias current $I_b > 30 \text{ } \mu\text{A}$, the low frequency noise power deviates monotonically from its quadratic behavior with respect to bias current. Large currents lead to deviation of I-V from its linear behavior, indicating onset of electron-phonon coupling in graphene bilayer.¹⁴ Alternatively, these fluctuations at higher bias are due to heating. On the contrary, at very low bias, noise power shows sub-quadratic dependence on I_b . The individual noise traces show the presence of Lorentzian bulges, indicating localized fluctuators which produce random telegraph noise.¹⁵

The current noise spectra are fitted using generalized Hooge's empirical relation¹⁶

$$S_I = A_n \frac{I_b^\gamma}{f^\beta}. \quad (1)$$

The I_b fit using Eq. (1), in all high bias spectra shows that $\beta \sim 1$ and $\gamma \sim 2$, which confirms that the nature of this low frequency noise in our bilayer graphene samples is of $1/f$ type.

The low frequency noise and the resistance of the sample S2 as a function of V_g are shown in Figure 2. By sweeping the gate voltage, charge carrier density in a sample is modulated. Since $A_n = \alpha_h / N$, where Hooge's parameter $\alpha_h = \text{const.}$, and N is number of charge carriers, one should expect $1/f$ noise power to be inversely proportional to the charge carrier density. This reduction of noise with an increase in charge carrier density is typically considered as a reduction in the relative fluctuation in the charge carrier number or by better screening of charged scattering centers at high charge density. Contrary to the behavior implied by Hooge's parameter, the measured noise power in our devices remains almost invariant.

This non-regular behavior of the invariant noise level with respect to charge carrier density hints its origin to be contact resistance noise. Since in graphene G is approximately proportional to N , hence $\delta G^2 / G^2 \propto \delta G^2 / N^2$, and the

FIG. 2. Resistance and low frequency noise characteristics for sample S2 with respect to charge carrier density. The low frequency noise was measured at $I_b = 53 \text{ } \mu\text{A}$. The dashed line yields $f * S_I / I_b^2 = 7.5 \times 10^{-9}$.

FIG. 3. Low frequency noise power measurement ($I_b = 54 \mu\text{A}$) vs. temperature T during a temperature sweep including variation in the number of external impurities due to degassing at high T : (a) Normalized noise with respect to temperature, measured on sample S3. The effective change in normalized noise at $T > 80 \text{ K}$ is $0.3 \times 10^{-11} \text{ 1/Hz}$. (b) Density of fluctuation states, i.e., $D(\epsilon)$ vs activation energy, i.e., ϵ . Data presented here are measured at charge density $n = 3 \times 10^{11} \text{ cm}^{-2}$ at $f = 10 \text{ Hz}$ and temperature in (a) corresponds to ϵ in (b). Experimental data are fitted with exponential function, i.e., $D(\epsilon) \sim D_0 \exp(-\epsilon/\Delta)$; $P_1 \sim 6.85 \times 10^{-11} \text{ 1/K}$, $\Delta \sim 0.12 \text{ eV}$. (c) The pressure log of the vacuum chamber while warming up of the pulse-tube-based dilution fridge; note that the pressure scale reflects the sample chamber pressure only above $T \sim 70 \text{ K}$. The pressure change at 80 K is in order of $1 \times 10^{-4} \text{ mbar}$.

fluctuations for conductance have to scale linearly with the charge carrier density. The simplest model to fulfill this is to have fluctuations in the contact resistance as this will modify all the transmission channels that are opened with increasing N . For independent mobility fluctuations, we would expect scaling as $\delta\mu^2 \propto N$ which does not fit with the experimental results. However, the appearance of uniform mobility fluctuations due to the presence of potential steps or trap-like lattice dislocation in close proximity to the Fermi level cannot be ruled out.^{17,18} Such charge traps could be formed during the annealing process in the graphene/bilayer graphene lattice under the metal contact. The charging and discharging of these charge traps modulate the electro-chemical potential more strongly than the gate, hence making the noise level insensitive to the gate voltage.^{8,19}

The noise power measured in our devices is down to $f * S_I/I_b^2 = 6.2 \times 10^{-10}$ (for the sample S3 having an area of $3.7 \mu\text{m}^2$), which is so far the lowest value ever reported for graphene based devices of similar size.^{2,20} This could well be anticipated for suspended bilayer graphene samples, where the contact resistance fluctuations due to charged traps can be better screened than in monolayer graphene.^{21,22} It is also possible that the fairly large electron beam dose used to suspend the graphene flake attributes to the reduction of contact noise due to secondary electrons at the contact region emanating from collisions with the contact metal. It was previously reported in Ref. 23 that electron beam irradiation can lead to a reduction of $1/f$ noise level. However, this reduction of noise is unlikely in the case of suspended part of the flake which resides far away from the main source of secondary electrons, the Si substrate, and is thus more protected than graphene under the contacts.

Owing to intrinsic low noise and large surface area, the suspended bilayer noise is susceptible to extrinsic scatterers. In the presence of extrinsic scatterers, Hooge's parameter will show complex behavior with its dependence upon

density of trap states, which itself depends upon the temperature in addition to mobility. The dependence of Hooge's parameter upon mobility $\mu(V_g)$, trap states, and temperature T can be approximated as⁷

$$\alpha_h = f(\mu(V_g)) \times g(T), \quad (2)$$

where we assume that the charge density is not influenced strongly by temperature, which means that this equation is only valid away from the Dirac point. The latter factor $g(T)$ is intimately related to the distribution of trap states in energy.²⁴ In bilayer graphene, however, $f(\mu(V_g))$ can be dropped as $\mu(V_g)$ is nearly constant.²⁵ $g(T)$ gives the measure of density of trap states in the low frequency noise.

The low frequency noise on sample S3 at fixed intrinsic charge density of $3.1 \times 10^{11} \text{ cm}^{-2}$ was measured with respect to temperature while warming up the cryostat. During the warm up, the mixing chamber plate temperature and the cryostat vacuum pressure were logged, while simultaneously pumping on the vacuum chamber using a turbomolecular pump. Additionally, the resistance of the sample was recorded after every low frequency noise spectrum measurement over the gate voltage range $V_g = \pm 5 \text{ V}$. The noise spectra showing a Lorentzian bulge are not included in the analysis. The temperature dependence of the normalized $1/f$ noise S_I/I_b^2 of sample S3 is shown in Figure 3(a). The noise level gradually increases up to 60 K , above which the noise level starts to decrease. At these higher temperatures, we see a correlation between the vacuum chamber pressure and the noise level, which is due to enhanced scattering/doping caused by residual gas pressure in the vacuum chamber surrounding the dry dilution refrigerator. As discussed below, the variation of the noise with temperature (see Figure 3(a)) is dominated by the main $1/f$ noise source, the contact resistance fluctuations, and not by the change in the amount of adsorbed gas.

The overall temperature dependence of the $1/f$ noise can be interpreted by the presence of thermally activated fluctuators. For a broad energy distribution $D(\varepsilon)$ of trap states, the noise $S_I(\omega, T) \propto \frac{k_B T}{\omega} D(\varepsilon)$, where $\varepsilon = -k_B T \ln(\omega \tau_0)$ with τ_0 as the characteristic frequency of trap fluctuations; we use $\tau_0 = 10^{-12}$ s.²⁴ Figure 3(b) displays the $D(\varepsilon)$ versus ε obtained from the data in Figure 3(a). The result is fitted with the exponential distribution function $D(\varepsilon) \sim D_0 \exp(-\varepsilon/\Delta)$ with characteristic energy $\Delta = 0.12$ eV and initial density of states of fluctuators, i.e., $D_0 \sim 6.85 \times 10^{-11}$ 1/K. Here, we assume implicitly that $\beta = 1$, although β shows linear increase from $\beta = 0.9$ to $\beta = 1$ with respect to temperature T (with small bulge for $30 \text{ K} < T < 70 \text{ K}$), which is consistent with exponentially decreasing density of states, i.e., $D(\varepsilon)$. The low energy behavior of $D(\varepsilon) \propto 1/\varepsilon$ could be due to overheating of the sample by large bias employed in the experiment.

The pressure trace shown in Figure 3(c) displays a sudden upsurge in the vacuum pressure at 30 K, but it is unlikely that this change would be equally significant at the sample, as the lower temperature section of the dilution fridge still adsorbs air at this stage, and a gradual increase in the measured $1/f$ noise is observed. Above 70 K, the residual air is expected to move freely within the vacuum chamber and the decrease in the pressure $T \sim 80 \text{ K}$ can be assigned to a true gas detection response of the sample to air. We note that the residual gas also led to a strong change in $R(V_g)$ over the temperature range of 60–70 K: the gate modulation due to the Dirac peak was lost above 70 K, which is an indication that oxygen did redistribute in this temperature interval and doped the sample. Hence, the change in noise at 80 K (resolvable at $S/N \sim 1$) with a change of air pressure of 10^{-4} mbar can be employed for estimating the gas sensitivity of suspended bilayer as a gas detector for air. Converting the absolute pressure decrease to partial pressure, we obtain a sensitivity of 0.3 ppm, using a carrier gas that would not bind to the surface.

To confer the gas sensing capability of suspended bilayer graphene, sample S4 was exposed to 10^{-4} mbar of Ne gas at 26 K. Later, sample was cooled down to 4 K. Sample was characterized before and after the Ne gas exposure. The resistance measurement as a function of charge carrier density indicates a very weak shift in charge

neutrality point, which is expected with a neutral gas like Ne. On contrary to this, the low frequency noise measurement displays a Lorentzian bulge. A typical spectrum prior and after Ne contamination of bilayer graphene, measured at bias current $I_b = 1.1 \mu\text{A}$ and charge carrier density $n = -6.3 \times 10^{10} \text{ 1/cm}^2$, is shown in Figure 4. The characteristic frequency of the Lorentzian bulge is $f_c = 70 \text{ Hz}$. After weak current annealing, this Lorentzian feature is suppressed. A well defined bulge above the $1/f$ noise background with a characteristic frequency indicates presence of localized fluctuators which produces random telegraph noise.¹⁵ We ascribe the fluctuators to the scattering by adsorbed Ne gas²⁶ which is able to diffuse along the bilayer graphene surface.

In summary, we have investigated $1/f$ noise in suspended bilayer graphene devices and found record-low noise power levels down to $f * S_I/I_b^2 = 6.2 \times 10^{-10}$. The $1/f$ noise power vs. charge carrier density measurements indicates that resistance fluctuations at the graphene-metal contact are the main origin of the noise. The contact noise can be modelled by fluctuations in charge traps due to thermal excitations. From our data, we obtain an exponential decay in the density of states of the charge traps in energy, which is also clearly reflected in the properties of the $1/f$ noise spectra, in particular, increase of the frequency exponent β from 0.9 to 1.0. Our noise measurements at high charge carrier density indicate a sensitivity of $1/f$ noise spectra to adsorption of gas molecules, and a sensitivity of 0.3 ppm was estimated for air at 80 K. Owing to the very low intrinsic $1/f$ noise level and its sensitivity to external impurity scatterers, the suspended bilayer device can have potential for applications in the field of on-chip gas sensing.

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FIG. 4. The normalized low frequency noise $f * S_I$ with respect to frequency for pristine (1), contaminated (2), annealed (3) bilayer graphene. The noise was measured at $I_b = 1.1 \mu\text{A}$ and $n = -6.3 \times 10^{10} \text{ 1/cm}^2$. The low frequency noise spectra for contaminated case shows small bulge at $f = 70 \text{ Hz}$. After annealing bulge is suppressed.

- ¹S. Das Sarma, S. Adam, E. Hwang, and E. Rossi, *Rev. Mod. Phys.* **83**, 407 (2011).
- ²A. A. Balandin, *Nat. Nanotechnol.* **8**, 549 (2013).
- ³S. Adam, E. H. Hwang, V. M. Galitski, and S. D. Sarma, *PNAS* **104**, 18392 (2007).
- ⁴Y. W. Tan, Y. Zhang, H. L. Stormer, and P. Kim, *Eur. Phys. J. Spec. Top.* **148**, 15 (2007).
- ⁵J. Chen, C. Jang, S. Xiao, M. Ishigami, and M. S. Fuhrer, *Nat. Nanotechnol.* **3**, 206 (2008).
- ⁶Y.-M. Lin and Ph. Avouris, *Nano Lett.* **8**, 2119 (2008).
- ⁷Y. Zhang, E. E. Mendez, and X. Du, *ACS Nano* **5**, 8124 (2011).
- ⁸A. N. Pal and A. Ghosh, *Phys. Rev. Lett.* **102**, 126805 (2009).
- ⁹R. Danneau, F. Wu, M. F. Craciun, S. Russo, M. Y. Tomi, J. Salmilehto, A. F. Morpurgo, and P. J. Hakonen, *Phys. Rev. Lett.* **100**, 196802 (2008).
- ¹⁰L. DiCarlo, J. R. Williams, Y. Zhang, D. T. McClure, and C. M. Marcus, *Phys. Rev. Lett.* **100**, 156801 (2008).
- ¹¹A. Laitinen, S. Paraoanu, M. Oksanen, M. F. Craciun, S. Russo, E. Sonin, and P. J. Hakonen, e-print [arXiv:1502.04330v1](https://arxiv.org/abs/1502.04330v1) (2015).
- ¹²N. Tombros, A. Veligura, J. Junesch, J. J. van den Berg, P. J. Zomer, M. Wojtaszek, I. J. V. Marun, H. T. Jonkman, and B. J. van Wees, *J. Appl. Phys.* **109**, 093702 (2011).
- ¹³X. Du, I. Skachko, A. Barker, and E. Y. Andrei, *Nat. Nanotechnol.* **3**, 491 (2008).
- ¹⁴A. Laitinen, M. Kumar, M. Oksanen, B. Plaçais, P. Virtanen, and P. Hakonen, *Phys. Rev. B* **91**, 121414(R) (2015).

- ¹⁵C. T. Rogers and R. A. Buhrman, *Phys. Rev. Lett.* **53**, 1272 (1984).
- ¹⁶F. N. Hooge, *Phys. Lett. A* **29**, 139 (1969).
- ¹⁷E. J. H. Lee, K. Balasubramanian, R. T. Weitz, M. Burghard, and K. Kern, *Nat. Nanotechnol.* **3**, 486 (2008).
- ¹⁸P. Karnatak, S. Goswami, V. Kochat, A. Nath Pal, and A. Ghosh, *Phys. Rev. Lett.* **113**, 026601 (2014).
- ¹⁹S. Ilani, A. Yacoby, D. Mahalu, and H. Shtrikman, *Phys. Rev. Lett.* **84**, 3133 (2000).
- ²⁰Y.-M. Lin, J. C. Tsang, M. Freitag, and Ph. Avouris, *Nanotechnology* **18**, 295202 (2007).
- ²¹H. Min, B. Sahu, S. Banerjee, and A. MacDonald, *Phys. Rev. B* **75**, 155115 (2007).
- ²²E. H. Hwang and S. Das Sarma, *Phys. Rev. Lett.* **101**, 156802 (2008).
- ²³M. Z. Hossain, S. Romyantsev, M. S. Shur, and A. A. Balandin, *Appl. Phys. Lett.* **102**, 153512 (2013).
- ²⁴P. Dutta, P. Dimon, and P. Horn, *Phys. Rev. Lett.* **43**, 646 (1979).
- ²⁵S. V. Morozov, K. S. Novoselov, M. I. Katsnelson, F. Schedin, D. C. Elias, J. A. Jaszczak, and A. K. Geim, *Phys. Rev. Lett.* **100**, 016602 (2008).
- ²⁶S. Romyantsev, G. Liu, M. S. Shur, R. A. Potyailo, and A. A. Balandin, *Nano Lett.* **12**, 2294 (2012).