Charge Noise in Graphene Transistors

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ABSTRACT We report an experimental study of 1/f noise in liquid-gated graphene transistors. We show that the gate dependence of the noise is well described by a charge-noise model, whereas Hooge’s empirical relation fails to describe the data. At low carrier density, the noise can be attributed to fluctuating charges in close proximity to the graphene, while at high carrier density it is consistent with noise due to scattering in the channel. The charge noise power scales inversely with the device area, and bilayer devices exhibit lower noise than single-layer devices. In air, the observed noise is also consistent with the charge-noise model.

KEYWORDS Graphene, liquid gate, transistor, 1/f noise, Hooge, charge noise

I nherent noise limits the performance of electronic devices in circuits and sensors. Here we focus on graphene, which has been shown to function as a promising sensor material in both the gas phase1 and the liquid phase.2 The sensing mechanism of these devices relies on local perturbations of the graphene sheet that modulate its global transport properties1,3 in a manner analogous to the field effect induced by a gate electrode.4 An exceptionally high sensitivity to adsorbed gas species was demonstrated, even down to single-molecule sensitivity.1 When employed in liquid, carbon field-effect devices based on carbon nanotubes, graphene, and chemically modified graphene can be used as sensors for dissolved species such as charged biomolecules.3,5–7 Because of the high sensitivity to local perturbations, it is expected that uncontrolled charge fluctuations in the vicinity of the device - as commonly associated with charge traps in the silicon oxide substrate8 - can result in considerable low-frequency noise, which is detrimental to device performance. To date, few studies have addressed the noise properties of graphene. In the low-frequency limit, where the graphene sheet is electrically contacted with Cr/Au electrodes patterned using e-beam lithography. Measurements were performed as described in ref 12. Two-terminal graphene devices were prepared from mechanically exfoliated graphite on oxidized silicon wafers (285 nm SiO2).4 The graphene flakes were identified by their optical contrast14 and electrically contacted with Cr/Au electrodes patterned using e-beam lithography. Measurements were performed in a home-built flow cell13 filled with an aqueous electrolyte buffered at pH 7.2 using 10 mM phosphate buffer. A liquid-gate potential, \( V_{lg} \), was applied to the graphene sheet. The Dirac point.21,22 We measured current-noise power spectra, voltage, the device dimensions, and the number of graphene layers. We find that the dependence of the noise on the gate-induced carrier density qualitatively disagrees with the Hooge relation. Instead, our experimental observations are consistent with an augmented charge-noise model,11–13 which distinguishes between two separate contributions to the noise. At low carrier density, the noise is dominated by charge noise associated with random charge fluctuations in the environment that couple to the device through a field effect. This charge noise scales inversely with the device area and is lower for BLG than for SLG devices. At high carrier density, a gate-independent noise source becomes apparent that can be associated with scattering in the channel. These findings are consistent with the augmented charge-noise model and previous observations of charge noise in liquid-gated carbon nanotube devices.12,13

Figure 1a depicts graphene in a liquid-gated transistor layout. We measured the source-drain current, \( I_{sd} \), while applying a small dc bias voltage \( V_{sd} \) (≤5 mV). All electrical measurements were performed as described in ref 12. Figure 1b shows typical source-drain conductance \( G(V_{sd}) \) curves measured for liquid-gated SLG and BLG devices. The curves exhibit a minimum in \( G(V_{sd}) \) at the Dirac point, and a monotonically increasing \( G(V_{sd}) \) on both sides away from the Dirac point.21,22 We measured current-noise power spectra,
Figure 2b,e shows $S_G$ following the arguments of ref 8, Hooge's relation predicts that inversely proportional to the number of charge carriers. Furthermore, $S_G$ does not increase monotonically with increasing $|V_{lg}|$ indicated in Figure 1b (grayscale dots labeled I). Conductance-noise power spectra are shown for three different gate voltages, as indicated in Figure 1b (grayscale dots labeled I—III). Strikingly, for both the SLG and the BLG device, the noise power does not increase monotonically with increasing $|V_{lg}|$. Instead, the noise power exhibits a maximum at intermediate carrier density (II) where $dS_G/dV_{lg}$ is largest. This gate dependence of the noise power is indicative of charge noise, as discussed below.11,12

To study in detail the dependence of the low-frequency noise on the number of gate-induced charge carriers, we characterized the noise as a function of $V_{lg}$. Figure 1c,d plots the normalized conductance-noise power spectra, $S_G(f)/G^2 = S(f)/\Delta S_G$, for the SLG and BLG devices of Figure 1b, respectively. As indicated in Figure 1b (grayscale dots labeled I—III). Strikingly, for both the SLG and the BLG device, the noise power does not increase monotonically with increasing $|V_{lg}|$. Instead, the noise power exhibits a maximum at intermediate carrier density (II) where $dS_G/dV_{lg}$ is largest. This gate dependence of the noise power is indicative of charge noise, as discussed below.11,12

Figure 2 presents typical transport and noise data for two SLG devices (Figure 2a—c), and two BLG devices (Figure 2d—f). In Figure 2a,d, the conductance $G$ for each device is plotted as a function of the gate voltage. To facilitate comparison between different devices, the $V_{lg}$ axes have been centered at $V_0$, defined as the gate voltage at which $G$ is minimum. We recorded the noise power spectrum at each gate voltage and, as a representative measure for the magnitude of the low-frequency noise, we extracted the conductance noise power spectral density at 1 Hz, $S_G(1\,\text{Hz}) = S(1\,\text{Hz})/\Delta S_G^2$, by fitting $S(f) = S(1\,\text{Hz})/f^\beta$ to each spectrum. Typically, the fitted noise exponent $\beta$ was $0.8 \leq \beta \leq 1.2$. Figure 2b,e shows $S_G(1\,\text{Hz})$ for the devices of Figure 2a,d, respectively. $S_G(1\,\text{Hz})$ is clearly at a minimum value at $V_0$, and passes through a local maximum negative of $V_0$. Comparing the Hooge prediction $S_H(1\,\text{Hz})/G^2 = \xi G$ to the data in Figure 2c,f (solid lines), where $\xi$ is treated as an adjustable parameter, it is clear that the gate dependence of the noise in liquid-gated graphene devices cannot be described by Hooge’s relation. Whereas Hooge’s model predicts a maximum in $S_G(1\,\text{Hz})/G^2$ at the Dirac point, where the carrier density is minimum, we instead observe a pronounced minimum in $S_G(1\,\text{Hz})/G^2$ for both SLG and BLG devices.

Alternatively, we compare the data to an augmented charge-noise model proposed by Tersoff,11 which we recently used to successfully describe low-frequency noise in liquid-gated carbon nanotube transistors.12,13 The augmented charge-noise model predicts that $S_G(1\,\text{Hz}) = V_{sd}^2 S(1\,\text{Hz}) = S_{\text{input}}(dI_{sd}/dV_{lg})^2 + A_d (R_d/R_{tot})^2 I_{sd}^2$. Here the first (charge-noise) term represents current noise associated with random charge fluctuations with power $S_Q$ in the vicinity of the device. These charge fluctuations couple to the transistor with an effective gate capacitance $C_{gate}$ and can thus be represented as random voltage fluctuations of the gate potential with power $S_{\text{input}} = (1/C_{gas})^2 S_Q$. The second term of the augmented charge-noise model represents current noise from a gate-independent series resistance $R_d$ that exhibits low-frequency noise with a noise amplitude $A_d = \alpha_d V_{sd} R_d^2$, such that the total contribution equals $A_d (R_d/R_{tot})^2 I_{sd}^2 = \alpha_d^4 I_{sd}^4$. The curves in Figure 2b,e are fits of the charge-noise model to the $S_G(1\,\text{Hz})$ data with $S_{\text{input}}$ and $\alpha_d$ as fit parameters. To minimize the influence of any residual hysteresis, $dI_{sd}/dV_{lg}$ was determined by measuring $I_{sd}$ at $V_{lg}$ and at $V_{lg} \pm \Delta V$ (with $\Delta V \leq 100\,\text{mV}$) and calculating...
The conductance and noise data exhibit significant electron–hole asymmetry, likely due to a p–n junction that can form by doping from the contact, we fitted the p region (V_{lg} < V_{0}) and n region (V_{lg} > V_{0}) separately.

The augmented charge-noise model describes the data well for both SLG and BLG devices (cf. Figure 2b,e). Especially striking for the SLG devices, the charge-noise term captures both the minimum in S_{lg} near the Dirac point and the maximum in S_{lg} at intermediate carrier concentrations, where dI_{sd}/dV_{lg} has a maximum. This indicates that for SLG devices charge noise dominates the noise properties. Although we have also observed a similar dominance of charge noise for some BLG devices, more typically the noise at high carrier density in BLG devices is dominated by the series-resistor term, which dominates noise at high carrier density since the typical residence time of such an ion within a Debye screening length of the surface is of the order of nanoseconds, a mechanism that is unique to electrolyte gating. Finally, another source of fluctuations comes from mobile ions in solution diffusing near the graphene. Because the typical residence time of such an ion within a Debye screening length of the surface is of the order of nanoseconds, however, this is not expected to contribute significantly to the low-frequency noise studied here.

In ref 12, the length-corrected S_{input} for CNTs was found to be 0.54 m^2/μm/Hz, which yields ξ_{cnt} ≈ 0.004 μm^2/μm^2/Hz (dotted line in Figure 3a), assuming an average CNT diameter of 2.5 nm. Strikingly, CNTs exhibit nearly 1 order of magnitude lower charge noise than BLG devices. This may be caused by the electrolyte that surrounds the CNT and screens out a large fraction of the charge fluctuations from the underlying substrate, suggesting that the dominant fluctuators are associated with the silicon oxide substrate rather than the graphene itself.

Next we analyze the geometry dependence of the 1/\mu noise of graphene at high carrier density. The fit parameter for the series-resistor term, which dominates noise at high carrier density, is α_{R} = A_{s}(R_{S}V_{sd})^2 = S_{R}V_{sd}^2, where S_{R} is the resistance-noise power of the series resistor. We assume for simplicity that R_{S} and S_{R} are independent of the gate voltage. The experimental scatter in our data however does not allow ruling out a weak gate dependence. Attributing the noise described by the series resistor term to mobility fluctuations caused by independent scatterers that are evenly distributed over the graphene sheet, α_{R}V_{sd}^2 is expected to scale as L/W^3, where L is the length, and W the width of the graphene (as derived in the Supporting Information). Figure 3b shows α_{R}V_{sd} as function of L/W^3, which is consistent with the data within experimental scatter. α_{R}V_{sd}^2 is significantly larger for SLG than for BLG devices, which is expected if the density of fluctuating scatterers is the same in the two cases (as expected for oxide- or surface-bound scatterers) or scales linearly with the number of layers (as expected for lattice defects). Alternatively, we show in the Supporting Information Figure S4 that the scaling of α_{R}V_{sd}^2 with geometry also appears consistent with a gate-independent contact resistance. It is however unlikely that this is the dominant source of noise at high carrier density since the contact resistance was found to be independent of the

\[ \Delta \text{I}_{sd}\Delta V_{lg} \]
The measured conditions in a back-gated transistor layout. Figure 4 plots frequency noise properties of graphene devices in ambient distributed over the graphene. The resistor term is also suppressed for BLG devices (cf. Figure 4). In addition, we observed that the noise power of the series-resistor term is also suppressed for BLG devices (cf. Figure 4). Roughly twice the quantum capacitance of SLG, both of which lead to a suppression of charge noise in BLG. In summary, we have studied the 1/f-noise properties of graphene in a liquid-gated transistor layout and have addressed the scaling of the noise properties with the gate-induced carrier density, the device dimensions, and the number of graphene layers. We find that the noise amplitude does not scale inversely with the number of gate-induced charge carriers as postulated by the empirical Hooge relation. Instead, for both SLG and BLG devices, the noise power is well described by an augmented charge-noise model, which reveals that at low carrier density the noise is dominated by charge noise that is associated with charge fluctuators in close proximity of the graphene sheet. The power of the charge noise scales inversely with the device area and the number of graphene layers. Interestingly, liquid-gated graphene exhibits a significantly higher charge-noise power in comparison to liquid-gated CNTs.

Acknowledgment. We acknowledge NWO and NanoNed for financial support.

Supporting Information Available. Fitted curves of Figures 2 and 4 without smoothing, additional noise data for a BLG device, analysis of noise associated with contact resistance, derivation of the scaling of $\alpha_f V_{sd}^2$ with device geometry, comparison of the noise in liquid and under ambient conditions, estimate of the ratio of quantum capacitances of SLG and BLG, and figures that show the relative contribution of charge-noise term and series resistor term to the fits of augmented charge noise model to data of Figure 2. This material is available free of charge via the Internet at http://pubs.acs.org.

REFERENCES AND NOTES