

Charge Transport in Dual Gated Bilayer Graphene with Corbino Geometry

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ABSTRACT The resistance of dual-gated bilayer graphene is measured as a function of temperature and gating electric fields in the Corbino geometry which precludes edge transport. The temperature-dependent resistance is quantitatively described by a two-channel conductance model including parallel thermal activation and variable range hopping channels, which gives the electric-field-dependent band gap whose magnitude is found to be in good agreement with infrared absorption experiments. Low-temperature transport is similar to that seen in previous studies of dual-gated bilayer graphene with edges, suggesting that edge transport does not play an important role.

KEYWORDS Bilayer graphene, tunable band gap, Corbino disk, edge transport

The fundamental physics of graphene as well as its potential for future electronic applications has attracted significant contemporary interest.^{1–3} The absence of a band gap in single layer graphene (SLG) and bilayer graphene (BLG) poses a significant challenge for many application purposes where the ability to turn off the current is desired.³ One solution to this problem is the opening of a band gap in BLG by the application of an electric field perpendicular to the graphene layers.^{4,5} However, while infrared absorption experiments have observed band gaps up to 250 meV,⁶ low-temperature electrical transport measurements show that the maximum resistance R_{\max} has weak temperature dependence characterized by much smaller energies in either supported^{7,8} or suspended⁹ BLG with dual gating. Recently it was suggested that this energy scale difference might result from conducting paths at the edges of BLG samples which are related to the topologically protected metallic edge states in topological insulators;¹⁰ transport experiments would probe these states while optical experiments would be relatively insensitive to them.

Here we report the first study of dual-gated bilayer graphene in the Corbino disk geometry which removes the possibility of any conductance channel through the edges. The temperature dependence of the conductance is found to be well described by considering a simple thermal activation (STA) channel in parallel with a variable range hopping (VRH) channel. The experimentally extracted band gap magnitude for STA is in good agreement with the values obtained from infrared spectroscopy⁶ and is insensitive to the specific model of variable range hopping used. The low-temperature transport behavior, which is consistent with VRH, is qualitatively similar to previous studies with geometries that allow edge transport.^{7,8} Our results thus suggest

that, at least for these dual-gated BLG devices, the on–off ratio is largely limited by disorder in the bulk BLG rather than by transport along its edges.

Various recent efforts have been made to engineer a band gap in graphene-based field effect transistors. One method is to spatially confine the electrons within a narrow channel by cutting graphene into nanometer size ribbons.^{11–14} Another avenue is chemical modification of graphene, such as oxidation, hydrogenation, and fluorination.^{15–17} While gapped transport behaviors have been revealed in these devices, it has been proven challenging to preserve the superior electrical properties of graphene after such tailoring and modifications. An alternative route is to introduce a sublattice asymmetry in graphene. For SLG, such efforts are so far largely limited to theoretical proposals.^{18–20} In the case of BLG, the sublattice asymmetry can be achieved more readily by introducing a potential difference δV between the two graphene layers^{4,5} as shown in Figure 1a. Such a potential difference naturally arises in a back-gated BLG device at finite gate fields, resulting in a doped semiconductor. If on the other hand the device is dual gated, the Fermi energy E_F and δV can be tuned independently by the difference and sum of the two displacement fields D_t and D_b in the regions above and below the BLG, controlled by the top and bottom gates, respectively. Particularly, the condition $D_t = D_b$ results in a charge neutral BLG with E_F lying in a tunable band gap, which opens the opportunity to create an “off” state for the bilayer graphene field effect transistors.⁶

In this manner, recent optical studies on dual-gated BLG convincingly demonstrated a tunable band gap reaching the infrared range.⁶ Transport studies on similar dual-gated BLG, however, show that the conductance does not turn off until very low temperatures.^{7,8} This greatly limits the on–off ratio and thus the potential usefulness of such devices. Identification of the leakage channel which gives rise to the increased low-temperature conductance is thus not only scientifically

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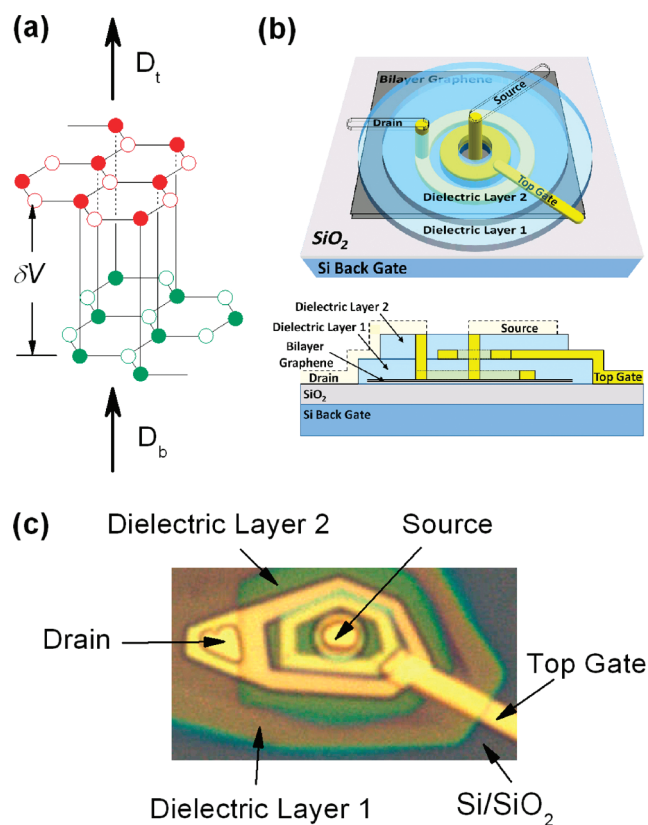


FIGURE 1. Dual-gated bilayer graphene with Corbino-disk geometry. (a) Bilayer graphene lattice sandwiched between top and bottom gating displacement fields. (b) Schematic drawing of the device. The upper plot is the top view and the lower is the side view. The top gate is sandwiched between dielectric layer 1 and dielectric layer 2. The source lead is on top of dielectric layer 2 and contacts the device via the center hole made in the two dielectric layers. (Fabrication details are in the Supporting Information.) (c) Optical microscope image of a BLG device taken after fabrication of the source, drain, and top gate electrodes and dielectric layers 1 and 2 but before deposition of the source and drain leads. The diameter of the center Cr/Au source electrode is 3 μm .

interesting but also practically important. Efforts to reduce disorder in BLG such as suspending the device as well as its top gate achieved improvements in R_{max} , but the characteristic excitation energy scale at low temperatures is found to be still much smaller than the expected band gap.⁹ Another possibility as was proposed recently is the leakage that might occur at the edges of bilayer graphene.¹⁰ Theoretical studies of SLG ribbons show that, depending on its direction with respect to the graphene lattice, the edge could be either conducting or insulating.^{21–23} For BLG with zigzag edges, it was shown that there exist bands of edge states inside the electric field induced gap.²⁴ A recent study found that metallic edge states of gapped BLG may be robust to edge disorder and could provide a significant leakage conductance path.¹⁰ In addition, asymmetry on the top and bottom gate geometries in real devices would lead to fringing electric fields in the device and a mismatch between the displacement fields D_t and D_b , resulting in doping of the edges when the bulk is insulating.

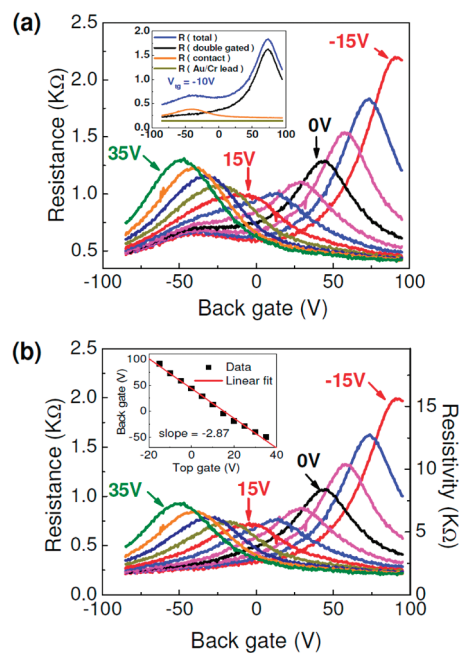


FIGURE 2. Room temperature transport characteristics of the dual-gated Corbino BLG. (a) Device resistance $R(V_{\text{bg}})$ as a function of back gate voltage V_{bg} for various values of V_{tg} . V_{tg} is changed in step size of 5 V. The inset shows an example of contact resistance subtraction for $V_{\text{tg}} = -10$ V. (b) $R(V_{\text{bg}})$ after subtraction of contact resistance as described in text. The inset shows the V_{bg} value where the peak resistance occurs for different V_{tg} .

In order to distinguish bulk transport from edge transport, we fabricated dual-gated BLG devices in the Corbino-disk geometry. The BLG sample was deposited on a Si/SiO₂ substrate by mechanical exfoliation of natural graphite (Nacional de Grafite Ltda.) and confirmed to be BLG by Raman spectroscopy (see Supporting Information).²⁵ Figure 1b shows a schematic and Figure 1c shows the optical image of a dual-gated Corbino-disk BLG device. The ring-shaped top gate is isolated from the BLG by electron-beam overexposed poly(methyl methacrylate) (PMMA) (see Supporting Information for more details).^{26,27} Note that the device is fabricated such that the source electrode crosses the device from above the top gate electrode, isolated by a second overexposed PMMA layer. This avoids screening of D_t by the source lead which would otherwise result in a leaking path for the device, and ensures an unbroken ring-shaped region of uniform D_t and D_b which separates the source and drain electrodes. The conduction path is thus forced to pass through the bulk of the dual-gated BLG. See Supporting Information for details of the device fabrication.

Figure 2a shows the room temperature resistance R of the dual-gated BLG Corbino disk as a function of back gate voltage V_{bg} at various values of the top gate voltage V_{tg} . The two-peak structure in the data results from two different device regions: the dual-gated region and the regions near the source and drain electrodes which are back-gated only. One resistance peak occurs consistently at $V_{\text{bg}} = -40$ V independent of V_{tg} ; we ascribe this to the part of the bilayer

graphene that is not covered by the top gate. The other resistance peak moves with top-gate voltage and corresponds to the dual-gated region. This peak occurs at increasingly positive V_{bg} for increasingly negative values of V_{tg} reflecting the condition $D_t = D_b$. This observation offers us a way to estimate the contact resistance which is usually difficult for Corbino geometry devices. We first obtain the resistance of the chromium/gold (Cr/Au) source–drain leads experimentally. In the last step of the sample fabrication, we made two source and two drain Cr/Au leads across the two holes shown in Figure 1c. We can then measure the source–source or drain–drain resistances bypassing the BLG device; both resistances are approximately 140Ω . The resistance of the un-top-gated BLG graphene is estimated using the trace with $V_{tg} = 30$ V. At this specific top gate voltage, the two peaks merge into one, indicating that the Fermi energies of the two regions match each other. After subtracting 140Ω , this trace is then scaled by a numerical factor (0.22) to estimate the un-top-gated bilayer graphene resistance, which can be subtracted to obtain an estimate for the resistance of the dual-gated portion of the device. The inset of Figure 1a shows an example of contact resistance subtraction for the $R(V_{bg})$ trace at $V_{tg} = -10$ V.

Figure 2b shows the extracted $R(V_{bg})$ data from Figure 2a with contact resistance removed. The minimum value of the peak resistance occurs at $V_{tg} \approx 15$ V and $V_{bg} \approx 0$ V, and presumably corresponds to the condition that $D_t = D_b = 0$; here $V_{tg} \neq 0$ indicates that the chemical doping of holes in the dual-gated region predominantly originates from the top surface of BLG, possibly due to the overexposed PMMA. Using the aspect ratio of the top gate, we can further estimate the resistivity of the device as a function of top and back gate voltages. This allows us to obtain the mobility of the device to be about $500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. As a comparison, a previous study reported a dual-gated BLG device with a mobility of $1000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.⁷

Figure 3 shows the resistance of the dual-gated BLG as a function of V_{tg} and V_{bg} at a temperature $T \approx 7$ K. At low temperatures, the top gate has a much larger effect on the peak resistance R_{max} ; at $V_{tg} = -30$ V, the peak resistivity reaches a value of about $1 \text{ M}\Omega$. Here the contact resistance is not removed which introduces some error to the resistivity; however since R_{max} at low T at the large displacement fields analyzed below is much larger than the contact resistance, the resulting error to our analysis is quite small. The inset plots the V_{bg} value at which R_{max} occurs as a function of V_{tg} . The slope gives the ratio of the two gate capacitances and indicates that the top gate is about twice as efficient as the back gate. The top gate dielectric thickness is measured to be approximately 130 nm by atomic force microscopy, from which we estimate the dielectric constant of the overexposed PMMA to be 3.4, somewhat smaller than that reported in ref 26 but in good agreement with ref 27.²⁸

We studied the temperature dependence of $R(V_{bg})$ of the dual-gated BLG at several fixed D_t values ranging from 0.78

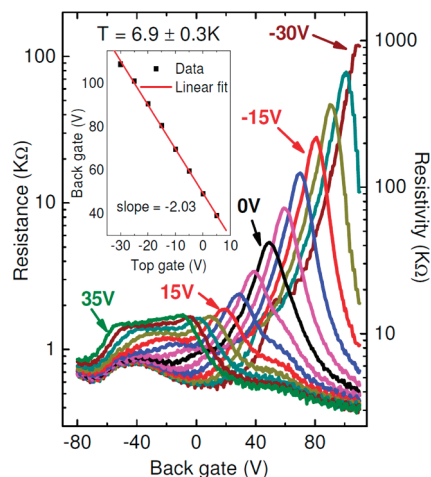


FIGURE 3. Low-temperature resistance (left scale) and resistivity (right scale) of the dual-gated Corbino-BLG as a function of V_{tg} and V_{bg} . V_{tg} is changed in step size of 5 V. The inset shows the V_{bg} value where the peak resistance occurs for different V_{tg} . Here the contact resistance is not removed.

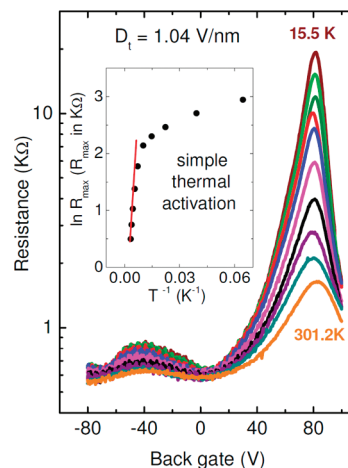


FIGURE 4. Temperature dependence of transport properties of the dual-gated Corbino-BLG at a fixed top gate displacement field of 1.04 V/nm . Different traces top to bottom are for temperatures at 15.5, 25.4, 44.6, 67.5, 98.5, 140, 181, 222, 261, and 301.2 K. The inset is an Arrhenius plot of the peak resistance; linear behavior corresponds to simple thermal activation.

to 1.17 V/nm .²⁹ The upper limit of D_t is set by the breakdown electric field of the gate dielectrics, while at low D_t values the smaller temperature dependence of R_{max} would make the errors caused by uncertainties in the contact resistance large. Figure 4 shows $R(V_{bg})$ at various temperatures at $D_t = 1.04 \text{ V/nm}$. The inset is the Arrhenius plot for R_{max} ; linear behavior here would indicate simple thermal activation (STA), i.e.

$$R_{max} = R_{S0} \exp\left[\frac{\Delta}{2k_B T}\right]$$

where Δ is the band gap and k_B is the Boltzmann constant.⁸ However, we found that the slope of $\ln R_{max}$ vs $1/T$ increases monotonically with decreasing $1/T$ (increasing temperature).

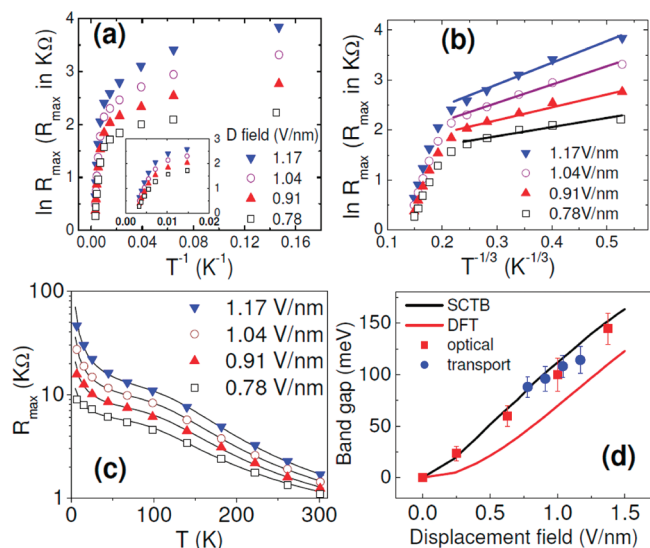


FIGURE 5. Analysis of temperature dependence of the peak resistance $R_{\max}(T)$. (a) Arrhenius plot of $R_{\max}(T)$ at four different displacement fields. The inset zooms in the high-temperature behavior for clarity. (b) Dependence of $\ln R_{\max}$ on $T^{-1/3}$; linear behavior indicates variable range hopping in two dimensions. (c) $R_{\max}(T)$ with fits to the two channel conductance model (eq 1 in text). Symbols are experimental data and smooth curves are theoretical fits. (d) Band gap of the dual-gated Corbino-BLG. The blue dots are experimental data from our transport measurements. Red squares are from optical studies in ref 6. Black and red curves are calculations using the self-consistent tight binding (SCTB) model³⁰ and density functional theories (DFT).³¹

Similar changes of the $\ln R_{\max}(1/T)$ slope are also observed for other displacement fields as shown in Figure 5a; $\ln R_{\max}$ vs $1/T$ is always sublinear in the temperature range studied. Moreover, at about 100 K, there is a sharp change in the slope; transport is poorly described by STA at low temperatures. Instead, we find that a plot of $\ln R_{\max}$ with respect to $T^{-1/3}$ (Figure 5b) shows roughly linear behavior below $T = 100$ K, indicative of variable range hopping (VRH) in a two-dimensional system of localized states.⁷

We interpret the full temperature dependence of the resistance as resulting from two conductance channels: VRH dominates at low temperature and STA to the valence or conduction band edge dominates at high temperature. The conductivities of the two channels are assumed to be additive

$$\sigma = \sigma_{\text{STA}} + \sigma_{\text{VRH}}$$

$$\sigma_{\text{STA}}^{-1} = R_{S0} \exp\left[\frac{\Delta}{2k_B T}\right] \quad (1)$$

$$\sigma_{\text{VRH}}^{-1} = R_{V0} \exp\left[\left(\frac{T_0}{T}\right)^{1/3}\right]$$

The values of R_{V0} and T_0 are extracted by fitting the low temperature portion of the data in Figure 5b. R_{S0} and Δ are then adjusted to find the best fit to the $R_{\max}(T)$ over the whole temperature range.

Figure 5c shows the results of the fits of the experimental data using eq 1. The two-channel model explains $R_{\max}(T)$ over the entire range of temperatures. Figure 5d shows the values of the band gap Δ obtained from the fits, along with the results obtained in infrared absorption studies in ref 6 as well as theoretical calculations.^{30,31} The magnitude of the band gap is in good agreement with the optical experiment⁶ and the self-consistent tight-binding calculation.³⁰ Because of the limited temperature range, there is a large uncertainty in determining the power of temperature dependence in the VRH model. Although physically $T^{-1/3}$ is expected for a 2D disordered system, we also tried powers ranging from $T^{-1/4}$ to $T^{-1/2}$ to obtain R_{V0} and T_0 before fitting the data over the entire temperature range and found that the values of the band gap Δ are quite robust and the changes are within the error bars displayed in Figure 5d. The facts that Δ does not depend on the details of the low-temperature model used and the magnitude of Δ is in excellent agreement with optical data together are strong evidence that Δ measures the band gap in dual-gated BLG and the temperature-dependent resistivity indeed reflects STA at high temperatures.

In conclusion, we measured the temperature and displacement field dependent resistance of dual-gated bilayer graphene (BLG) in the Corbino disk geometry. Our data are qualitatively similar to previous results,^{7,8} suggesting that for such dual-gated BLG devices, the edges are not dominant conduction paths. The temperature dependence of the resistance is quantitatively explained within a two-channel conductance model with high-temperature behavior determined by simple thermal activation and low-temperature behavior dominated by variable range hopping. The band gap of dual-gated BLG determined from electrical transport is found to be in excellent agreement with infrared spectroscopy studies.⁶ The fact that the VRH contribution to the conductance is significant even up to room temperature indicates that reducing disorder in BLG is necessary to increase performance (e.g., on/off ratio) in dual-gated BLG devices.

Note Added in Proof. After submission of this paper, we became aware of two related works on dual gated bilayer graphene in Hall bar geometry.^{32,33} The similarity of electronic transport between those works and ours for similar temperature range further substantiates our conclusion that edge transport is unimportant in the temperature range we study.

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Supporting Information Available. Details on the fabrication of the dual-gated bilayer graphene with Corbino-disk geometry are given, and a Raman spectrum of the bilayer

graphene used in this work is shown. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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- (28) We note that the room temperature data in the inset of Figure 2b indicates a dielectric constant of 4.8 which agrees better with ref 26. Since at low temperatures the traces display less hysteresis than at room temperature, we believe 3.4 is a more reliable value.
- (29) Due to the uncertainties in the dielectric constant of the overexposed PMMA, D_i is calculated using the fact that D_i is equal to D_b at R_{max} . D_b is given by $D_b = \epsilon_{SiO_2}(V_{bg} - V_{bg0})/d_{SiO_2}$, where $\epsilon_{SiO_2} = 3.9$, $d_{SiO_2} = 300$ nm are dielectric constant and thickness of SiO_2 , V_{bg0} is the back gate voltage at which $D_b = 0$. For the device reported here $V_{bg0} \approx 0$ and is not sensitive to temperature changes.
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