Imaging the Breakdown of Ohmic Transport in Graphene

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Ohm’s law describes the proportionality of the current density and electric field. In solid-state conductors, Ohm’s law emerges due to electron scattering processes that relax the electrical current. Here, we use nitrogen-vacancy center magnetometry to directly image the local breakdown of Ohm’s law in a narrow constriction fabricated in a high mobility graphene monolayer. Ohmic flow is visible at room temperature as current concentration on the constriction edges, with flow profiles entirely determined by sample geometry. However, as the temperature is lowered below 200 K, the current concentrates near the constriction center. The change in the flow pattern is consistent with a crossover from diffusive to viscous electron transport dominated by electron-electron scattering processes that do not relax current.

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Ohm’s law states that the current flow through an electrical conductor is proportional to a voltage difference across it. While this introductory textbook physics is ubiquitous in macroscopic electrical devices, Ohm’s law need not hold locally at every point inside of a conductor. Specifically, Ohm’s law arises only on length scales sufficiently long that microscopic scattering processes completely relax the electrical current. In an ordinary metal, impurity scattering and umklapp processes, each of which relax current, dominate the electronic dynamics; hence Ohm’s law arises on scales larger than the electronic mean free path, $\ell_{\text{mr}}$. In this regime, electrical transport is diffusive.

However, in low-density, low-disorder Fermi liquids, it was predicted decades ago that dynamics could be dominated by electron-electron collisions, which conserve momentum. In the regime where the electron-electron scattering length $\ell_{\text{ee}} \ll \ell_{\text{mr}}$, the momentum-conserving collisions do not completely relax the electrical current, resulting in viscous rather than diffusive transport, with current flow resembling that of a fluid [1]. Following preliminary work in the 1990s on III-V semiconductor heterostructures [2], a slew of electrical and thermal transport anomalies observed in clean graphene heterostructures have been linked to the onset of electron hydrodynamics [3–8]. Most recently, imaging studies of the Hall voltage in a small magnetic field have revealed a crossover with rising temperature from a ballistic regime, where voltage is out of equilibrium, to a regime of strong voltage equilibration [9], interpreted as evidence for a viscous regime. Nitrogen vacancy (NV) imaging of narrow graphene channels at room temperature has shown parabolic current profiles at the charge neutrality point (CNP) [10]. However, the breakdown of Ohmic transport due to the onset of electron-electron dominated scattering has only been observed indirectly in its effect on transport coefficients.

Here we use direct imaging of the current flow profile to observe the local breakdown of Ohm’s law in a monolayer graphene device in which a narrow constriction has been etched. Using a scanning NV center magnetometer, we image the local magnetic field above the device, related by the Biot-Savart law to the current flow profile through the constriction. These current profiles are expected to be different if the flow is limited by impurities (Ohmic), electron-electron collisions (hydrodynamic), or boundary scattering (ballistic) [4,11–14]. In the Ohmic regime, current concentrates near the constriction boundaries, mathematically equivalent to the bunching of the electric field lines near the corners of a lightning rod. Hence, the presence or absence of the current bunching provides a clear means of distinguishing the transition. This clear Ohmic signature in a narrow constriction contrasts with the subtle differences between Ohmic and hydrodynamic or ballistic current density signatures in a long narrow channel. By directly comparing our images of current through a narrow slit and a long channel, we find that at room temperature and CNP, a viscous hydrodynamic fit to the current density in a long channel is inconsistent with the current densities measured in a narrow constriction, thus ruling out hydrodynamics at CNP in our samples, in contrast to recently published results in Ref. [10]. In our experiment, the relevant ratios between $\ell_{\text{ee}}$, $\ell_{\text{mr}}$, and the constriction width $w$ can be tuned in situ via control of the
carrier density and temperature. Our measurements definitively resolve the dramatic transition from Ohmic to non-Ohmic flow and provide evidence of a robust collision-dominated regime in which $\ell_{ee} < \ell_{nr}$.

Figures 1(a) and 1(b) show a schematic diagram of our experimental setup [15] and optical image of the graphene device. Current ($I = 150 \mu$A) is passed through a graphene constriction of nominal width $w = 3 \mu$m and thickness $t = 0.4 \mu$m etched in a monolayer of high-quality graphene encapsulated by hexagonal boron nitride. The flowing current produces a magnetic field that is sensed by the NV center. The magnetic resonance signal of the NV center is detected optically as the sample is scanned with respect to the NV at a constant height, with NV-graphene separations ranging from $z_{NV} = 140–170$ nm between different scans. The NV axis is oriented with a polar angle of $\theta = 50^\circ$ relative to the device normal and an azimuthal angle of $\phi = 173^\circ$ relative to the $x$ axis as defined in Fig. 1(c). The resulting spatial map of the stray magnetic field [Figure 1(c)] is then converted using standard Fourier domain techniques [16,17] into the total current density ($|j|$) in the vicinity of the constriction [see Figs. 1(d)–1(e) and Ref. [18]]. The uncertainty in the reconstructed current density is dominated by two main systematic sources: the uncertainty in the NV orientation relative to the sample normal, estimated to be $\pm 4^\circ$, and the uncertainty in the NV-graphene separation, estimated to be $\pm 15$ nm (see the Supplemental Material [18]).

We first image room temperature current flow at the charge neutrality point, shown in Figs. 1(d)–1(e). Here graphene behaves as a non-Fermi liquid, with electrical transport dominated by a current-relaxing recombination of thermally excited electrons and holes. The current profile is thus expected to be Ohmic [27]. Figure 1(e) shows the total reconstructed current density $|j|$ across the graphene constriction. The current profile shows distinctive peaks near the constriction boundaries, consistent with expectations for Ohmic transport. Indeed, the data are quantitatively well matched by a parameter-free fit to an Ohmic model (dashed red line) that assumes a spatially uniform local conductivity, whose value is independently measured with transport. We compare this to the small-$\ell_{ee}$, hydrodynamic limit (dashed orange line), with the Gurzhi length taken from a fit to the current density in a $2.7 \mu$m-wide channel (see the Supplemental Material [18]).

The excellent agreement to the Ohmic model provides strong evidence that conductivity is uniform across the...
constriction at room temperature and charge neutrality, implying that other possible explanations for a nonuniform flow play a minor role [28]. It bears noting that the finite distance between the NV center and the sample puts a fundamental limit on spatial resolution. The reconstructed \(|j|\) in Figs. 1(d)–1(e) is thus related to the physical current density via a spatial low pass filter. Figures 1(f)–1(g) show the expected current distribution used to generate the fit in Fig. 1(e). We conclude that at room temperature and at the CNP, transport through our device is diffusive, and momentum conserving electron-electron scattering is unimportant. This result stands in contrast to recently published results that attributed a parabolic current profile in a long channel to viscous flow at room temperature and CNP [10].

In order to understand the qualitative behavior of current flow away from the Ohmic regime, we perform simulations of the quantum Boltzmann equation (QBE) [18] in our constriction geometry, which allow us to capture the effects of finite \(\ell_{\text{ee}}\) and \(\ell_{\text{we}}\). Figure 2(a) shows simulation results assuming \(w = 3 \mu m\) for varying \(\ell_{\text{ee}}\) and \(\ell_{\text{we}}\). Evidently, current flow profiles can vary dramatically between transport regimes; in particular, the strong current concentration on the slit boundary is specific to the Ohmic regime. To capture these qualitative differences in a single quantitative figure of merit, Fig. 2(b) shows the curvature of \(|j|\) at the center of the slit plotted as a function of \(\ell_{\text{ee}}\) and \(\ell_{\text{we}}\). Deep in the Ohmic regime (I) where \(\ell_{\text{we}} \ll w, \ell_{\text{ee}}\), the expected flow profile shows good agreement with the data and Ohmic model fit of Fig. 1(g). The ballistic regime (II) is the limit of \(w \ll \ell_{\text{we}}, \ell_{\text{ee}}\), and results in a flat current profile. Hydrodynamic effects become visible when momentum conserving collisions are dominant and the momentum-relaxing length scale is large compared with the device size, \(\ell_{\text{ee}} \ll w < \ell_{\text{we}}\) (III). At extremely small \(\ell_{\text{ee}} \ll w^2/\ell_{\text{we}}\) there exists a final regime (IV), deep within the hydrodynamic limit, where viscous effects are so strong that a weakly double-peaked current profile again arises, as interactions reduce the effective momentum relaxation length to \(\sqrt{\ell_{\text{ee}}\ell_{\text{we}}}\) [11,27]. In a realistic device and measurement geometry, the ballistic and weakly hydrodynamic regimes (II and III) exhibit current maxima near the constriction center and can be difficult to distinguish: the subtle quantitative differences in boundary profiles are easily obscured by the finite spatial resolution arising from the finite distance between current and magnetic field sensor.

Presented in Fig. 3(a) are the experimentally measured current flow profiles at several carrier densities, including charge neutrality, at both \(T = 298\) K and \(T = 128\) K. At room temperature, the double-peaked current profile persists as the density is tuned away from charge neutrality. However, the size of the peaks is reduced with density, consistent with \(\ell_{\text{we}}\) increasing with density as expected from transport theories of monolayer graphene [29]. At \(T = 128\) K and at the CNP, we again observe the double-peaked profile, indicating that charge recombination dominates scattering near the CNP even at low temperatures. However, at finite densities and \(T = 128\) K, we observe the emergence of a single-peaked current profile, an unambiguous demonstration of locally non-Ohmic transport.

Because both ballistic and hydrodynamic transport are expected to be peaked in the center of the constriction, we turn to a quantitative comparison of our experimental data to the QBE simulations described above to place bounds on the possible values of \(\ell_{\text{ee}}\) and \(\ell_{\text{we}}\) in our device. Simulations and measurements are compared over a

FIG. 2. Boltzmann transport model. (a) Four examples of current flow profiles for a slit of finite thickness and a width \(w = 3 \mu m\) and thickness \(t = 0.4 \mu m\). The free parameters in the model are \(\ell_{\text{ee}}\) and \(\ell_{\text{we}}\). The current density is normalized by the average current density through the slit. Line profiles of the current across the center of the slits are shown underneath. Region I corresponds to the Ohmic regime where \(\ell_{\text{we}} = \ell_{\text{ee}} \approx 0\). Region II is in the deep ballistic regime with \(\ell_{\text{we}} = \ell_{\text{ee}} = 10 \mu m\). The hydrodynamic regime is represented by Region III (\(\ell_{\text{ee}} = 1 \mu m, \ell_{\text{we}} = 10 \mu m\)) where the current shape assumes a more elliptical profile. A final region, IV (\(\ell_{\text{ee}} \approx 0, \ell_{\text{we}} = 10 \mu m\)), corresponds to when electron-electron scattering becomes so dominant that it begins to reduce the effective current relaxation length and results in viscous bunching near the slit edges. (b) The curvature of the current, \(\delta^2|j|/\delta x^2\), at the center of the slit, normalized by the average current density through the slit. The changes in profiles in the regimes of Regions II and III are subtle to resolve when uncertainty in the slit width is taken into account.
two-dimensional area of dimensions $4.0 \times 1.6$ microns centered on the constriction (see [18]). The dashed red lines in Fig. 3(a) at carrier densities $n = 5 \times 10^{11}/\text{cm}^2$ and $n = -1 \times 10^{12}/\text{cm}^2$ are slices through the best-fit current patterns of the QBE simulations. At the CNP and 298 K, we find good agreement between a purely Ohmic model (red dashed line) and a slice through the reconstructed current density.

Figure 3(b) shows the root mean square (RMS) residual per pixel of the fit normalized by the average uncertainty in the current reconstruction, plotted as a function of the simulation input parameters $\ell_{ee}$ and $\ell_{mr}$. The white dashed lines correspond to contours with average residuals equal to the average current reconstruction uncertainty (see the Supplemental Material [18]). We take areas of the parameter space bounded from above by these contours [darker shades in Fig. 3(b)] as consistent with experimental data.

At room temperature, magnetometry data constrain $\ell_{mr} \lesssim 1 \mu$m, while providing no constraint on the value of $\ell_{ee}$. This is consistent with estimates for scattering by momentum-relaxing phonons, which dominate scattering on experimentally relevant length scales resulting in Ohmic flow. Best fit regions are markedly different at $T = 128$ K, and most consistent with the crossover regime intermediate between hydrodynamic and ballistic flow. At $T = 128$ K, the average RMS residual is minimal for $\ell_{ee} = 0.4 \mu$m and $\ell_{mr} = 3.1 \mu$m for both $n = 5 \times 10^{11}/\text{cm}^2$ and $n = -1 \times 10^{12}/\text{cm}^2$. However, larger values of $\ell_{ee}$ and $\ell_{mr}$ are only weakly constrained, primarily due to uncertainty in the precise nature of the boundary conditions, as well as uncertainty in the constriction width. An independent check on these fits can be obtained from measurements of the conductivity $\sigma$ in the same device (see [18]), from which we extract the mean free path $\ell_{\text{mfp}} = \hbar \sigma / 2k_F e^2$, where $k_F = \sqrt{\pi n}$ is the Fermi wavevector. In the Fermi liquid regime, $\ell_{\text{mfp}}$ approximates $\ell_{mr}$. We find that at both 298 K ($\ell_{\text{mfp}} \approx 0.9 \mu$m) and 128 K ($\ell_{\text{mfp}} \approx 4.3 \mu$m) the measured mean free path agrees with the momentum-relaxation length obtained from the NV magnetometry fits. Our data thus completely rule out both the strongly interacting hydrodynamic regime (IV) and the Ohmic regime (I).

In order to conclusively resolve the subtle differences in flow patterns in the hydrodynamic and ballistic crossover regime, a geometry better suited to measuring these differences or a sharper understanding of the realized boundary conditions will be required. However, our results, when taken together with those of Ref. [9], suggest that monolayer graphene hosts a weakly interacting hydrodynamic regime at intermediate temperatures, manifesting in strongly modified
local current and voltage distribution patterns. Additionally, in this Letter we use a two-dimensional geometry designed to minimize the importance of uncontrolled scattering at the etched walls of the device in order to rule out spurious flow patterns. Reference [9] explores hydrodynamic effects in a one-dimensional geometry that can be susceptible to effects from imperfect boundaries.

Looking forward, locally resolved current measurements may be useful in conclusively resolving hydrodynamic effects (or the lack thereof) in more exotic materials [30,31]. More broadly, these techniques provide a powerful method for visualizing electronic dynamics normally invisible in bulk resistivity measurements.

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[18] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.129.087701 for a description of device fabrication, our magnetometry methods, details on the Boltzmann Transport theory, and a comparison between the slit and channel geometries. The supplement includes the references listed below, which includes Refs. [19–26].