Rippled Graphene in an In-Plane Magnetic Field: Effects of a Random Vector Potential

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We report measurements of the effects of a random vector potential generated by applying an in-plane magnetic field to a graphene flake. Magnetic flux through the ripples cause orbital effects. Phase-coherent weak localization is suppressed, while quasirandom Lorentz forces lead to anisotropic magnetoresistance. Distinct signatures of these two effects enable the ripple size to be characterized.
Spin-resolved quantum interference in graphene

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WL in graphene

- Graphene: Dirac carriers with **chirality**
  - intrinsic: weak antilocalization (Berry’s phase of $\pi$ !)

- weak localization: for broken valley symmetry
  - by trigonal warping
  - by atomically sharp disorder (e.g. voids, sample edges)
  - SO interaction

- rippled Graphene in B-field
- random vector potential due to local misalignment

- $\delta B_\perp \sim B_\parallel Z/R$ induces local Aharonoc-Bohm phases
  - suppression of WL at a rate
  
  $$\tau^{-1} \rightarrow B_\parallel^2 Z^2 R$$

[Mathur and Baranger; PRB, 64, 235325 (2001)]

[Physics Procedia, 3, 1249 (2010)]
devices and setup

- device:
  - flakes exfoliated onto Si/SiO$_2$
  - SiO$_2$ etched down to 260nm in CF$_4$/O$_2$
  - e-beam for Cr/Au contacts
  - $V_D = 1 – 23$ Volt (Si-backgate)
    - depending on cooldown
    - and current path (!)
  - QHE: single layer graphene

- setup:
  - fridge $\sim 10$ mK ($T_e = 40$ mK)
  - 2-axis magnet ($B_{||} = 12$ T ; $B_{\perp} = 120$ mT)
  - orientation ensured by WL-signature
  - LockIn, 10nA bias
  - flake A: 3.2 k$\Omega$ contact resistance
  - flake B: 4-wire measurement
\[ \hat{H} = v \Pi_z \otimes \sigma \mathbf{p} - \mu [\sigma_x(p_x^2 - p_y^2) - 2\sigma_y p_x p_y] \]

\[ \Sigma_x = \Pi_z \otimes \sigma_x, \quad \Sigma_y = \Pi_z \otimes \sigma_y, \quad \Sigma_z = \Pi_0 \otimes \sigma_z, \]

\[ \Lambda_x = \Pi_x \otimes \sigma_z, \quad \Lambda_y = \Pi_y \otimes \sigma_z, \quad \Lambda_z = \Pi_0 \otimes \sigma_0. \]

\[ \Delta \rho(B) = -\frac{e^2 \rho^2}{\pi h} \left[ F\left( \frac{B}{B_\varphi} \right) - F\left( \frac{B}{B_\varphi + 2B_i} \right) - 2F\left( \frac{B}{B_\varphi + B_*} \right) \right] \]

\[ F(z) = \ln z + \psi \left( \frac{1}{2} + \frac{1}{z} \right), \quad B_{\varphi,i,*} = \frac{\hbar c}{4De^{-\tau_{\varphi,i,*}}} \]

\[ \psi \text{ is the digamma function} \]

[McCann et al.; PRL 97, 146805 (2006)]
magnetoconductance

- $g$ averaged over density range
- evaluated by
  \[
  \Delta g_{\text{WL}}(B_\perp) = \frac{e^2}{\pi \hbar} \left[ F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1}}\right) - F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + 2\tau_i^{-1}}\right) - 2F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + \tau_i^{-1} + \tau_s^{-1}}\right)\right],
  \]
- results for $B_\parallel = 0$:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Hole</th>
<th>Flake B Low density</th>
<th>Electron</th>
<th>Flake A Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>$10^{11}/\text{cm}^2$</td>
<td>$-13 \ldots -5$</td>
<td>$-2 \ldots 2$</td>
<td>$5 \ldots 13$</td>
<td>$-5 \ldots -3$</td>
</tr>
<tr>
<td>$W/L$</td>
<td>\ldots</td>
<td>$2.4 \pm 0.8$</td>
<td>$2.0 \pm 0.7$</td>
<td>$1.6 \pm 0.6$</td>
<td>$0.7 \pm 0.3$</td>
</tr>
<tr>
<td>$\tau_m^{-1}$</td>
<td>$10^{12}/\text{s}$</td>
<td>$15 \pm 5$</td>
<td>$20 \pm 10$</td>
<td>$15 \pm 5$</td>
<td>$11 \pm 5$</td>
</tr>
<tr>
<td>$\tau_s^{-1}$</td>
<td>$10^9/\text{s}$</td>
<td>$11 \pm 1$</td>
<td>$35 \pm 8$</td>
<td>$11 \pm 1$</td>
<td>$11 \pm 2$</td>
</tr>
<tr>
<td>$\tau_i^{-1}$</td>
<td>$10^9/\text{s}$</td>
<td>$70 \pm 50$</td>
<td>$170 \pm 70$</td>
<td>$120 \pm 80$</td>
<td>$20 \pm 10$</td>
</tr>
<tr>
<td>$\tau_s^{-1}$</td>
<td>$10^{12}/\text{s}$</td>
<td>$5.3 \pm 0.4$</td>
<td>$2.7 \pm 0.5$</td>
<td>$2.1 \pm 0.4$</td>
<td>$4.0 \pm 0.3$</td>
</tr>
</tbody>
</table>
- changes in conductance for low $B_{\perp}$
- for various $B_{\parallel}$
- at different density ranges

fitting with dephasing rate as the only free parameter:

$$\tau_{\phi}^{-1} \rightarrow \tau_{\phi}^{-1} + \sqrt{\frac{\pi}{\hbar^2}}(e^2/\hbar^2)vZ^2RB_{\parallel}^2$$

- good agreement with predicted dependence on $B_{\parallel}^2$
high $B_\perp$ regime

- change in Drude conductivity:
- higher momentum scattering rate due to Lorentz forces from the RVP
- predicted anisotropy

$$\Delta \rho(n, \theta, B_\parallel) = \frac{\sin^2 \theta + 3\cos^2 \theta}{4} \frac{1}{\hbar|n|^{3/2}} \frac{Z^2}{R} B_\parallel^2$$

- nicely fits density dependence
- anisotropy confirmed by high density average for different angle between current and $B_\parallel$

however: extracted ripple topography ($Z=0.6 \pm 0.1$ nm, $R=4 \pm 2$ nm)

does not match AFM and STM studies ($Z=0.2 \pm 0.1$ nm, $R=5 - 32$ nm)

- possible influence of spin orbit effects (intrinsic, Rashba, ripples)?