Flexural-phonon scattering induced by electrostatic gating in graphene

Graphene device – a vibrating membrane in an electrostatic and dielectric environment. Electron-phonon coupling and mobility limitations from the environment.

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Motivation – novel 2D materials and el-ph scattering

MoS$_2$ monolayer transistors

B. Radisavljevic et al., Nature Nanotechnology, VOL 6 (2011)

Graphene monolayer transistors

90,000 cm$^2$/V·s @300K and 1 $10^{12}$/cm$^2$.
45,000 cm$^2$/V·s @300K and 3 $10^{12}$/cm$^2$.

Silicene monolayer transistors

Li Tao et al., Nature Nanotechnology, VOL 10 (2015)

Encapsulation, edge contacting
suspend in high-$\kappa$ liquid->
screen charged impurities

B. Radisavljevic et al., Nature Nanotechnology, VOL 6 (2011)

One-Dimensional Electrical Contact to a Two-Dimensional Material
L. Wang et al., Science, VOL 342 (2013)
Motivation – Silicene (a 2D material with broken planar mirror symmetry)

\[ \mu_e \approx 10 \text{ cm}^2/\text{Vs} \ (T = 300K \text{ and carrier density } = 3 \times 10^{12} \text{ cm}^{-2}) \]
Silicon \[ \mu_e \approx 1400 \text{ cm}^2/\text{Vs} \]
Putting graphene in a gated device stack can also break the planar mirror symmetry!
Temperature regimes

$T \ll T_{BG}$: phonon system is degenerate [Bloch-Grüneisen (BG)]

$T >> T_{BG}$: phonon system is nondegenerate [equipartition (EP)].

$$T_{BG} = \frac{2\nu_{ph} k_F}{k_B} \approx 54\sqrt{n} \text{ K}$$

With $n$ in units of $n = 10^{12} \text{ cm}^{-2}$

**BG regime:**

- Backscattering

**EP-regime:**

- $n_B(\omega_q) \approx \frac{k_B T}{\hbar \omega_q}$

$T$ dependence -> details of phonons (flexural, substrate interaction) and impurities.

Phonon scattering rates (from $k$ to $k'$) – absorption/emission of a phonon (FGR):

$$P_{kk'}^{\lambda nn'} = \frac{2\pi}{\hbar} |g_{kk'}^{\lambda nn'}|^2 \left[ n_q^\lambda \delta (\epsilon_{k'n'} - \epsilon_{kn} - \hbar \omega_{q\lambda}) \delta_{k',k+q} + (n_q^\lambda + 1) \delta (\epsilon_{k'n'} - \epsilon_{kn} + \hbar \omega_{-q\lambda}) \delta_{k',k-q} \right]$$

Transport relaxation time:

$$\frac{1}{\tau_{kn}} = \sum_{k'n'} \frac{(1 - f_{k'n'}^0)}{(1 - f_{kn}^0)} (1 - \cos(\theta_{kk'})) P_{kk'}^{nn'} , \quad \cos(\theta_{kk'}) = \frac{\mathbf{v}_{k'n'} \cdot \mathbf{v}_{kn}}{\|\mathbf{v}_{k'n'}\| \|\mathbf{v}_{kn}\|}$$

Mobility:

$$\mu_e = -2q \frac{\sum_{kn \in c} |v_{kn}|^2 \partial f_{kn}^0 / \partial \epsilon_{kn} \tau_{kn}}{\sum_{kn \in c} f_{kn}^0}$$

A graphene capacitor

Highly doped graphene is efficient in screening the potential.
Behaves much like a metal-plate capacitor.
Gate field breaks planar mirror symmetry!

$$E(V) = \frac{1}{2} \int \delta n(r,V) \delta n(r,V) dr$$

$$= \frac{1}{2} C V_G^2$$
Mobility degradation

**300K:**
606.000 cm²/Vs to 208.500 cm²/Vs at $n_0 = 10^{12}$ cm⁻² (blue; scaled by 0.1)
118.000 cm²/Vs to 11.400 cm²/Vs at $n_0 = 10^{14}$ cm⁻² (red)

Significant (field-induced) degradation!
Modified scaling with temperature and carrier density!
Ingredients - Field-induced flexural scattering

(a) ZA

(b) ZO

Field-induced DP:

\[ D_0(V_G) \equiv \gamma n_0 \]

\[ \gamma = 35 \text{ (55) eV} \cdot \text{Å} \]

for \( \kappa = 2.5 \text{ (22)} \)

High occupation of (low frequency, constant DOS) ZA mode.

Nonzero coupling induced by the gate.

Coupling is linear in the induced carrier density and increases with dielectric constant.
Temperature scaling

Dirac model:

\[ \frac{1}{\tau_{ZA}^{k}} = \frac{v_F D_0^2(V_G)}{2\pi \rho b^2} \varepsilon_k^{-2} \frac{k_B T}{q_c} \]

\[ \mu \propto T^{-\alpha} \]

- Gate, \( n_0 = 2 \times 10^{13} \)
- Isolated, \( n_0 = 2 \times 10^{13} \)
- Gate, \( n_0 = 10^{14} \)
- Isolated, \( n_0 = 10^{14} \)

BG regime:

- \( q_{\text{max}} = 2k_F \)
- \( k_B T_{BG} = \hbar \omega_{q_{\text{max}}} \)
- \( T_{BG}^{LA} = 57 \sqrt{\tilde{n}} \text{ K} \)
- \( T_{BG}^{ZA} = 0.46 \tilde{n} \text{ K} \)
- \( \tilde{n} = n/10^{12} \text{ cm}^{-2} \)

Dominant mechanism at room temperature and even more at low T!
Modified scaling with temperature!
Room T: Indistinguishable from in-plane scattering (Higher DP).
Electrode configuration – controlling the effect

**Double gate stack**

![Graph showing energy levels](image)

**Dielectric sandwich**

![Diagram of dielectric sandwich](image)

**Breaking the symmetry or not?**

Sandwiching graphene between two layers with different dielectric constants or electrodes at different potentials degrades mobility significantly.
Experimental signatures

Modified carrier density scaling:

\[ \mu \sim n_0^{-3/2} \text{ Vs. } \mu \sim 1/n_0 (\sqrt{n_0}) \]

When gate-induced flexural scattering dominates.

Modified temperature scaling:

\[ \mu \propto T^{-\alpha} \quad \alpha=1 \text{ Vs. } 1 < \alpha \lesssim 5 \]

When gate-induced flexural scattering dominates transport in the in-plane BG regime.

\[ T < T_{BG} \approx 57 \sqrt{\tilde{n}} \text{ K} \quad \tilde{n} = n/10^{12} \text{ cm}^{-2} \]

Gating strategy:

Double gate setup can be utilized to turn the effect on and off by generating a symmetric or asymmetric potential across the device.

Conclusions:

- New “Field induced flexural-phonon” scattering mechanism defines a relation between device symmetry and resulting mobility.
- Protecting the planar mirror symmetry is of utmost importance to fully exploit the unique transport properties of graphene.