Electron Optics in Graphene Heterostructures with Nanopatterning

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Agenda

• Background
  • Electron optics in conventional semiconductors
  • Current state of graphene FETs and the Veselago lens

• Metrology of split-gate junctions
  • Quantifying device quality
  • Transverse magnetic focusing experiments
  • Snell’s Law
  • Measuring effective junction width

• Band structure engineering through superlattice gating
  • Dielectric modulation technique
  • Device design
  • Application to a split-gate graphene FET
Ballistic electron refraction

$$l_{mfp} = \tau \cdot v_F > L_{device}$$
Ballistic electron optics

2DEG ballistic transport
- Snell’s Law
- Electron optics “lens”

Ballistic p-n junctions in graphene

Veselago lens

Electronic switches

Theoretical n-p-n junction beam splitter

Graphene field effect transistors (gFETs)

**Bilayer (non-ballistic)**

![Diagram of bilayer graphene with gate and drain contacts](image)


**Sawtooth gated ballistic monolayer**

![Graph showing I_d vs V_g and V_d for sawtooth gating](image)

Previous work: beam splitter

Previous work: angular-dependent transmission

PNP junctions

Background by normal incident electrons

Yet to be observed
Challenges in achieving a sharp edge

Smooth junction edge
(compared with $\lambda_F$)

Rough edge refracts electron randomly

Angle dependent transmission
(sharp junction)

Advances in graphene device fabrication

van der Waals Transfer

1D Edge Contacts

Metallic gates

STM study of local potential
Zhu, X., et al. unpublished
Metric for device quality

Landau level broadening $\Gamma = \hbar/2\tau_q$

Graphene on SiO$_2$ (Zhu, 2009)
Straight edge junction

Measurement configuration

Large background
Achieving a smaller incident angle

Zero magnetic field

Transverse magnetic focusing (TMF)
Transverse magnetic focusing in 2DEGs

\[ L = 2n \times R_{\text{cyclotron}} \quad n = 1, 2, 3... \]


V_{\text{col}} (arb. units)

B (Gauss)
Transverse magnetic focusing in graphene

Resonance condition: $p$ is integer

$B_f^{(p)} = \left( \frac{2\hbar k_F}{eL} \right) p = \left( \frac{2\hbar \sqrt{\pi n}}{eL} \right) p$

Matched density TMF

\[ B = j \left( \frac{2\hbar \sqrt{\pi n}}{eL} \right) \quad j = 1,2,3... \]

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TMF across junctions

\[ p-p' \]
\[
\sqrt{1-\frac{n_1}{n_2}} \left( \frac{R_1-a}{R_1} \right)^2 + \sqrt{\frac{n_1}{n_2}} \cdot \frac{R_1-a}{R_1} \cdot a - a \frac{n_1}{n_2} = 0
\]

\[ p-n \]
\[
\sqrt{1-\frac{n_1}{n_2}} \left( \frac{R_1-a}{R_1} \right)^2 \left( W - \sqrt{2R_1 a - a^2} \right) + \frac{n_1}{n_2} \cdot \frac{R_1-a}{R_1} \cdot a - \frac{(W-\sqrt{2R_1 a - a^2})^2 + a^2}{2R_1} \frac{n_1}{n_2} = 0
\]

TMF across junctions

$p-p'$

$p-n'$

$p_1$ fixed

$p_1 = \text{const}

p_{1, \text{varying}}$

$p_1 = \text{const}

n_{2, \text{varying}}$

$p_1 = 1.61 \times 10^{12} \text{ cm}^{-2}$

Experiment vs. Simulation

Explanation of kinks

- Case 1: $p_1 > p_2$
- Case 2: $p_1 = p_2$
- Case 3: $p_1 < p_2$

Diagram showing the behavior of $R$ (a.u.) as a function of $n_2$ (10$^{12}$ cm$^{-2}$) and $B$ (mT), with distinct regions marked for each case.
Compare different modes

Extract 1\textsuperscript{st} order peaks:

\[ p-p \]
\[ n-n \]
\[ p-p' \]
\[ p-n \]

\[ p_1 = 6.76 \times 10^{11} \text{ cm}^{-2} \]

Snell’s law for ballistic electrons

\[ k_1 \sin \theta_1 = \pm k_2 \sin \theta_2 \]

Angular dependent transmission

\[ T = \left[ \frac{\cos(\theta_1) \cos(\theta_2)}{\cos^2\left(\frac{\theta_1 + \theta_2}{2}\right)} \right] e^{-\pi \hbar v_f k_f^2 d \sin^2(\theta_1)/V_o} \]

Toward sharper junctions

S. Chen, et al. *unpublished*
Back to zero field

Room temperature devices

Challenges with ballistic split-gate transistors

- Diffusive scattering due to roughness at device edges and gates boundaries
- Imperfect collimation of transport at first gate

**Deeper solution:**
band structure engineering

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Graphene superlattices: Hofstadter

Hexagonal geometry
\( \lambda \geq 14 \text{nm} \)

Dielectric-modulated electrostatic gating

Induced charge variation on graphene

\[ \Delta \sigma \quad (mC/m^2) \]

\[ V_{bg} = 10V \]
\[ V_{bg} = 30V \]
\[ V_{bg} = 50V \]

graphene

hBN

vacuum \( \varepsilon_r = 1 \)

SiO\(_2\) \( \varepsilon_r = 3.9 \)

Etched SiO\(_2\)

Si gate

metal gate hBN graphene
SiO$_2$ patterning

Triangular 40nm pitch

Square 35nm pitch
Triangular superlattice

$n_0 = \frac{1}{A} = \frac{2}{\sqrt{3}a^2} \quad a = 40\text{nm}, \text{triangular lattice}$

- Highly customizable
- Switchable
- Interesting physics at easily-achieved B-field (3.5T rather than 35T)
- Significantly altered electronic properties

Mikito Koshino – Tohoku University

C. Forsythe, et al. unpublished
One-dimensional superlattices

Initial device design

- Graphite
- BN
- G
- SiO₂
- 1D superlattice
- Si

20nm pitch HSQ

60nm pitch SiO₂ trenches
Measuring anisotropic transport

\[ \sigma_\perp \neq \sigma_\parallel \]

\( \sigma_\perp \) (n) reduced Fermi velocity

\( \sigma_\parallel \) (n) satellite Dirac peaks
Application to split-gate gFETs

- Superlattice parameters tuned to suppress perpendicular conduction ($\sigma_\perp \sim v_\perp \rightarrow 0$)
- Right-angle junction to further collimate ballistic electrons
- Angled junction to switch on/off

Proposed device design
Summary

• High-quality ballistic graphene junction
  • Negative refraction
  • Angular dependent transmission

• Band structure engineering
  • 2D superlattice gating achieved
  • 1D superlattices near

• Future of electron optics switch
  • Sharper junction
  • Angled-gate with anisotropic transport
  • Scaling for room temperature applications
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