Electron Optics in Graphene Heterostructures with Nanopatterning

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Agenda

- Background
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  - Current state of graphene FETs and the Veselago lens

- Metrology of split-gate junctions
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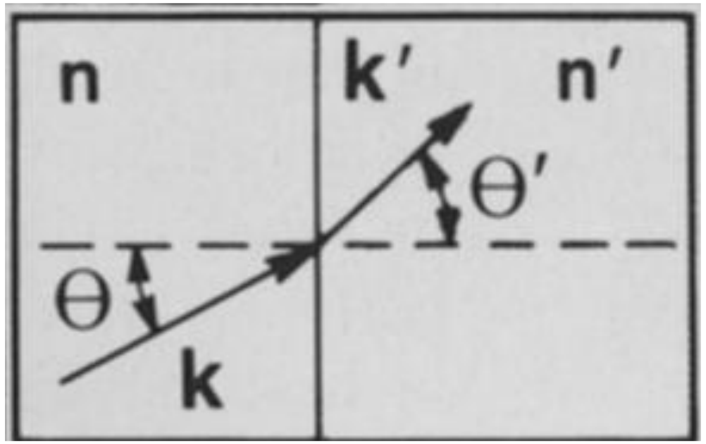
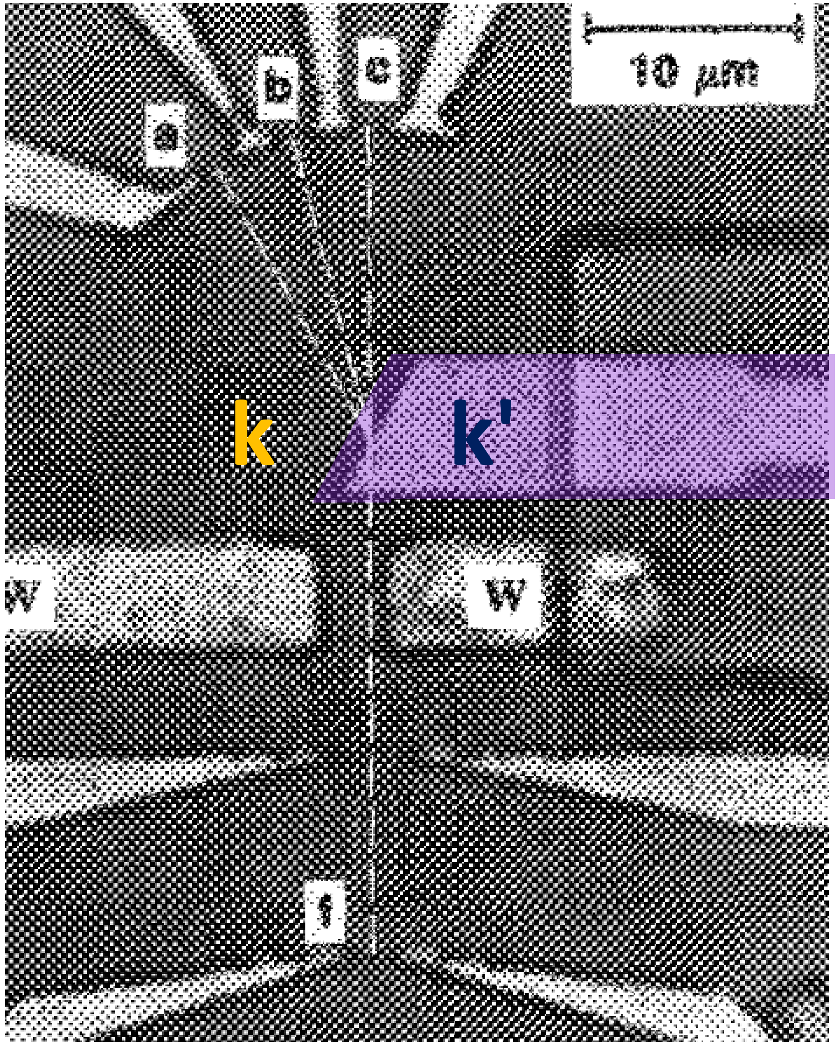
  - Snell’s Law
  - Measuring effective junction width

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

Ballistic electron refraction

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



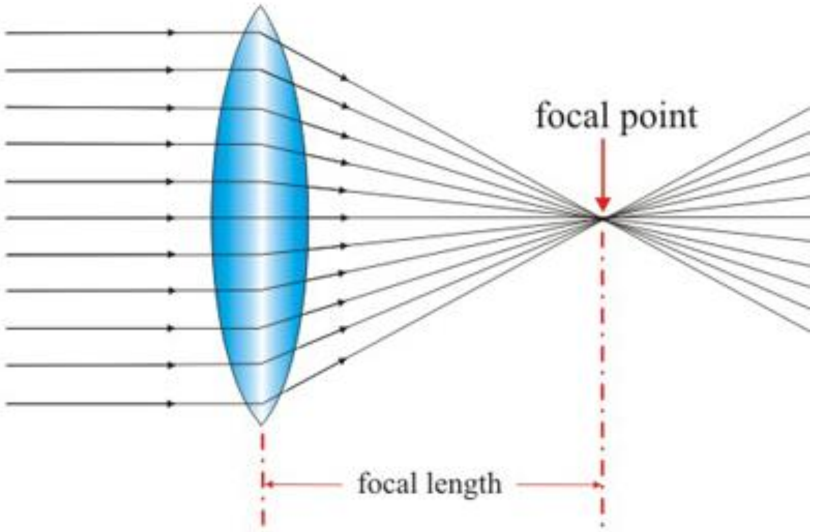


Spector, et al. *Appl. Phys. Lett.* 56 (1990) 967.
Spector, et al. *Appl. Phys. Lett*. 56 (1990) 2433.

Ballistic electron optics

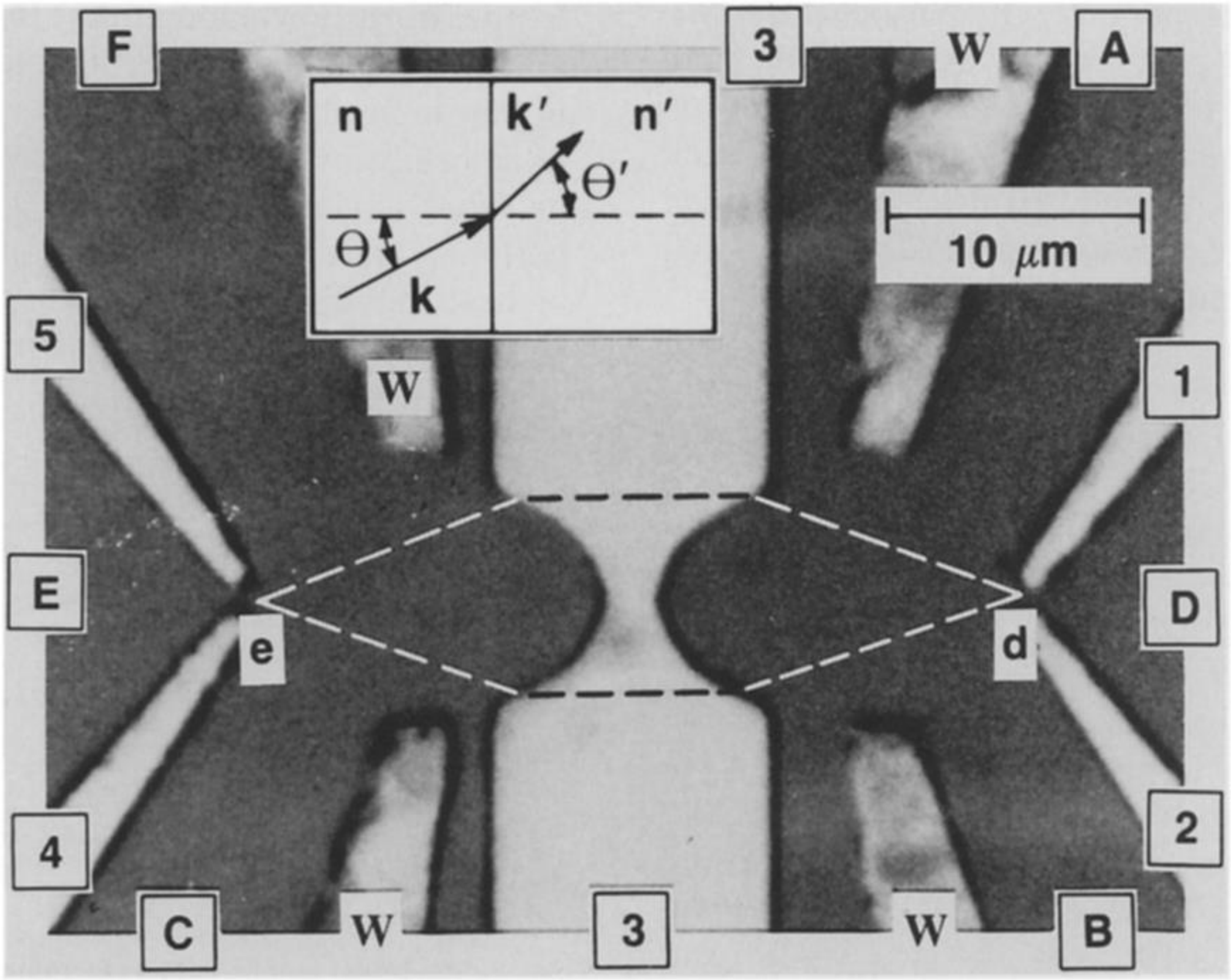
2DEG ballistic transport

- Snell's Law
- Electron optics "lens"



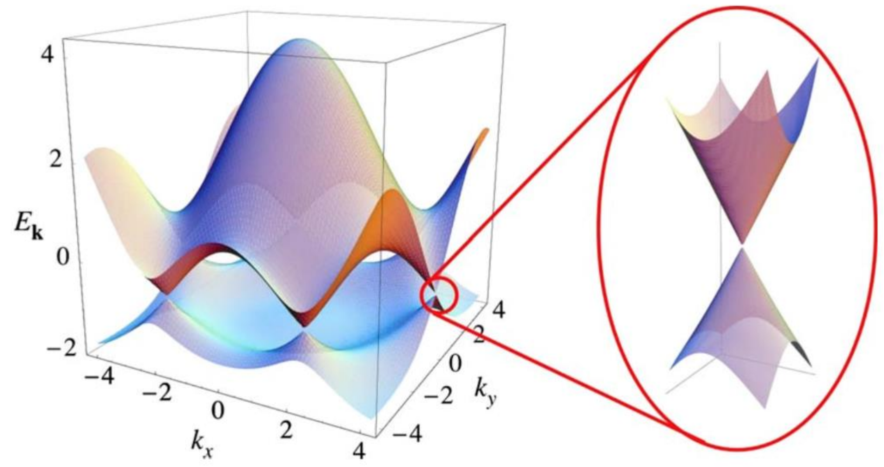
Analog of an optical convex lens

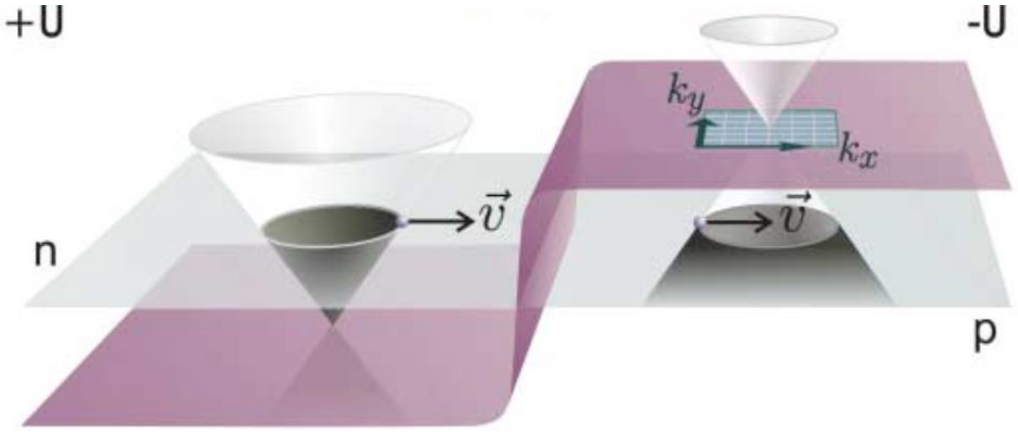
Conserve transverse momentum

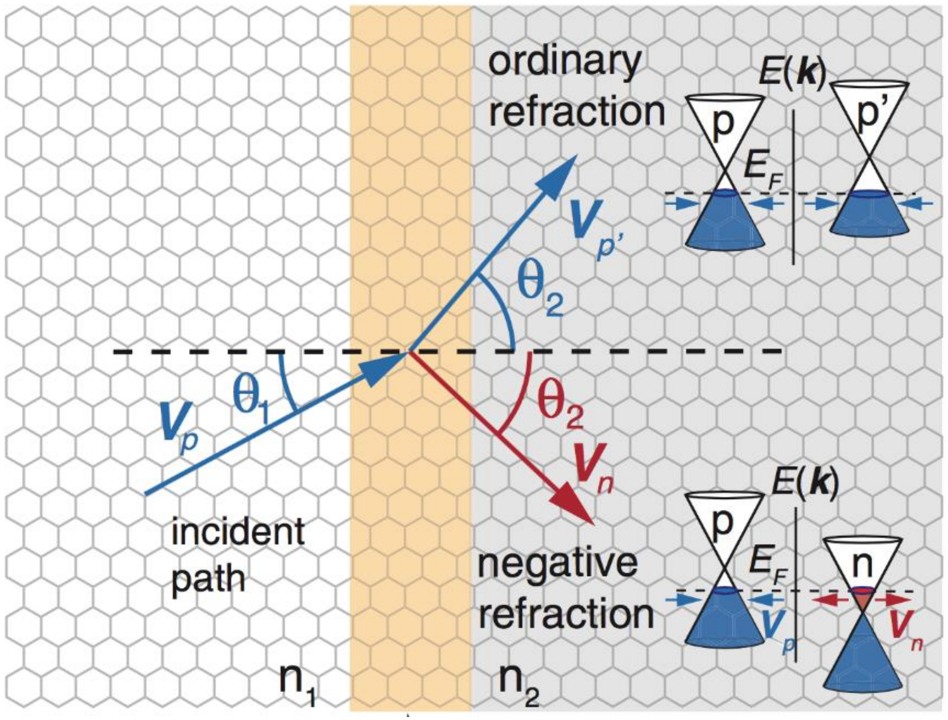


Spector, et al. *Appl. Phys. Lett*. 56 (1990) 967.

Ballistic p-n junctions in graphene



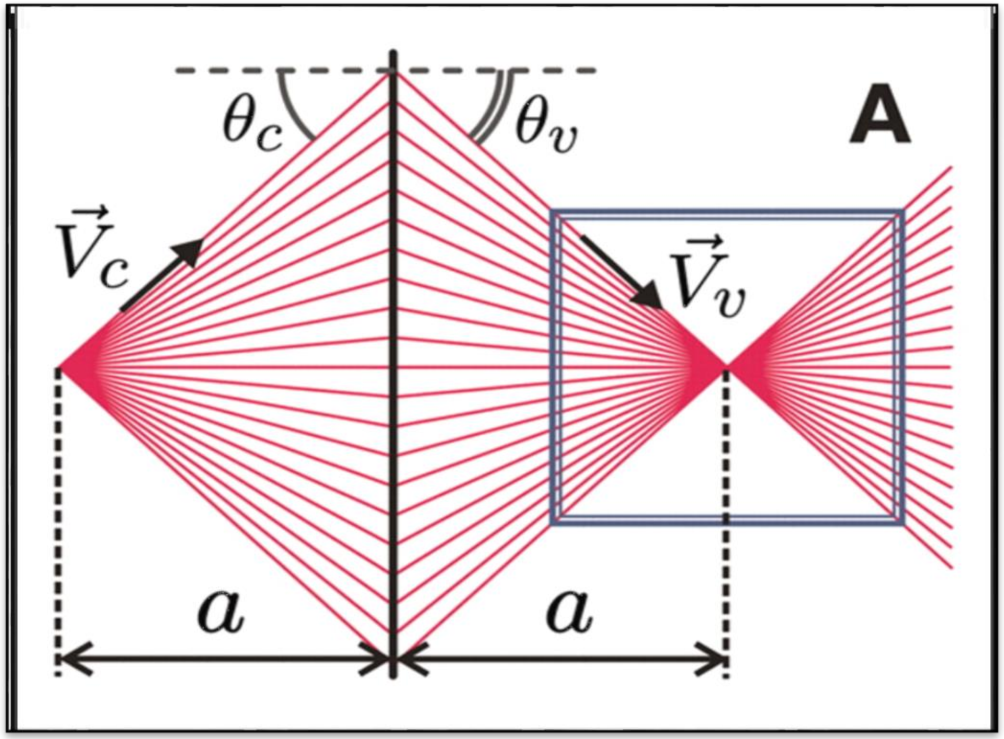


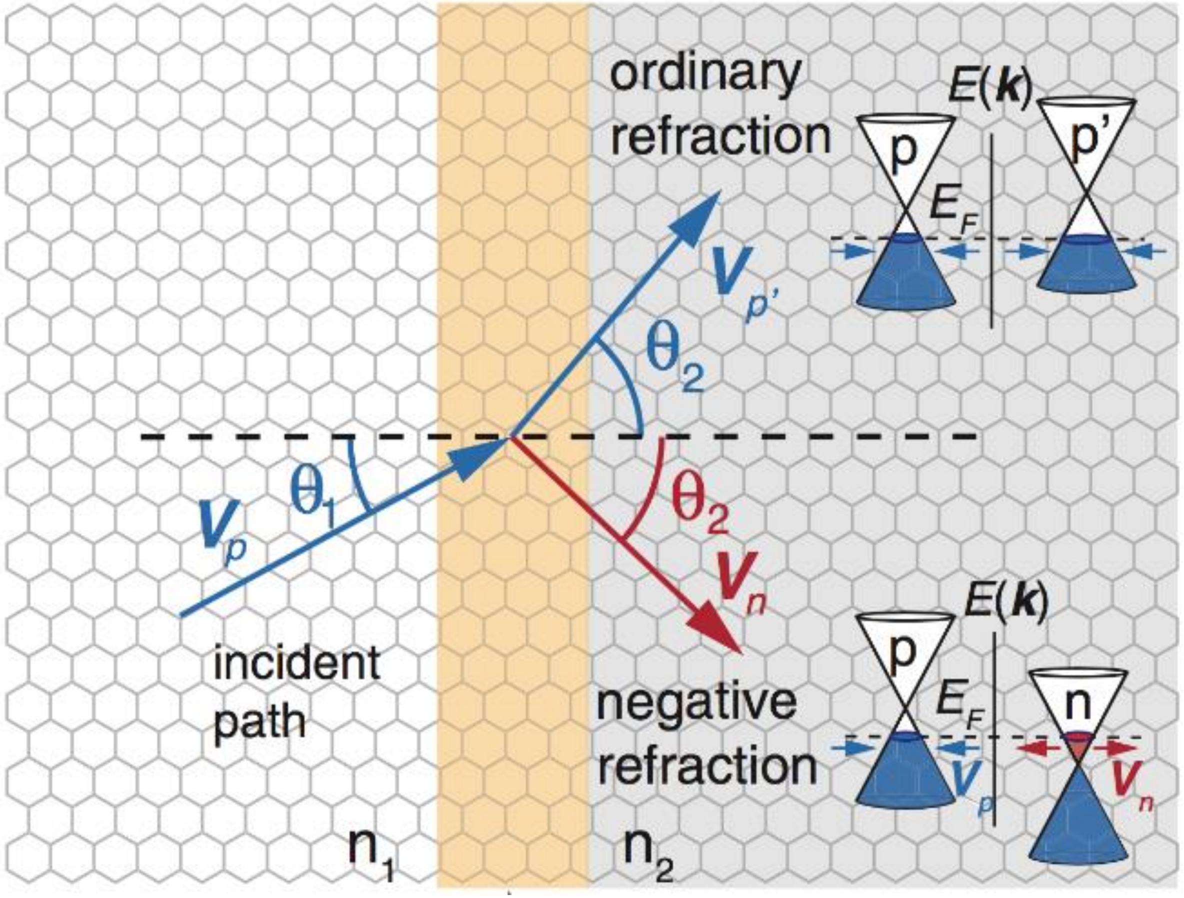


$$\frac{\sin\theta}{\sin\theta'} = -\frac{k'}{k}$$

Cheianov, et. al. *Science* **315** (2007).

Veselago lens





Ballistic p-n junction

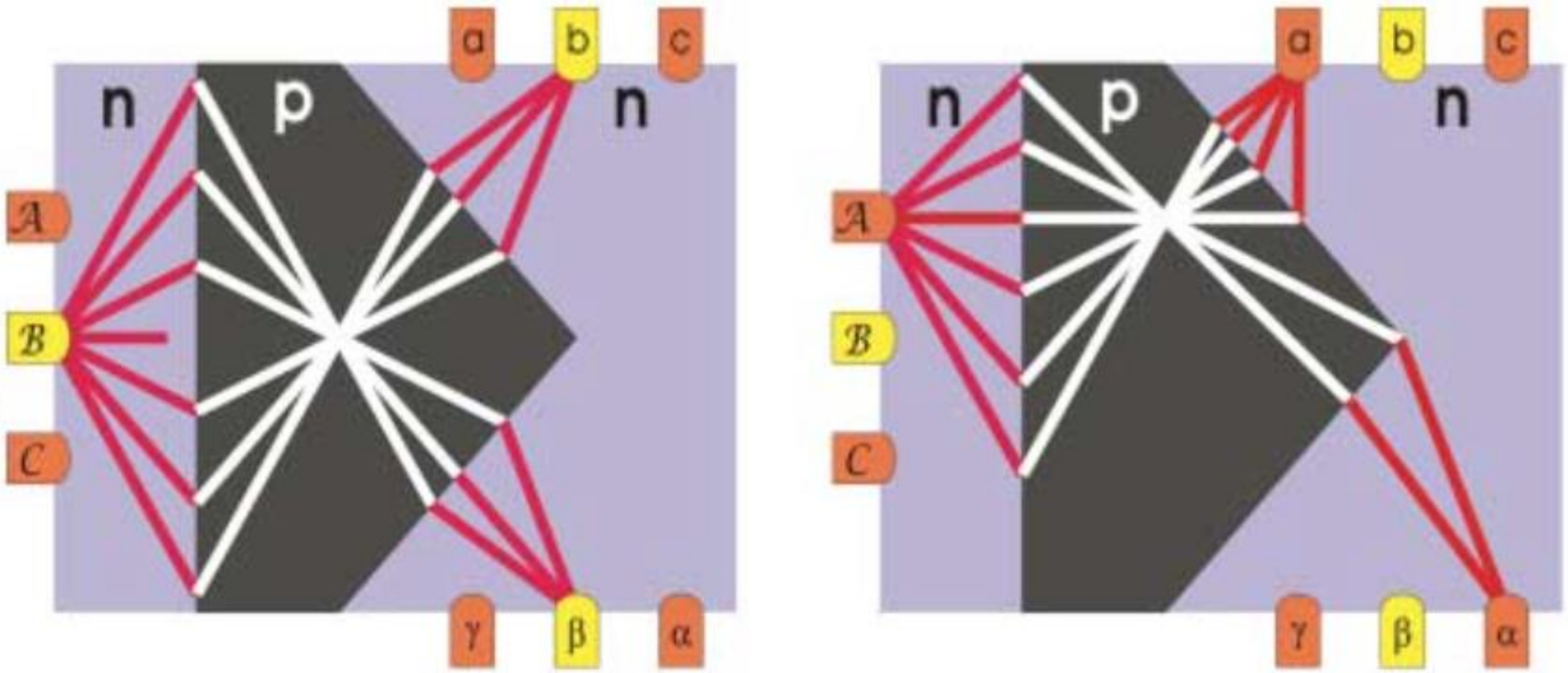
Negative refraction

Perfect lens ($p = n$)

Cheianov, et. al. *Science* **315** (2007): 1252-1255.

Electronic switches

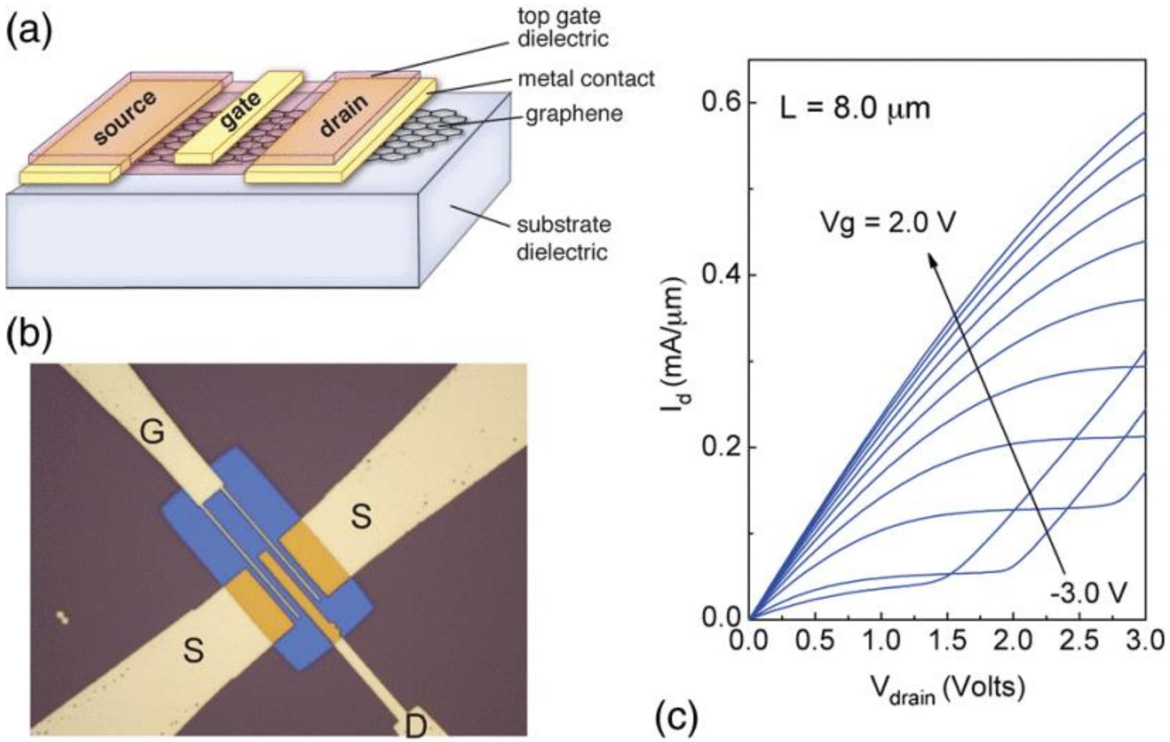
Theoretical n-p-n junction beam splitter



Cheianov, et. al. *Science* **315** (2007): 1252-1255.

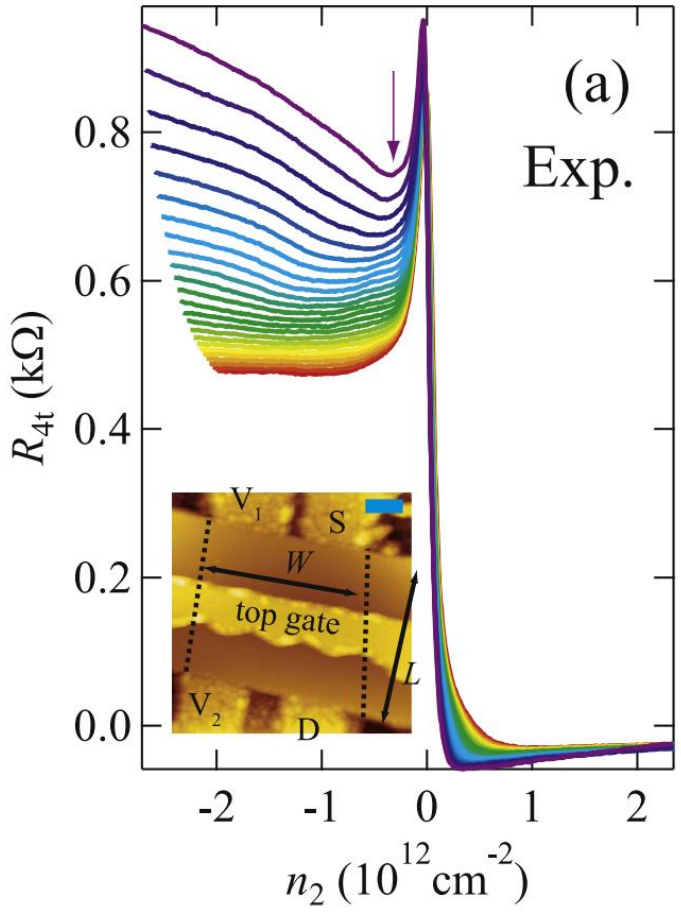
Graphene field effect transistors (gFETs)

Bilayer (non-ballistic)



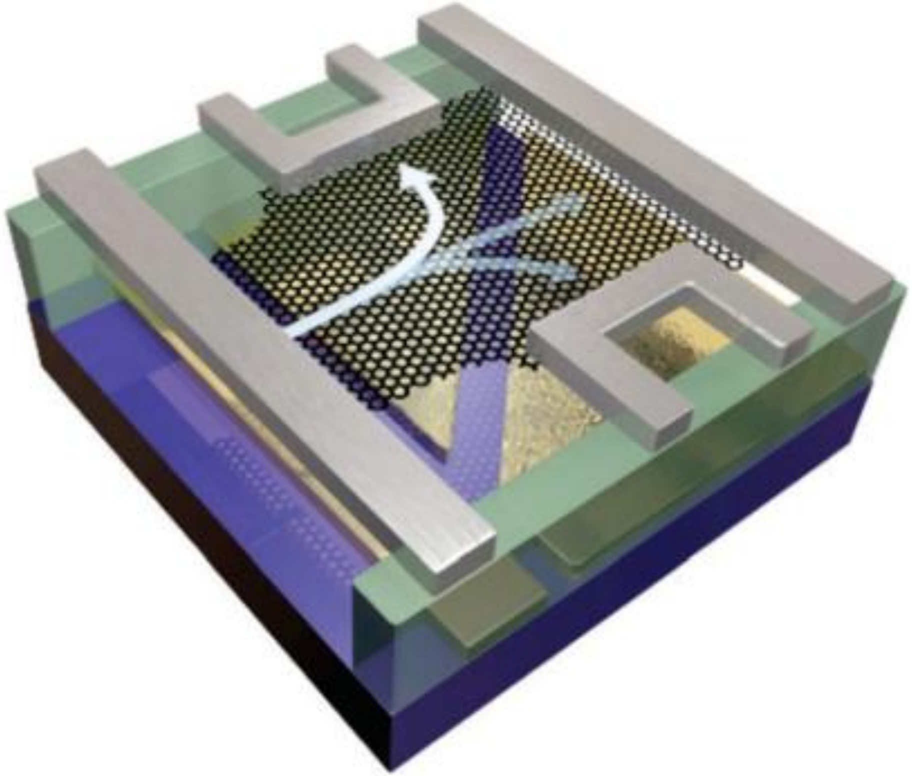
Kim et. al. *Proceedings of the IEEE* 101, 7 (2013)

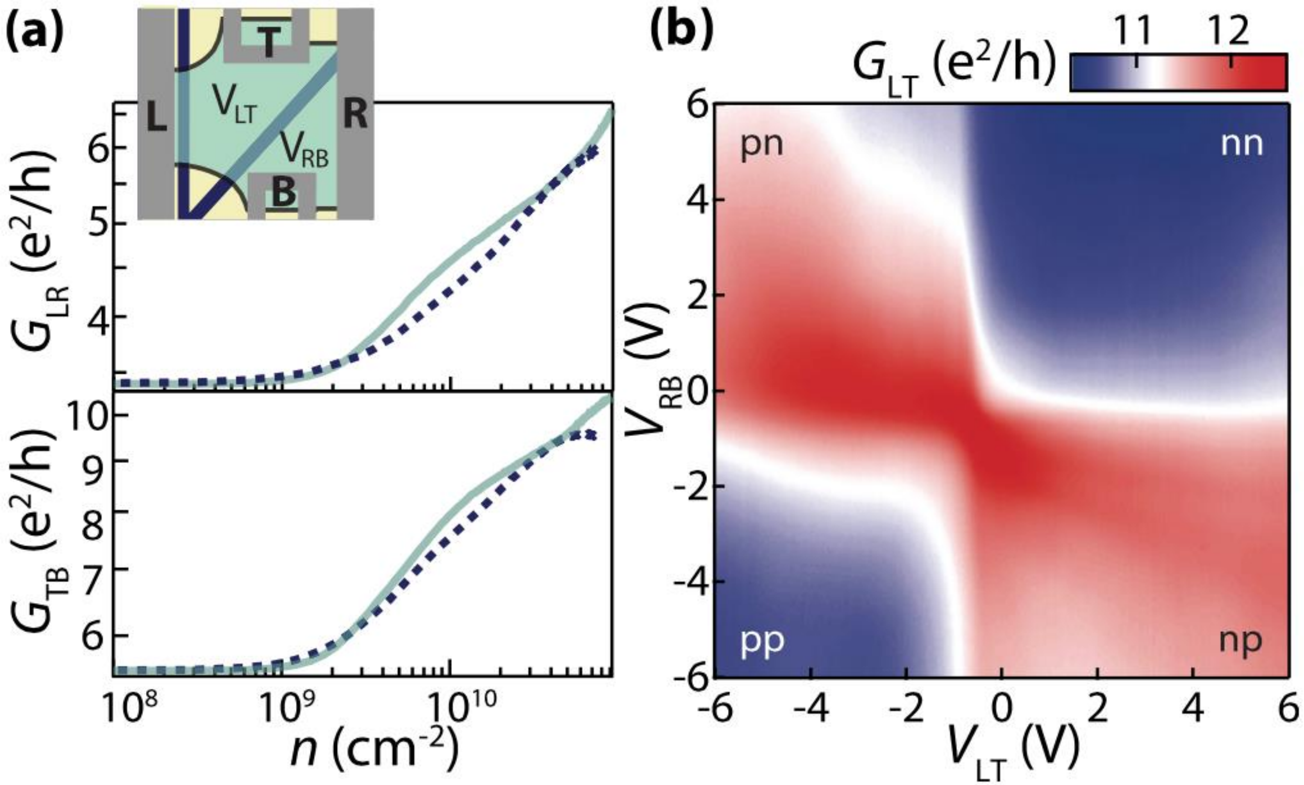
Sawtooth gated ballistic monolayer



Morikawa, et al. arXiv:1702.04039 (2017)

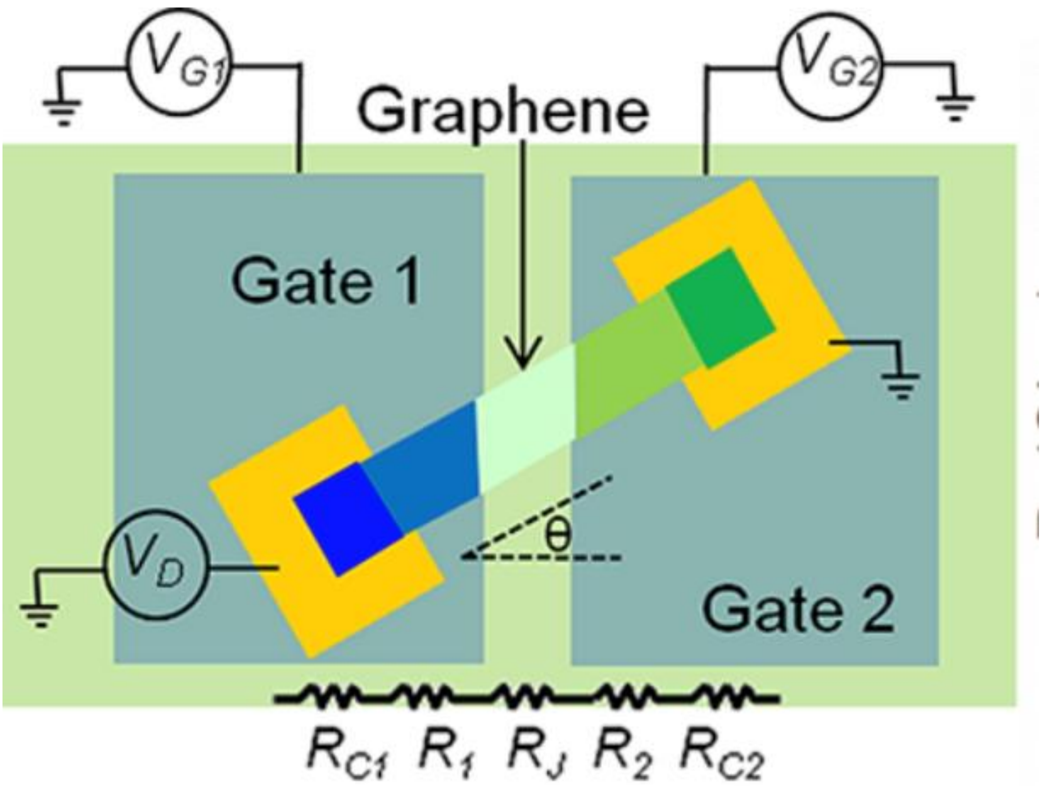
Previous work: beam splitter

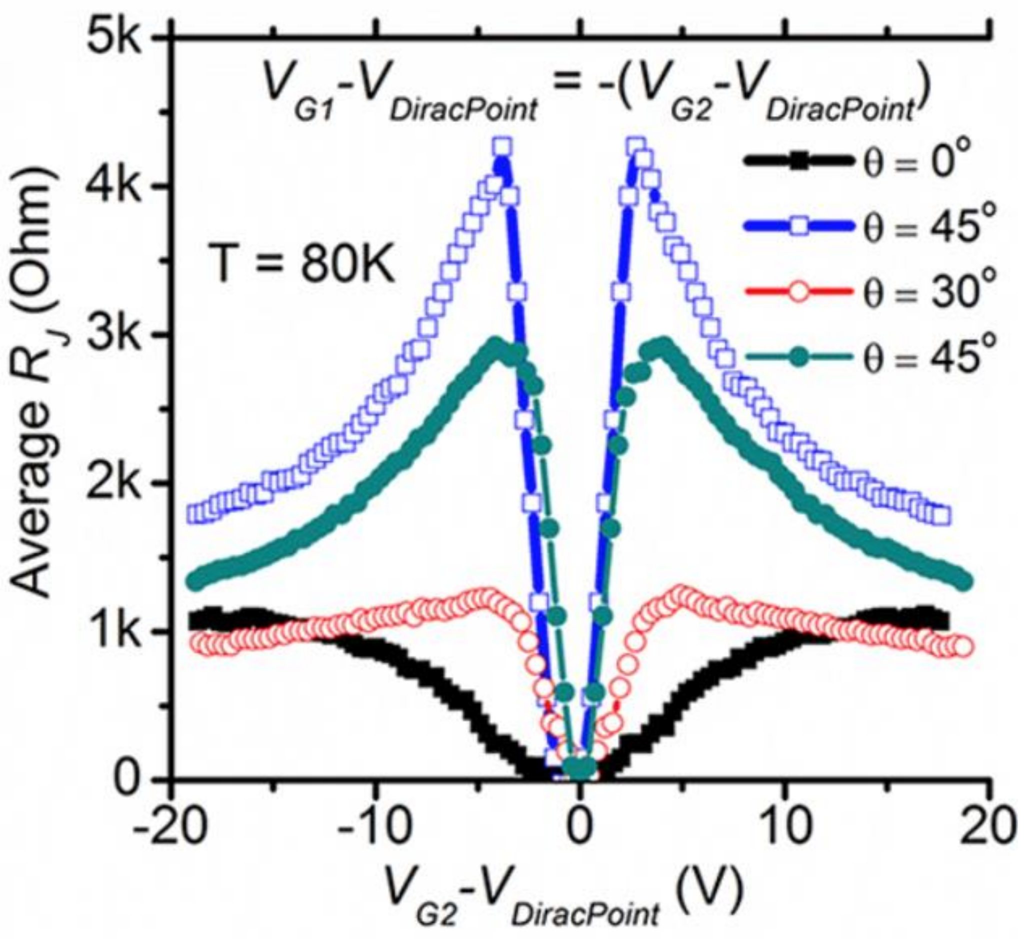




Rickhaus, et al. APL 107.25 (2015)

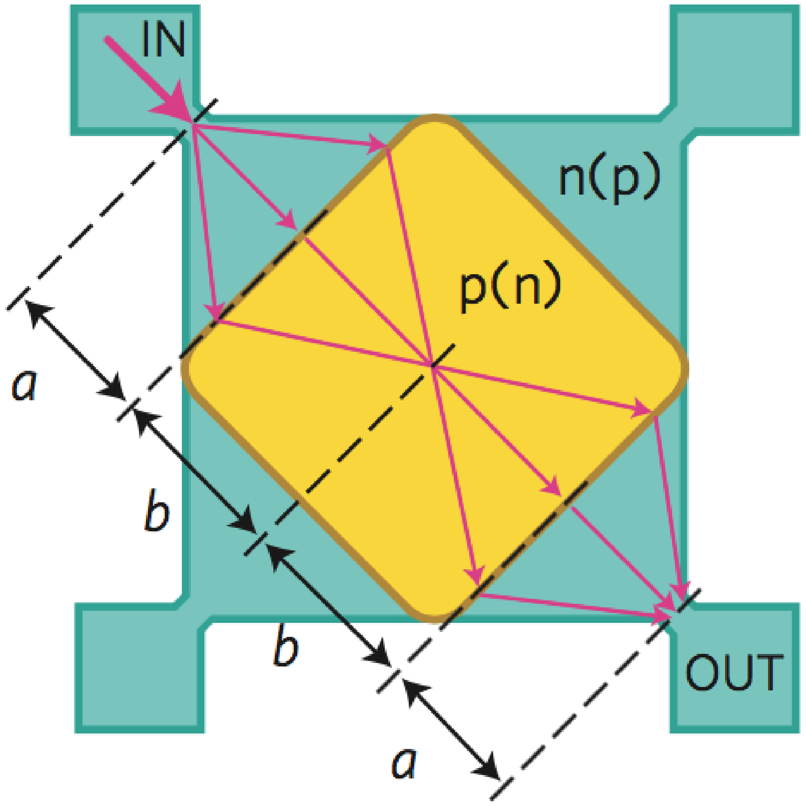
Previous work: angular-dependent transmission



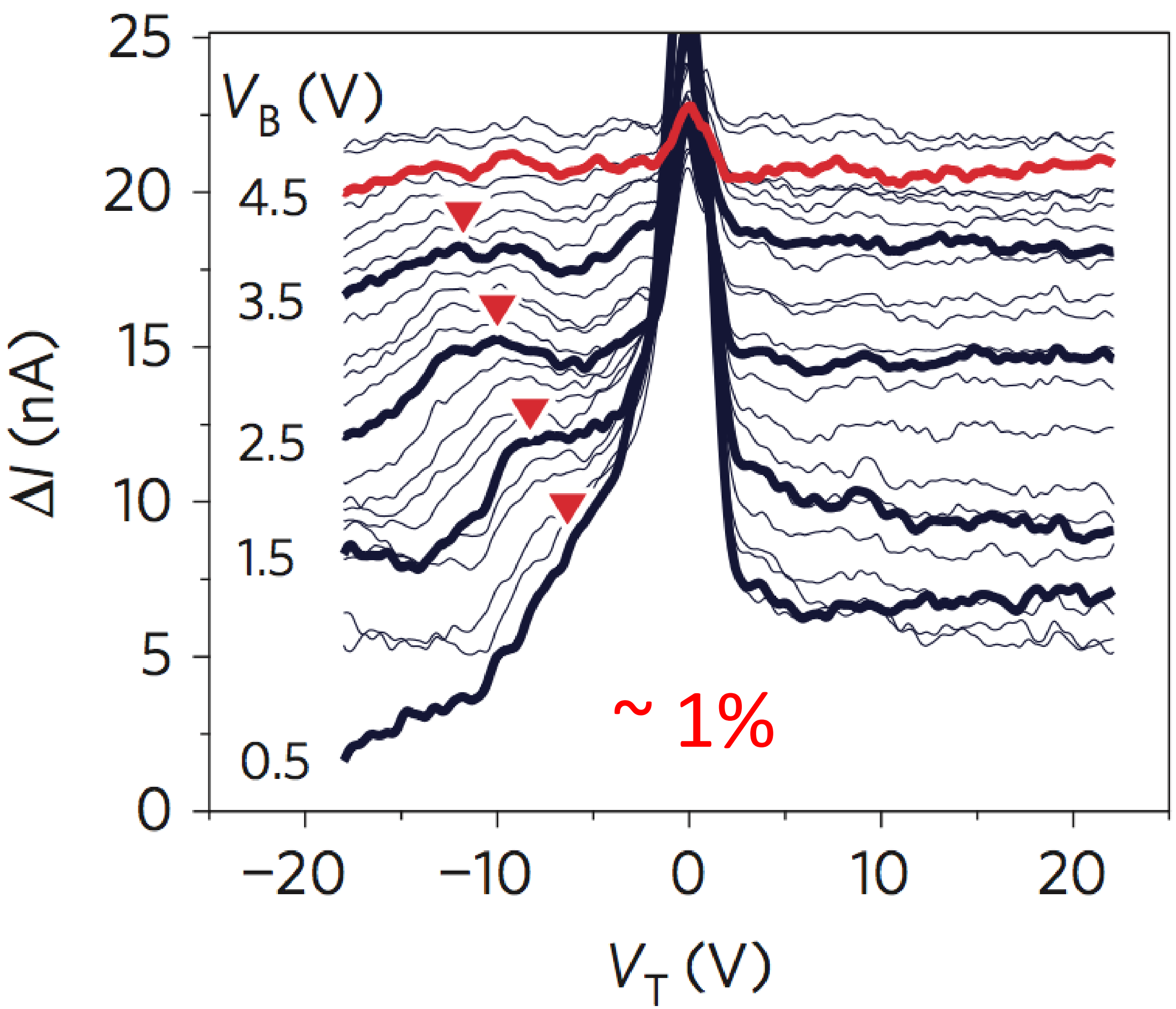


Sutar, et al. *Nano letters* 12.9 (2012)

PNP junctions



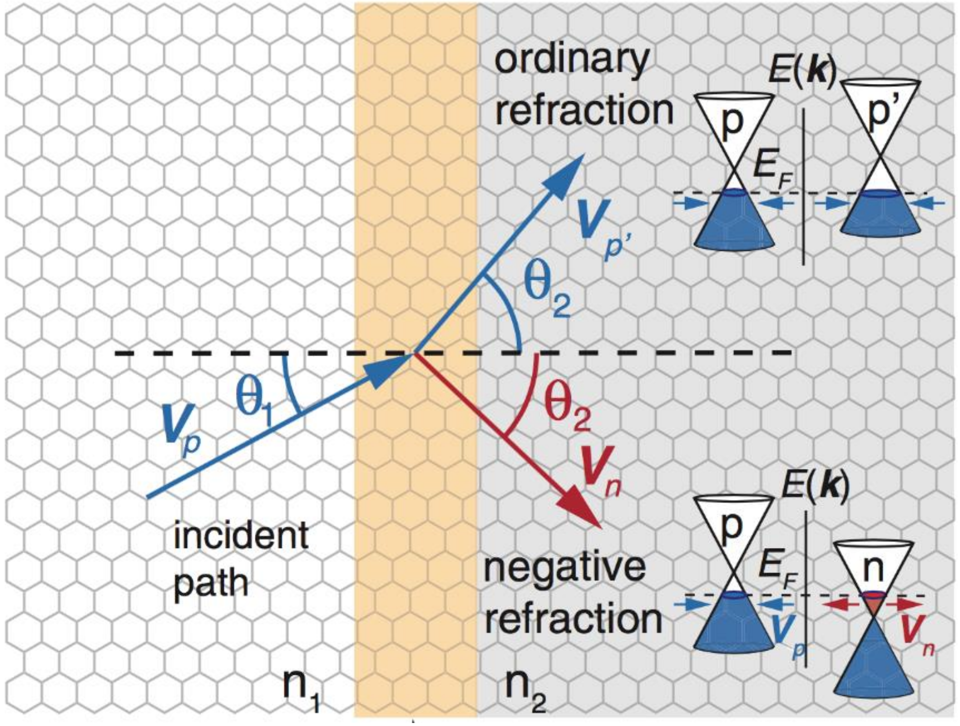
Background by normal incident electrons



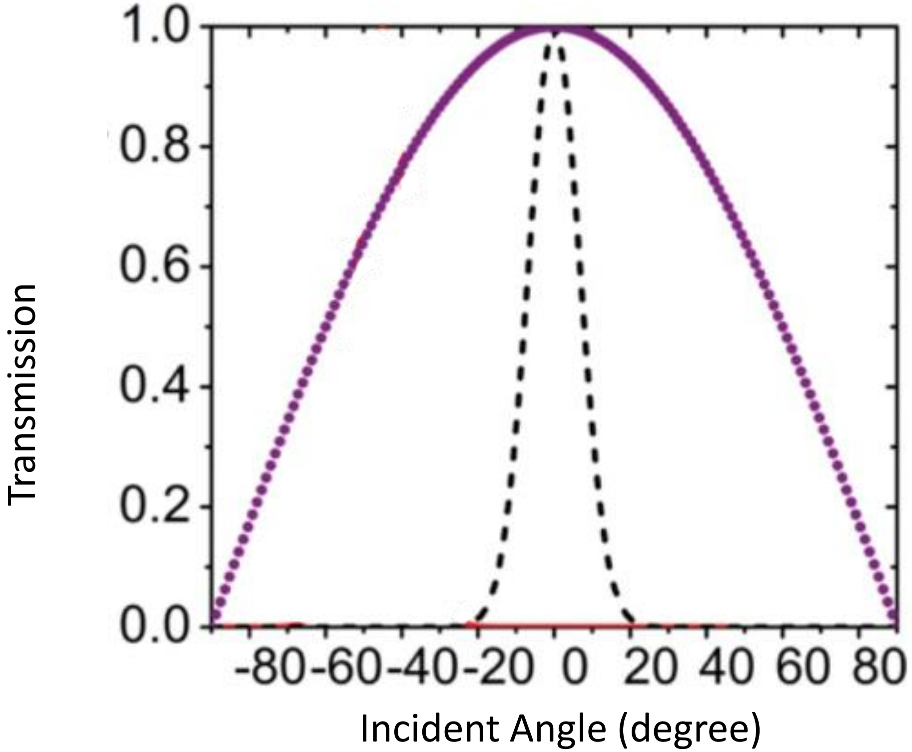
Lee, et al. *Nature Physics* 11.11 (2015)

Yet to be observed

Negative refraction

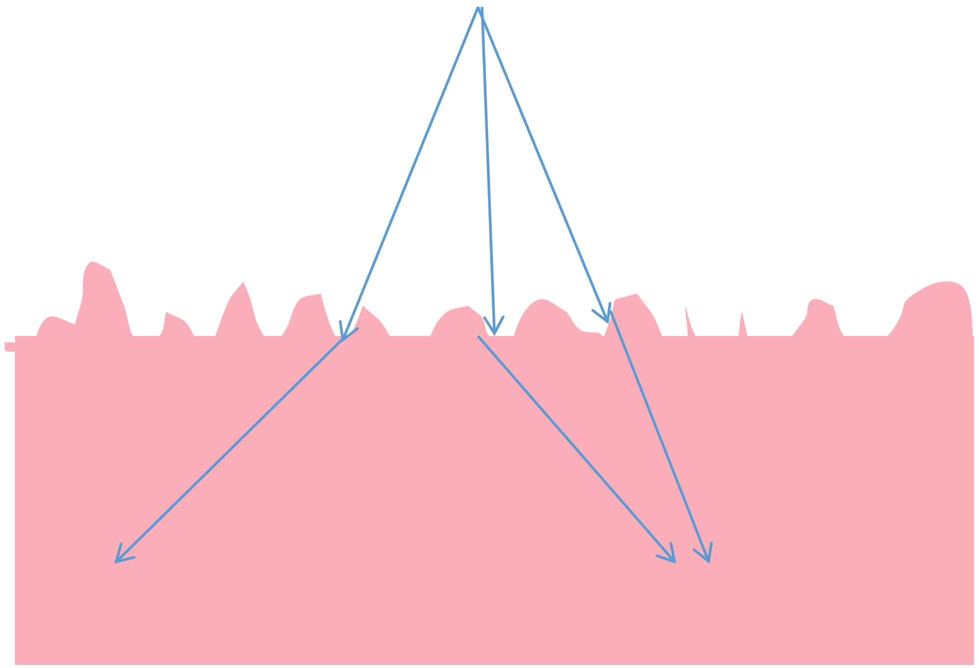


Angular-dependence



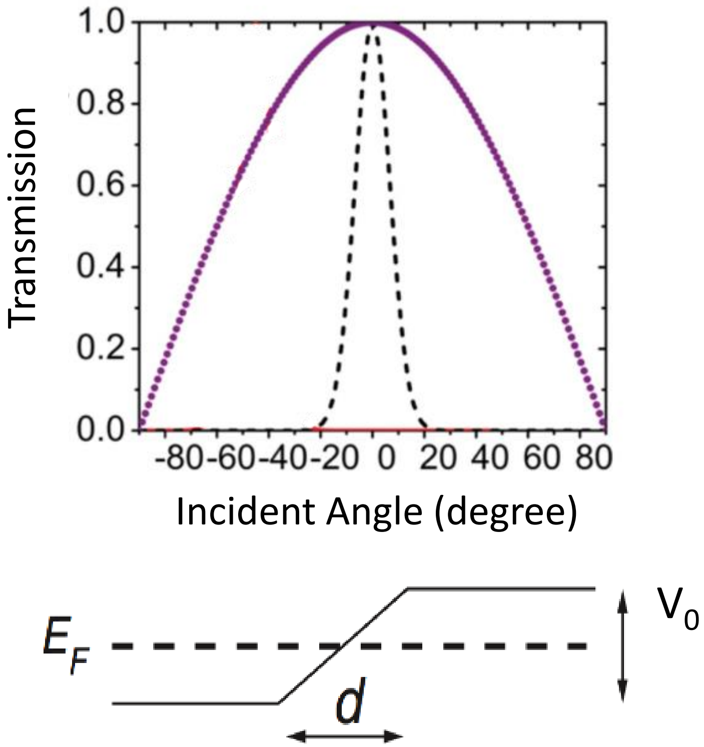
Challenges in achieving a sharp edge

Smooth junction edge
(*compared with λ_F*)



Rough edge refracts electron randomly

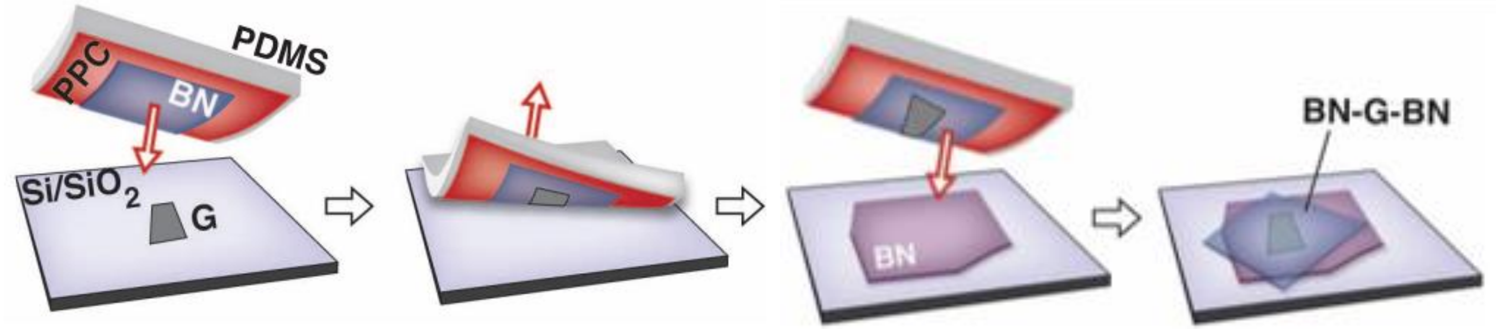
Angle dependent transmission
(*sharp junction*)

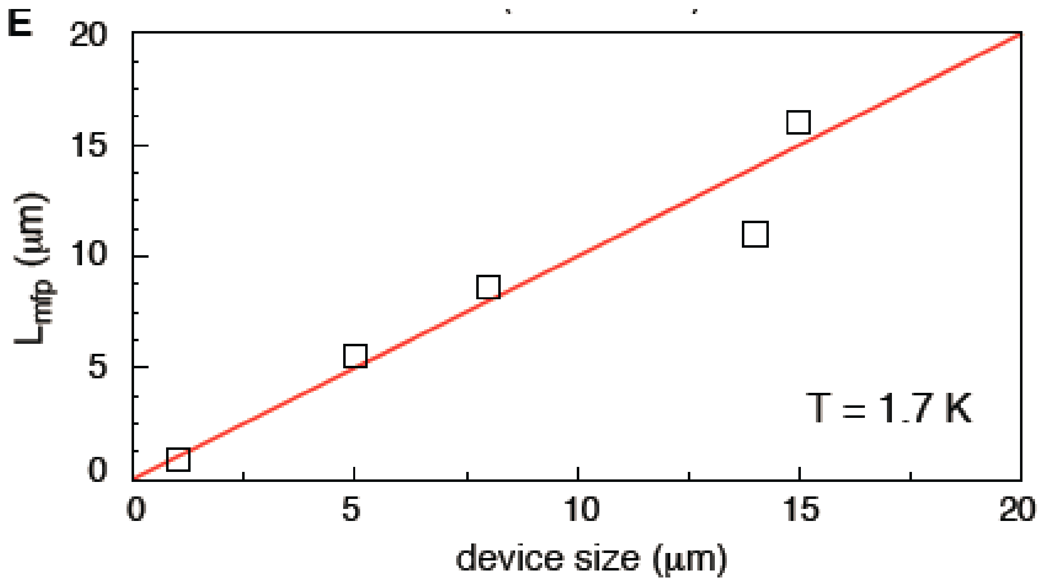


Sajjad, et al. Phys. Rev. B ***86****, 155412 (2012)*

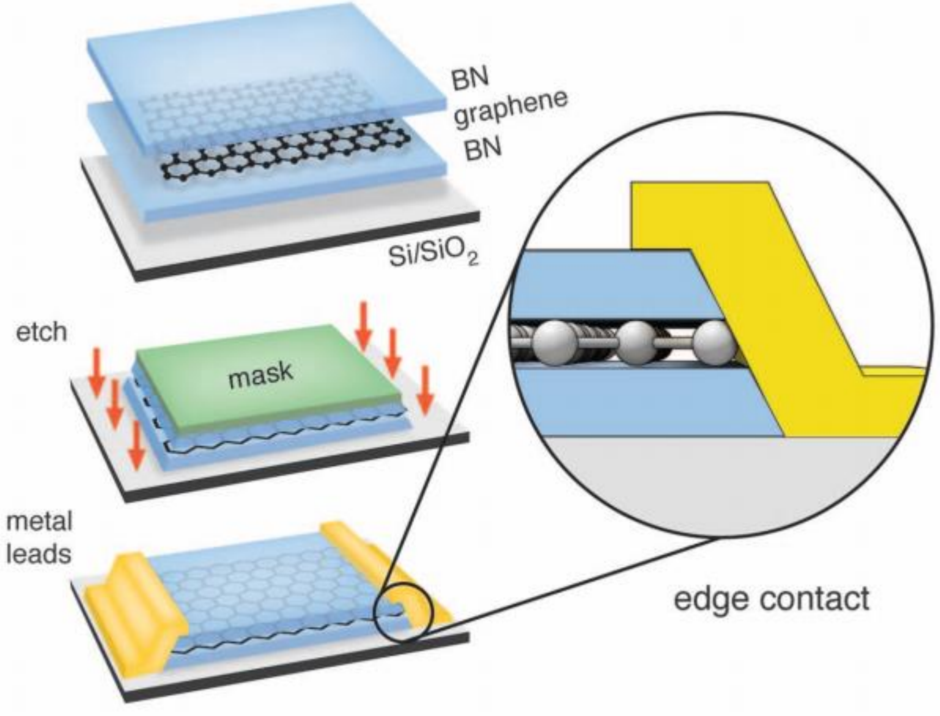
Advances in graphene device fabrication

van der Waals Transfer



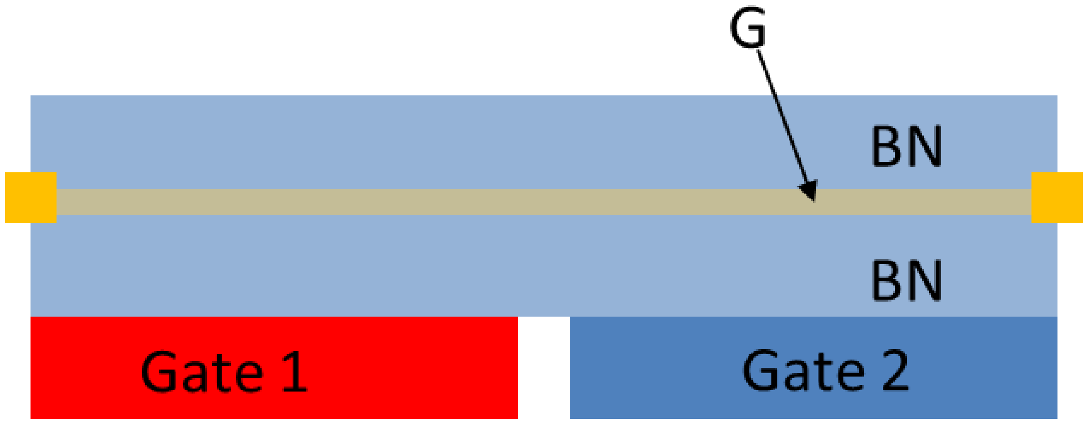


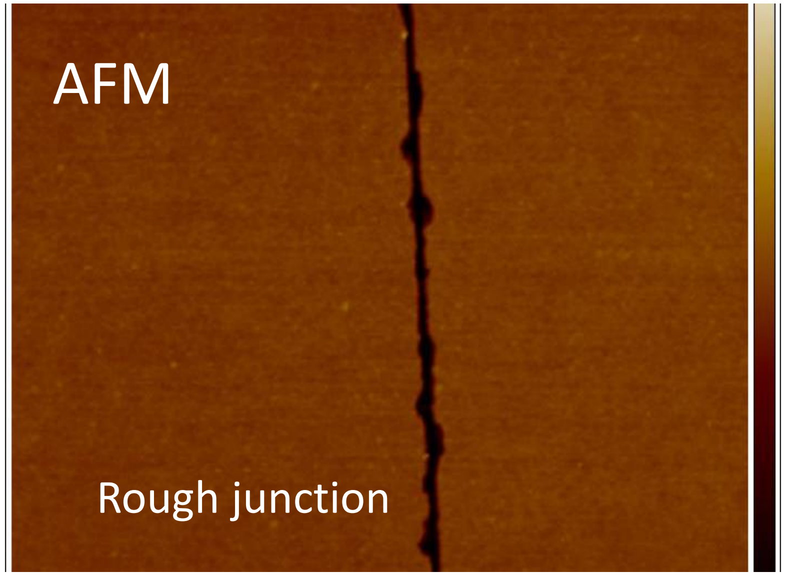
1D Edge Contacts

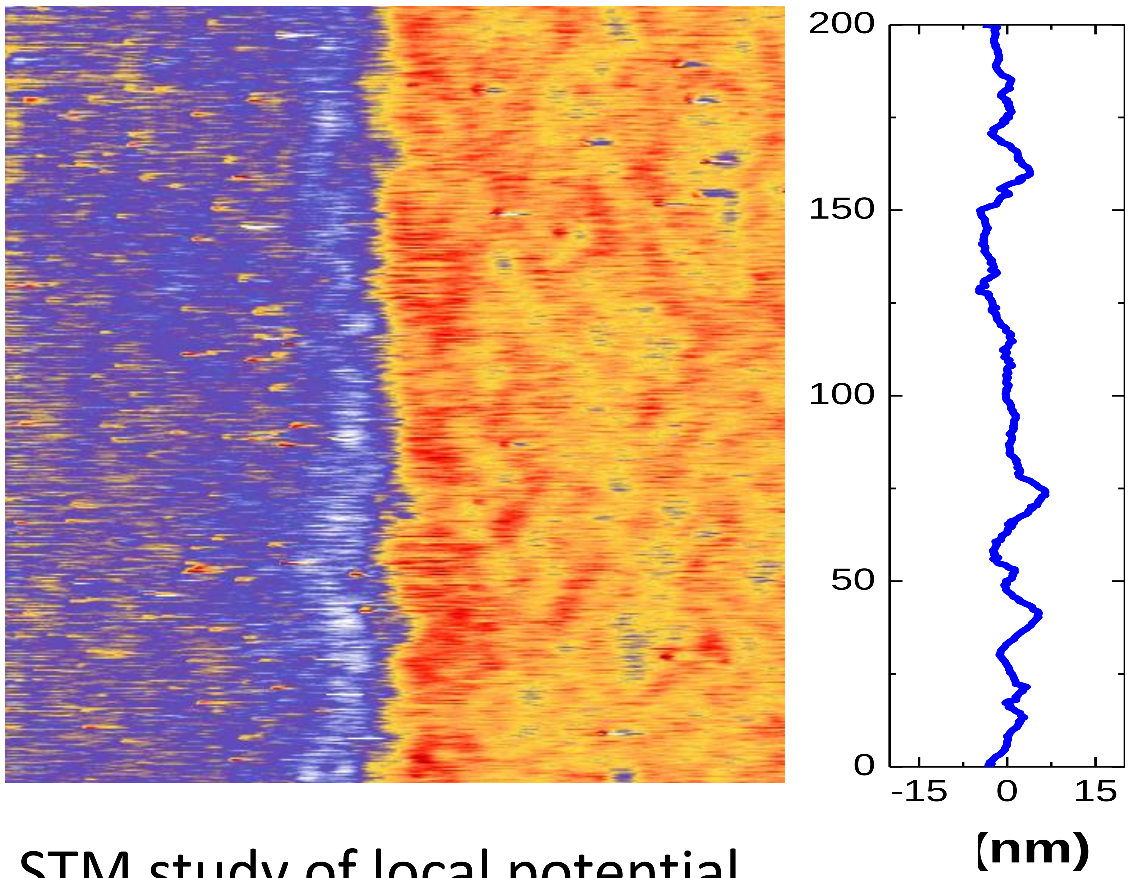


Wang, L., et al. Science 342.6158 (2013)

Metallic gates



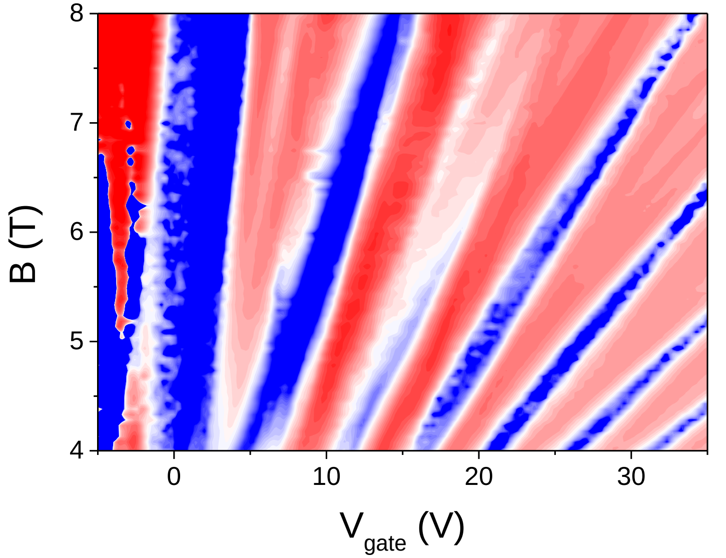




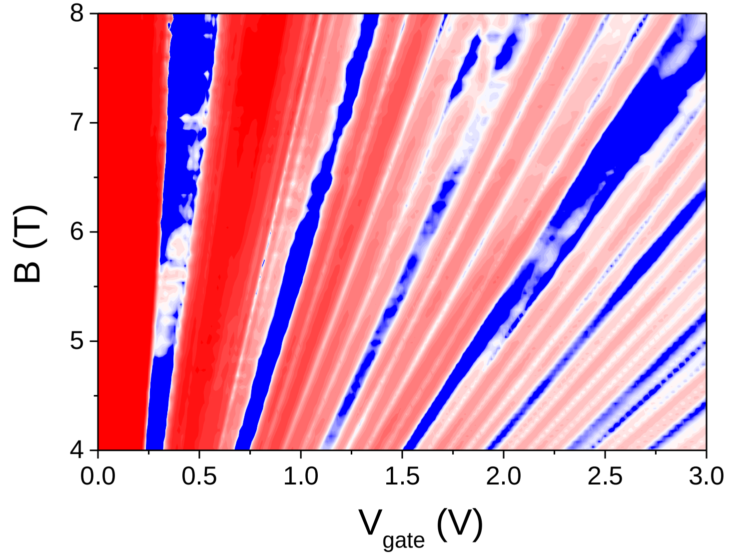
STM study of local potential

Zhu, X., et al. unpublished

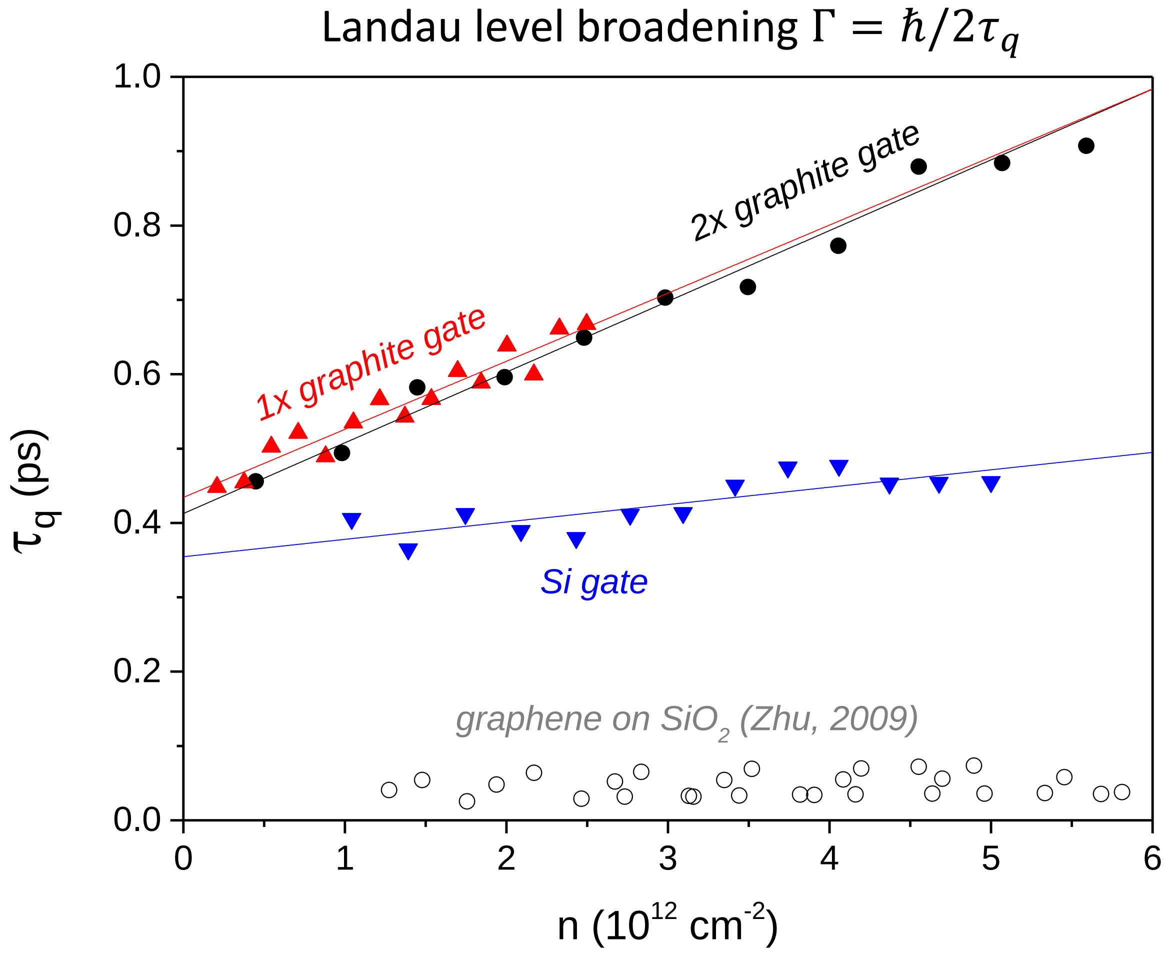
Metric for device quality



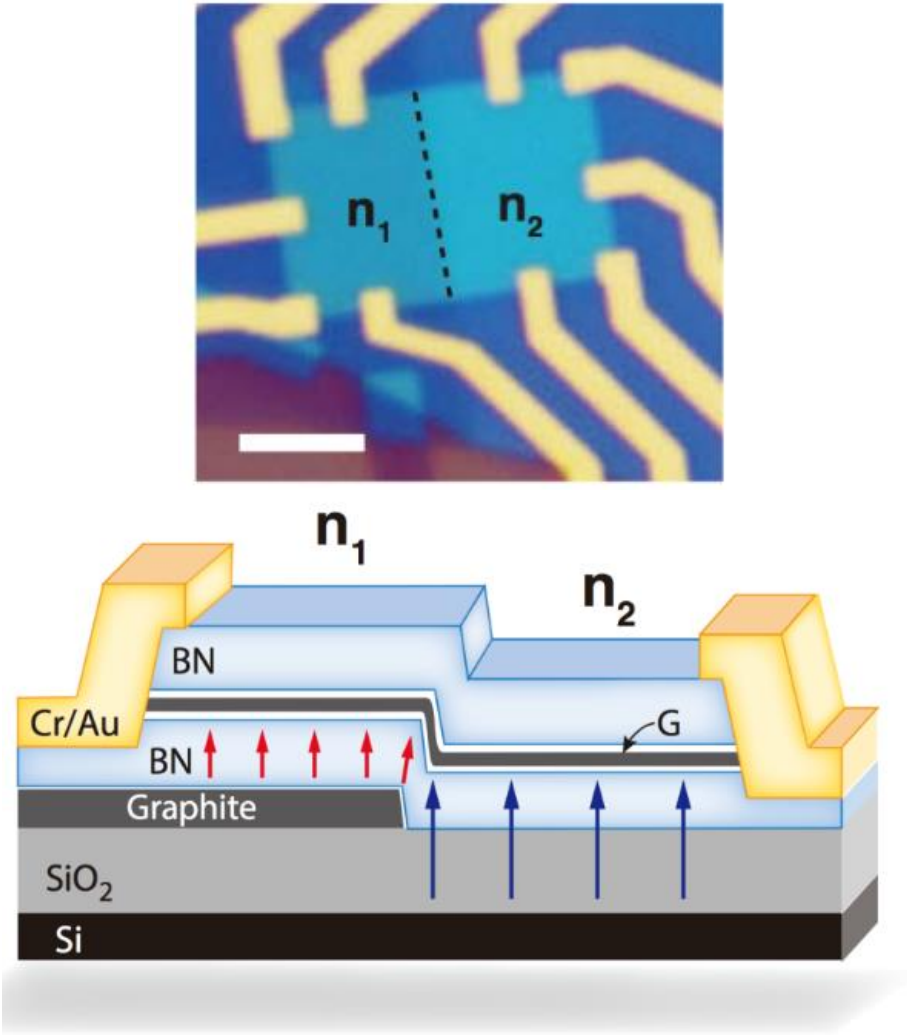
Silicon Gate

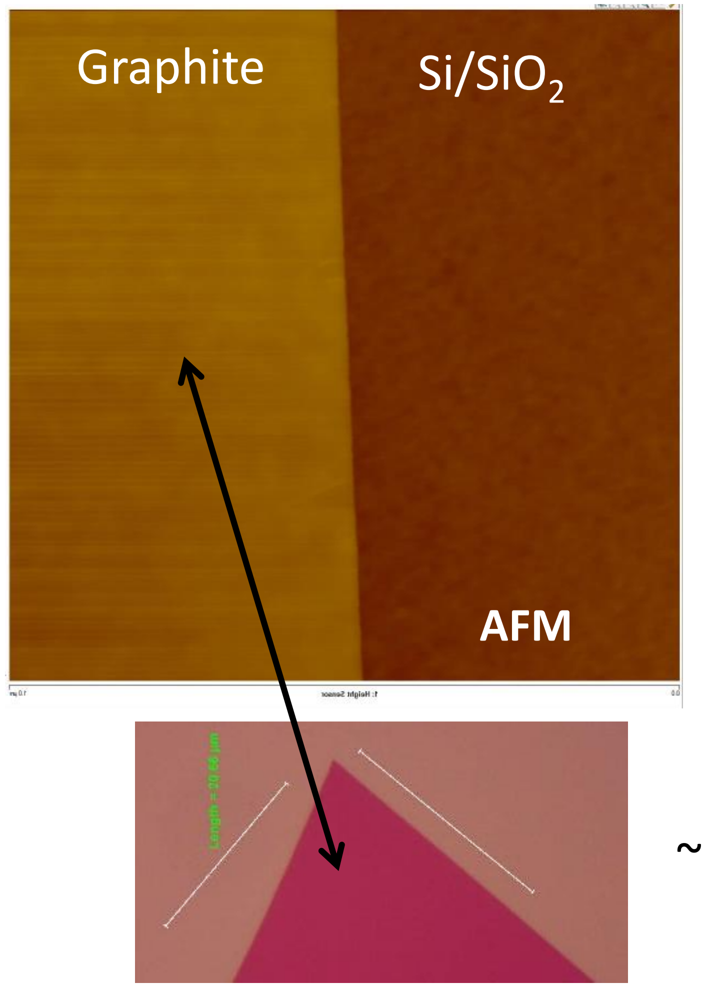


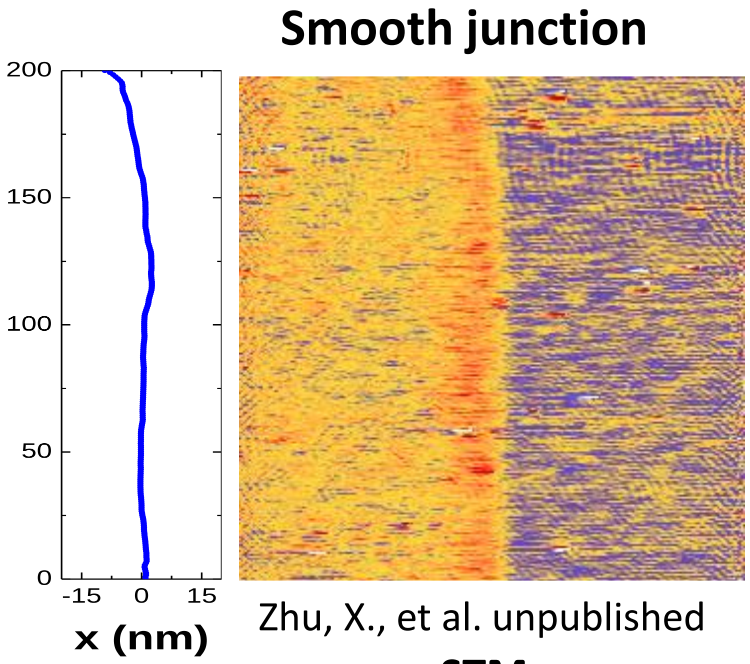
2x Graphite Gate



Straight edge junction







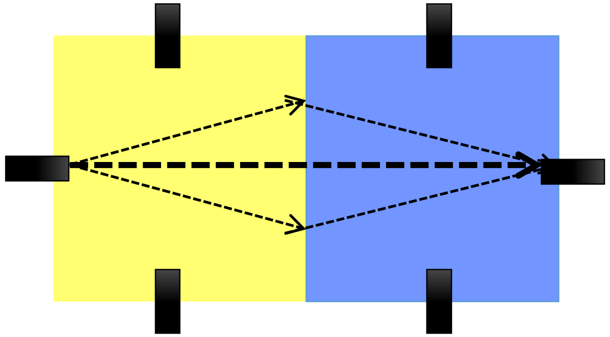
Zhu, X., et al. unpublished

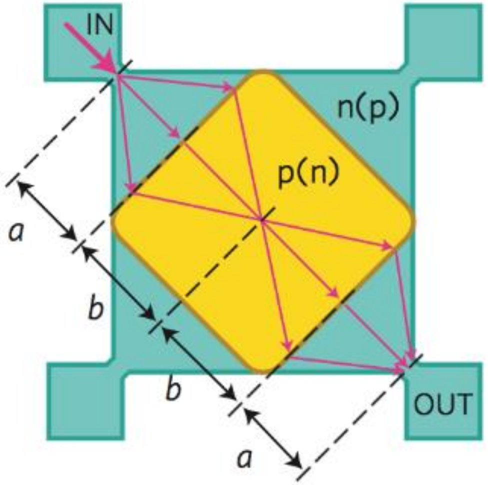
STM

~ atomically smooth

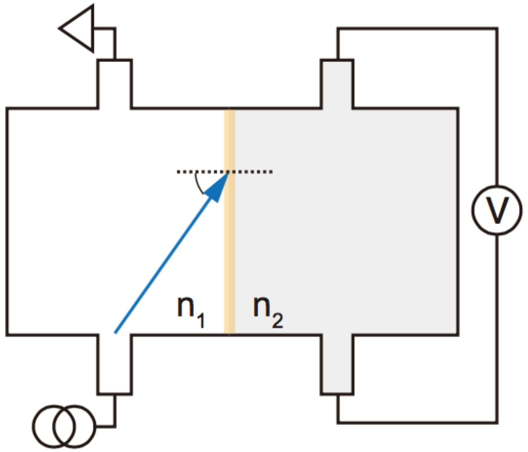
S. Chen, Z. Han, et al. *Science* **353** 1522 (2016).

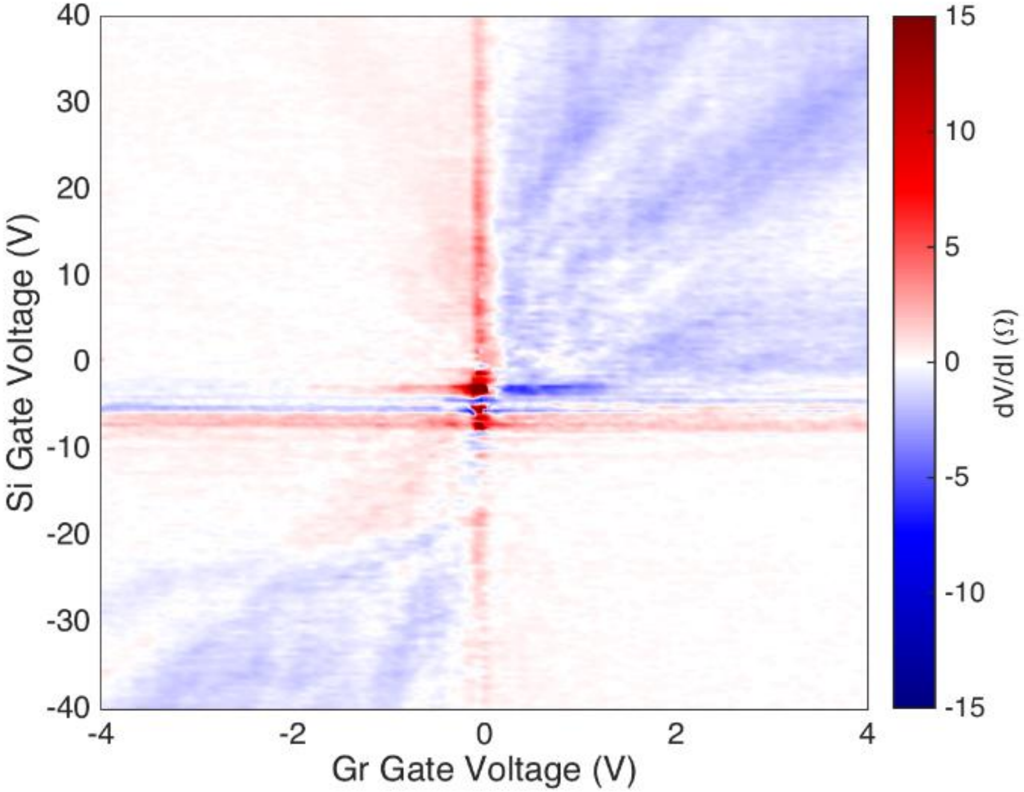
Measurement configuration



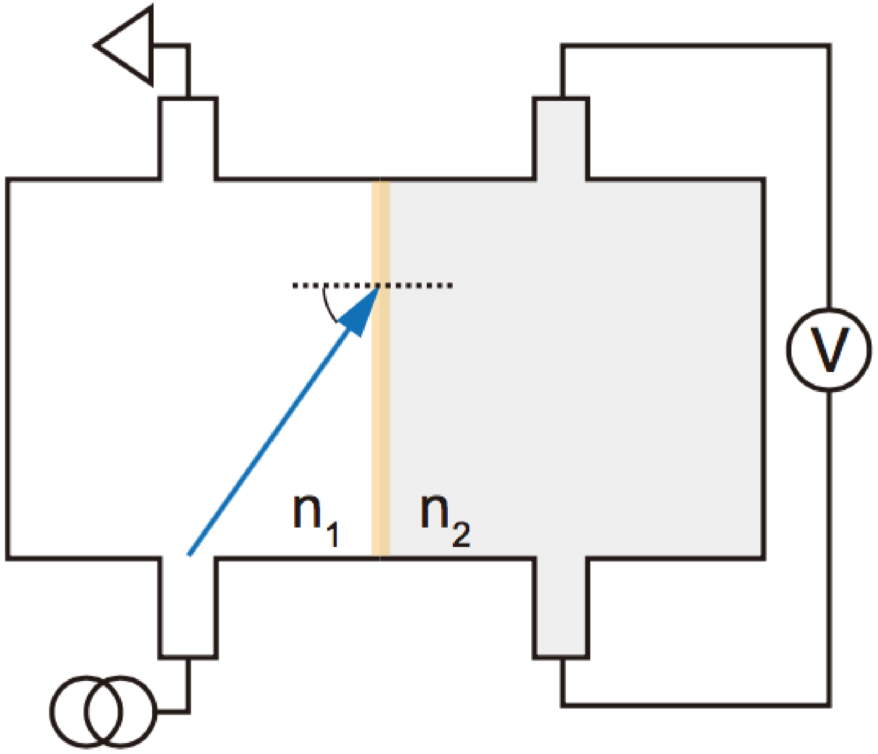


Large background

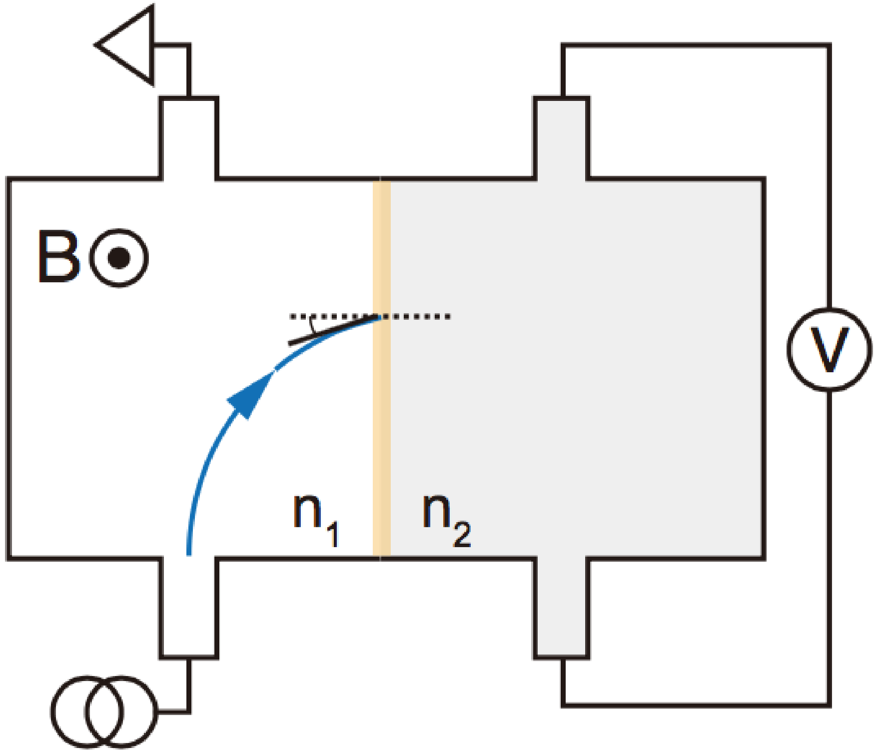




Achieving a smaller incident angle



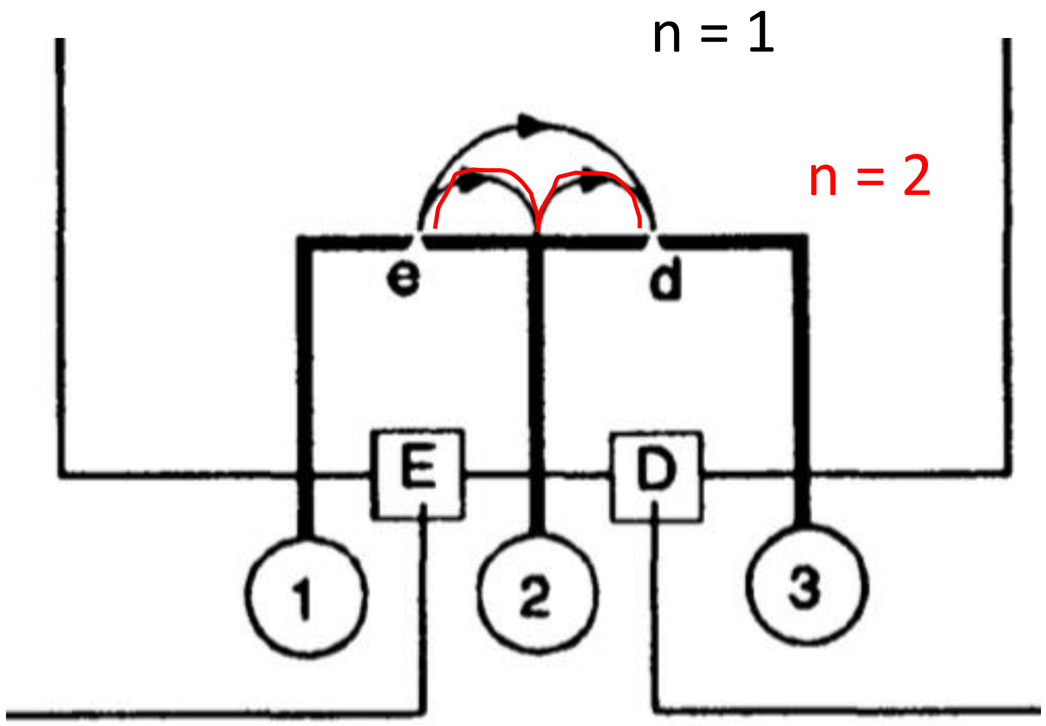
Zero magnetic field

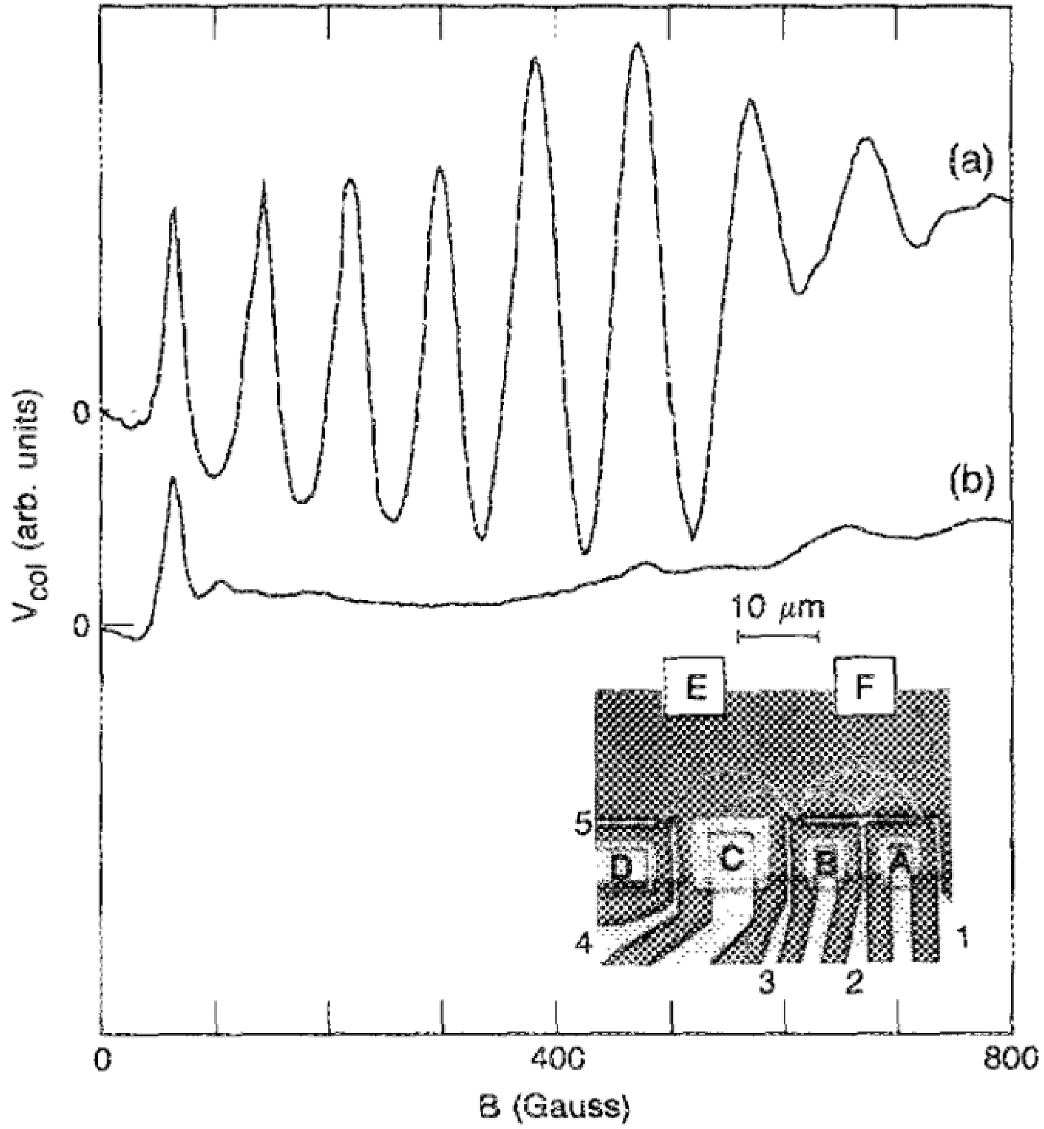


Transverse magnetic focusing (TMF)

Transverse magnetic focusing in 2DEGs

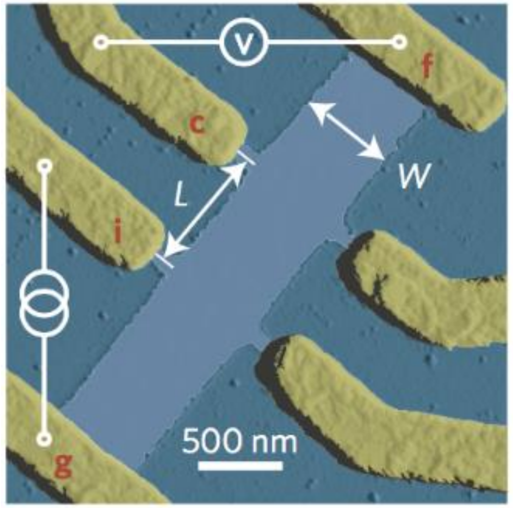
$L = 2n \times R_{cyclotron}$ n = 1, 2, 3...





Spector, et al. Springer Berlin Heidelberg, 1992. 66-77.

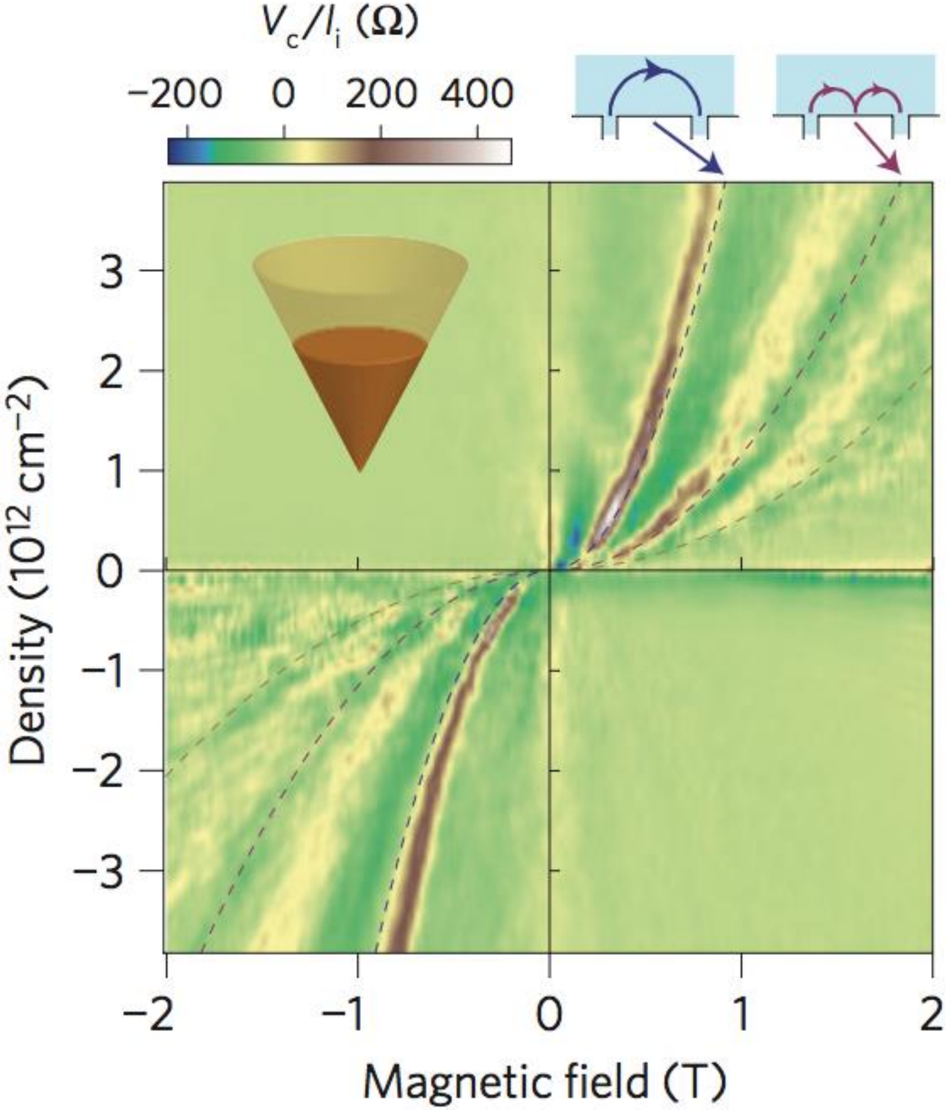
Transverse magnetic focusing in graphene



Resonance condition:

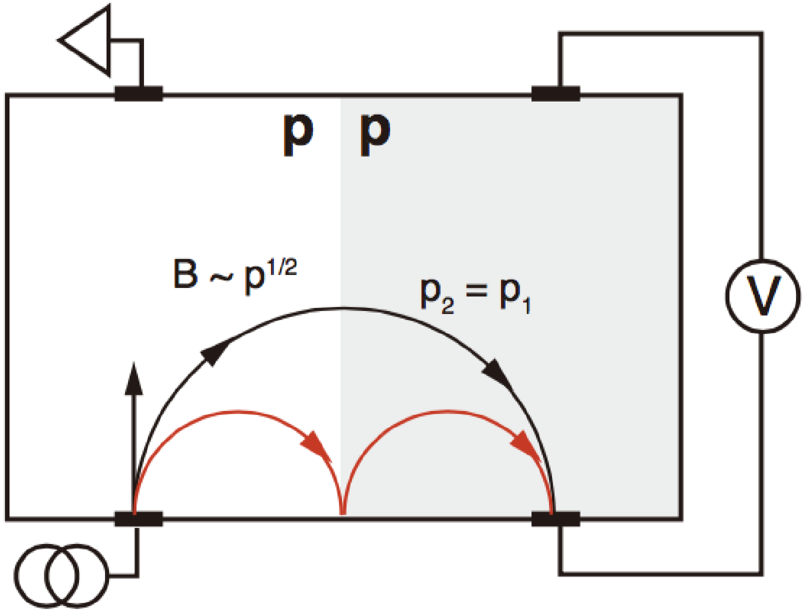
p is integer

$$\boxed{B_{\mathrm{f}}^{(p)} = \left(\frac{2\hbar k_{\mathrm{F}}}{eL}\right)p = \left(\frac{2\hbar\sqrt{\pi n}}{eL}\right)p}$$



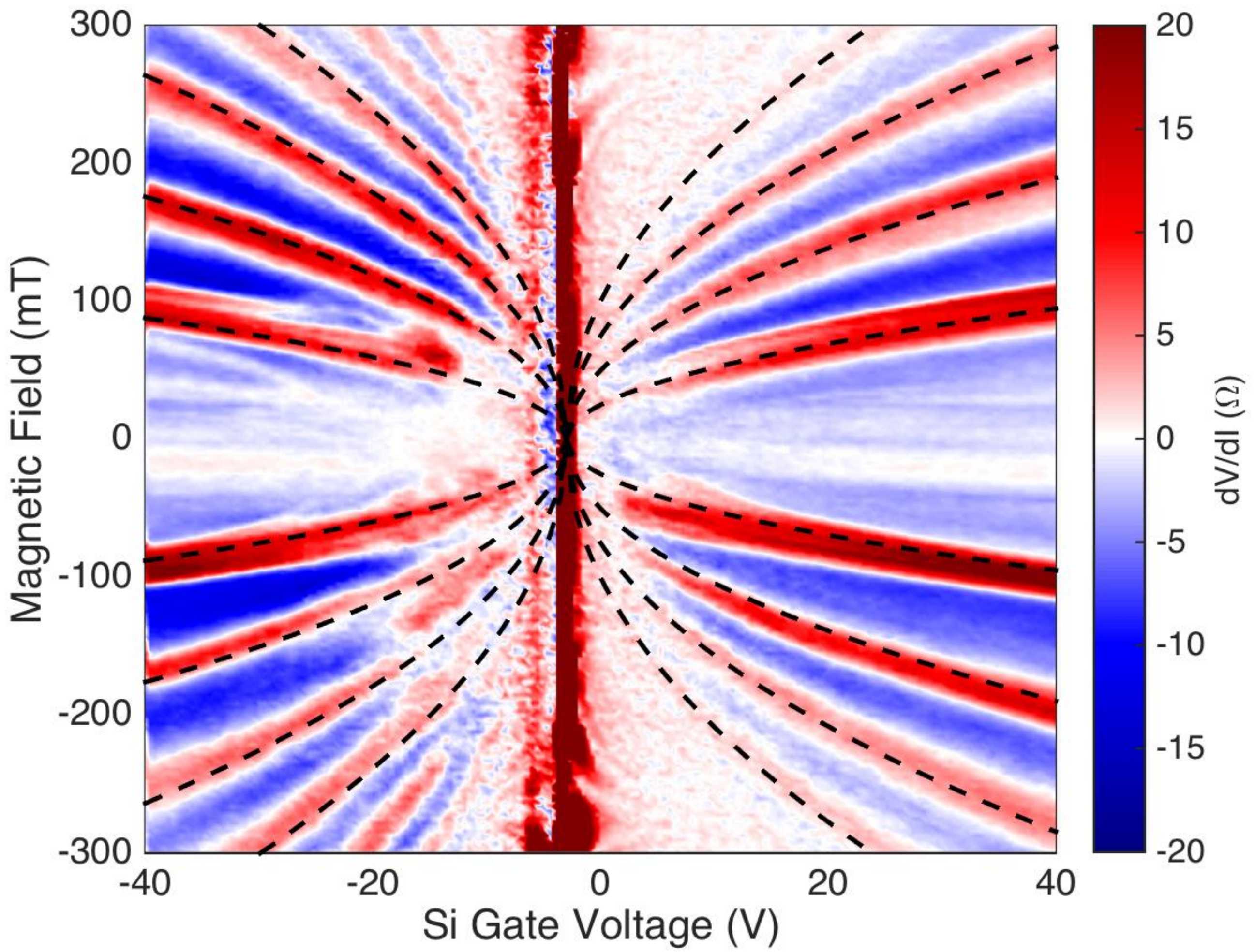
Taychatanapat, Thiti, et al. *Nature Physics* 9.4 (2013)

Matched density TMF



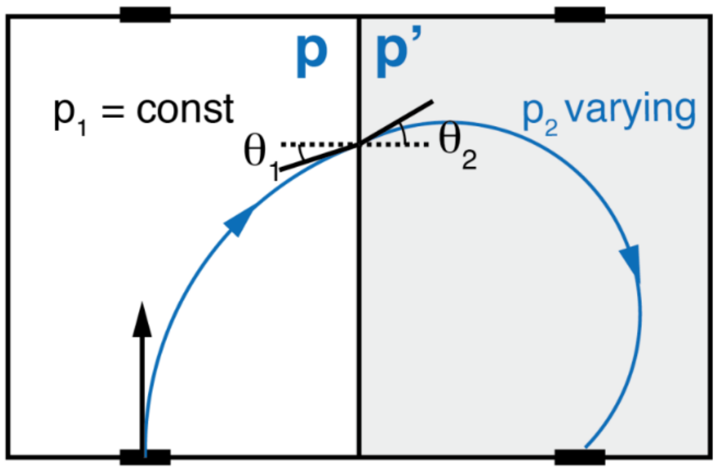
$$B = j\left(\frac{2\hbar\sqrt{\pi n}}{eL}\right)$$

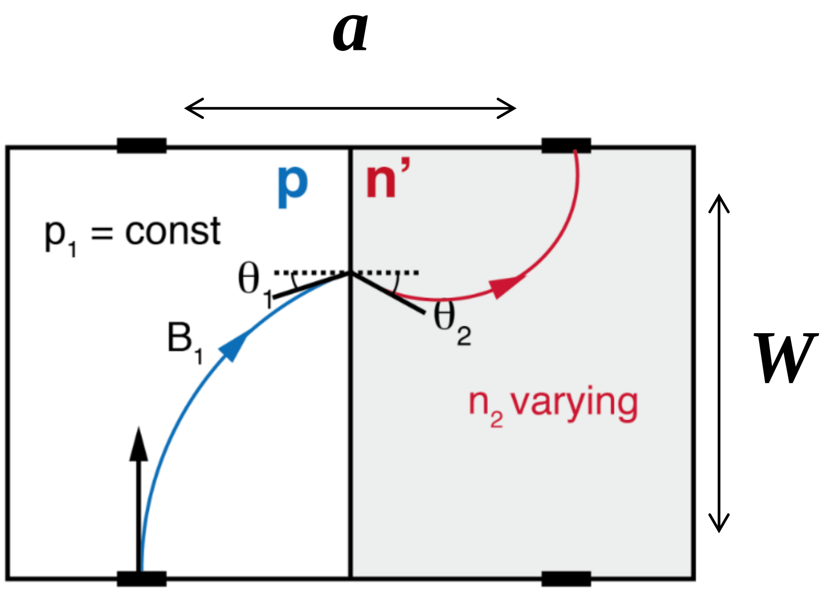
j = 1,2,3…



S. Chen, et al. *Science* (2016).

TMF across junctions





p-p’

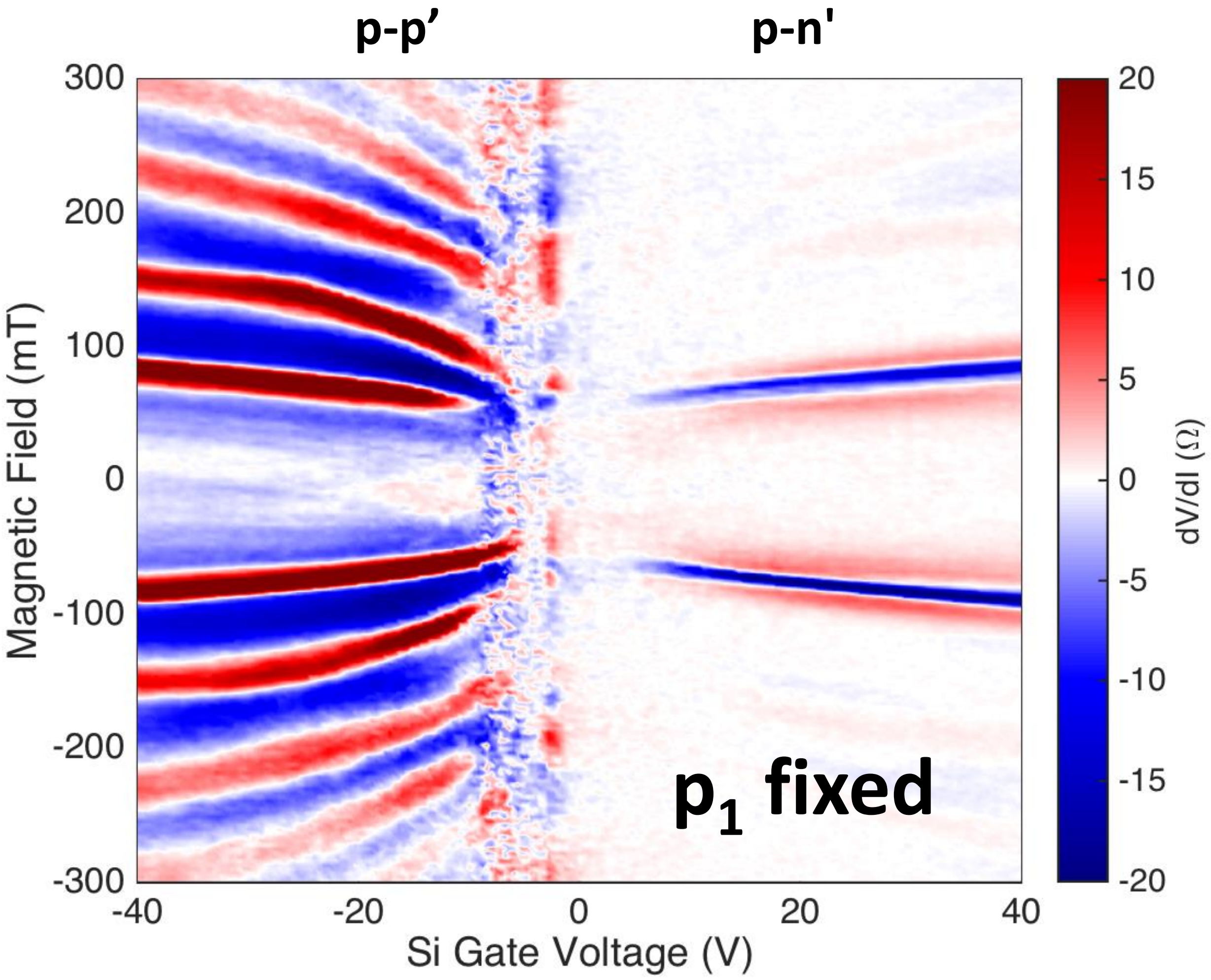
$$\sqrt{1-\frac{n_1}{n_2}\left(\frac{R_1-a}{R_1}\right)^2}\sqrt{2R_1a-a^2}+\sqrt{\frac{n_1}{n_2}}\cdot\frac{R_1-a}{R_1}\cdot a-a\sqrt{\frac{n_1}{n_2}}=0$$

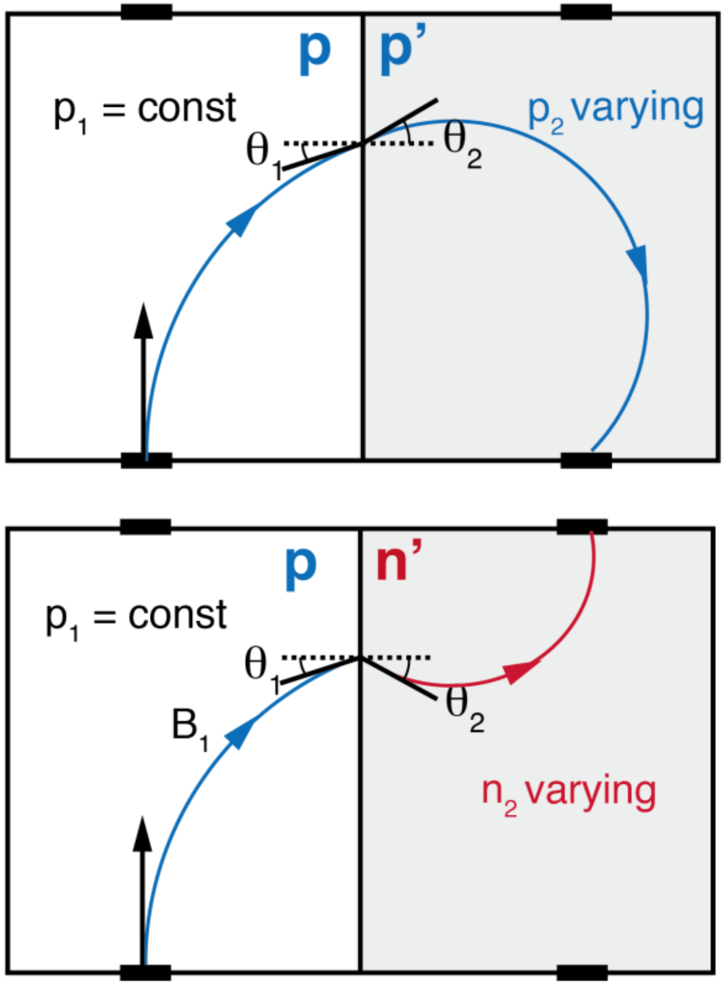
p-n

$$\sqrt{1-\frac{n_1}{n_2}\left(\frac{R_1-a}{R_1}\right)^2}\left(W-\sqrt{2R_1a-a^2}\right)+\sqrt{\frac{n_1}{n_2}}\cdot\frac{R_1-a}{R_1}\cdot a-\frac{(W-\sqrt{2R_1a-a^2})^2+a^2}{2R_1}\sqrt{\frac{n_1}{n_2}}=0$$

S. Chen, et al. *Science* (2016).

TMF across junctions

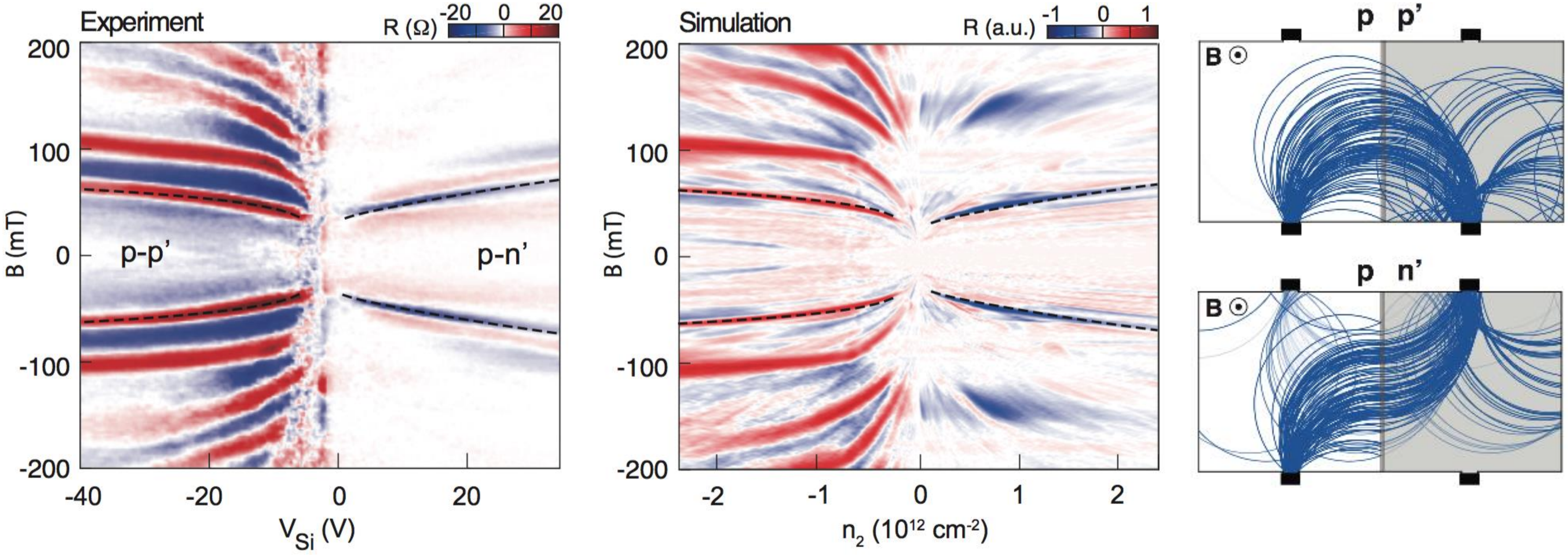




$p_1 = 1.61e12\ cm^{-2}$

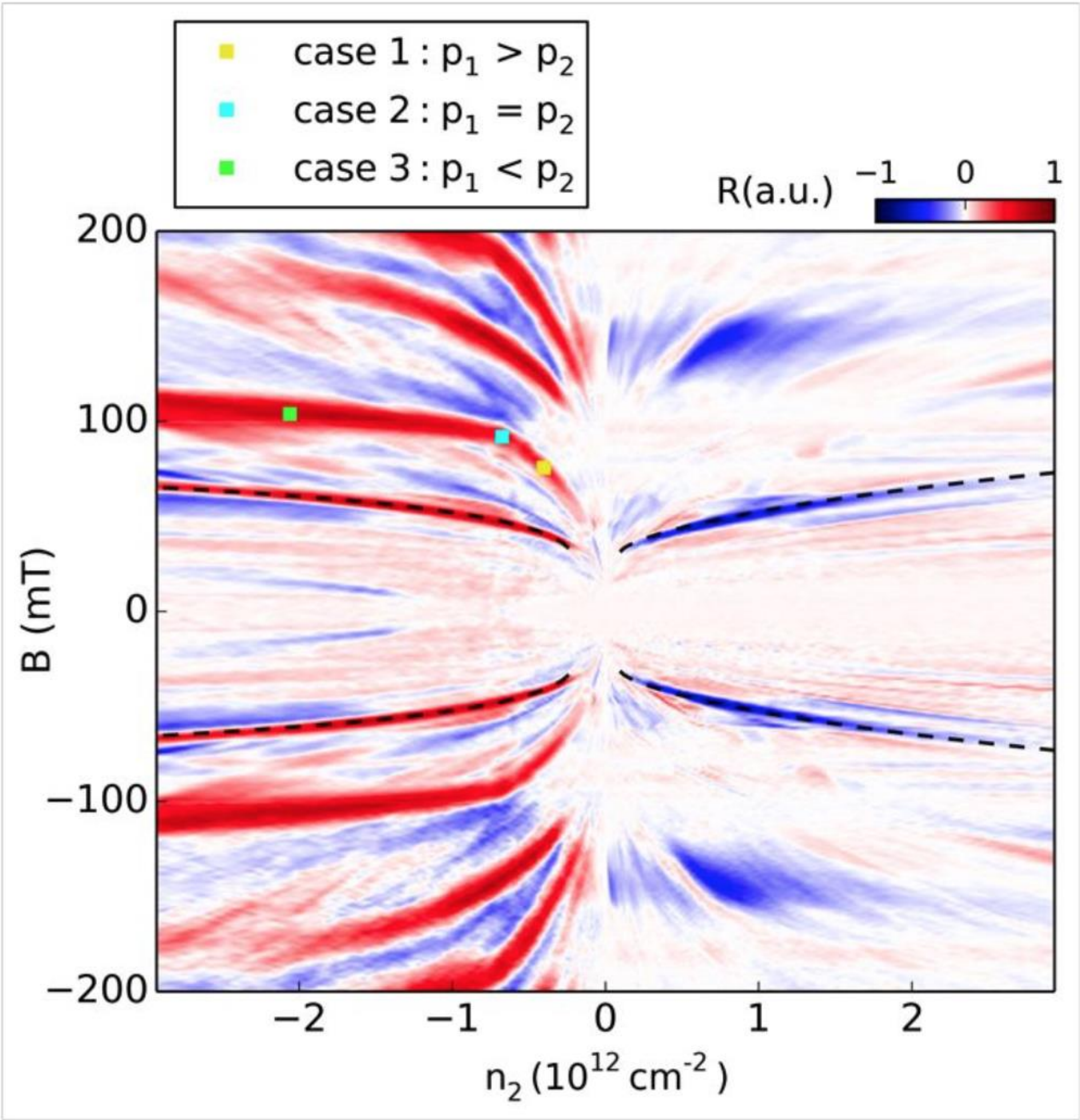
S. Chen, et al. *Science* (2016).

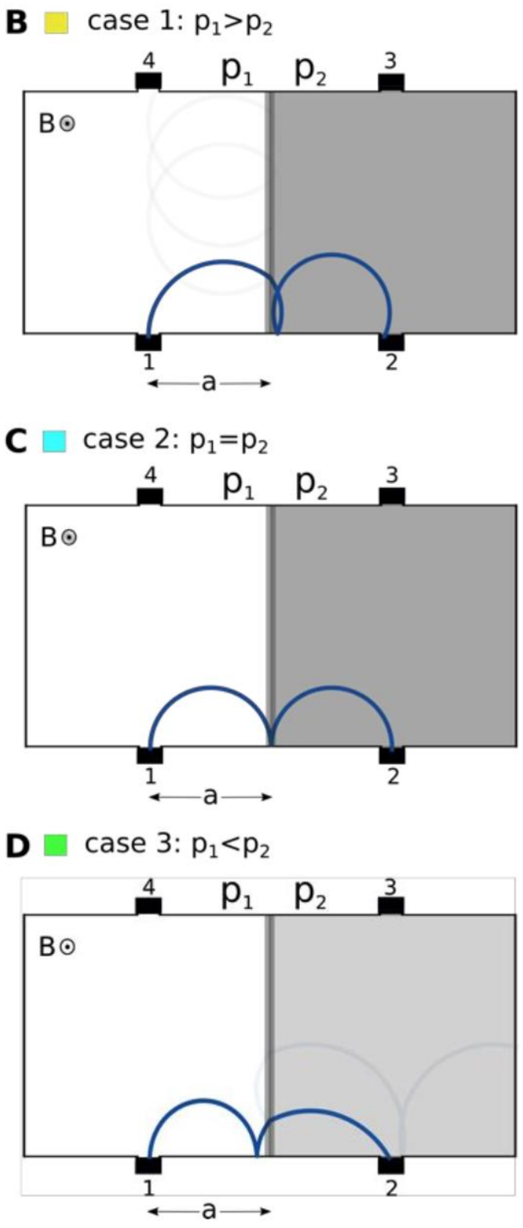
Experiment vs. Simulation



S. Chen, et al. *Science* (2016).

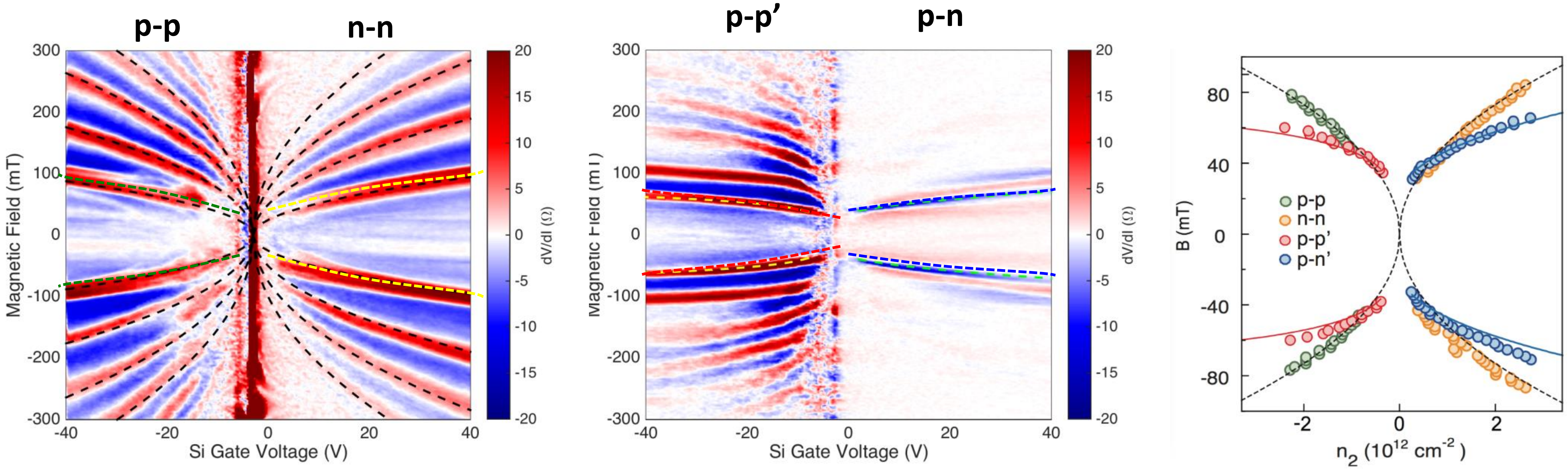
Explanation of kinks





Compare different modes

Extract 1st order peaks:

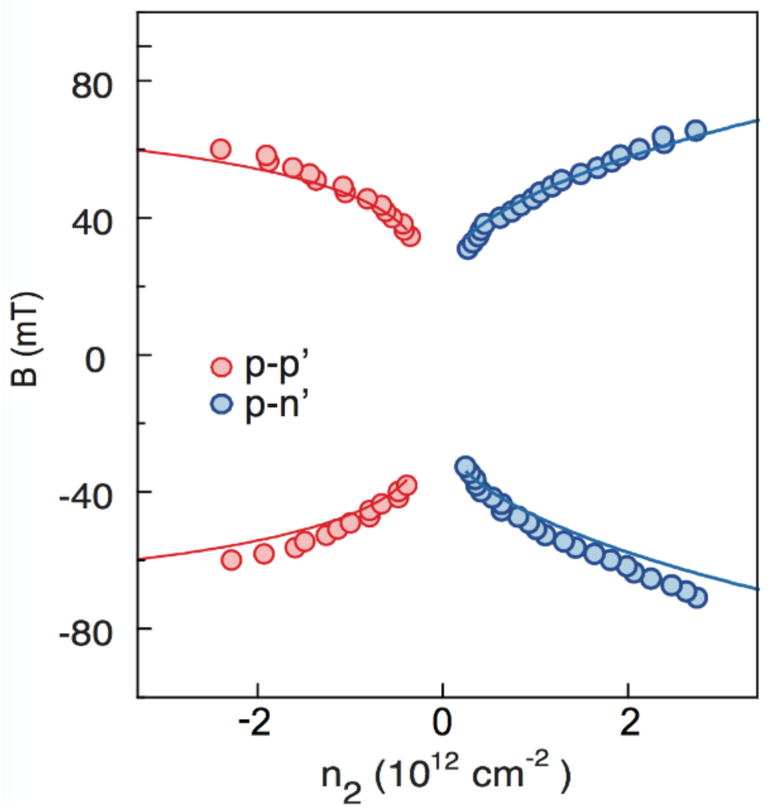


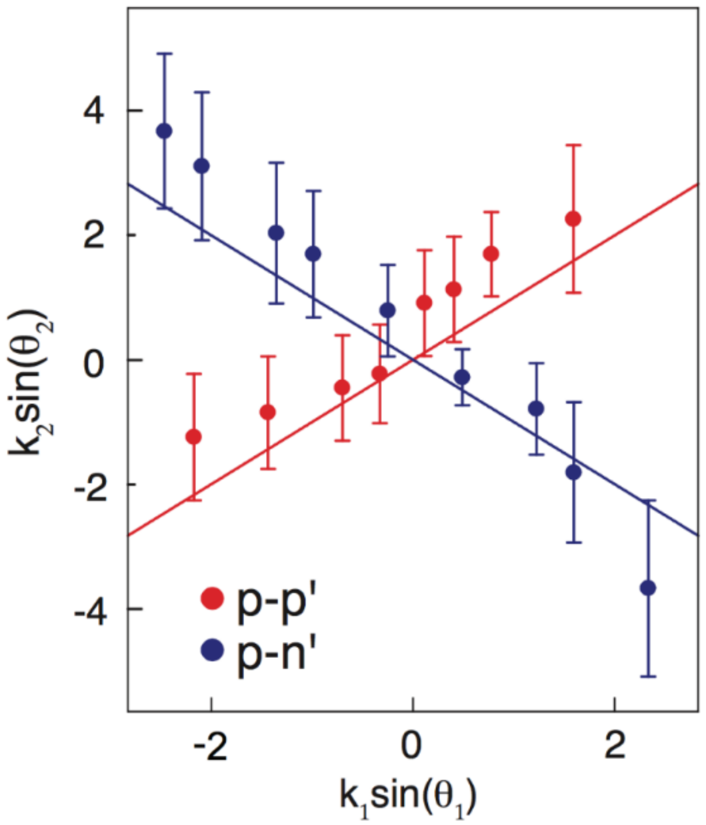
p_1 = 6.76e11 cm^{-2}

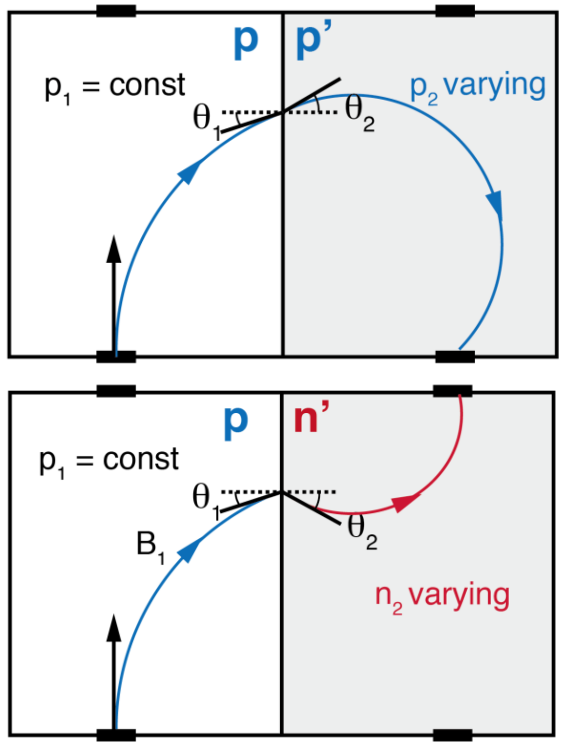
S. Chen, et al. *Science* (2016).

Snell's law for ballistic electrons

$$k_1 \sin\theta_1 = \pm k_2 \sin\theta_2$$

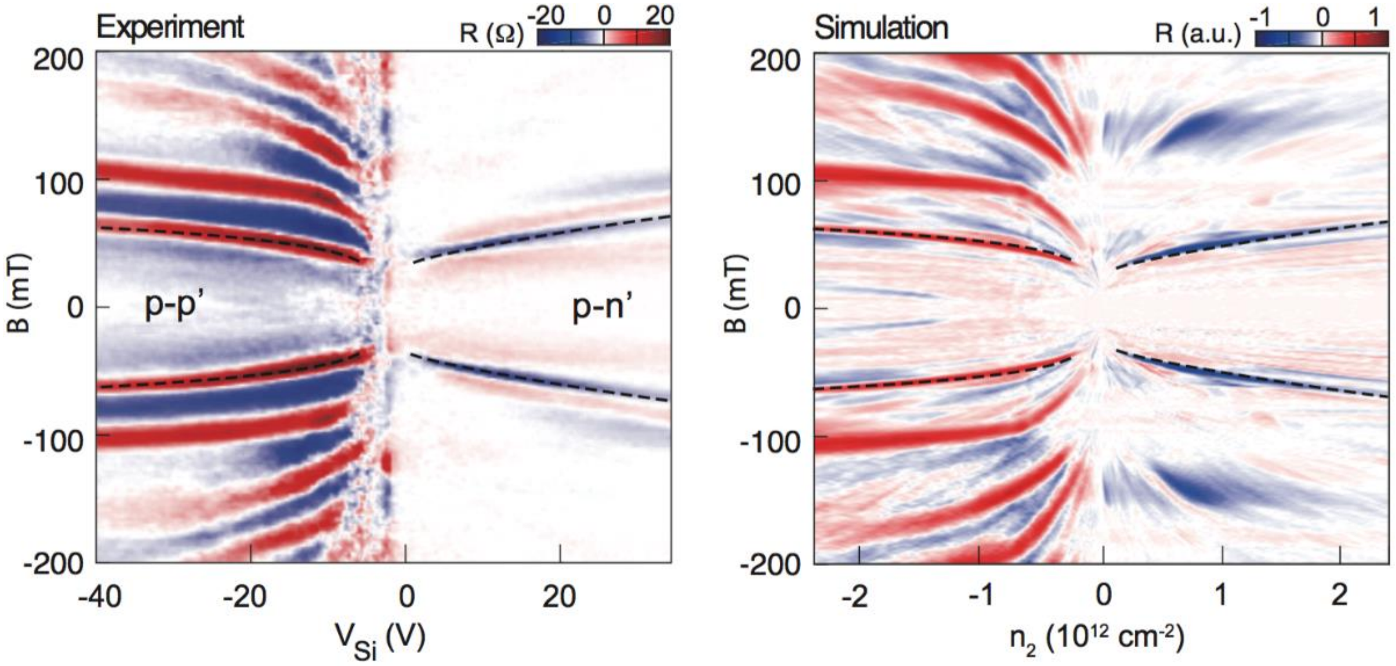


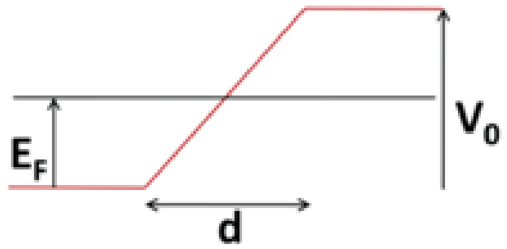


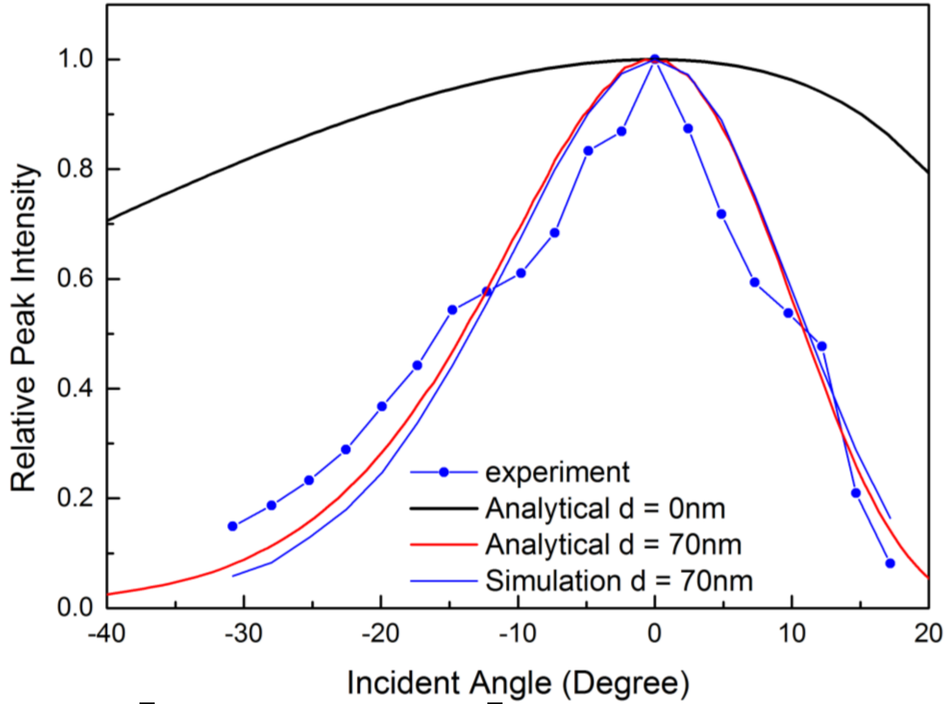


S. Chen, et al. *Science* (2016).

Angular dependent transmission



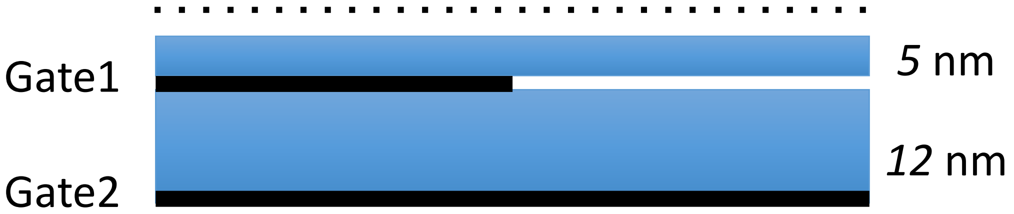


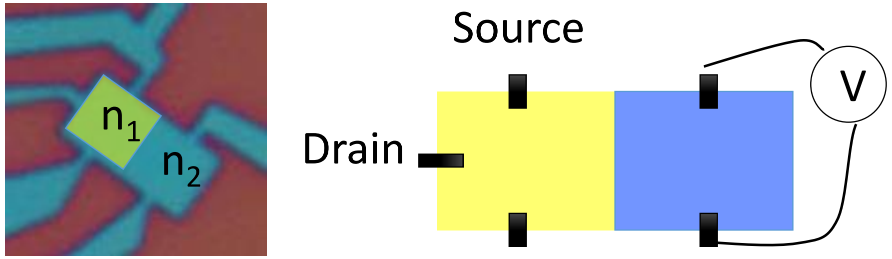


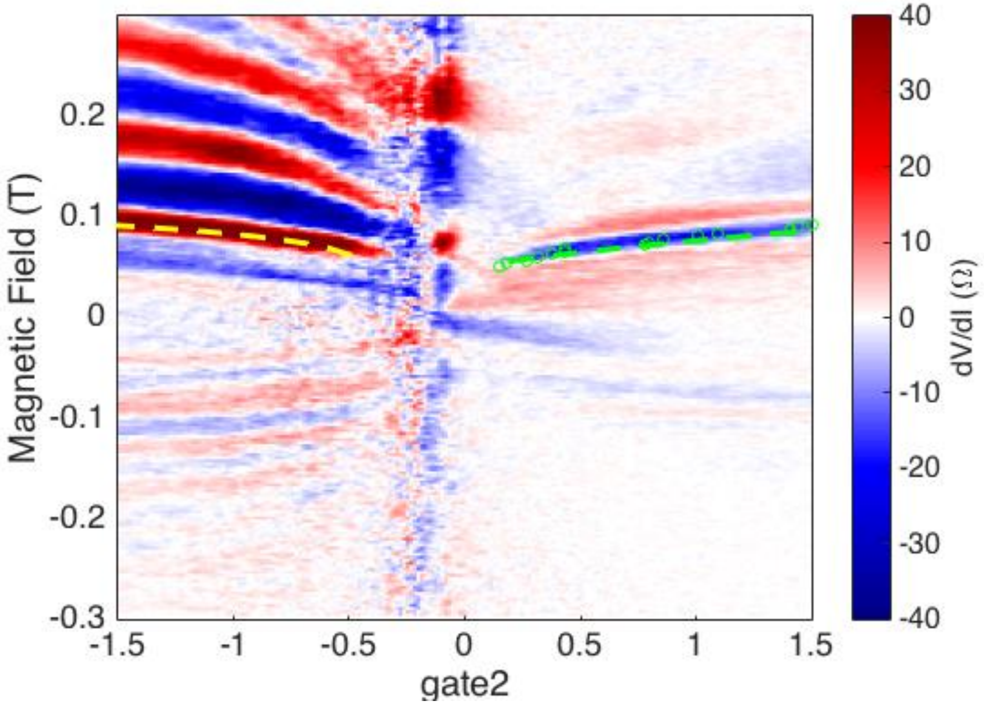
$$T = \left[\frac{\cos(\theta_1)\cos(\theta_2)}{\cos^2(\frac{\theta_1+\theta_2}{2})}\right] e^{-\pi\hbar v_f k_f^2 d \sin^2(\theta_i)/V_o}$$

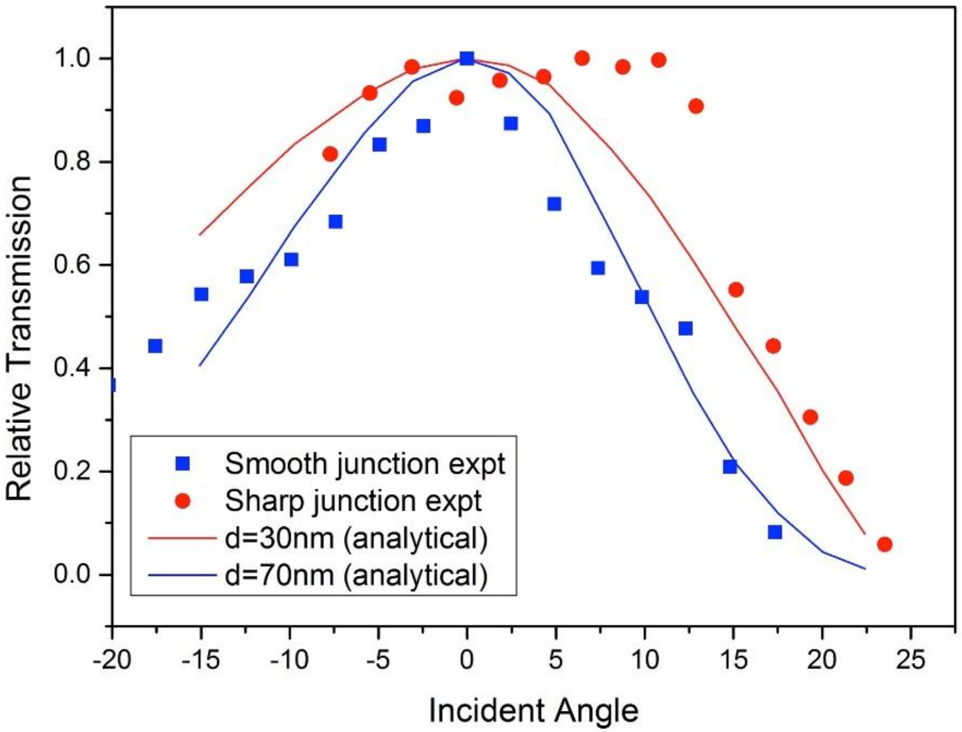
S. Chen, et al. *Science* (2016).
Sajjad, Redwan N., et al. *Phys. Rev. B* **86** (2012): 155412.

Toward sharper junctions



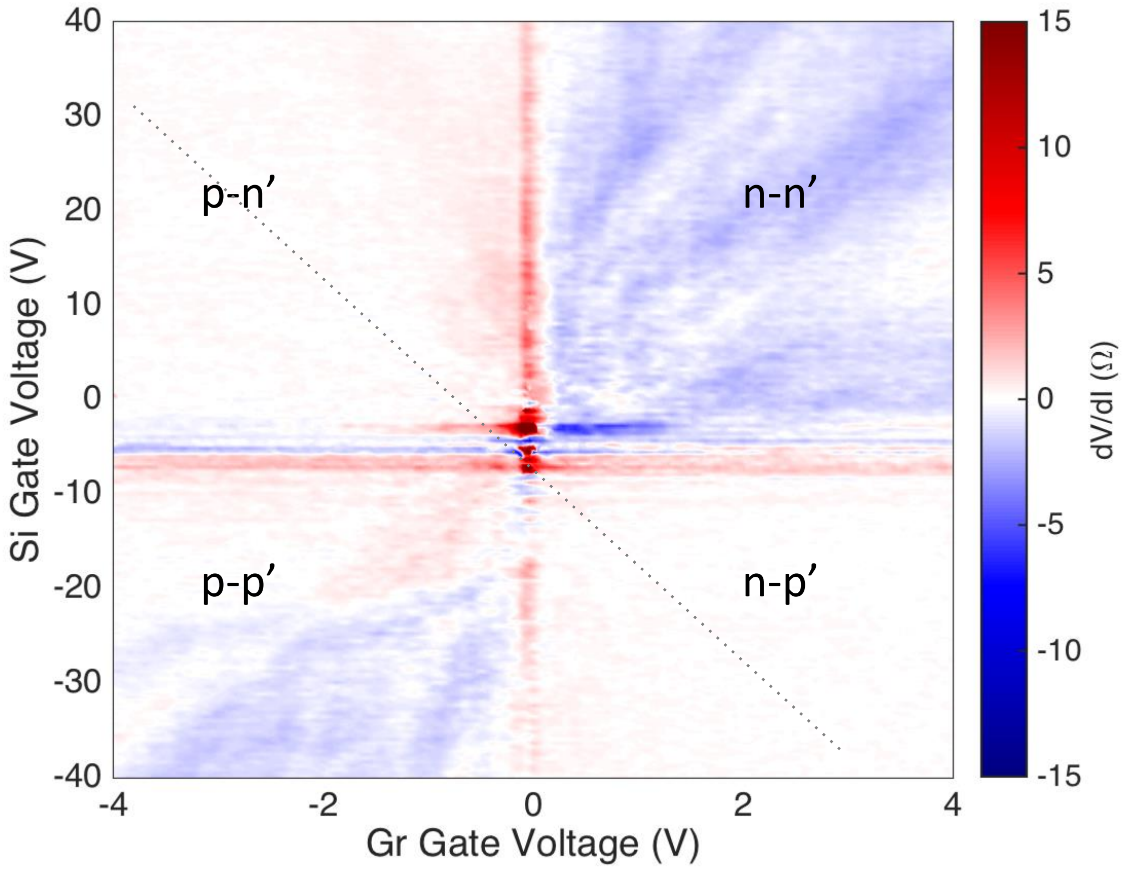


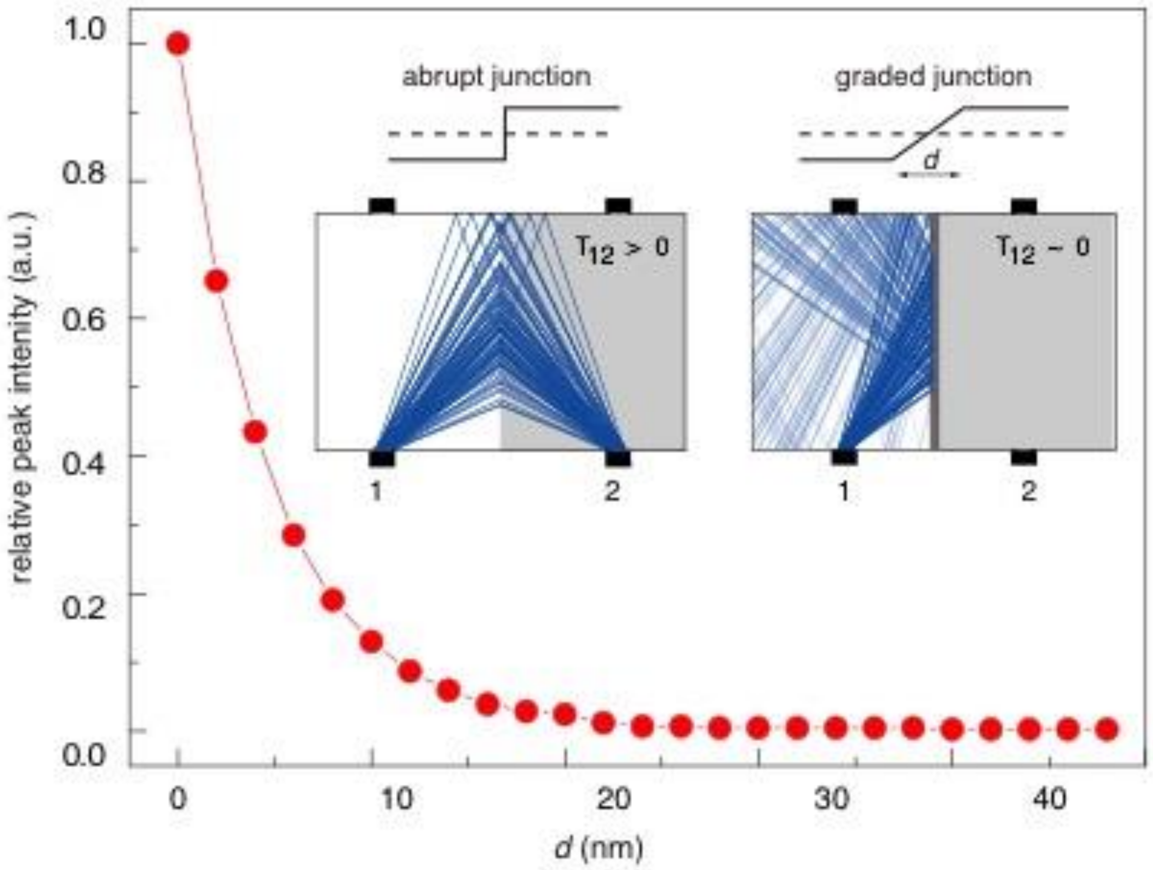




S. Chen, et al. *unpublished*

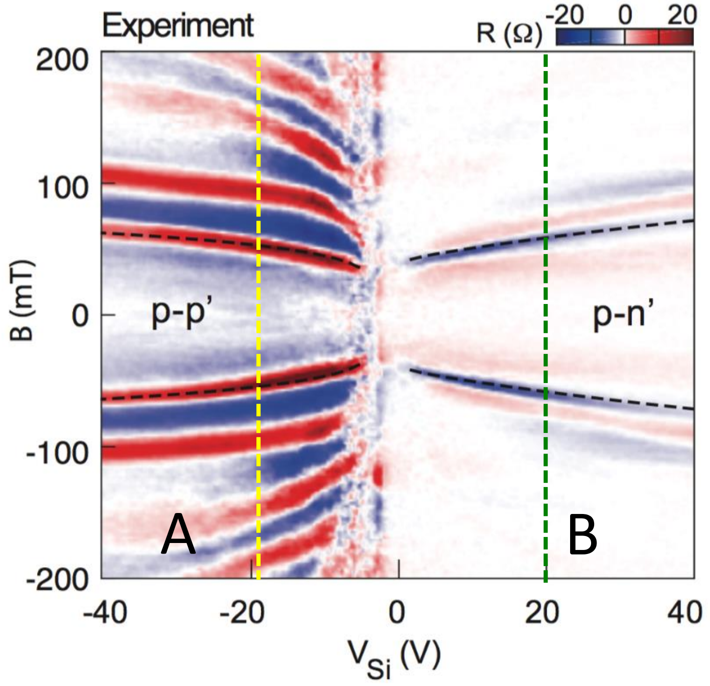
Back to zero field

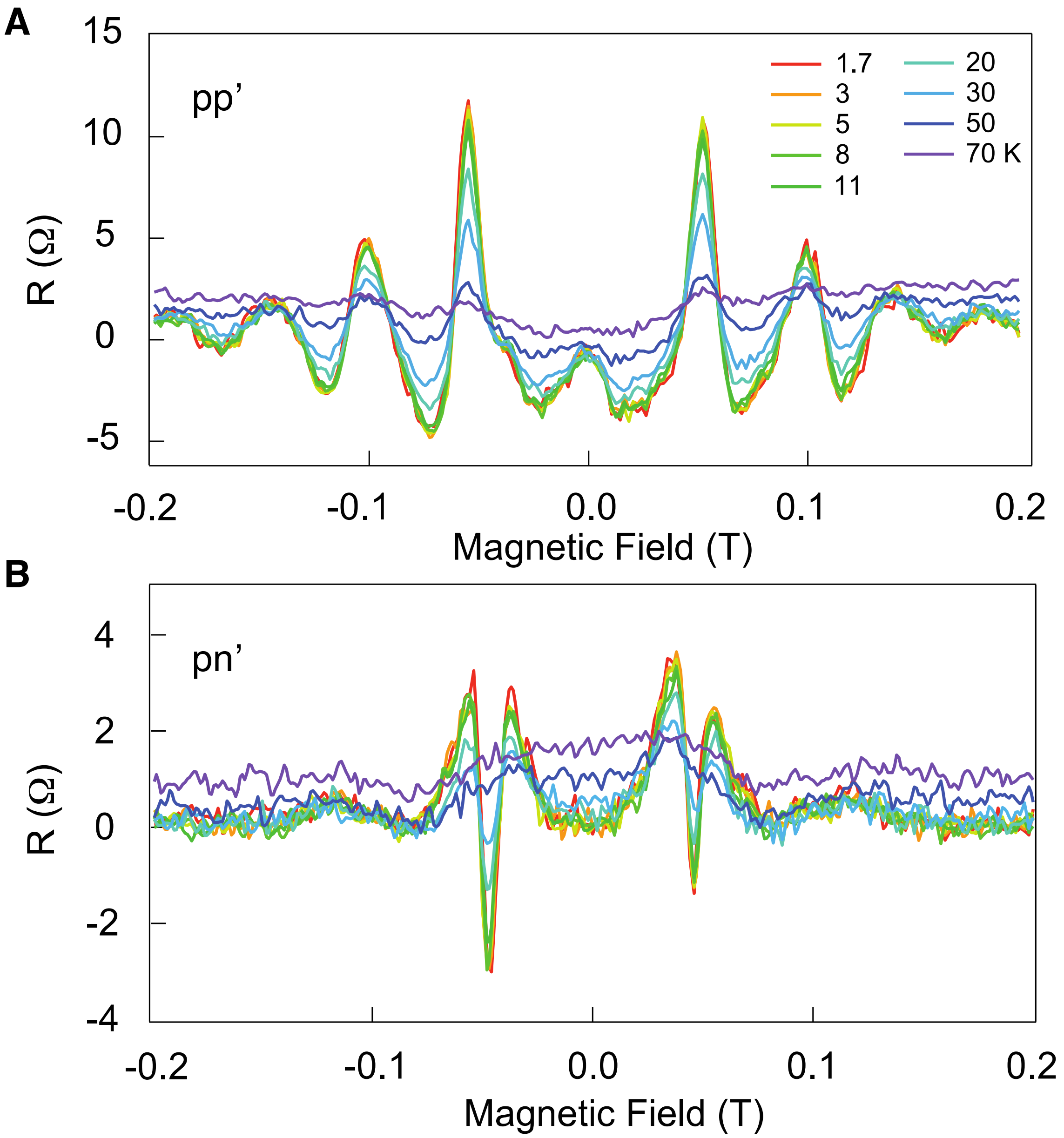




S. Chen, et al. *Science* (2016).

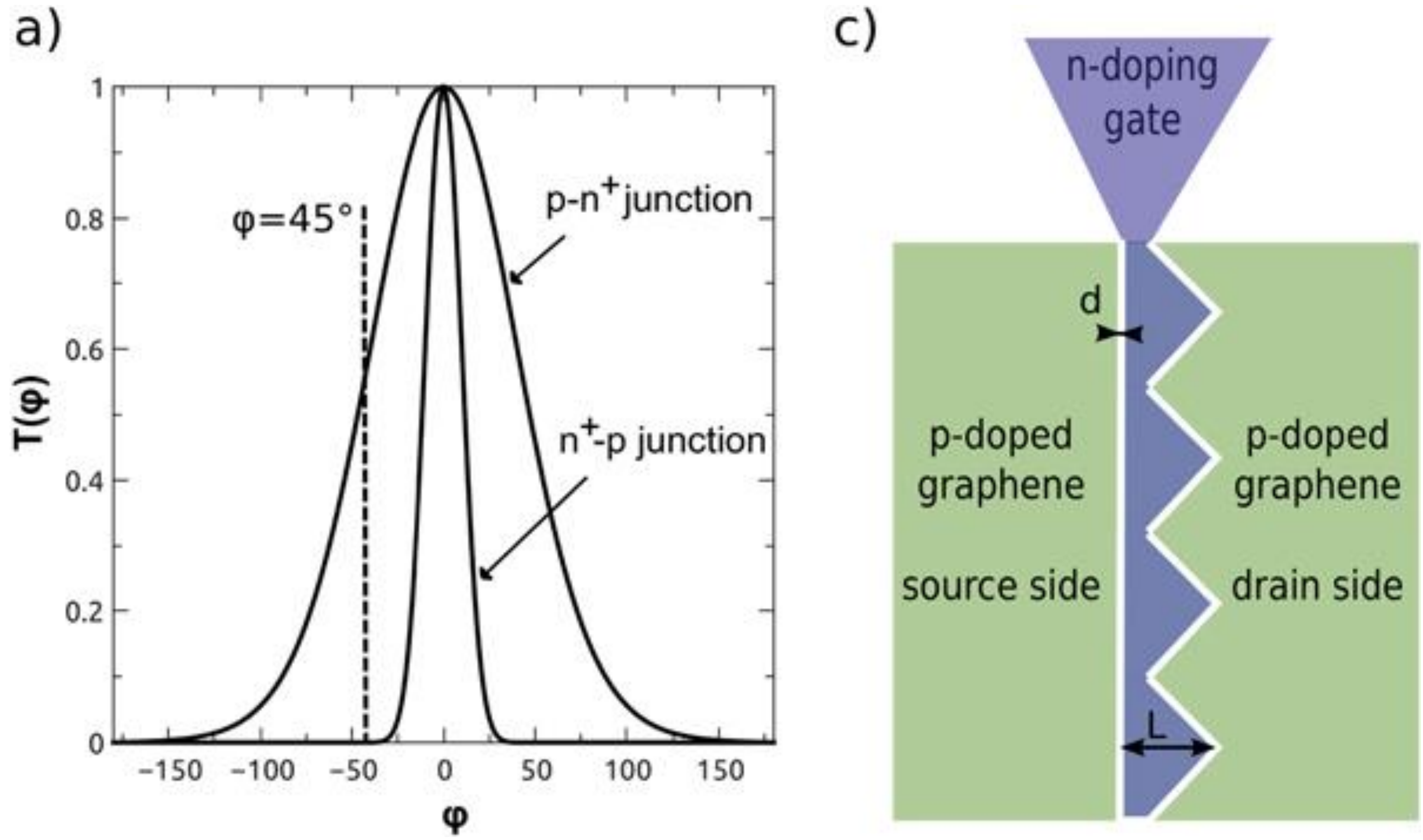
Room temperature devices





S. Chen, et al. *Science* (2016).

Challenges with ballistic split-gate transistors

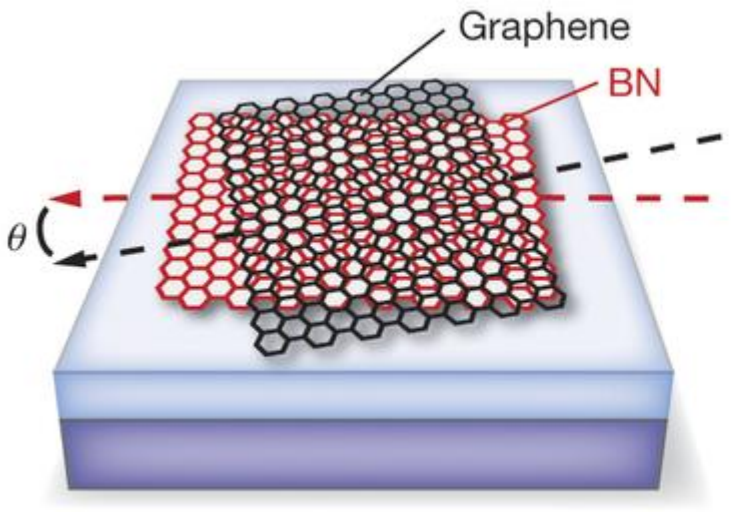


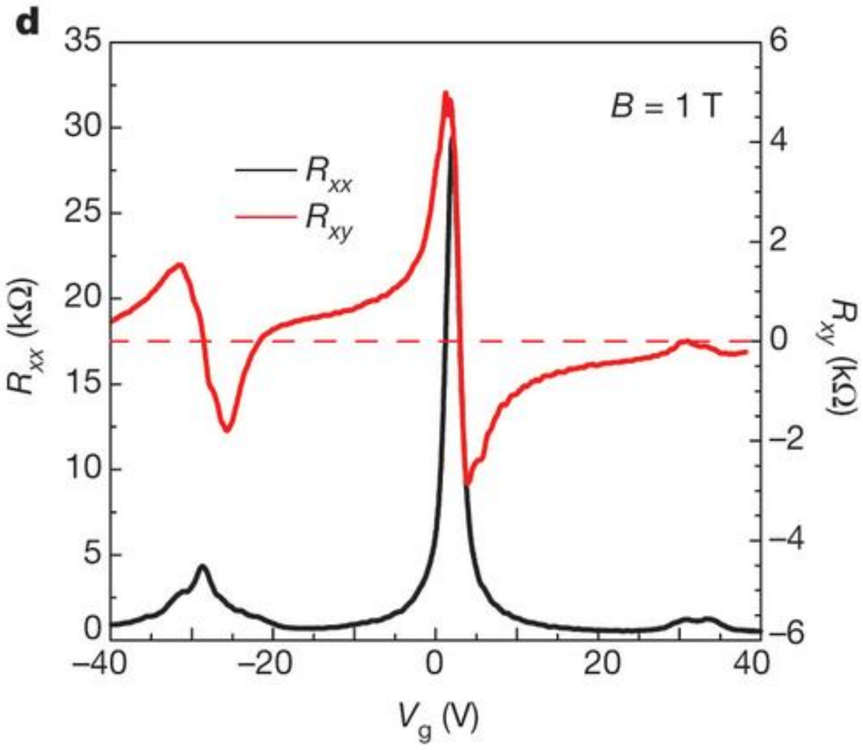
Wilmart, et al. *2D Materials* 1.1 (2014)
Morikawa, et al. arXiv:1702.04039 (2017)

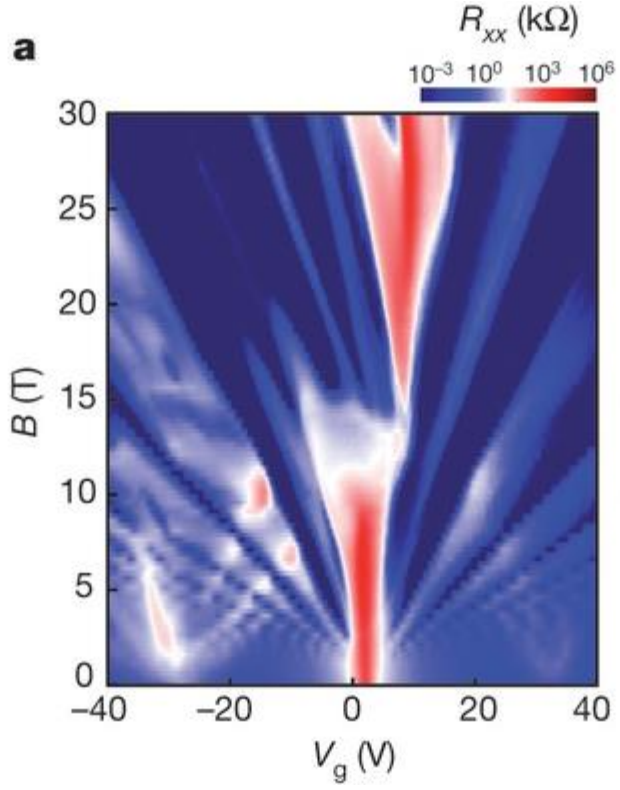
- Diffusive scattering due to roughness at device edges and gates boundaries
- Imperfect collimation of transport at first gate

Deeper solution:
band structure engineering

Graphene superlattices: Hofstadter



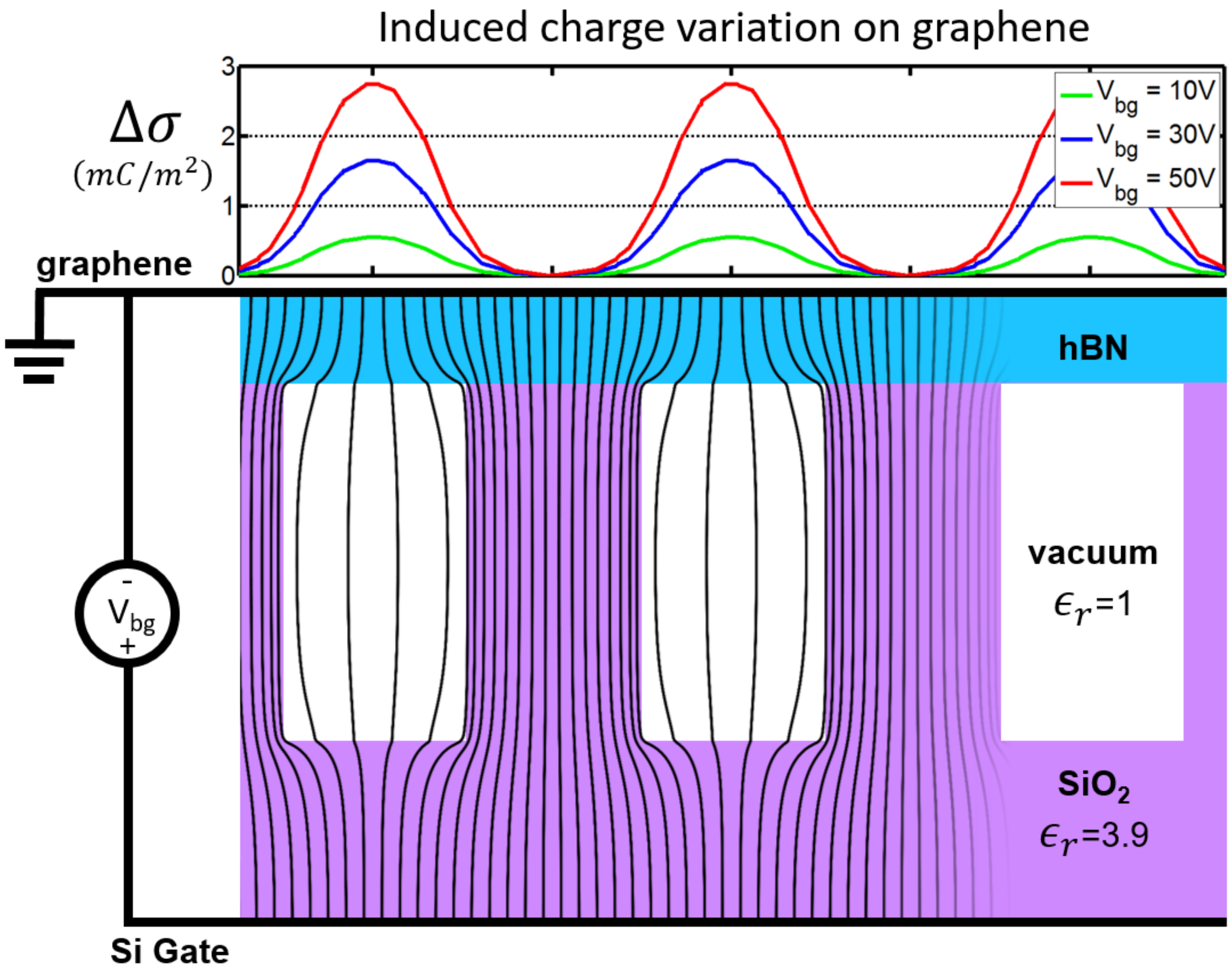


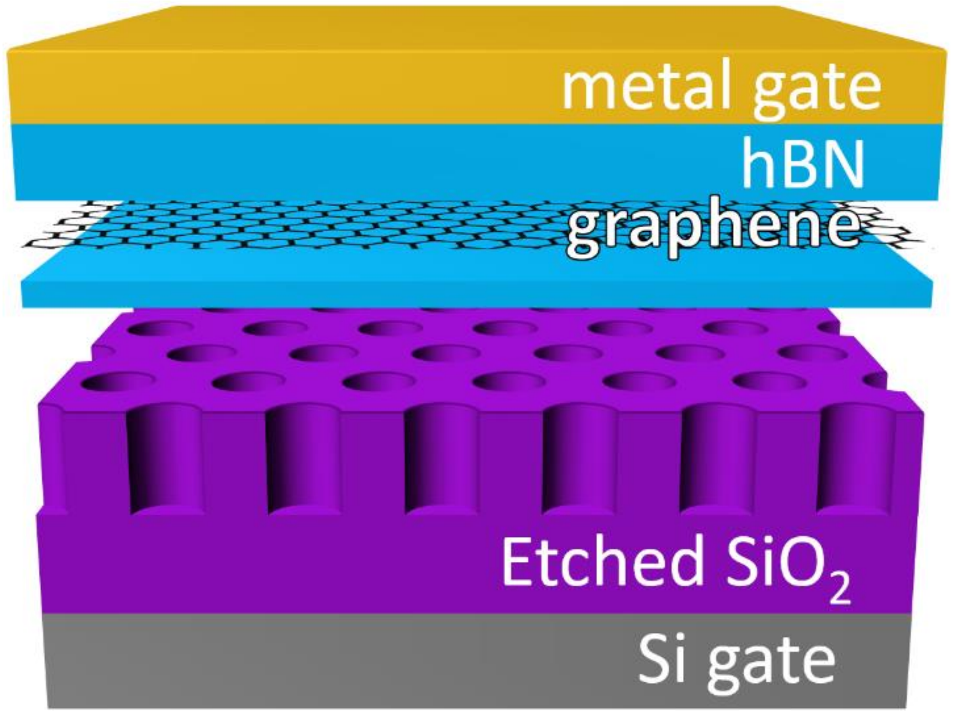


Hexagonal geometry
$\lambda \geq 14nm$

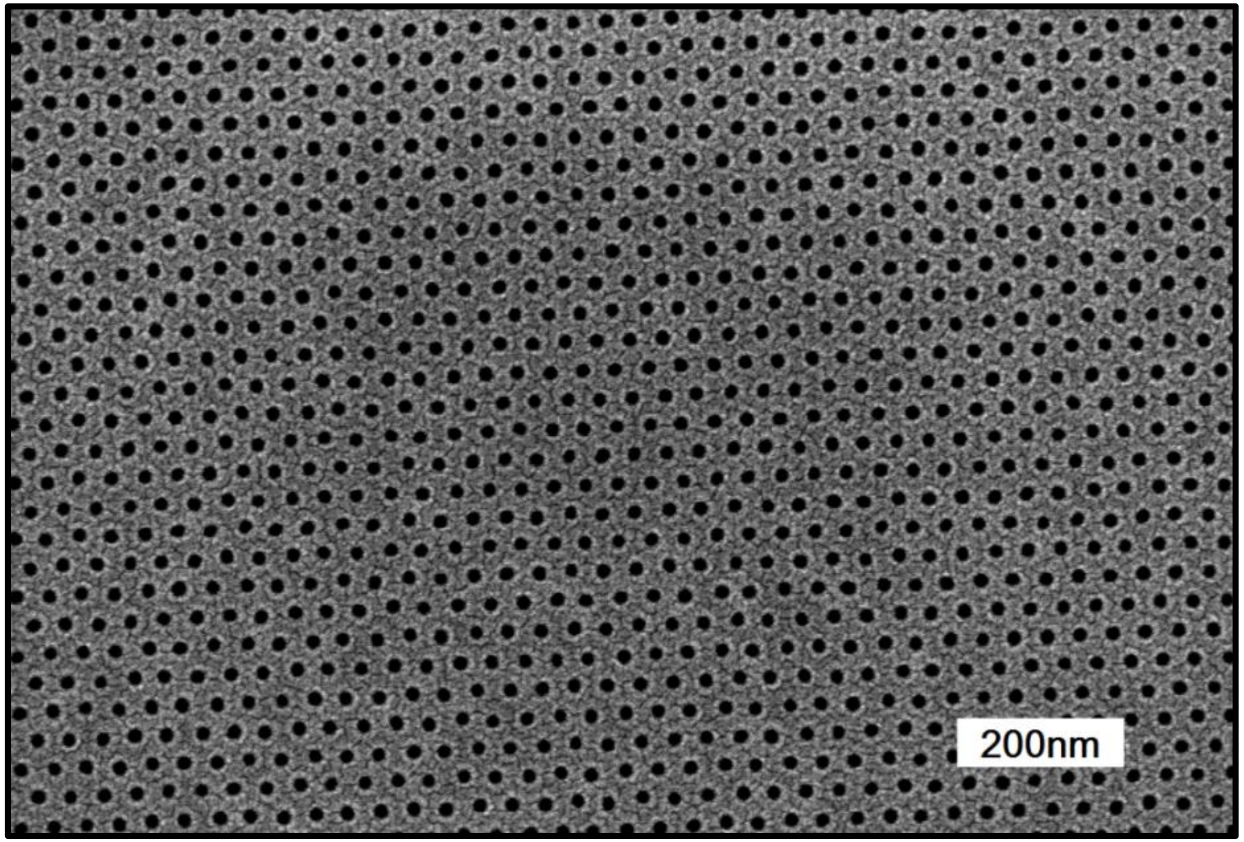
C.R. Dean, et. al., Nature **497**, 598–602 (2013)

Dielectric-modulated electrostatic gating

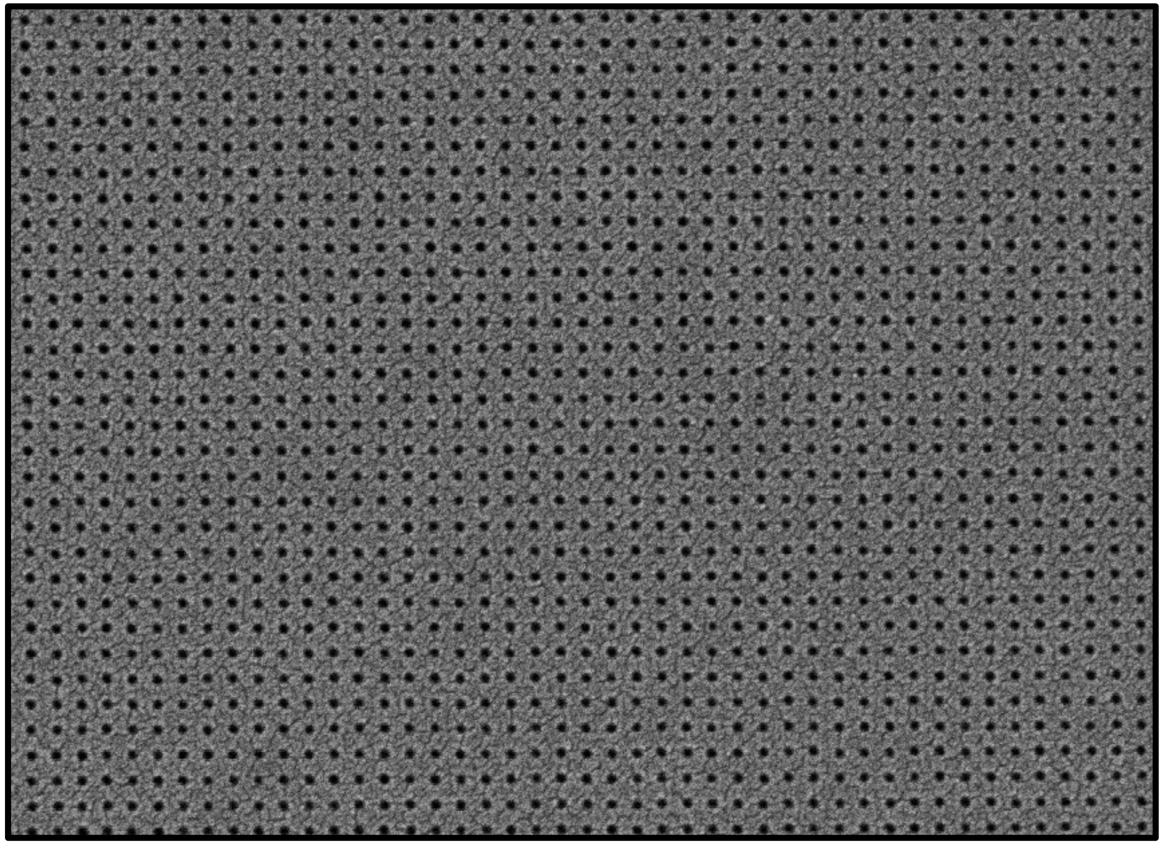




SiO_2 patterning

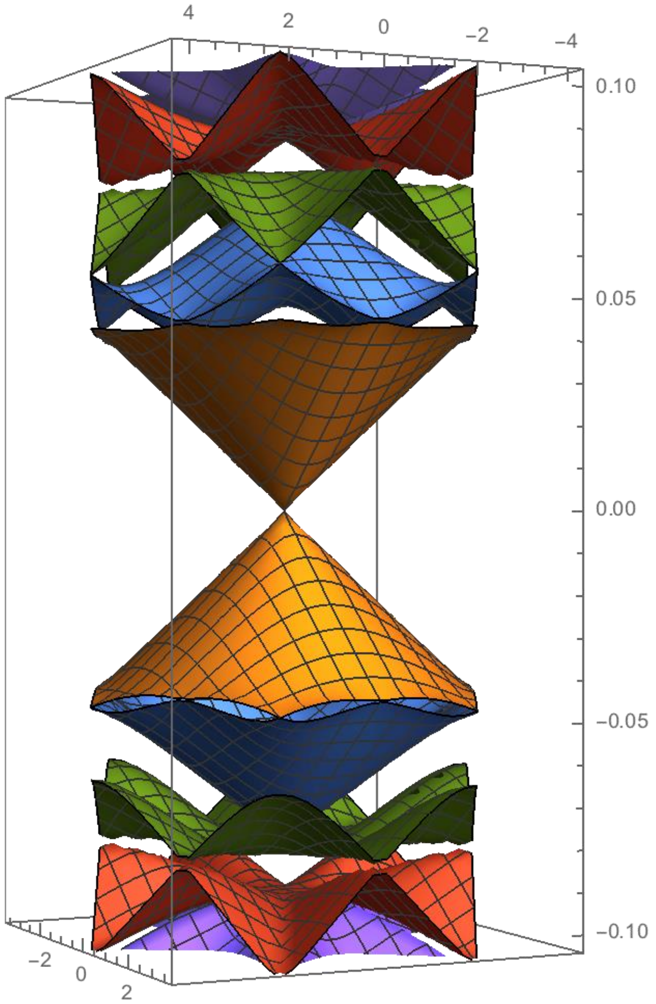


Triangular 40nm pitch



Square 35nm pitch

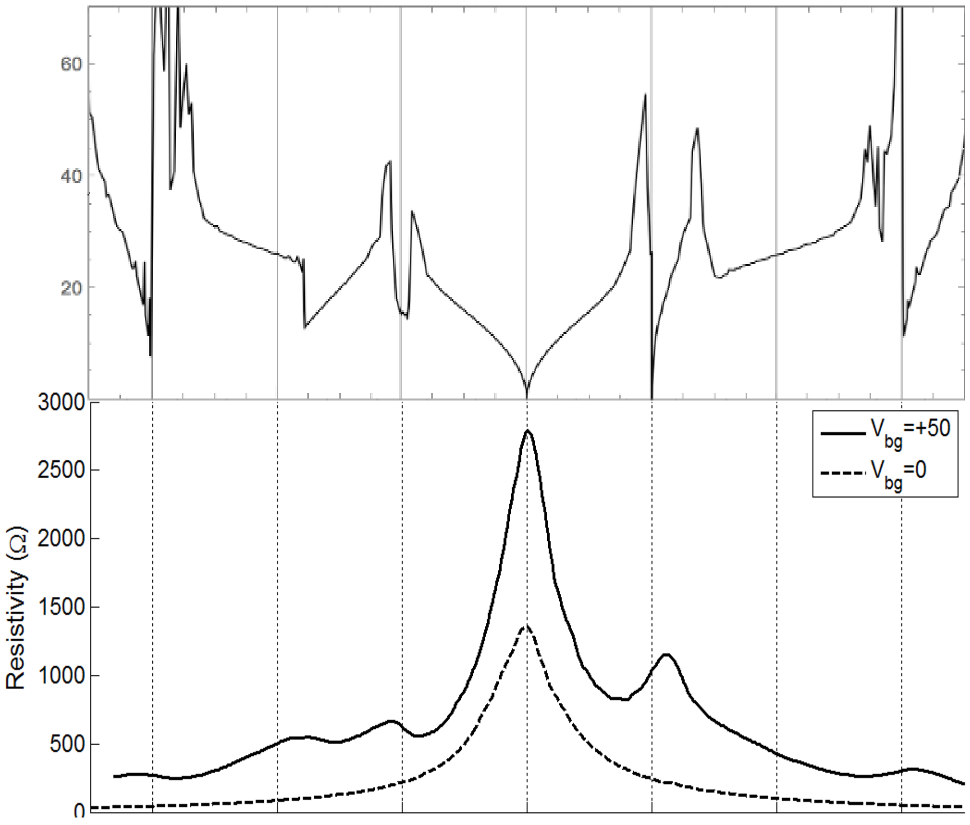
Triangular superlattice



Mikito Koshino – Tohoku University

$$n_0 = \frac{1}{A} = \frac{2}{\sqrt{3}a^2}$$

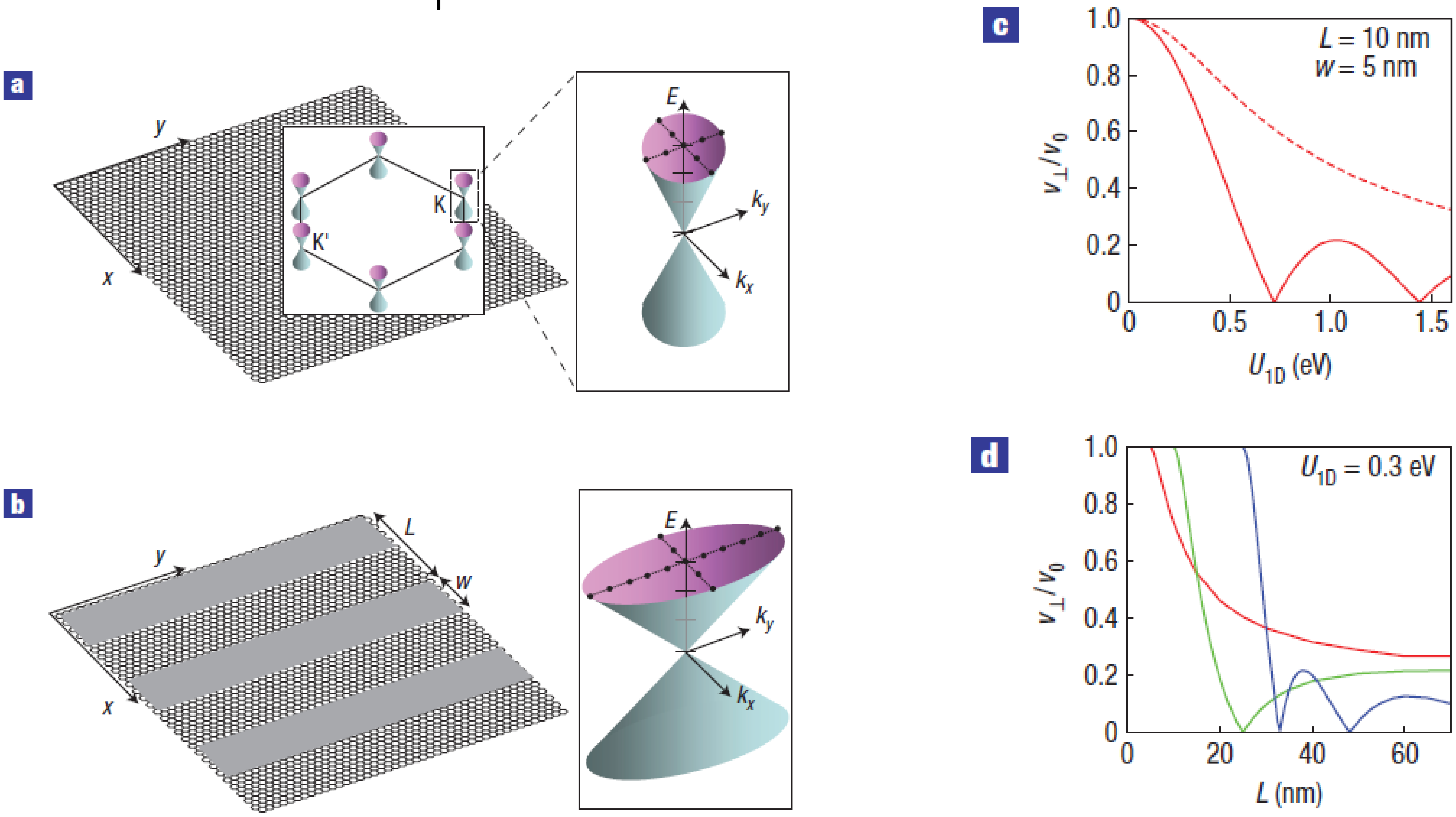
$a = 40nm$, triangular lattice



C. Forsythe, et al. *unpublished*

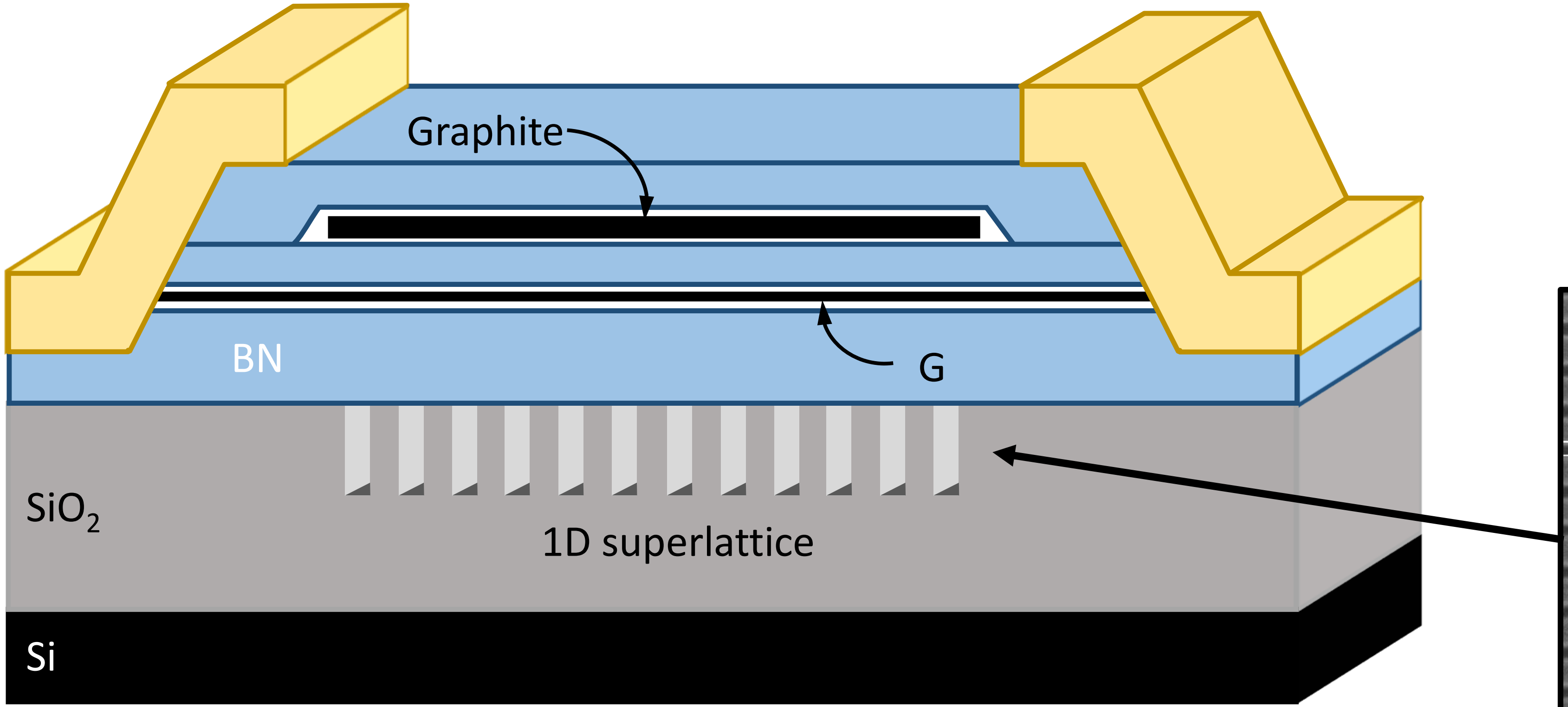
- Highly customizable
- Switchable
- Interesting physics at easily-achieved B-field (3.5T rather than 35T)
- Significantly altered electronic properties

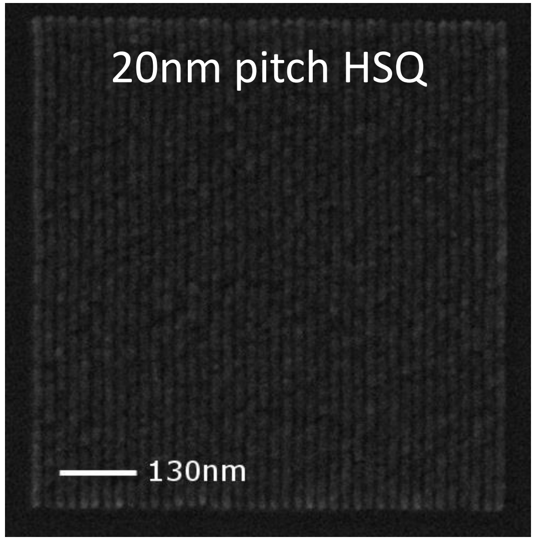
One-dimensional superlattices

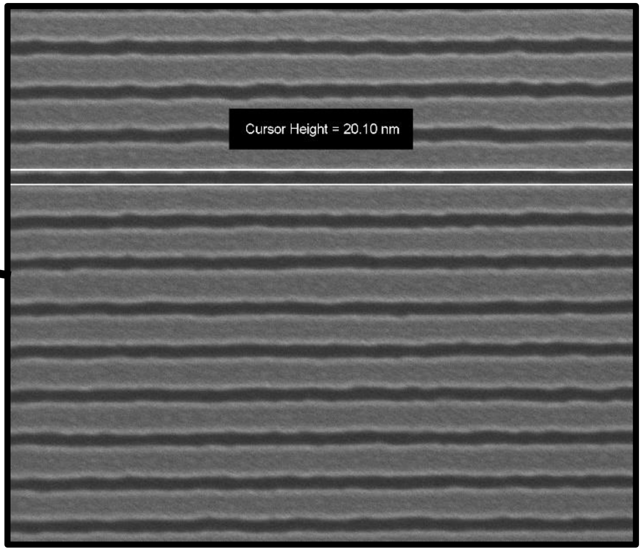


H-W Park et al., *Nature* (2008)

Initial device design



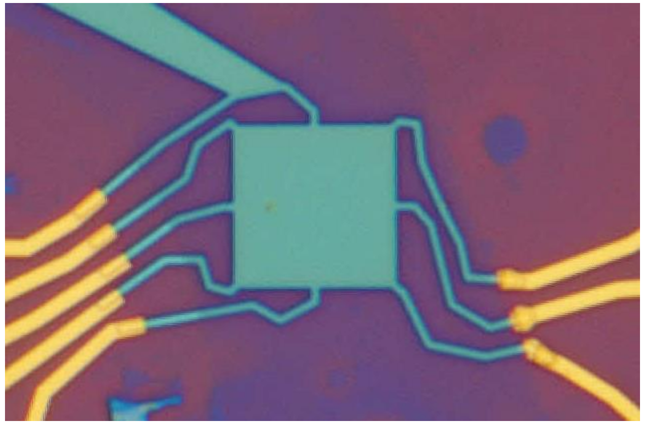


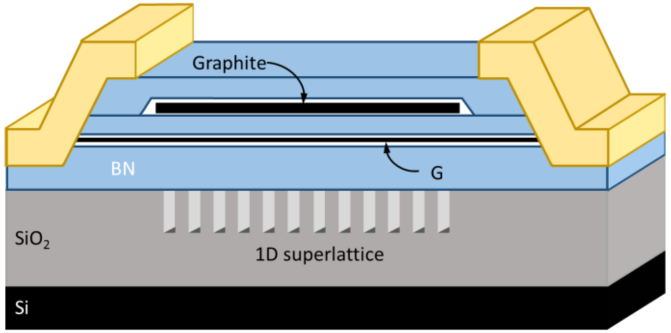


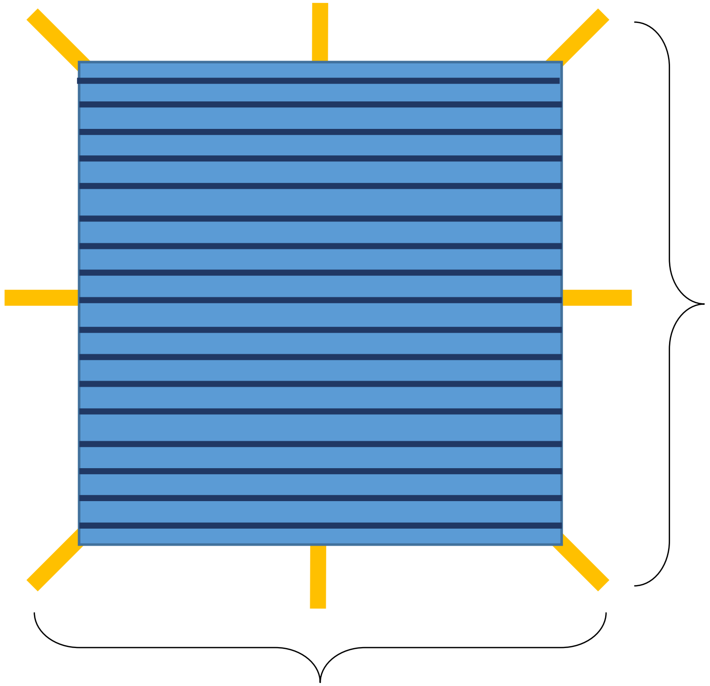
60nm pitch SiO_2 trenches

Measuring anisotropic transport

$$\sigma_\perp \neq \sigma_\parallel$$





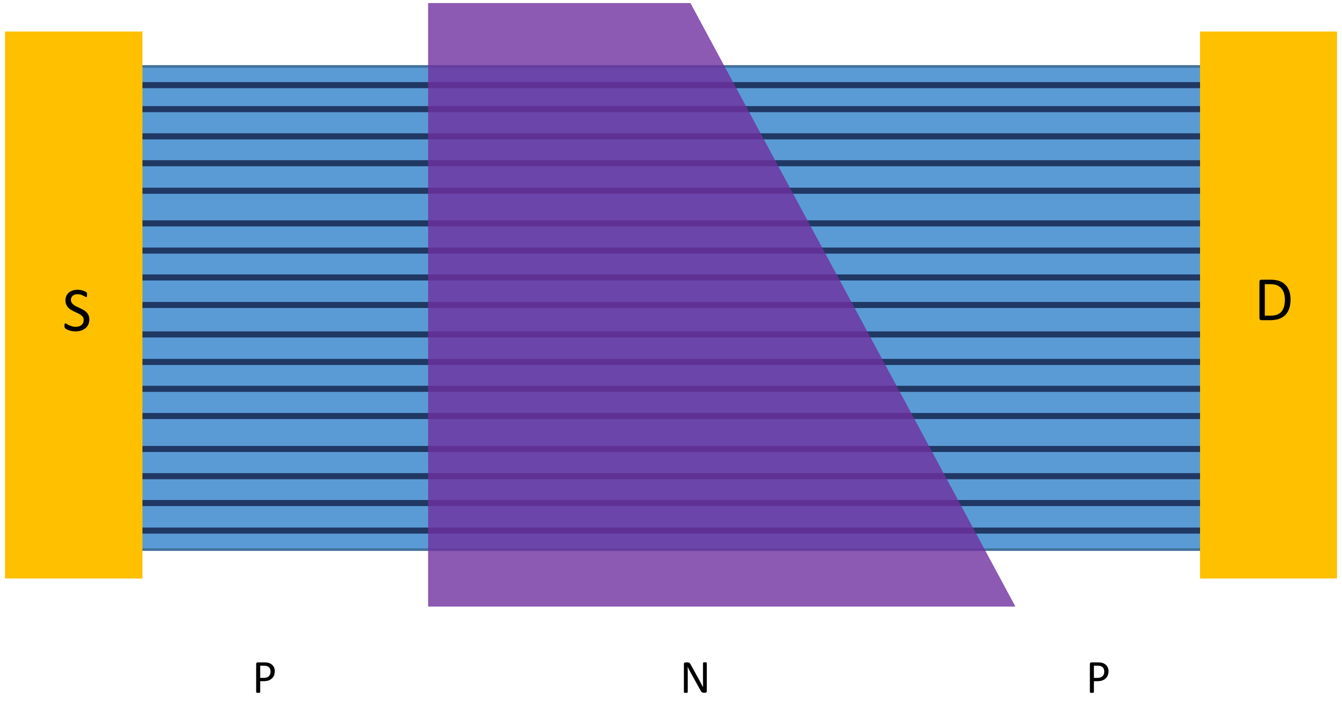


$\sigma_\perp(n)$
reduced Fermi velocity

$\sigma_\parallel(n)$
satellite Dirac peaks

Application to split-gate gFETs

Proposed device design



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

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

Acknowledgements

We thank P. Kim, A. Pasupathy and J.-D. Pillet for helpful discussion, and R. Ribeiro for fabrication assistance.

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Columbia University in the City of New York

INDEX Institute for Nanoelectronics Discovery and Exploration

Thank you.