Dirac Electronic Optics in Graphene Devices

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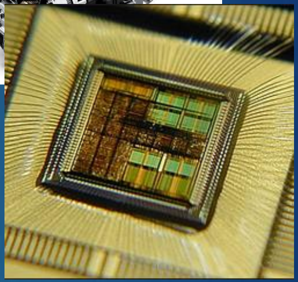
SNU 콜로퀴움 (2018/5/2)

Quantum Electronics

- Study of quantum mechanical behavior of electrons in solids

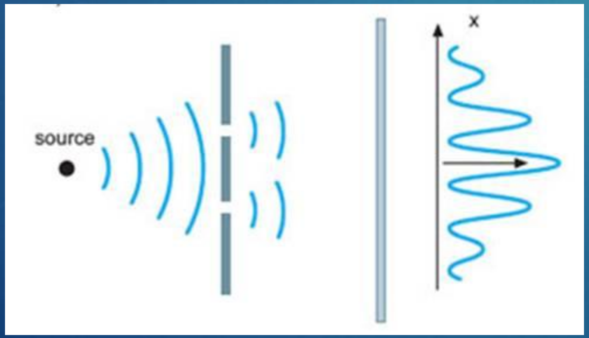
Fundamental Science		Applied Science
Classical Mechanics	→	Mechanical Engineering
Electromagnetics	→	Electrical Engineering
Quantum Mechanics	→	**Quantum Engineering**

e.x.)
Engine



e.x.)
CPU

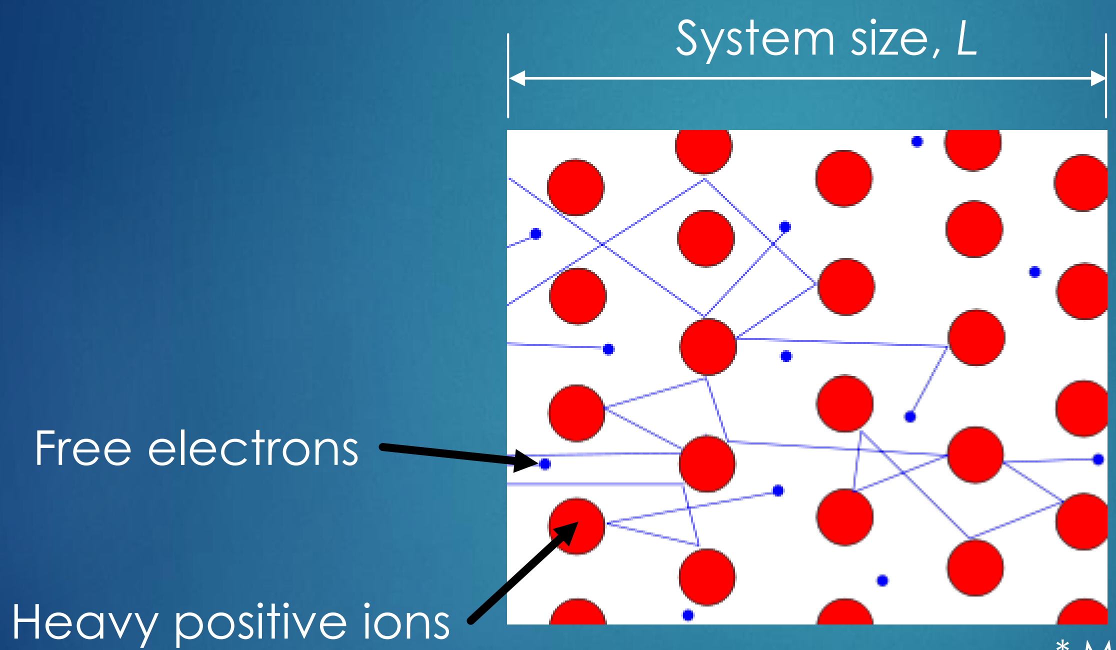
e.g.) quantum coherence,
superconductivity



e.x.)
Quantum Computers

How Electrons Move in Solid

- Drude's view (1900) : Electrons keep colliding with ions.



* Mean free path l_{mfp} ~ atomic scale

Diffusive system ($l_{mfp} << L$): Resistance $\propto L$

Bloch Wave by F. Bloch in 1928

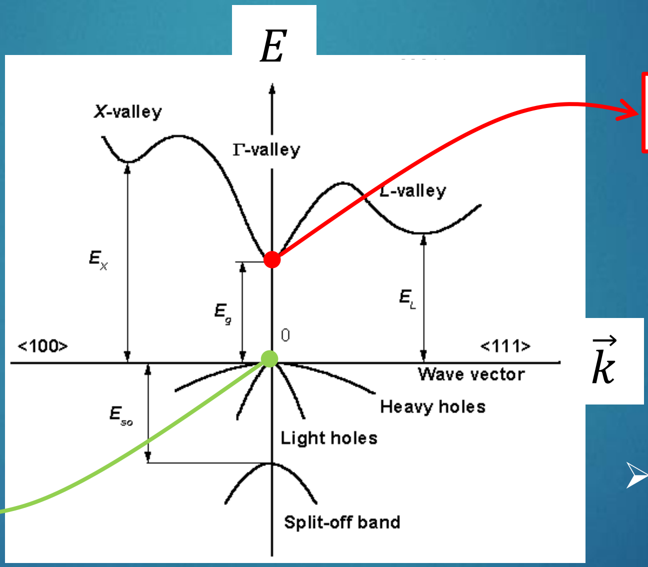
- Electrons in solid feels periodic potentials, $V(x+a) = V(x)$

$\Psi_k(x) = u_k(x)e^{ikx}$, where $u_k(x+a) = u_k(x)$

, $E = E_k$: Multiple solutions assigned by k *correspond to* ***Bands***.

e.g.) **Band structure** of Germanium

$$\frac{1}{m^*} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$$



$\boxed{m^* > 0}$ Charge: **e**

"Electron-*like* quasiparticles"

"Hole-*like* quasiparticles"

Charge: **e** $\boxed{m^* < 0}$

- They bend opposite direction under same magnetic field.

Real electron in complicated interactions ≈ 'Quasiparticle' in free space

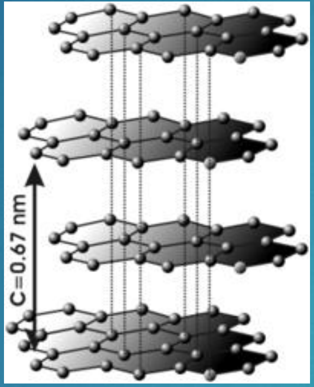
Graphene

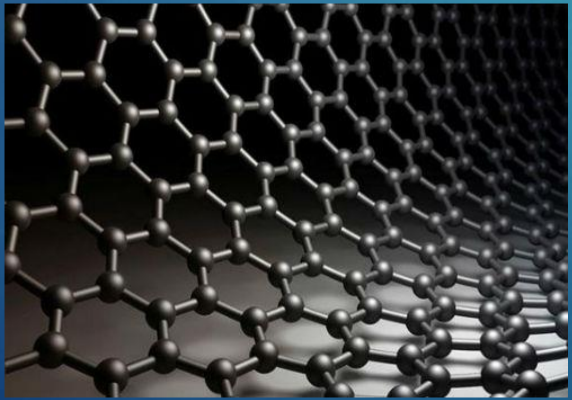
-Playground for condensed-matter physicists

Graphite

2-Dimensional Wan der Waals materials

Graphite (흑연)





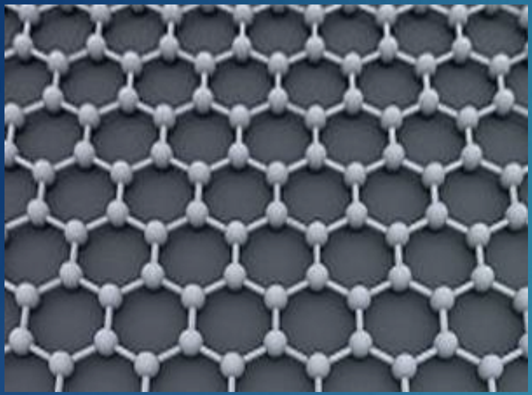
Graphene (그래핀)

[Isolation of graphene with Scotch tape]
(2004)

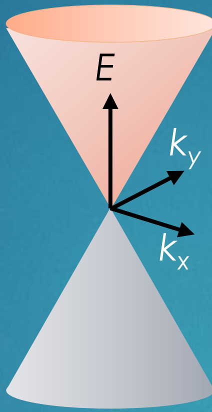
[Youtube, Prof. Kostya Novoselov and Dr. Peter Blake]

Graphene

Monoatomic layer of carbon atoms



Electronic structure

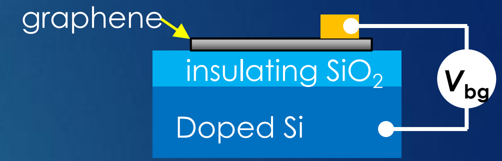


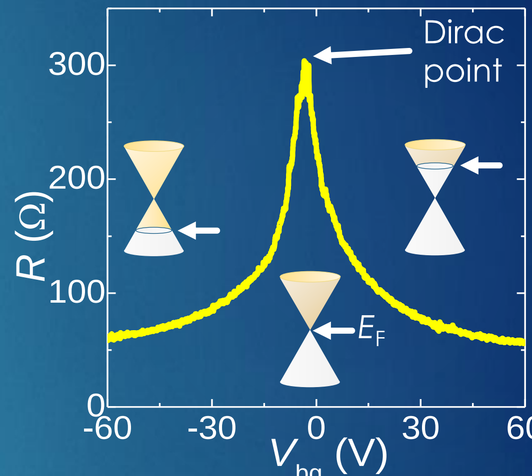
Dirac cone

Linear band structure

$E \propto k$ (similar to Light)

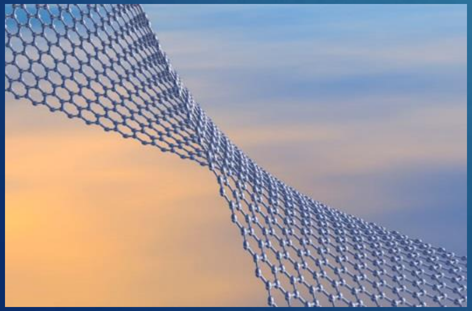
Electrically tunable





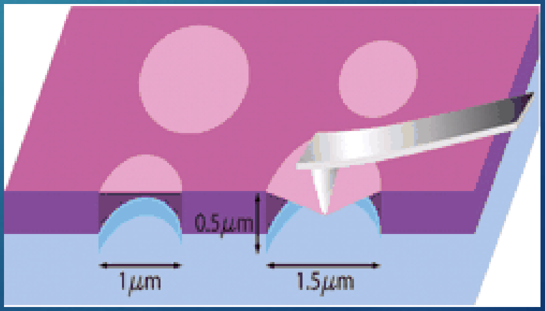
[Other properties]

Atomically thin

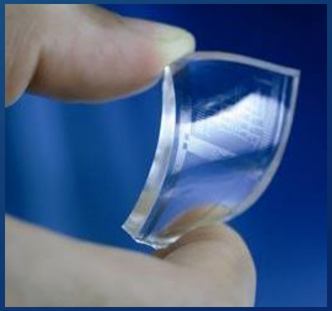


Chemically inert

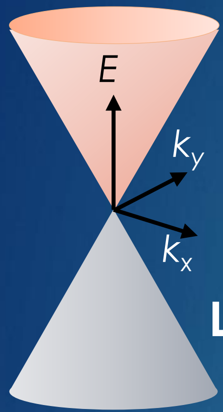
Mechanically strong



Transparent, Flexible & Conductive



Relativistic Dirac Fermion

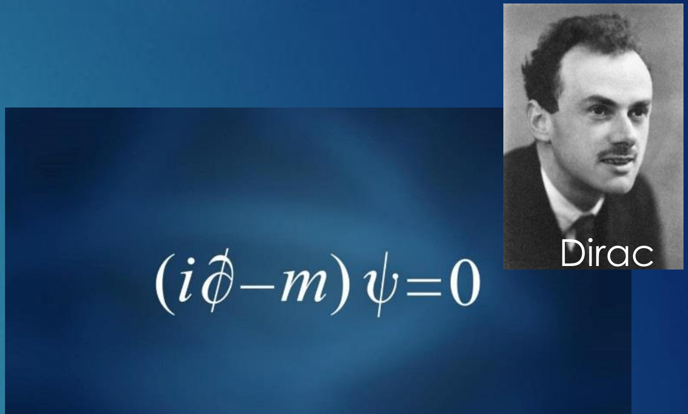


Dirac cone

$$E^2 = (pc)^2+(\cancelto{0}{mc^2})^2$$

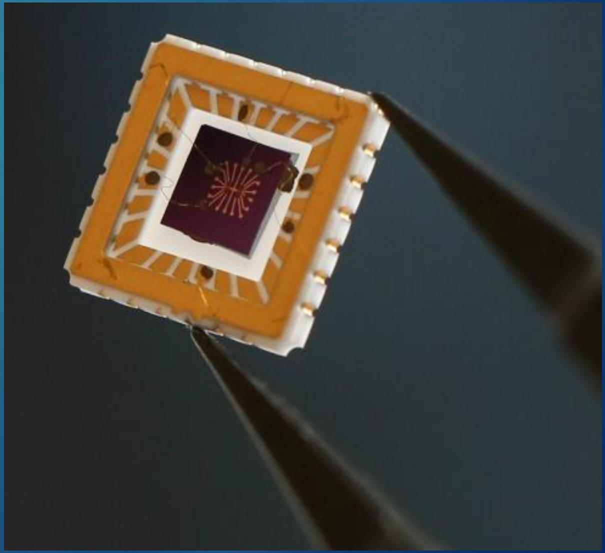
Linear band structure

$E \propto \pm k = \pm p/\hbar$



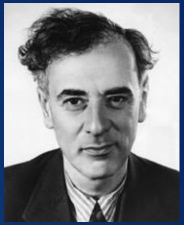
Quantum Mechanics + Special Relativity

Studying on relativistic quantum mechanics using nano-electronic devices



[LHC]

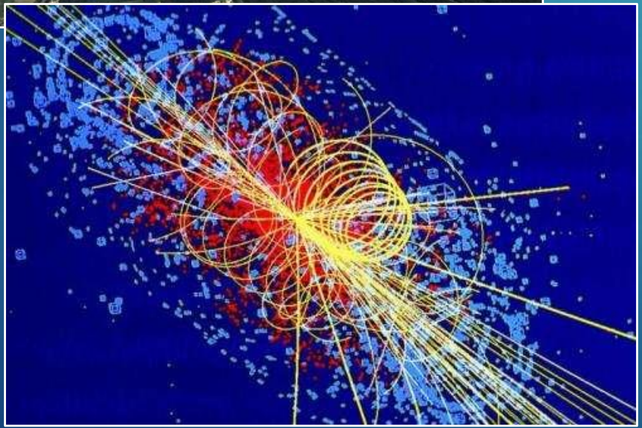
Quasi-Particles in Solid


[Lev Landau]

- **"Real"**-particles in particle physics

High-energy creates particles

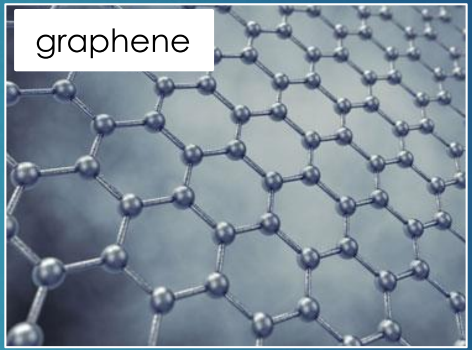
Large Hadron Collider (LHC)

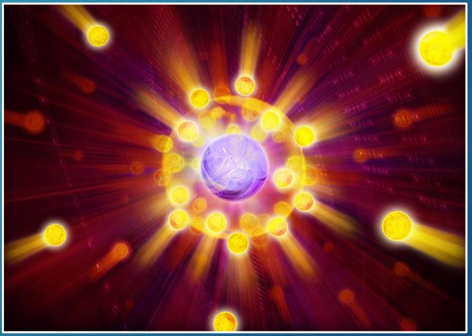


- **"Quasi"**-particles in solid physics

"Engineering" a new kind of particles

graphene





Examples)

- Electron/hole-like
- Phonon
- Bogoliubon
- Exiton
- Trion
- Holon
- Spinon
- Magnon
- Phason
- Polaron
- Roton
- Soliton
- Dirac Fermion
- Majorana fermion
- Parafermion

⋮

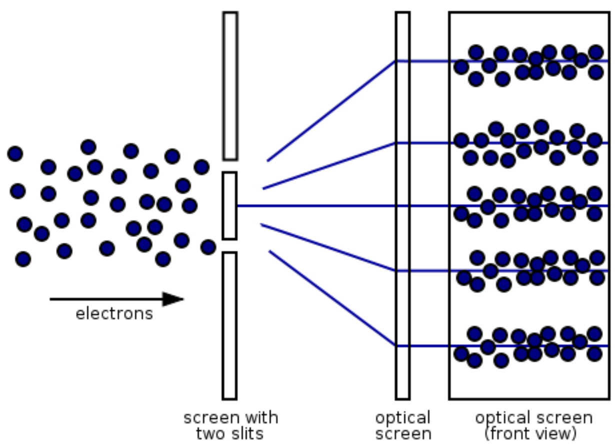
✓ More control
✓ Confined in solid

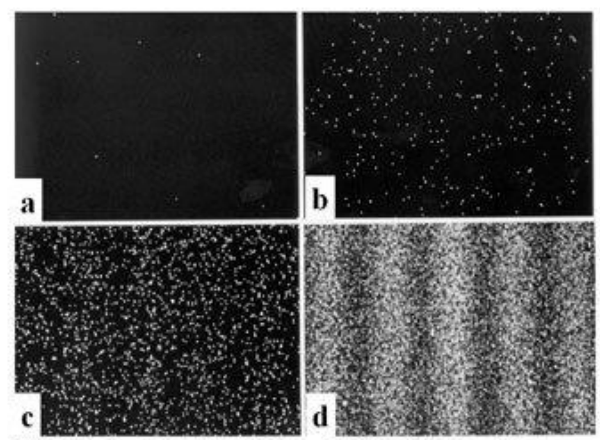
Searching for **New Fundamental Particle**

Dirac Electronics Optics

Wave-particle Duality

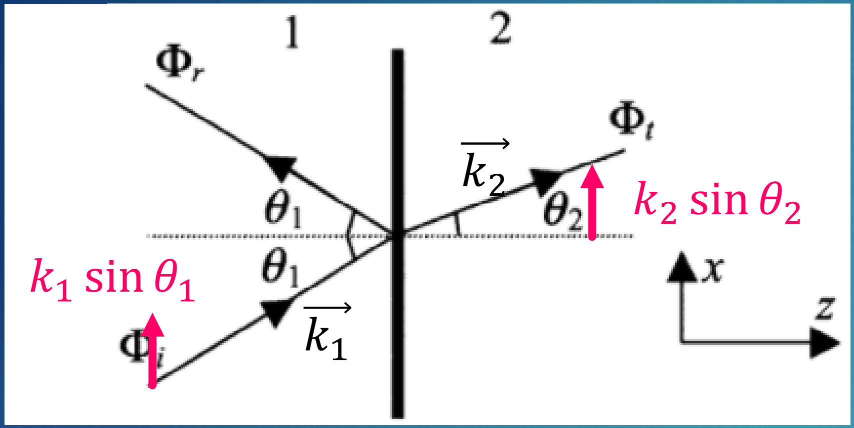
ELECTRON





Single-electron Build-up of Interference Pattern

Electronic Optics

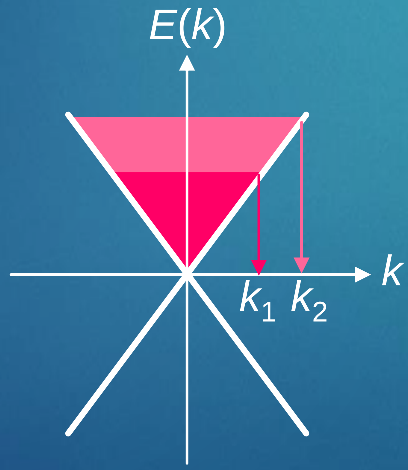


Momentum conservation along x-direction:

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

or, $n_1 \sin\theta_1 = n_2 \sin\theta_2$

$n \equiv k/k_0\,,\ \ k_0 = k$ in vacuum

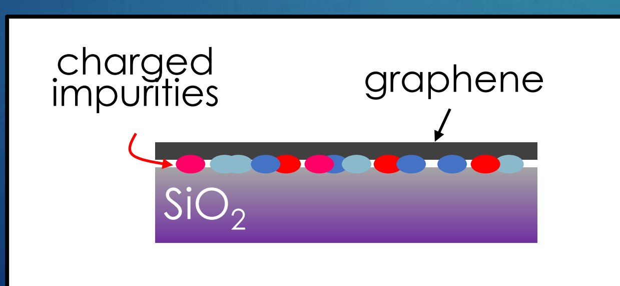


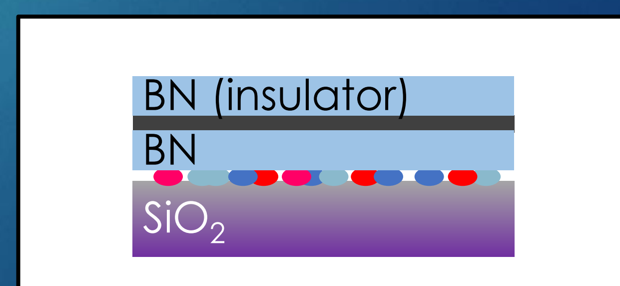
Refractive index n is gate-tunable.

Optics v.s. (Dirac) Electronic Optics

	Optics	(Dirac) Electronic Optics
Particles	Photon	(Dirac) Electrons
Type	Bosons	Fermions
Charge	No charge	Negative or positive charge
Refractive index	Given by materials	Gate-tunable
Wave length	1000 nm	10 nm
System size	1 m	1 μm

Cleaning Graphene for Electronic Optics



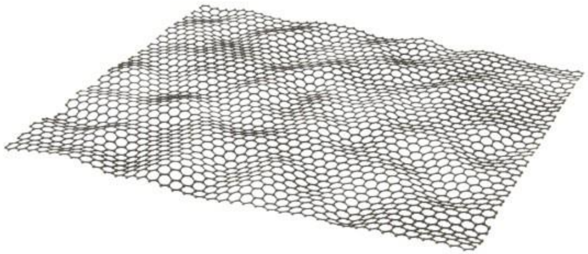


Layer-by-Layer Stacking

Early days,

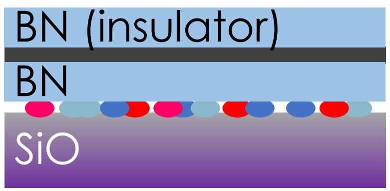
1. Impurities on substrate

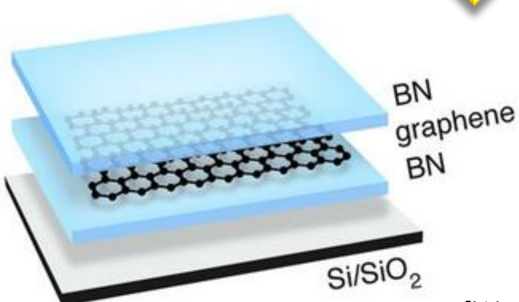
2. Rough surface of substrate

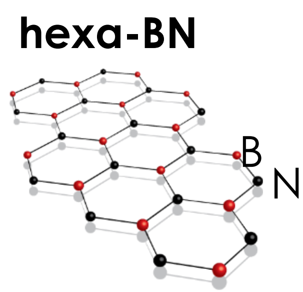


* Mean free path l_{mfp} ~ 100 nm

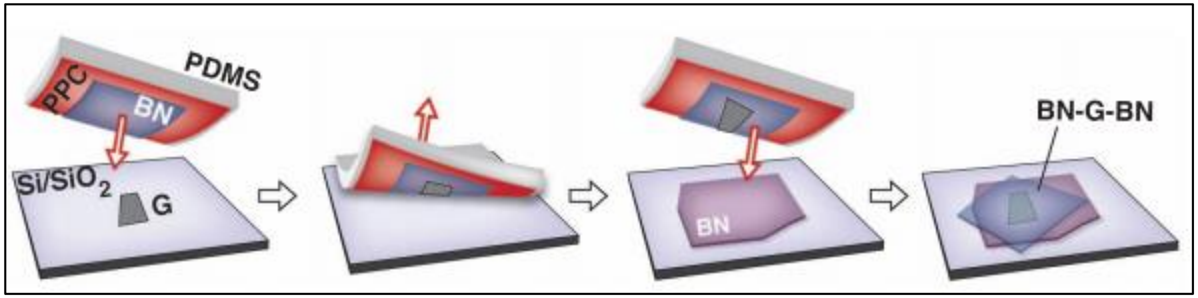
Recently,







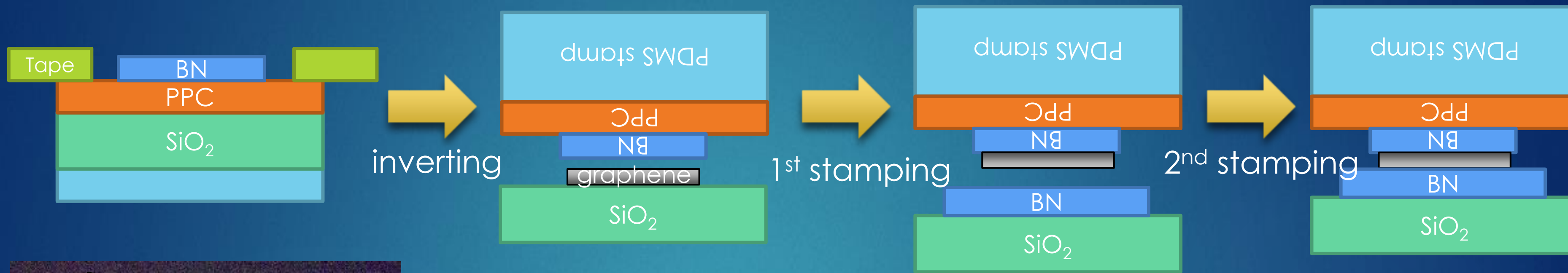
[Wang *et al.*, Science(2013)]

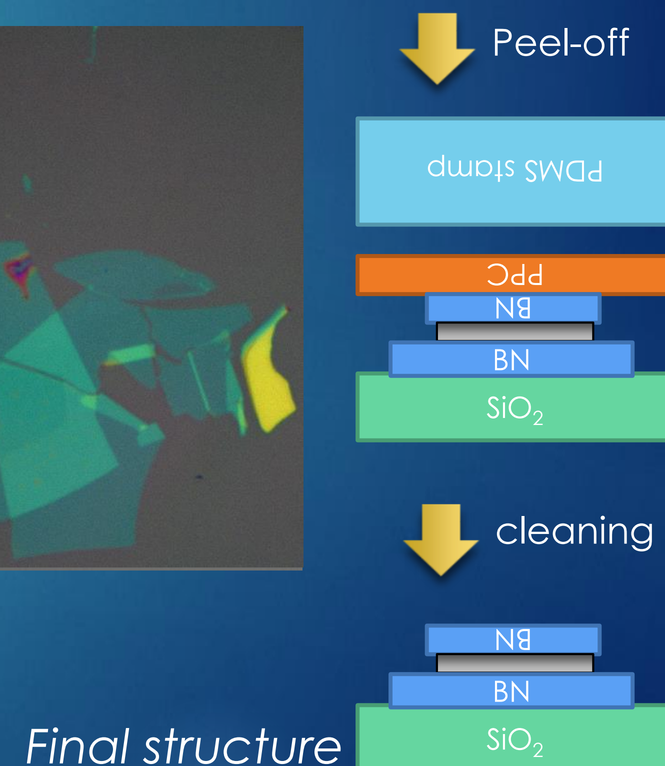


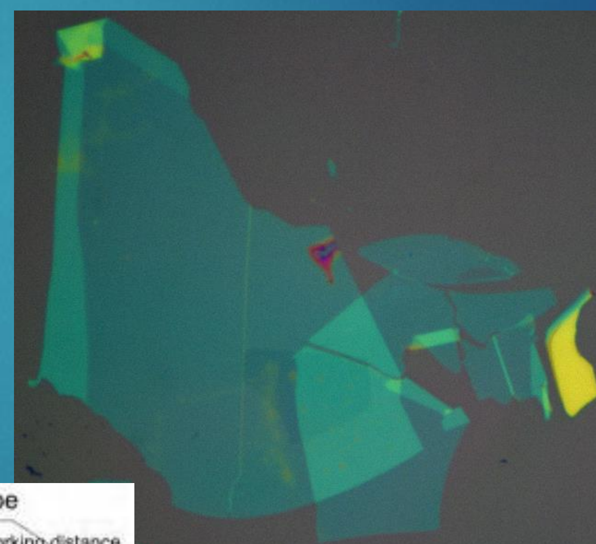
Transfer stage in POSTECH

* Mean free path l_{mfp} > 10 μm

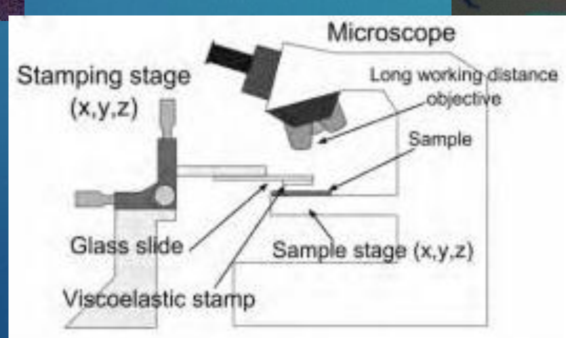
Dry-Transfer Technique





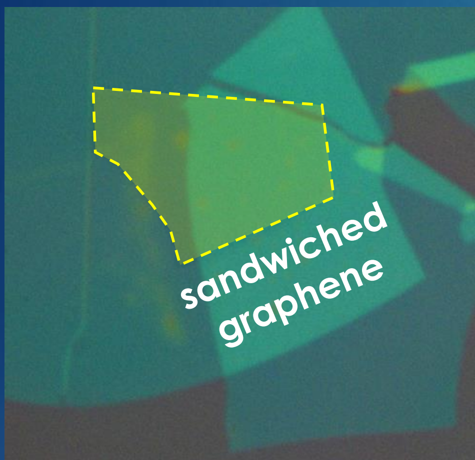


PDMS: transparent polymer

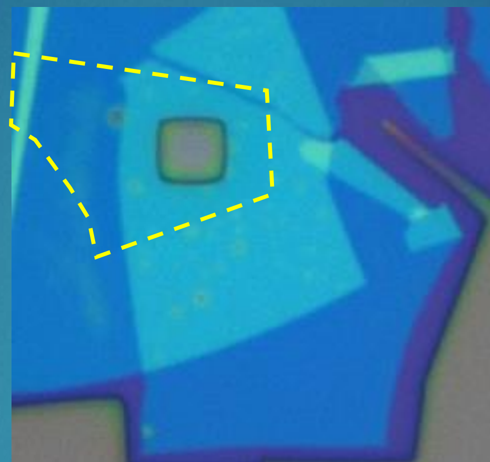


Edge Contacts

BN/Graphene/BN structure

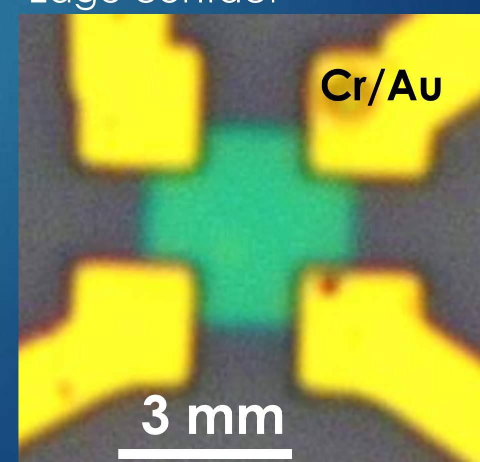


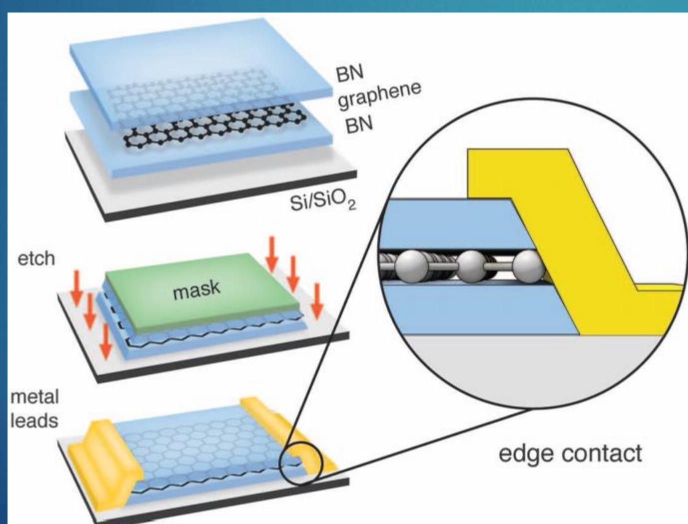
Masking



Reactive Ion Etching

Edge contact

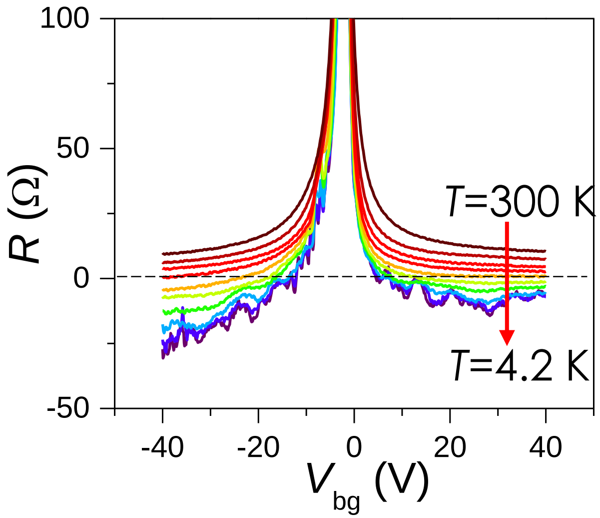




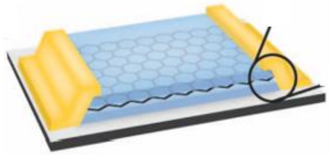
[L. Wang *et al.*, *Science* **342**, 614 (2013)]

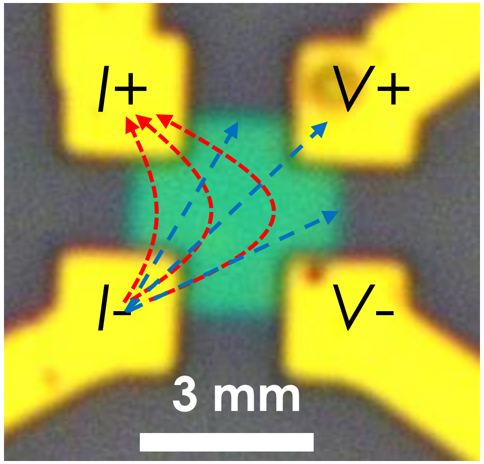
Ballistic Transport in Graphene

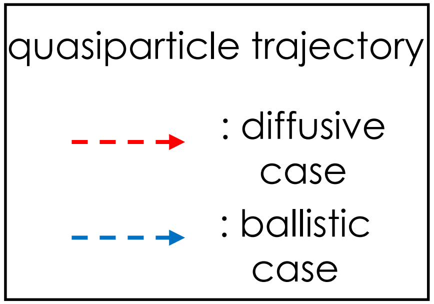
Temperature dependence of *R*



Negative resistance



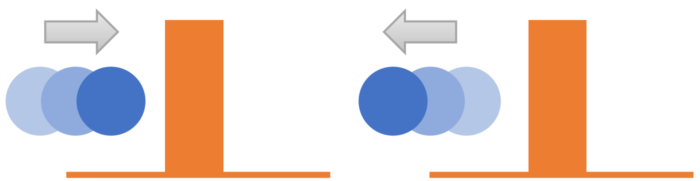




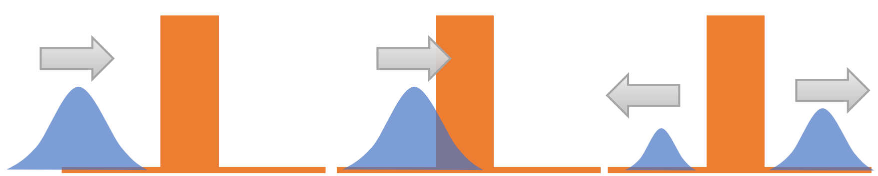
Klein Paradox by Oskar Klein in 1929

Klein paradox

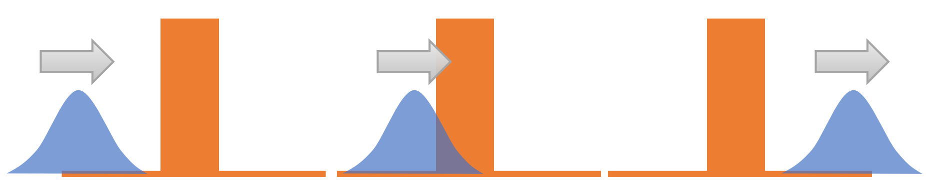
- Classical picture



- Quantum picture



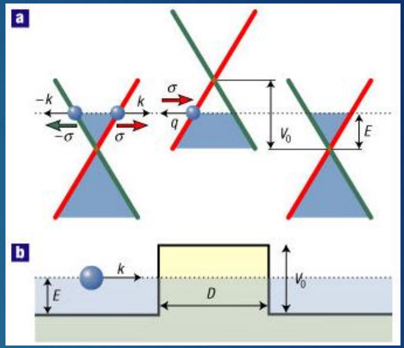
- **Relativistic** Quantum picture (Klein tunneling)



100 %

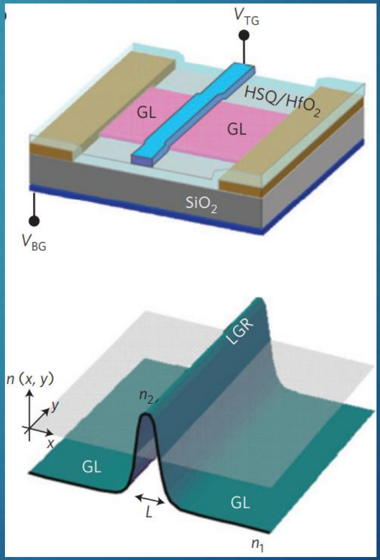
Klein tunneling in graphene

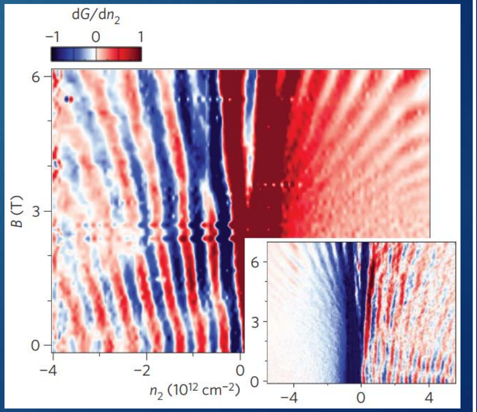
Theory



[Katsnelson *et al.*, *Nature Phys.* (2006)]

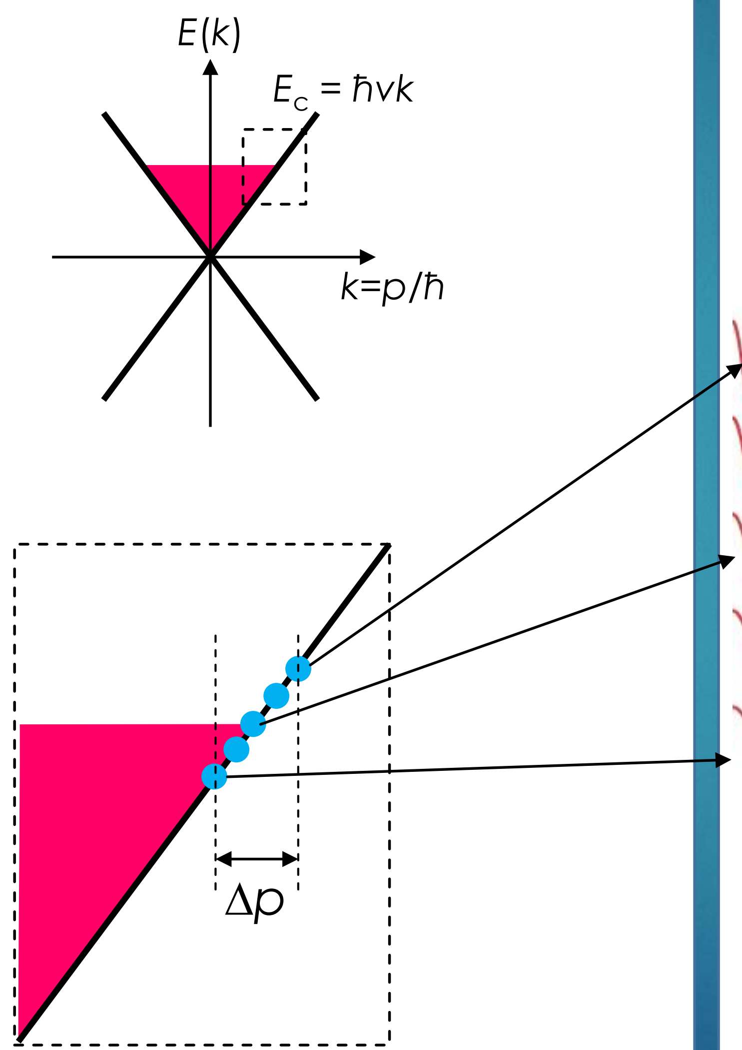
Experiment

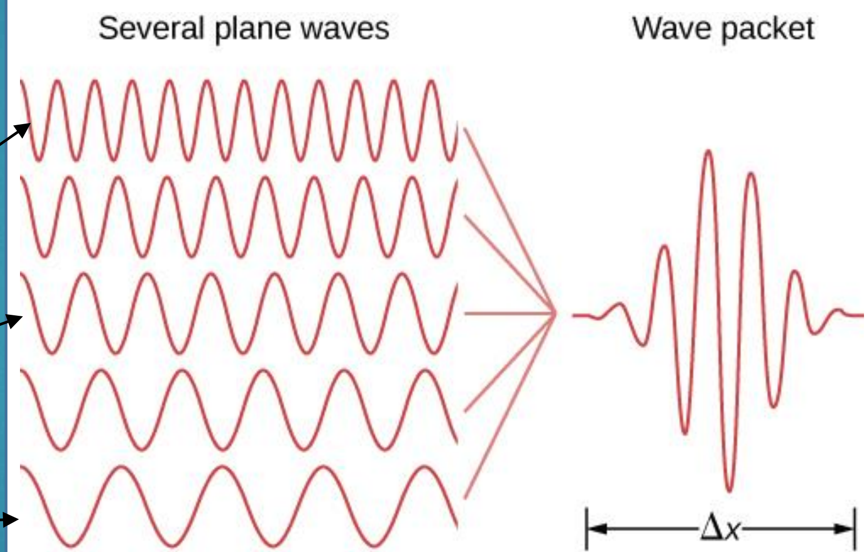




[A. Young and P. Kim, *Nature Phys.* (2009)]

Wave Packet



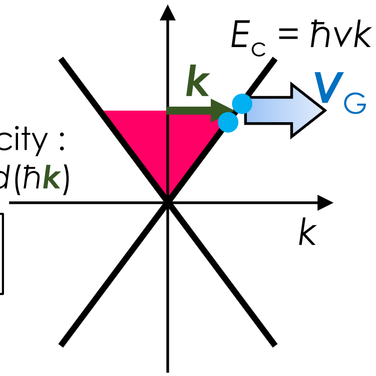


Heisenberg Uncertainty Principle

$$\Delta x \Delta p = \hbar/2$$

Group Velocity

n-doped

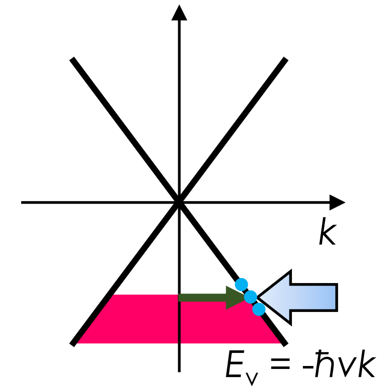


- Group velocity :
  $\mathbf{V}_G = dE(k)/d(\hbar\mathbf{k})$

$\boxed{\vec{V}_G = v\hat{k}}$

p-doped

* v ~ c/300

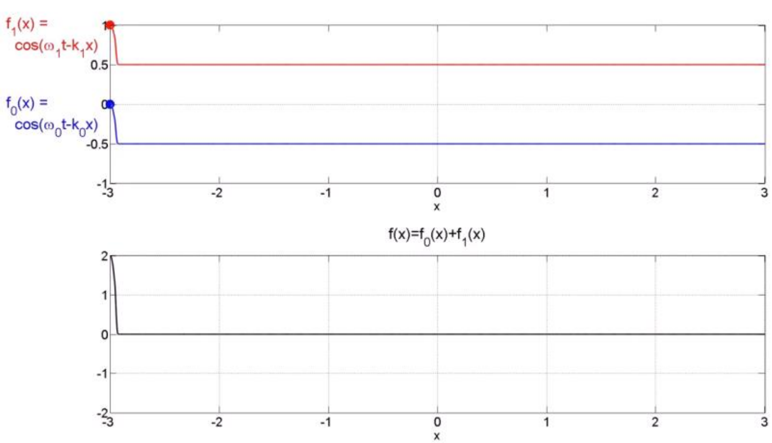


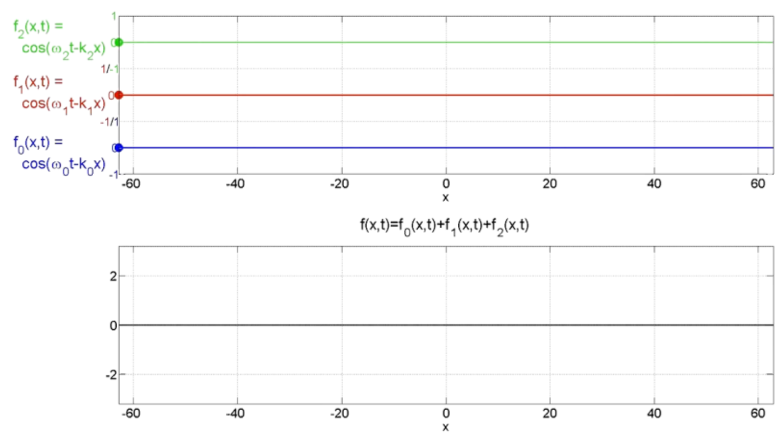
$\boxed{\vec{V}_G = -v\hat{k}}$

$$\boxed{\Psi \sim e^{ikx - iEt/\hbar}}$$

<u>Bigger k</u> has <u>*higher* energy</u>
(Shorter λ) (Faster)

<u>Bigger k</u> has <u>*lower* energy</u>
(Shorter λ) (Slower)

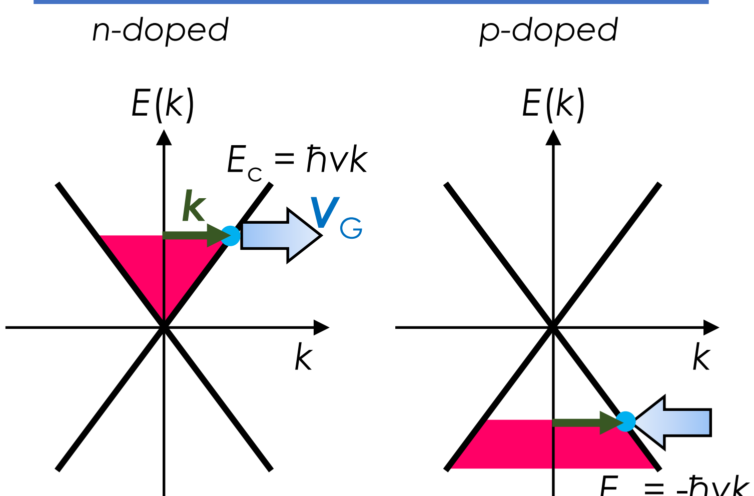




Negative Refraction

By V. G. Veselago (1967)

Ambipolar band structure w/o gap



- Group velocity : $V_G = dE(k)/d(\hbar \mathbf{k})$

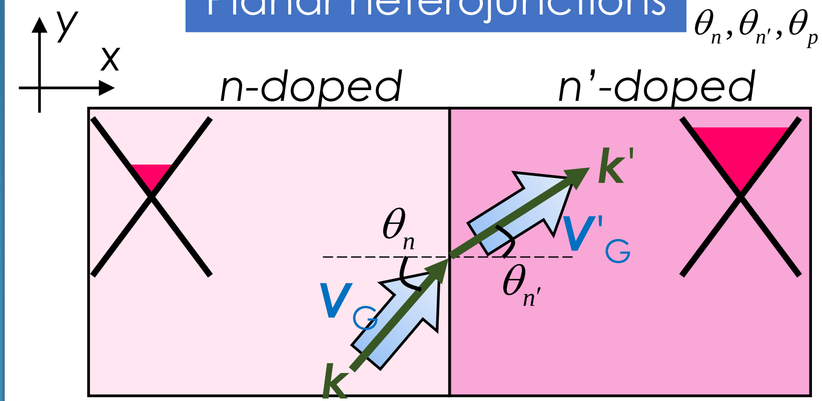
$$\boxed{\vec{V}_G = v\hat{k}}$$

$$\boxed{\vec{V}_G = -v\hat{k}}$$

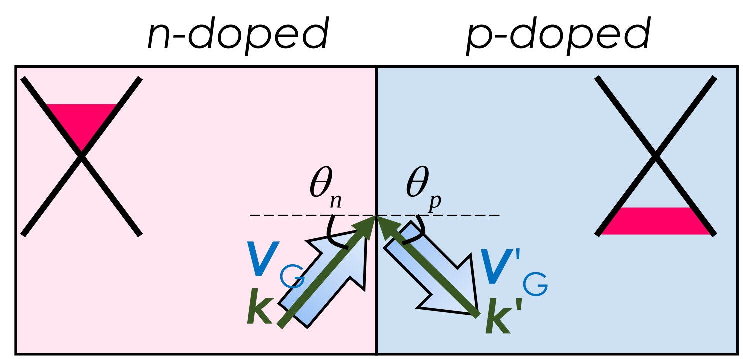
* v ~ c/300

Planar heterojunctions

$\theta_n, \theta_{n'}, \theta_p > 0$



$$k_n \sin\theta_n = k_{n'} \sin\theta_{n'}$$



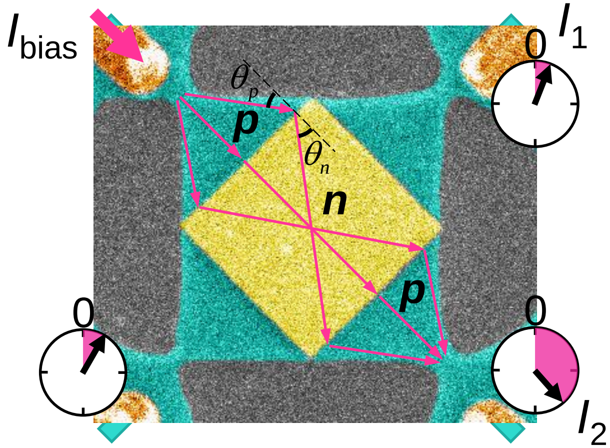
$$k_n \sin\theta_n = -k_p \sin\theta_p$$

$$\boxed{\frac{\sin\theta_n}{\sin\theta_p} = -\frac{k_p}{k_n} = -\sqrt{\frac{\rho_p}{\rho_n}} \equiv n}$$

[Cheianov, Fal'ko, & Altshuler, Science (2007)]

Experiments

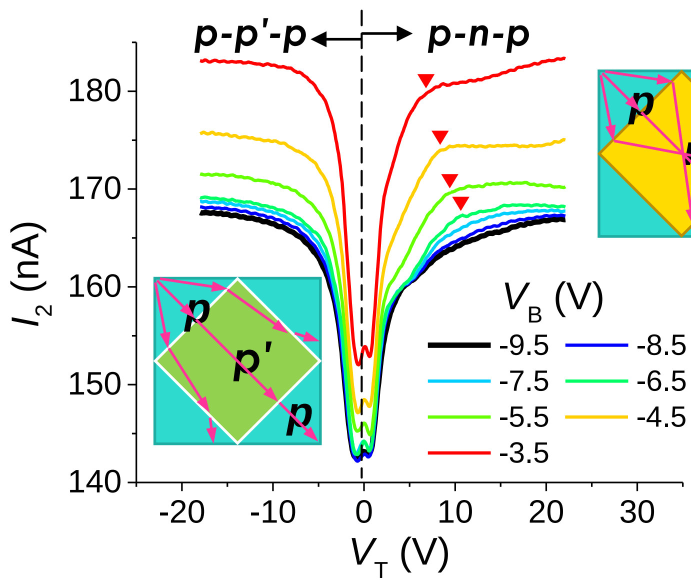
Veselago's lens



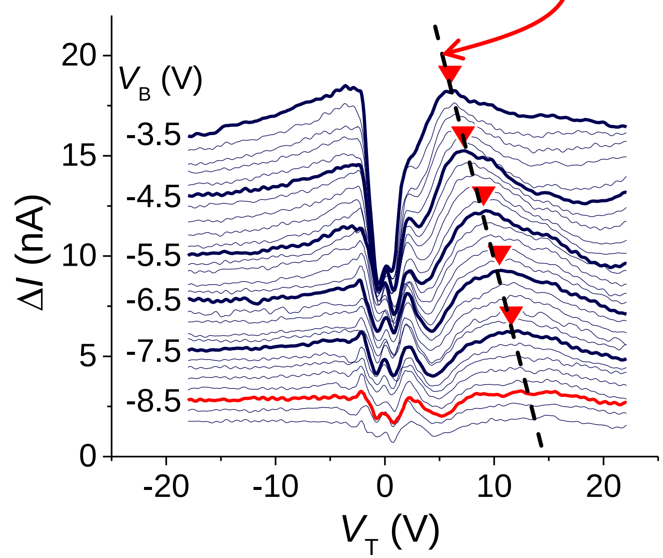
[**G.-H. Lee**, G.-H. Park, H.-J. Lee, *Nature Physics* (2015)]

$$\frac{\sin\theta_n}{\sin\theta_p} = -\frac{k_p}{k_n} = -\sqrt{\frac{\rho_p}{\rho_n}} \equiv n$$

Draining current



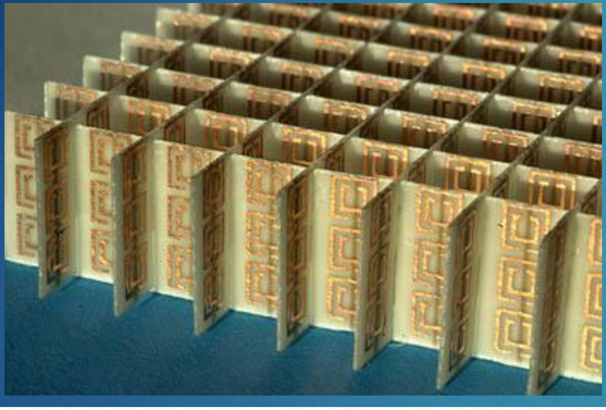
Background subtracted

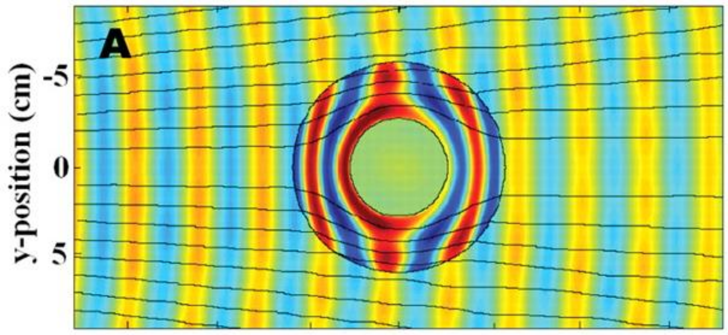


Comparing to Metamaterials

Meta-materials: Reparative structures smaller than wavelength

e.g.) Microwave λ~10 cm,
Electrons, λ_F~10 nm,

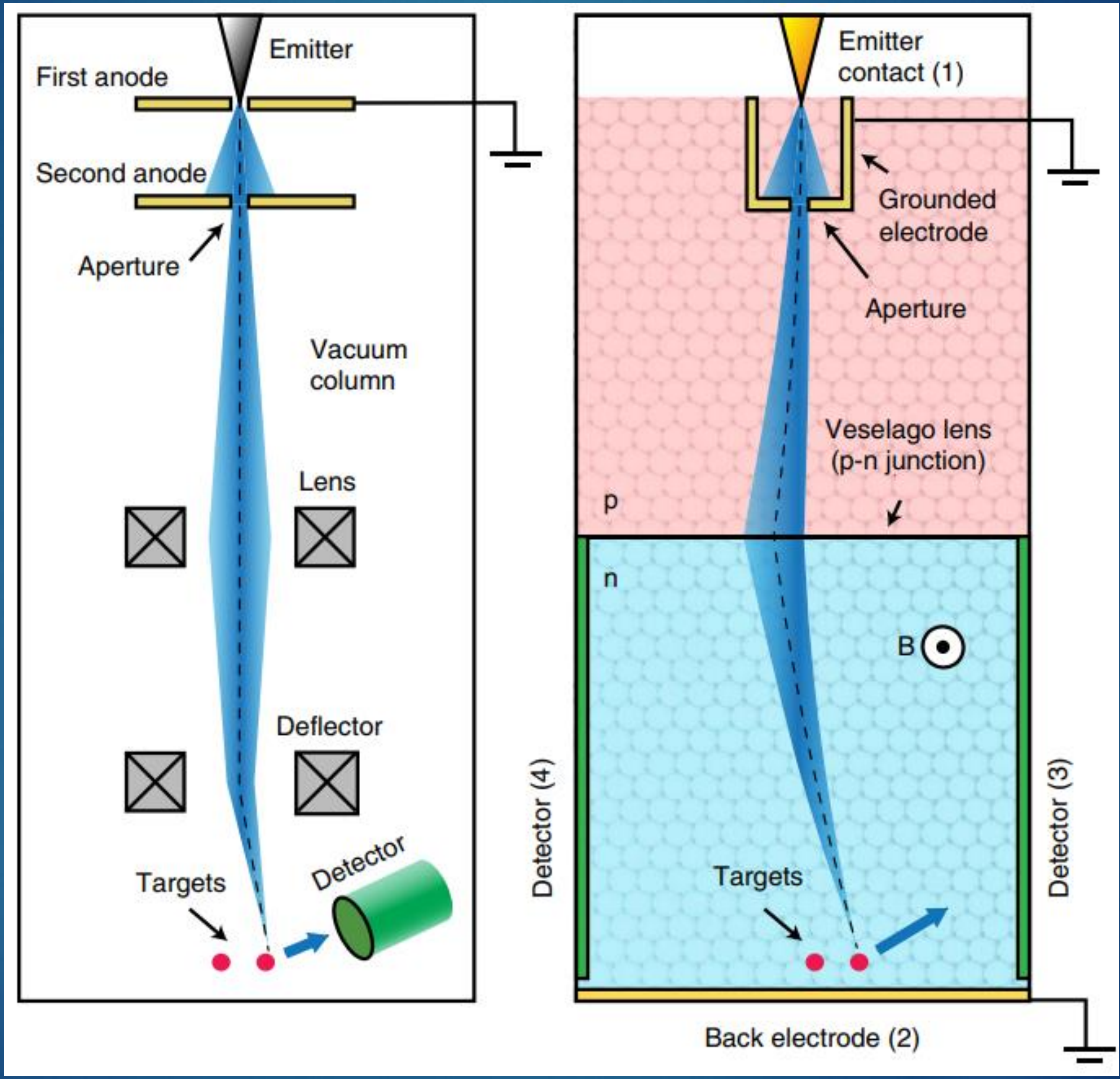




[D. Schurig *et al.*, Science 2006]

Invisible blanket

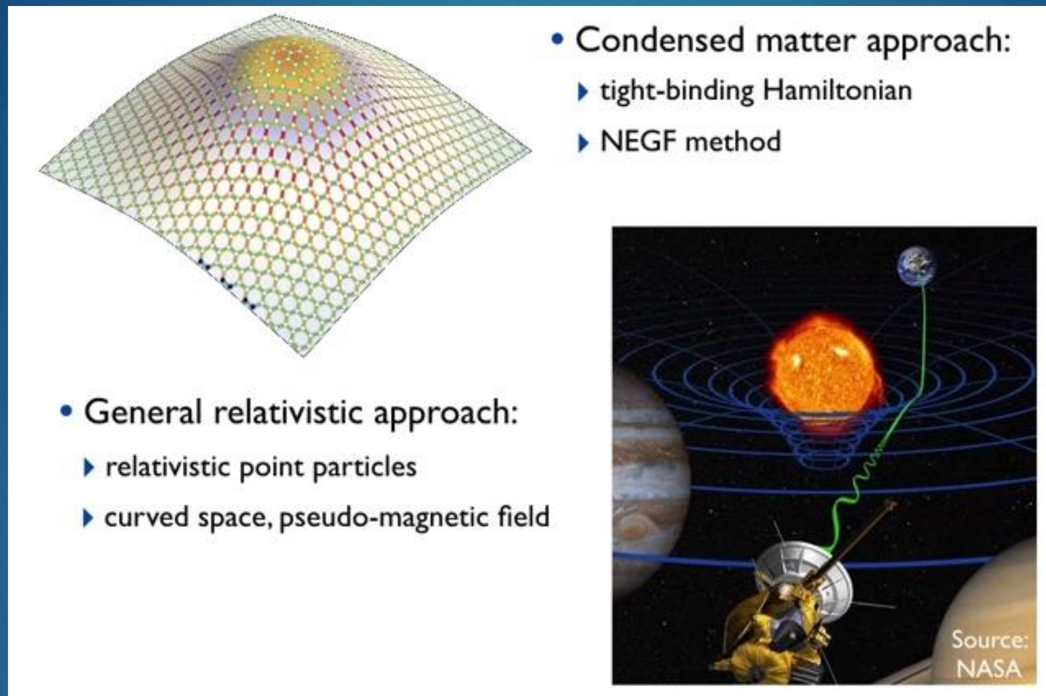
Dirac Fermion Microscope

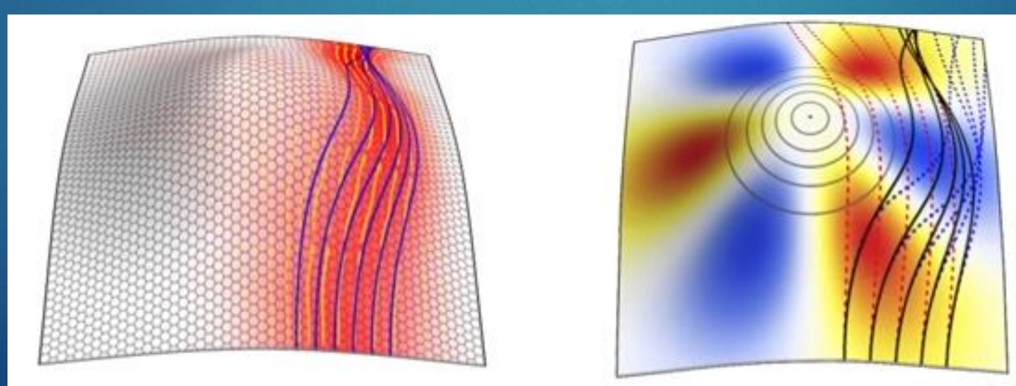


[Peter Bøggild et al., Nat. Comm. (2017)]

Stretched Graphene

- Relativistic particle in a curved space



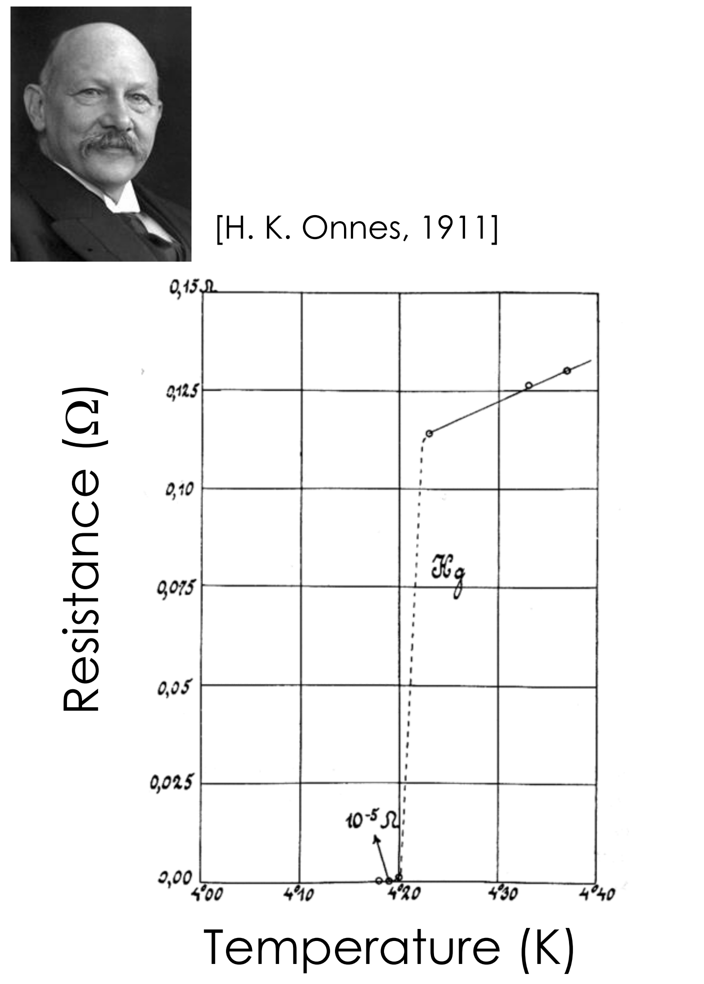


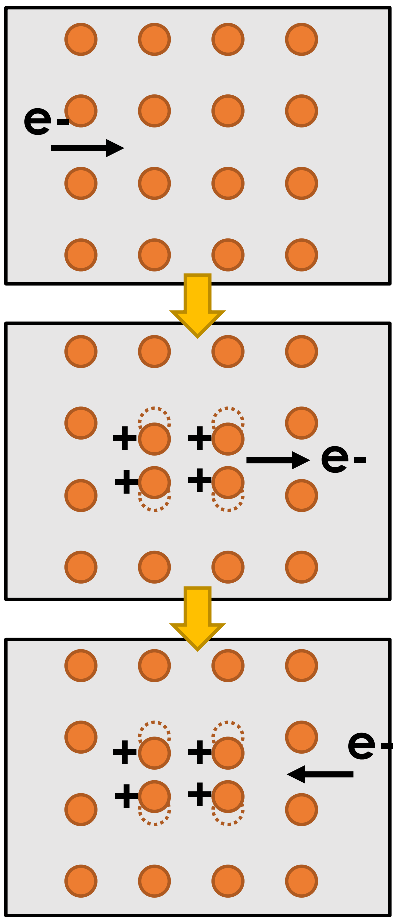
[Stegmann and Szpak, NJP (2016)]

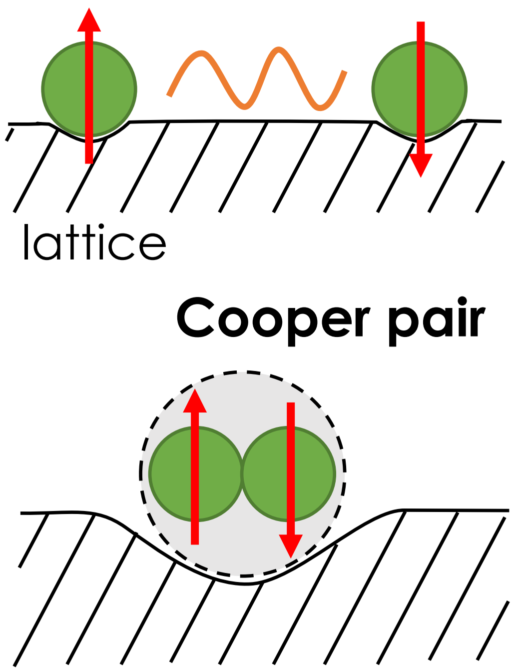
Brief Introduction to Superconductivity

Superconductivity

- **Superfluidity** of boson-like **Cooper pairs** made up of two fermions







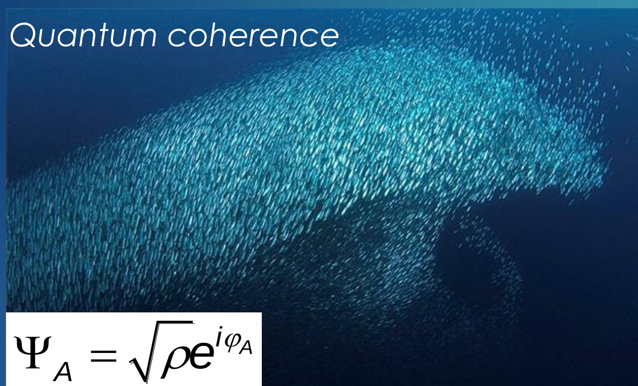
Spin-singlet (anti-sym.)

$$|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

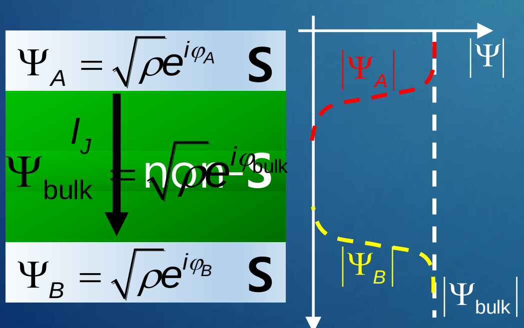
Orbital : *s*-wave (sym.)

Macroscopic Quantum Phenomena

All 10^{23} electrons in superconductor behaves as a single quantum object.

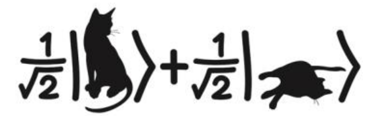


e.g.) Josephson junction
- Macroscopic quantum device



Application for Quantum Computer

Using **superposition** of quantum mechanics



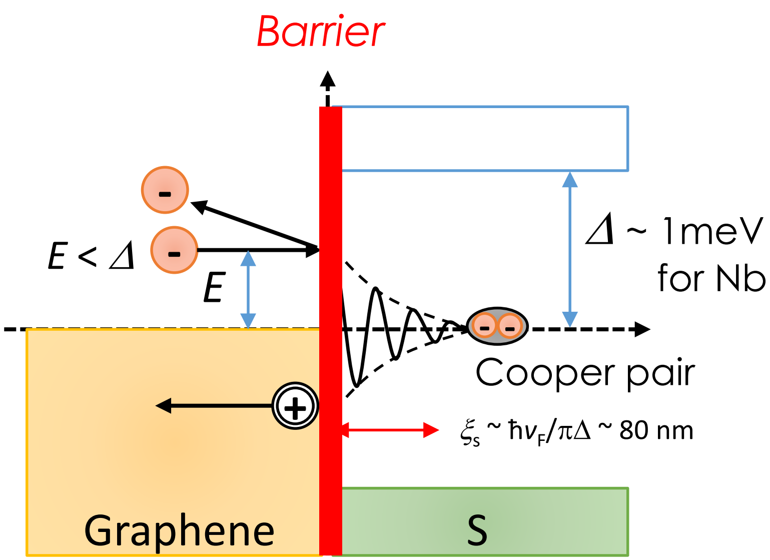
- Classical computer: $f: 00 \to f(00)$
  $f: 01 \to f(01)$
  $f: 10 \to f(10)$
  $f: 11 \to f(11)$
- Quantum computer:

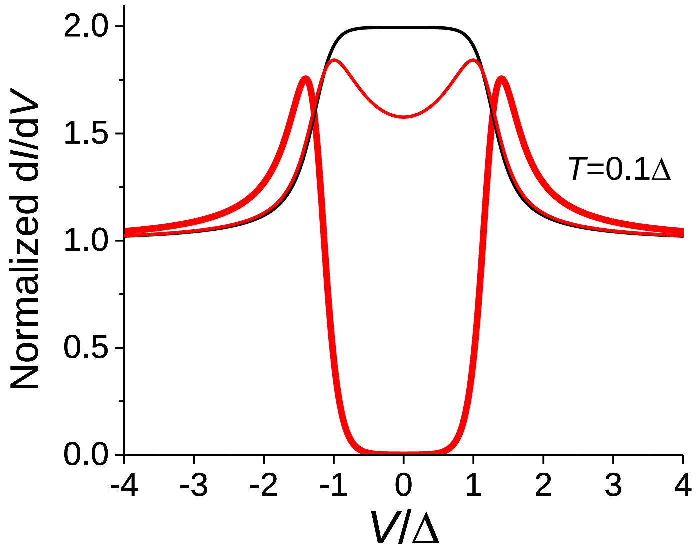
$$U_f : \frac{1}{\sqrt{4}}\left(|00\rangle + |01\rangle + |10\rangle + |11\rangle\right)$$
$$\to \frac{1}{\sqrt{4}}\left(U_f|00\rangle + U_f|01\rangle + U_f|10\rangle + U_f|11\rangle\right)$$

Quantum parallelism gives exponential computation power.

Google, IBM, Intel, Microsoft, *etc. are actively working on it.*

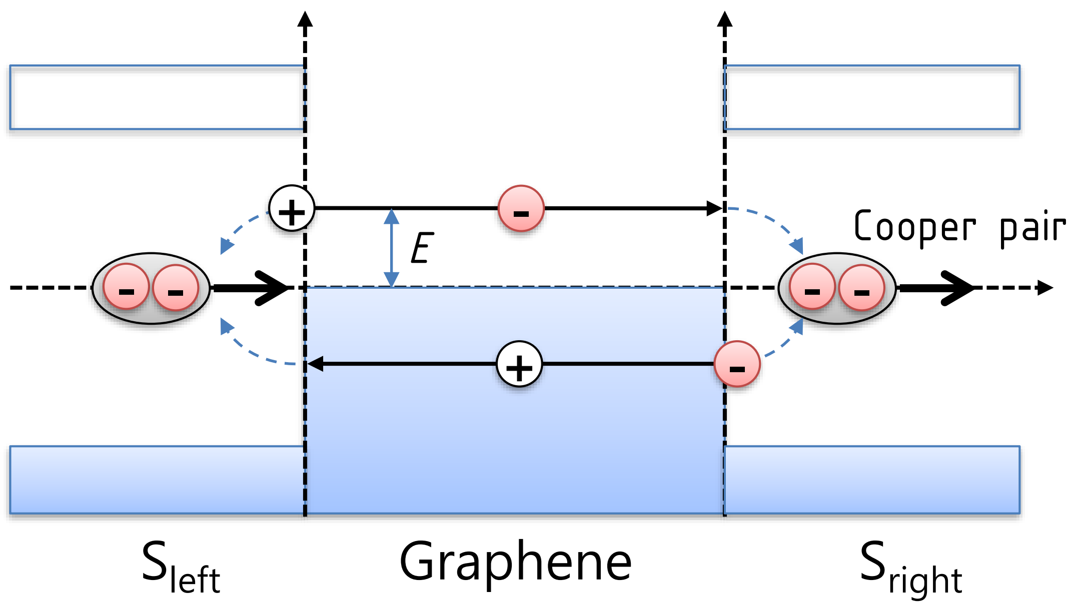
Andreev Reflection





Andreev-reflected hole is highly coherent with incident electron.

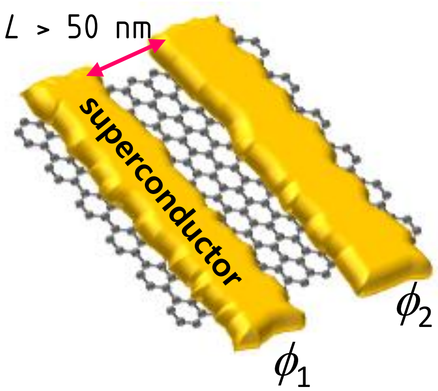
Josephson Junction

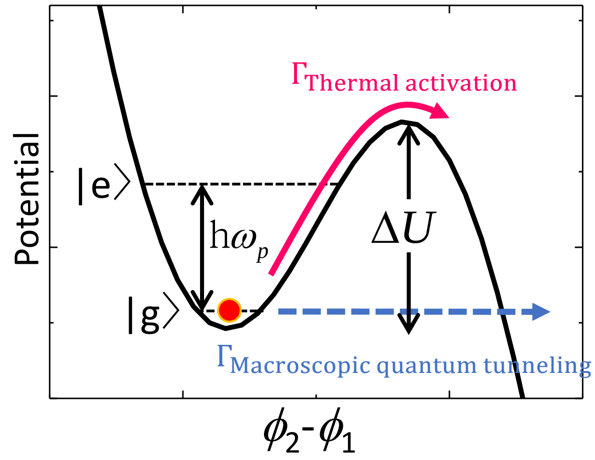


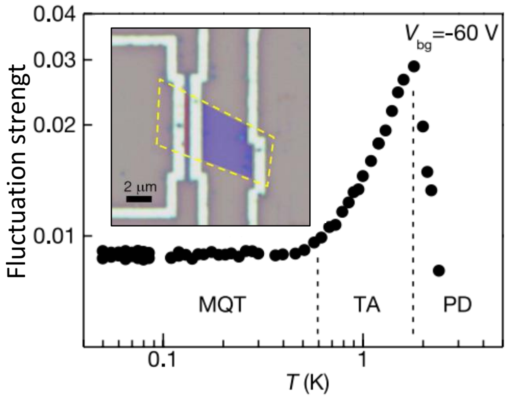
Cooper pairs are transferred *coherently*.

Examples of Hybrid Devices (1)

Gate-tunable Macroscopic Quantum Tunneling

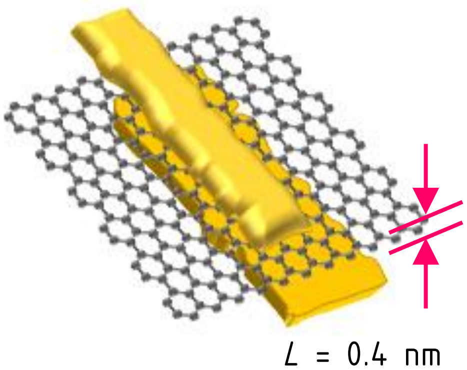


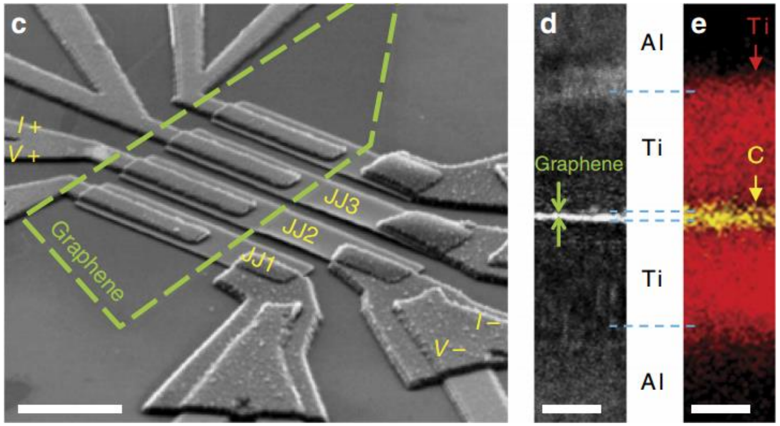




[G.-H. Lee *et al.*, *PRL*(2011)]
[D. Jeong, G.-H. Lee *et al.*, *PRB*(2011)]

First Short-Ballistic Josephson Junction

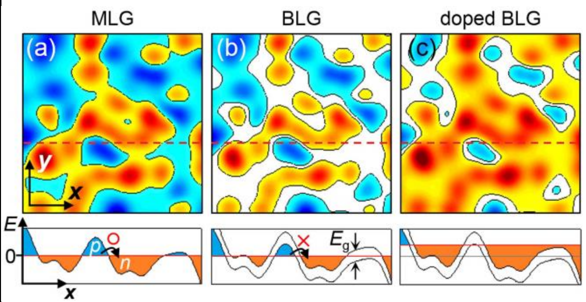


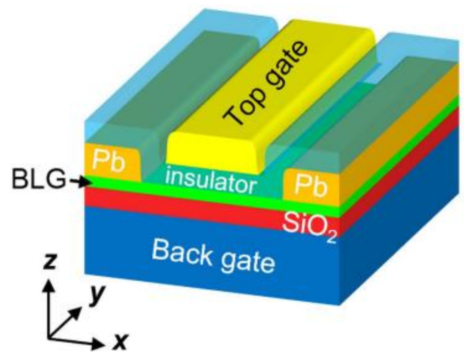


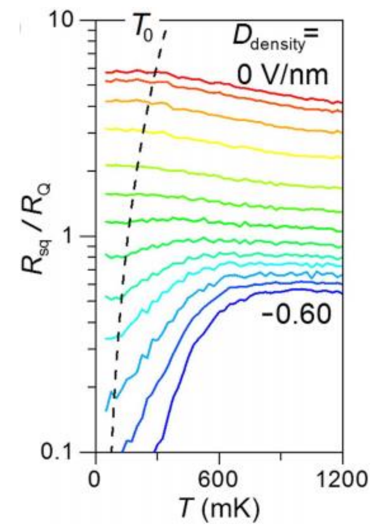
[G.-H. Lee *et al.*, *Nature Comm.* (2015)]
[G.-H. Lee *et al.*, *APEX* (2013)]

Examples of Hybrid Devices (2)

Superconductor-Insulator Transition

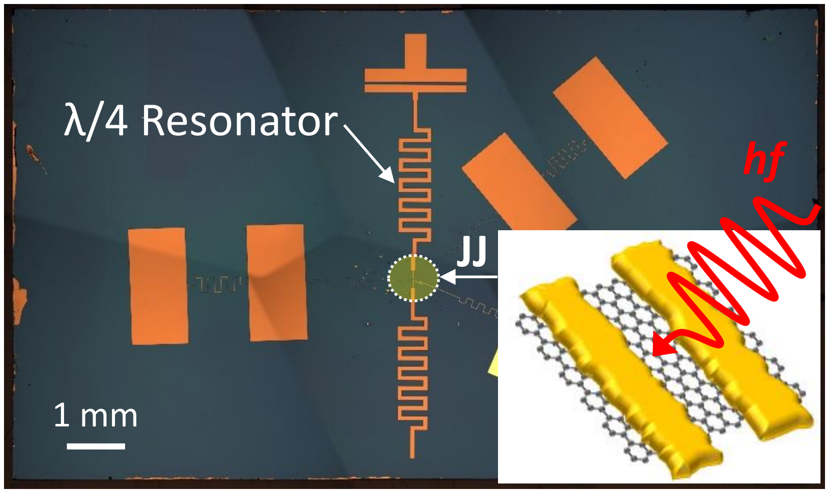




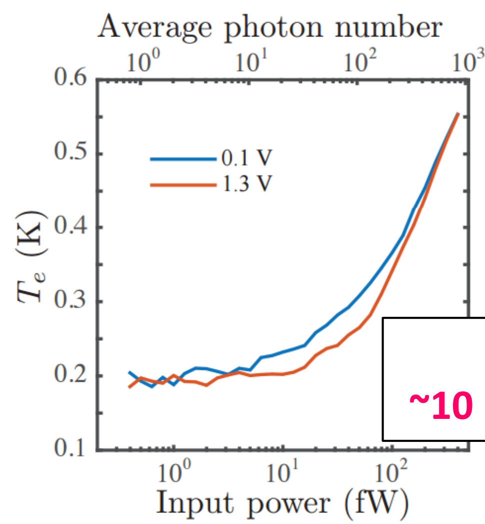


[G.-H. Lee *et al.*, *Scientific Report* (2015)]

Microwave Single Photon Detector



Crucial step towards quantum information



Sensitivity :
~10 photons (@8GHz)

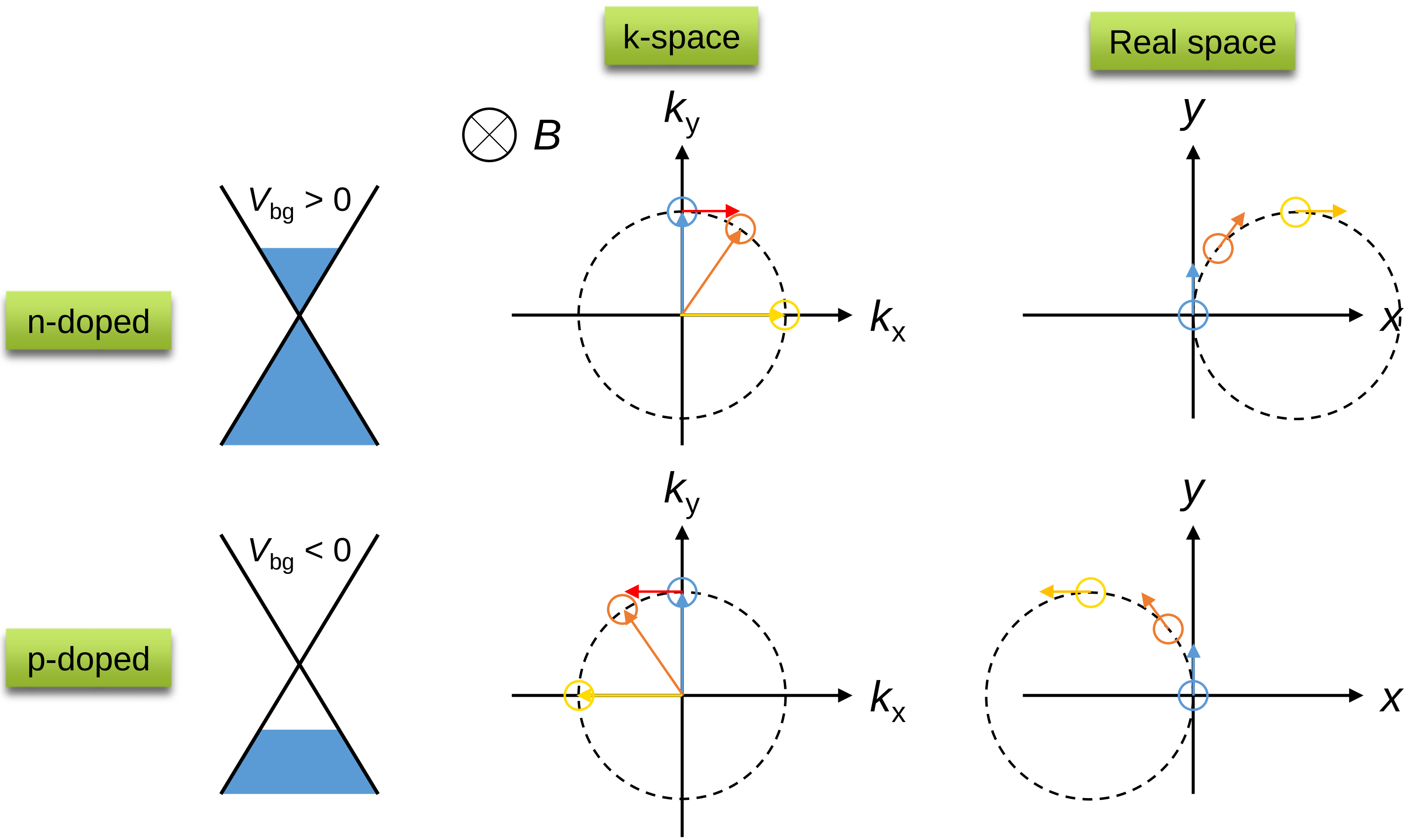
[G.-H. Lee, *et al.*, (*In preparation*)]

Visualizing Andreev-pairs

(Magnetic Focusing)

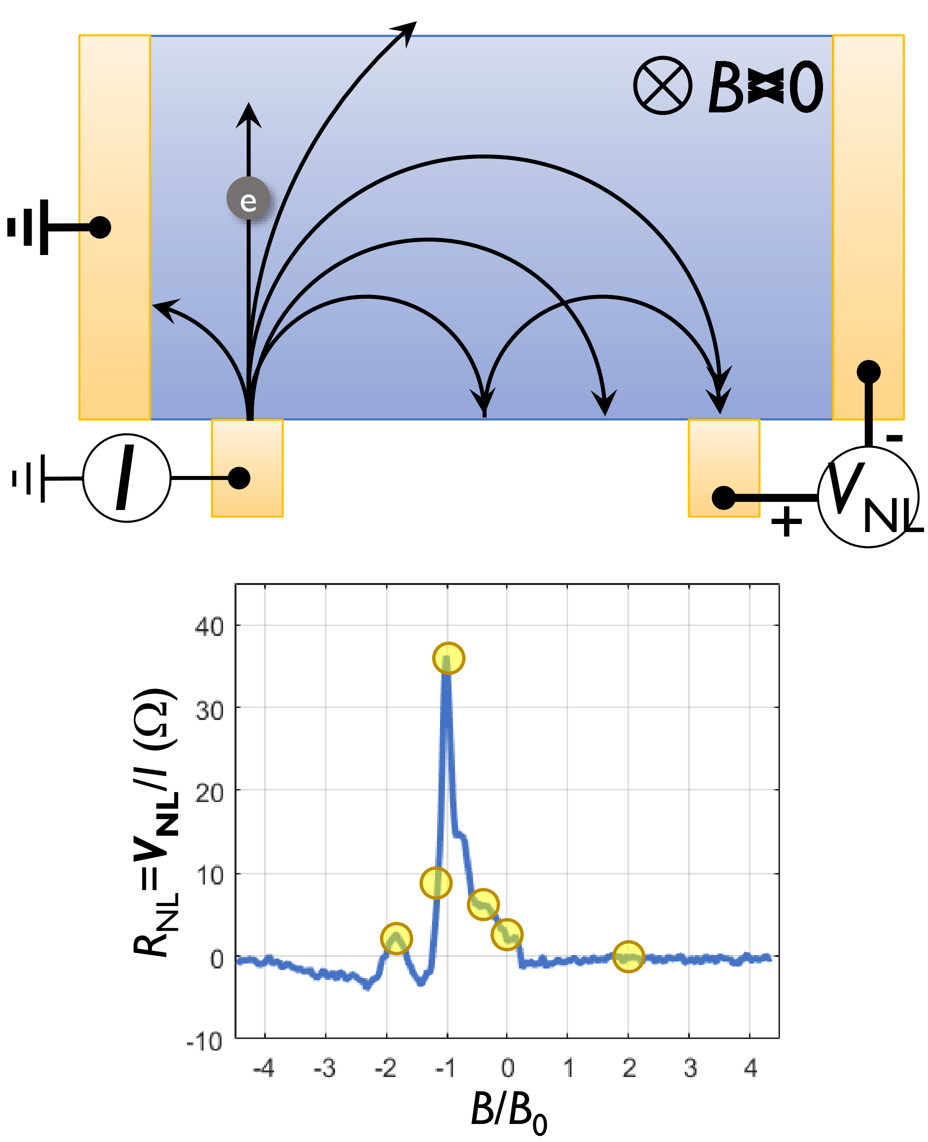
Electrons under Magnetic Field

$$\vec{F} = q\overrightarrow{v_g} \times \vec{B} = d(\hbar\vec{k})/dt$$

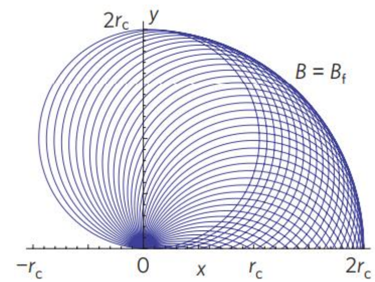


Cyclotron effective mass : $m^* > 0$ for CB, $m^* < 0$ for VB

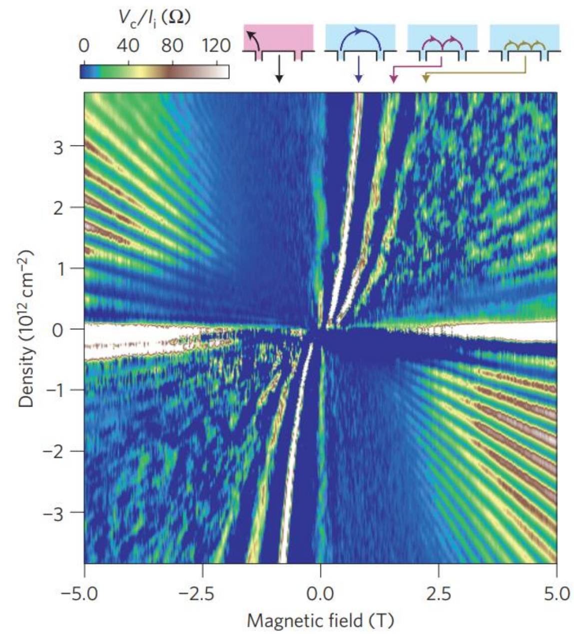
Steering Electron Beam



Electronically tunable magnetic focusing

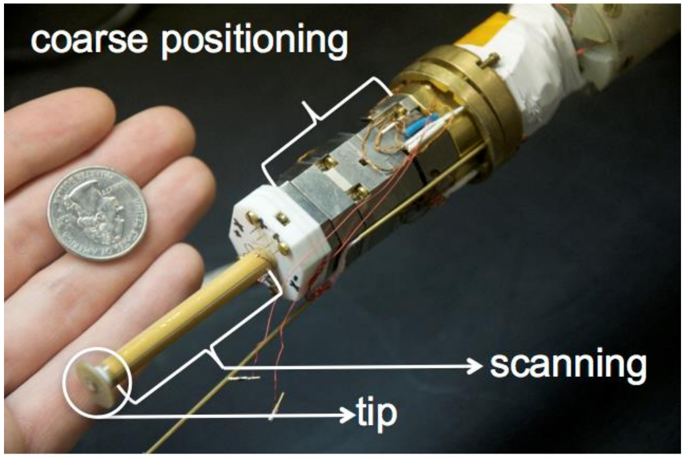


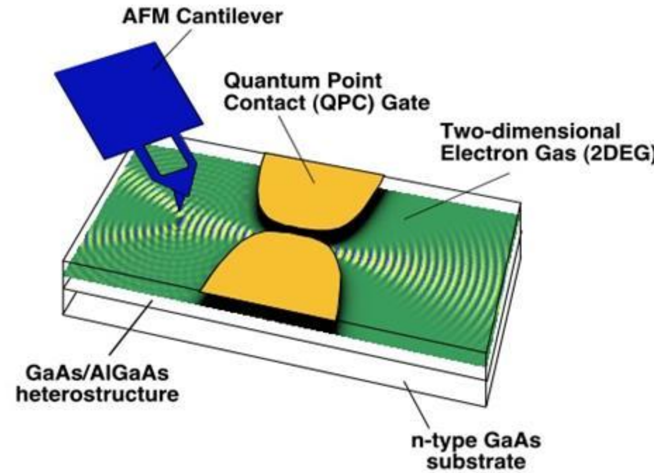
$$B_f^{(p)} = \left(\frac{2\hbar k_F}{eL}\right)p = \left(\frac{2\hbar\boxed{\sqrt{\pi n}}}{eL}\right)p$$



[Taychatanapat et al., Nature Phys. (2013)]

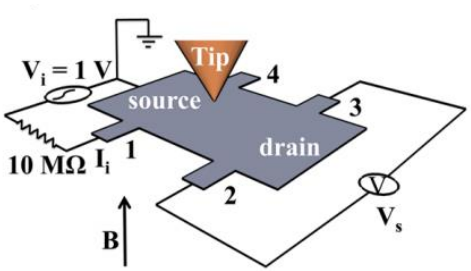
Imaging Electron Path

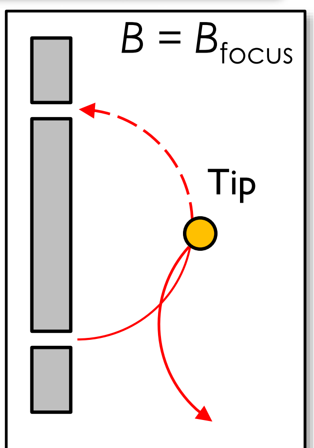




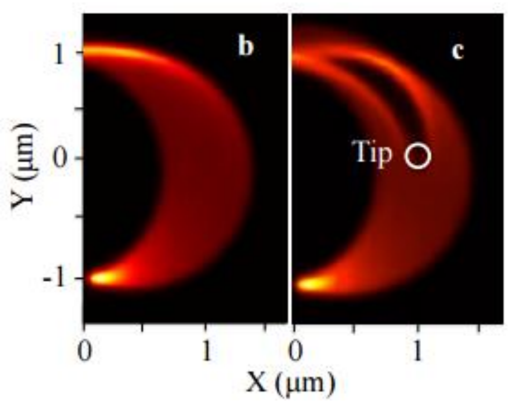
[Goldhaber-Gordon group, Westervelt group]

Imaging bent electrons in graphene

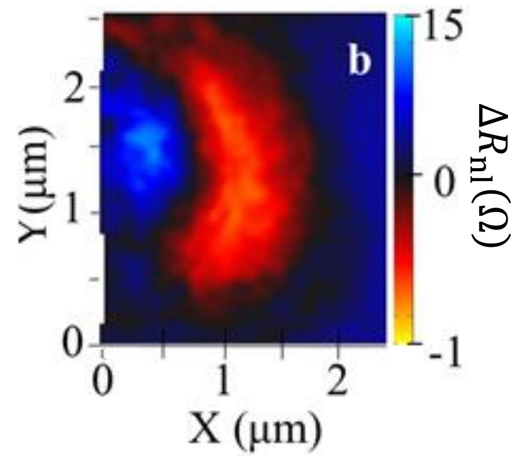




Simulation

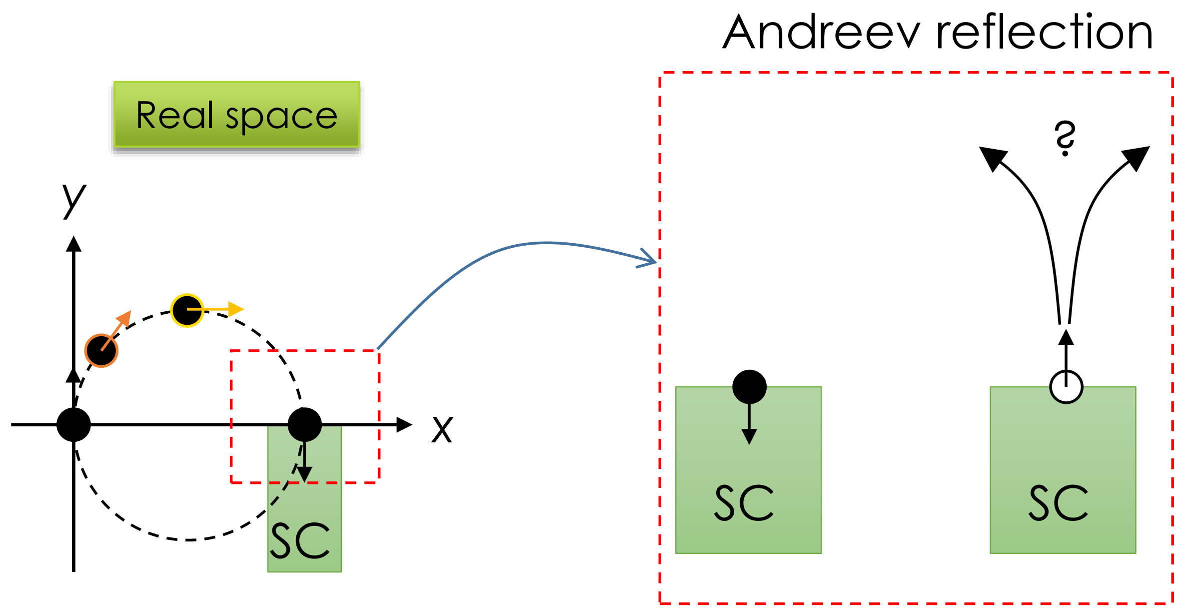


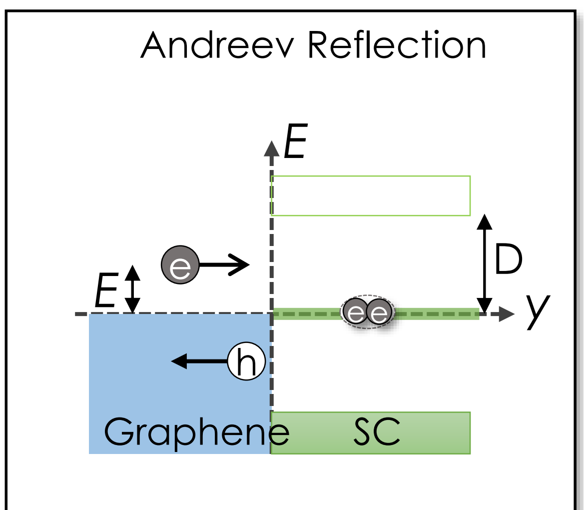
Measurement



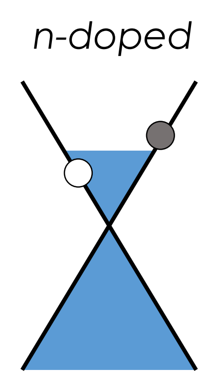
[S. Bhandari, G.-H. Lee, *et al.*, *Nano Lett.*, (2016)]

Which Way to Go?





Hint,



Andreev reflected hole
= Hole in CB ($m^* < 0$)
= Absence of electron in CB ($m^* > 0$)

Summary

- Dirac Electronic optics in high-quality graphene
  - Study on relativistic quantum mechanics in solid system.
- Magnetic focusing in graphene
  - Playground to investigate behavior of Andreev pairs under magnetic field
  - Scanning gate microscopy images path of quasi-particles
- Quantum Hall with superconductor
  - Promising candidate to realize elusive non-Abelian anyon in 2D platform.