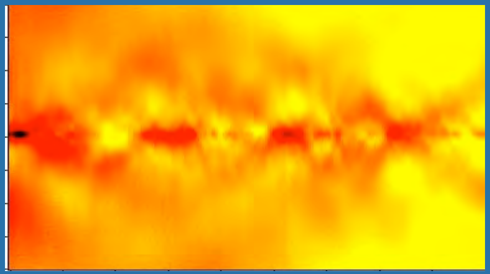
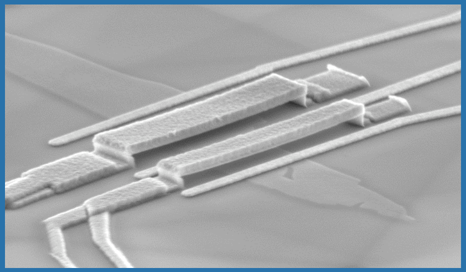
Chun Ning Lau
(Jeanie)

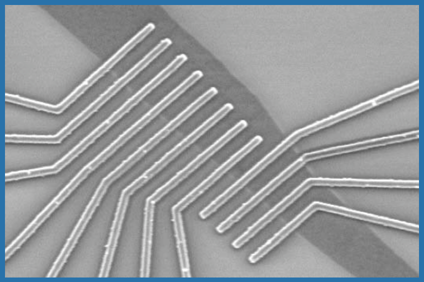
UNIVERSITY of CALIFORNIA
Riverside

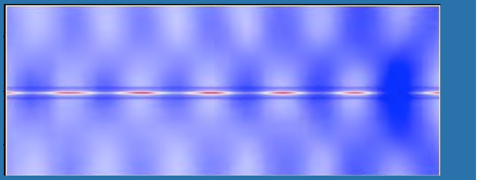
Department of Physics





Quantum Transport in Graphene

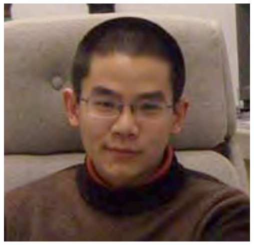




Acknowledgement

Graduate Students


Feng Miao


Wenzhong Bao

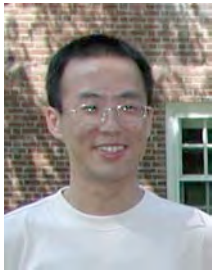

Gang Liu


Jairo Velasco

Undergraduate Students


Sitara Wijeratne

(Former) Postdocs

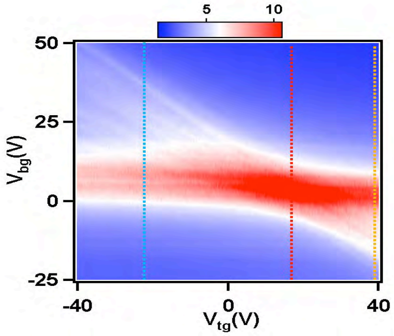

Yong Zhang


Ulas Coskun

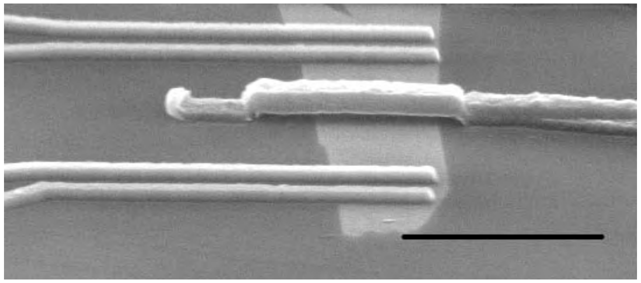
Discussion With

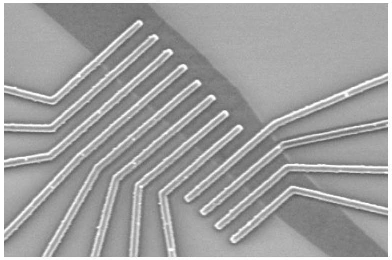
Shan-Wan Tsai, Marc Bockrath, Antonio Castro-Neto, Michale Fogler, Gil Refael, Dmitri Abanin, Philip Kim, Chandra Varma, Leonid Pryadko, Dmitry Novikov, Alex Bratkosvki

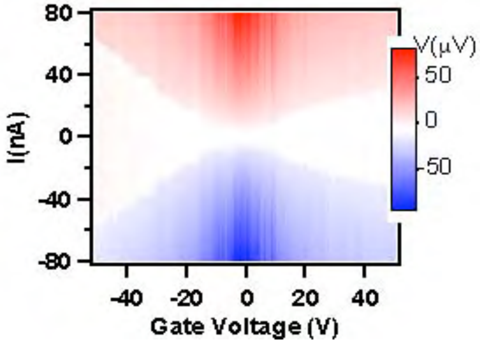
Outline

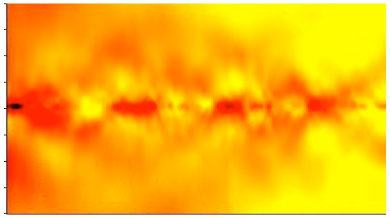


- Rise of Graphene
- Overview of recent experimental progresses
- Minimum conductivity
- Quantum interference of charges
- Supercurrent Transistors
- Quantum Hall states in p-n junctions
- Conclusion and outlook







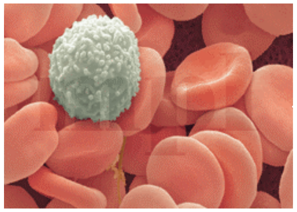


Scale of Things

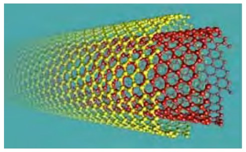
Self-assembled

Human hair

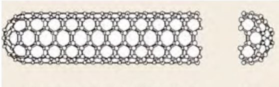
Blood cells



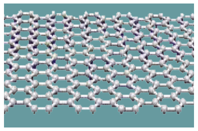
E. Coli Bacteria

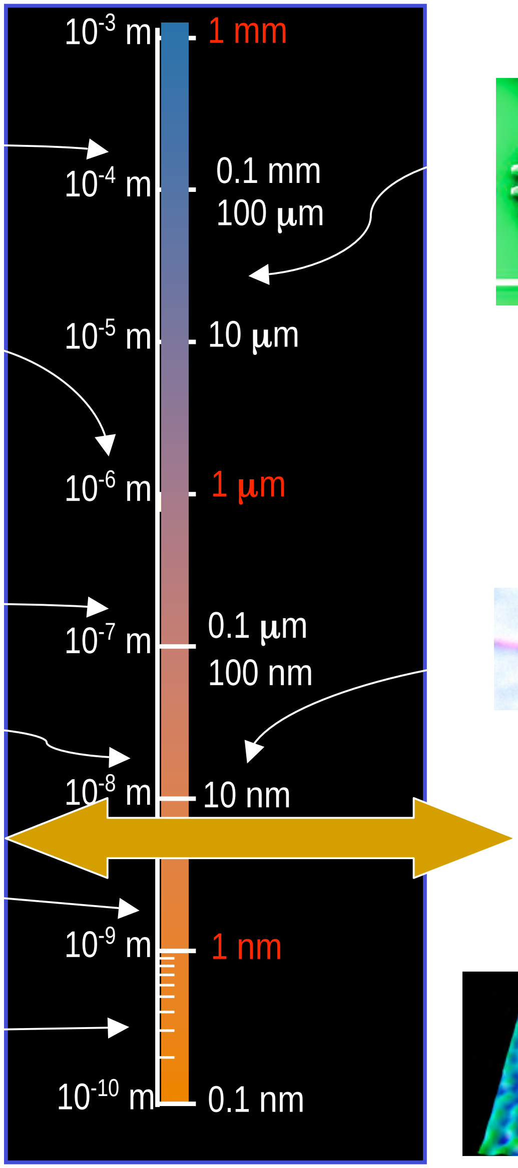


Carbon nanotubes



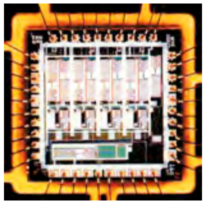
Graphene





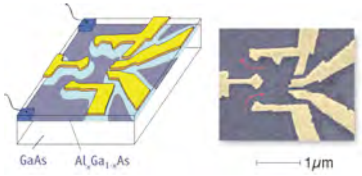
Human-assembled

Micro-Electro-Mechanical devices

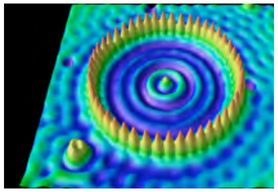


Micro-electronics

Nnanowires



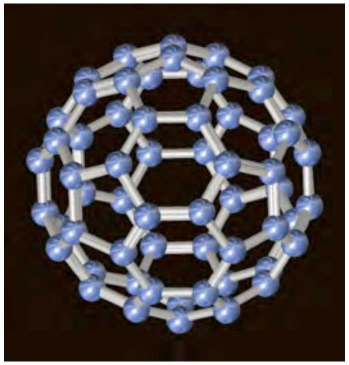
Semiconductor Heterostructures
- quantum dots
- quantum wires
- 2DEG



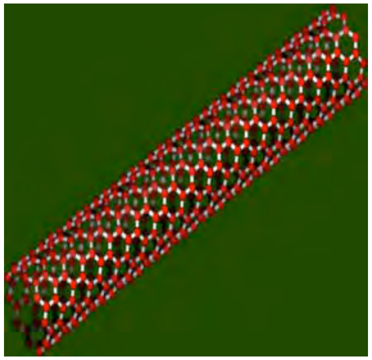
48 iron atoms on copper

0D, 1D, 2D and 3D Carbon

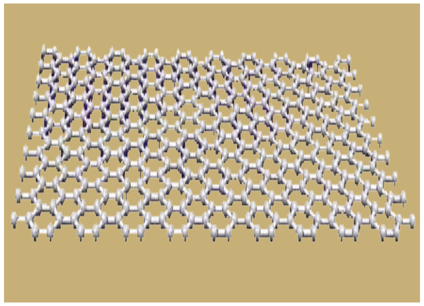
0D



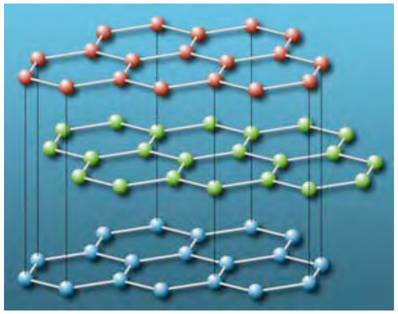
1D



2D

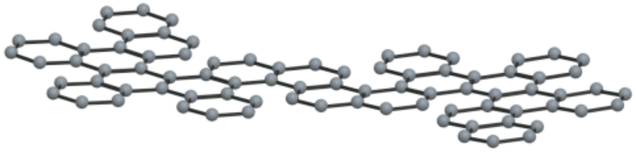


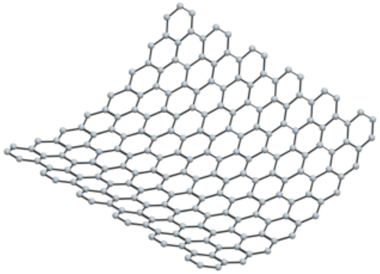
3D



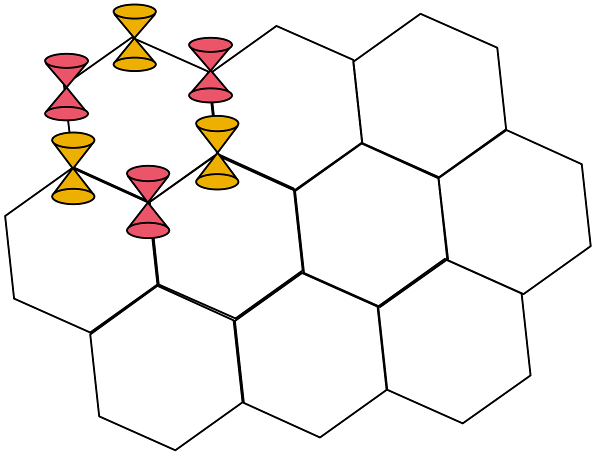
Images taken from scifun.ac.uk

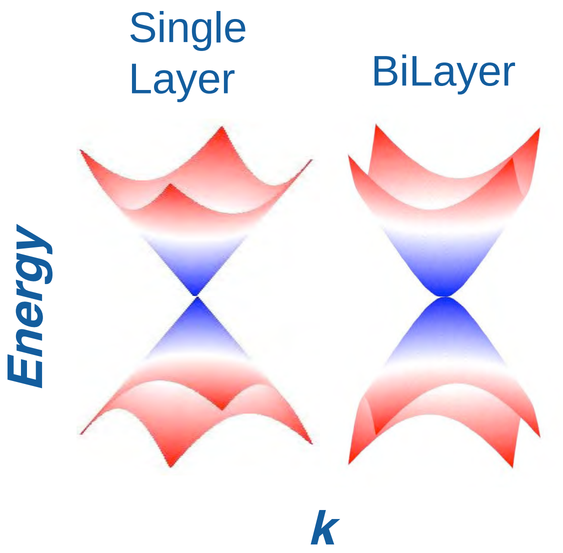
From Novoselov’s presentation at IWCNM,
Kirchberg, 2007





Two-Dimensional Crystal

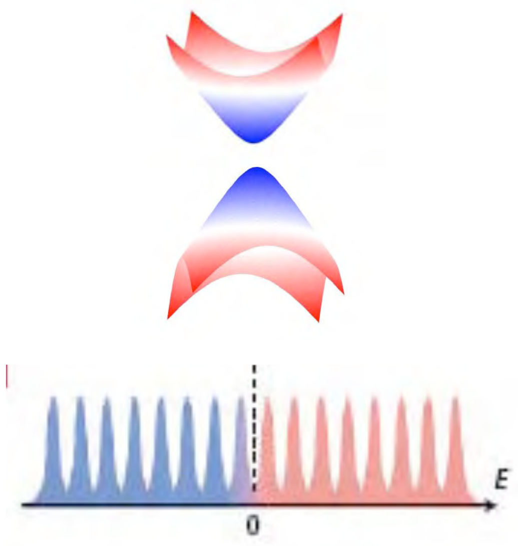




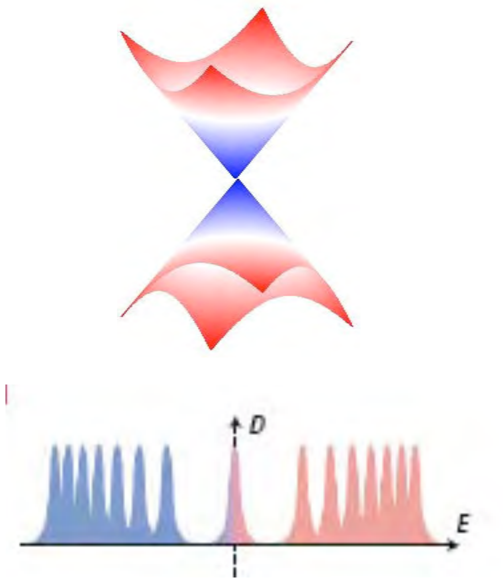
- Honeycomb lattice, two sub-lattices
- Unique Dispersion Relations: massless Dirac Fermions
- First experimental isolation by Geim’s group in 2004
  Novoselov *et al*, *Science*.

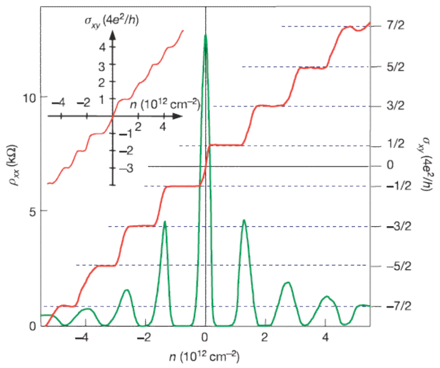
Half-integer Quantum Hall Effect

Semiconductors



Graphene





Landau Levels

$$E_N = \pm\frac{\hbar eB}{m}\left(N+\tfrac{1}{2}\right)$$

$$E_N = \pm v_F\sqrt{2e\hbar BN}$$

$$\sigma_{xy} = \pm\frac{4e^2}{h}\left(N+\tfrac{1}{2}\right)$$

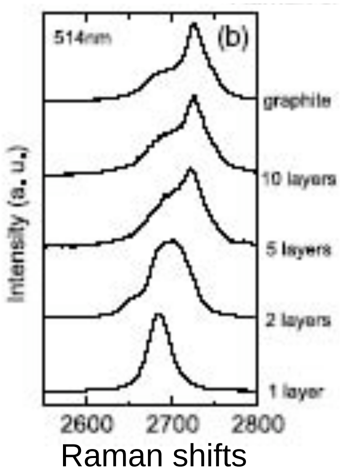
Novoselov *et al Nature* 2005;
Zhang *et al*, Nature 2005.

- New model system for condensed matter research
  Veselago lensing, Klein tunneling, Spin transport, Supercurrent transistor…

- Surface 2DEG
  •Optical, STM and mechanical measurements
  •Easily coupled to special electrodes (superconductors, ferromagnets)

Optical Probes

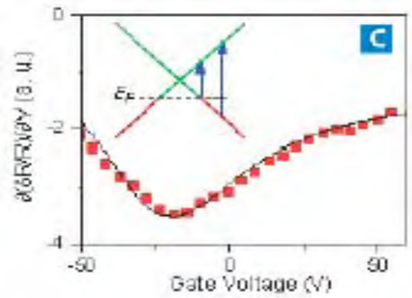
Raman spectroscopy



Ferrari *et al*, *PRL* (2006).
Yan *et al*, PRL (2007).
Pisana *et al*, Nature Mat. (2007)
Balandin *et al*, Nano Lett. (2008)

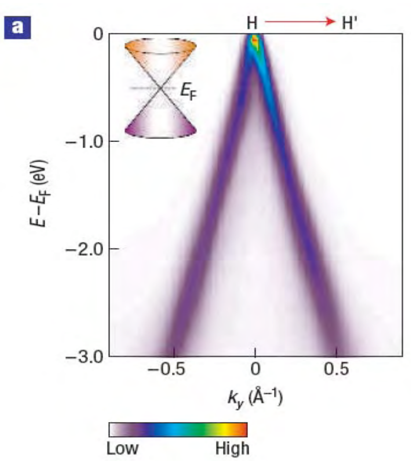
- Identify number of layer
- Study electron-phonon dynamics
- Measure thermal conductivity

Gate-Variable IR Transitions



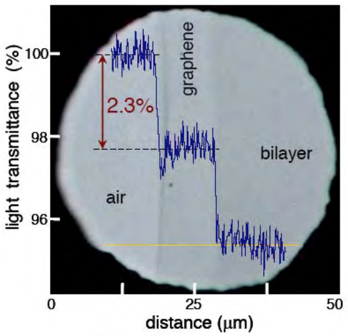
Wang *et al*, Science(2008)

ARPES probe of Electronic structures



Zhou *et al*, Nature Physics (2006)
Bostwick *et al*, Nature Physics (2007)

Optical Transmission & Conductivity



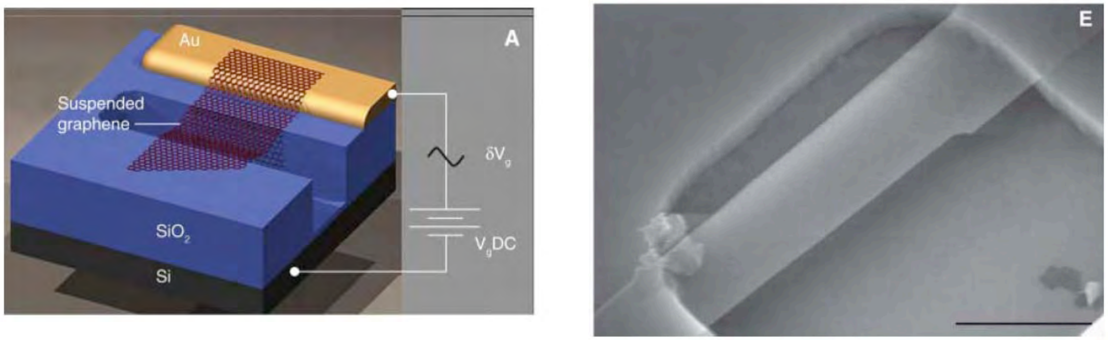
Nair *et al*, cond/mat (2008)

See also Kuzmenko *et al*, PRL (2008) for multilayer graphite

Optical absorbance ~ $\pi \frac{e^2}{\hbar c}$ *(# layers)*

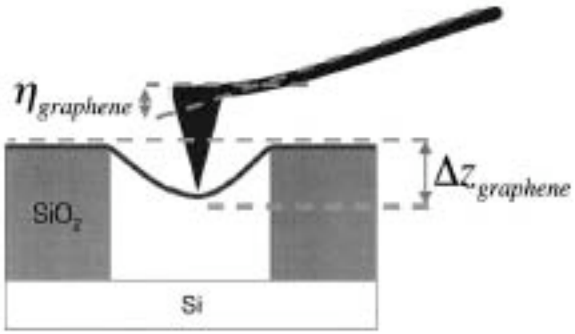
Mechanical Properties

- Single Atomic Layer Mechanical Resonator



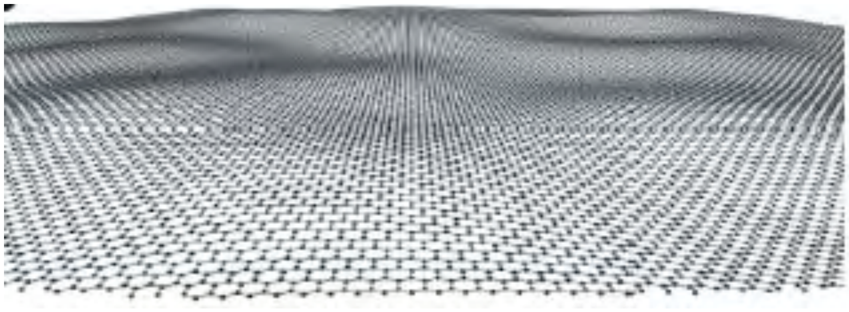
Bunch *et al*, Science (2007)

- Measured Young’s modulus 0.5TPa
- Spring constant 1-5 N/m



Frank *et al*, J. Vac. Sci. Technol. B (2007)

- Ripples in Suspended Graphene

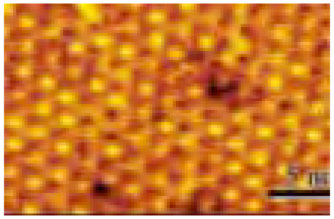


Meyer *et al*, Nature (2007)

Applications

Post-silicon electronic material

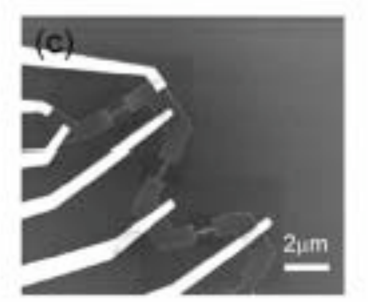
- With advantages of carbon nanotubes
  - ✓high thermal conductivity (5000 W/mK)
  - ✓high current density (~ mA/μm width)
  - ✓high mobility (~10,000 V/cm-s in as-prepared samples)
- 2D → compatible with lithographic techniques
- Potential for large scale synthesis

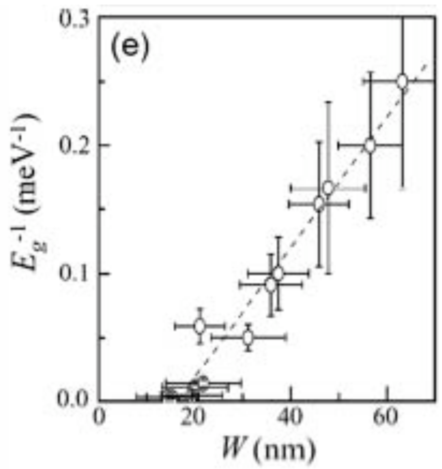


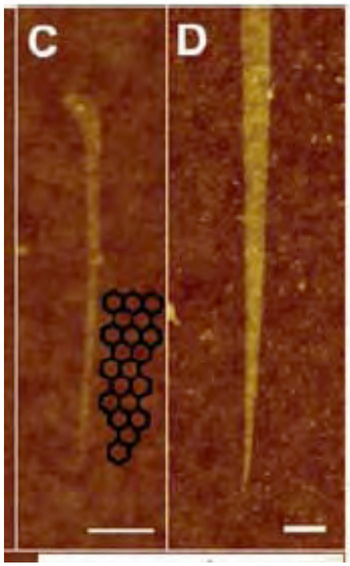
Epitaxially grown graphene
Berger *et al*, *Science* (2006)

Graphene Field-Effect Transistors

- Graphene Nano-ribbon FET
- Band induced by quantum confinement







$$E_g \approx \frac{0.2}{W - W^*} \frac{eV}{nm}$$

Han *et al*, PRL (2007)
Chen *et al*, Physica E (2007)

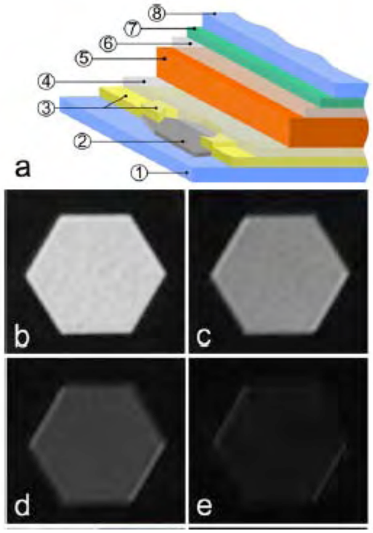
Li *et al*, Science (2008)
Wang *et al*, cond/mat (2008)

- Lithographically defined nanoribbons

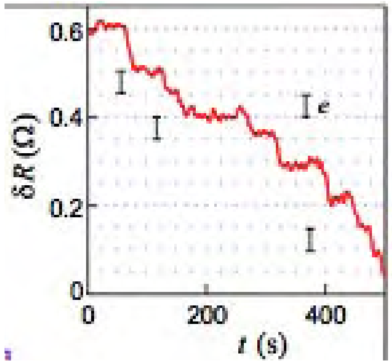
- Chemically derived nanoribbons
- Almost all semi-conducting
- On/off ratio ~10^6, mobility ~200 cm^2/Vs

Applications

- Post-silicon electronic material
- With advantages of carbon nanotubes
  ✓high thermal conductivity (5000 W/mK)
  ✓high current density (~ mA/μm width)
  ✓high mobility (~10,000 V/cm-s in as-prepared samples)
- 2D → compatible with lithographic techniques
- Transparent electrodes for solar cells, LCD, etc
- Chemical and biological sensors based on graphene
- Electronics, Spintronics, and Valley-tronics

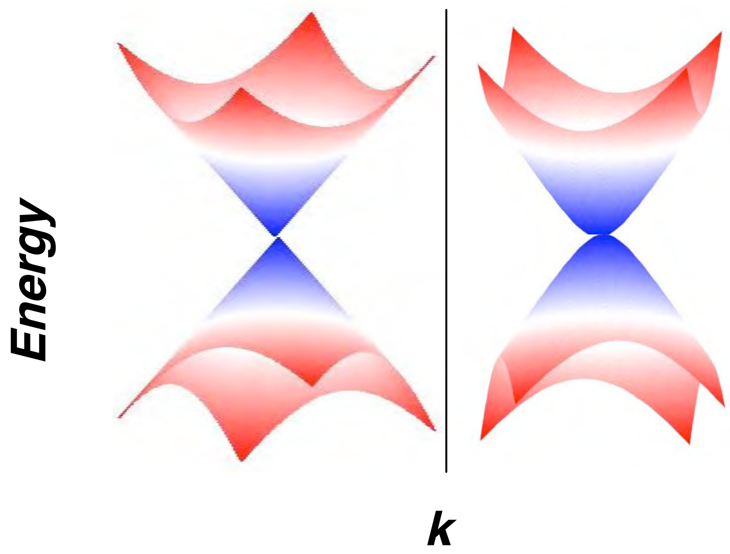


Blake *et al*, cond/mat (2008)



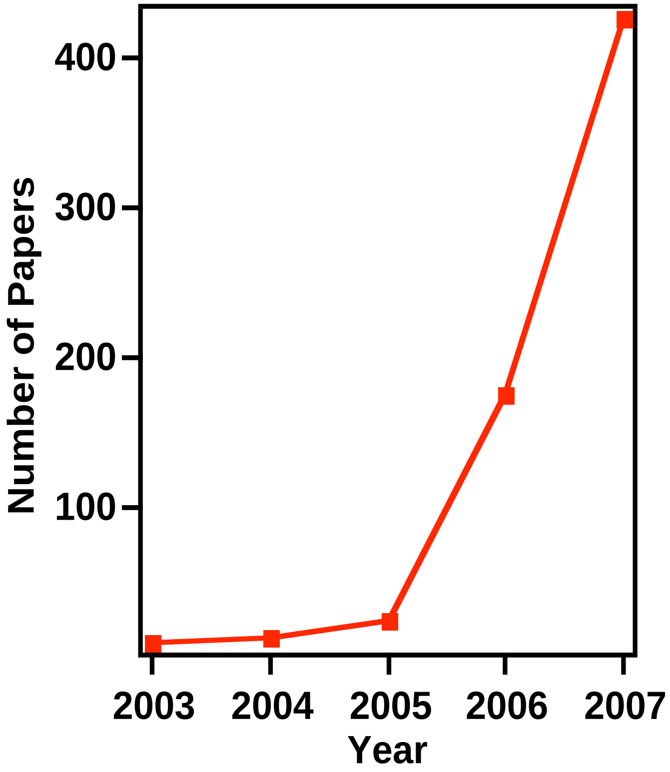
Ultra-sensitive gas sensors
Schedin *et al*, Nature Materials (2006).

The Band…



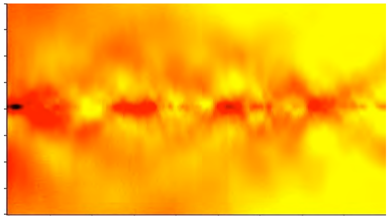
The Bandwagon!

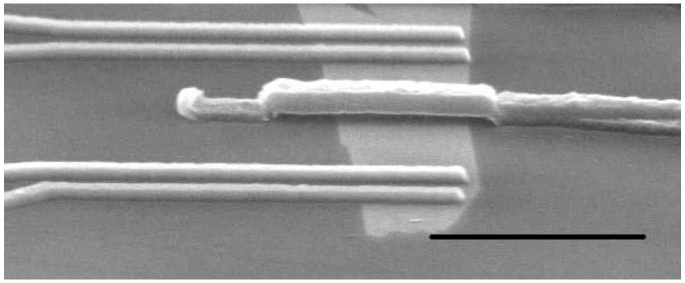
Number of papers on arXiv
with keyword graphene

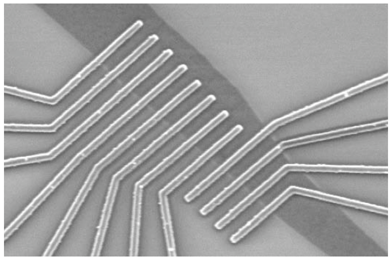


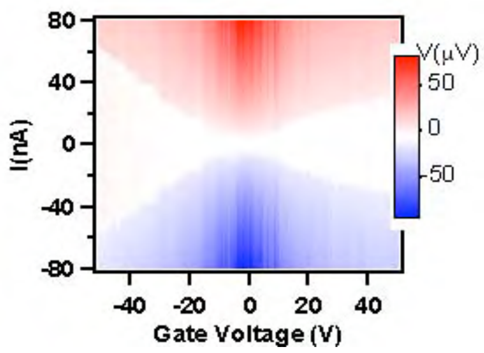
Outline

- Rise of Graphene
- Overview of recent experimental progresses
- **Minimum conductivity**
- **Quantum interference of charges**
- Supercurrent Transistors
- Quantum Hall states in p-n junctions
- Conclusion and outlook





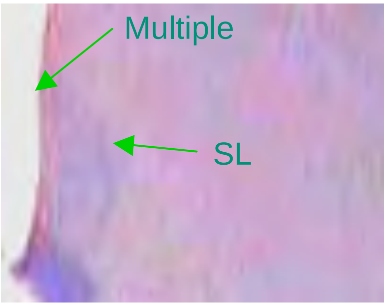




Extraction of Single- and Bi-Layer Graphene

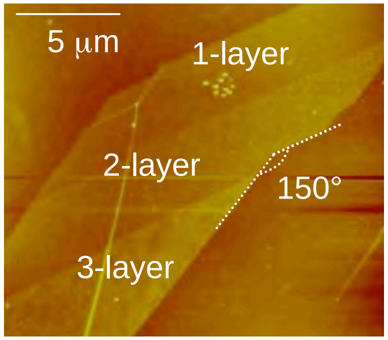
Optical Microscope

Single-layer graphene



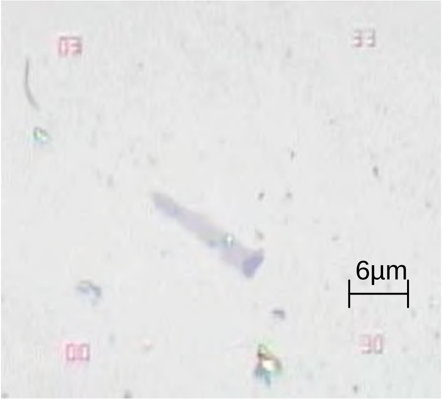
Bi-layer graphene

AFM



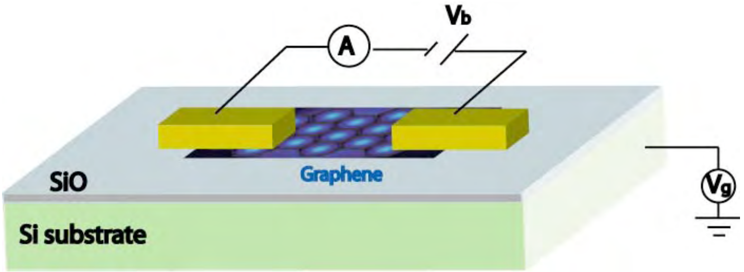
- Mechanical exfoliation -- rub natural graphite flakes onto SiO_2 substrate
- Identify the number of layers by color contrast in optical microscopes
(other methods: Raman and transport)
- AFM images reveal mesoscopic features

Device Fabrication

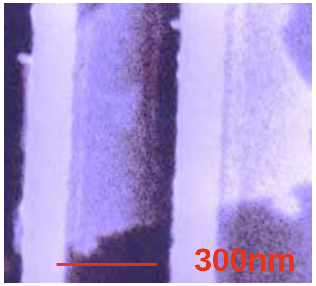


Two steps of E-beam lithography

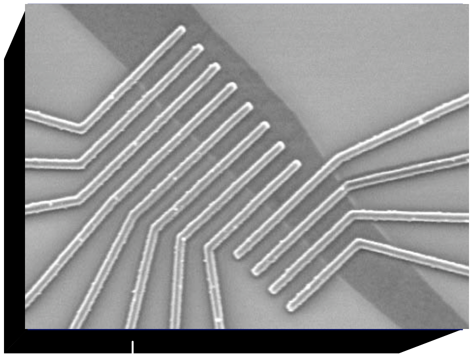
- Alignment Marks
- Electrodes (3-10 nm Ti or Pd + 70 nm Al)



Bi-layer graphene device



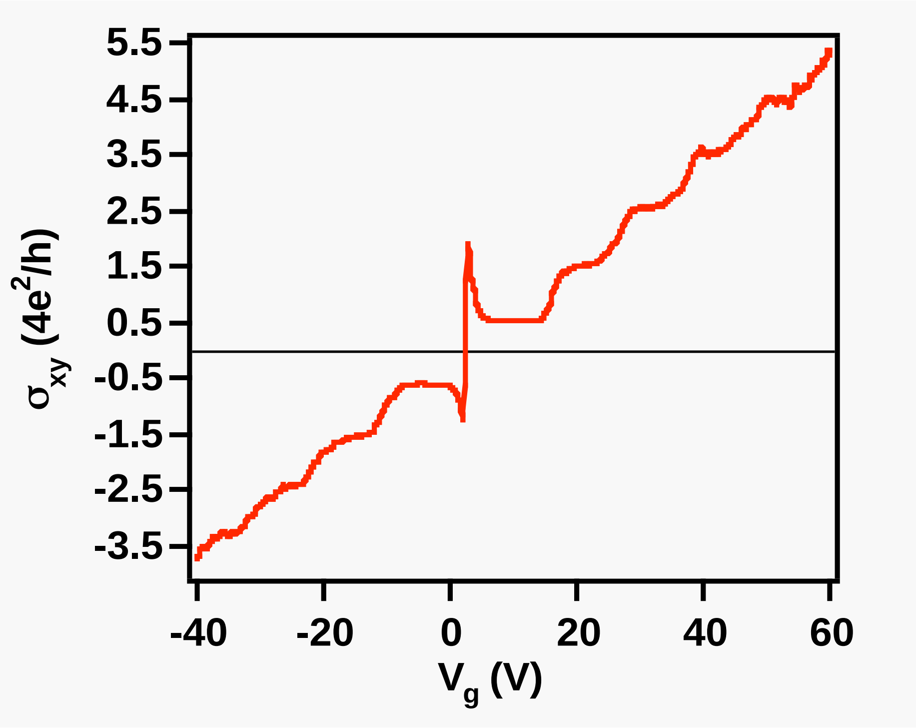
Single-layer graphene device



Half Integer Quantum Hall Effect

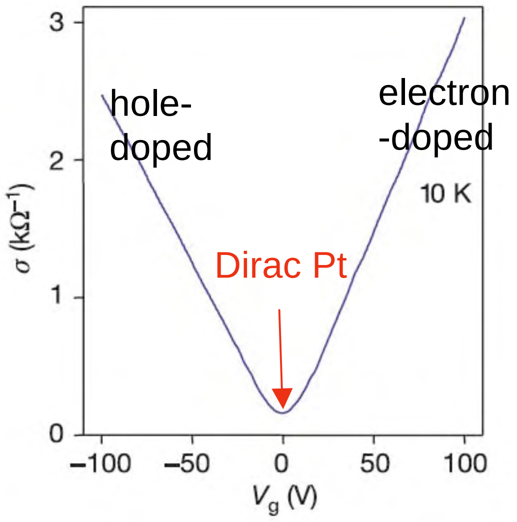
Conductivity of single layer graphene quantized at half-integral values of $4e^2/h$

–> confirmed selection of single layer graphene



Minimum Conductivity Controversy

- Graphene as bipolar field-effect transistors
  - Conductivity increases linearly with charge density *n*
    $\sigma \propto V_g \propto n$
  - σ remains finite at Dirac point → σ_{min}

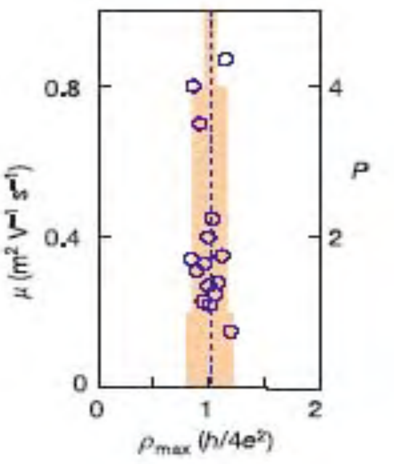


- Theoretical prediction: universal value of $G_Q=4e^2/\pi h$
  - independent of v_F,
  - for both ballistic and disordered regimes.

Fradkin 1986; Lee 1983; Peres *et al* (2006), Nilsson *et al* (2006), Katsnelson (2006), Tworzydlo *et al* (2006)…..

- Experimental measurements: $4e^2/h$, π times larger than theory (Novoselov *et al*, *Nature*, 2005.)

  →the mystery of missing π



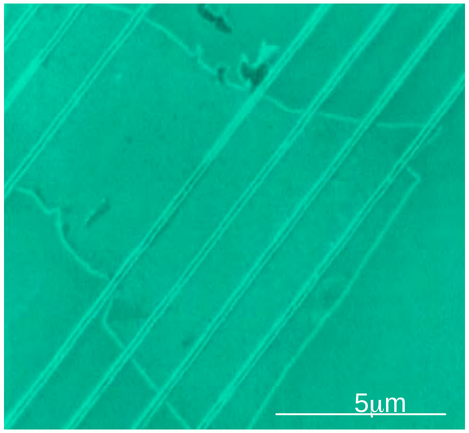
- **What limits mobility?**

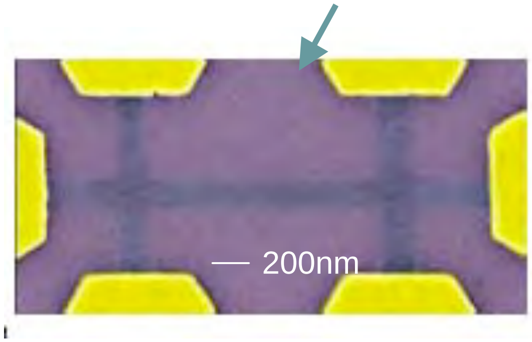
Our Findings

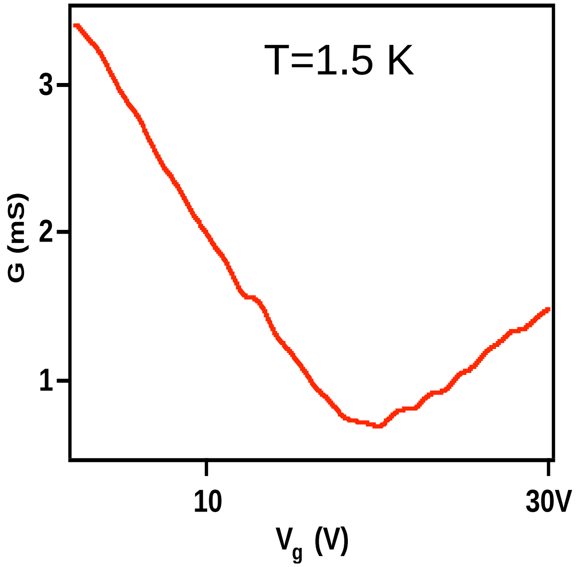
Devices with large source-drain separation (> 1μm) and large areas (>0.3 μm^2)

- $\sigma_{min} \sim 4e^2/h$
- σ linear in gate voltage
- mobility μ=8000 - 15000 cm^2/Vs

→ Fully consistent with results in Novoselov et al, Nature, 2005.

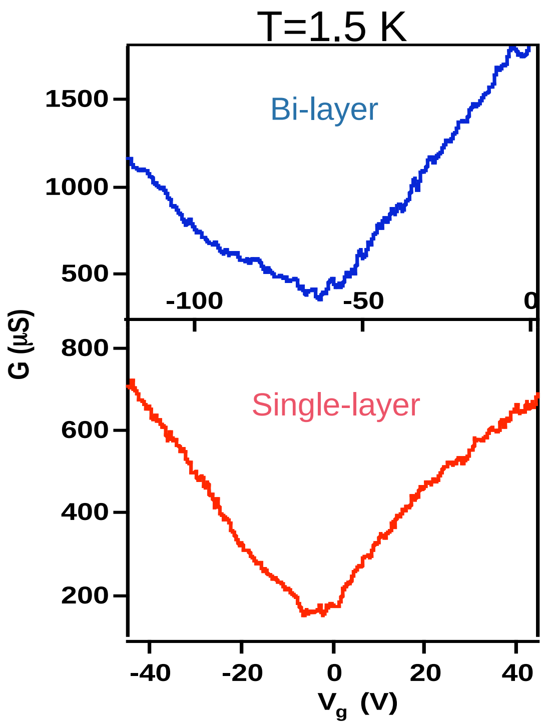


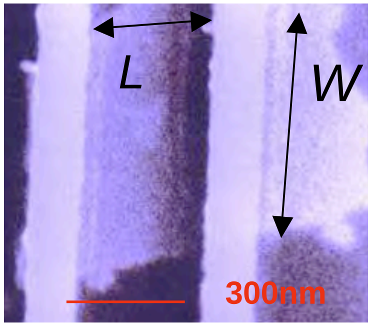




Our Findings

Devices with small source-drain separation (< 400 nm) and small areas (<0.1 μm^2)





- Minimum conductivity ranges from 0.8 to 4.3 ($4e^2/\pi h$)

- G-V_g frequently displays sub-linear relationship

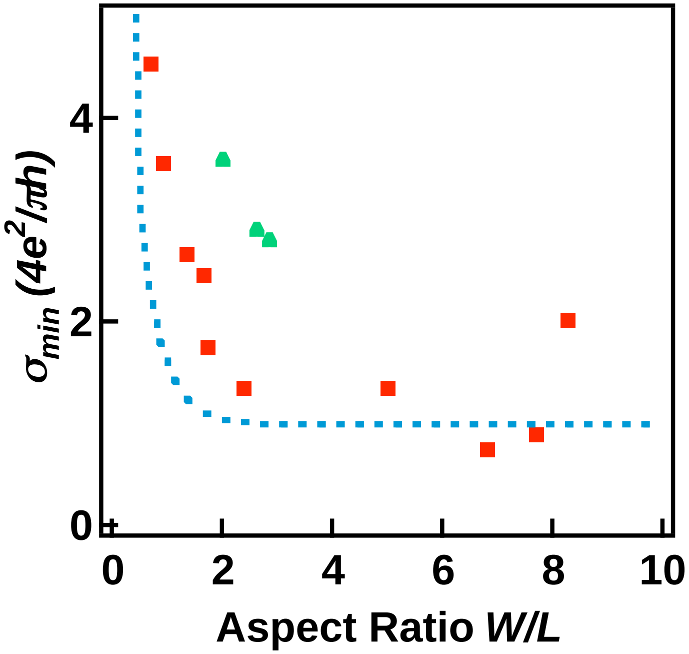
What's Going On???

Tworzydlo *et al*, *PRL*, 2006:

- σ_{min} depends on devices' aspect ratio *W/L* for a ballistic transport in graphene
  - At Dirac point, transmission via evanescent modes
  - Use Landauer formula
  - Only approaches $4e^2/\pi h$ for *W/L* >>1

$$T_n = \frac{1}{\cosh^2(\pi n L/W)}$$

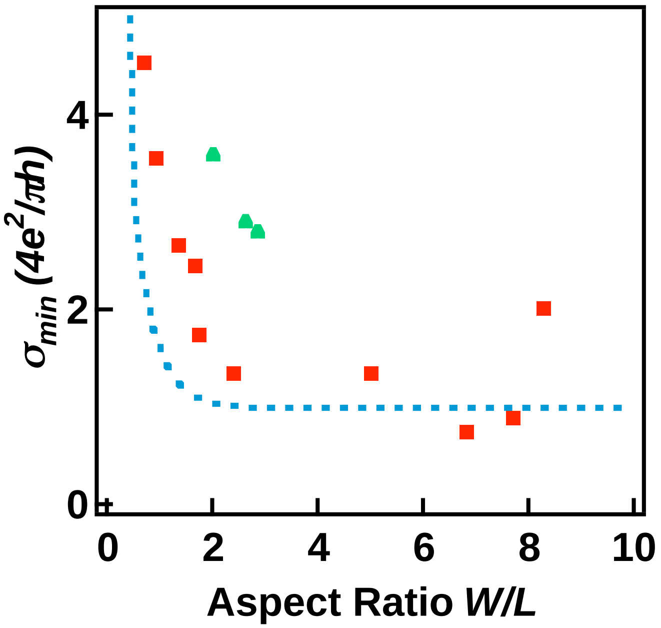
$$\sigma_{\min} = G_{\min}\frac{L}{W} = \frac{2e^2}{h}\frac{L}{W}\sum_{n=-(N-1)}^{N-1} T_n$$



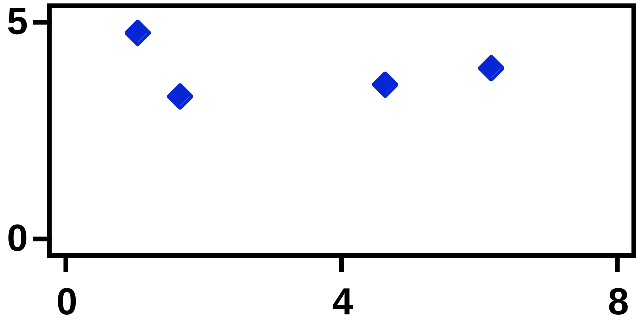
Good agreement with data.

Minimum Conductivity

Small Devices



Large Devices



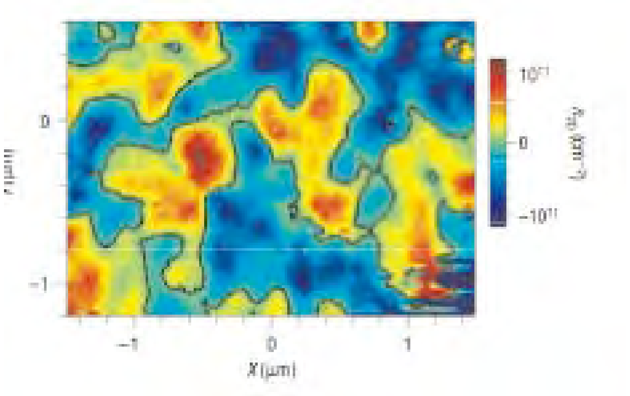
- Transition from ballistic transport to quasi-diffusive regimes
- charge transport is ballistic up to ~ 500 nm
- Possible mechanisms of transition
    - inhomogeneous doping; long range Coulomb scatterers

What Limits Mobility?

- Charge inhomogenity, atomic defects, rough edges
- Contaminants
  - Thermal and chemical annealing
  - Current annealing

    (Bachtold group, Fuhrer group)
- Substrate
  - Use different substrates
  - Free-standing graphene

    (Kim group, Andrei group, cond/mat 2008)
- Ripples -- intrinsic!
  - Apply tension?

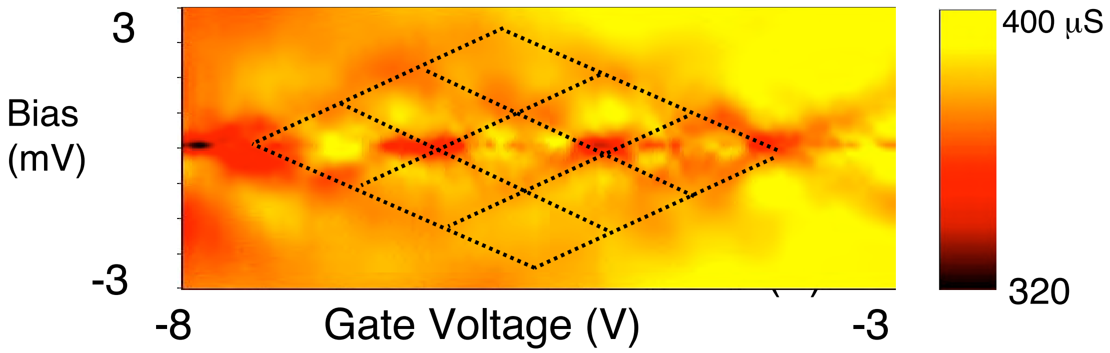


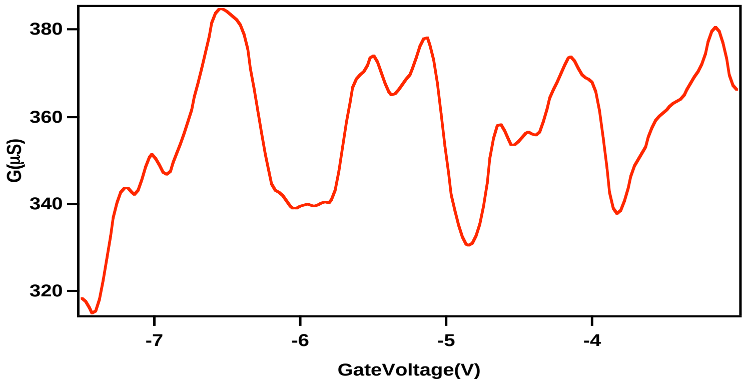
Spatial variation of charge density

Martin *et al*, Nature Physics (2008)

Charge Transport in Graphene Devices

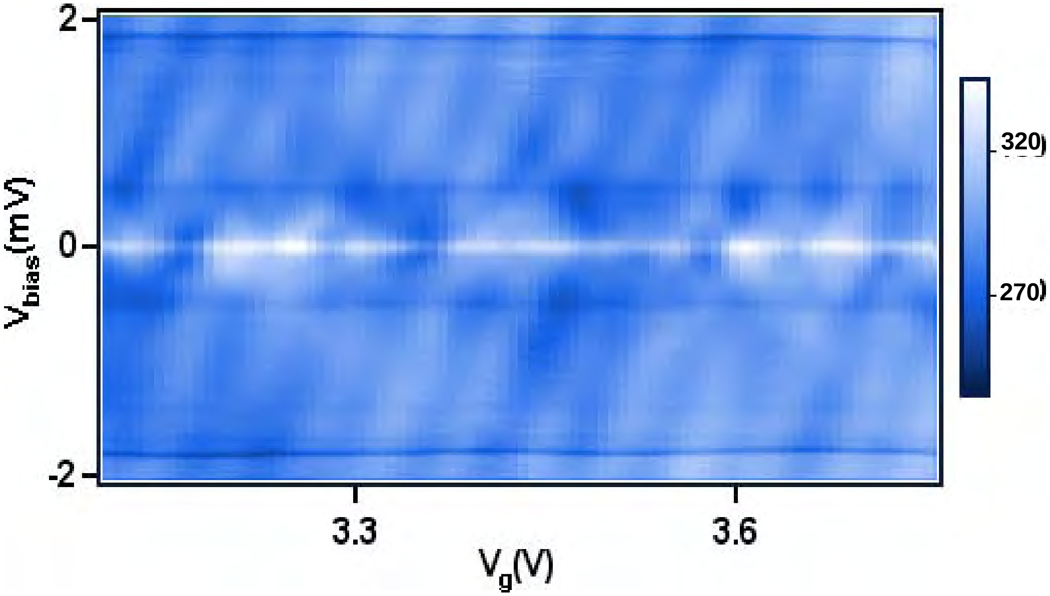
Graphene Coupled to Normal Electrodes at 260mK
(B= 40mT to suppress superconductivity in aluminum.)





Periodic conductance oscillation as functions of both gate voltage and bias.

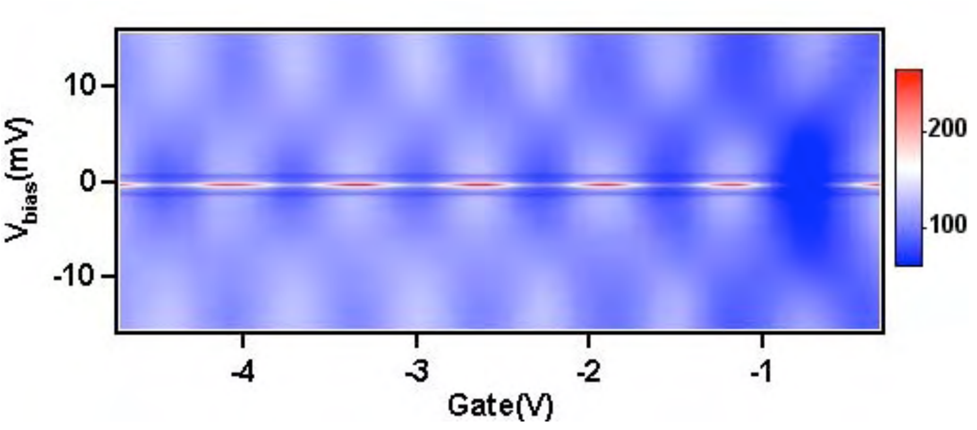
Charge Transport in Graphene Devices

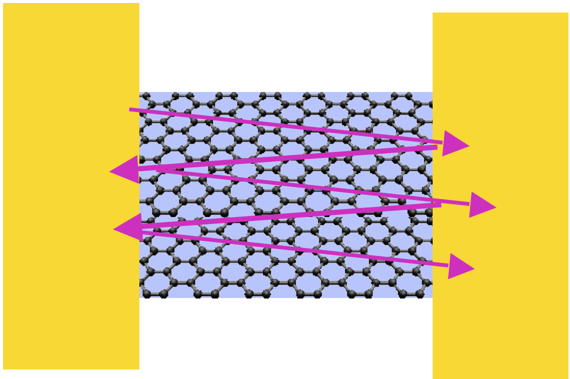


- Robust phenomena -- observed for both single and bi-layer devices, and for both hole- and electron-doped regimes.

Quantum Interference of Electron Waves in Graphene

Carbon Nanotubes

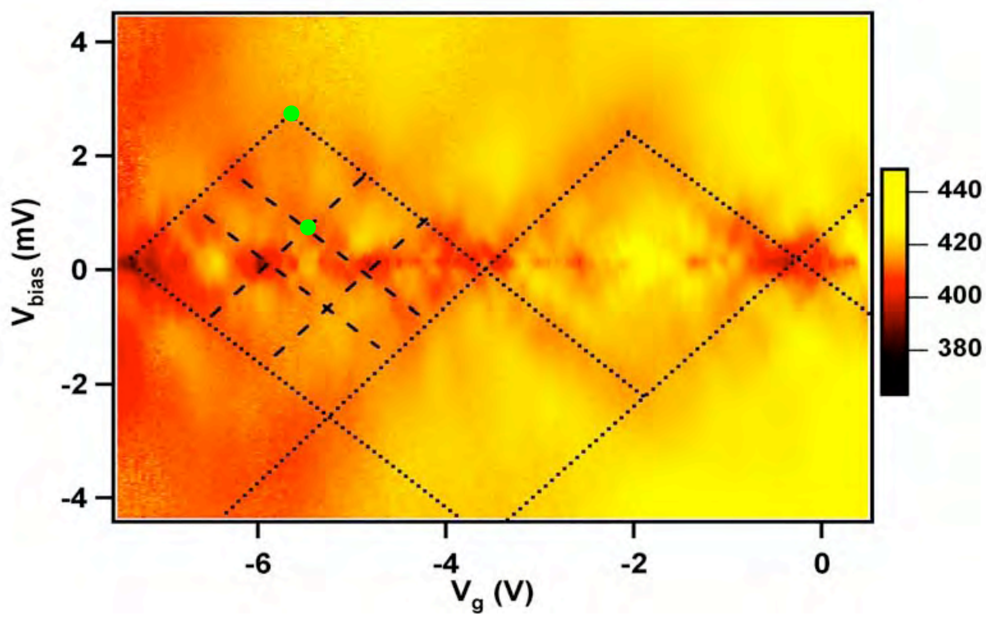




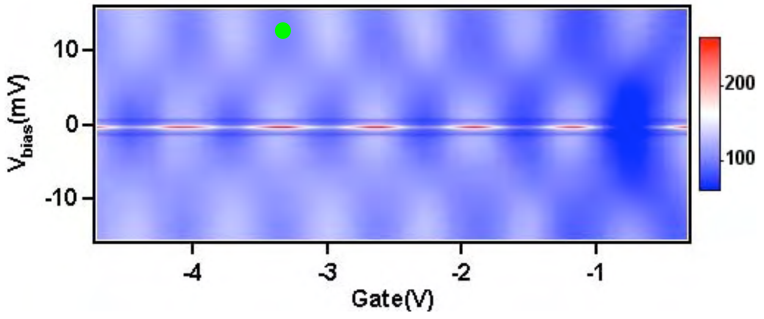
- Similar conductance oscillation observed in carbon nanotubes
- Fabry-Perot resonant cavity -- interference of multiply-reflected electron and hole waves between partially transmitting electrodes.

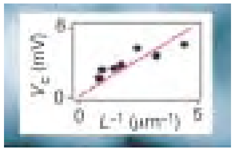
Graphene as a Quantum Billiard

Graphene



Nanotubes





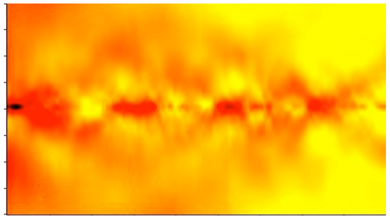
Liang *et al*,
Nature (2001).

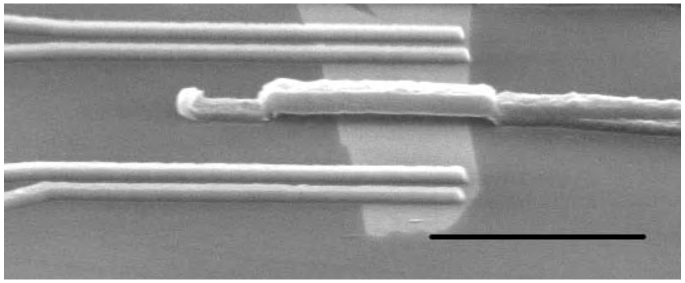
- Typically more than 1 period was observed in graphene devices
- Characteristic energy scale $E_o = hv_F/2L$
  - Nanotubes: L ~ inter-electrode spacing for nanotubes
  - Graphene: L ~ ?
- Electron paths in 2D graphene are not well-defined as in 1D nanotubes
- Smallest E_o ~ 0.7 meV → Charge coherence length ~3- 5 μm in graphene

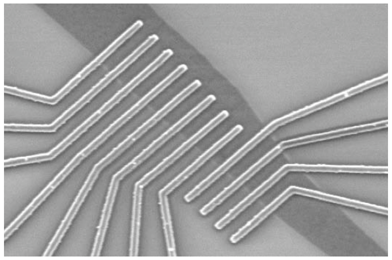
F. Miao, S. Wijeratne, Y. Zhang, U. C. Coskun, W. Bao, C. N. Lau, Science, 2007.

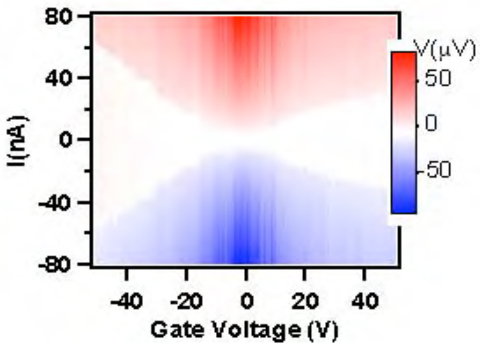
Outline

- Rise of Graphene
- Overview of recent experimental progresses
- Minimum conductivity
- Quantum interference of charges
- **Supercurrent Transistors**
- Quantum Hall states in p-n junctions
- Conclusion and outlook



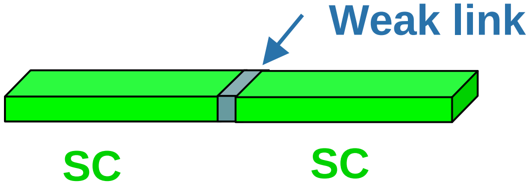




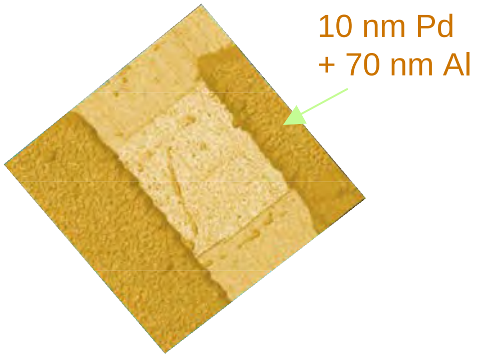


Graphene Coupled to Superconducting Electrodes

Josephson junction with 2D massless Dirac fermions



$$I_s = I_c \sin(\varphi_1 - \varphi_2)$$



New phenomena expected:

- Specular Andreev reflection

  (Beenakker, *PRL* 2006, Titov and Beenakker, *PRB* 2006)

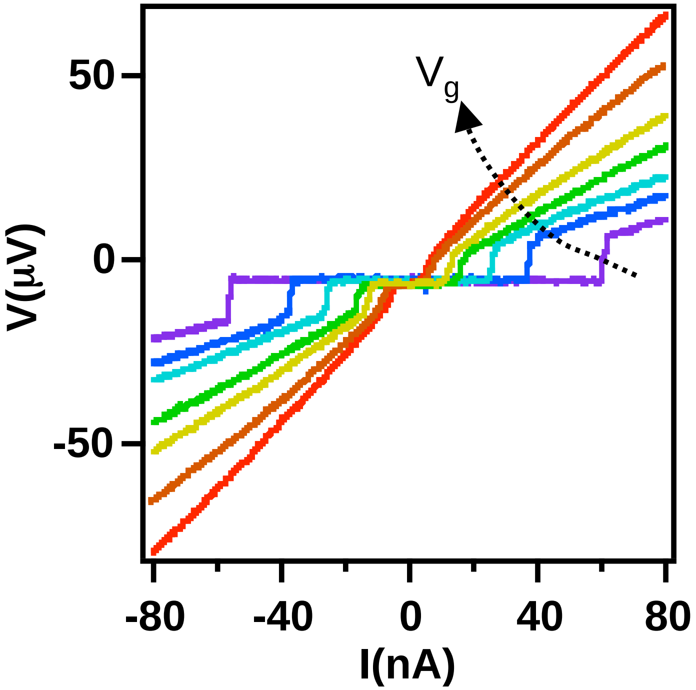
- Novel propagating modes of Andreev electrons (Titov, Ossipov and Beenakker, 2006)

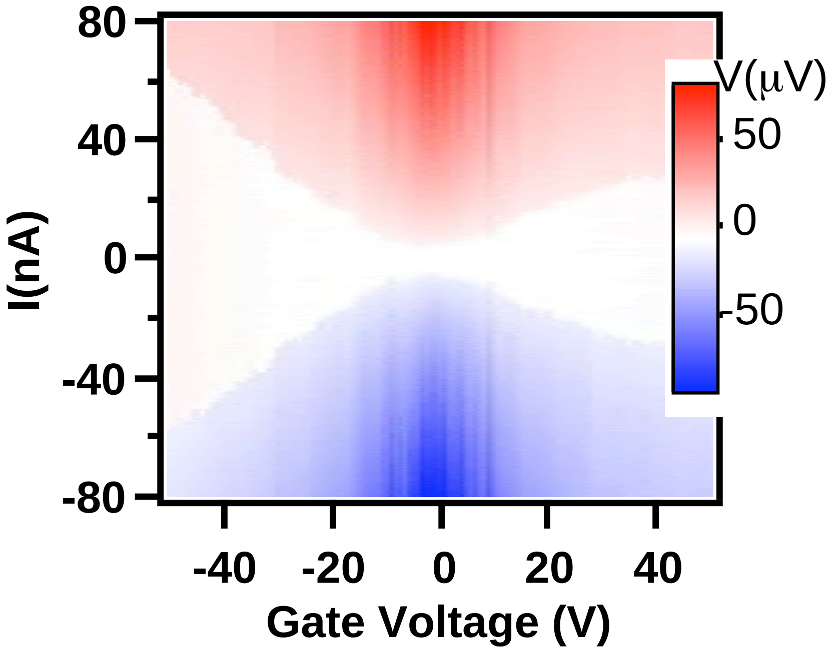
- Oscillation of tunneling probability with barrier width (Sengupta 2006)

…

Graphene Supercurrent Transistor

Single Layer Graphene Device with Ti (5nm)/ Al (80 nm) electrodes.



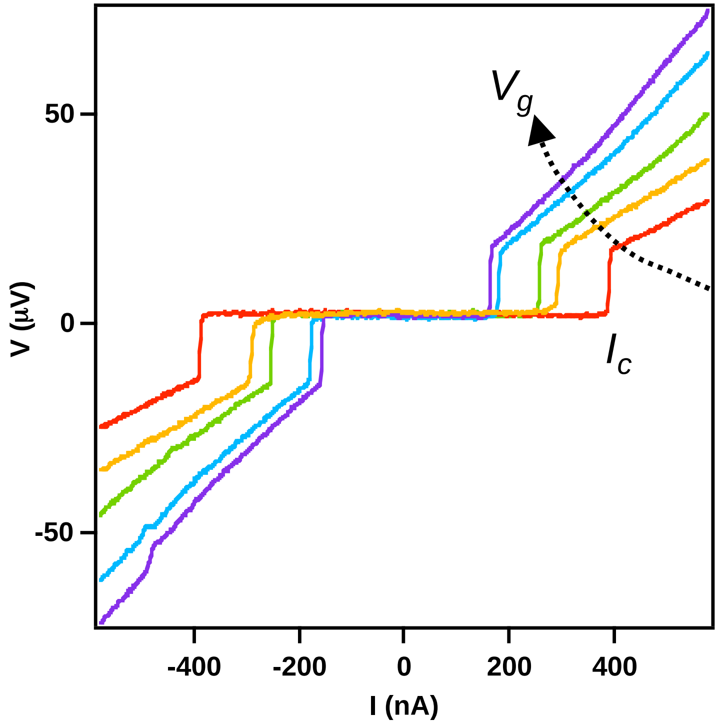


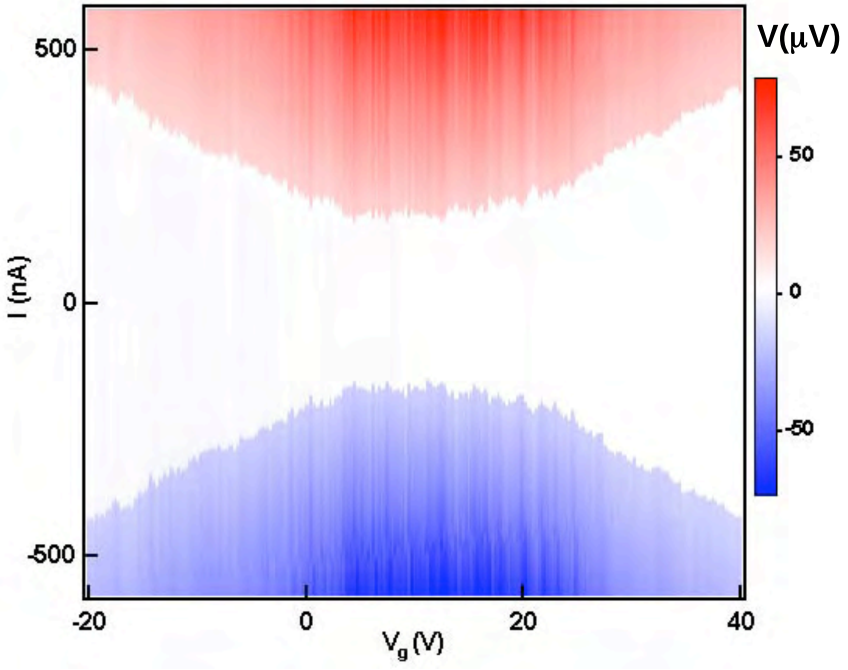
- Supercurrent in graphene

  first reported by Heersche *et al, Nature*, 2007 and Du et al, cond/mat, 2007.

- *V-I* characteristics tuned by gate voltages

Graphene Supercurrent Transistor





- Supercurrent carried by electrons, holes and in nominally undoped regimes.
- Critical current depends on gate voltage.

I_c and I_cR_N Product

Regular Josephson Junction

- tunnel or diffusive SNS junction:

  $I_c \sim 2\Delta/R_N$

- ballistic single channel junction:

  $I_c \sim 2\pi e\Delta/h$

  $I_cR_N \sim 2\Delta/e$

- I_c *and* I_cR_N product are typically constant for a given device

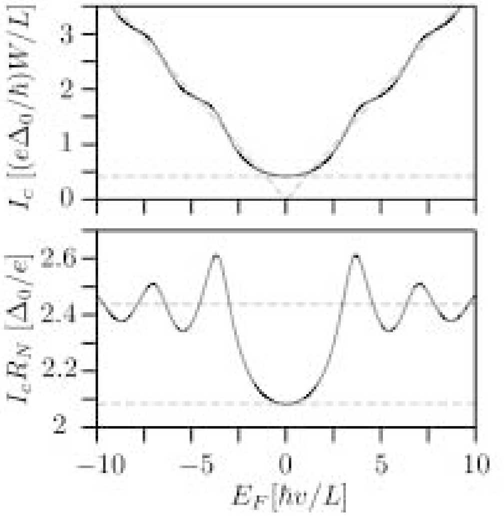
Graphene Josephson Junction

in the ballistic limit

$$I_c \approx \frac{e\Delta}{\hbar}\frac{W}{L}$$

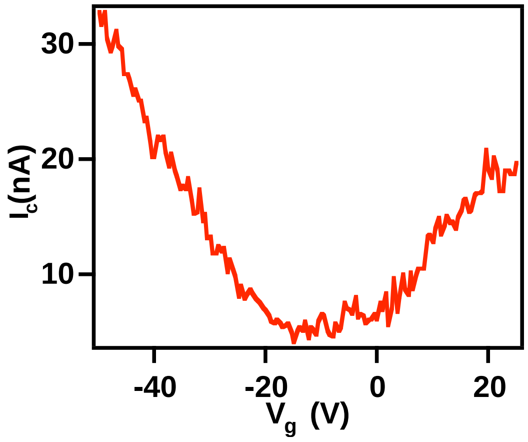
change with V_g

$$I_cR_N \sim 2\Delta/e$$

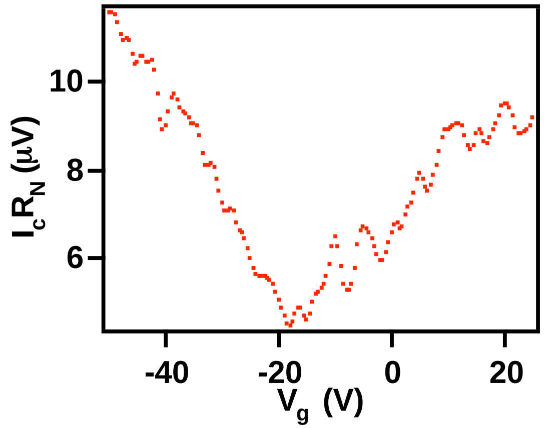


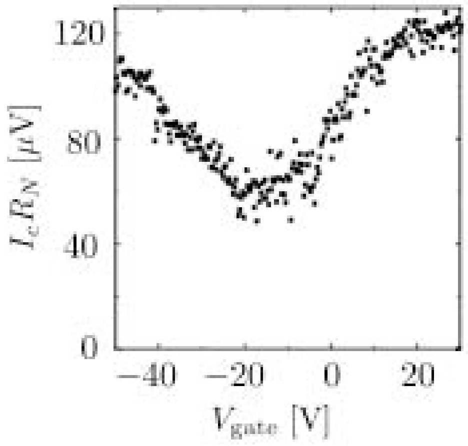
Titov and Beenakker (2006)

Experimental Measurements of I_cR_N

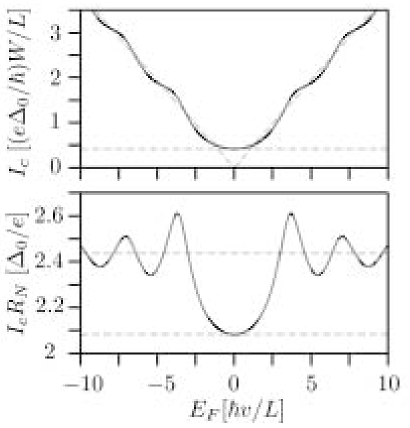


- $I_{c,expt} < I_{c,\ theory}$ and $I_cR_{N,\ expt} < I_cR_{N,\ theory}$ by a factor of 5-10
  - thermal fluctuation(?)
- Large variation in I_cR_N product
- Similar observation reported by Heersche *et al.*



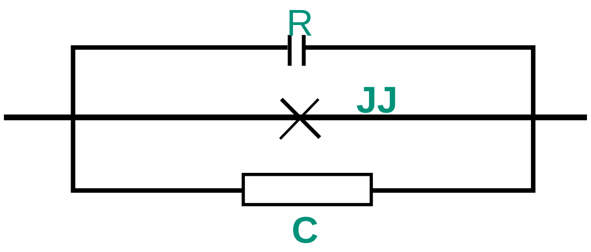


Heersche *et al*, Nature, 2007



Titov and Beenakker (2006)

Dissipation in Josephson Junctions



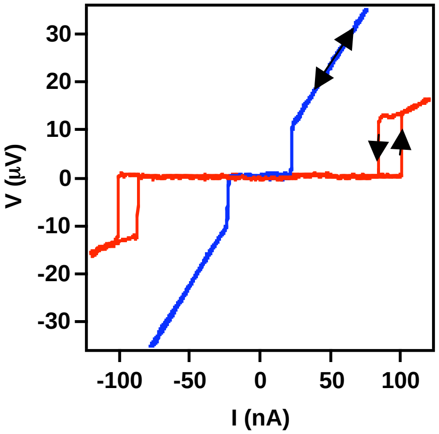
Resistively and Capacitively Shunted Junction

Phase across junction ⇔ particle in a titled washboard potential

Dissipation ⇔ friction ~ $1/R_N$

Superconducting state ⇔ localized particle

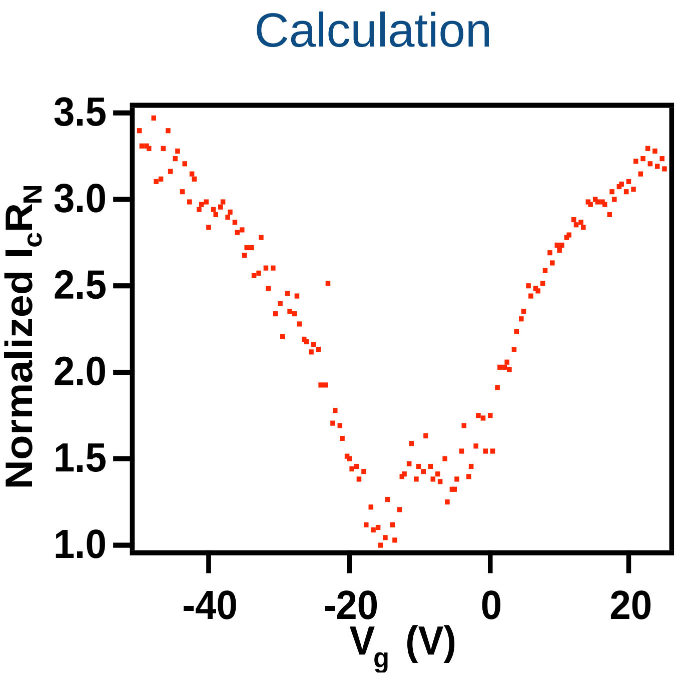
Normal state ⇔ particle running down the potential

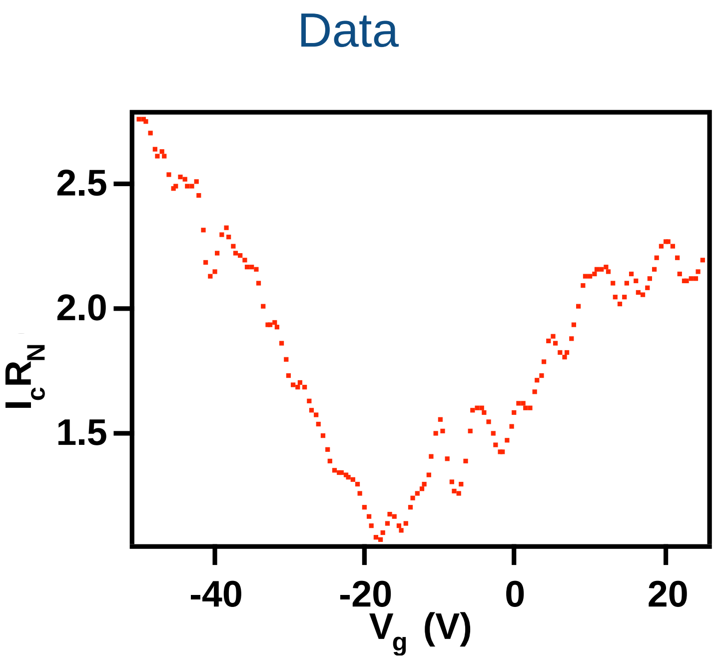


Dissipation ~ 1/hysteresis

- Underdamped Josephson junction with premature switching
- Dissipation changes with gate voltage

Evidence for Gate Tunable Dissipation





- Qualitatively account for the large variation in $I_c R_N$
- Role of massless Dirac Fermions?

Outline

- Rise of Graphene
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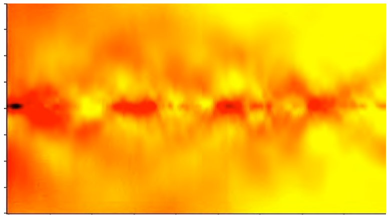
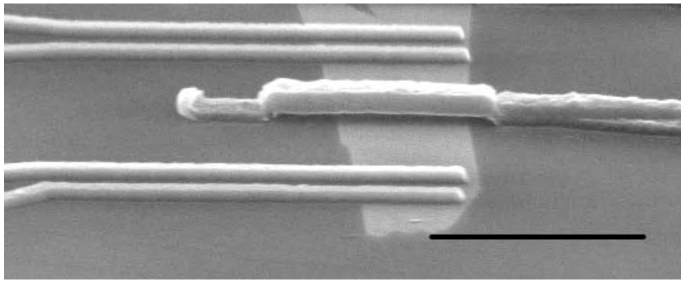
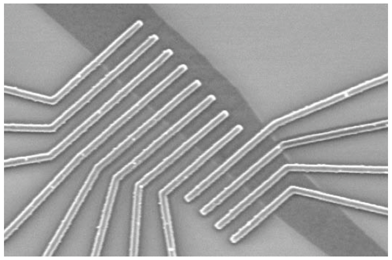
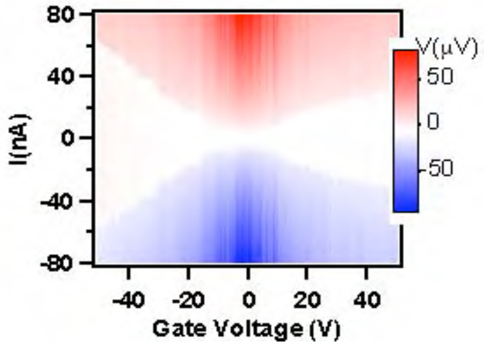
- Conclusion and outlook







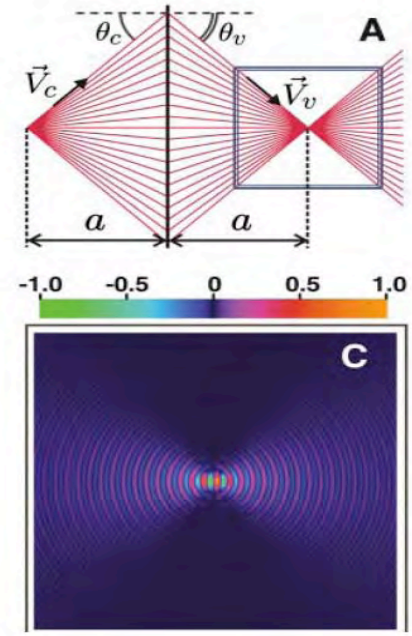


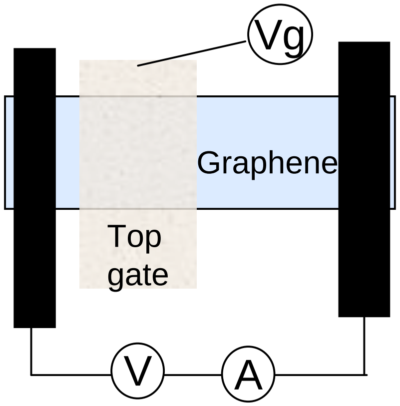
Graphene *p-n* Junctions

- Unique advantage: local control of charge density and *type*

- Graphene p-n junctions with top gate(s):
  - allow *in situ* tuning of junction polarity and dopant levels
  - Partial equilibration of quantum hall edge states

- Application
  - Band gap engineering of bi-layer graphene
  - Veselago lensing (optics-like focusing of electron rays)
  - Particle collimation
  - Valley polarization

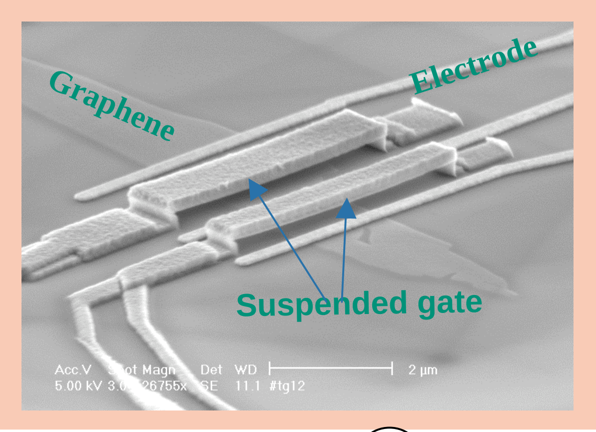


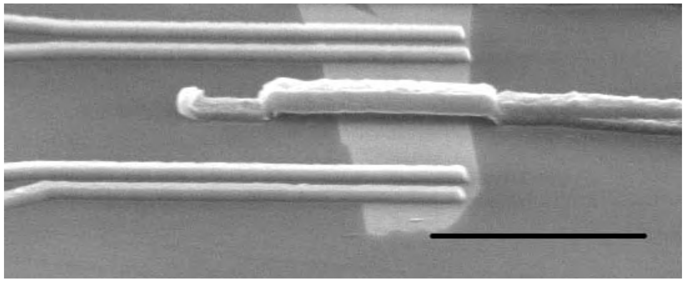


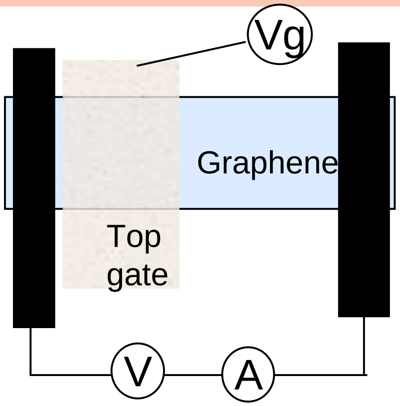
Theories: Abanin *et al* 2006, 2007; Fogler *et al* 2007; Shytov *et al* 2007; Katsnelson *et al* 2006; Beenakker group, Cheianov *et al* 2006, 2007
Experimental demonstration: Huard *et al* 2007; Williams *et al* 2007, Ozyilmaz *et al* 2007, Oostinga *et al* 2007

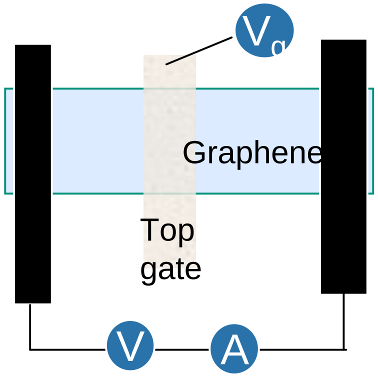
Graphene *p-n* Junctions

- Challenge deposition of top gate tends to dope or damage the atomic layer
- Innovation: Suspended, contactless top gate
    - Gentle process
    - Graphene can be annealed
- Quantum Hall conductance plateau at fractional values of e^2/h



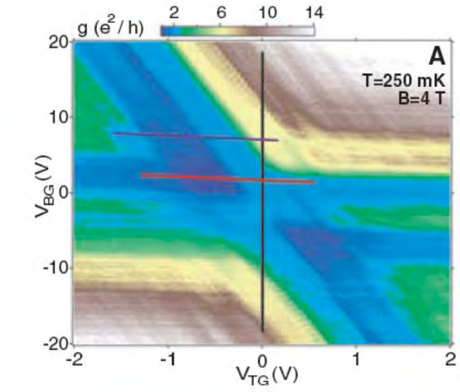




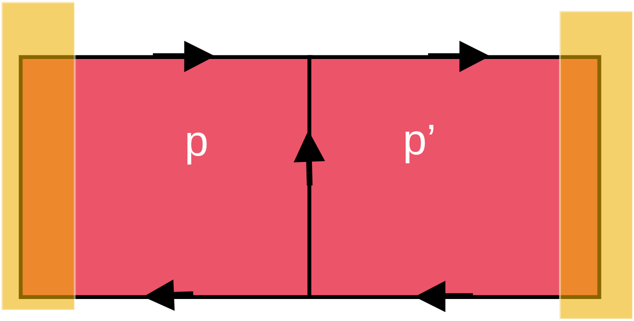


Quantum Hall States in graphene *p-n* Junctions

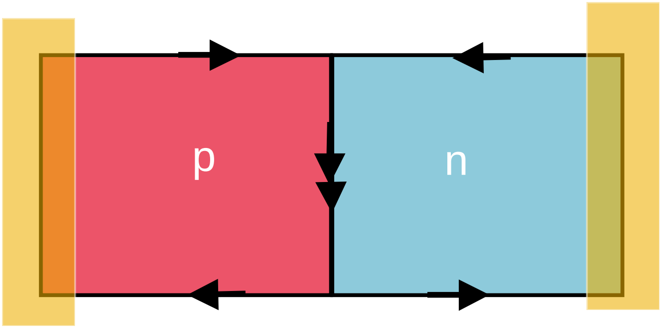
- Fractional quantum Hall plateau observed
- Edge state equilibration, full mixing of propagation modes at interface



Marcus group, *Science*, August 2007.



$$G = \frac{e^2}{h}\min\left(|\nu_1|,|\nu_2|\right)$$



$$G = \frac{e^2}{h}\frac{|\nu_1||\nu_2|}{|\nu_1|+|\nu_2|}$$

Abanin & Levitov, *Science*, 2007

Quantum Hall States in graphene *p-n-p* Junctions

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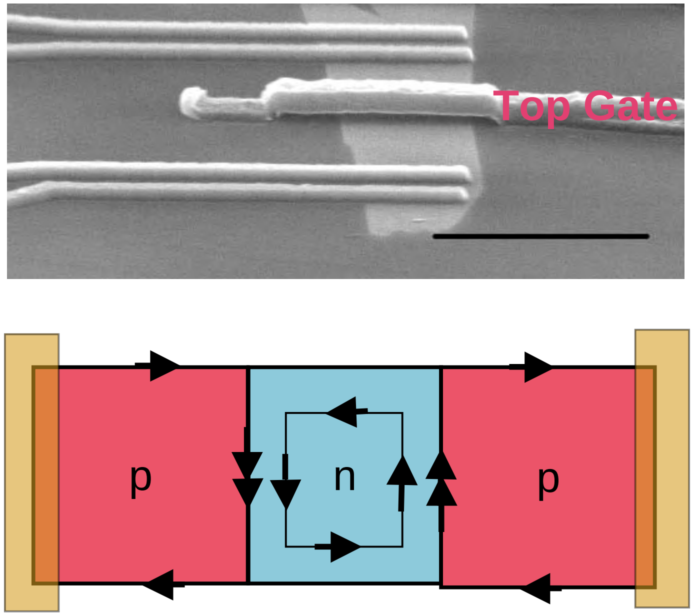
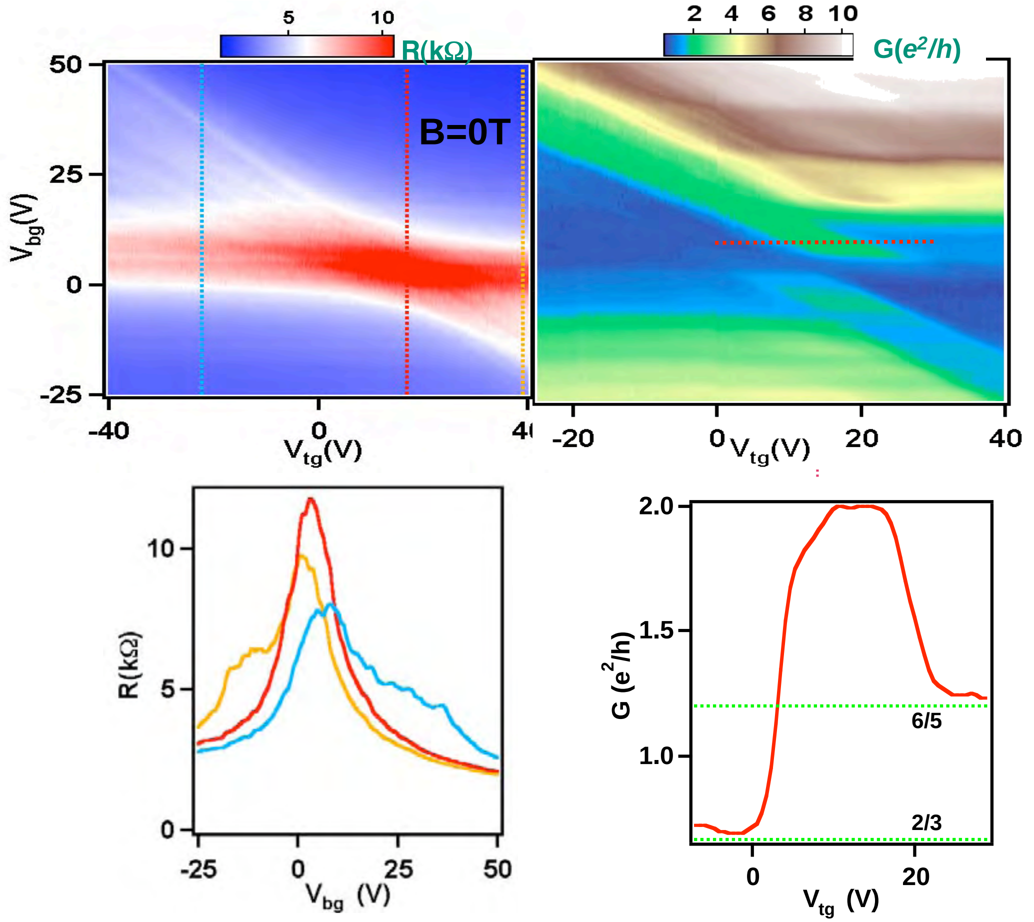


Ozyilmaz *et al* 2007



Liu, Velasco Jr. and Lau, submitted (2007)

On-going Collaborations

- Spin transport (with Kawakami at UCR)
- Thermopower (with Shi at UCR)
- Thermal conductivity (with Dames at UCR)
- STM (with Yeh at Caltech, LeRoy at U. Arizona)
- Photoconductivity (with Kalugin at New Mexico Tech)
- Raman spectroscopy (with Alex Balandin at EE, UCR)

Graphene as an electronic material (with Bockrath at Caltech)

Challenges and Promises

Graphene is a fascinating platform for investigating 2D, relativistic and/or many-body physics

- Many novel phenomena predicted
- More surprises ahead

→**Specular Andreev reflection**
→**Valley control**
→**Spin manipulation**
→**Fractional quantum Hall effect(?)**
→**Bilayer Dirac fermion quantum Hall systems**
→**Veselago lensing…**

- Material optimization to improve mobility

- Precision control of crystallographic edges

Challenges for Technological Applications

3. Band Gap engineering

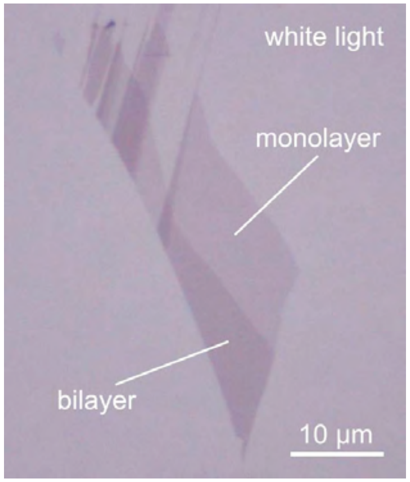
- nanoribbon
- chemical modification
- strain
- local gates

2. Precision crystallographic edge control

- Chemical modification

Graphene for Sale

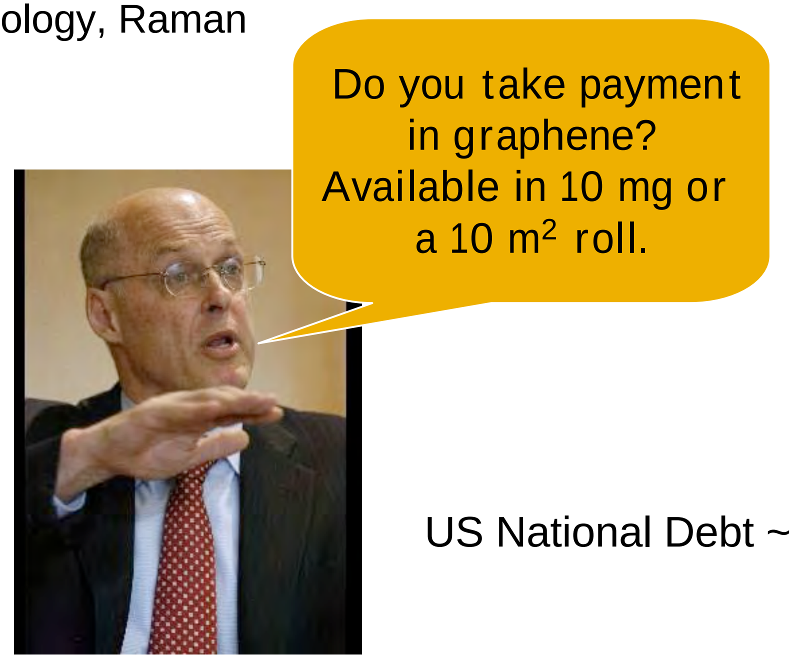
GRAPHENE INDUSTRIES



Flake sizes
Largest monolayer found to date: 7000 μm^2, but typically < 600 μm^2
Pricing guide
≈ £ 0.50 -- 2 per μm^2 area
Applications
transistors, spintronics, gas sensors, metrology, Raman spectroscopy, AFM, STM, etc.

1 μm^2 contains 3 x 10^7 atoms
1g contains 5 x 10 ^{22} atoms
1 £ ~ 2 US $

Cost per gram: ~ US $ 10^{15}



US National Debt ~ $ 9 x 10 ^{12}

Challenges for Technological Applications

1. Large Scale Synthesis & Production

- wafer-scale
- high mobility
- precision control of number of layers.

- CVD epitaxial growth:
  - Thermally remove Si from SiC substrate
  - Grow graphene on BN substrates

- Chemical method
  - Reduction of graphite oxide
  - Intercalation and exfoliation of bulk graphite

The bandwagon in 10 years

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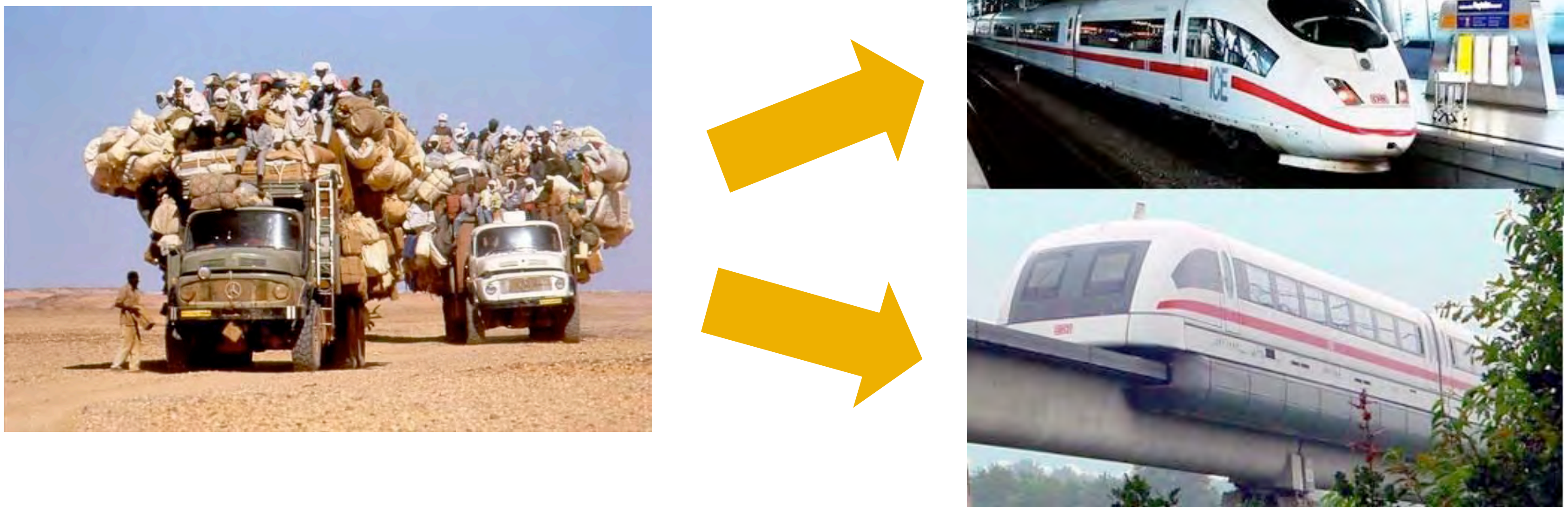
The bandwagon in 10 years



Science

Technology

Thank You!