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Graphene Quantum Electronics: p-n Junctions and Atomic Switches

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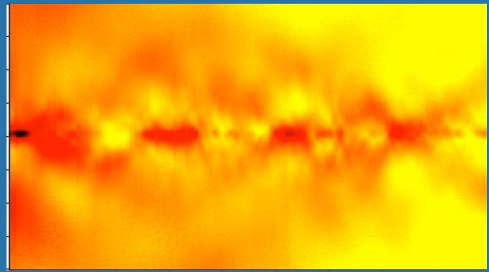
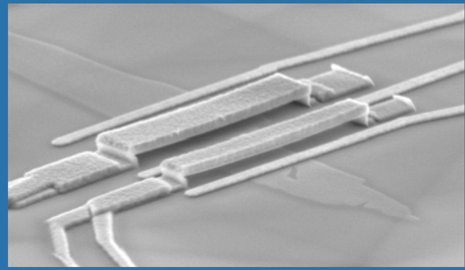
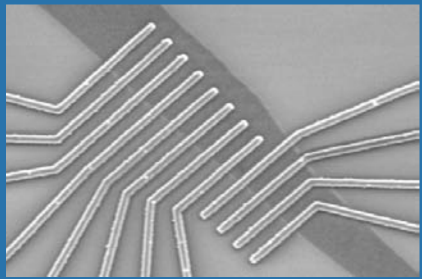
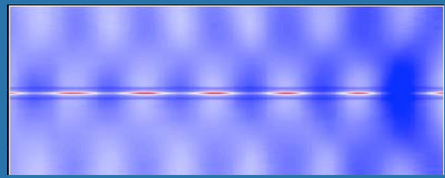




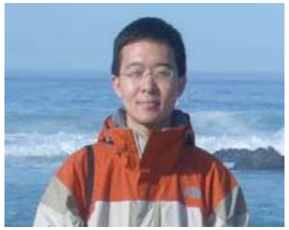
Graphene Quantum Electronics: *p-n* Junctions and Atomic Switches



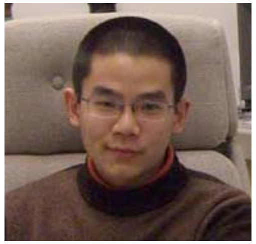


Acknowledgement

Graduate Students



Feng Miao



Wenzhong Bao

Gang Liu

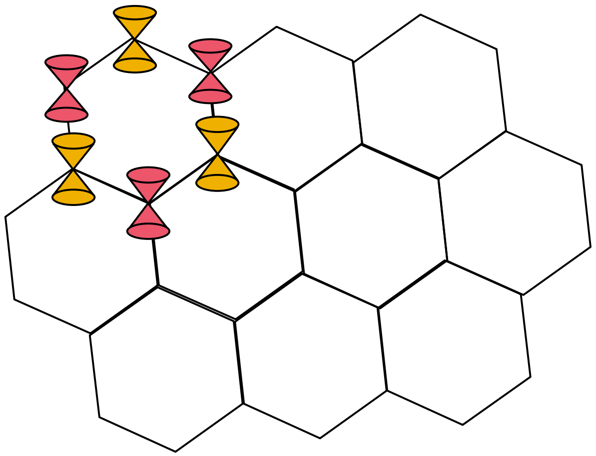
Jairo Velasco

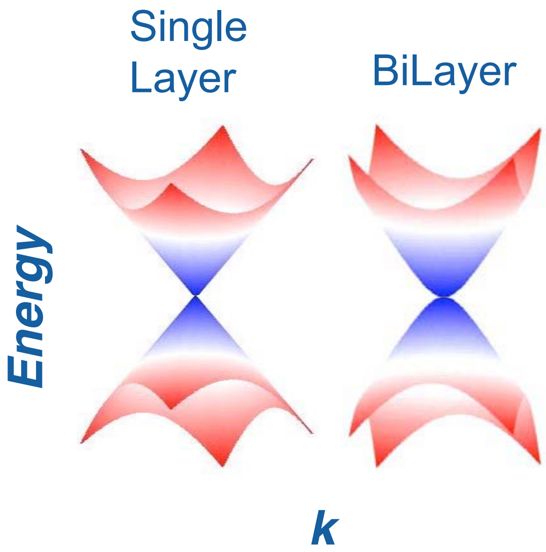
Hang Zhang

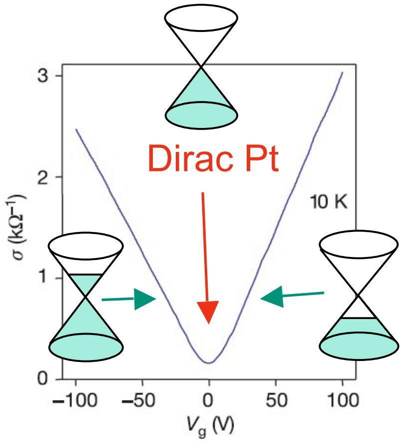
Discussion With

Shan-Wan Tsai, Antonio Castro-Neto, Michael Fogler, Gil Refael, Dmitri Abanin, Chandra Varma, Leonid Pryadko, Dmitri Novikov, Alex Bratkosvki

Two-Dimensional Crystal







Novoselov *et al*, *Science* (2004).

- Honeycomb lattice, two sub-lattices
- Unique Dispersion Relations: massless Dirac Fermions
- First experimental isolation by Geim's group in 2004

- New model system for condensed matter research

  Veselago lensing, Klein tunneling, Spin transport, Supercurrent transistor…

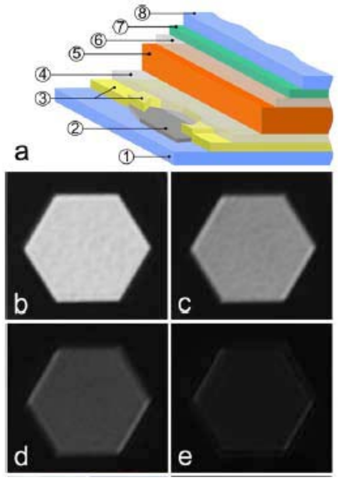
- Surface 2DEG with tunable charge density and type

  •Optical, STM and mechanical measurements

  •Easily coupled to special electrodes (superconductors, ferromagnets)

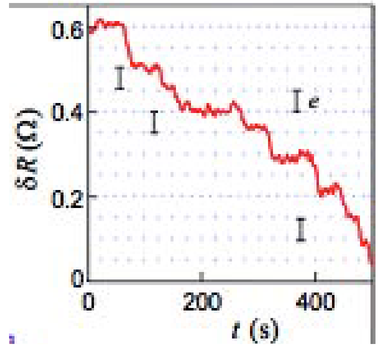
Applications

- <u>Post-silicon electronic material</u>
  - •With advantages of carbon nanotubes
    - ✓ high thermal conductivity (~5000 W/mK) Balandin *et al*, Nano Lett. (2008)
    - ✓ high current density (~ mA/μm width)
    - ✓ high mobility (~10,000 cm^2/Vs in as-prepared samples)
  - •2D → compatible with lithographic techniques, e.g. nanoribbon FET
    Han *et al*, PRL (2007); Chen *et al*, Physica E (2007); Li *et al*, Science (2008)
  - •Potential for large scale synthesis



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

- Transparent electrodes for solar cells, LCD, etc
- Robust, non-volatile, atomic switches
  (Bockrath+Lau+Bruck group, see also Echtermeyer *et al*, cond/mat 2008)
- Chemical and biological sensors
- Electronics, Spintronics, and Valley-tronics
  Experiments: van Wees group, Kawakami group, Fuhrer group
  Theories: Beenakker and co.

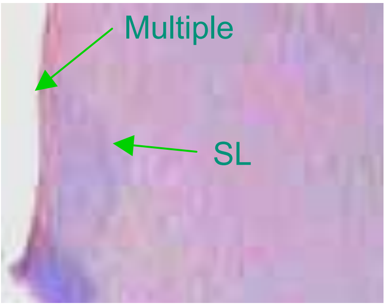


Ultra-sensitive gas sensors
Schedin *et al*, Nature Materials (2006).

Extraction of Single- and Bi-Layer Graphene

Optical Microscope

Single-layer graphene

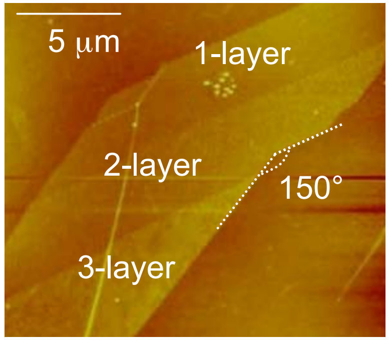


2μm

Bi-layer graphene

2μm

AFM

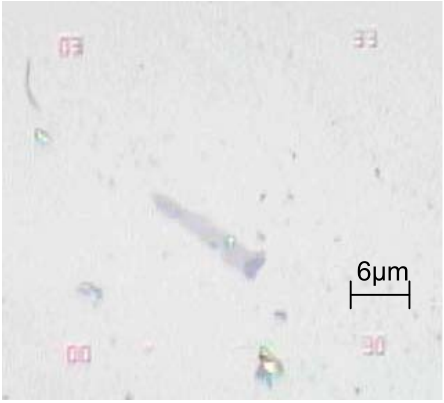


- Mechanical exfoliation -- rub natural graphite flakes onto SiO_2 substrate

- Identify the number of layers by
  - Raman spectroscopy
  - Transport measurement
  - Color contrast in optical microscope

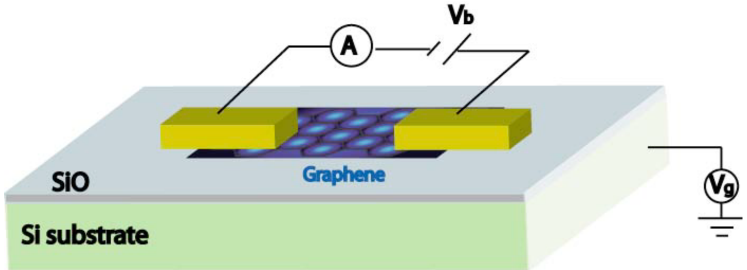
- AFM images reveal mesoscopic features

Device Fabrication

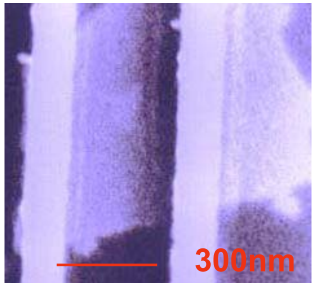


Two steps of E-beam lithography

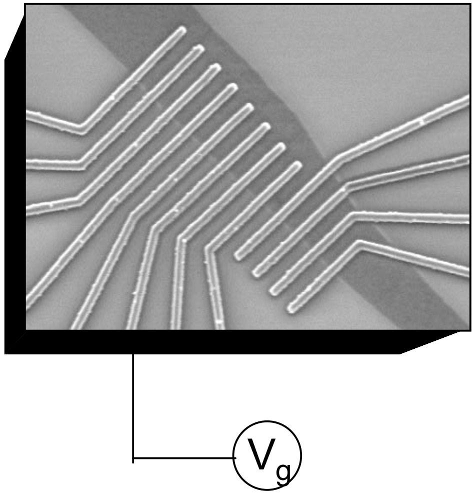
- Alignment Marks
- Electrodes (3-10 nm Ti or Pd + 70 nm Al or Au)



Bi-layer graphene device



Single-layer graphene device

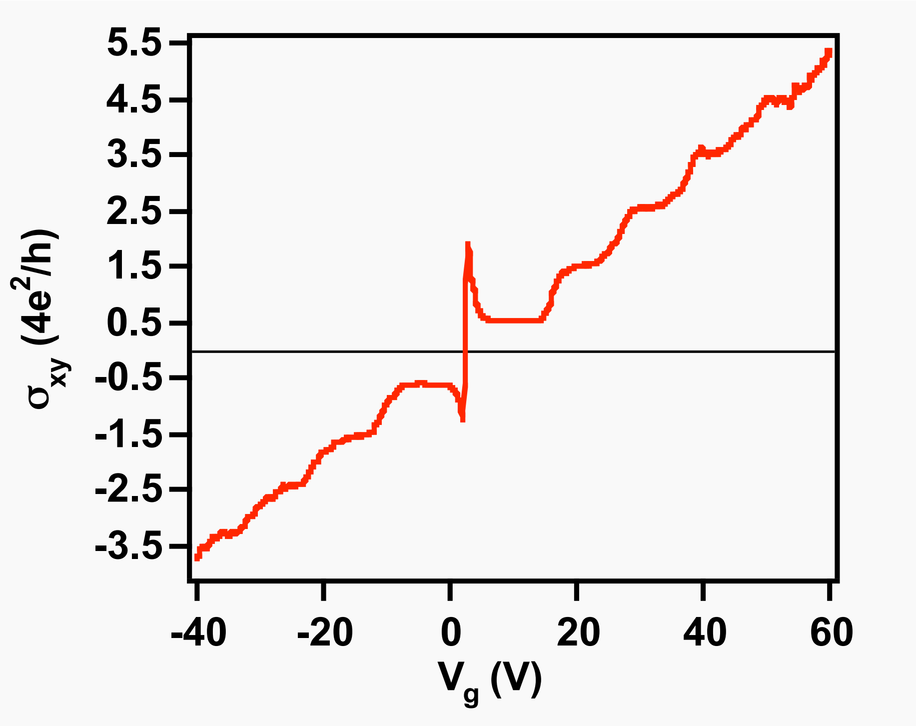


Back gate controls charge density and type.

Half Integer Quantum Hall Effect

Hall conductivity of single layer graphene quantized at half-integral values of $4e^2/h$ at high field.

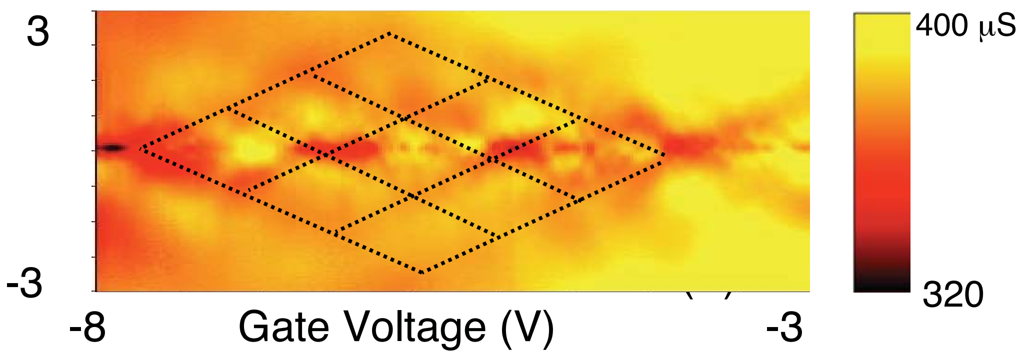
–> confirmed selection of single layer graphene

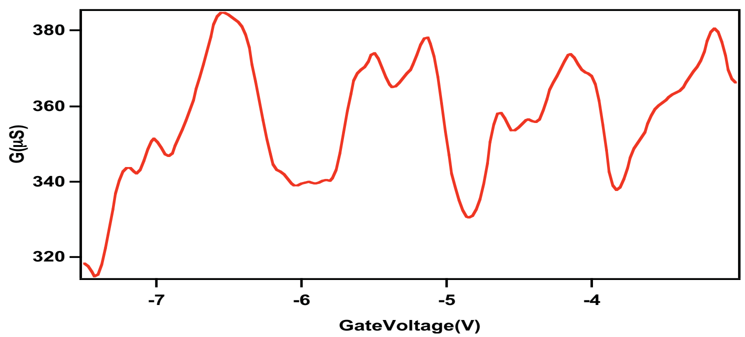


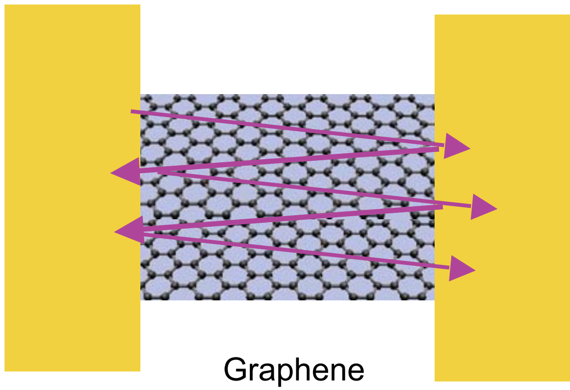
Measurement performed at B=8T and T=260mK

Coherent Charge Transport in Graphene

Graphene Coupled to Normal Electrodes at 260mK.







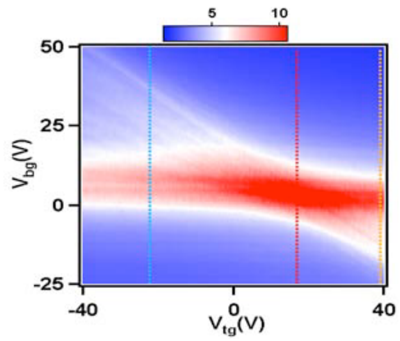
F. Miao, S. Wijeratne, Y. Zhang, U. C. Coskun, W. Bao, C. N. Lau, Science, 2007.

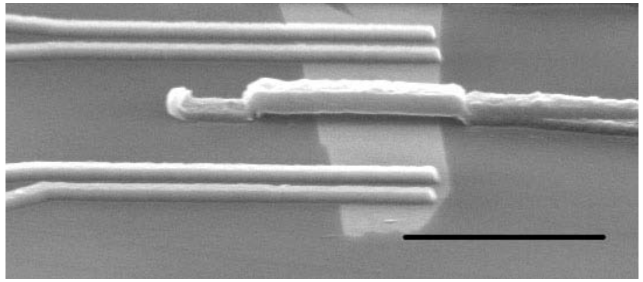
•Periodic conductance oscillation in both gate voltage and bias.

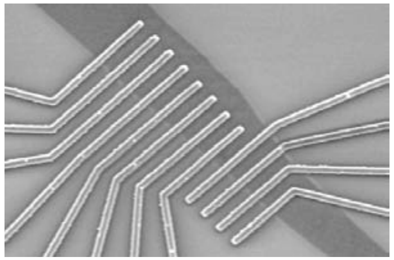
•Graphene electron resonator -- interference of multiply-reflected electron and hole waves between partially transmitting electrodes.

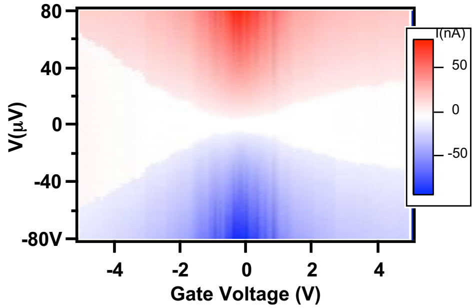
Outline

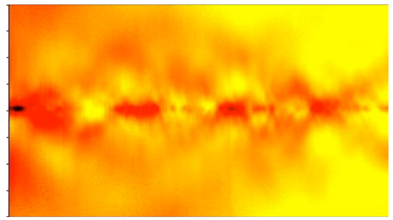
- Introduction
- Graphene *p-n* junctions
- Graphene Atomic Switches









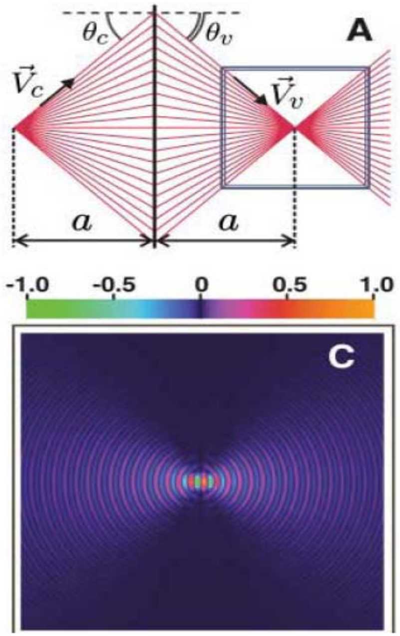


Graphene *p-n* Junctions

- 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

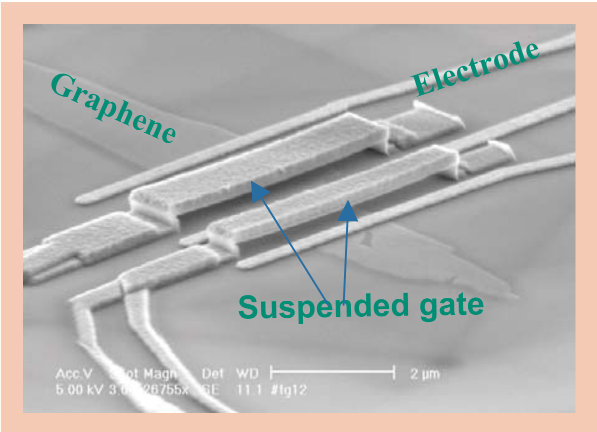
- Novel Phenomena and Applications
  - Veselago lensing (optics-like focusing of electron rays)
  - Klein tunneling
    (perfect transmission of relativistic particles across high barrier)
    recently observed by Kim's group, Goldhaber-Gordon's group, & Savchenko's group.
  - Band gap engineering of bi-layer graphene
  - Particle collimation
  - Valley polarization

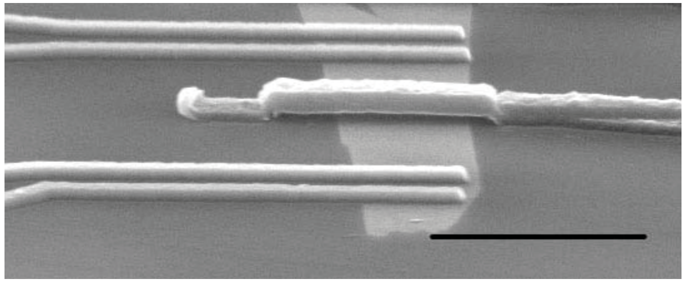


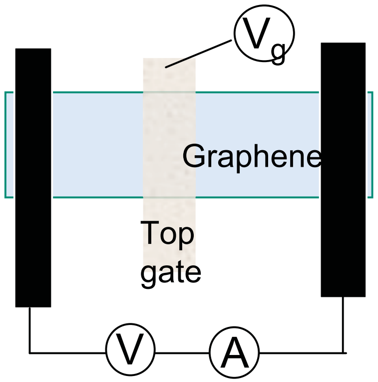
Theories: Abanin *et al* 2006, 2007; Fogler *et al* 2007; Shytov *et al* 2007; Katsnelson *et al* 2006; Beenakker group, Cheianov *et al* 2006, 2007
Experimental demonstration: Huard *et al* 2007; Williams *et al* 2007, Ozyilmaz *et al* 2007, Oostinga *et al* 2007

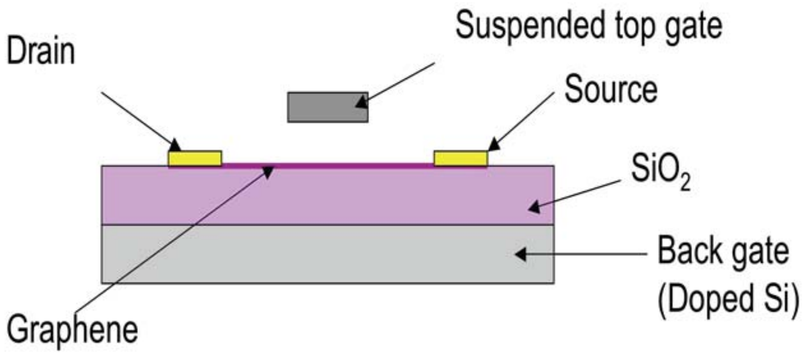
Graphene *p-n* Junctions

- Challenge deposition of top gate tends to dope or damage the atomic layer
- Innovation: Suspended, contactless top gate
  - Gentle process
  - Graphene can be annealed to improve mobility and contact

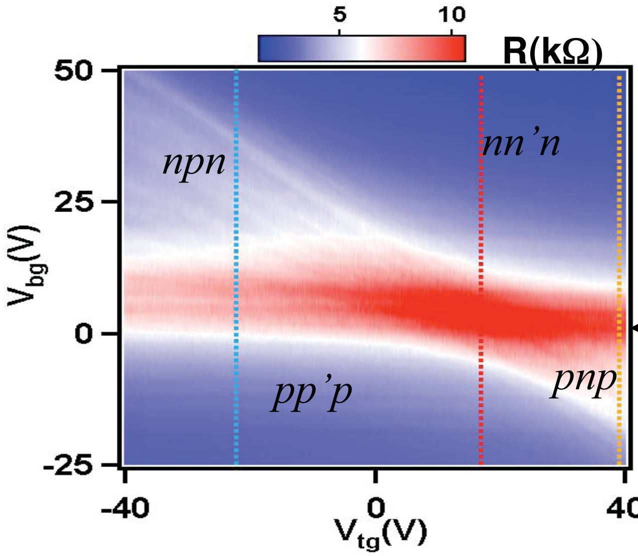






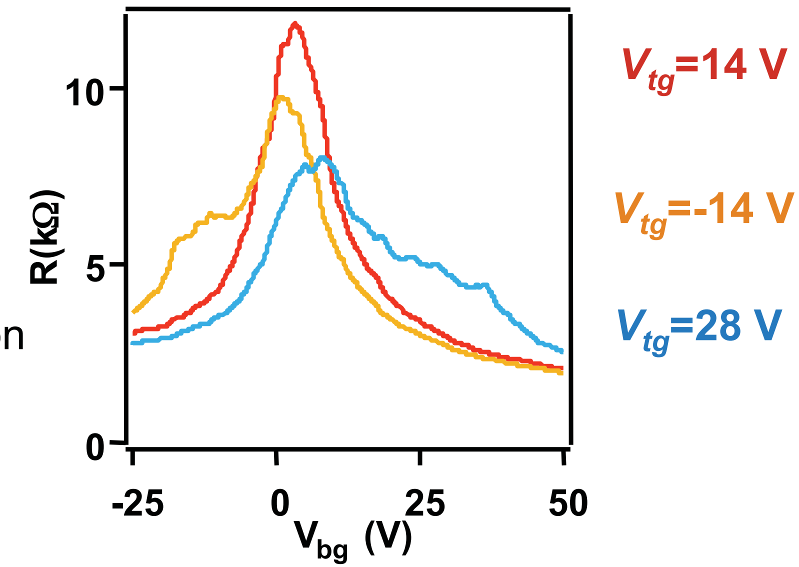


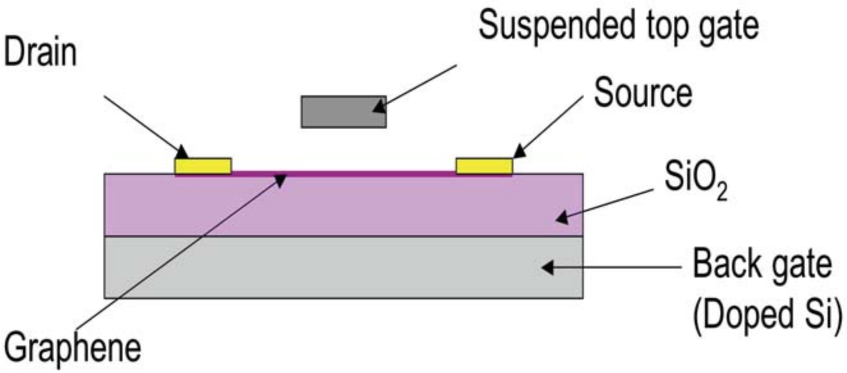
Conductance of *p-n-p* Junctions



Dirac point of the "bare" region

Dirac point of the top gated region



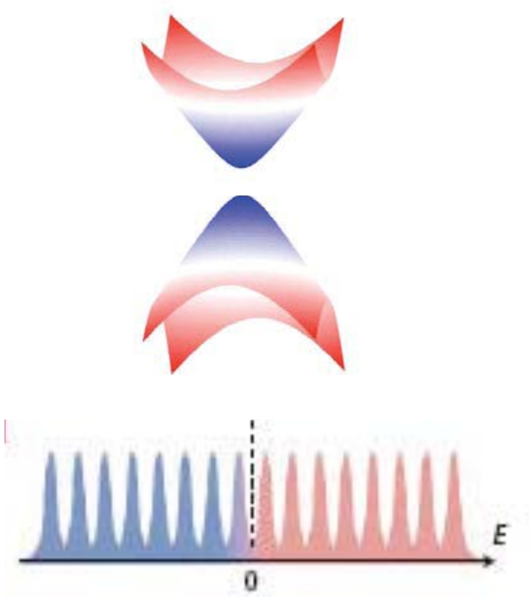


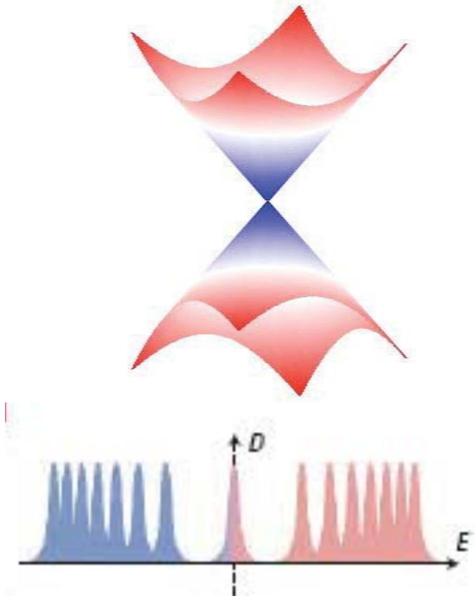
•Individual control of charge density and type of different regions

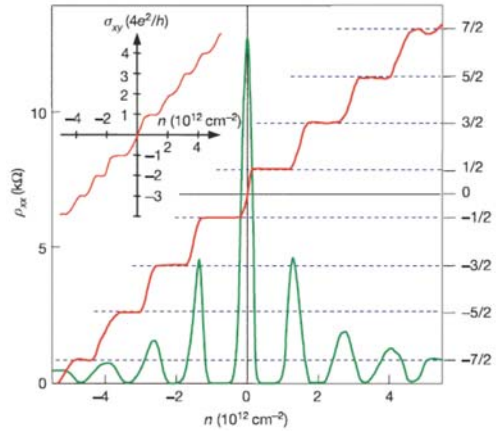
Liu, Velasco Jr. and Lau, APL (2008);
see also Gorbachev et al, Nano Letter (2008).

Half-integer Quantum Hall Effect

Semiconductors **Graphene**







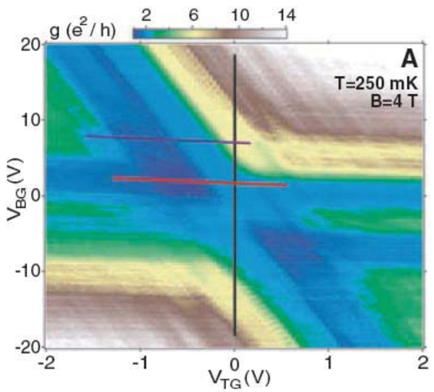
Novoselov *et al Nature* 2005;
Zhang *et al*, Nature 2005.

Landau Levels $E_N = \pm \frac{\hbar e B}{m}\left(N + \tfrac{1}{2}\right)$ $E_N = \pm v_F \sqrt{2e\hbar B N}$

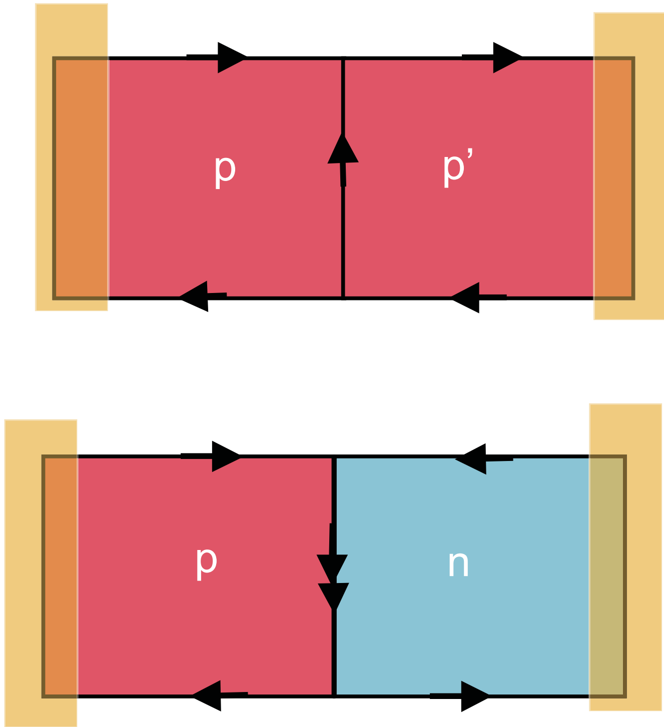
$$\sigma_{xy} = \pm \frac{4e^2}{h}\left(N + \tfrac{1}{2}\right) = \pm 2, \pm 6, \pm 10 \ldots \frac{e^2}{h}$$

Quantum Hall States in graphene *p-n* Junctions

- At high magnetic fields, quantum Hall plateau at fractional values of e^2/h observed
- Edge state equilibration, full mixing of propagation modes at interface



Marcus group, *Science*, August 2007.



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

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

2 resistors in series

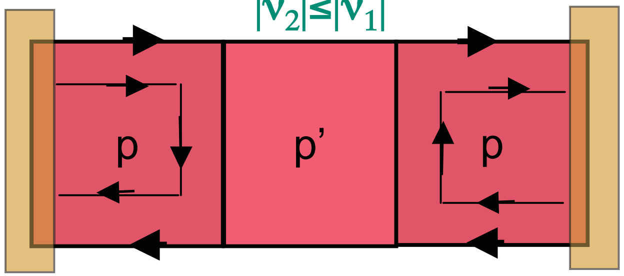
Abanin & Levitov, *Science*, 2007

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

Ozyilmaz *et al* 2007

- 2 interfaces in p-n-p junctions
- Full and partial edge state equilibration

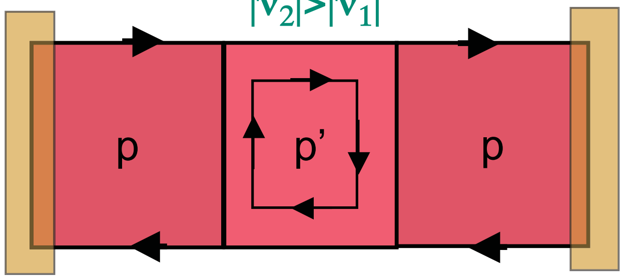
$|\nu_2| \leq |\nu_1|$



Edge State transmission

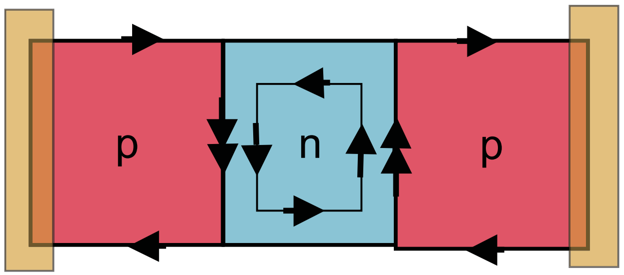
$$G = \frac{e^2}{h}\min\left(|\nu_1|,|\nu_2|\right)$$

$|\nu_2| > |\nu_1|$



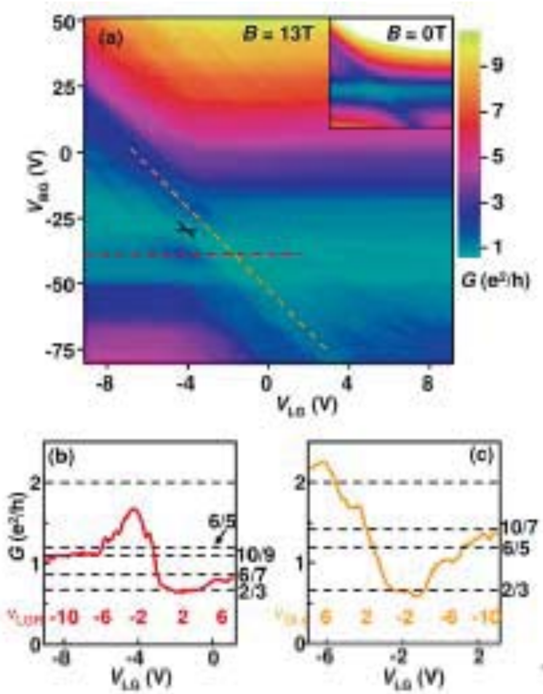
Partial Equilibration

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



Full Equilibration

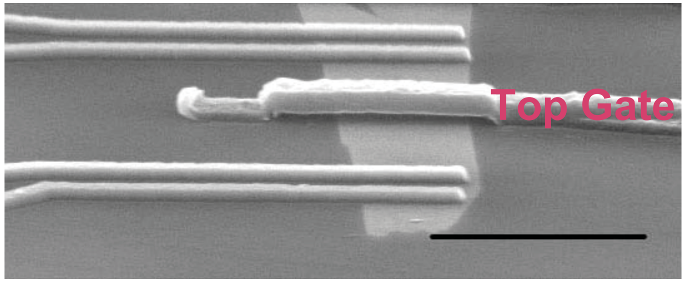
$$G = \frac{e^2}{h}\frac{|\nu_1||\nu_2|}{2|\nu_1| + |\nu_2|}$$



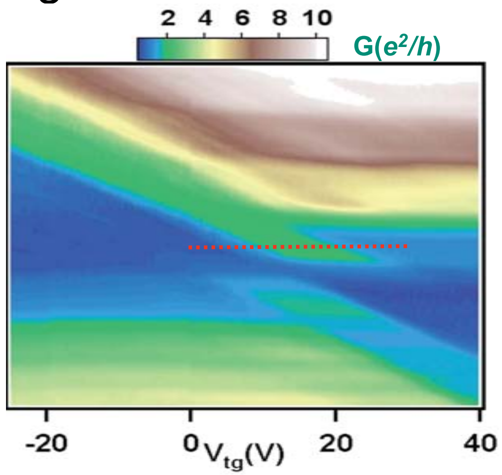
$2e^2/h$ plateau sensitive to disorder, not observed

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

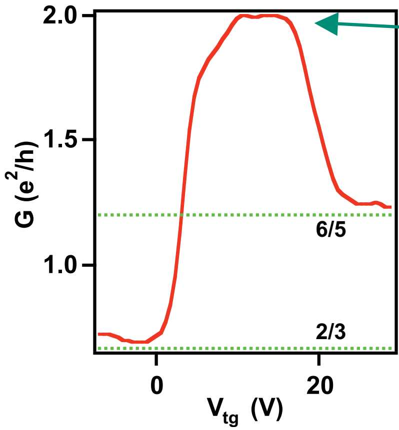
- Quantum Hall plateaus at fractional values observed
- Edge state equilibration, full mixing of propagation modes at interface



B=8T



Observation of $2e^2/h$ plateau
→ very clean junctions



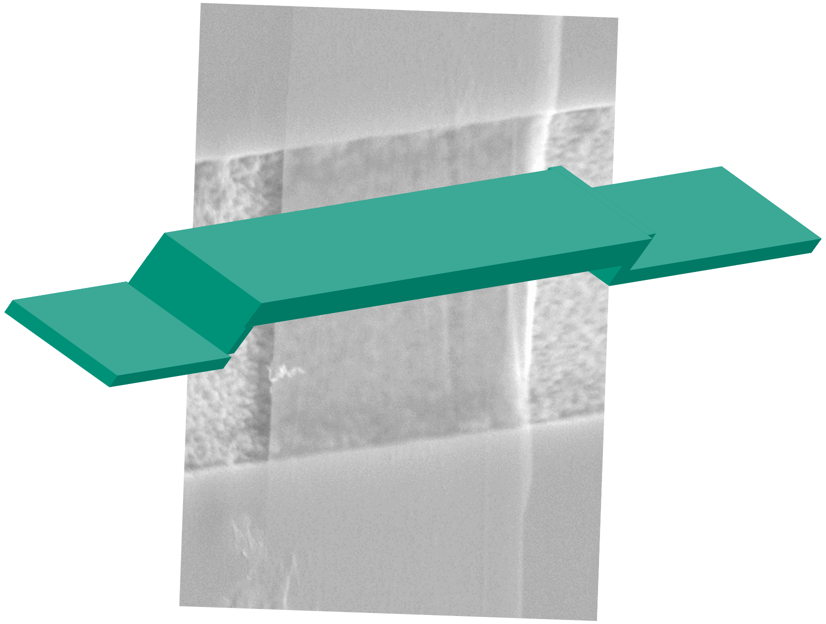
Plateau sensitive to disorder

Ongoing Work

- Effect of disorder, junction shape

Abanine & Levitov, PRB, 2008; Cheianov *et al* 2006, 2007, Fogler et al, 2008; Zhang & Fogler, 2008.

- Veselago Lensing?

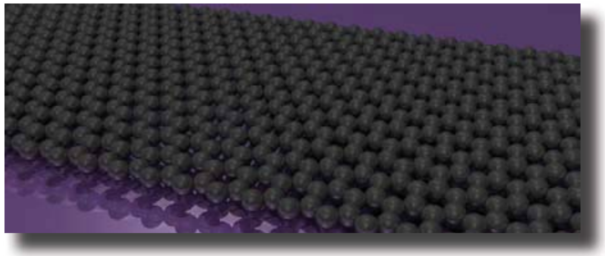


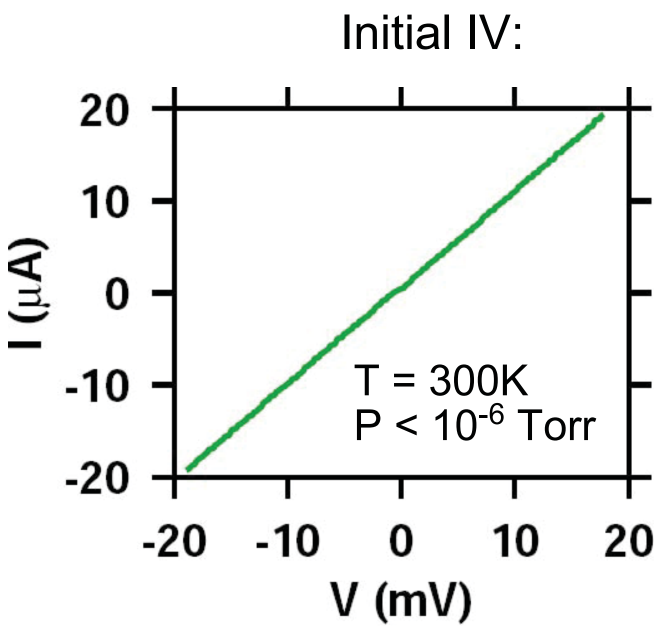
Outline

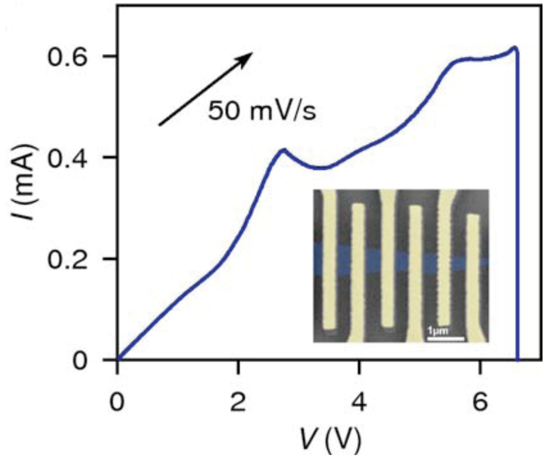
- Introduction
- Graphene *p-n* junctions
- **Graphene Atomic Switches**

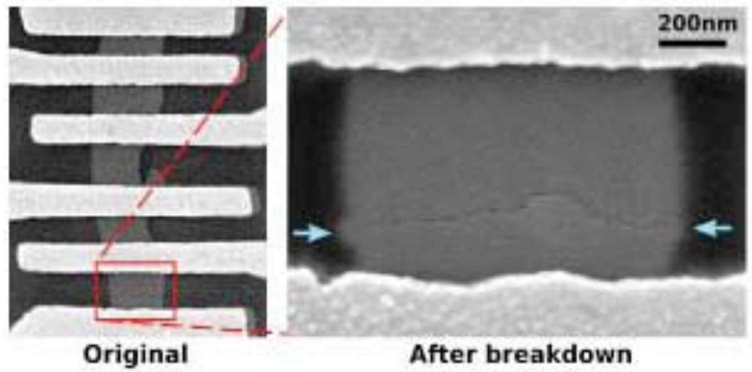
•Brian Standley, Marc Bockrath
(Applied Physics, Caltech)
•Wenzhong Bao, Hang Zhang, Chun Ning Lau
(Physics, UCR)
•Jehoshua Bruck
(Electrical Engineering, Caltech)

Device Fabrication





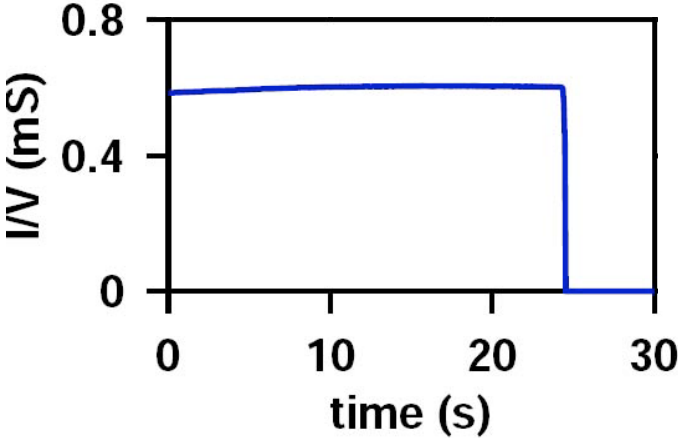




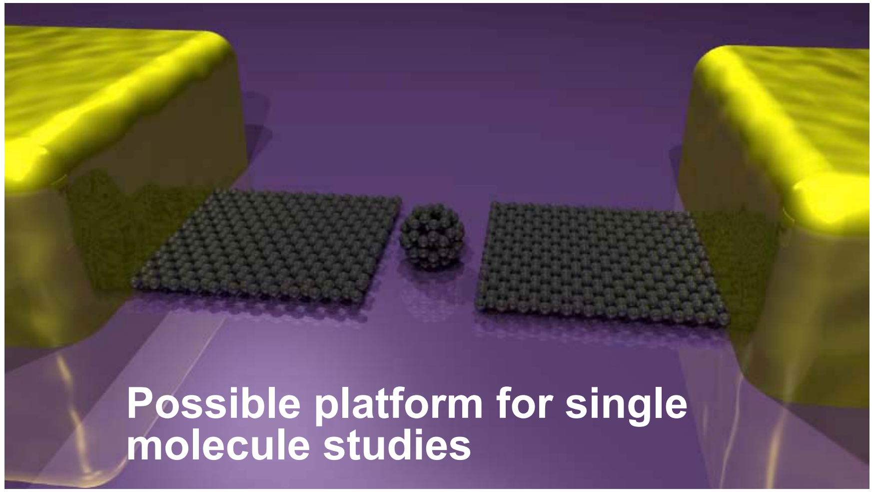
- Electrical breakdown to create nanoscale gaps
- Typical breakdown current density ~ 1.6 mA/μm ~ 1 μA/atom

Two Types of Nanogaps

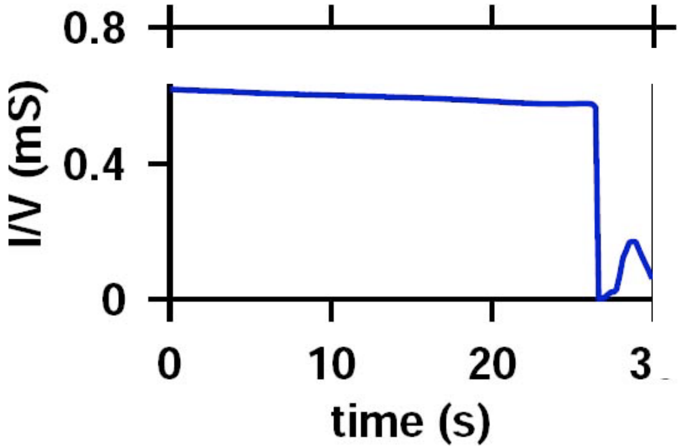
R_{gap} = 1MΩ - 10GΩ



Tunnel gap



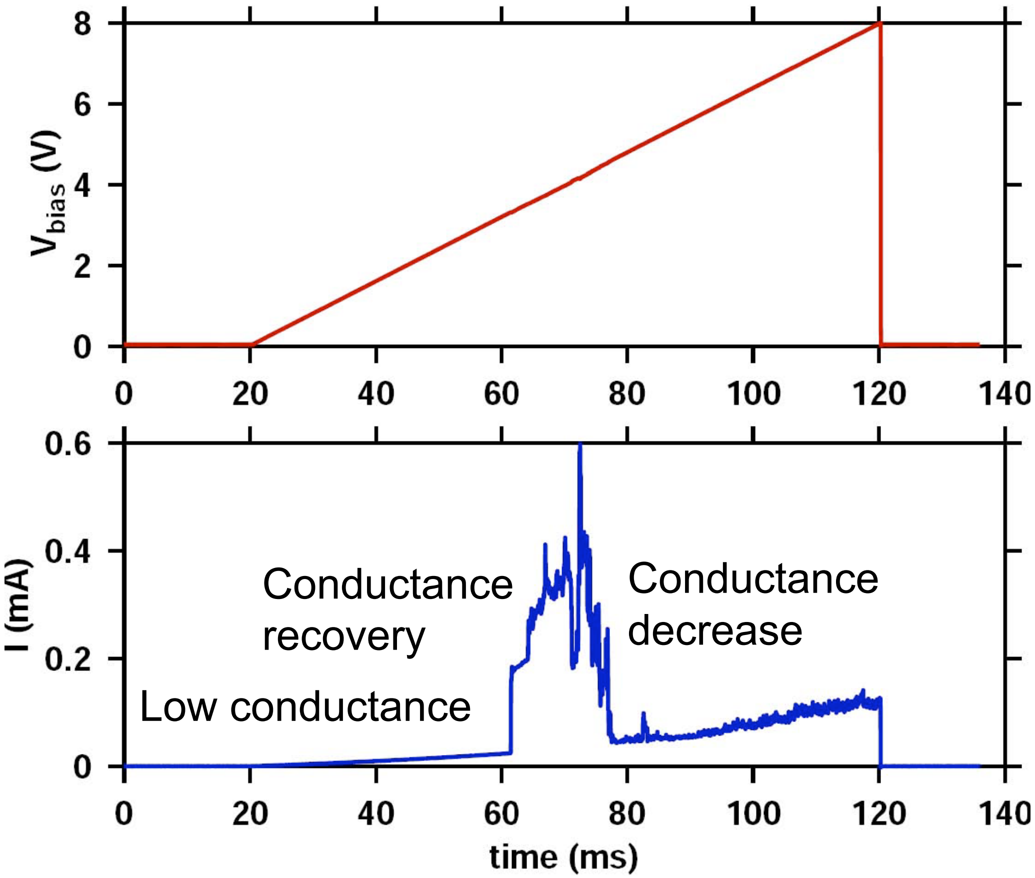
R_{gap} = 10kΩ - 500kΩ



?

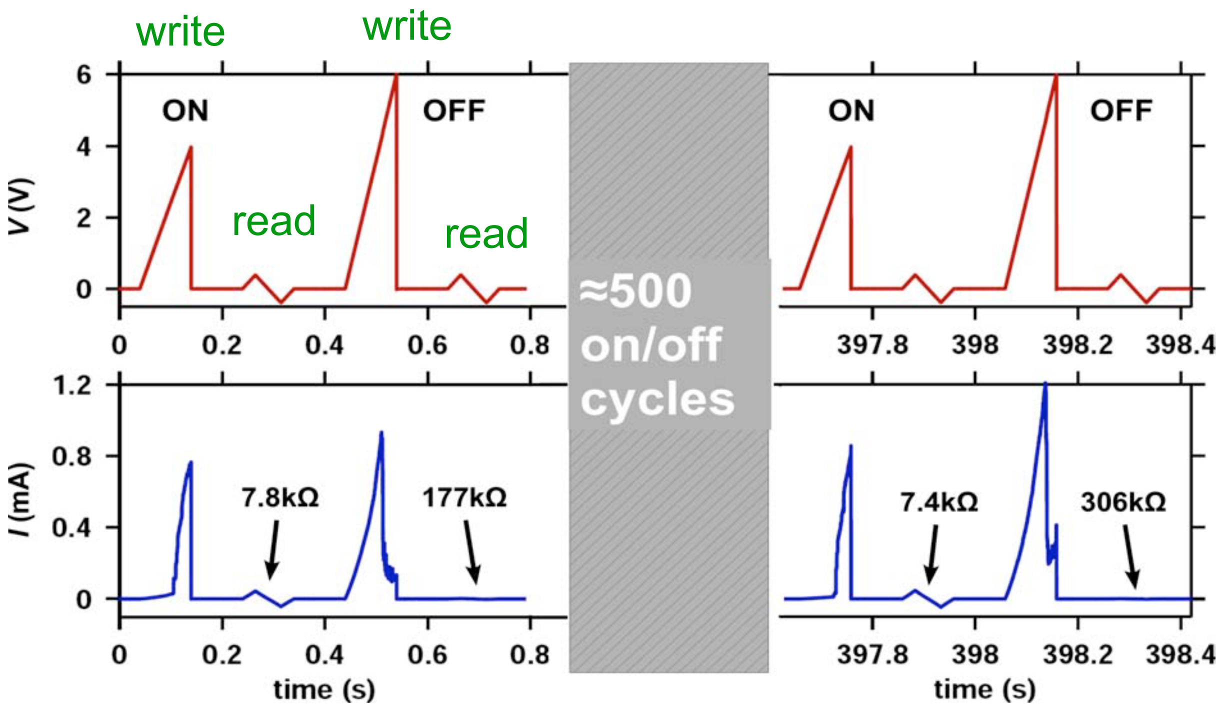
Need to time-resolve resistance fluctuations

Bias Dependent Conductance Switching



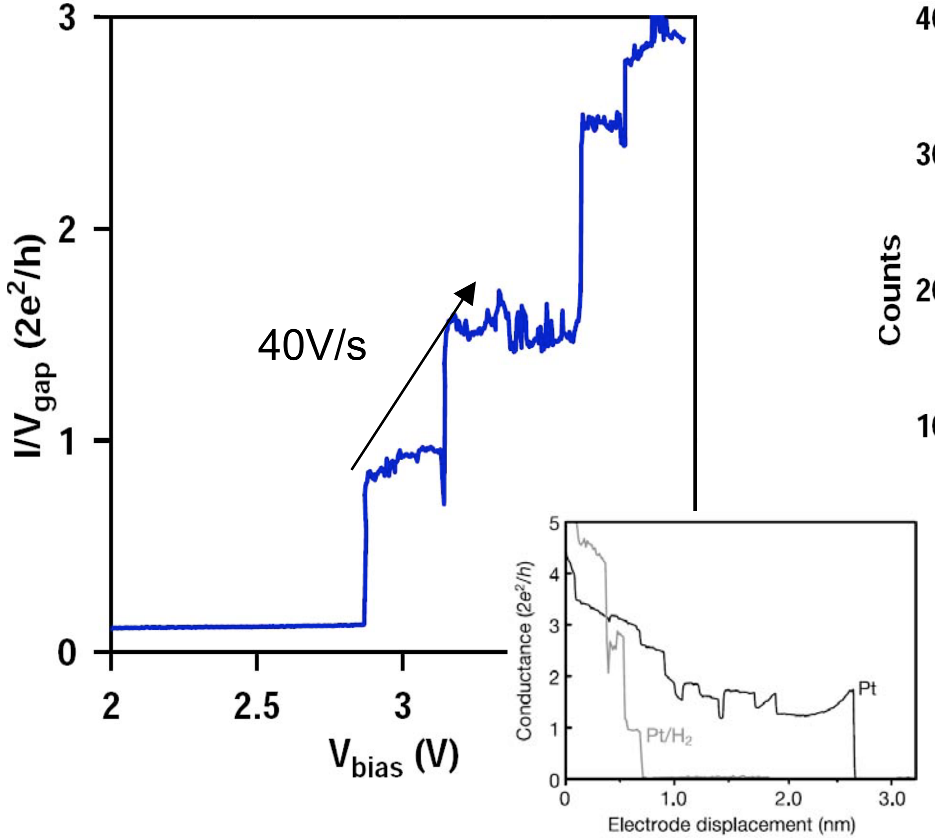
- 6V pulse → "OFF", 4V pulse → "ON"
- Reversible conductance switching by bias voltage

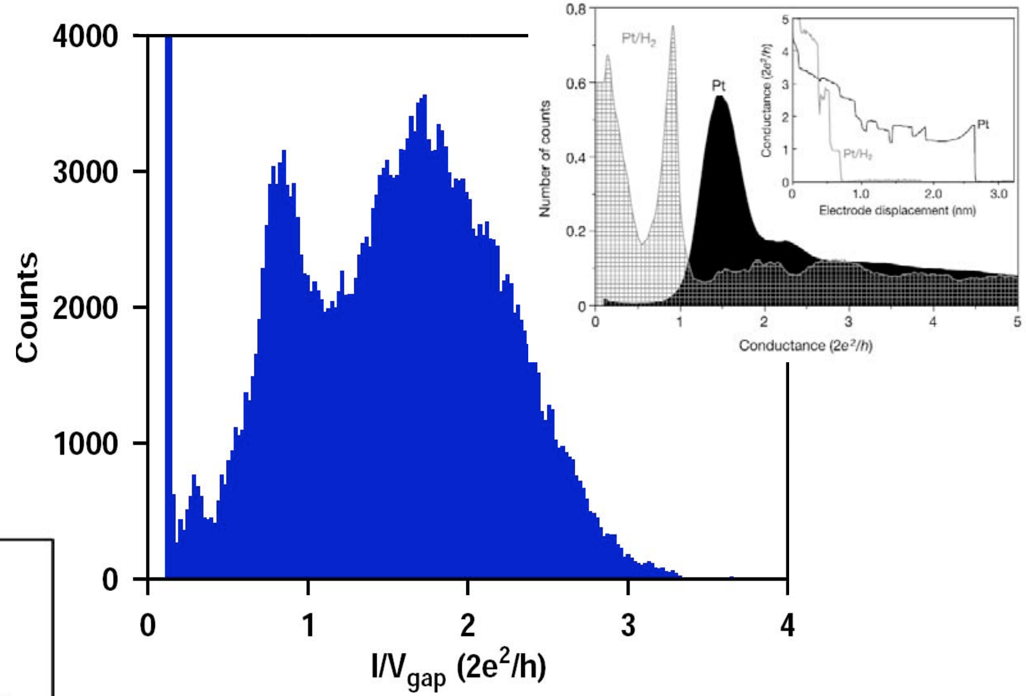
Device Operation



- **Robust**: Operates for thousands of cycles without degradation
- **Non-volatile**: maintains last written state without external voltage for >24 hours, possibly indefinitely

Recovery Steps

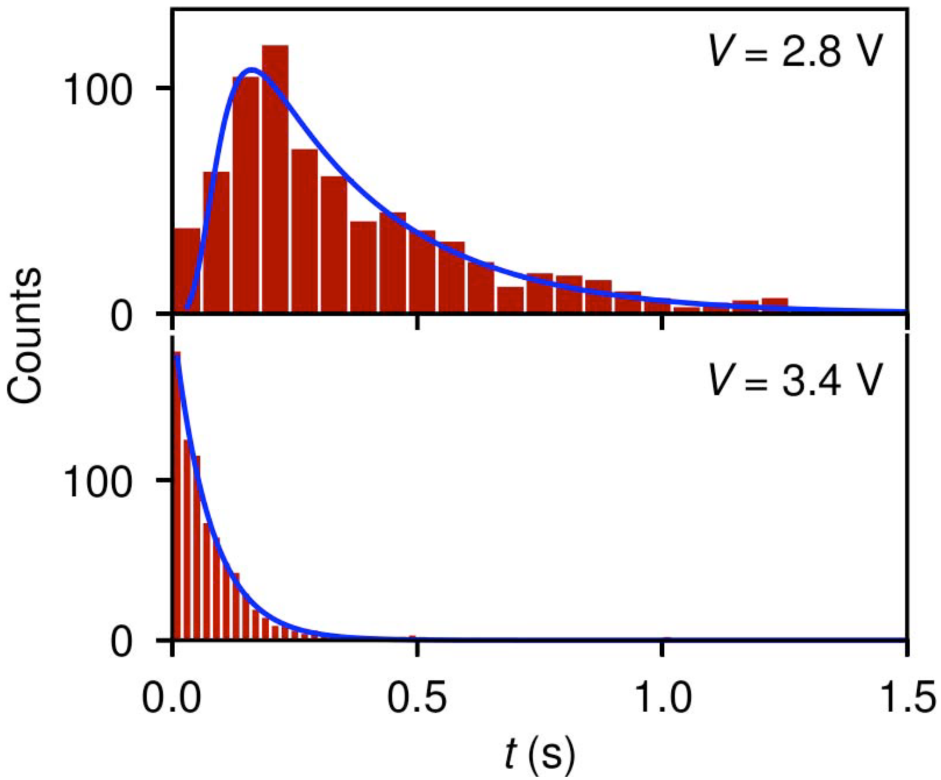




Smit, *et al.*, *PRL* (2002)

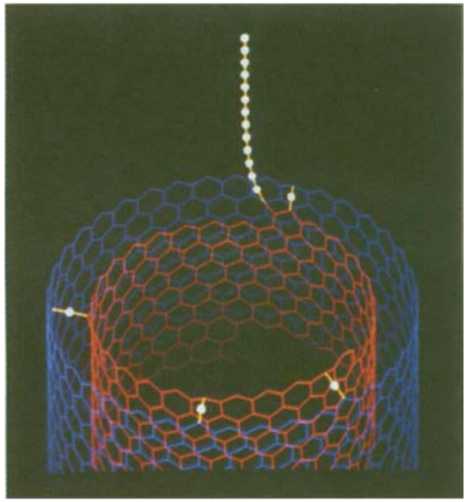
- Device conductance recovers in steps
- Conductance histogram shows peaks at ~2*e*²/*h*
- No gate dependence
- Reminiscent of mechanically controlled break junctions

Distribution of waiting times to switch



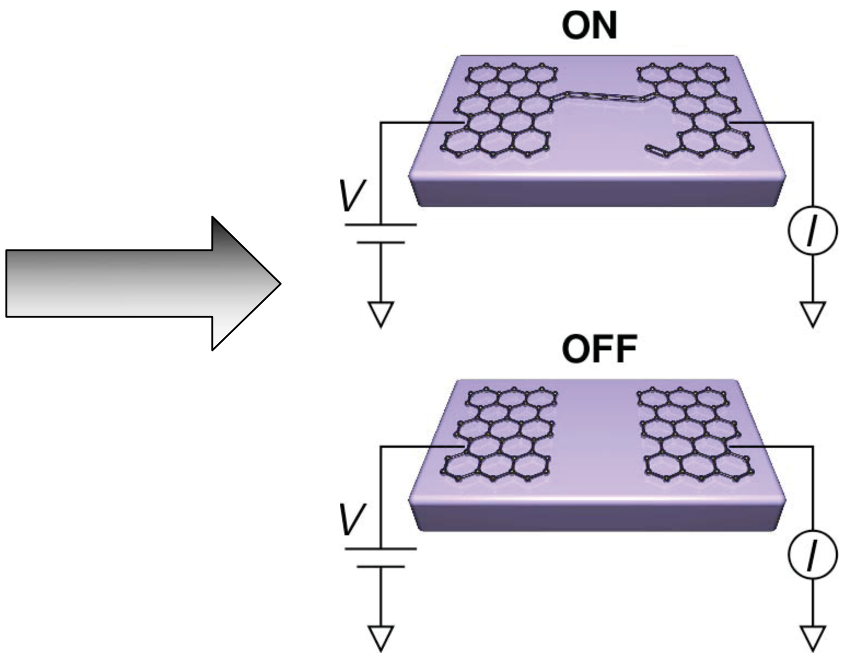
- Wait times follow a non-Poissonian distribution at lower voltages.
- Wait times are strongly temperature dependent.

Switching Mechanism



Rinzler *et al.* Science (1995)

theory: Lee, Kim and Tomanek
Chem. Phys. Lett. (1997)

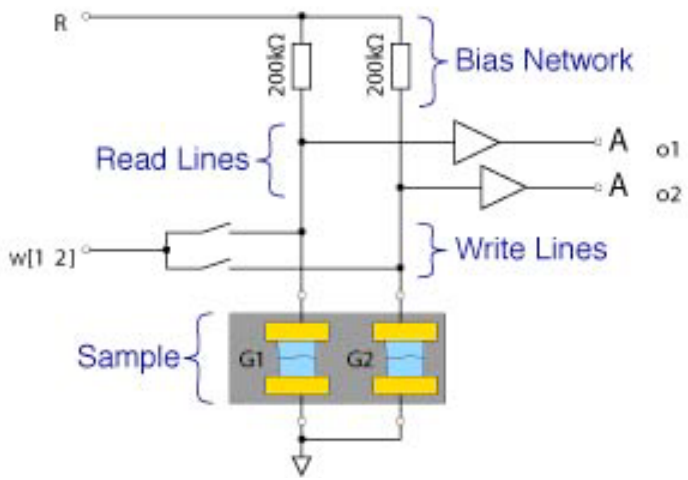


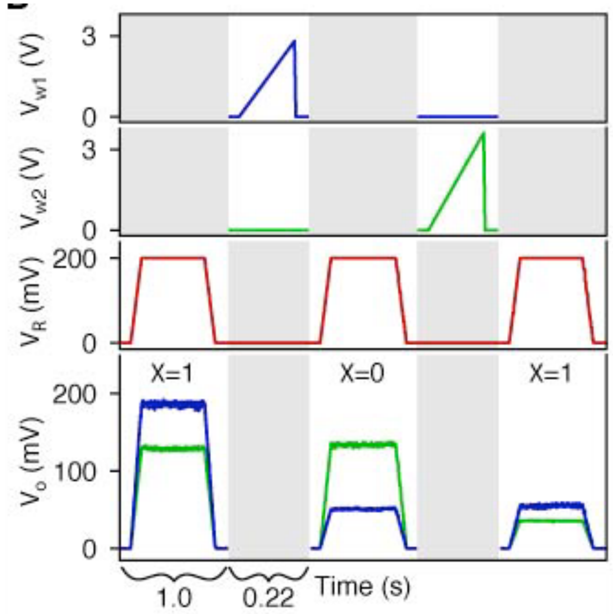
•Formation and breaking of atomic chains of carbon atoms that bridge across the nano-size gap

Lang & Avouris PRL (1998).

Information Storage

B. Standley, W. Bao, H. Zhang, J. Bruck, C.N. Lau and M. Bockrath, *Nano Lett.*, to appear (2008).





- Rank coding: store information by the relative magnitudes of the memory elements
- Information capacity for an N-element cell is $log_2 N!$
- **Demonstrated storage of 1-bit based on rank coding using 2 graphene atomic switches**

Graphene Atomic Switches

Ultimate miniaturization: atomic scale

Novel Materials

Graphene

•Extremely high mobility
•Superior thermal conductivity
•High current carrying capacity
•Planar, CMOS compatible

Novel Operating Principles

Atomic scale switches

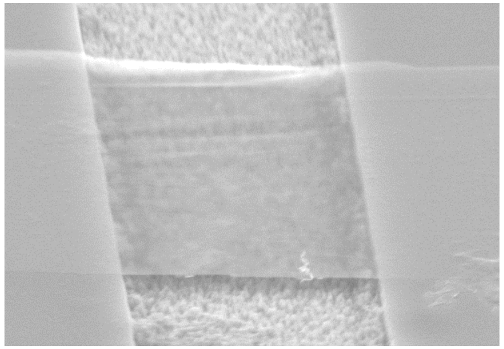
•Non-Volatile
•Based on movement of atoms, not charges

Novel Architecture

Rank coding

On-going: device optimization, ultra-high density integration

Other On-going Work and 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)

Thank You!