Graphene Quantum Electronics: 
$p-n$ Junctions and Atomic Switches
Acknowledgement

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

From Novoselov’s presentation at IWCNM, Kirchberg, 2007

Images taken from scifun.ac.uk
Two-Dimensional Crystal

- 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

- **Post-silicon electronic material**
  - With advantages of carbon nanotubes
    - high current density (~ mA/µm width)
    - high mobility (~10,000 cm²/Vs in as-prepared samples)

- **2D →** compatible with lithographic techniques, e.g. nanoribbon FET

- Potential for large scale synthesis

- 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
Extraction of Single- and Bi-Layer Graphene

- 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.
Coherent Charge Transport in Graphene

Graphene Coupled to Normal Electrodes at 260mK.

• 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 \textit{p-n} Junctions

- Unique advantage: local control of charge density and \textit{type}

- Graphene \textit{p-n} junctions with top gate(s):
  - allow \textit{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)
    - recent evidence by Kim’s group, Goldhaber-Gordon’s group, & Savchenko’s group.
  - Band gap engineering of bi-layer graphene
  - Particle collimation
  - Valley polarization


Klein Tunneling

Relativistic charged particles at normal incidence has perfect transmission across a high barrier ($V_0 \sim 2 mc^2$).

- Thought to be realizable at the edge of blackholes
- Graphene: electrons in conduction band $\rightarrow$ holes in valence band
- Transmission probability depends on incidence angle

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 \textit{p-n-p} Junctions

- Dirac point of the “bare” region
- Dirac point of the top gated region

\begin{itemize}
\item Individual control of charge density and type of different regions
\end{itemize}

Liu, Velasco Jr. and Lau, APL (2008);
see also Gorbachev et al, Nano Letter (2008).
Evidence for Klein Tunneling?

- Conductance oscillation with top gate voltages in \textit{pnp} regions

- Fabry-Perot interference of charges reflecting between 2 \textit{p-n} interfaces.

- $R_{\text{pnp}} > R_{\text{pp}'}$
- $R_{\text{pnp}}$ increases with B
- Evidence for particle collimation effect due to \textit{pnp} junctions

Young and Kim, arXiv (2008; Shytov, Levitov et al, arxiv (2008)).
Half-integer Quantum Hall Effect

**Semiconductors**

Landau Levels

\[ E_N = \pm \frac{eB}{m} \left( N + \frac{1}{2} \right) \]

**Graphene**

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

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

Half Integer Quantum Hall Effect

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

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

$$G = \frac{e^2}{h} \min(|v_1|,|v_2|)$$

$$G = \frac{e^2}{h} \frac{|v_1||v_2|}{|v_1| + |v_2|}$$

2 resistors in series


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

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

$$G = \frac{e^2}{h} \min(|v_1|, |v_2|)$$

$|v_2| \leq |v_1|$

$|v_2| > |v_1|$

Full Equilibration
$$G = \frac{e^2}{h} \frac{|v_1||v_2|}{2|v_1| - |v_2|}$$

Partial Equilibration
$$G = \frac{e^2}{h} \frac{|v_1||v_2|}{2|v_1| + |v_2|}$$

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

Ozyilmaz et al 2007
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

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

Plateau sensitive to disorder
Ongoing Work

- Effect of ballistic/diffusive transport
- Klein Tunneling
- Junction shape
- Veselago Lensing
  (requires extremely clean devices → suspended graphene + suspended gate?)
- Supercurrent in p-n junctions
- Spin transport in p-n junctions

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- 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 $\sim 1.6 \text{ mA/µm} \sim 1 \text{ µA/atom}$

Initial IV:

$T = 300K$
$P < 10^{-6} \text{ Torr}$
Two Types of Nanogaps

- **Tunnel gap**
  - $R_{\text{gap}} = 1 \text{M} \Omega - 10 \text{G} \Omega$
  - Possible platform for single molecule studies
  - Need to time-resolve resistance fluctuations

- **Contact gap**
  - $R_{\text{gap}} = 10 \text{k} \Omega - 500 \text{k} \Omega$
Bias Dependent Conductance Switching

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

![Graph showing conductance switching](image)

- Conductance recovery
- Conductance decrease
- Low conductance
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

- Device conductance recovers in steps
- Conductance histogram shows peaks at \( \sim 2e^2/h \)
- No gate dependence
- Reminiscent of mechanically controlled break junctions

Wait times follow a non-Poissonian distribution at lower voltages.

Wait times are strongly temperature dependent.
Switching Mechanism

“atomic drawbridges”

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


  Lang & Avouris PRL (1998)
Information Storage


- 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

November 2008
California Condensed Matter Theory Meeting
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)