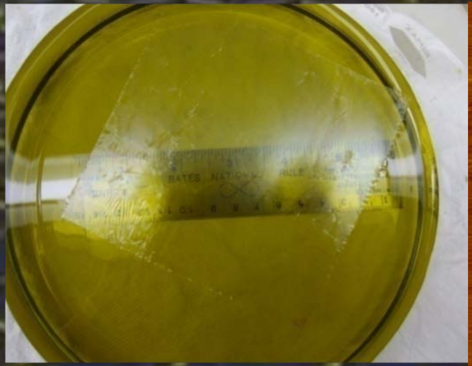
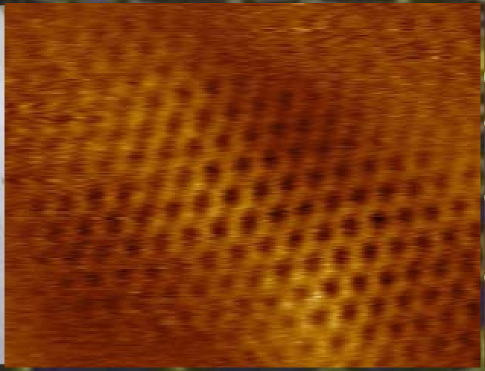
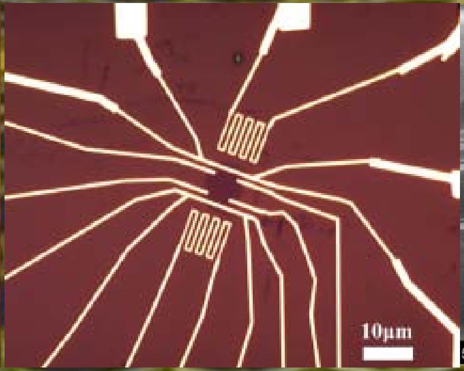
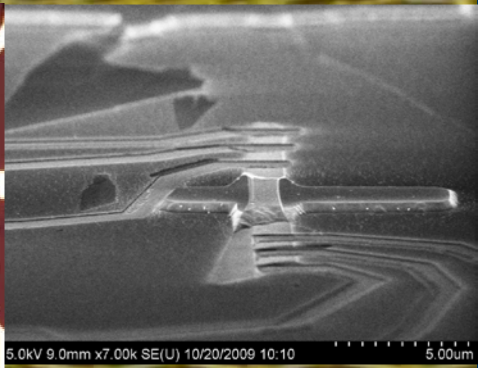
Graphene: materials, physics and devices of a unique 2D electronic system (2DES)

Yong P. Chen, *Quantum Matter and Devices (QMD) Lab*
Department of Physics, Birck Nanotechnology Center
and School of Electrical & Computer Engineering
Purdue University, West Lafayette IN
http://www.physics.purdue.edu/quantum



Talk at NCN (Network for Computational Nanotechnology), Purdue University 4/2/2010

Outline

- Review of Graphene: A 2DES perspective

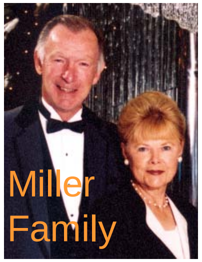
  Graphene: a unique 2DES ---
  "relativistic"; "exposed", tunable (disorder and interaction),"flexible" …
  --- lots of potential for new physics

- **Combining surface probes with transport measurements**
  - Scanning gate microscopy: **charge inhomogeneity**
  - **Artificial defect** engineering by particle-beam irradiation
  - Raman-electrical measurement of Thermal transport in graphene
  - Potential for various device applications, eg. sensors
- Material: **Large, flexible, transferrable graphene**

  by Chemical Vapor Deposition (CVD)

Acknowledgement of Support

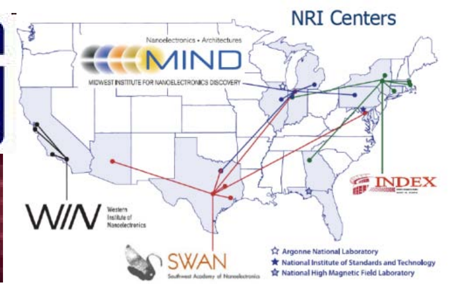
American Chemical Society



IBM

SRC

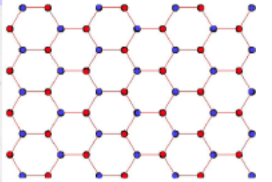
NRI

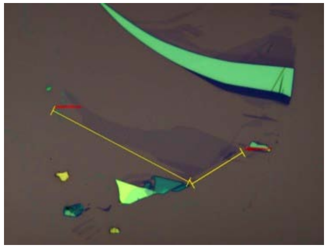


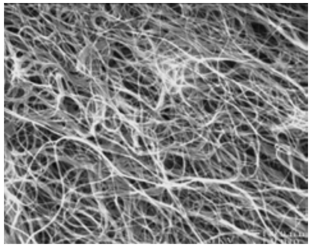
Nanoelectronics • Architectures
MIND
MIDWEST INSTITUTE FOR NANOELECTRONICS DISCOVERY

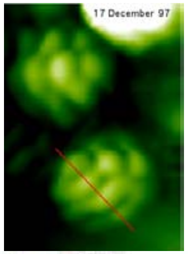
Introduction to Graphene

Building block of (sp^2) Carbon





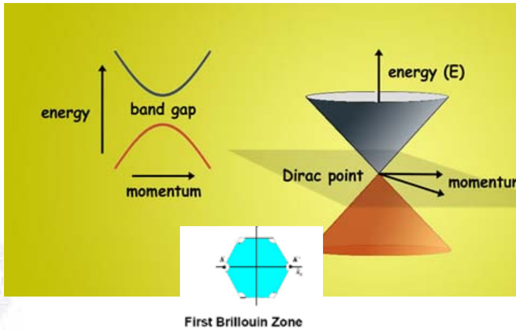


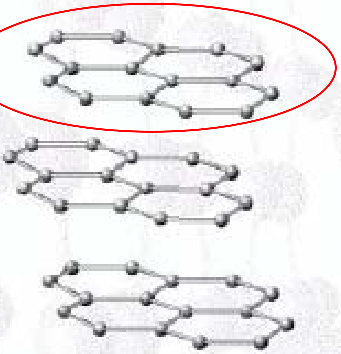


3D 2D 1D 0D

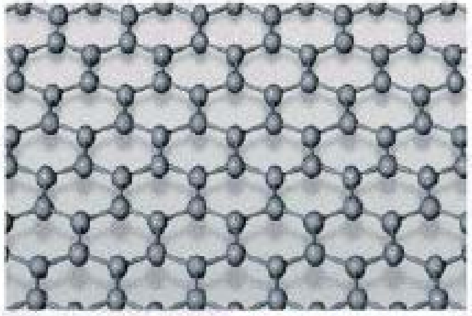
1000+ papers in 2008

Usual solid graphene

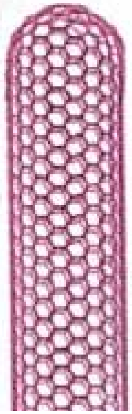


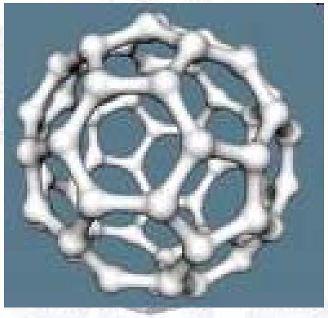


Graphite



graphene





Buckyballs

Electrons in graphene

$$E = pv_F = \hbar k v_F$$

$$v_F \sim 1\times10^6\,\mathrm{m/s} = c^*$$

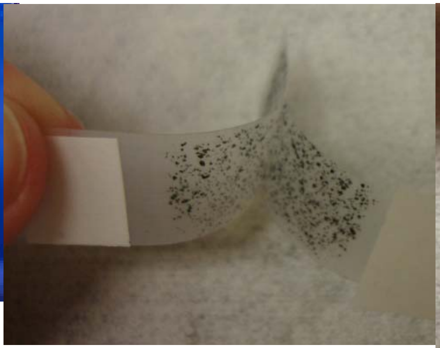
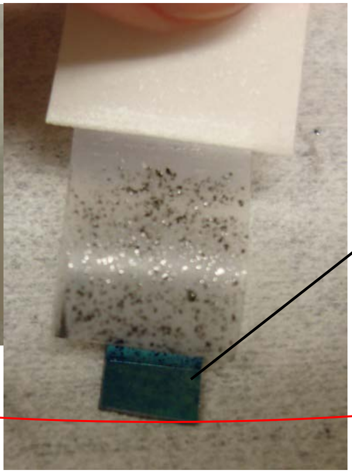
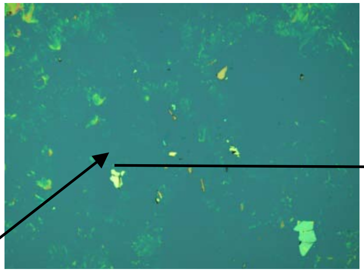
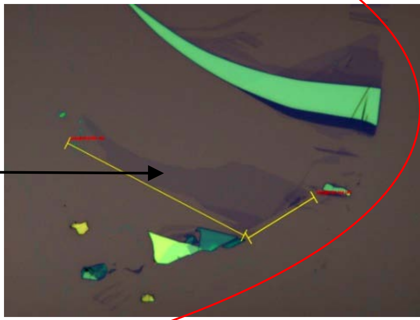
- (electrically isolated) "discovered" in 2004
- Building block of many carbon (nano)materials
- New "wonder" semiconductor/semimetal
- Amazing Electrical Properties – (*"post Si" electronics/"Moore"*)
- Amazing Mechanical Properties --- highest strength (~CNT)
- Amazing Thermal properties – highest thermal conductivity & tunable
- *Easy* to make and work with (2D planar fabrication)
- Lots of opportunities for organic chemists …

- High conductivity/mobility (>10X Si @ room T)
- Tunable (electr.) properties
  -ambipolar FET
  -band gap
- Low (electronic) noise
- Exposed to environment --- excellent sensor mat.

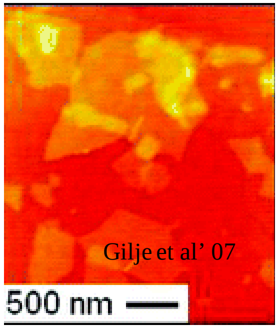
How to make graphene?

["top-down"] "exfoliation" (scotch tape)

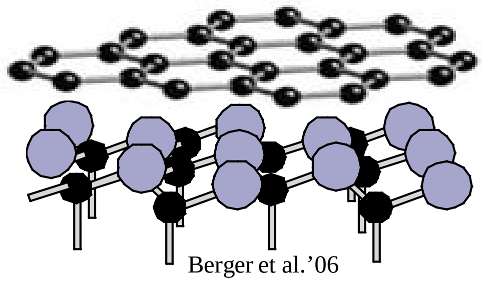
**easy *great for physics/single devices *not scalable*

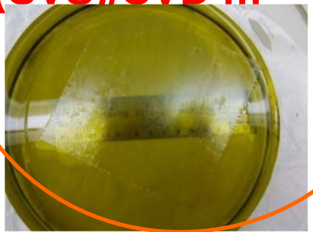
"top-down": large scale exfoliation

"bottom-up": large scale synthesis



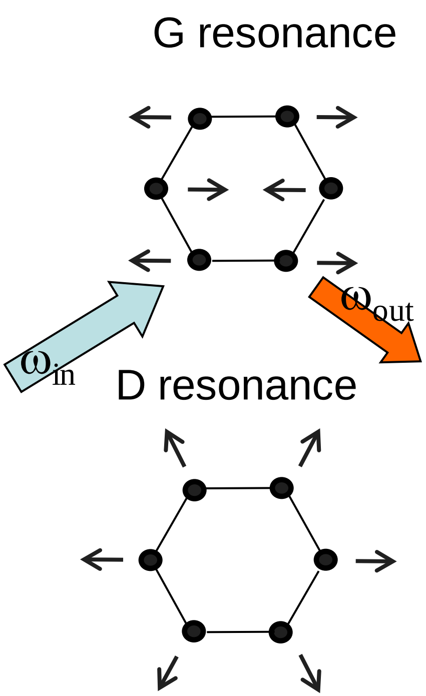
- **Sublimation of SiC**
- **Chemical Vapor Synthesis (CVS)/CVD ...**

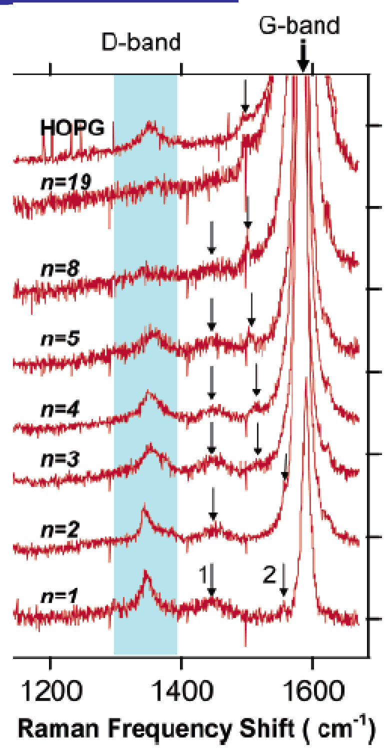


How to identify graphene

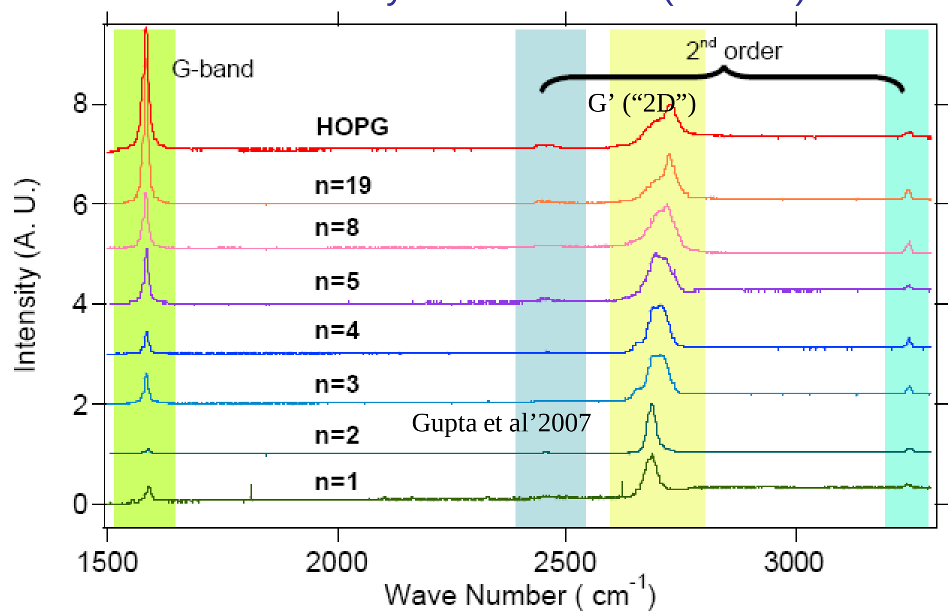
Optical microscopy -- seeing is believing

Raman Spectroscopy



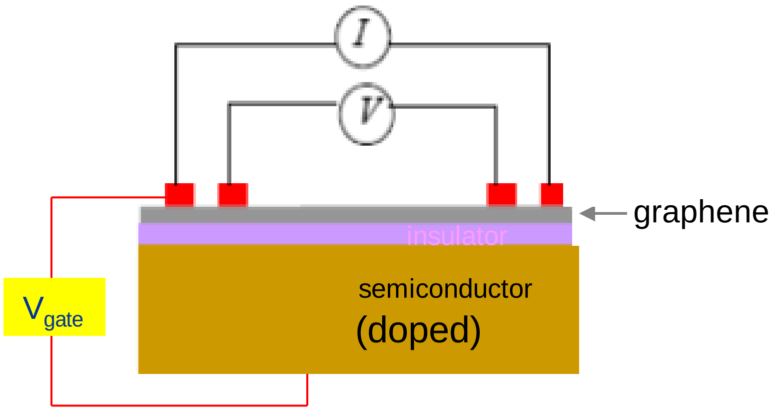


- 2D/G is sensitive to number of layers
- D/G is sensitive to crystalline defects (domain)

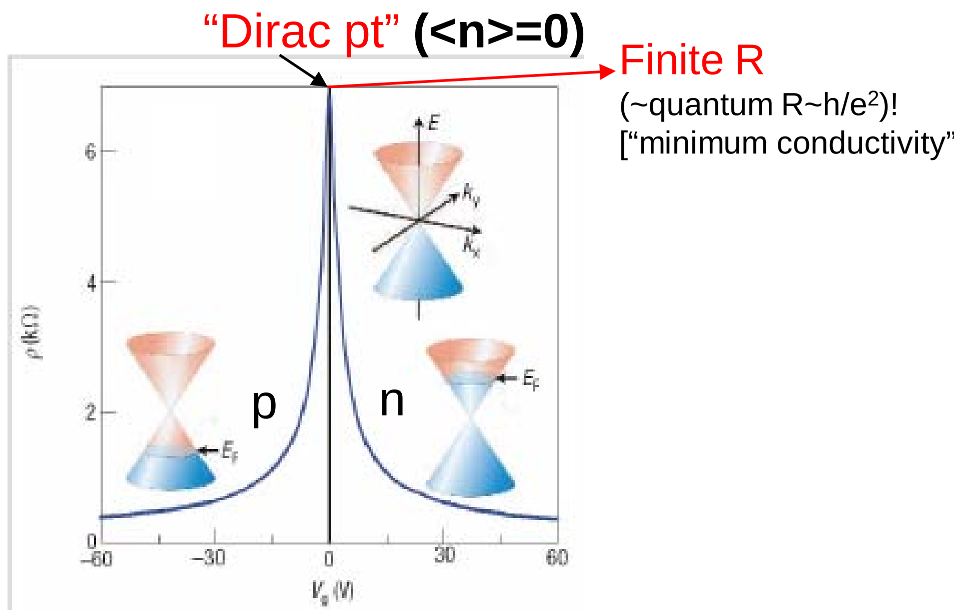


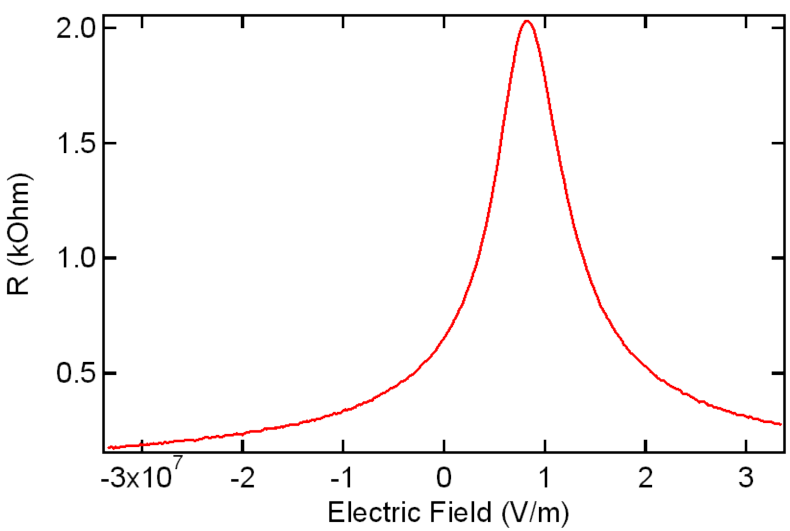
Many other methods, incld. QHE

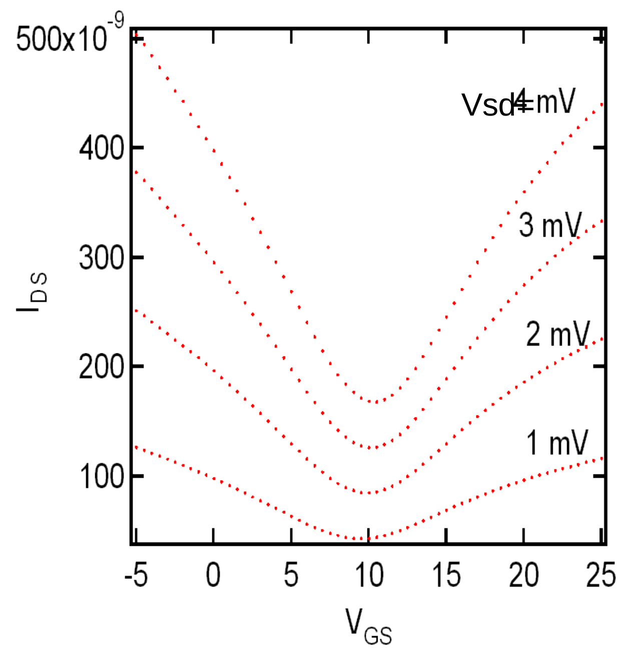
Electric Field Effect and Dirac point



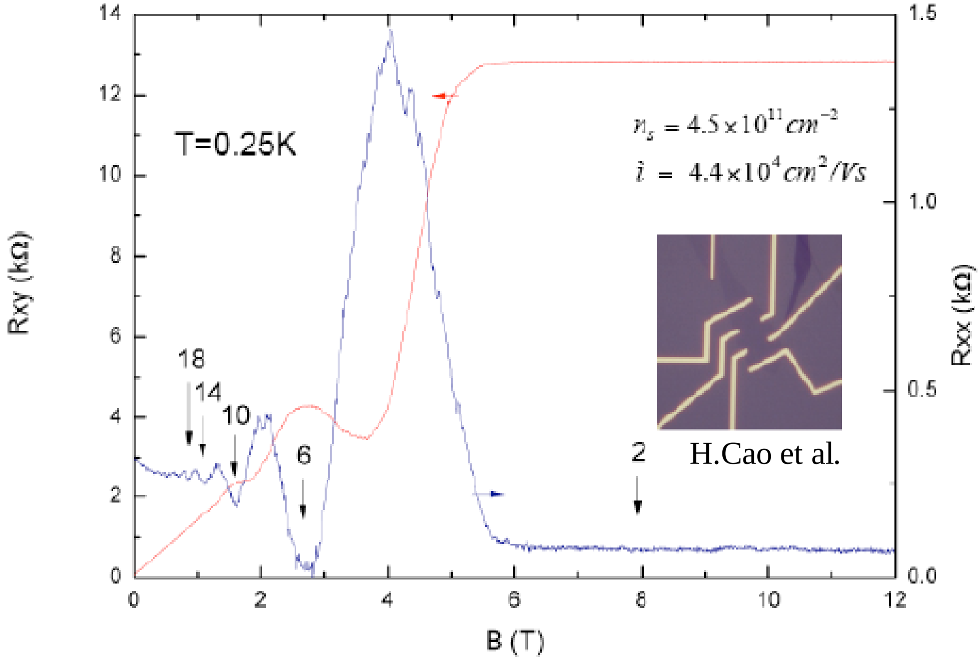
Insulator=300nm SiO2
(global) back gate: doped Si





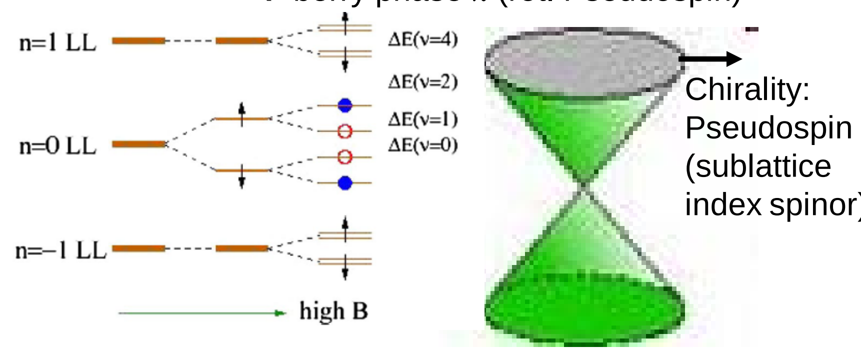


"Anomalous" QHE of chiral massless fermions



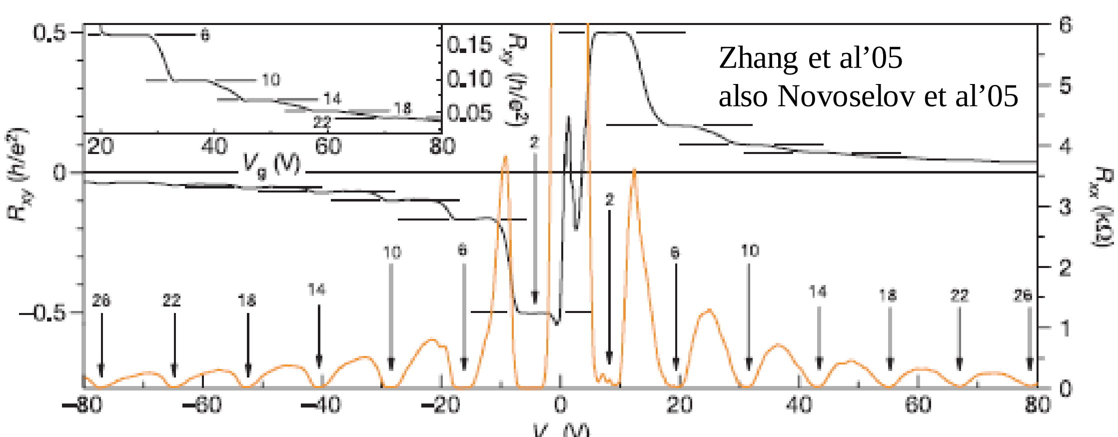
QHE for single layer graphene occurs at Filling factor nh/eB=2,6,10….=**4(K+1/2)**
---"anomalous" (half-integer QHE)

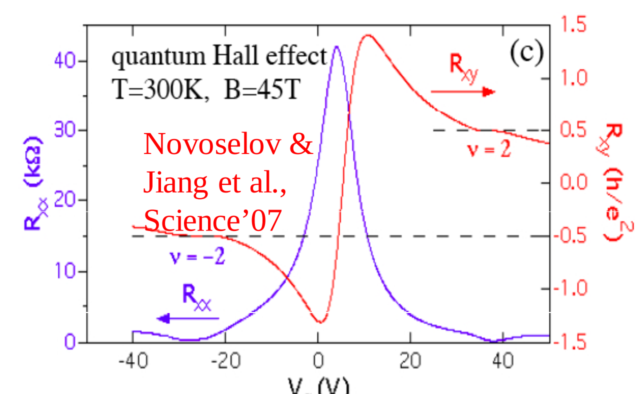
4=LL degeneracy (spin+pseudospin)
½ ← electrons & holes sharing N=0 LL
← berry phase π (rot. Pseudospin)



$$E_n = \mathrm{sgn}(n)\sqrt{2e\hbar v_F^2 B|n|},$$

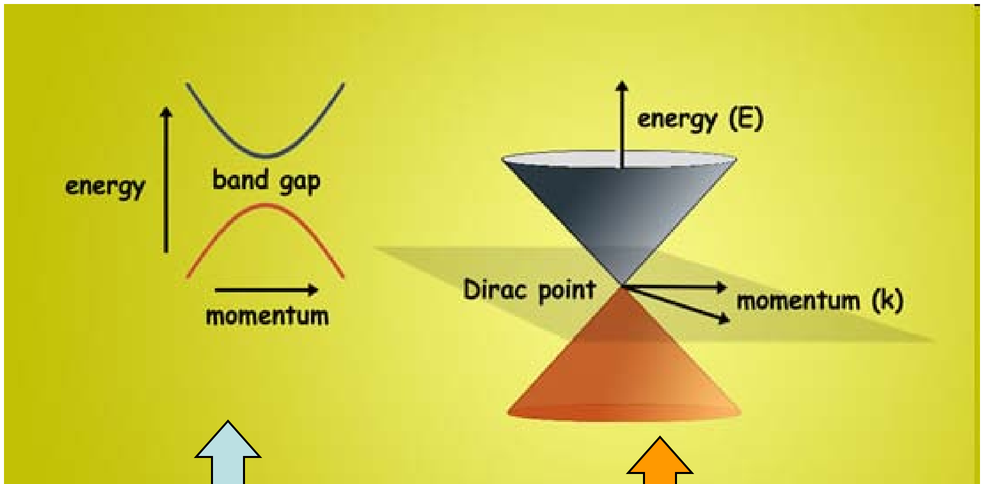
Huge QH energy gap
→ room T QHE!





"Relativistic" 2DES: Chiral Massless Dirac Fermions

Unique band structure of graphene



Electrons in usual solids (Schrodinger equation) Energy-momentum:

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

$$(k = \frac{2\pi}{\lambda})$$

Electrons in graphene (Dirac equation) Energy-momentum

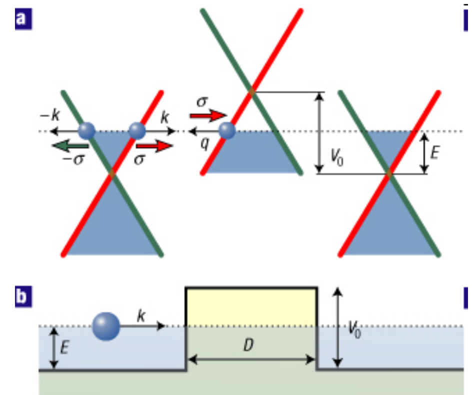
$$E = p v_F = \hbar k v_F$$

$$v_F \sim 1 \times 10^6 \,\mathrm{m/s}$$

Electrons in graphene behave as (massless) photons with effective speed of light ~1/300 of c!

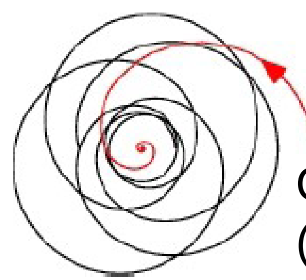
Physics of (ultra)relativistic electrons

- Klein tunneling (Klein paradox)



Experiments: Goldhaber-Gordon Kim

- QED vacuum breakdown (Coulomb collapse) [Shytov et al'08]



Atom with $Z > Z_c \sim 1/\alpha$ collapses (unstable)

QED coupling constant (fine structure constant)

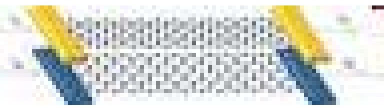
$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137} \quad \text{in vacuum}$$

$$\sim 2 \quad \text{in graphene}$$

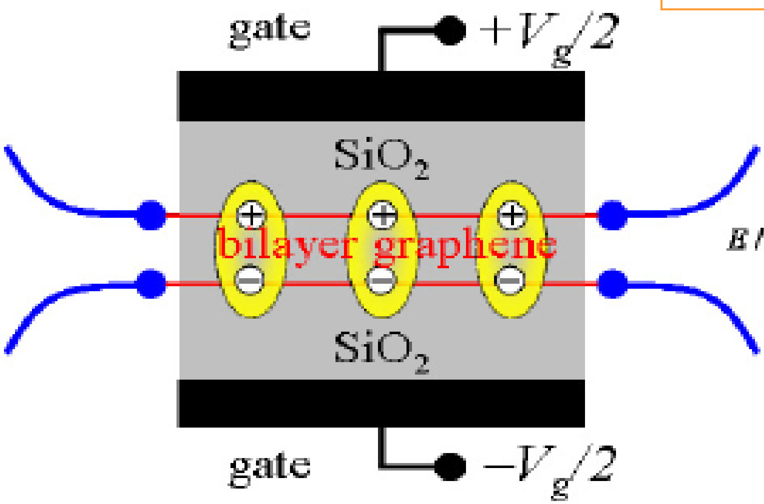
Many-body physics of interacting Dirac/chiral-massless fermions?

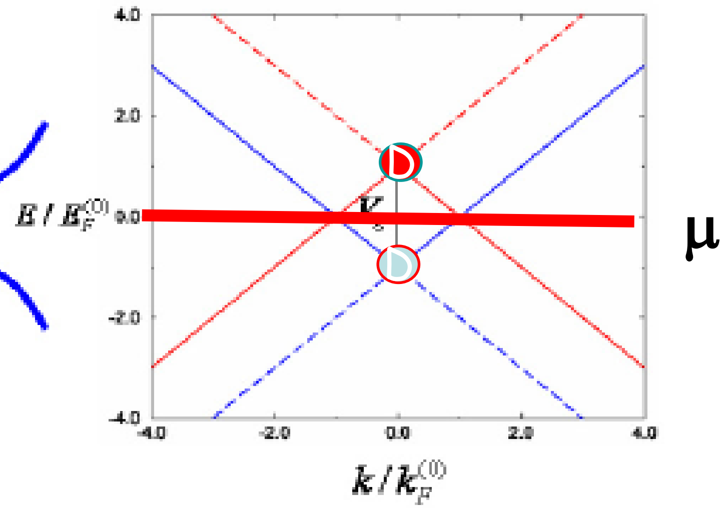
- Two component (coupled) graphene systems

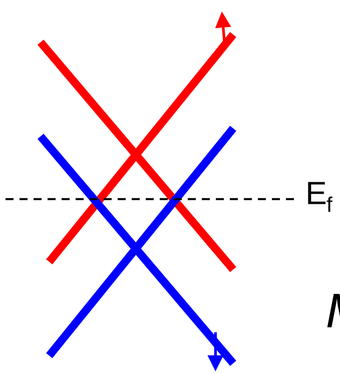
Excitonic condensate
(room T) counterflow superfluidity?
➔ **dissipationless interconnect for CMOS!**



Electrically-isolated (Coulomb-coupled) Bilayer graphene





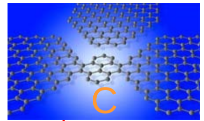


Min et al. , Joglekar, Aleiner PRB (2008)

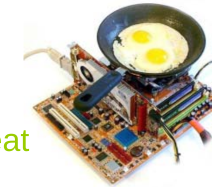
Monolayer graphene with (large) in-plane B (Aleiner et al)

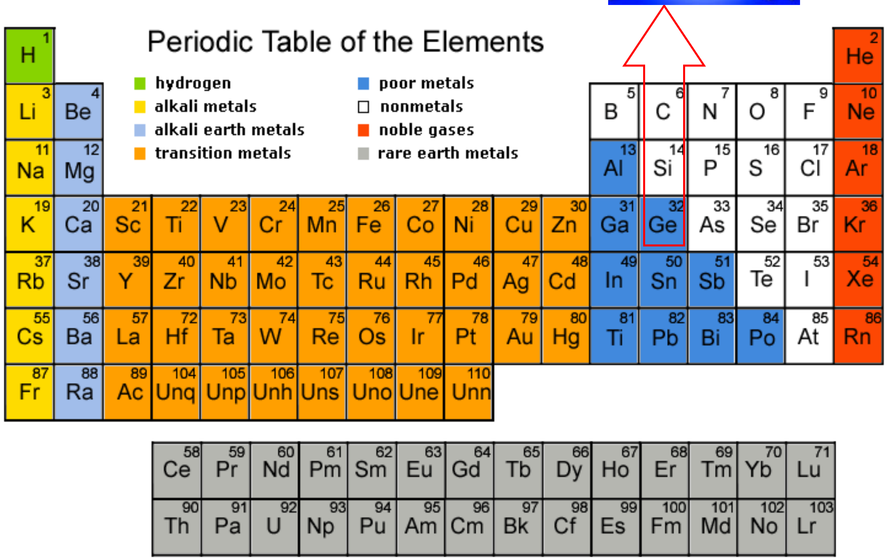
- Dirac/chiral-massless fermions: quantum chromodynamics (QCD) physics in graphene?

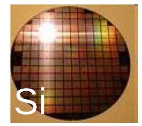
Graphene Devices:

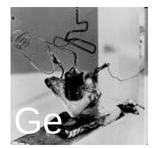


Faster electronics & less heat

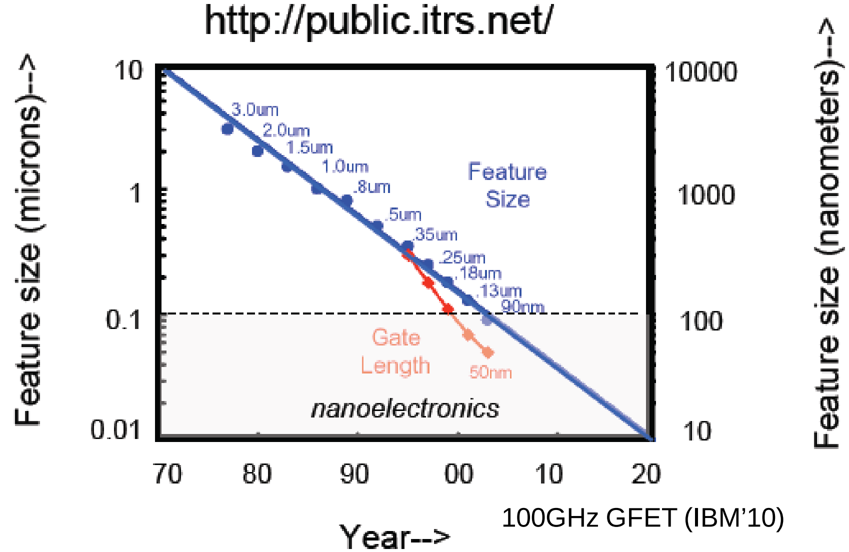








Nanoelectronics ----"save" Moore's law?



100GHz GFET (IBM'10)

Nanosensor ---- single atom/molecule/charge detection

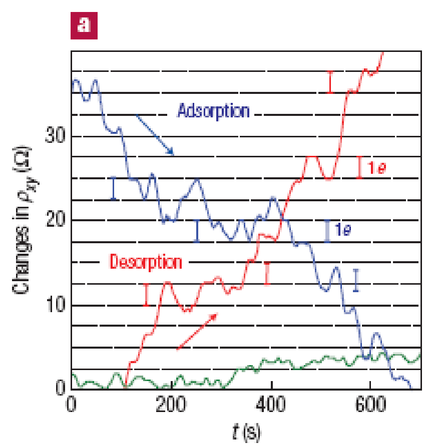
LETTERS

Detection of individual gas molecules adsorbed on graphene

F. SCHEDIN[1], A. K. GEIM[1], S. V. MOROZOV[2], E. W. HILL[1], P. BLAKE[1], M. I. KATSNELSON[3] AND K. S. NOVOSELOV[1]*

[1]Manchester Centre for Mesoscience and Nanotechnology, University of Manchester, Manchester, M13 9PL, UK
[2]Institute for Microelectronics Technology, 142432 Chernogolovka, Russia
[3]Institute for Molecules and Materials, University of Nijmegen, 6525 ED Nijmegen, Netherlands
*e-mail: Konstantin.Novoselov@manchester.ac.uk

Published online: 29 July 2007; doi:10.1038/nmat1967



The ultimate aim of any detection method is to achieve such … can cause notable relative changes in carrier concentration, n.

Macroelectronics ---- flexible & transparent

B.Hong et al'09'10;

Graphene

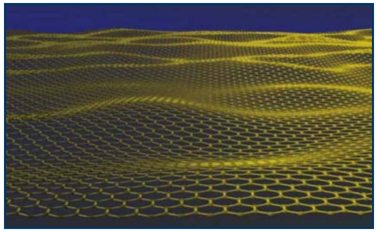
- Single particle dynamics:
  Dirac eq.
  massless particles (m*=0)
  *E~pc**
  chirality
- energy scales –LARGE! (quantum at room T)

$$E_f \sim \hbar\sqrt{\pi n}c^* \sim 1000K \ \ (@n \sim 1\times10^{12}\,\mathrm{cm}^{-2})$$

$$E_c \sim c^*\sqrt{2\hbar eB} \sim 500K \ \ (@B = 1T)$$

$$E_e \sim \frac{e^2}{4\pi\varepsilon\varepsilon_0 r} \sim 3000K \ \ (@n \sim 1\times10^{12}\,\mathrm{cm}^{-2})$$

- 2DES is the surface (exposed)
  direct imaging/SPM/light scattering easy
- one atomic layer thick --- ultimate 2D
  excellent electrostatic control (device)
- material form is flexible (membrane)



?

A unique & new 2DES!

Conventional 2DES

- Single particle dynamics:
  Schrodinger eq.
  massive particle (m*>0)
  *E~p²/2m**
- energy scales

$$E_f \sim \frac{\hbar^2 \pi n}{m_*} \sim 30K \ \ (@n \sim 1\times10^{11}\,\mathrm{cm}^{-2})$$

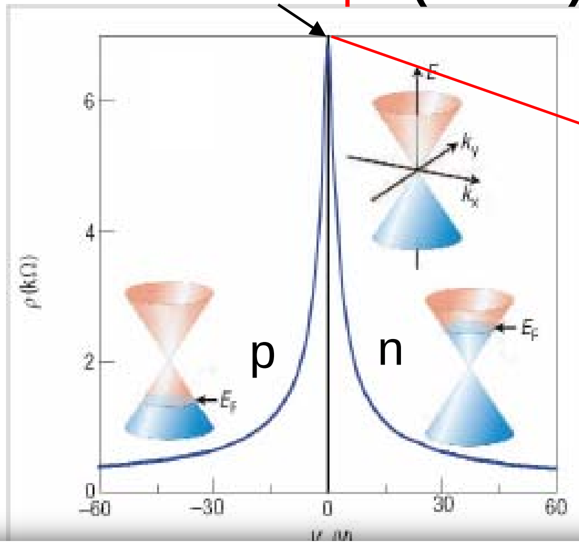
$$E_c \sim \frac{\hbar eB}{m_*} \sim 20K \ \ (@B = 1T)$$

$$E_e \sim \frac{e^2}{4\pi\varepsilon\varepsilon_0 r} \sim 80K \ \ (@n \sim 1\times10^{11}\,\mathrm{cm}^{-2})$$

- 2DES typically *buried* under surface
  non-transport probe hard
  [light scattering; SPM…]
- 2DES has finite thickness
- material form is rigid

AFM Scanning Gate Microscopy to probe **charge inhomogeneity** in graphene

"Dirac pt" (<n>=0)



Transport near DP

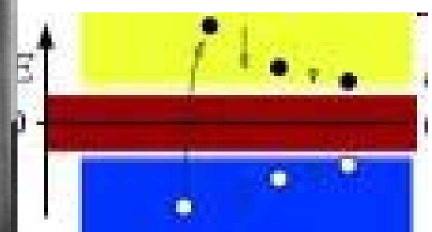
Finite R

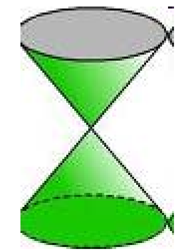
["minimum ***conductivity***"]

"simple" quantum transport of Dirac particles predicts

$$\sigma_m = \frac{4e^2}{\pi h}$$

"*vacuum* is not empty"





Reality: measured σ_m non-universal and > prediction

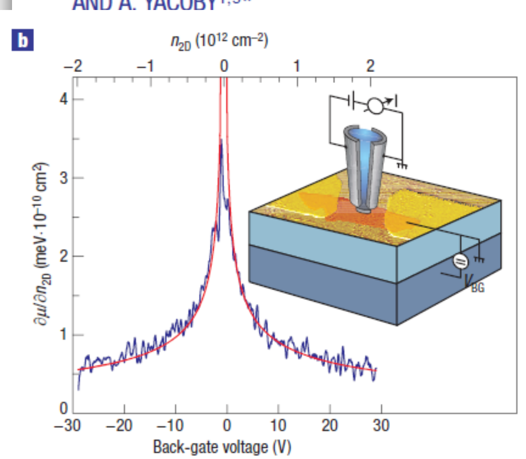
"*vacuum*" is messy – electron/hole puddles
← extrinsic impurities/doping

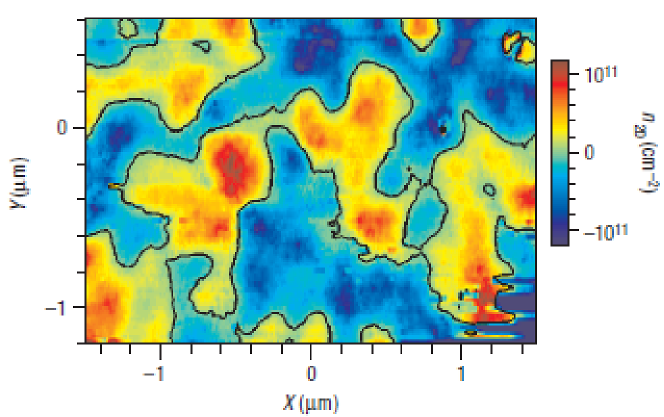
ARTICLES

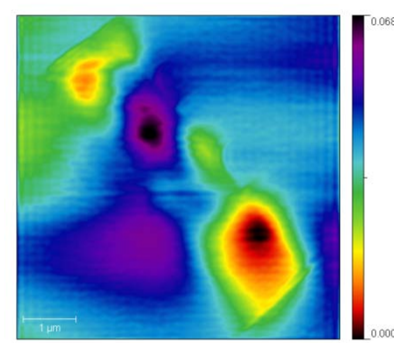
Observation of electron–hole puddles in graphene using a scanning single-electron transistor

Nat. Phys. 2008

J. MARTIN[1], N. AKERMAN[1], G. ULBRICHT[2], T. LOHMANN[2], J. H. SMET[2], K. VON KLITZING[2] AND A. YACOBY[1,3]*



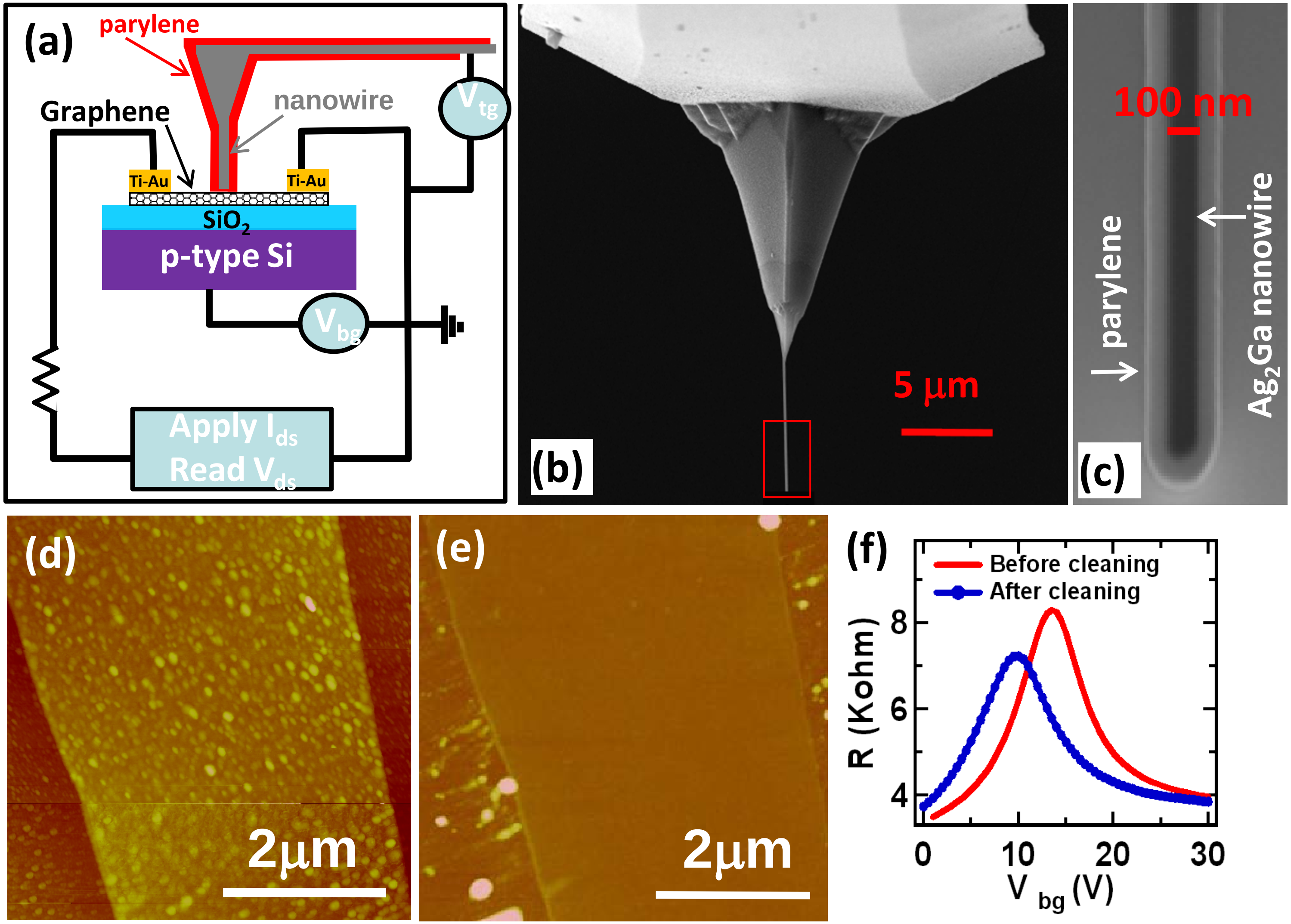




R. Jalilian et al.,arXiv:1003.5404 (2010)

Contact mode SGM:

Tip as top gate: metallic nanowires (D~50-100nm) coated with parylene dielectric (~30-100nm).

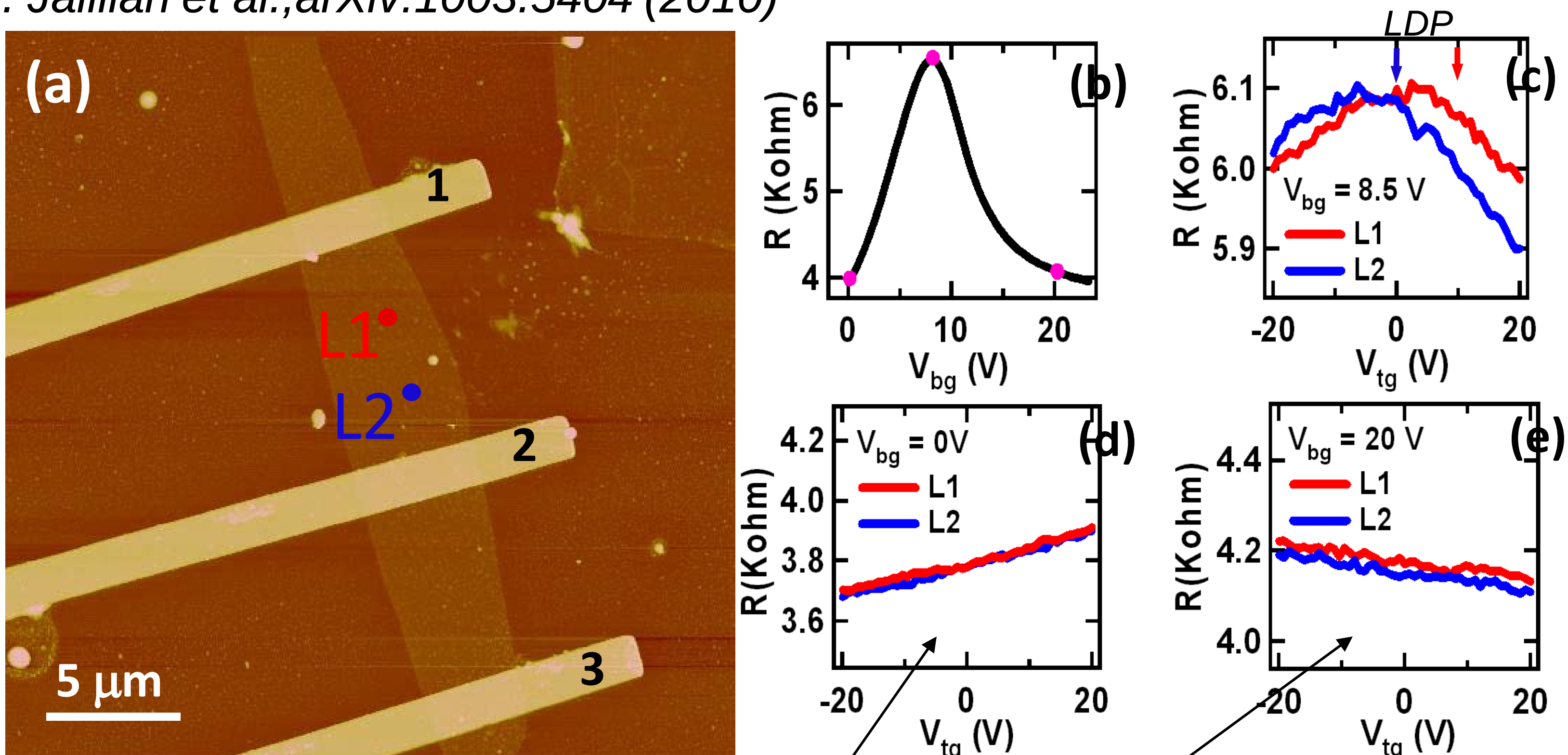


"nano broom": dusts/resist residues p-dope graphene!

Local charge density change→ global resistance change

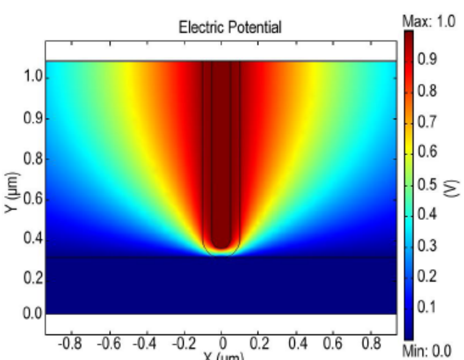
Graphene is special

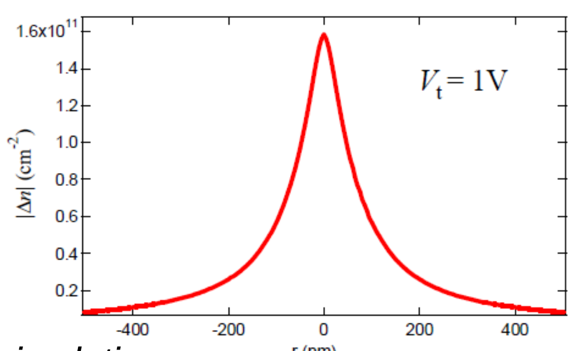
R. Jalilian et al.,arXiv:1003.5404 (2010)

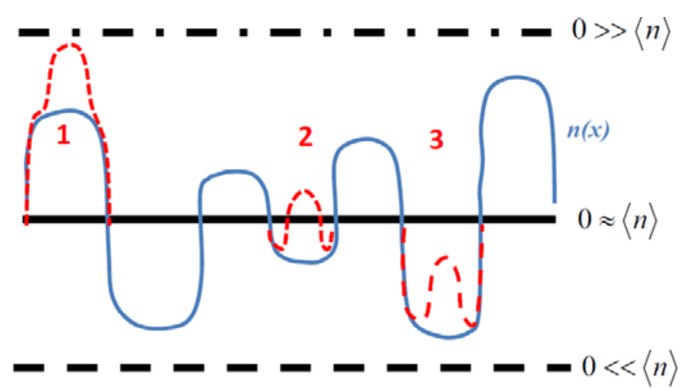


$\delta n \sim 10^{12}\,\mathrm{cm}^{-2}$

ΔR~1Ω for ~10 electrons induced/depleted in graphene – **superb charge sensor**!



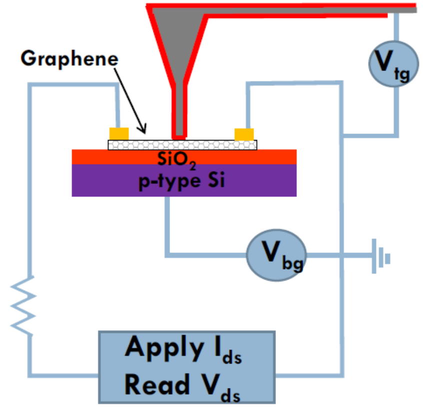




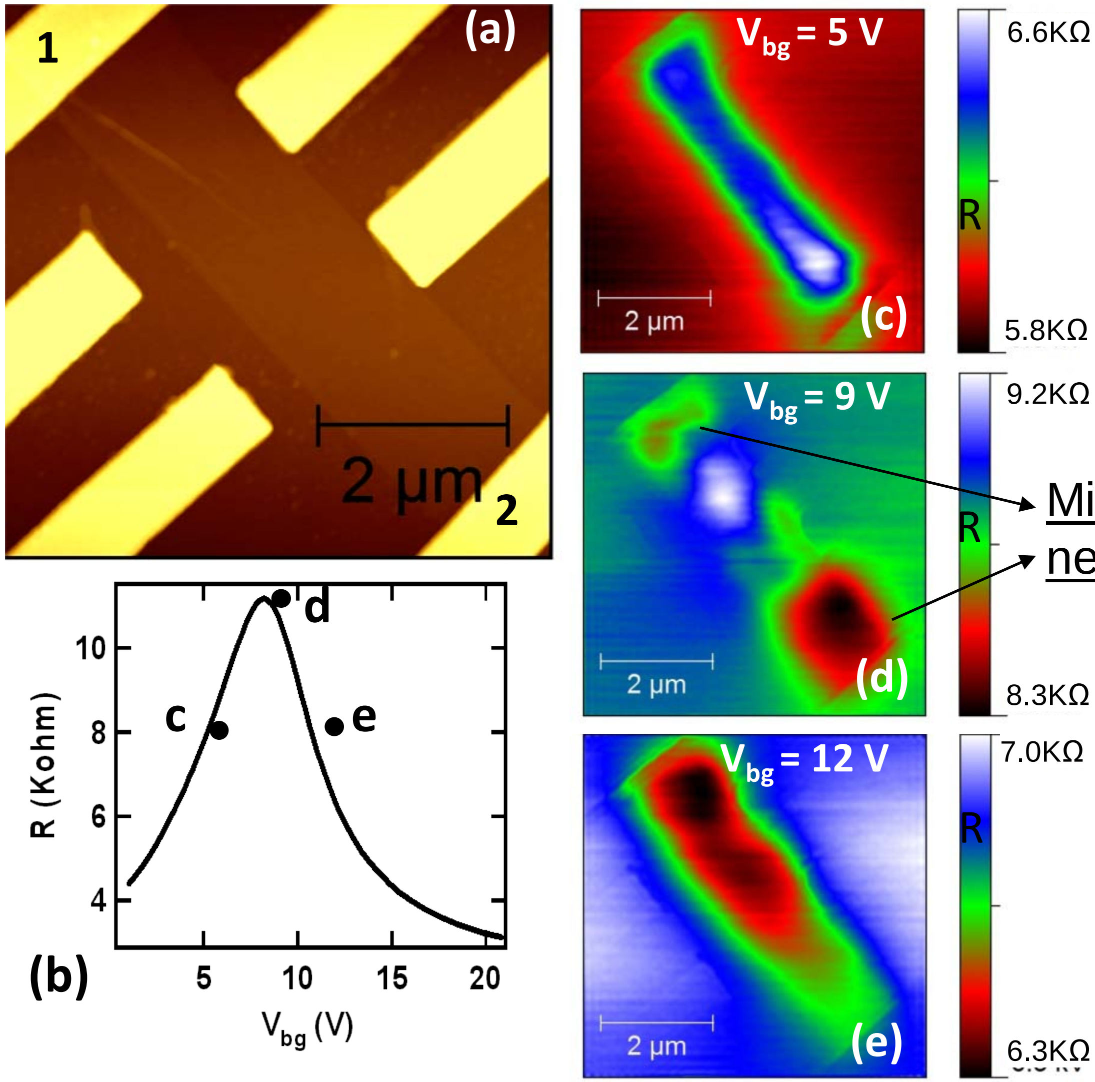
COMSOL simulation

Surface+Transport

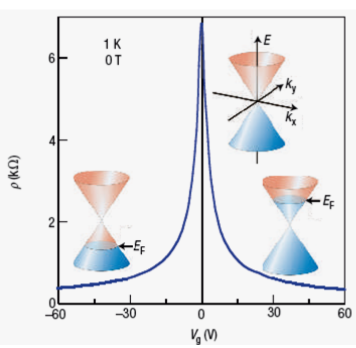
SGM images



Ids =500nA
Vtg= 20V
Global Dirac point = 9V
Parylene thickness= 100nm



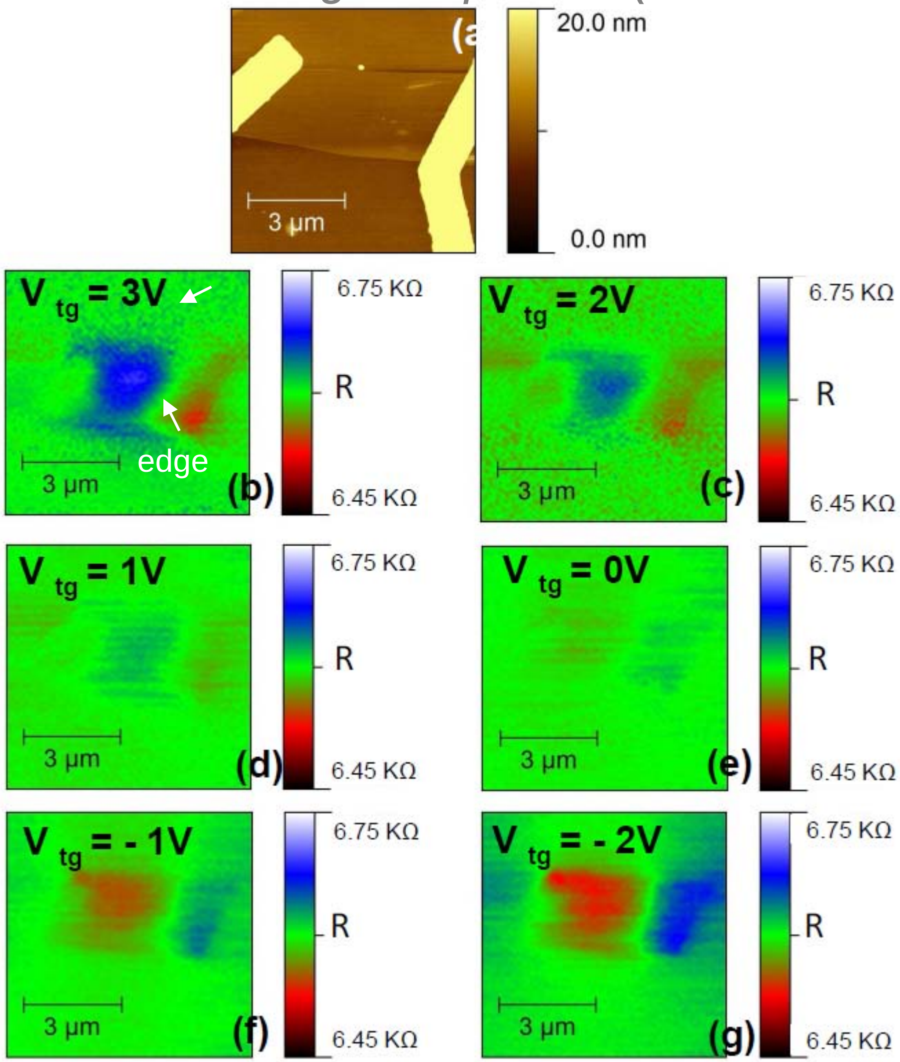
Micron-scale “puddles” near DP!

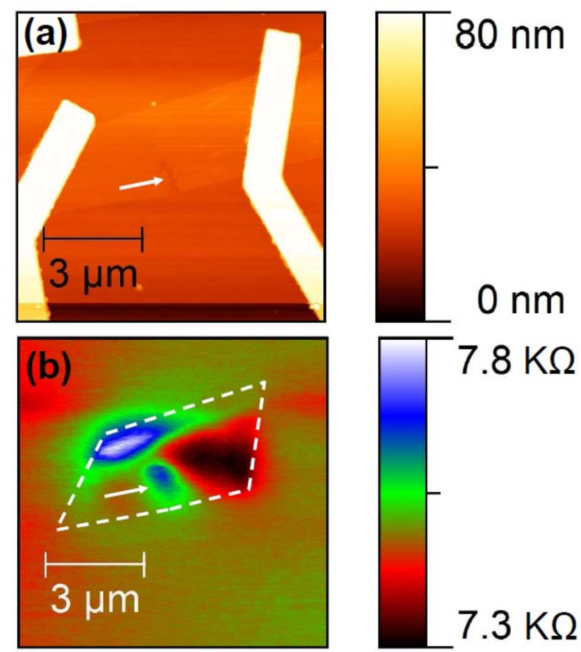


R. Jalilian et al.,arXiv:1003.5404 (2010)

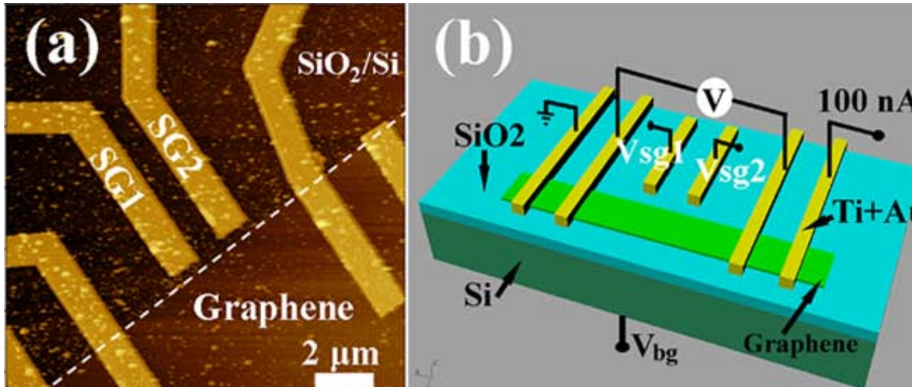
Sources of extrinsic local doping → charge inhomogeneity

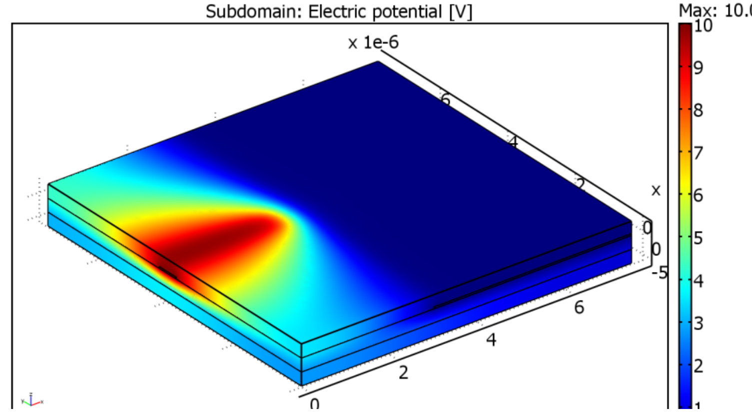
- contact electrodes (Ti/Au: e-doping) – micron scale
- edges, scratches/defects (p-doping)
- residues (p-doping)
- *isolated charged impurities (from STM/SET data) –nm scale [Zhang'09]*

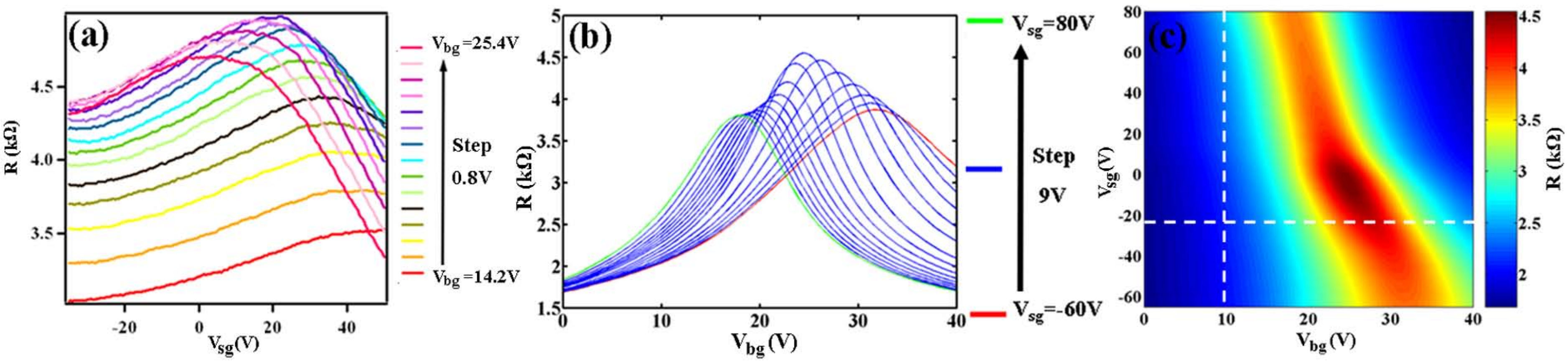




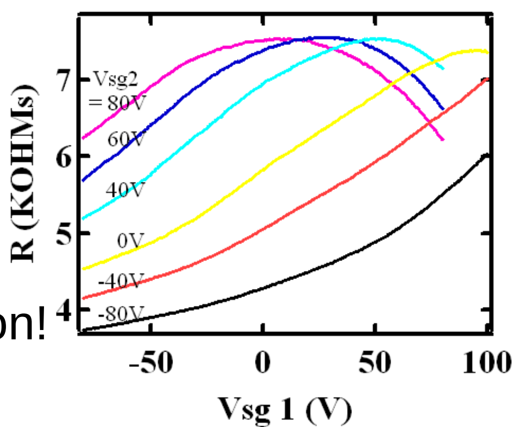
Metal Side Gated **Local** Ambipolar GFET

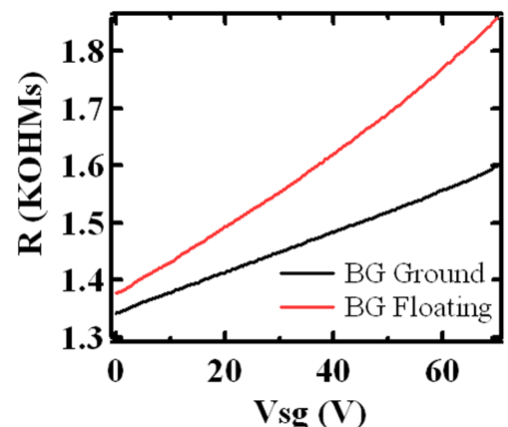






Side gate gives
Ambipolar FET
→
Gates individual
Devices w/o
Dielectric deposition!

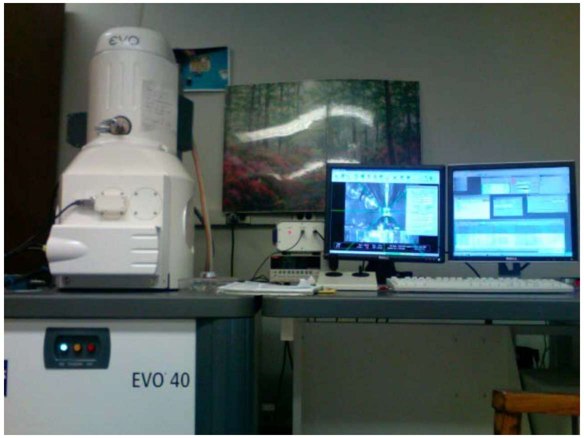


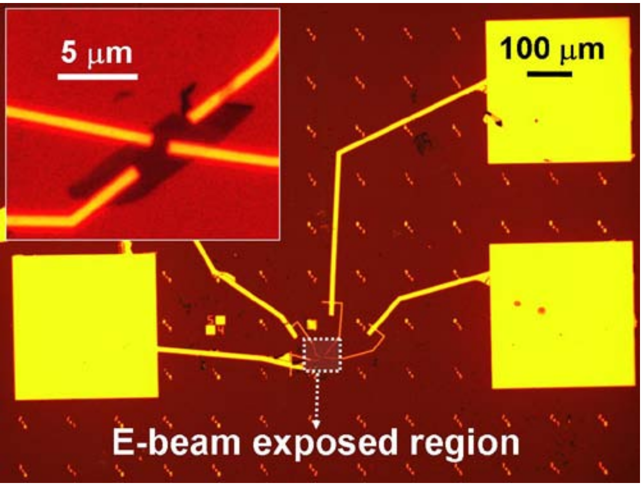


Jifa Tian et al.,
arXiv:1003.5855

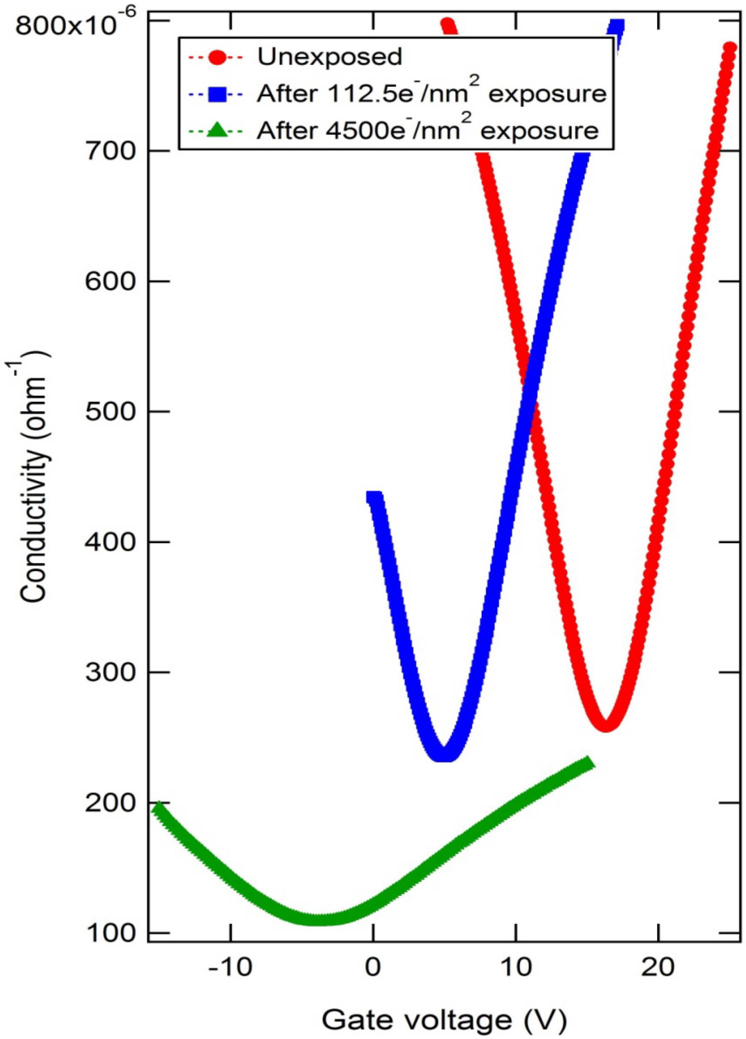
Surface+Transport

Irradiation with electron beams





30keV electron beam
I= 0.15nA; Time=5mins;
Expose area: 50um x 50um
Estimated dose: 112.5 e-/nm^2



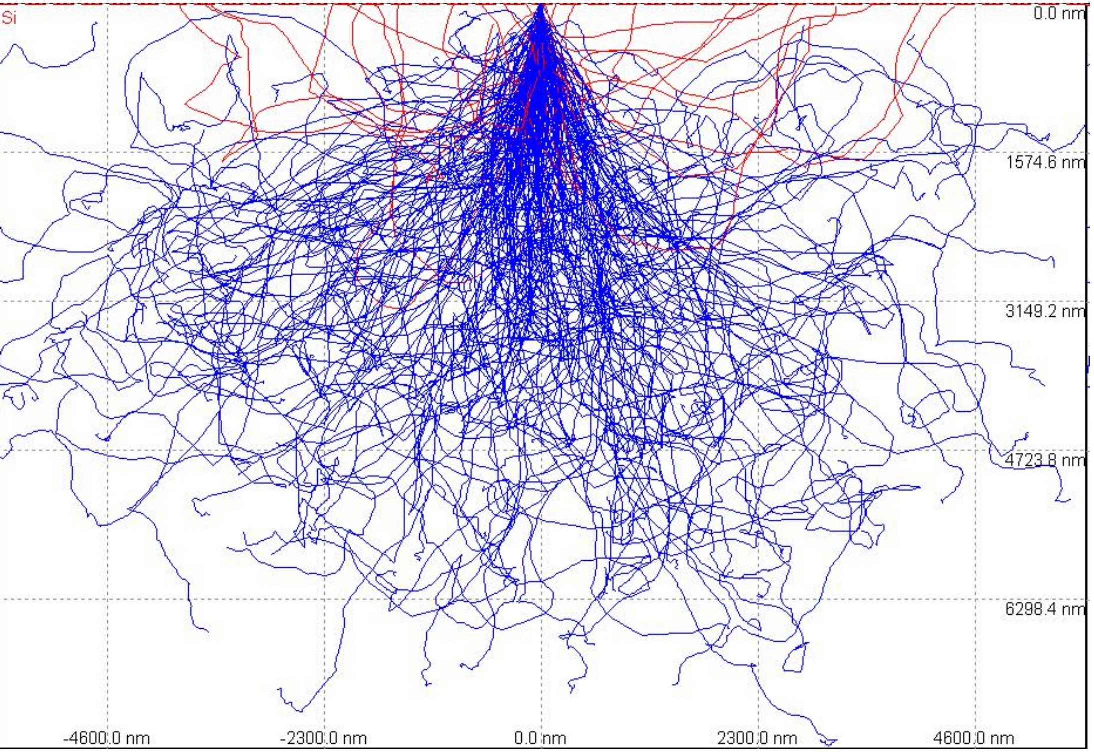
e- beam:
- *n*-dope graphene
- reduce mobility

I.Childres et al. AIP Conf. Proc. 1194, 140 (2009)
I.Childres et al, to be submitted (2010)

Modeling:
interaction of energetic electrons with semiconductor substrates

energetic electron transport through substrate (CASINO modeling)

Collaborators: Prof. Igor Jovanovic & Mike Foxe (Nuclear Eng.)



Monte Carlo ionization tracks generated by 30keV electrons in Si wafer

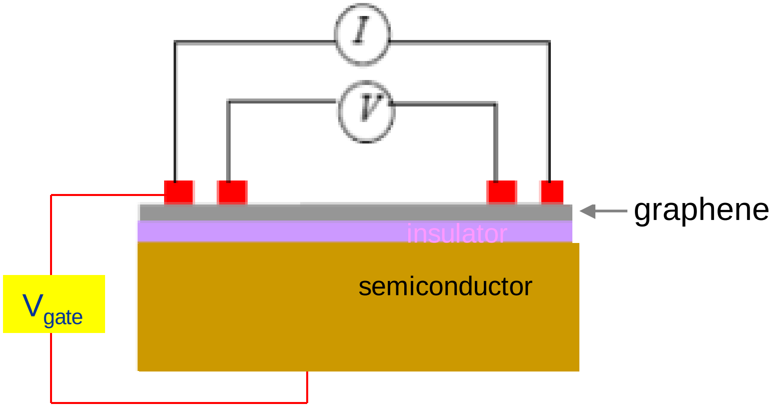
I.Childres et al. AIP Conf. Proc. 1194, 140 (2009)

Explanation:

-High energy electrons ionize e-h pairs in Si wafer

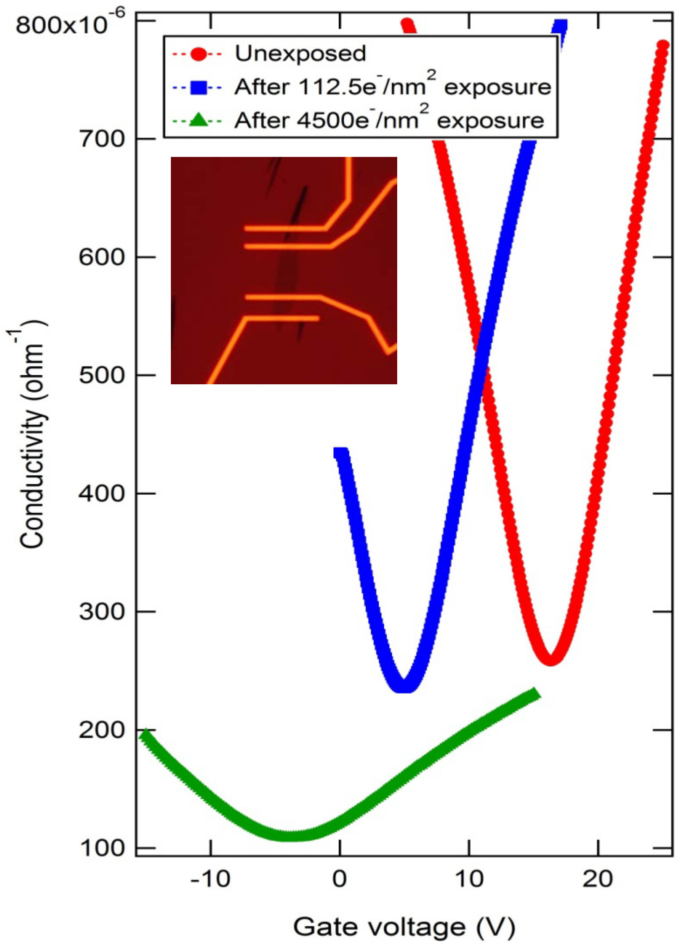
-Less mobile holes trapped at oxide-Si interface, inducing electrons in the channel (graphene)

-Analogous to the well-known reduction of threshold voltage in MOSFET subject to ion radiaton (**radiation-hard electronics**)

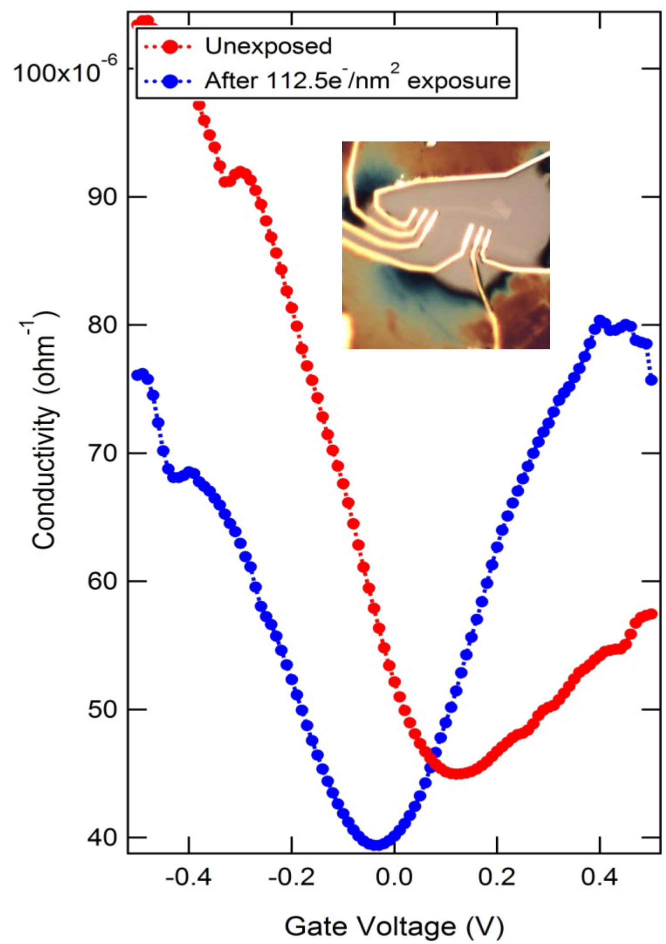


Suspended Graphene for Rad-hard electronics?

Supported on SiO2/Si

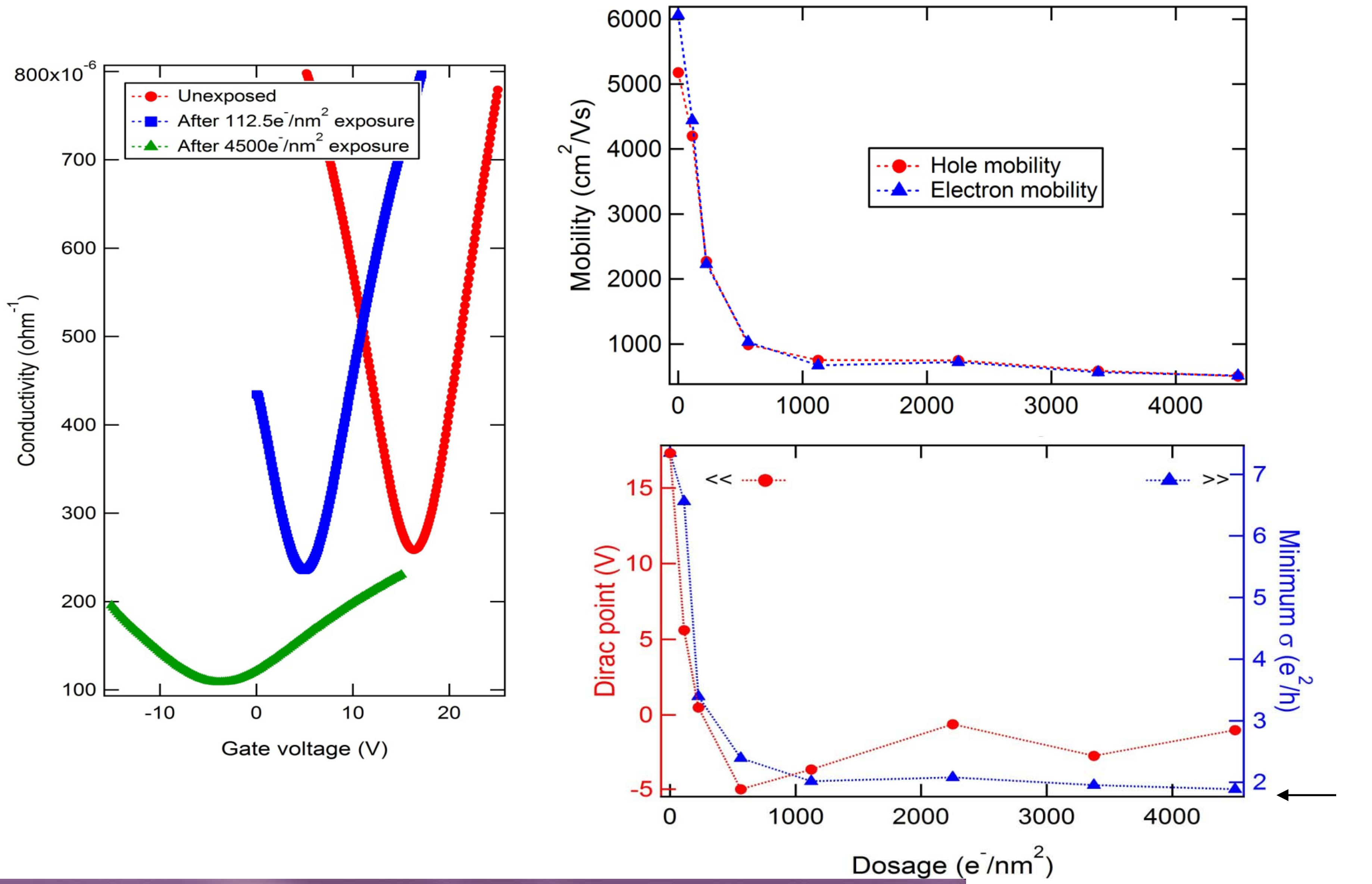


Suspended



I.Childres et al, to be submitted (2010)

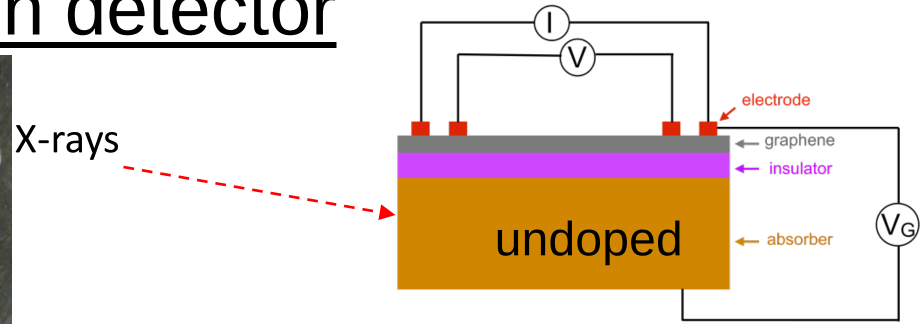
Transport & Scattering by *Tunable* Artificial Disorder

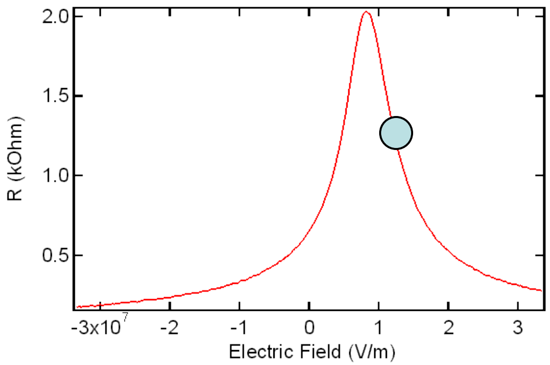


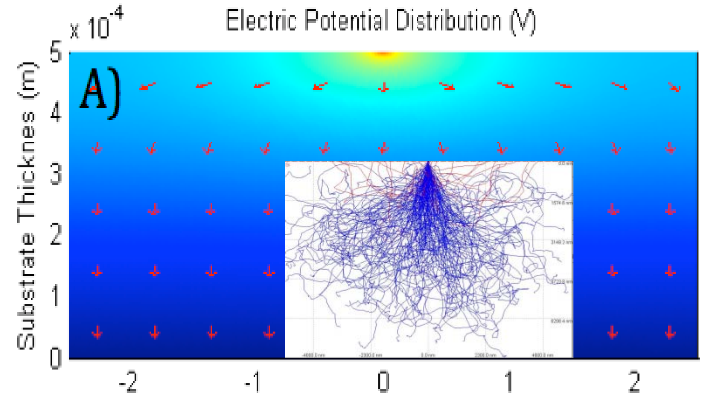
Graphene FET as radiation detector

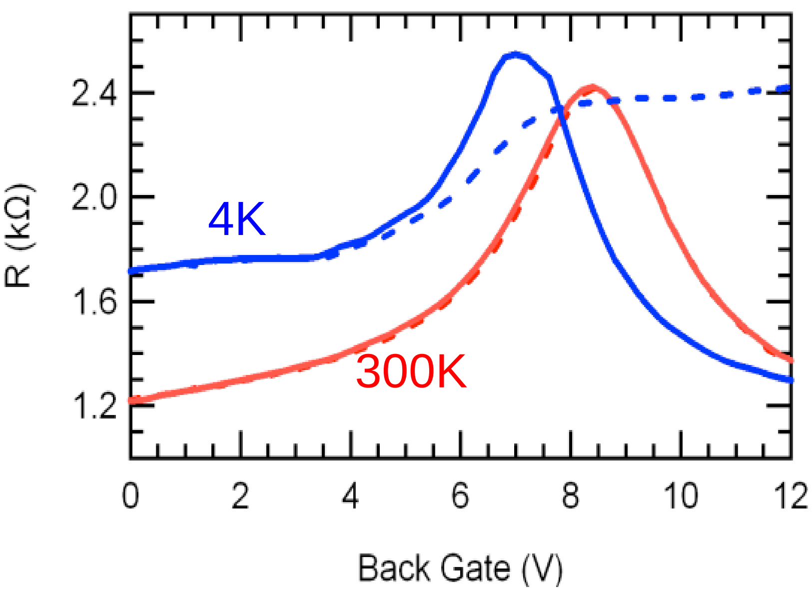
collab:
I. Jovanovic
(NuclE)

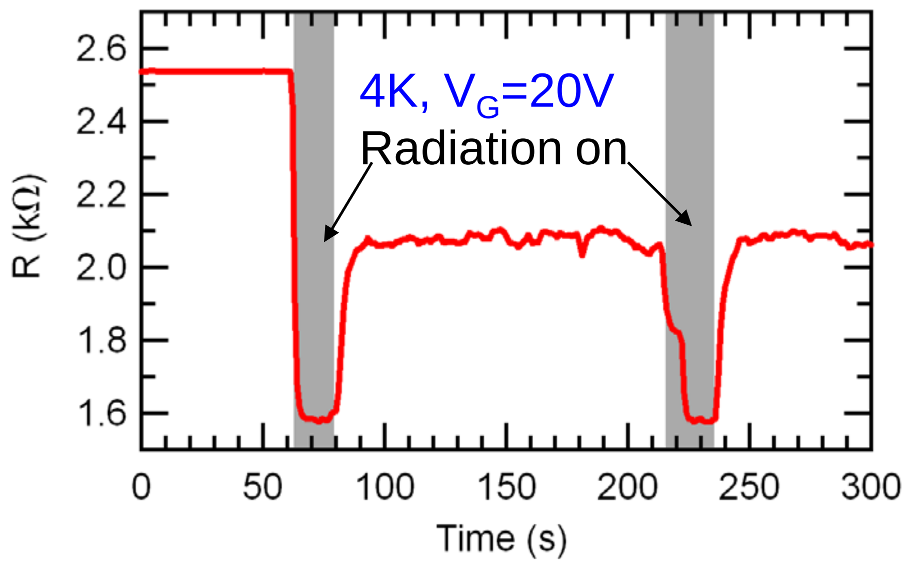
M. Foxe &
G. Lopez et al.
2010







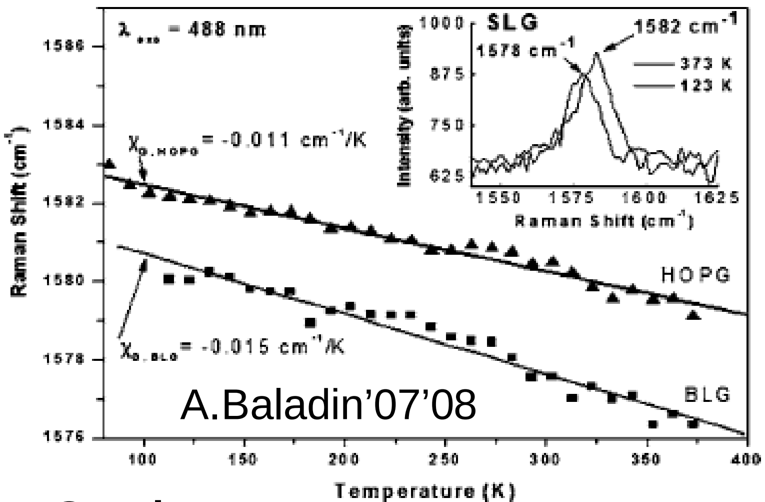


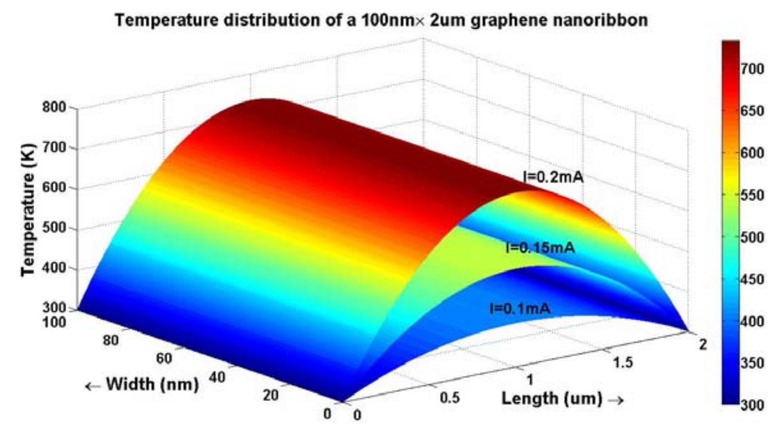


Raman+Electrical Transport→ measure thermoconductivity

L.A. Jauregui et al. (2010), ECS Trans. in press (2010)

Raman vs temperature shift as intrinsic **thermometry**





Graphene

k~ 3000-5000 W/mK

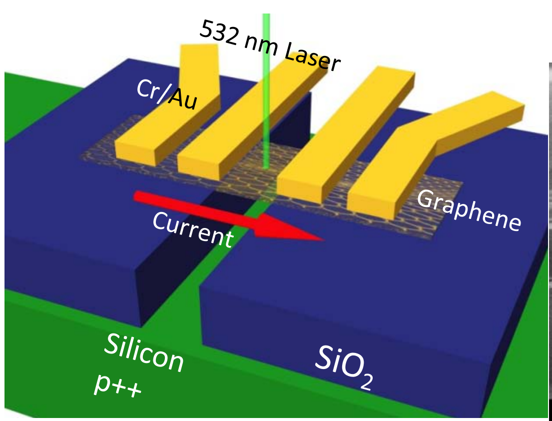
[Balandin'08: optical heating]

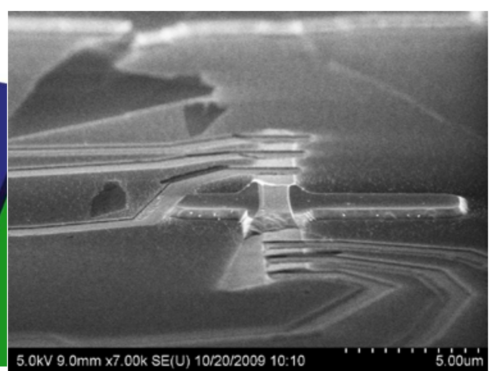
highest k material

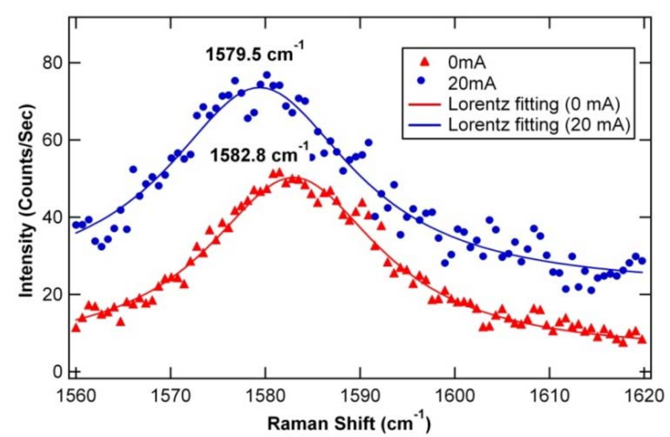
Our measurements:

K~2000-4000 W/mK for suspended exfoliated and CVD graphene

$$\kappa = RI^2L/\ (8\Delta TWh)$$



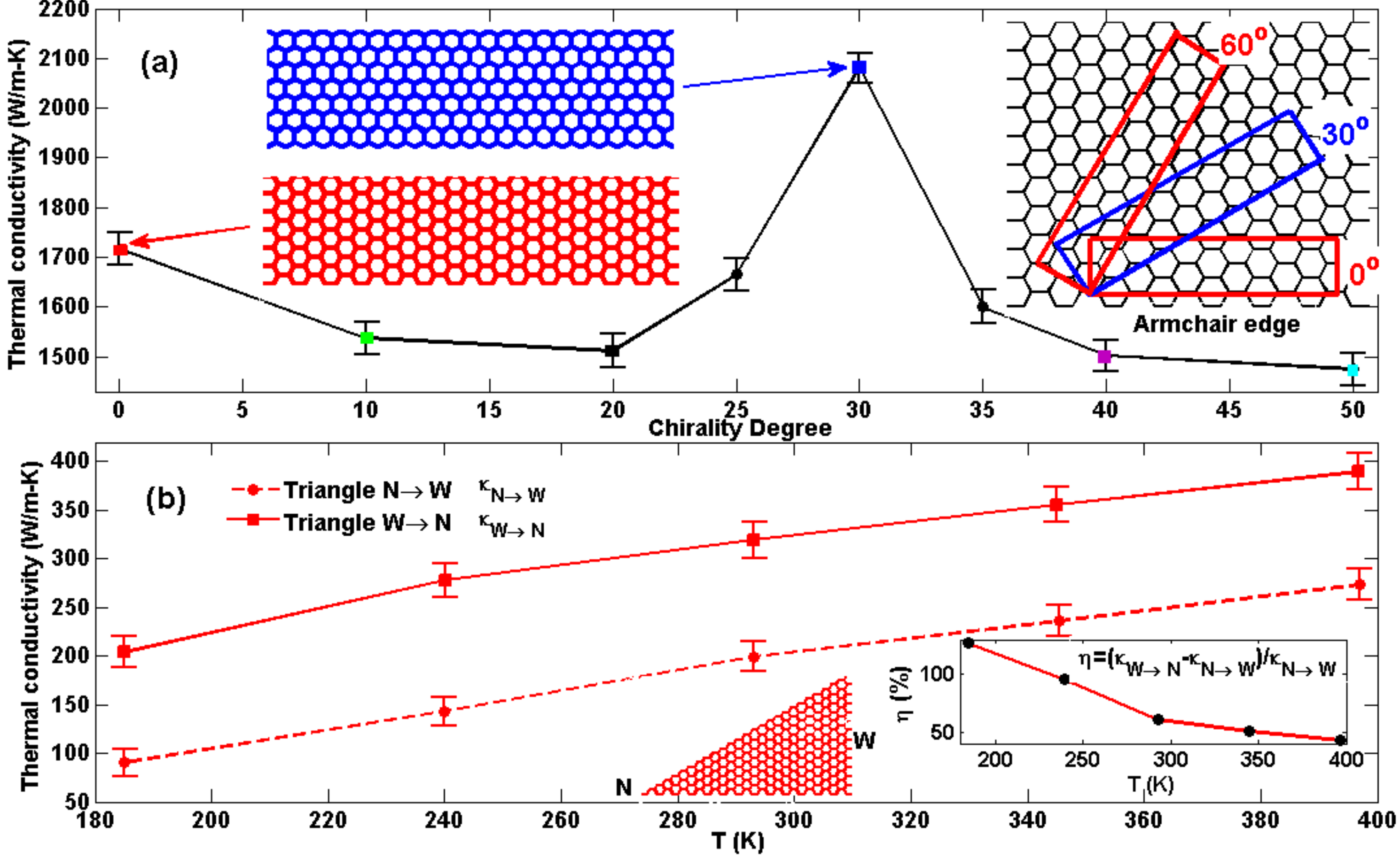




Graphene based thermal management and ***thermonics***?

Patterning Graphene Nanoribbons to control thermoconductivity

Thermal conductivity dep. on edge chirality!

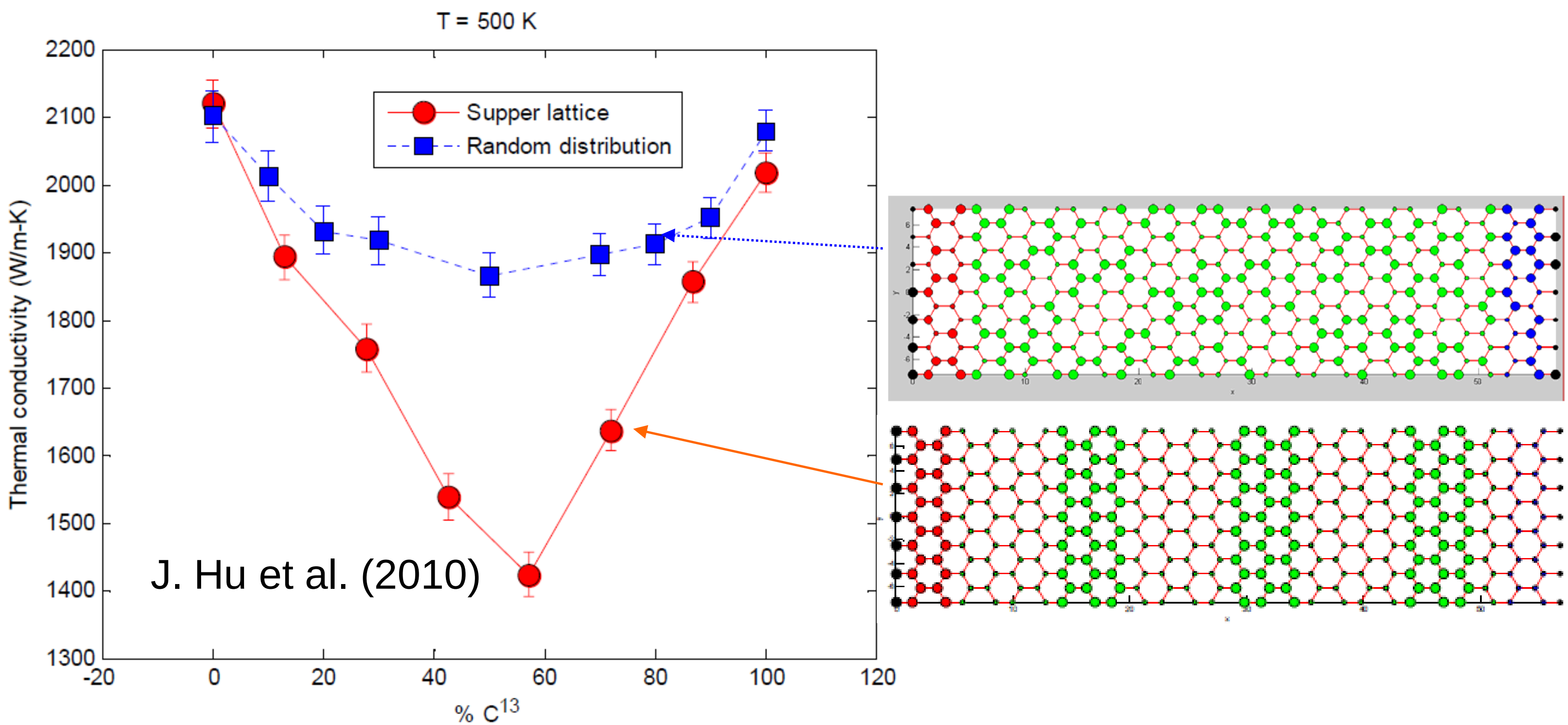


Thermal rectification in asymmetric GNR!

MD simulation of lattice thermal conductivity: J.Hu, X.Ruan, YPC, Nano Letters 9, 2730 (2009)

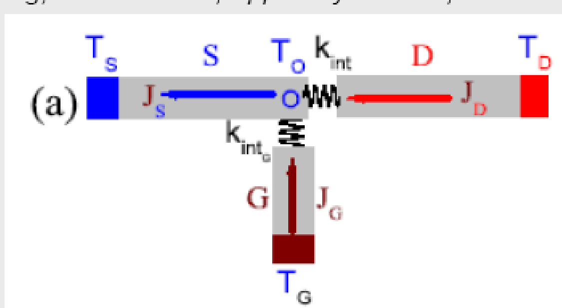
Method: Classical MD with Brenner potential and Nosé-Hoover thermostats: Fourier's law ➔ $\kappa = Jd/(\Delta Twh)$

Control thermal conductivity by engineering isotope distribution

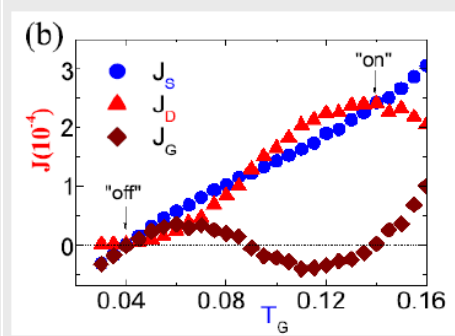


Thermal transistor

BL, L Wang, and G Casati, *Appl. Phy. Lett* 88, 143501 (2006).



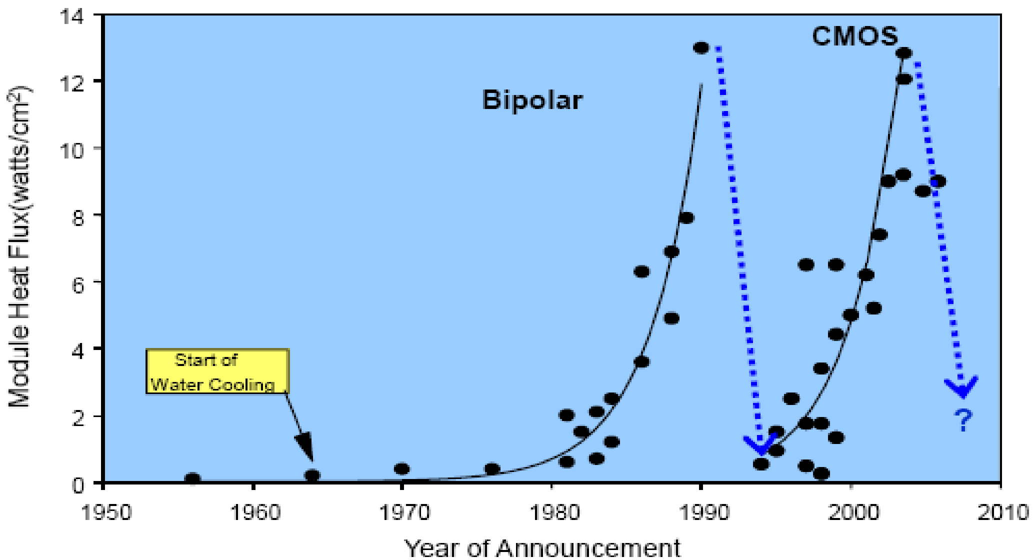
Function 1: Switch

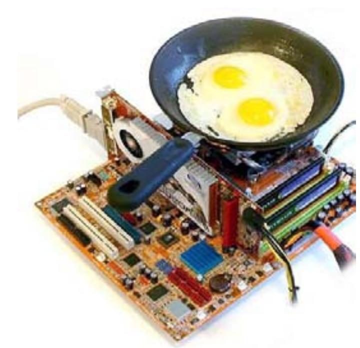


T_G=.04, .09, .14, J_G=0, J_D=2.4e-6, 1.1e-4, 2.3e-4

Graphene thermal interface

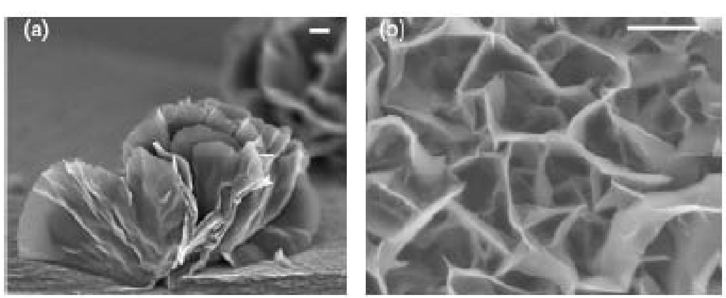
Heating pre-empties Moore's scaling



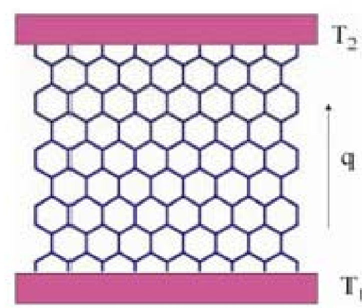


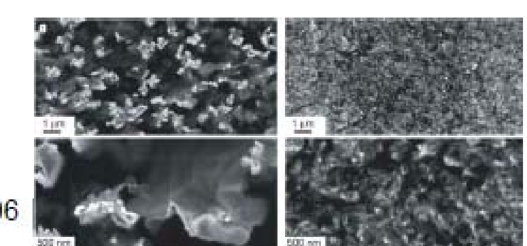
>300 W/cm² (core logic)
-- can't get this heat out!

Vertically aligned graphene-based **thermal interface** to aid vertical heat dissipation [Chen, Ruan and Fisher, Purdue CTRC]



Malesevic et al., Nanotechnology'2008





Stankovich et al., Nature'2006

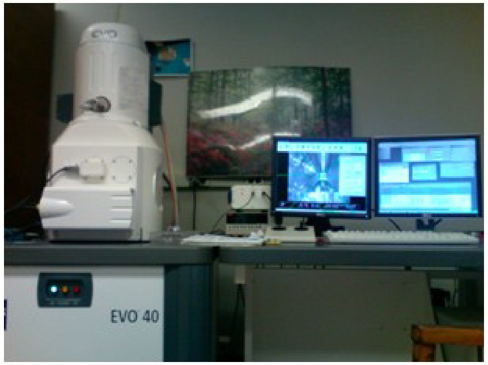
Large-scale, flexible and transferrable graphene by Ch... als

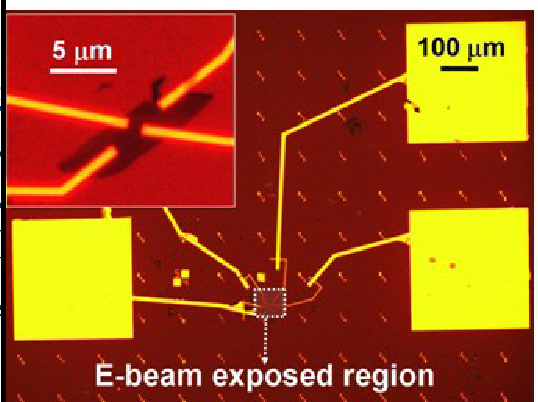
•CVD
Y
R
K
H
G

•CVD
X.
X.
M
H.
S.

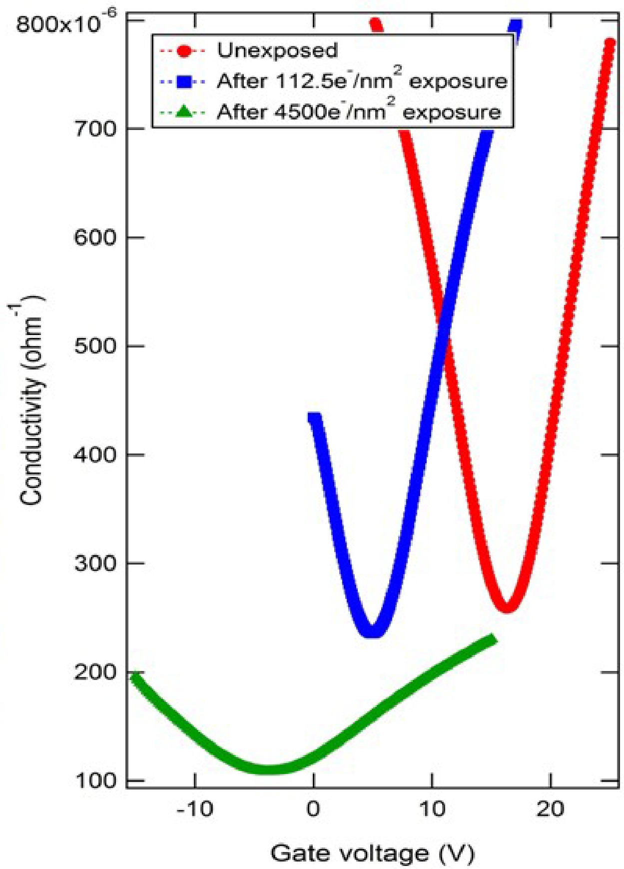
Surface+Transport

Irradiation with electron beams





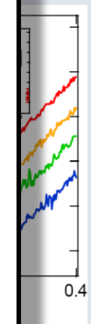
30keV electron beam
I= 0.15nA; Time=5mins;
Expose area: 50um x 50um
Estimated dose: 112.5 e-/nm^2



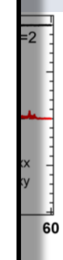
e- beam:
- *n*-dope graphene
- reduce mobility

I.Childres et al. AIP Conf. Proc. 1194, 140 (2009)
I.Childres et al, to be submitted (2010)

...ation

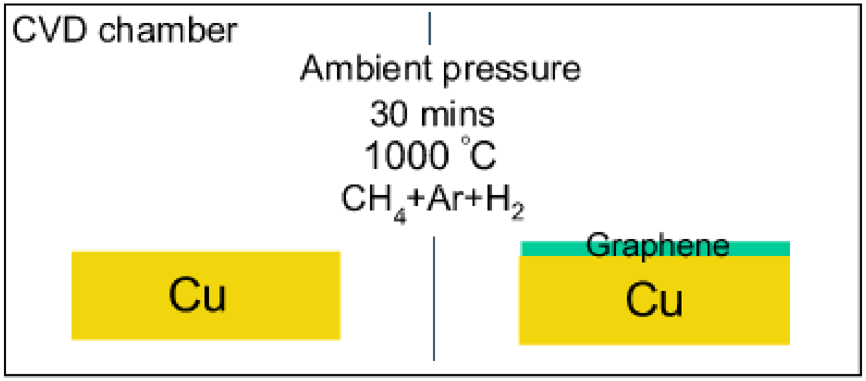


...ect

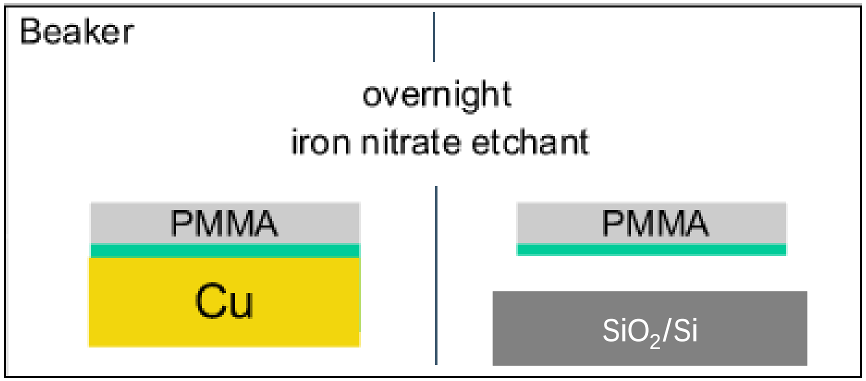


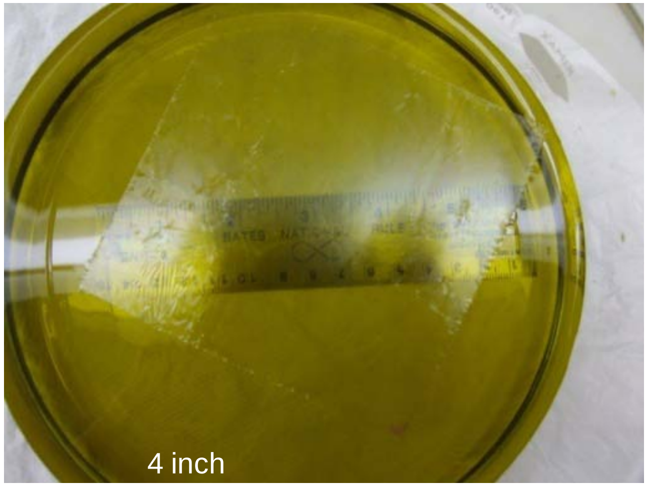
Graphene Growth by CVD on Cu at ambient pressure

1 CVD growth



2 transfer



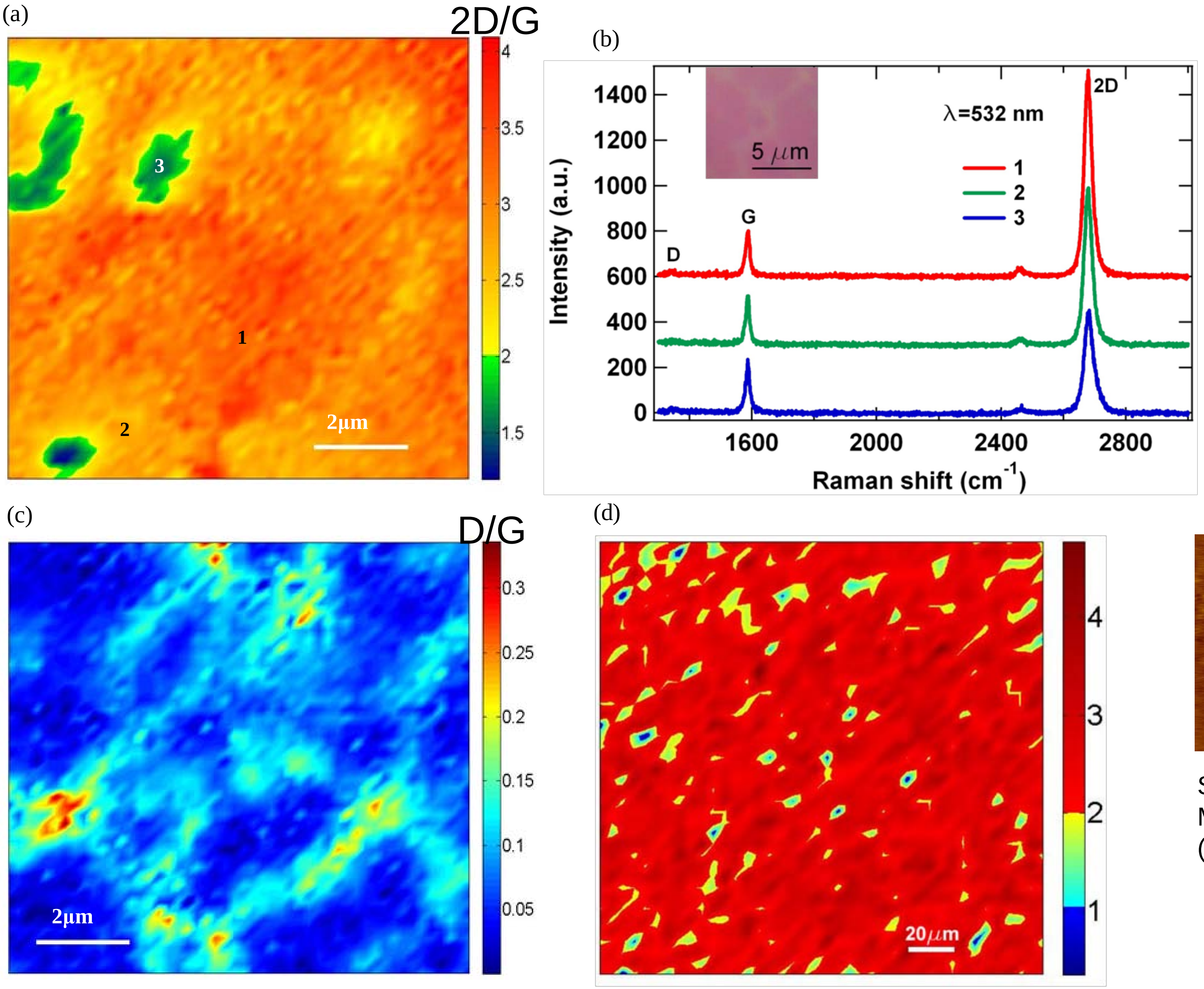


From Qingkai Yu (U Houston)

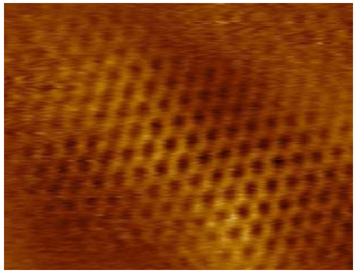
Thanks to Charles F. and Theresa Day
for donating furnaces

Helin Cao
cao2@purdue.edu

Raman Mapping: uniformity of graphene film



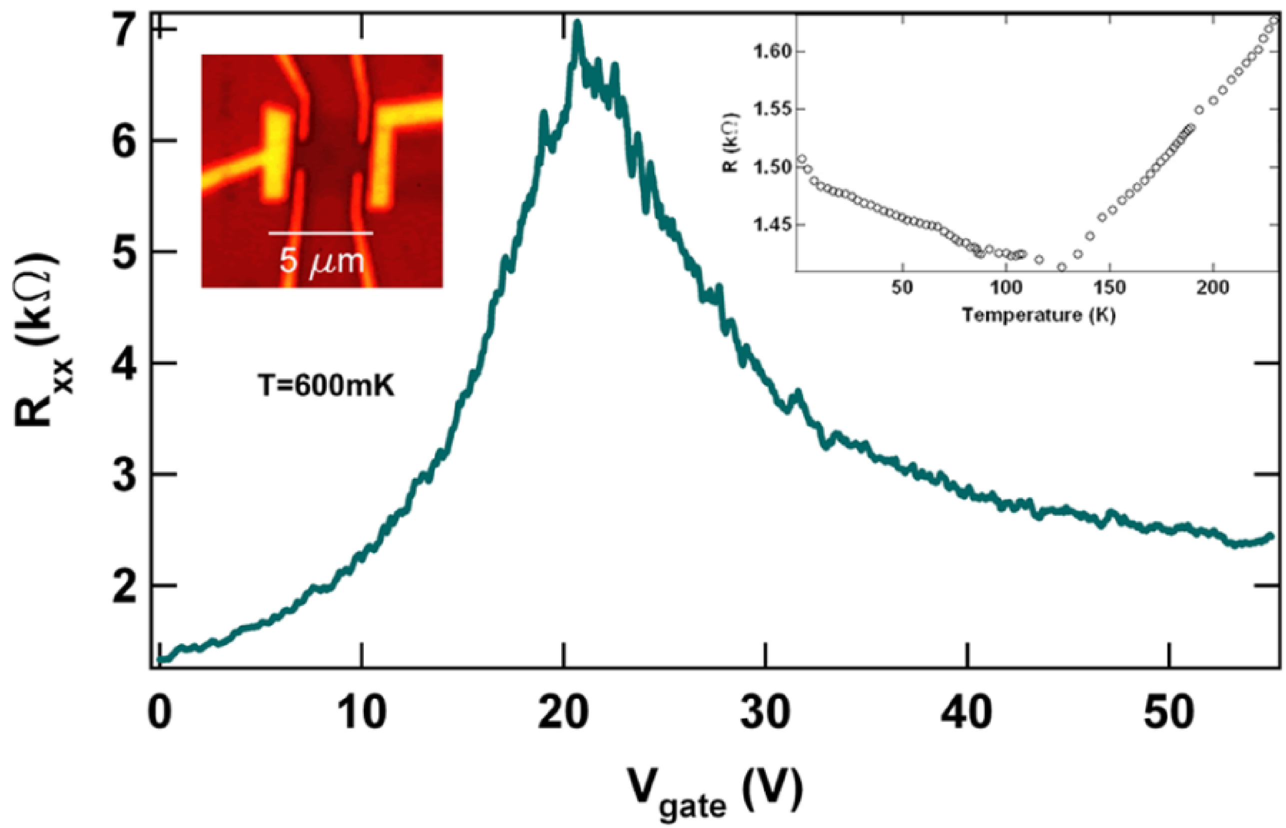
~90% area covered by monolayer graphene (2D/G>2)



STM image of Monolayer CVD graphene (collab. N.Guisinger, ANL)

H. Cao *et al.*, APL (2010)

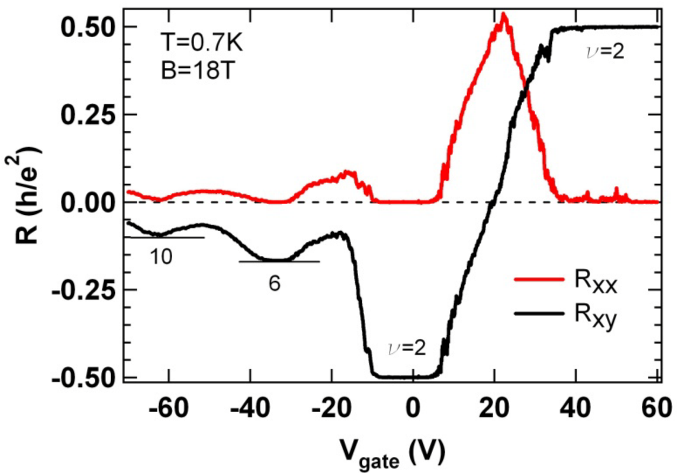
Field Effect

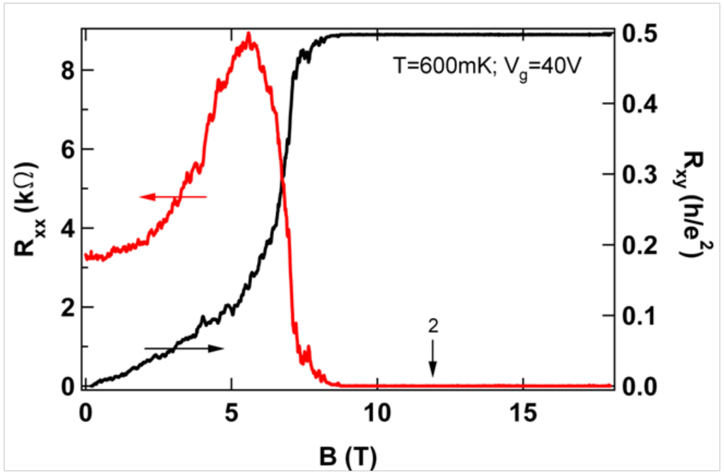


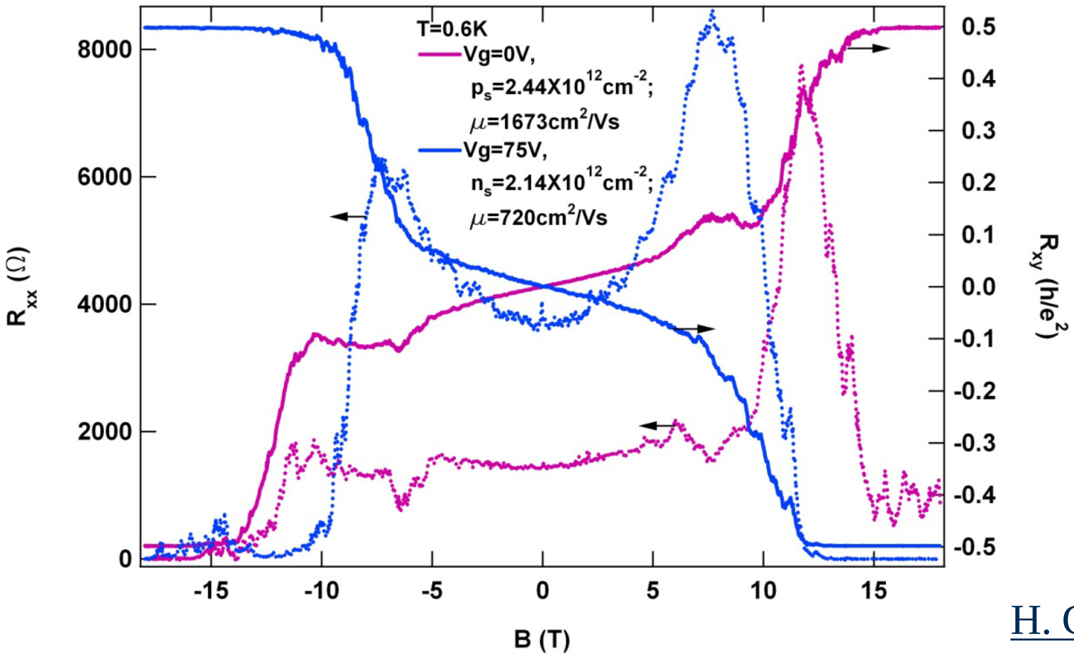
Mobilities up to 3000 cm^2/Vs
On/off ratio ~5

H. Cao *et al*., APL (2010)

Half-integer Quantum Hall Effect
--electronic hall-mark of monolayer graphene

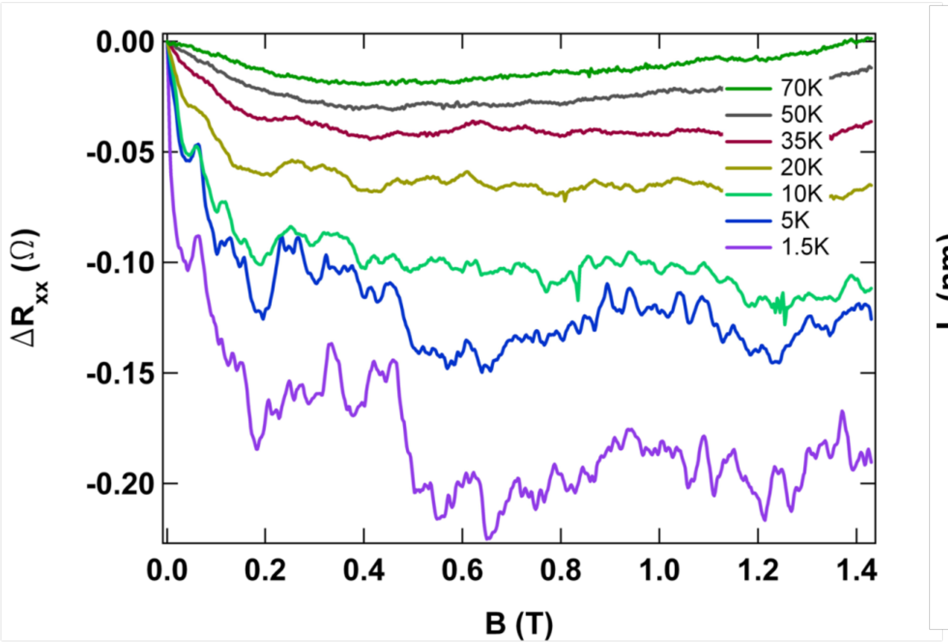


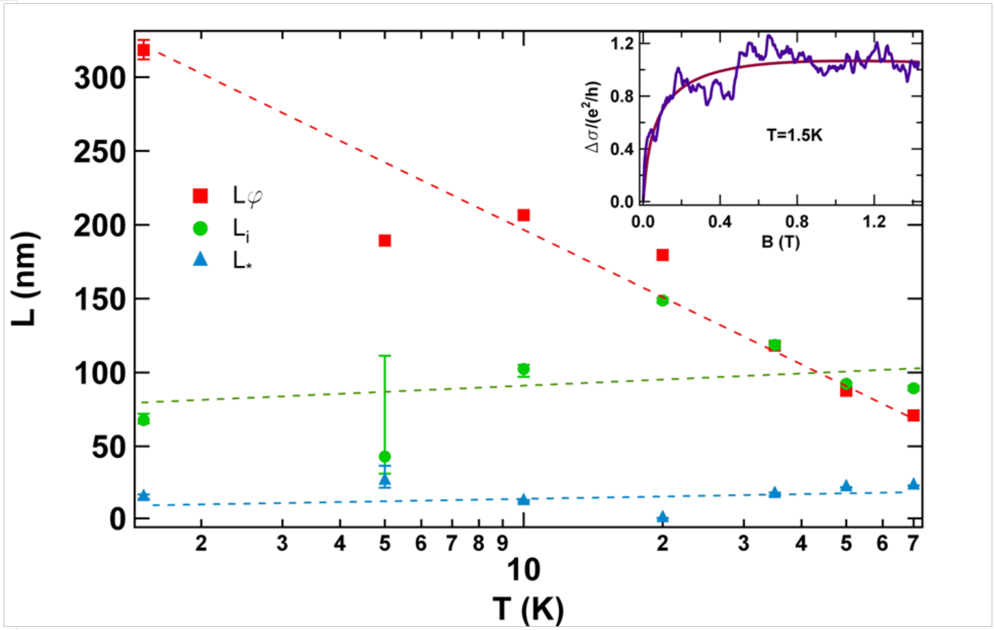


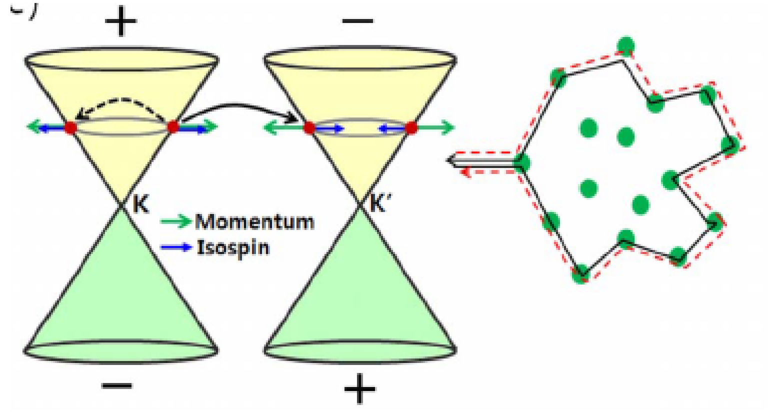


H. Cao *et al.*, APL (2010)

Weak Localization and Universal Conductance Fluctuation (UCF)







WL probes disorder and carrier scatterings (both inelastic & elastic in graphene)

H. Cao *et al.*, APL (2010)

Flexible, large-scale 2DES

- **Wafer-scale production of graphene is available, with intrinsic graphene properties**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Page last updated at 19:05 GMT, Wednesday, 14 January 2009

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Bendy gadget future for graphene

By Jason Palmer
Science and Technology reporter, BBC News

SCIENCE PHOTO LIBRARY

A pencil's 'lead' is primarily graphite, made up of millions of sheets of graphene

A remarkable material called graphene could soon be used to make flexible and transparent high-speed electronics, researchers say.

Graphene's incredible mechanical and electronic properties are well known, but it is difficult to make in bulk.

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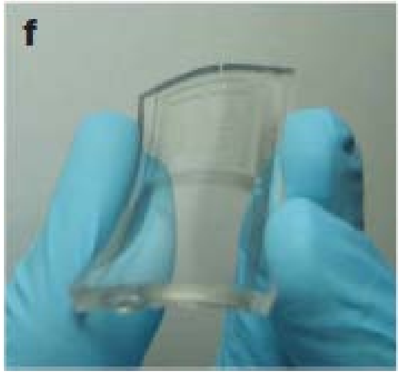
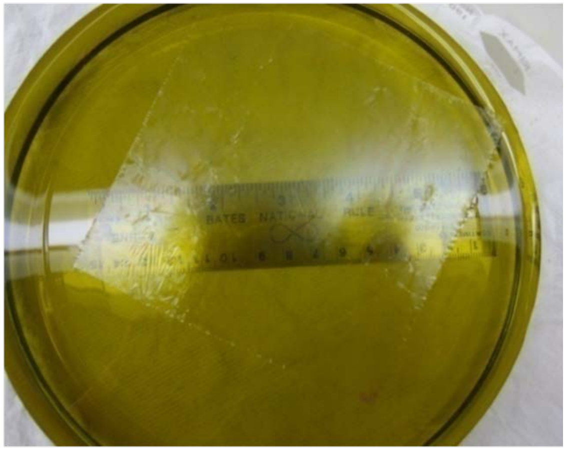
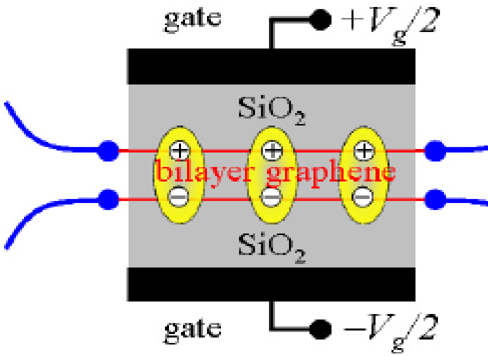
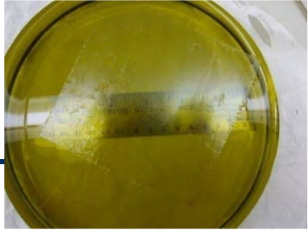


- **easily transferrable (to arbitrary substrates)**
  - build "multilayer" structure: excitonics!?
- **soft, flexible "curved" 2DES?**
  - guage field
  - strain engineering
  - effect of global geometry/topology on quantum electronic properties?

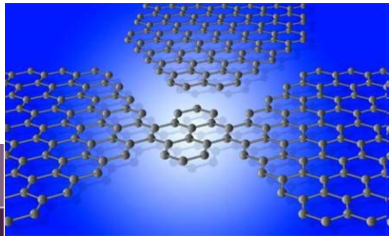




Summary & Outlook



- Graphene is a new and unique 2DES:
  - "relativistic" (**high energy** scale) --- massless chiral fermions
  - exposed surface: combining **transport** with **surface measurements** (Raman; SPM etc.) to get in depth understanding of what's going on
    - A tunable and sensitive playground to study fundamental surface physics and chemical processes!
    - Potential as sensor material & devices; heat management
  - Material maturity is still at early stage (compare with eg. GaAs) – but progresses extremely rapid
  - Soft, flexible, bendable, "curved" 2DES: significant for both practical and fundamental interests



Quantum Matter and Devices (QMD) Lab @ Purdue

- *Nanoscience (esp. graphene)*
- *Quantum Information (atoms)*

Question 1