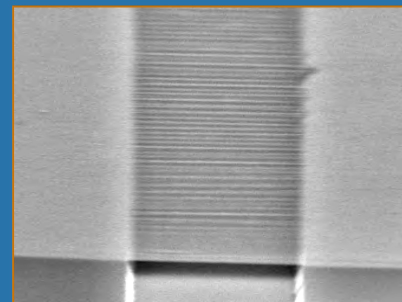
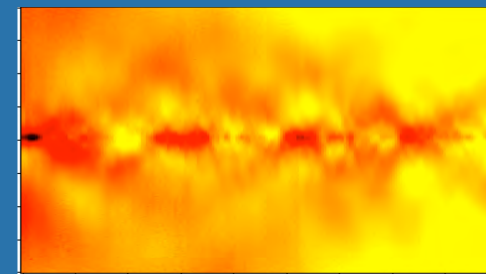
Chun Ning Lau
(Jeanie)

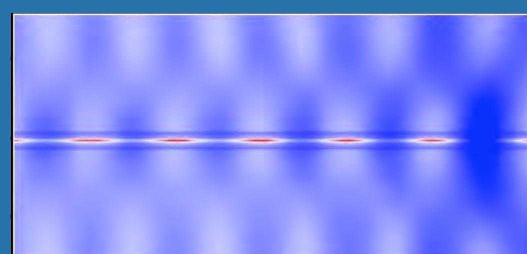
UNIVERSITY of CALIFORNIA
Riverside

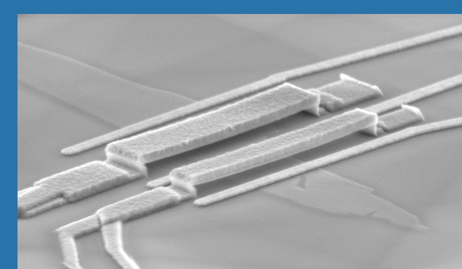
Department of
Physics





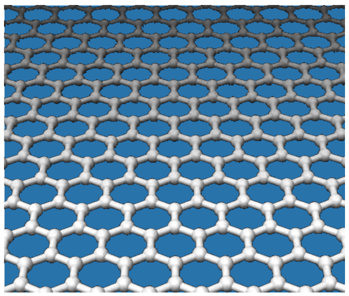
Graphene: Quantum Transport in a 2D Membrane

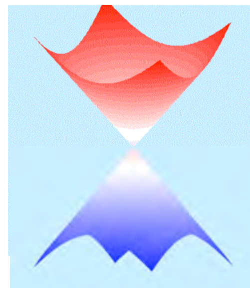


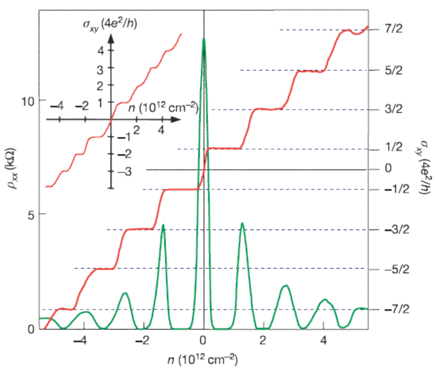


Graphene's Double Identity

Extraordinary Conductor







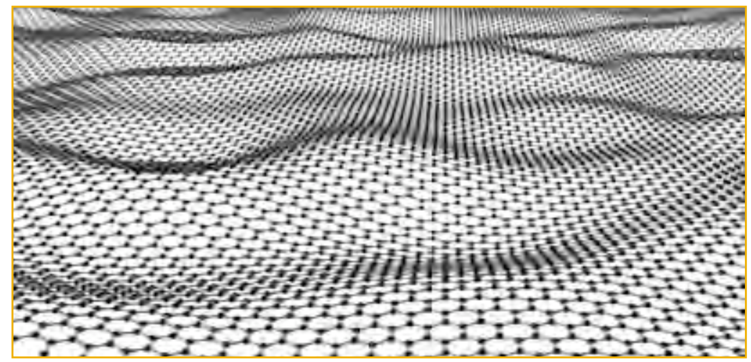
Novoselov *et al*
Nature 2005;

Zhang *et al*,
Nature 2005.

New model system for condensed matter research and electronic materials

Linear dispersion, tunable carrier, surface 2DEG, high thermal and electrical conductivity
….

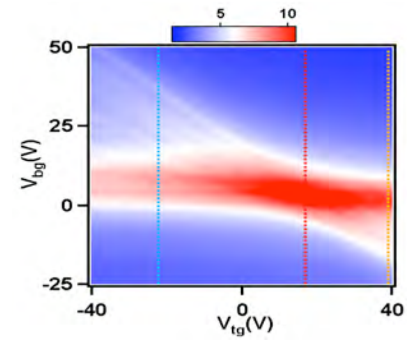
2D Elastic Membrane

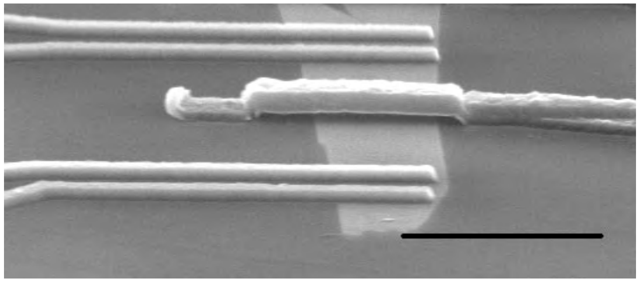


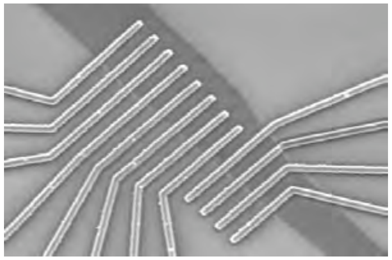
Thinnest isolated membrane with exceptional mechanical properties

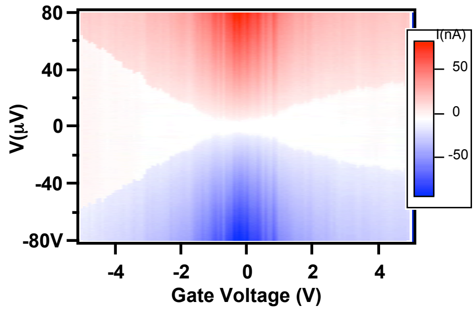
Outline

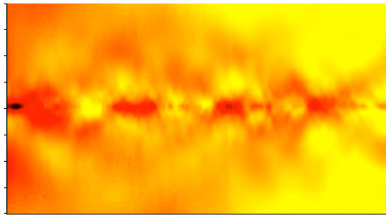
- Quantum Transport of charges
  - Tunable *pn* junctions
- Graphene as a 2D membrane
  - A new wrinkle









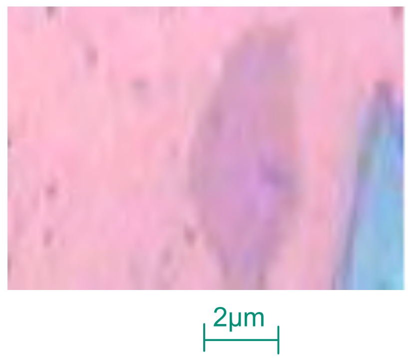


Extraction of Single- and Bi-Layer Graphene

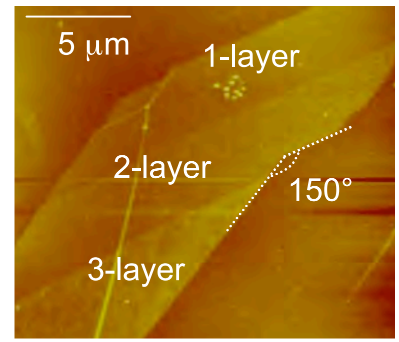
Optical Microscope

Single-layer graphene

Bi-layer graphene



AFM

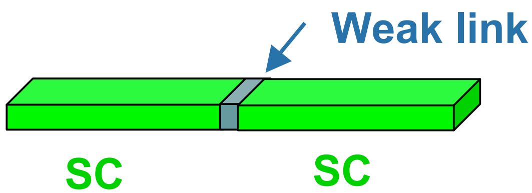


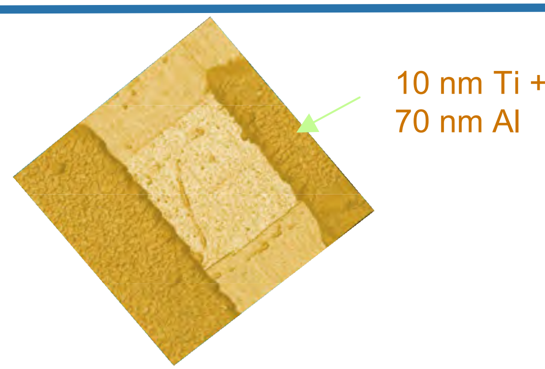
- Mechanical exfoliation -- rub graphite flakes onto SiO_2 substrates

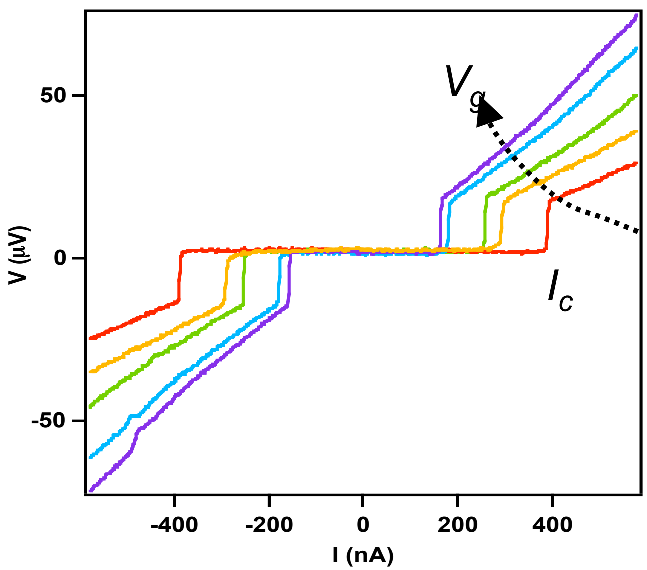
- Identify the number of layers by
  - Raman spectroscopy
  - Transport measurement
  - Color contrast in an optical microscope

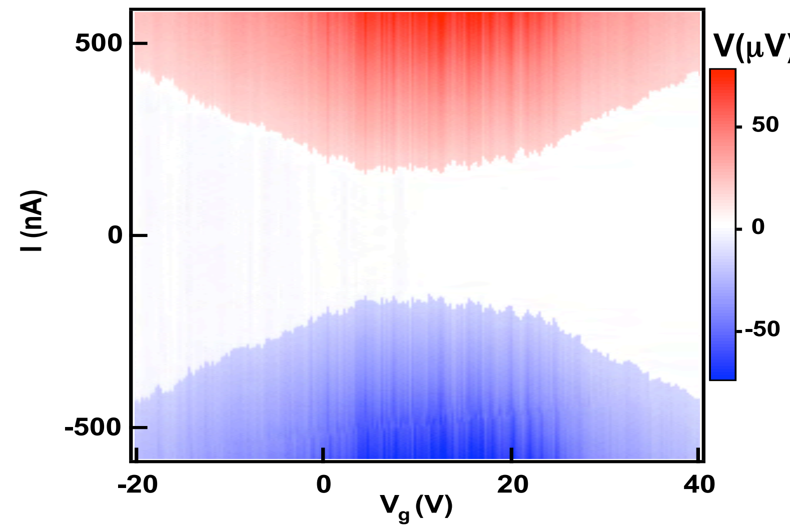
- AFM images reveal mesoscopic features

Graphene Supercurrent Transistor









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

Miao, Bao, Zhang, CNL, Solid State Comm.(2009)

Graphene *p-n* Junctions

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

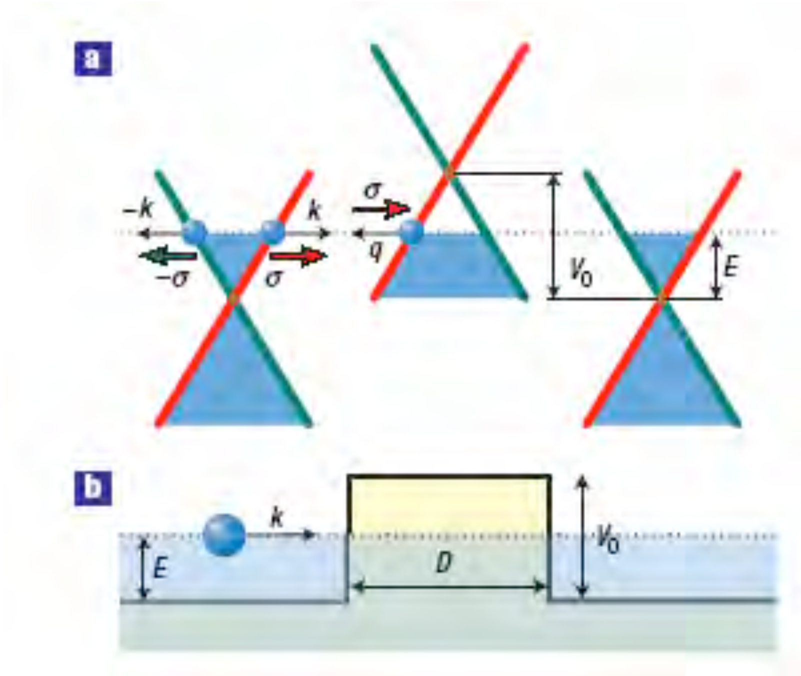
- Graphene p-n junctions with top gate(s):
  - allow *in situ* tuning of junction polarity and dopant levels

- Application
  - Klein tunneling
    (perfect transmission of relativistic particles across high barrier)
    recent evidence: Kim's group, Goldhaber-Gordon's group, & Savchenko's group.
  - Veselago lensing (optics-like focusing of electron rays)
  - Band gap engineering of bi-layer graphene
  - Particle collimation
  - Valley polarization

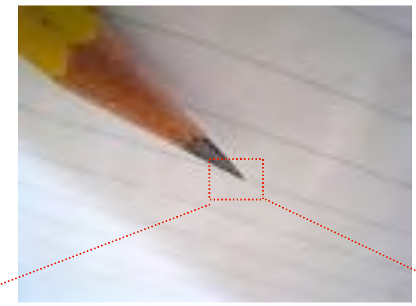
Theories: Abanin *et al* 2006, 2007; Fogler *et al* 2007; Shytov *et al* 2007; Katsnelson *et al* 2006; Beenakker group, Cheianov *et al* 2006, 2007
Experimental demonstration: Huard *et al* 2007; Williams *et al* 2007, Ozyilmaz *et al* 2007, Oostinga *et al* 2007

Klein Tunneling

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



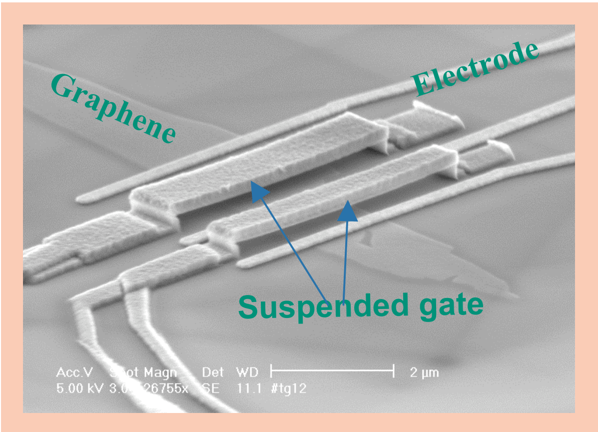
Cheianov and Falko, PRB (2006).
Katsnelson *et al*, Nature Physics (2006).

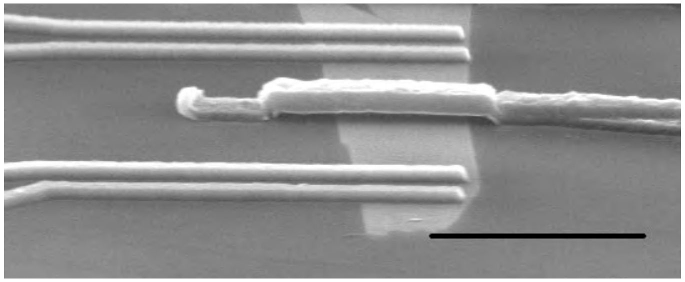


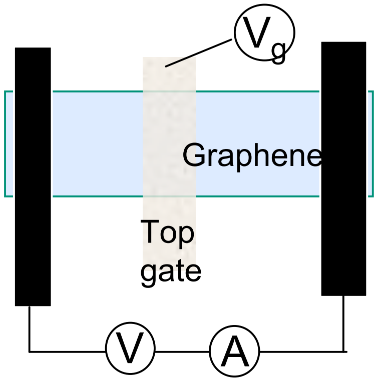
- Thought to be realizable at the edge of blackholes
- Graphene: electrons in conduction band → holes in valence band
- Transmission probability depends on incidence angle

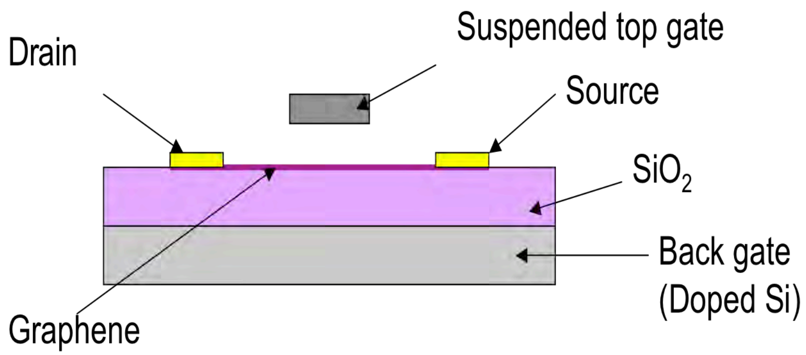
Graphene *p-n* Junctions

- 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

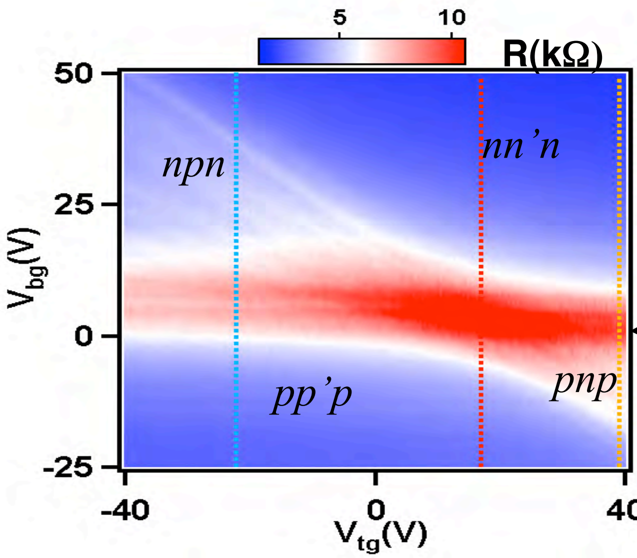






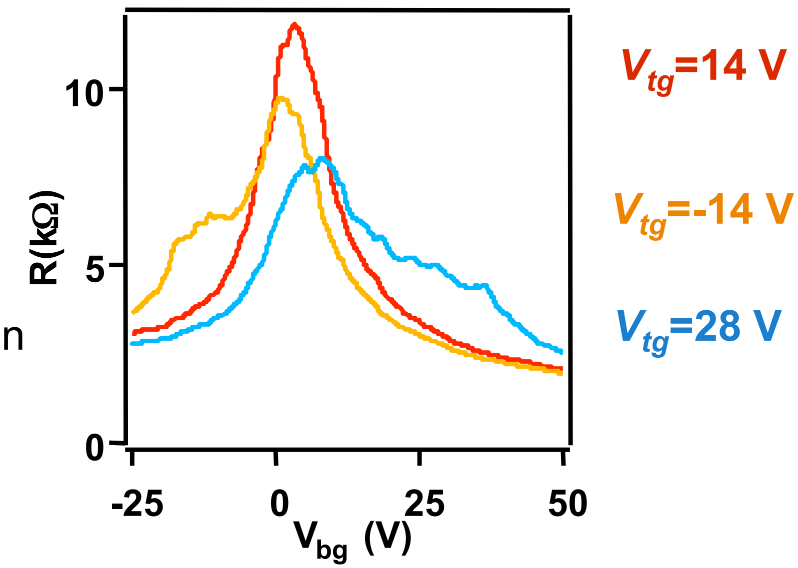


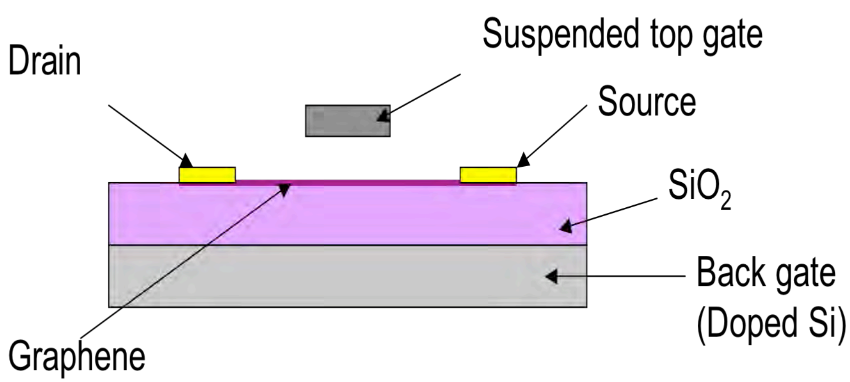
Conductance of *p-n-p* Junctions



Dirac point of the "bare" region

Dirac point of the top gated region

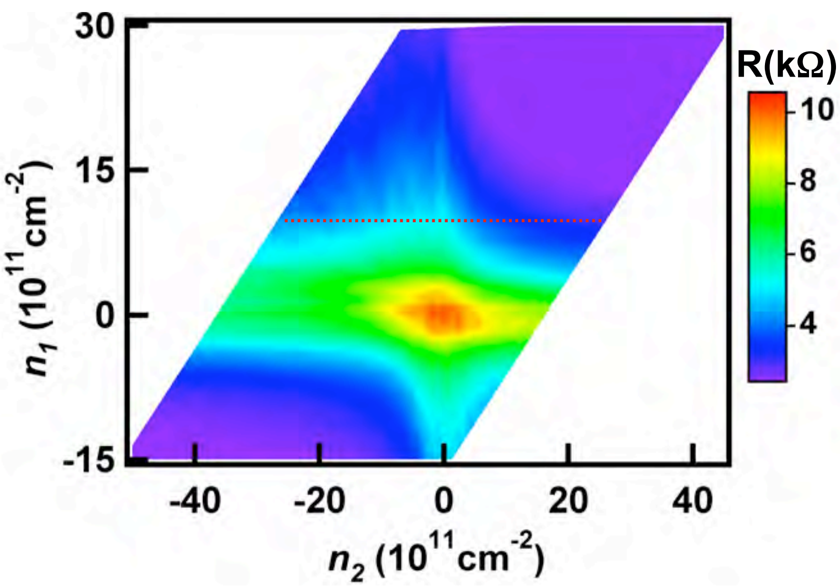


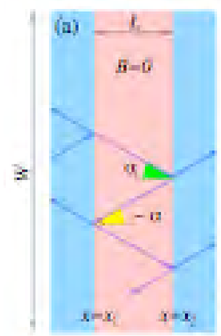


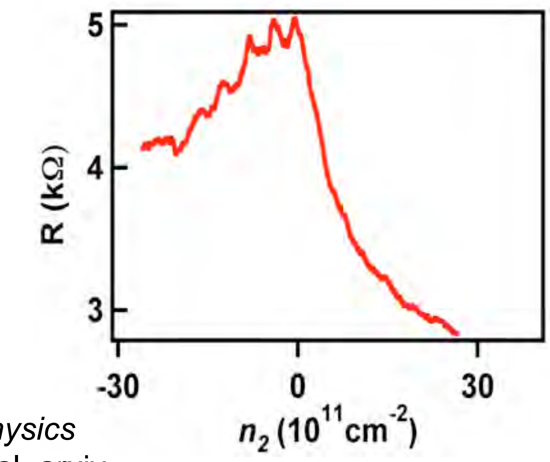
•Individual control of charge density and type of different regions

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

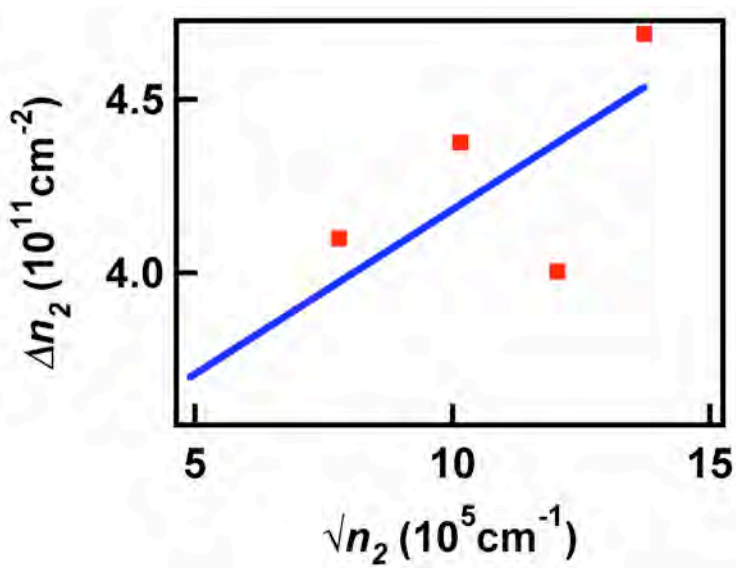
Fabry Perot Interference







Young and Kim, *Nature Physics* (2009); Shytov, Levitov et al, arxiv (2008).



•Fabry Perot Interference of holes at *pn* interferences

• between successive peaks $k_F\,(2L) = 2\pi$

$$\Delta n_2 = \frac{4\sqrt{\pi n_2}}{L}$$

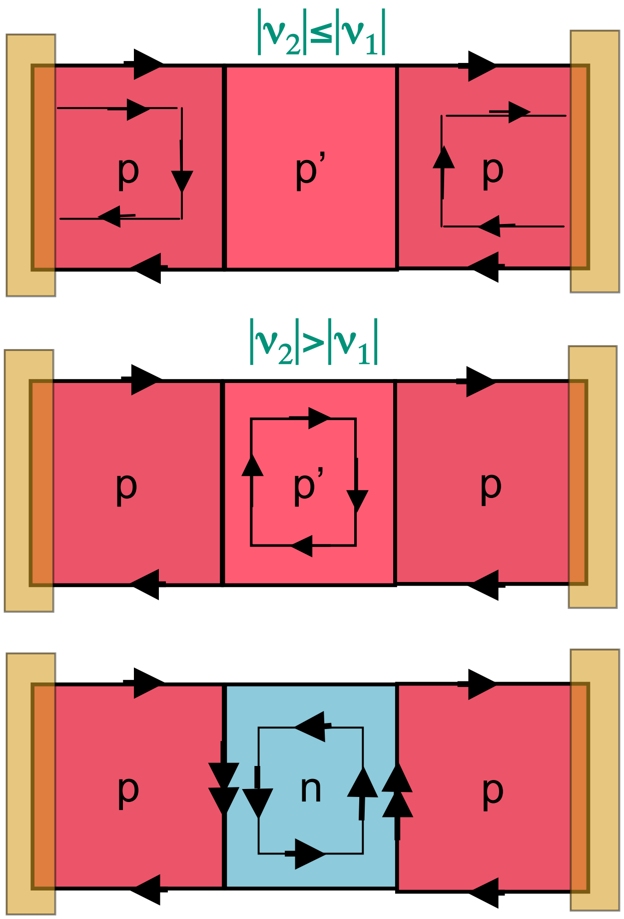
• slope of linear fit: ~ 1 x 10^5 /cm

→ *L* ~ 740 nm

•width of top gate ~ 500 nm, distance from substrate ~ 100 nm

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

- Quantum Hall plateau at fractional values of e^2/h
- Edge state equilibration, full mixing of propagation modes at interfaces
- Full and partial edge state equilibration



Edge State transmission **B=8T**

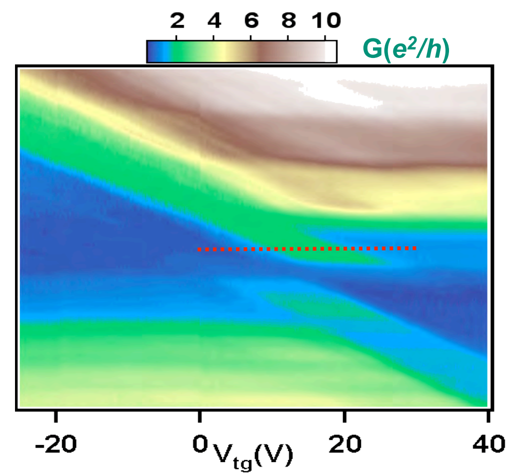
$$G = \frac{e^2}{h}\min(|\nu_1|,|\nu_2|)$$

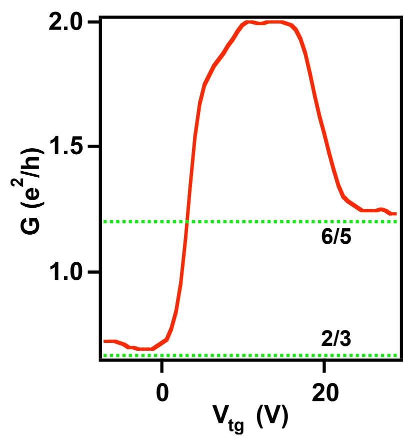
Partial Equilibration

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

Full Equilibration

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





Marcus group, *Science* (2007).

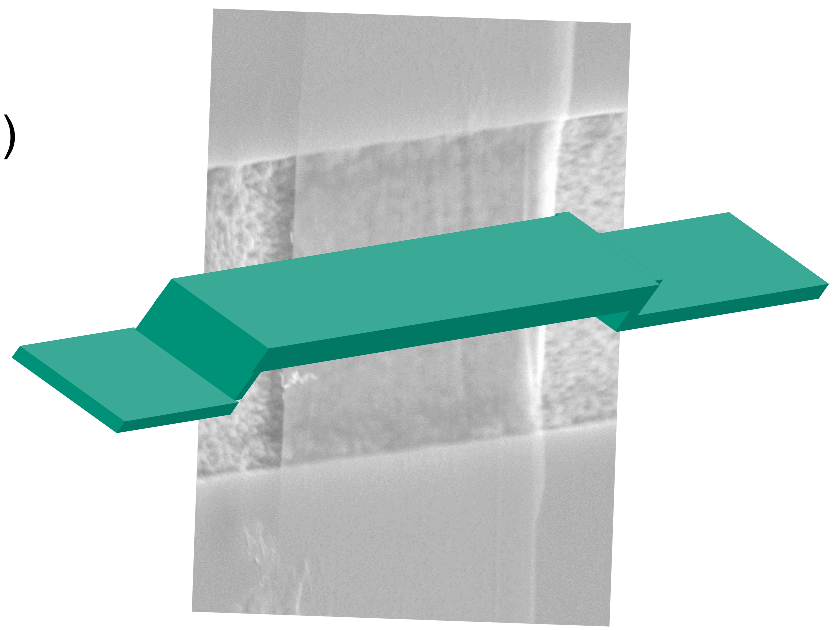
G. Liu, J. Velasco Jr, C.N. Lau, APL (2008)

Abanin & Levitov, *Science* (2007). Ozyilmaz *et al* , *PRL* 2007

Future Work

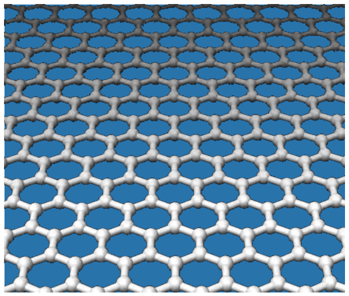
- Spin transport in p-n junctions
- Junction shape
- Veselago Lensing
  (requires extremely clean devices
  →suspended graphene + suspended gate?)
- Supercurrent in p-n junctions

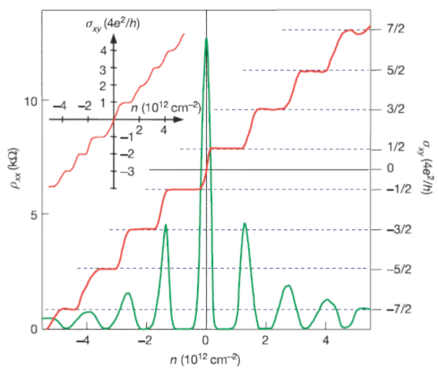
Abanine & Levitov, PRB, 2008; Cheianov *et al* 2006, 2007, Fogler et al, 2008; Zhang & Fogler, 2008.



Graphene's Double Identity

Extraordinary Conductor





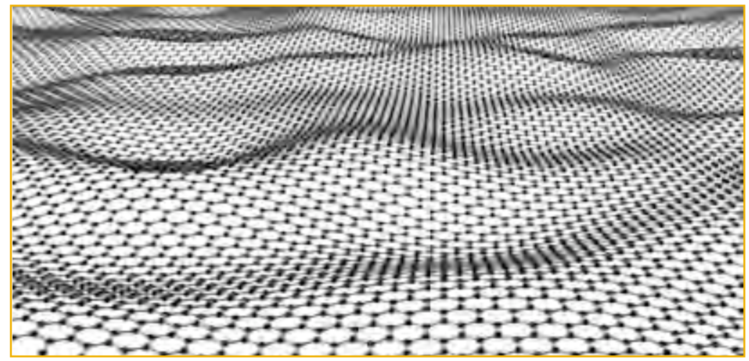
Novoselov *et al* *Nature* 2005;

Zhang *et al*, Nature 2005.

New model system for condensed matter research and electronic materials

Linear dispersion, tunable carrier, surface 2DEG, high thermal and electrical conductivity ….

The Softer Side of Graphene



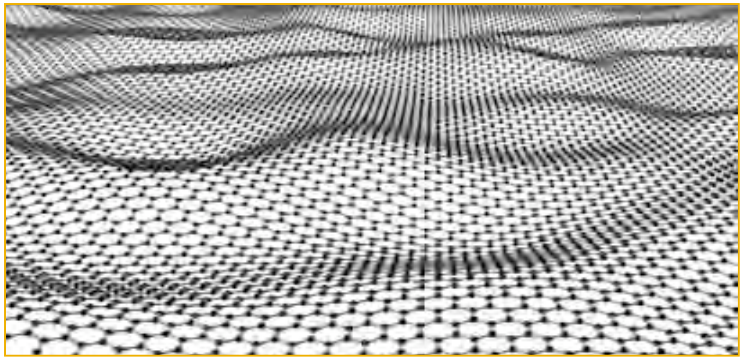
Collaborator: Chris Dames, ME@UCR

Thinnest isolated membrane with exceptional mechanical properties

Ripples in Graphene

- Presence of ripples in suspended graphene
- *inferred* from electron diffraction patterns
- Significant implication on electrical transport properties
  - induce local gauge field
  - change local chemical potential
  - ultimate bottleneck for mobility?

(Theories by Louie, Castro Neto, Katnelson, Guinea, Herbut *et al*, Juan *et al*…)



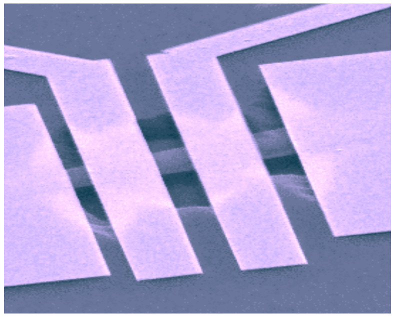
Meyer *et al*, Nature (2007)

No direct observation of ripples

(Attempts to) Fabricate Suspended Graphene Devices

<u>Successful Technique</u> (Kim and Andrei groups, 2008)

- Exfoliate graphene onto substrates
- Deposit electrodes
- Release completed devices from SiO_2 using HF etching
- Anneal
- Observed much higher mobility (up to 250,000)

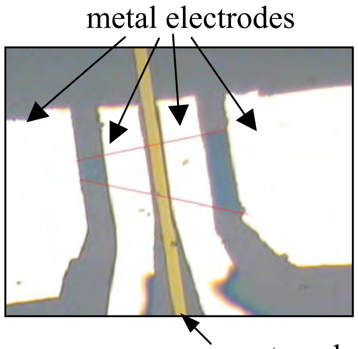


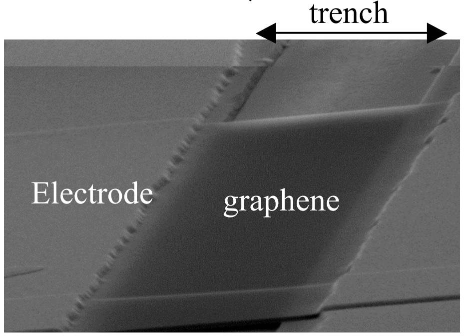
Du et al, *Nature Physics* (2008)

<u>Our technique</u>

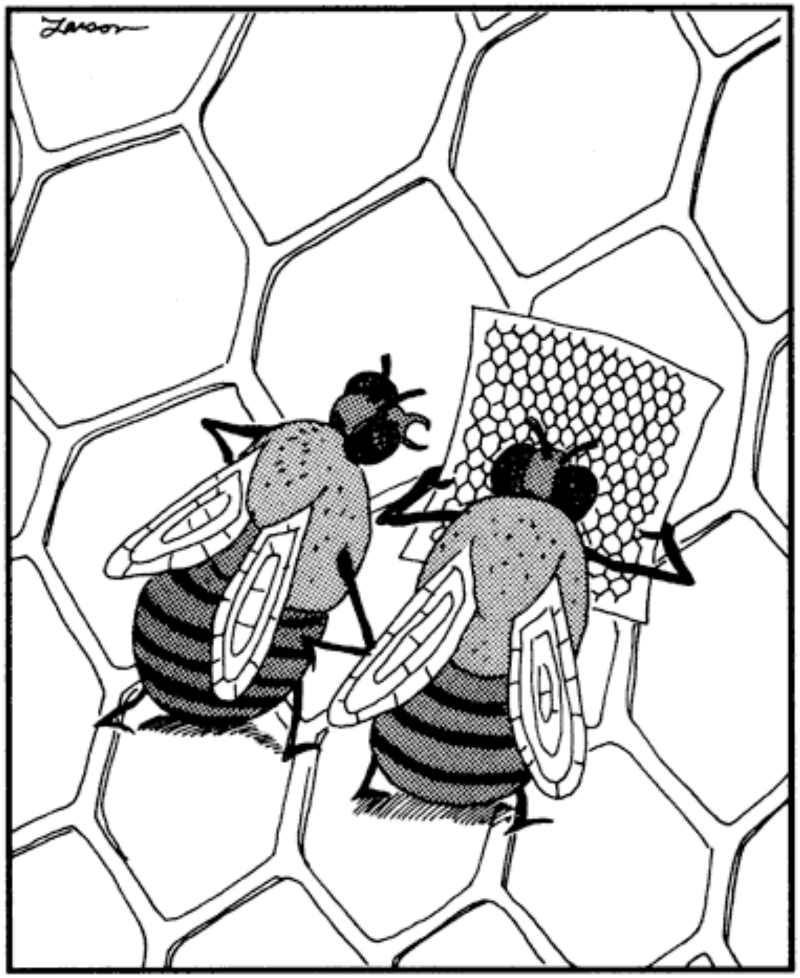
- Etch trenches on substrates
- Directly exfoliate graphene sheets across trenches
- Deposit electrodes
- Anneal
- Initial test: very low mobility (~100-500)

our typical substrate-supported devices: ~ 2,000-10,000





Huh?

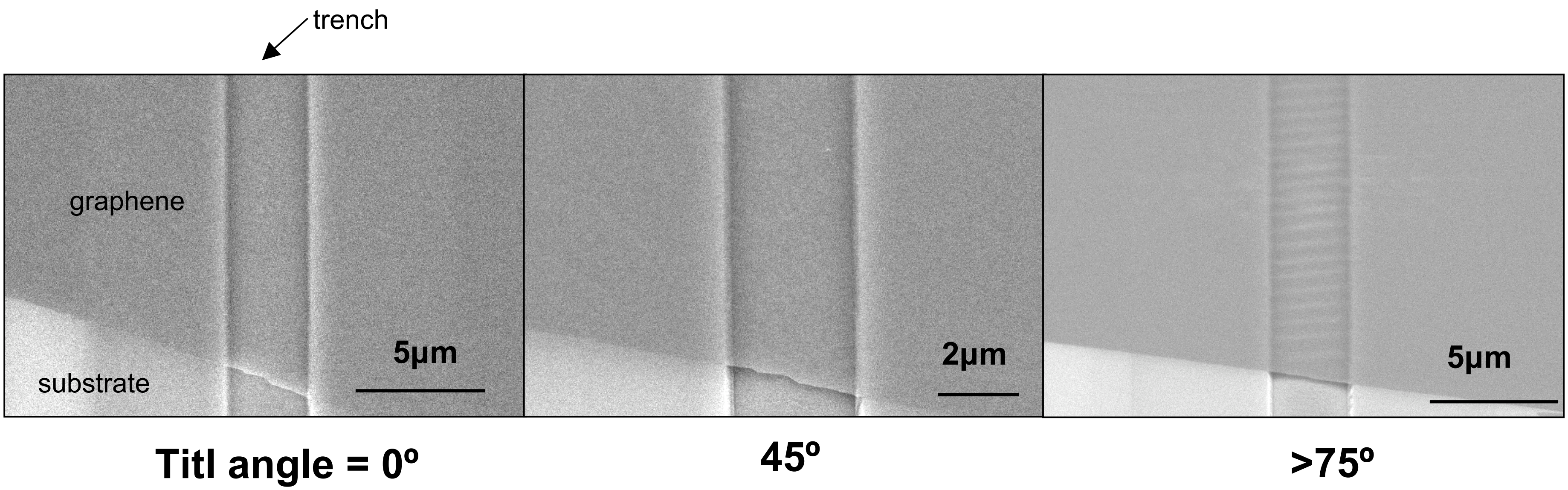


“Face it, ~~Fred~~—you’re lost!”
Jeanie

“read the map!”

Imaging Suspended Graphene

- Directly exfoliate graphene sheets across pre-defined trenches
- Image under SEM

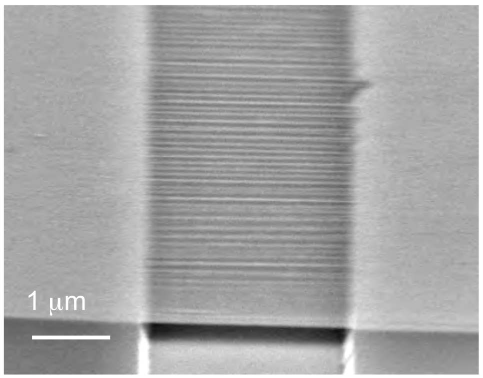


Spontaneous, Periodic Ripple Formation in Graphene

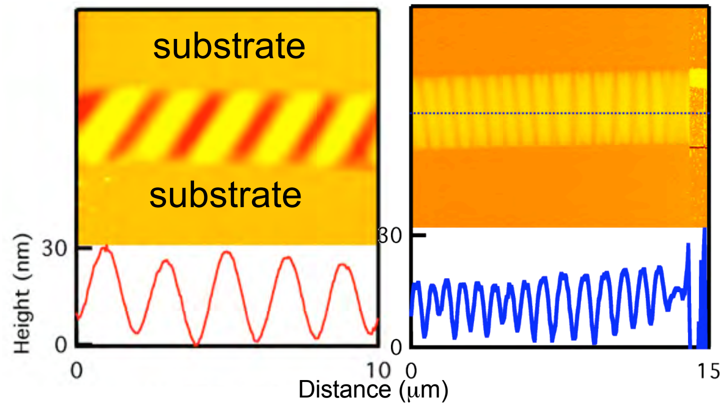
Directly exfoliate graphene sheets across pre-defined trenches

- Many graphene sheets are not flat, but spontaneously form ripples
- Almost perfectly sinusoidal profile
  - ♦ thickness: 0.3 nm (single layer) -- 16 nm
  - ♦ amplitude: 0.7 to 30 nm
  - ♦ wavelength: 370 nm -- 5 μm

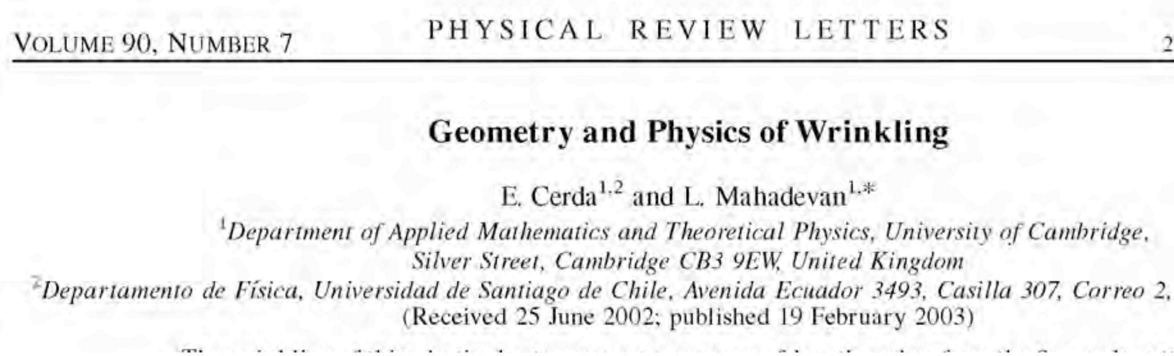
SEM



AFM



Origin of Ripples


VOLUME 90, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 21 FEBRUARY 2003

Geometry and Physics of Wrinkling

E. Cerda[1,2] and L. Mahadevan[1,*]
[1]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, United Kingdom*
[2]*Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, Casilla 307, Correo 2,*
(Received 25 June 2002; published 19 February 2003)

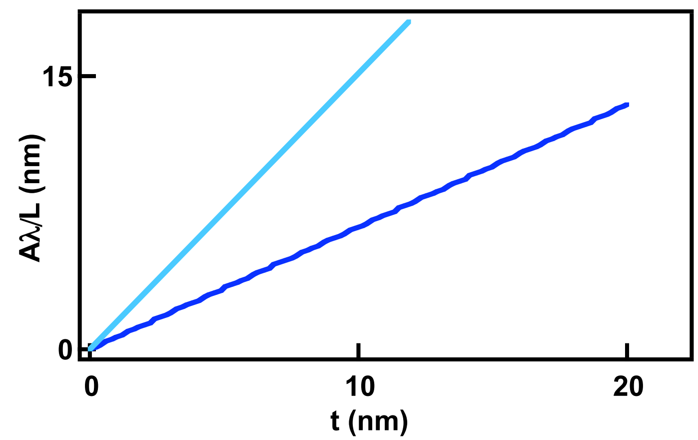
- competition between bending and stretching
- ripples can be induced by longitudinal strains or shears

$$\frac{A\lambda}{L} = \sqrt{\frac{8\nu}{3(1-\nu^2)}}\,t$$

in-plane shear

$$\frac{A\lambda}{L} = \sqrt{\frac{8}{3(1+\nu)}}\,t$$

in-plane strain



A=amplitude, *L*=length, λ=wavelength,
t=thickness, ν=Poisson ratio ~0.165

Graphene as an Elastic Membrane

VOLUME 90, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 21 FEBRUARY 2003

Geometry and Physics of Wrinkling

E. Cerda[1,2] and L. Mahadevan[1,*]
[1]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, United Kingdom*
[2]*Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, Casilla 307, Correo 2, Santiago, Chile*
(Received 25 June 2002; published 19 February 2003)

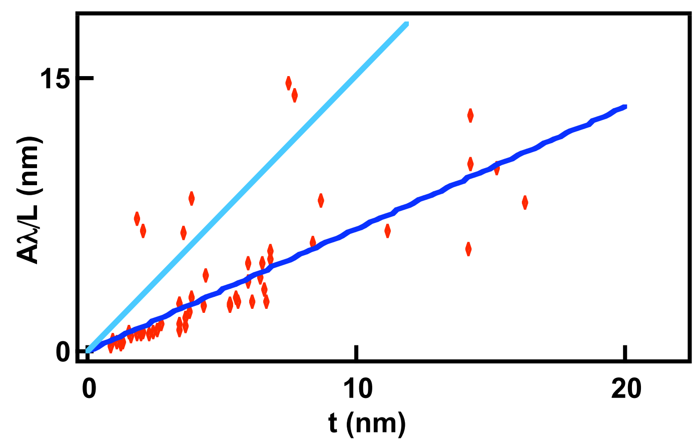
- competition between bending and stretching
- ripples induced by longitudinal strains or shears

$$\frac{A\lambda}{L} = \sqrt{\frac{8\nu}{3(1-\nu^2)}t}$$ in-plane shear

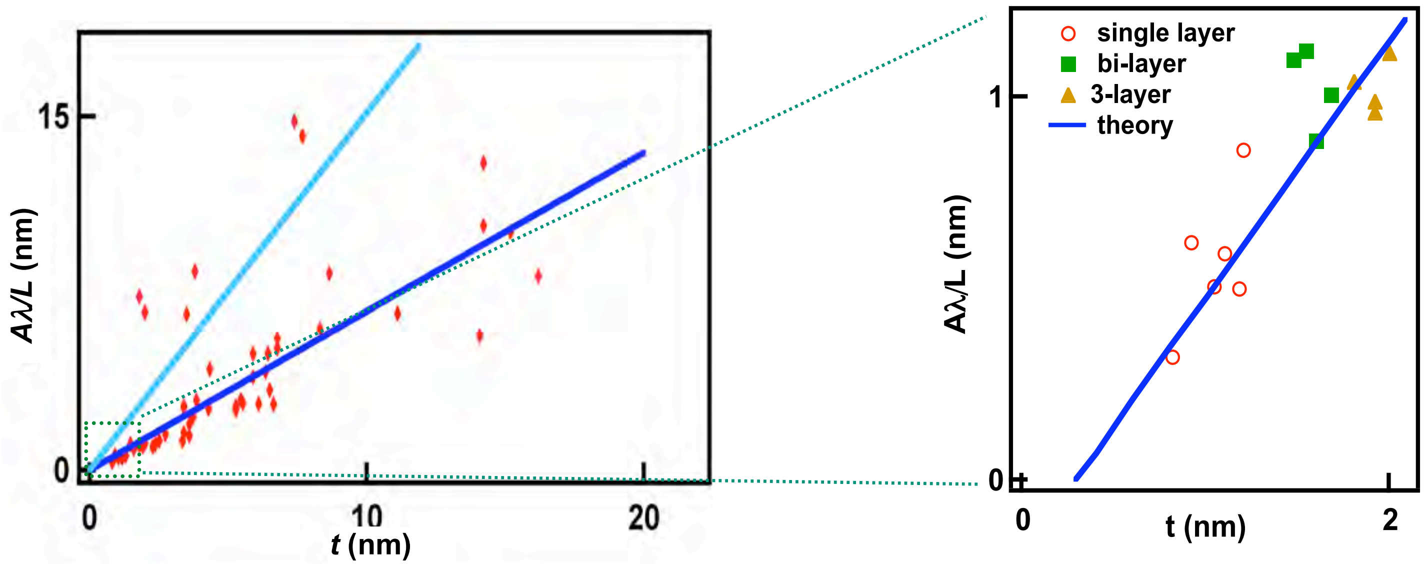
$$\frac{A\lambda}{L} = \sqrt{\frac{8}{3(1+\nu)}t}$$ in-plane strain

A=amplitude, *L*=length, λ=wavelength,
t=thickness, ν=Poisson ratio~0.165

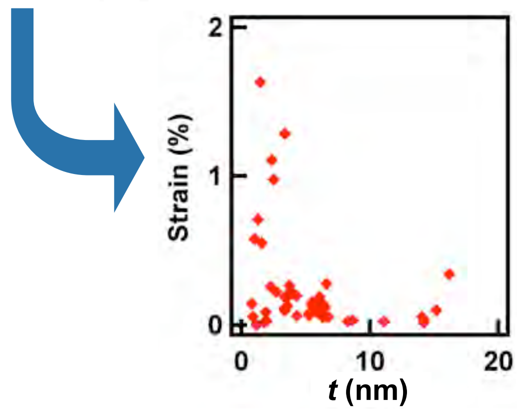
Data from 51 samples



Strain-Induced Ripples in *Atomic* Membranes



strain $\gamma = \dfrac{4\pi^2}{3(1-\nu^2)} \dfrac{(tL)^2}{\lambda^4}$

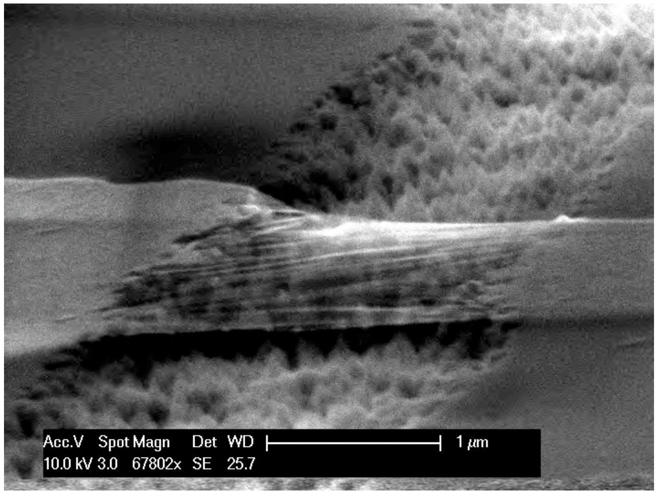


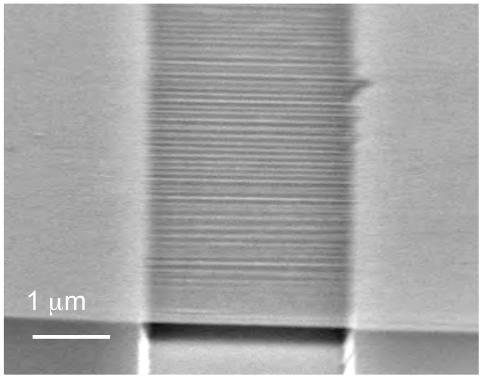
- Membranes that are a few atomic layers thick obeys thin film mechanics
- Larger range of strains (up to 2%) observed for thinner membranes

Graphene as the World's thinnest Saran Wrap

macroscopic

mesoscopic



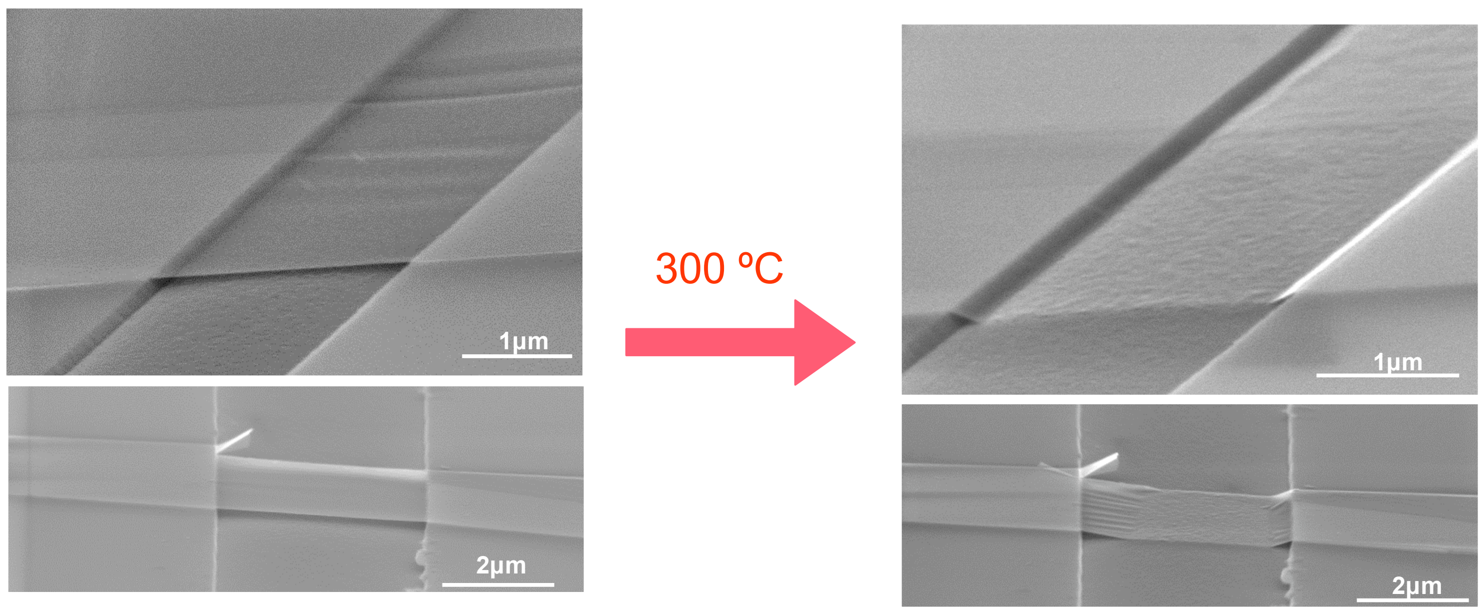


Device Fabrication Attempt

Ripples are the culprits for low mobility of our devices?

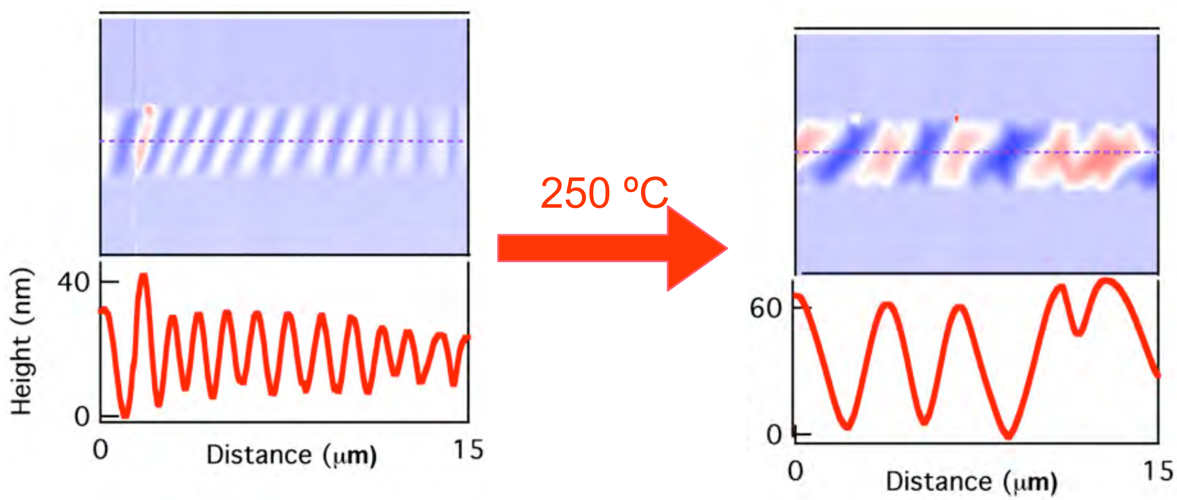
Not so fast!

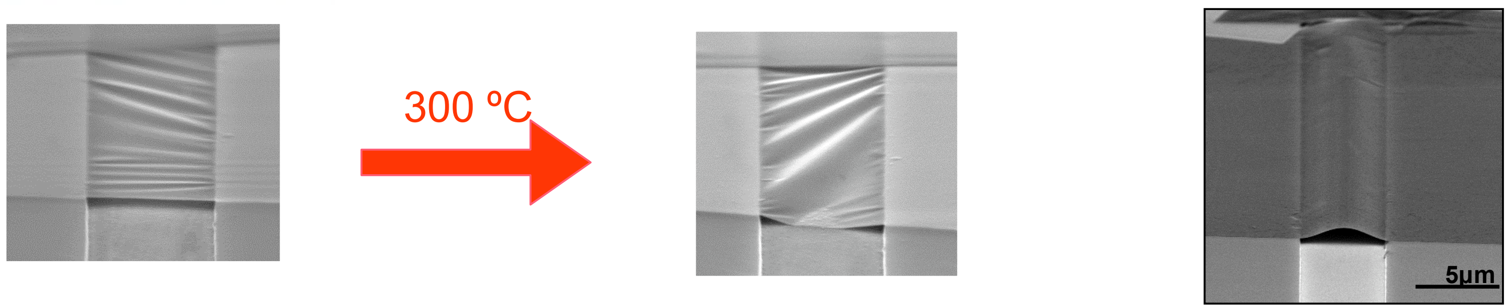
Devices were annealed to improve mobility



→ graphene sheets collapsed

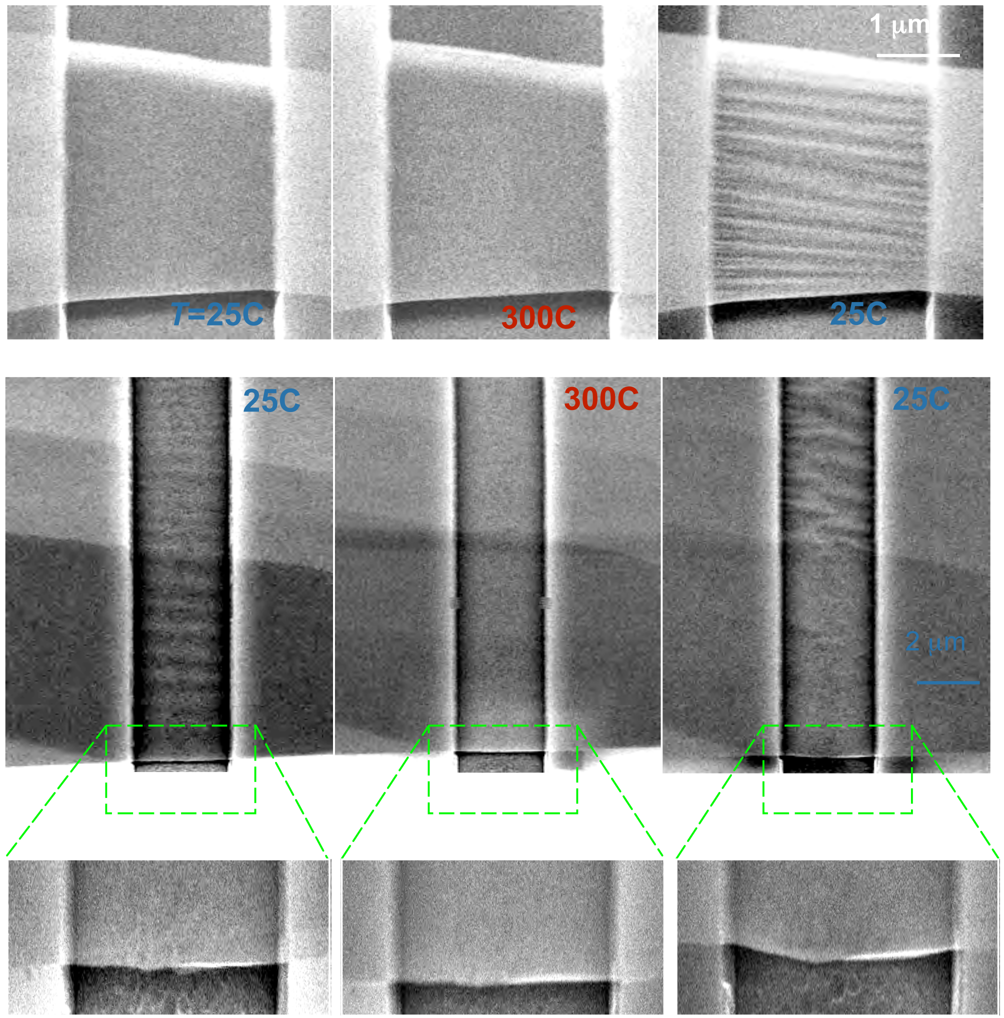
Thermal Effect on Ripples



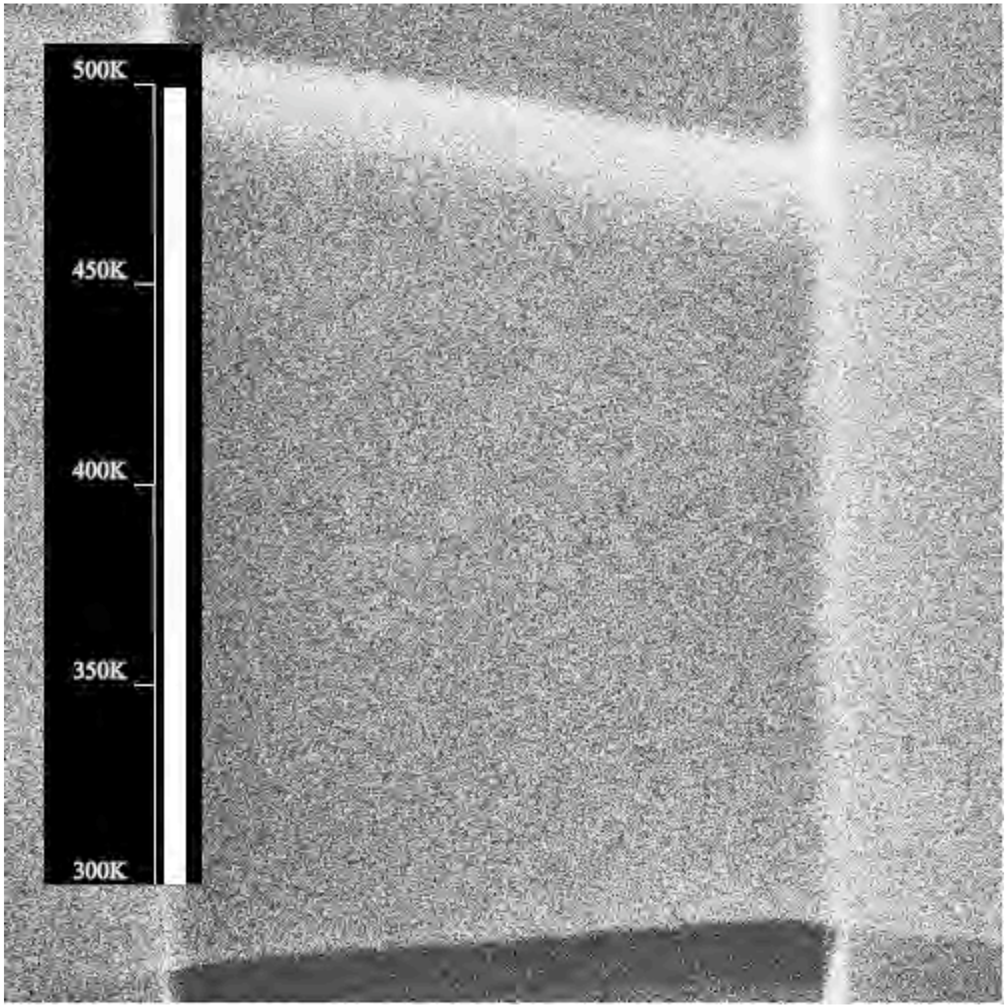


- Ripples have larger wavelengths and amplitudes
- Membranes buckles upward or towards the bottom of the trench

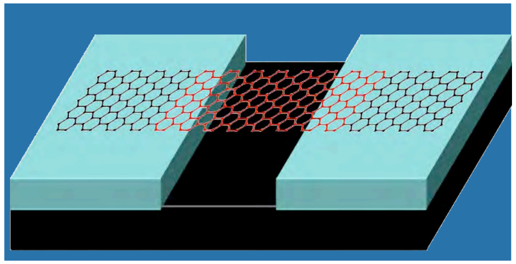
In Situ SEM imaging of ripple formation



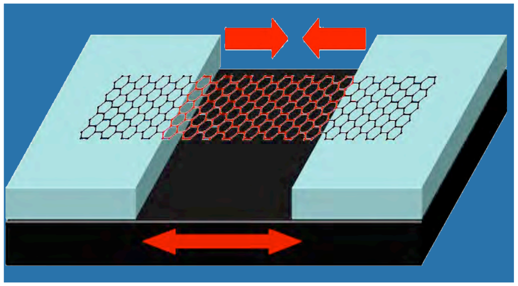
Movie of ripple formation



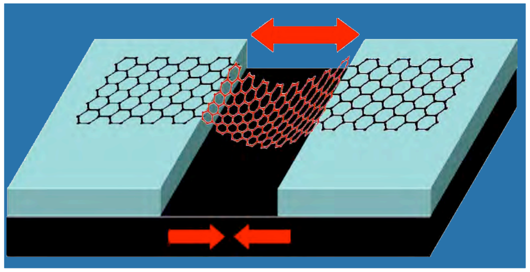
Mechanism of ripple formation



Graphene has a *negative* thermal expansion coefficient



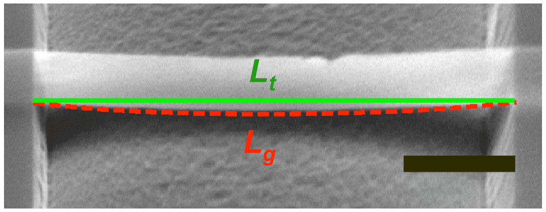
Heating
graphene contracts, substrate expands
→ erasing pre-existing ripples



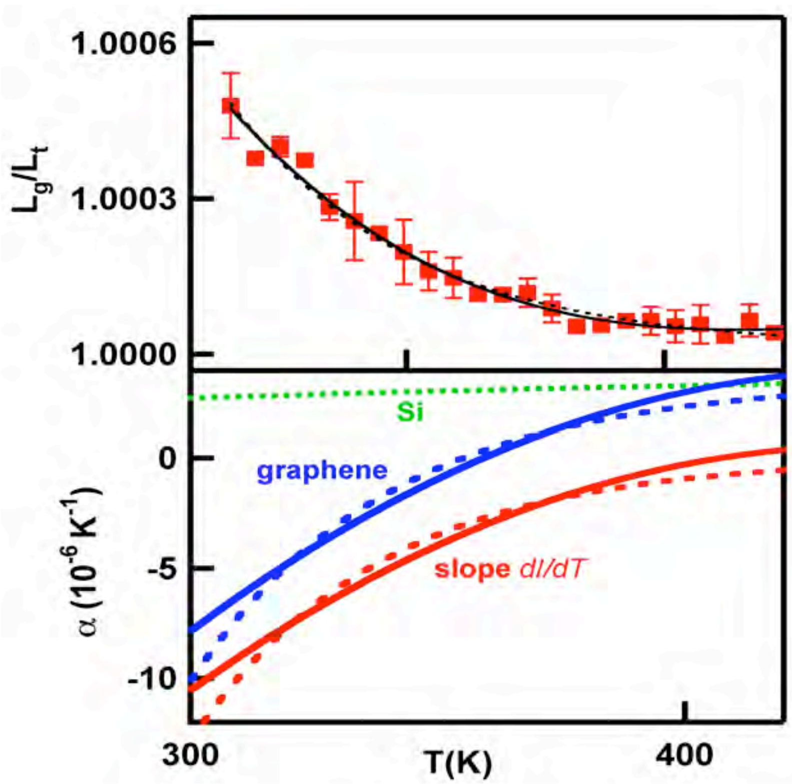
Cooling
- graphene expands, substrate contracts
- bending is easier than sliding

→ edges remain pinned by the trench edges
→ ripples (transverse)
slacks (longitudinal)

Measurement of Thermal Expansion Coefficient α

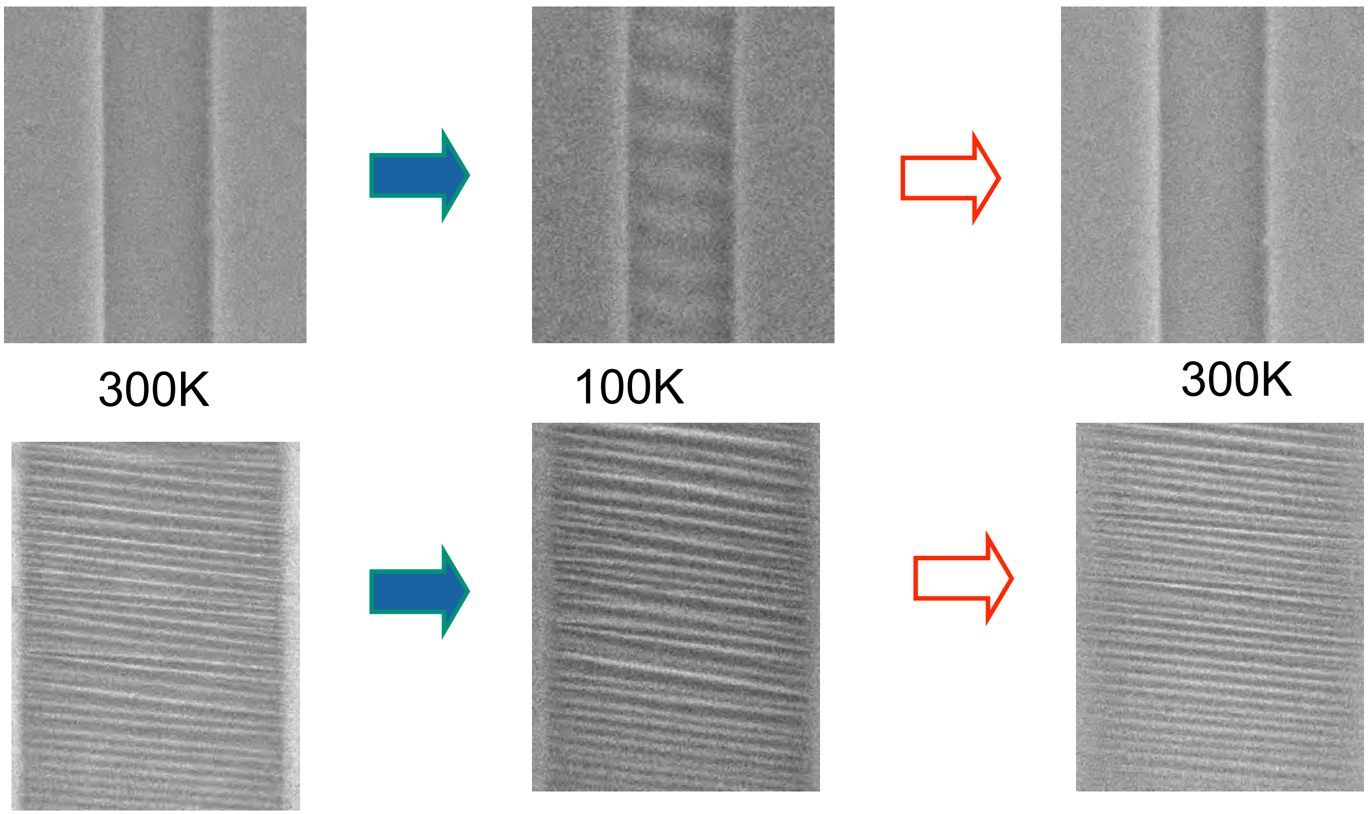


- Single layer graphene heated to 500 K and cools down slowly
- Compute $l(T)=L_g(T)/L_t(T)$ at different temperatures
- Slope $b = \frac{dl}{dT} \approx \alpha - \alpha_{Si}$

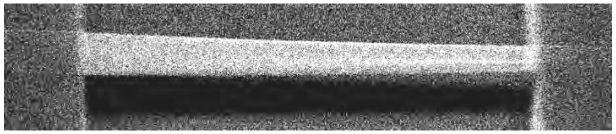


Bao, Miao,Chen, Zhang, Jung, Dames and CNL, *Nature Nanotechnol.* (2009)

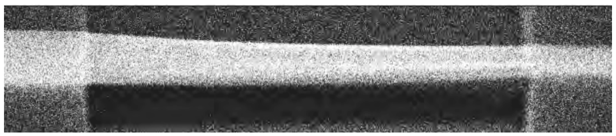
Ongoing: Cooling Suspended Graphene



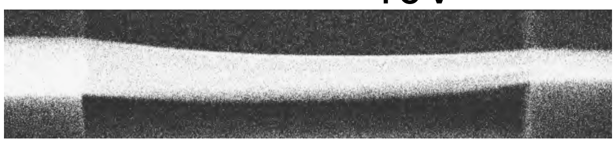
Ongoing: Electrostatic Distortion of Suspended Graphene



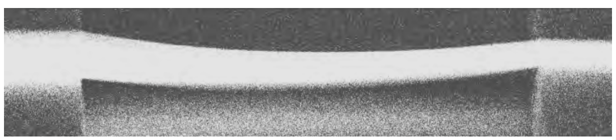
Gate Voltage = 0V



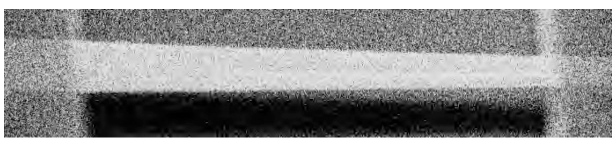
10V



20V

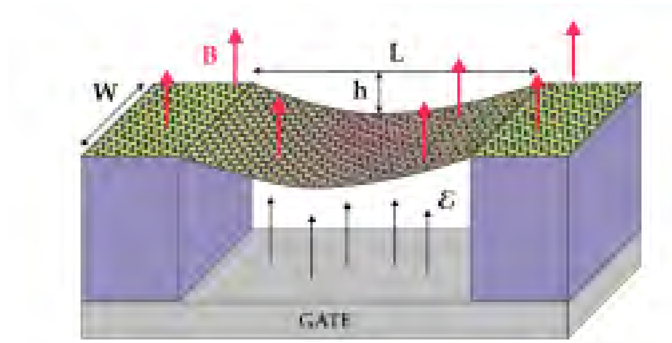


30V



Back to 0V

Gate voltages induces deformation in suspended graphene membranes.



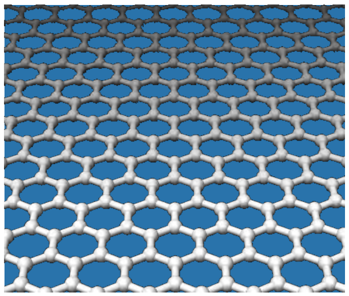
Leon, Prada, San-Jose, Guinea, *PRL* (2009)

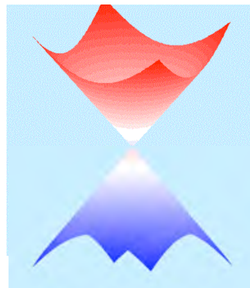
Lessons Learnt

- **Always look at the devices**
- **Suspended graphene membranes are very finicky!**
  - often have ripples
  - anneal with care
    - collapse graphene
    - cause ripples to form or change
  - morphology is strongly temperature dependent
    - resistance is strongly temperature dependent
    - quantum Hall plateaus disappear after annealing
    - nanoelectromechanical resonator’s characteristic frequency shifts with temperature
  - shape changes with gate voltages

Graphene's Double Identity

Extraordinary Conductor

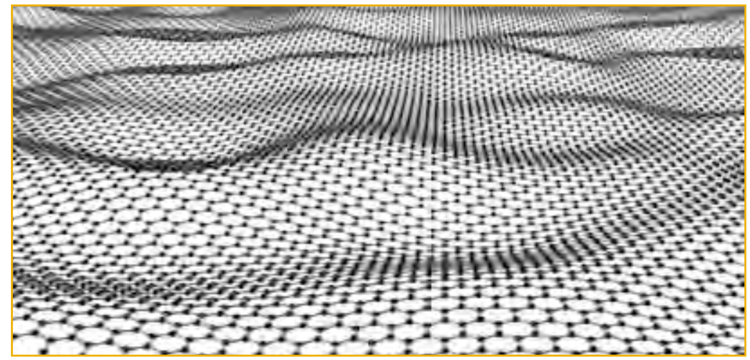




New model system for condensed matter research and electronic materials

Linear dispersion, tunable carrier, surface 2DEG, high thermal and electrical conductivity ….

2D Elastic Membrane



Thinnest isolated membrane with exceptional mechanical properties

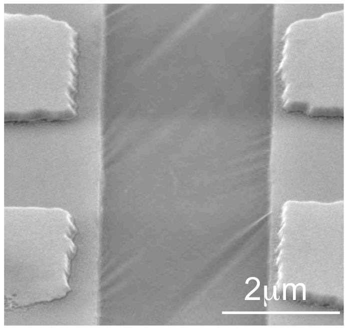
Castro Neto, Guinea, Katsnelson, Brey, Louie, etc

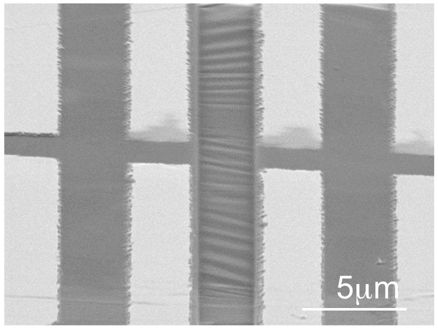
Exploit Electrical Properties of Rippled Graphene?

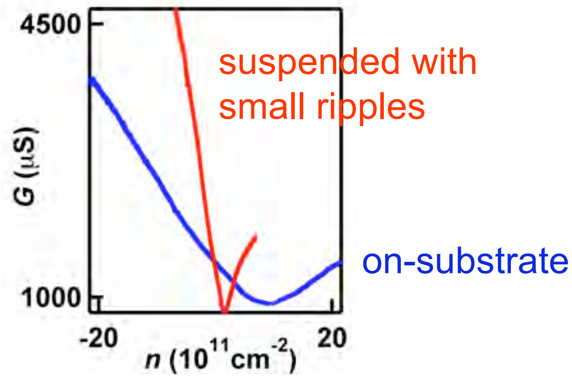
superlattices, strain-based engineering…

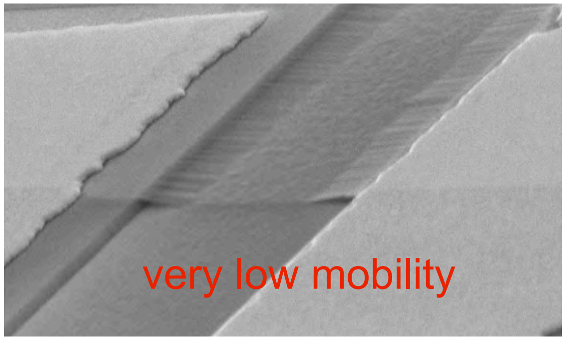
Coming soon -- Electrical Measurement

- Device with random or periodic ripples
- suspended and substrate supported portions of the same graphene sheet





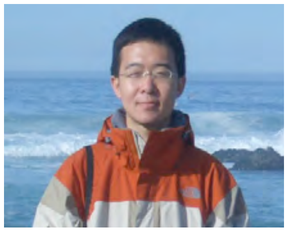




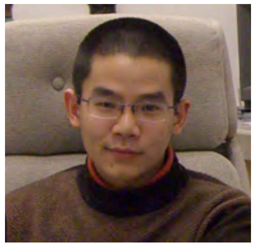
- Despite small random ripples, suspended graphene has higher mobility
- Collapsed graphene (with very severe strain) does have very low mobility
- Ripple's *T*-dependence: relevant for suspended graphene devices

Acknowledgments

Graduate Students



Feng Miao



Wenzhong Bao

Gang Liu

Jairo Velasco

Hang Zhang

Discussion With

Shan-Wan Tsai, Marc Bockrath, Antonio Castro-Neto, Misha Fogler, Paco Guinea, Gil Refael, Dmitri Abanin, Philip Kim, Chandra Varma, Leonid Pryadko, Dmitri Novikov, Alex Bratkosvki, Volodya Falko, Maria A.H. Vozmediano, Misha Katsnelson