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Uniaxial strain on graphene: bandgap opening

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Uniaxial strain on graphene: *bandgap opening*

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Singapore

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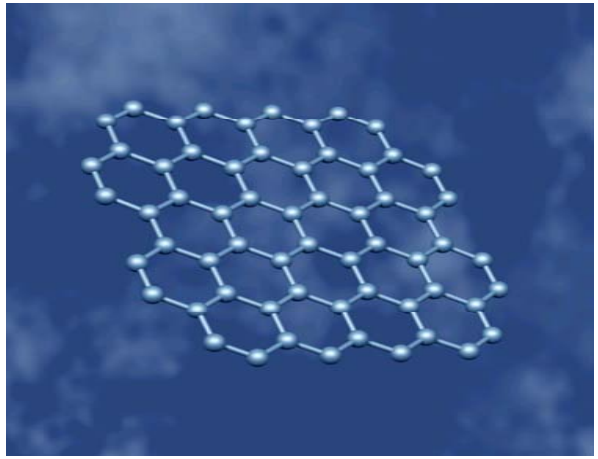
Outline:

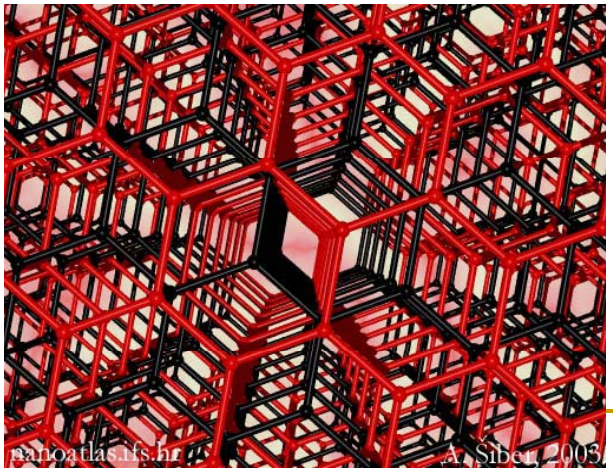
- Introduction of graphene
- Motivation
- Experimental
- Results & discussion
- Summary

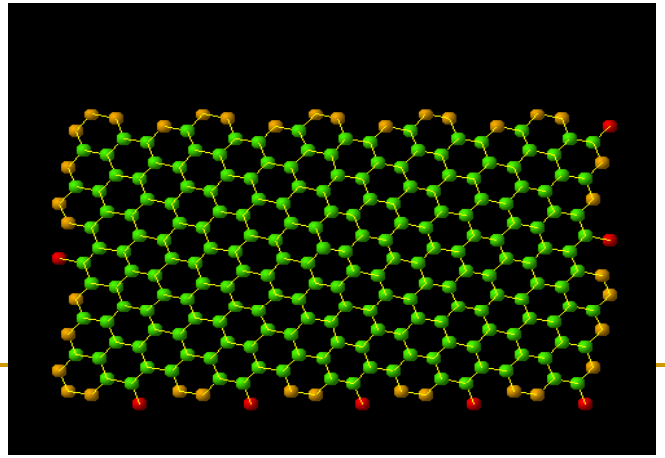
Introduction to graphene

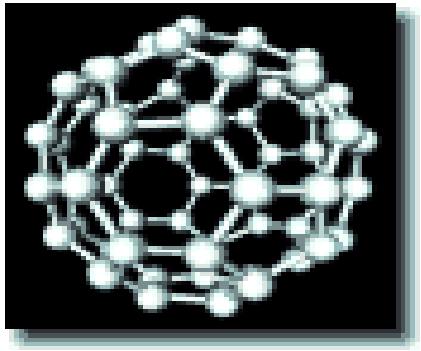


Novoselov KS *et al.* **Science** 2004, **306**, 666
Zhang YB *et al.* **Nature** 2005, **438**, 201
Geim AK and Novoselov KS **Nature Materials** 2007, **6**, 183

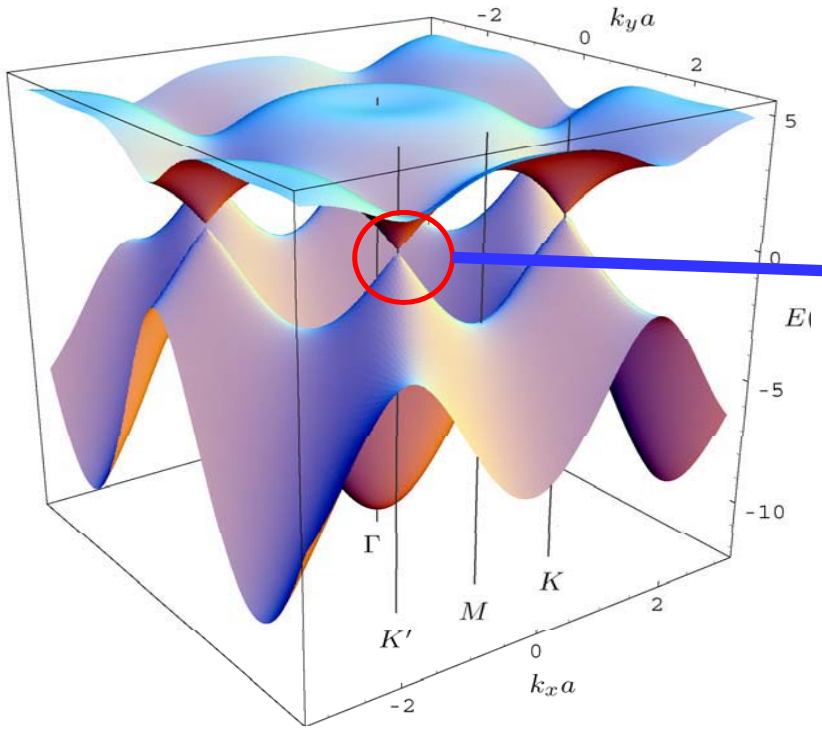
- *High crystal quality*
- *Ballistic transport under ambient condition*
- *The massless Dirac fermions like charge carriers*



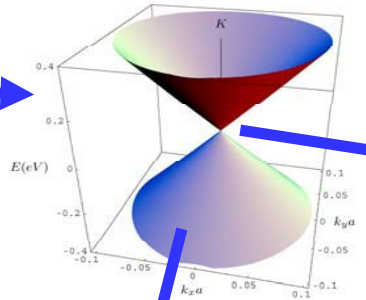




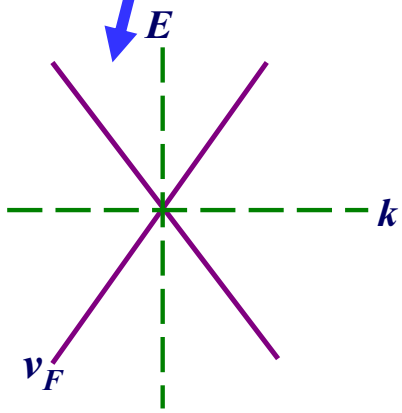
In momentum space



Dirac Cone

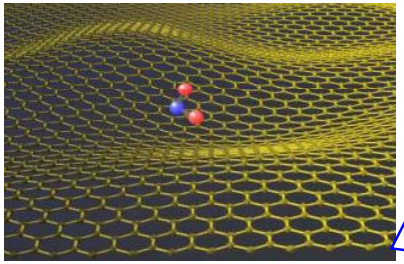


Semi-Metal



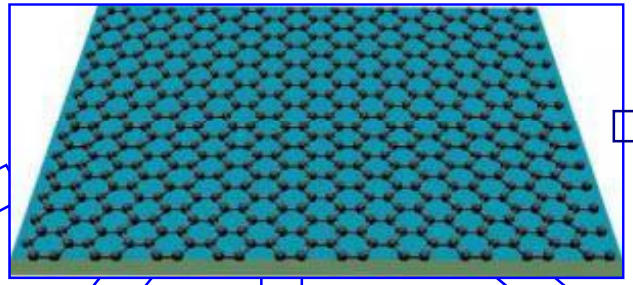
$E = \hbar k v_F$ $\quad$ $v_F \approx 10^6$ ms^{-1}=c/300

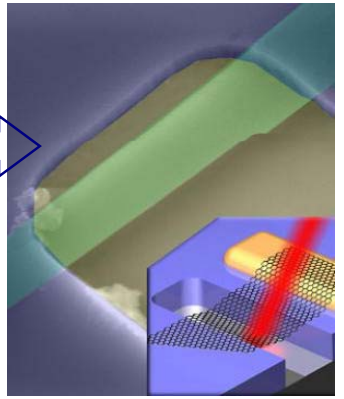
Application of Graphene



'Detection of individual gas molecules adsorbed on graphene

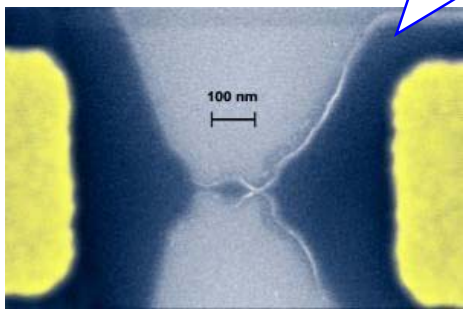
Nature Materials, 2007 vol. 6 p652



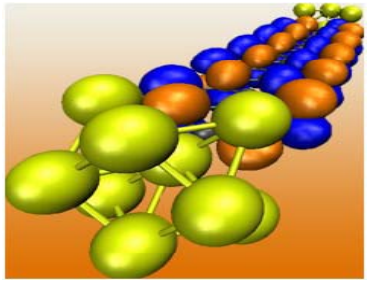


Nano-Resonator

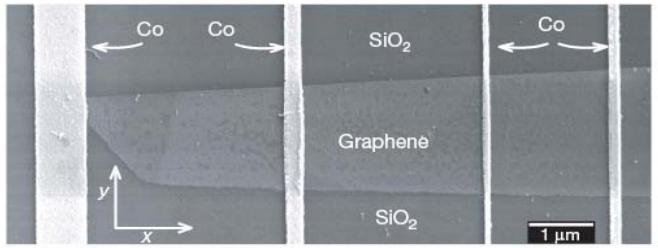
Cornell University. "Thin But Tough: Graphene Sheets Could Have Many Uses, Cornell Student Discovers." ScienceDaily 28 February 2007. 3 December 2007



University of Manchester. "**New Graphene Transistor** Promises Life After Death Of Silicon Chip." ScienceDaily 2 March 2007. 3 December 2007



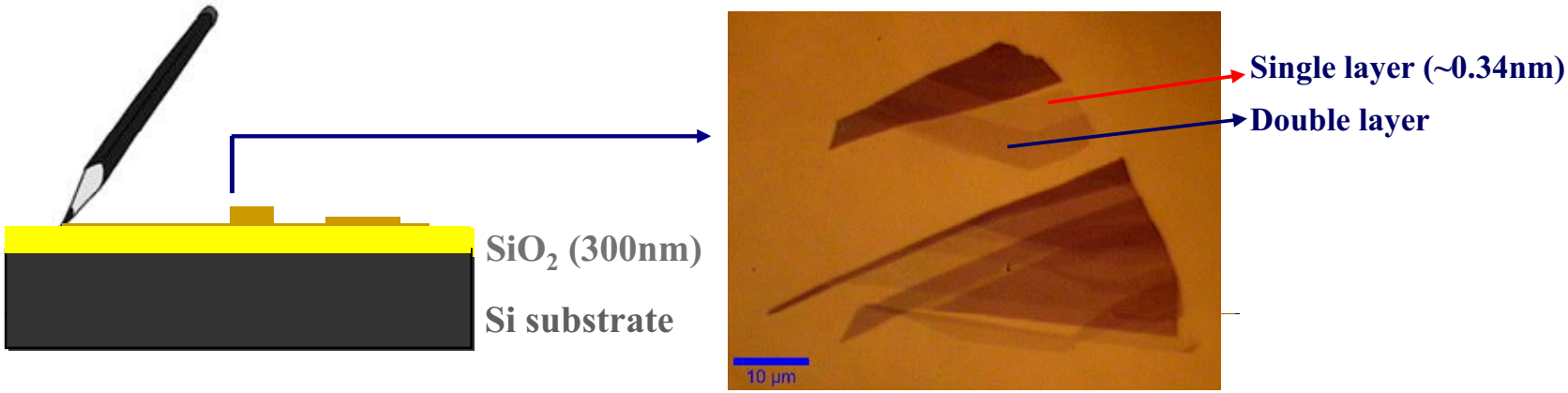
Rensselaer Polytechnic Institute. "Graphene Nanoelectronics: **Making Tomorrow's Computers From A Pencil Trace**." ScienceDaily 25 July 2007. 3 December 2007

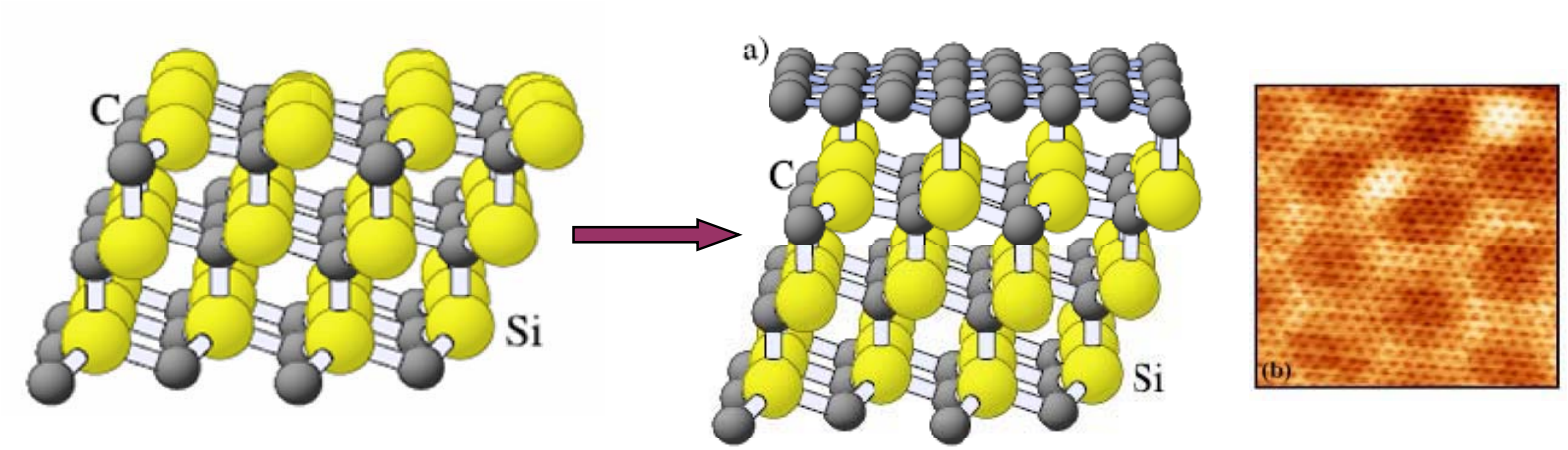


Graphene spintronics

Tombros et al. Nature 448, 571 (2007)

Graphene Fabrication : Mechanical cleavage from graphite (MCG)
High temperature epitaxial growth graphene (EG)

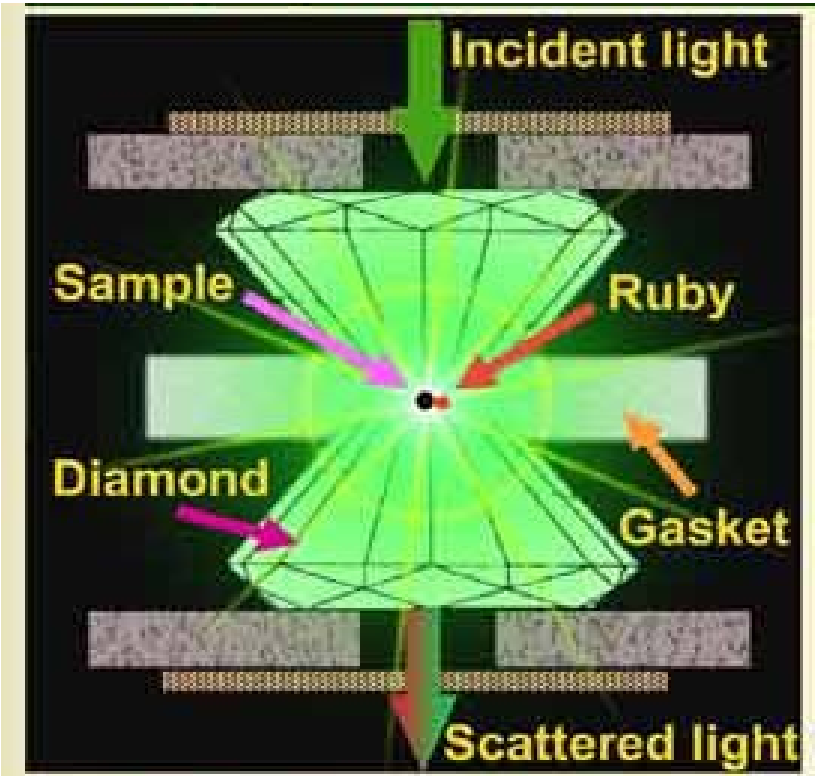




Motivation:

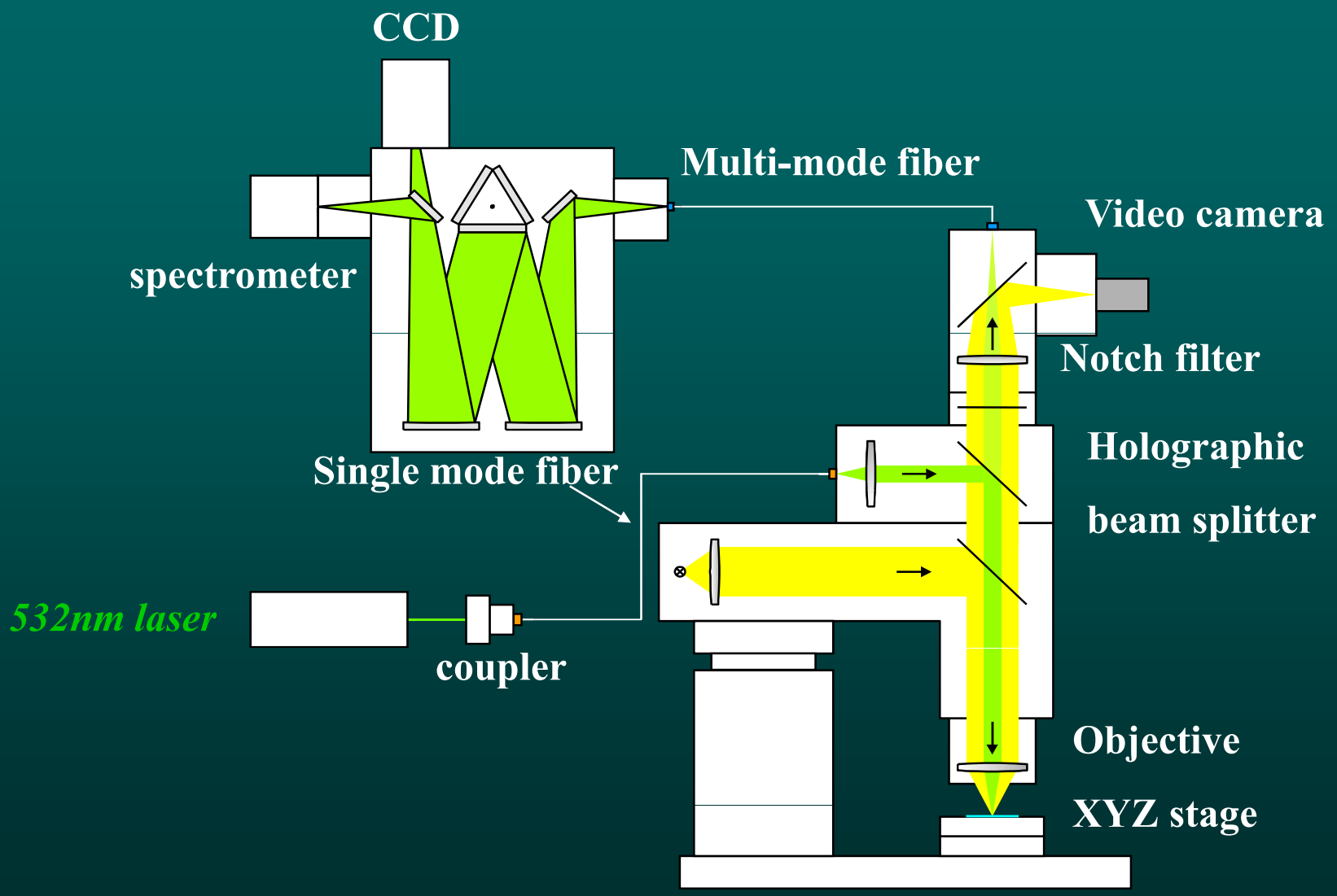
- High pressure Raman of graphene 
- Strain effects on graphene 
- Strained engineering, i.e. strained Si
- Strained graphene 

High pressure effects probed by Raman Spectroscopy

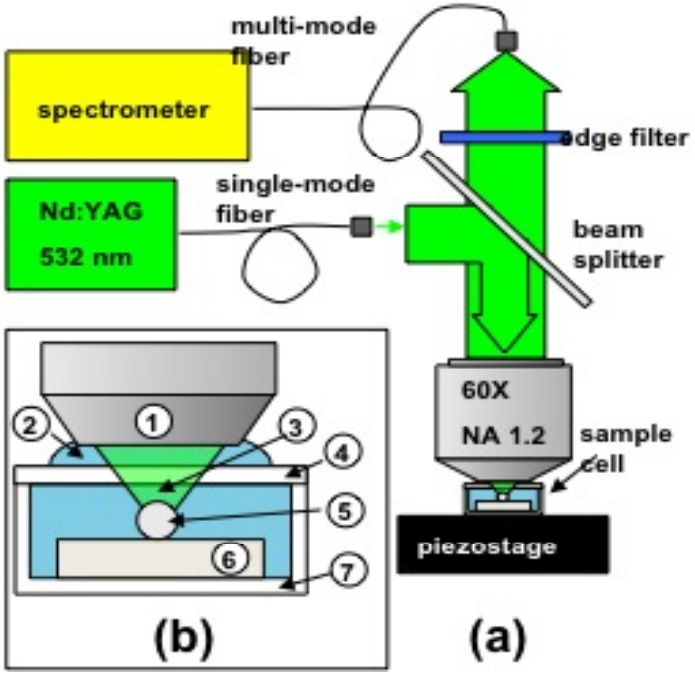


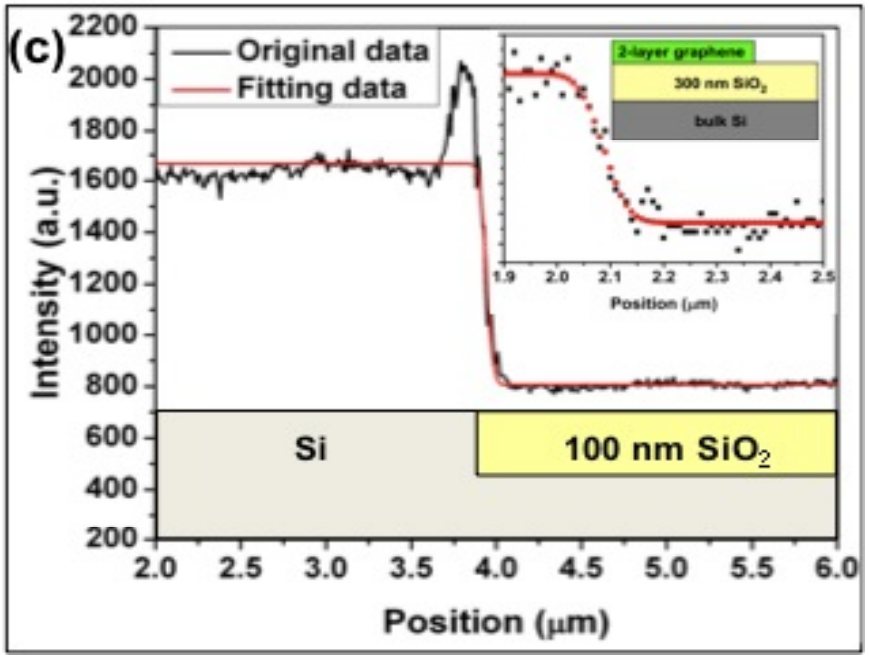
ONLY comprising!

Schematic of Raman system



Near-field Raman imaging using optically trapped dielectric microsphere





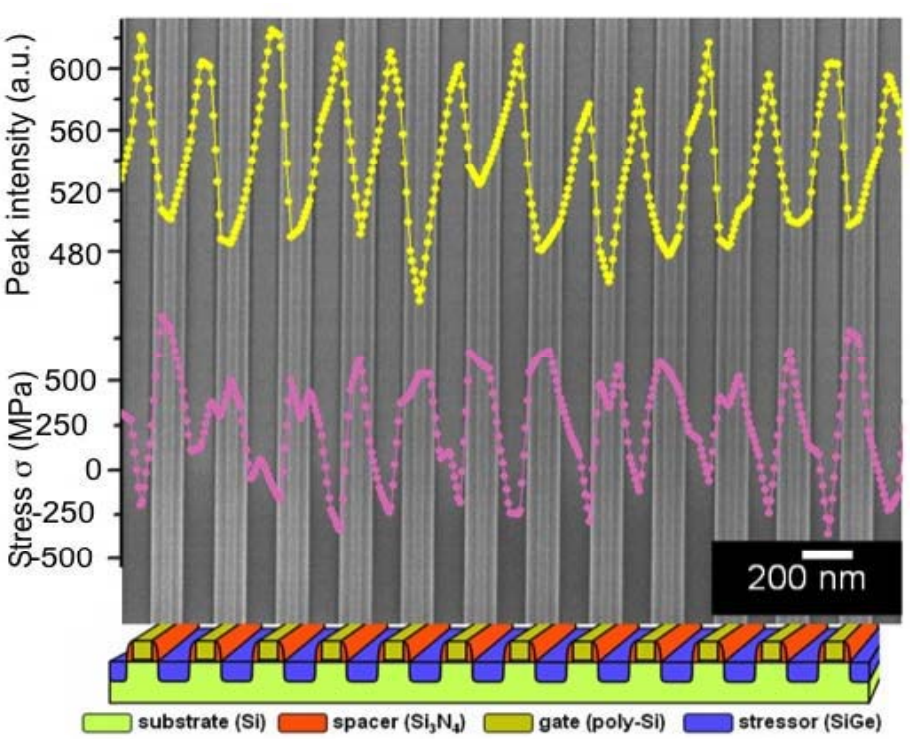
$$I(x) = \frac{P}{2}\left\{1 - erf\left(\frac{\sqrt{2}(x - x_o)}{w}\right)\right\}$$

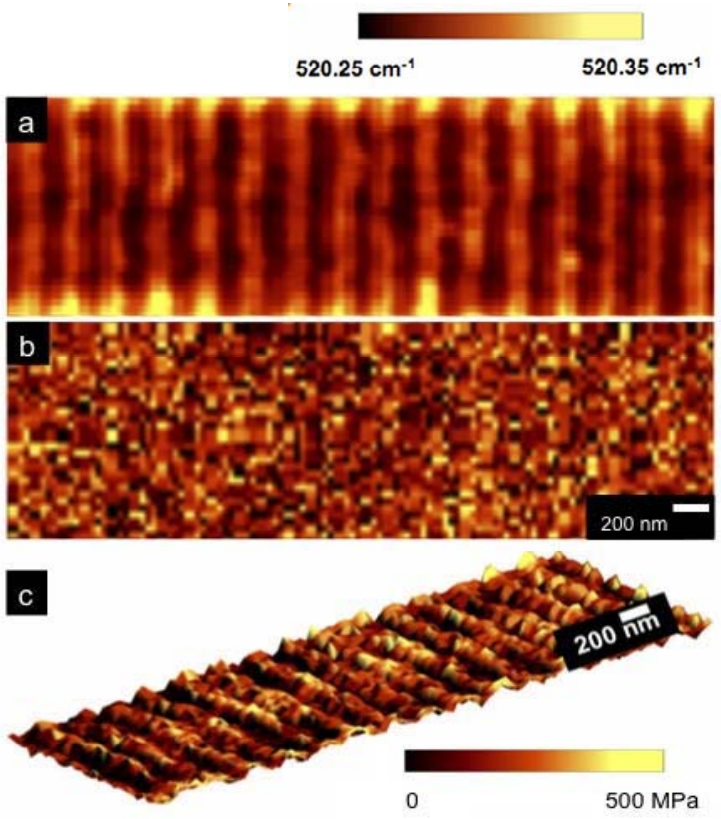
Spot size = $FWHM = \sqrt{2\ln 2}\,w$ **= 80 nm**

***P*: power of laser beam; *x*: scanning edge position; x_0: centre of beam; *w*: 1/e^2 half width**

J. Kasim, T. Yu, et al Optics Express 16, 7976 (2008).

Visualizing stress in 45 nm Strained Si device





Near-field

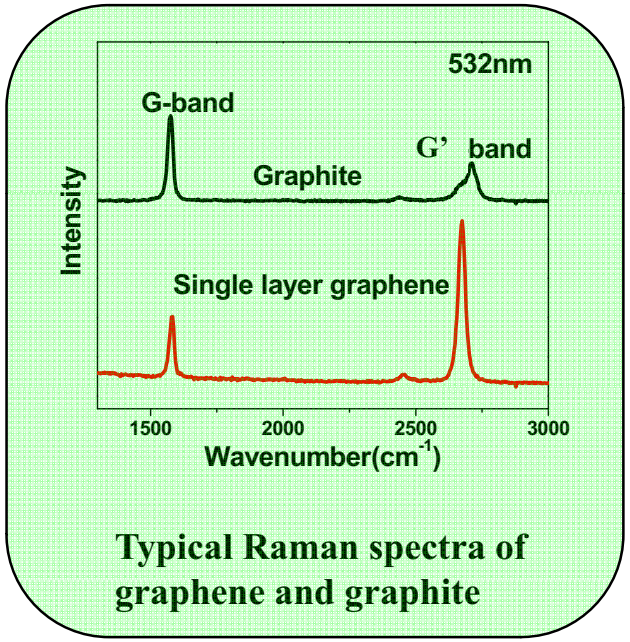
Confocal

Near-field Raman of graphene edge???

Kasim J, Yu T, et al. ***Optical Express***, 16, 7976 (2008).

Strained graphene on flexible substrate

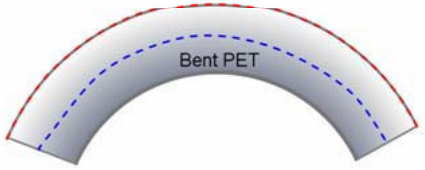
Part I: bending substrate

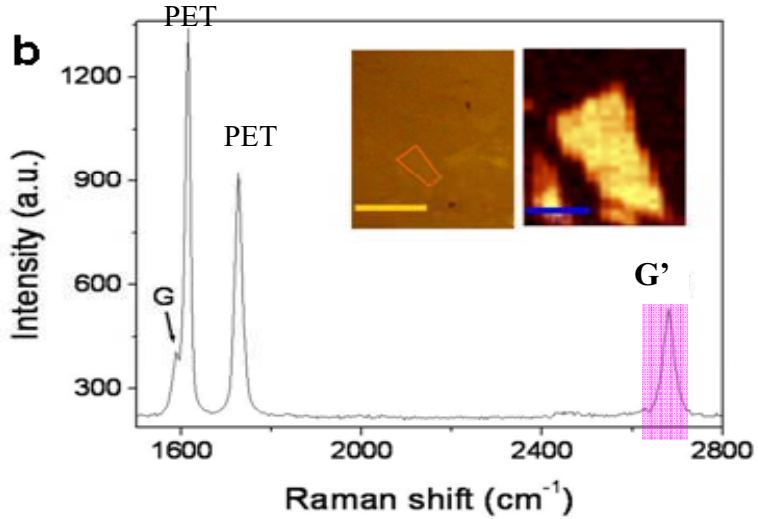


Typical Raman spectra of graphene and graphite

a

Bending the PET to apply strain



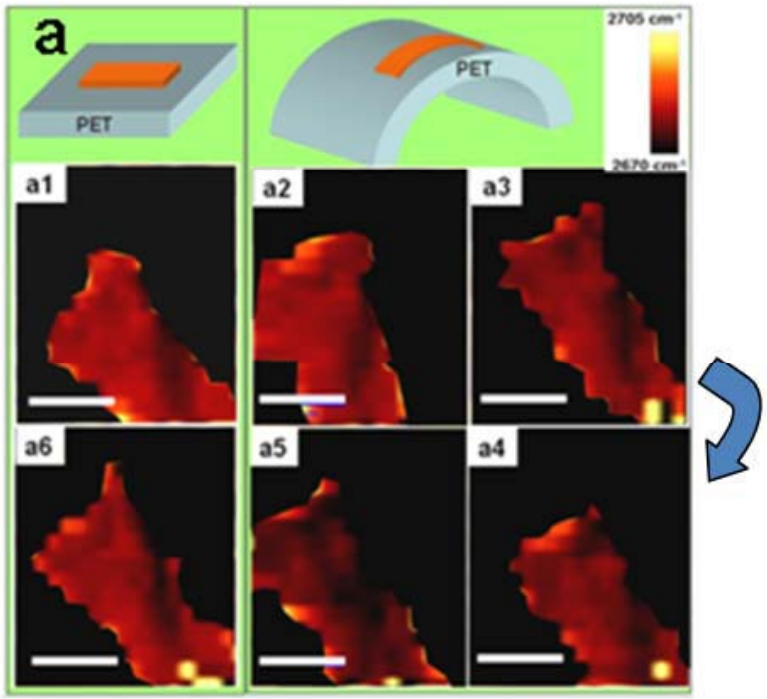


Graphene on polyethylene terephthalate (PET) substrate

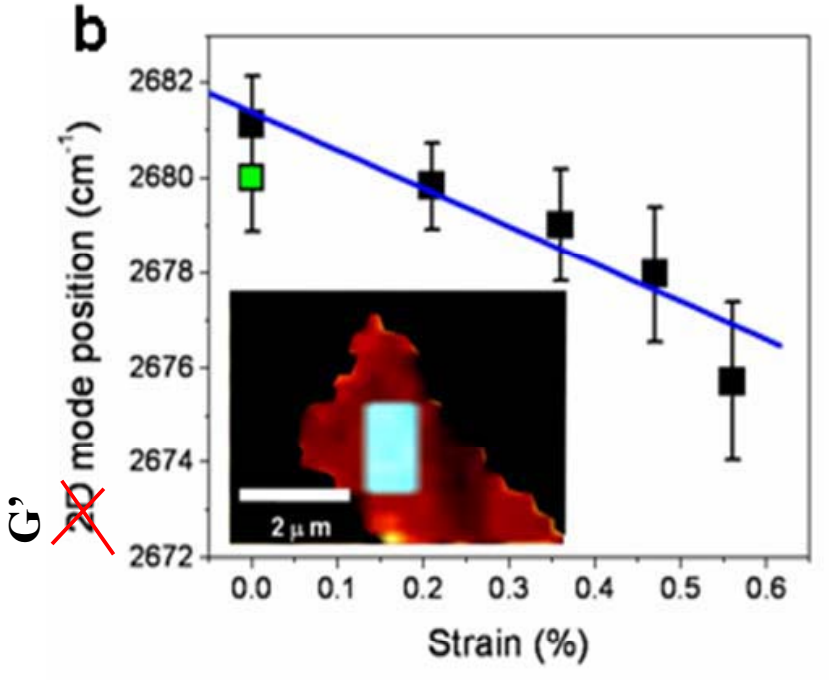
J.-H. Chen et al Adv Mater 19, 3623, (2007).

Yu T, Ni ZH et al. Journal of Physical Chemistry C 112, 12602 (2008)

Part I: bending substrate



(a) Raman images of (a1) unstrained graphene, (a2-a5) strained graphene, (a6) relaxed graphene by extracting G' mode frequency.

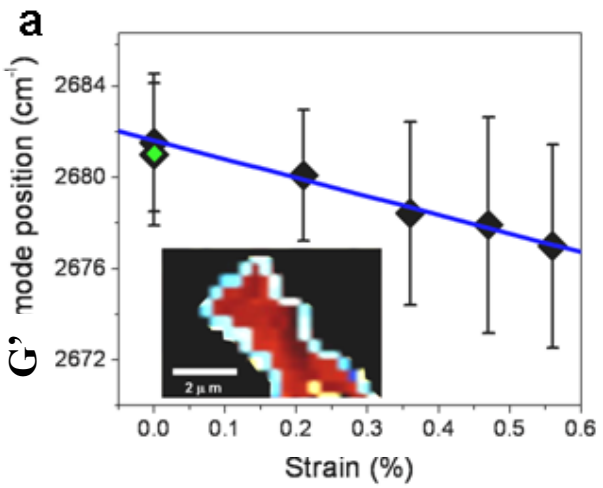


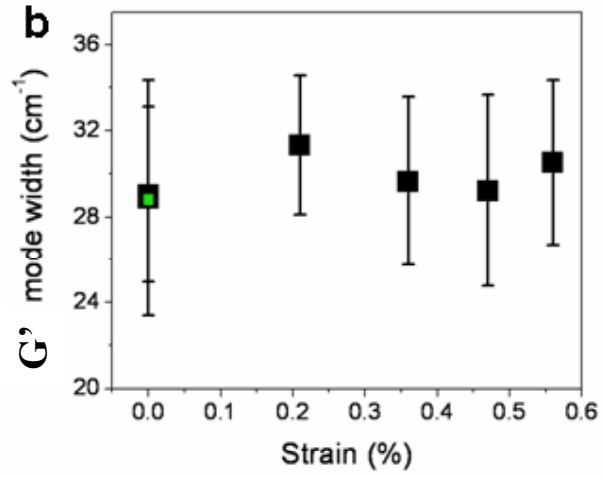
(b) Mean of G' mode frequency from the interested part of graphene as a function of strain. Scale bar = 2 um.

- Strain coefficient: -7.8 cm^{-1}/%strain
- Immediate recover after strain relax

C. Thomsen, et al PRB 65, 073403 (2002).

Yu T, Ni ZH et al. Journal of Physical Chemistry C 112, 12602 (2008)





(a) The mean of G' mode frequency from the edge of graphene as a function of strain. The scale bar is 2 um.

(b) The mean of G' mode linewidth from the corresponding edges as a function of strain. The data points in green are from the relaxed graphene.

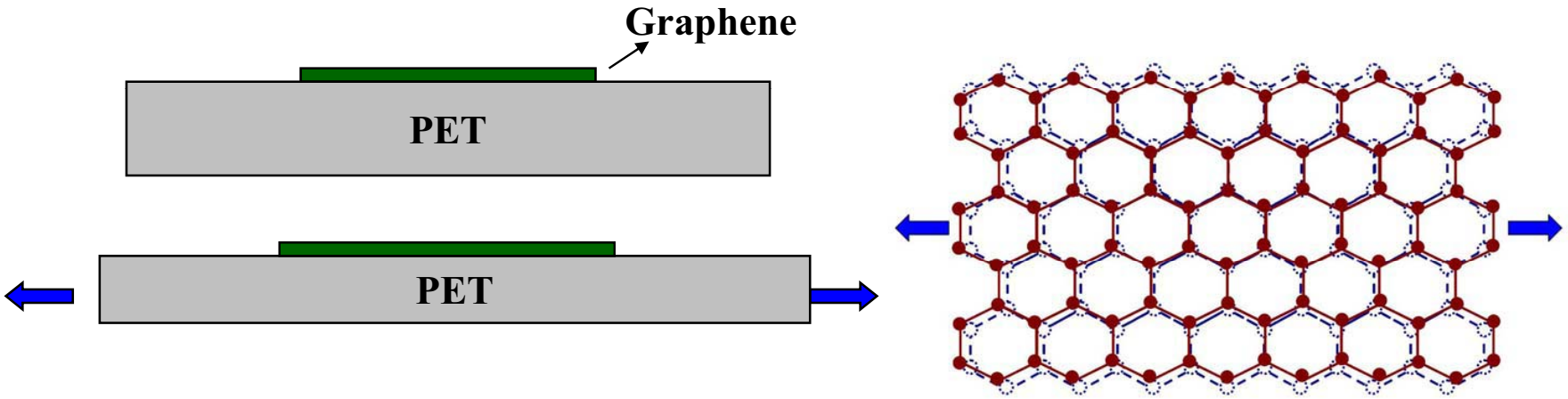
Strain coefficient: -8.0 cm^{-1}/%strain

The results from edges show no difference from the body.

Yu T, Ni ZH et al. Journal of Physical Chemistry C 112, 12602 (2008)

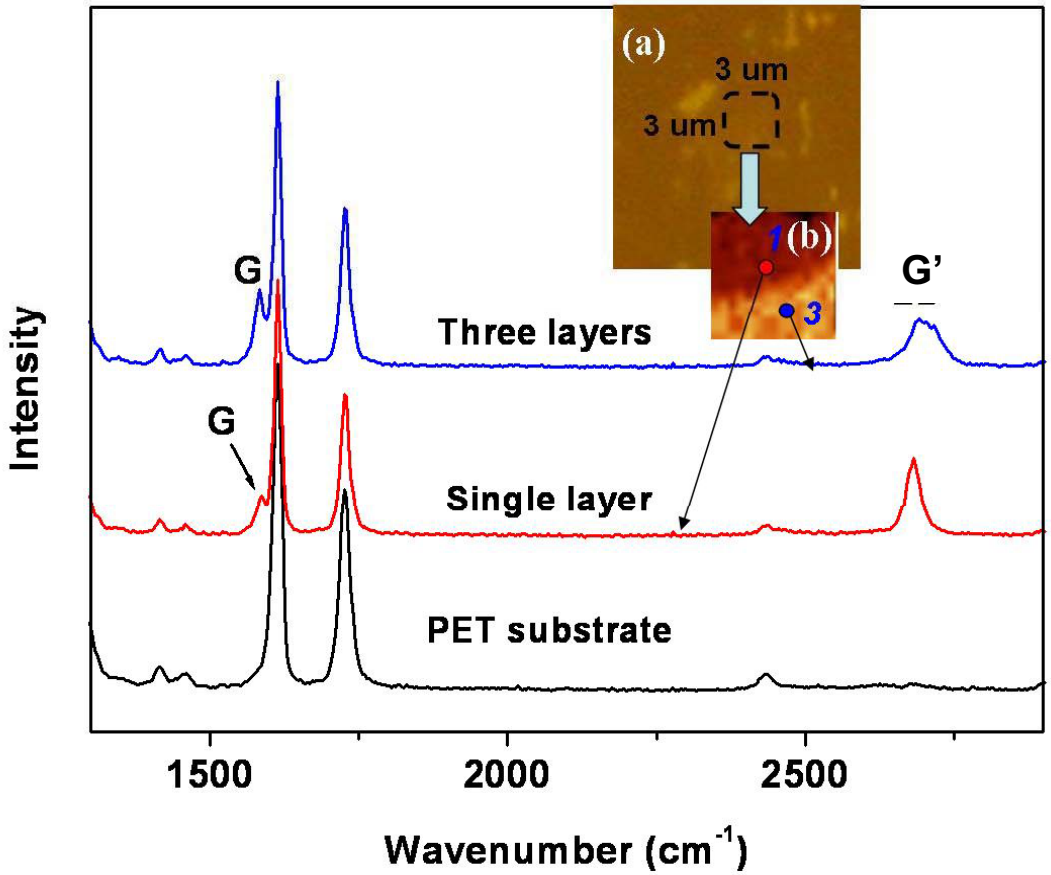
Strained graphene on flexible substrate

Part II: stretching substrate



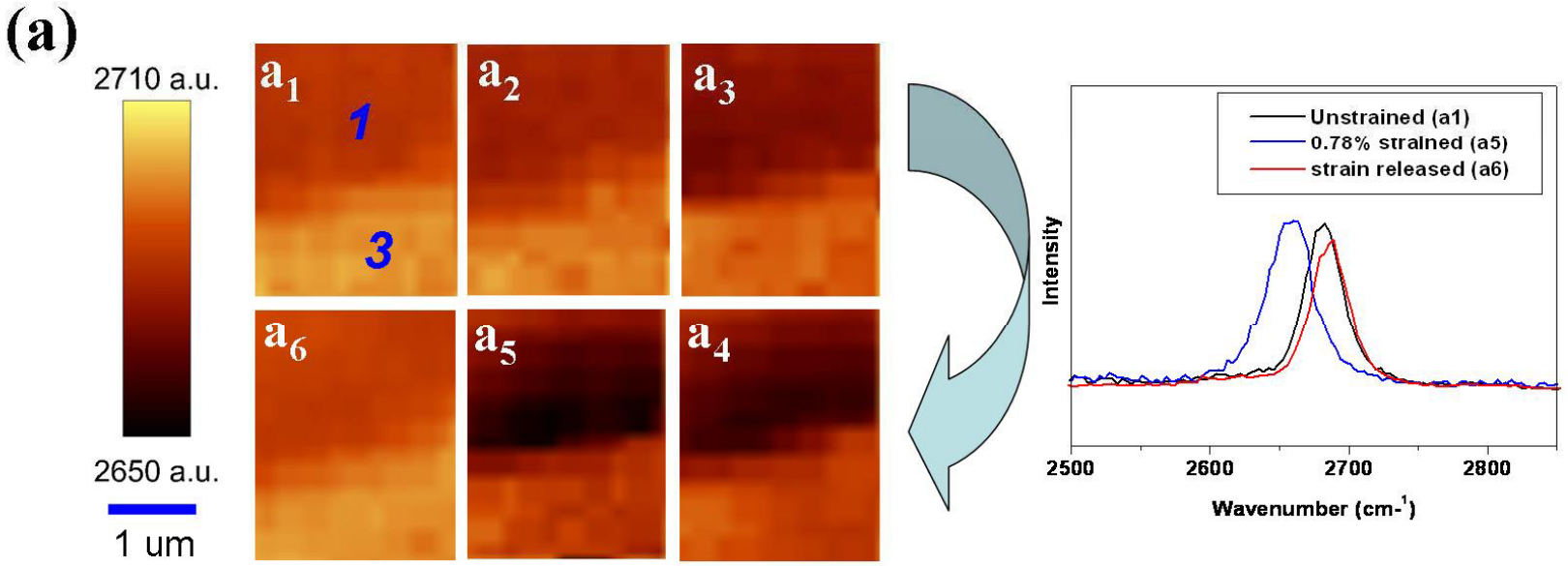
Ni ZH, Yu T, *et al.* ACS Nano (to be published)

1- and 3- layer Graphene on PET substrate



Ni ZH, Yu T, *et al.* ACS Nano (to be published)

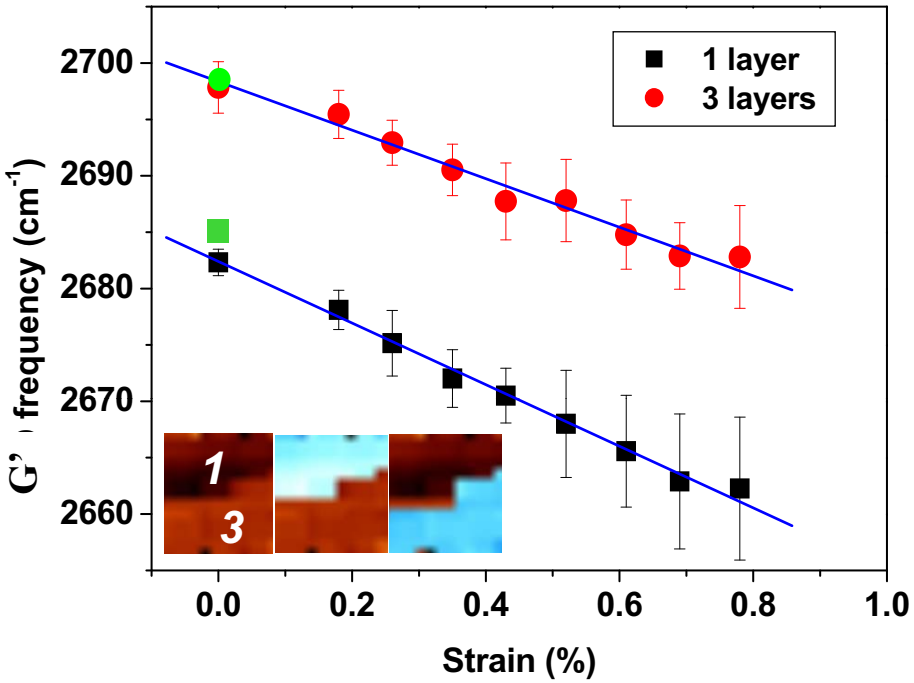
Part II: stretching substrate



Raman images (G' mode position) of (a1) unstrained (a2) 0.18% (a3) 0.35% (a4) 0.61% (a5) 0.78% (a6) released graphene.

Ni ZH, Yu T, *et al.* ACS Nano (to be published)

Part II: stretching substrate

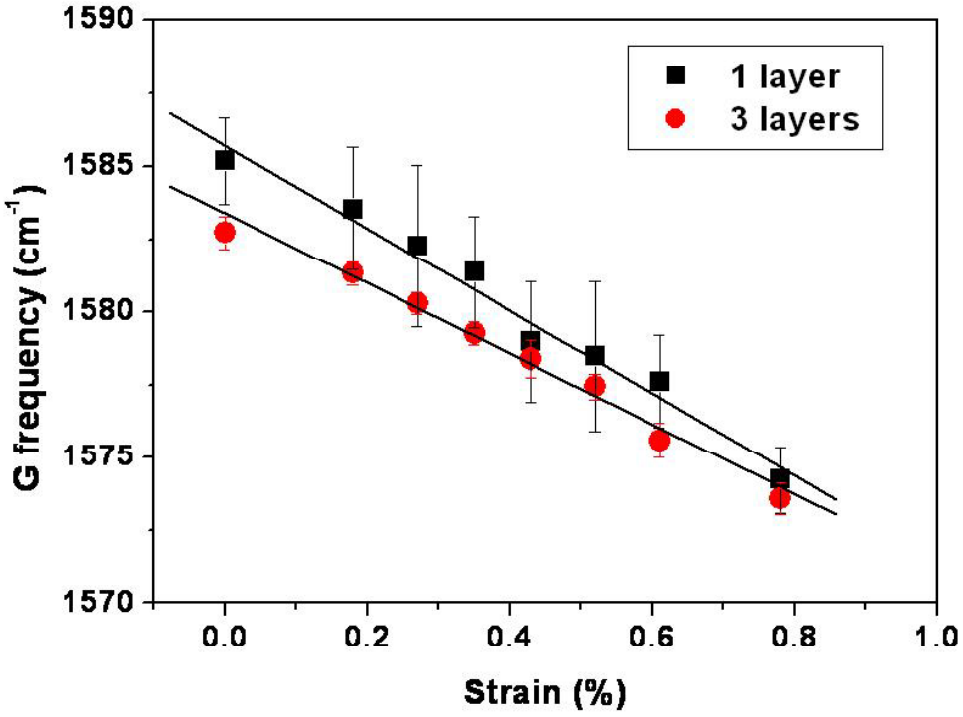


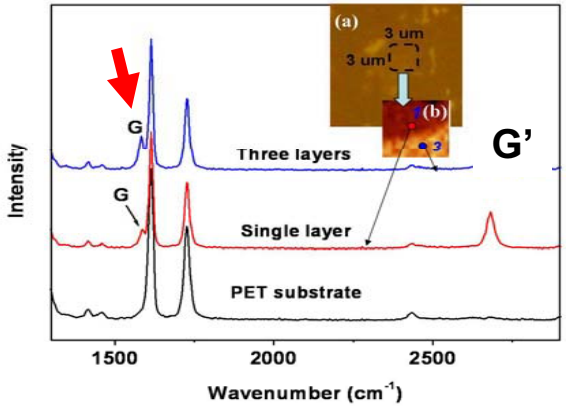
Slope $_{1\text{-layer}}$ = -27.8 cm^{-1}/%

Slope $_{3\text{-layer}}$ = -21.9 cm^{-1}/%

G' mode frequencies of single- and three-layered graphene plotted as a function of strain. The strain sensitivity of G' band of graphene is very high, and comparable to that of CNTs.

Ni ZH, Yu T, *et al.* ACS Nano (to be published)





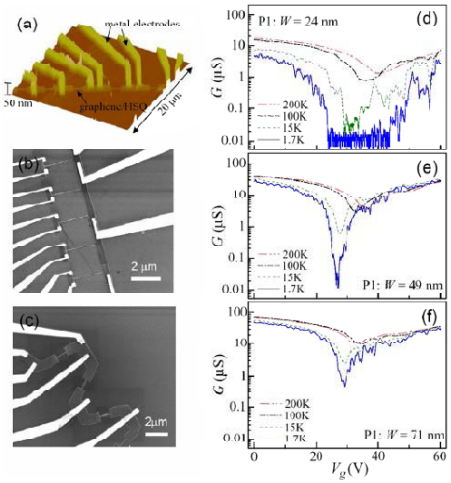
Slope $_{1\text{-layer}}$ = -14.2 cm^{-1}/%

Slope $_{3\text{-layer}}$ = -12.1 cm^{-1}/%

The red-shift: elongation of the carbon-carbon bonds, which weakens the bonds and therefore lowers their vibrational frequency.

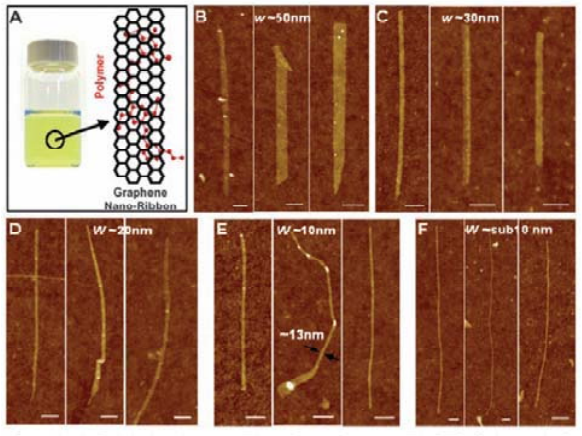
Lager shift of SLG compared to 3 layer graphene might because strain is more effectively applied on thinner graphene sheet. (no shift is observed on bulk graphite in the strain experiment)

Opening bandgap of graphene

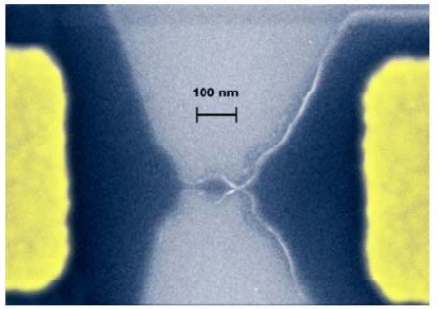


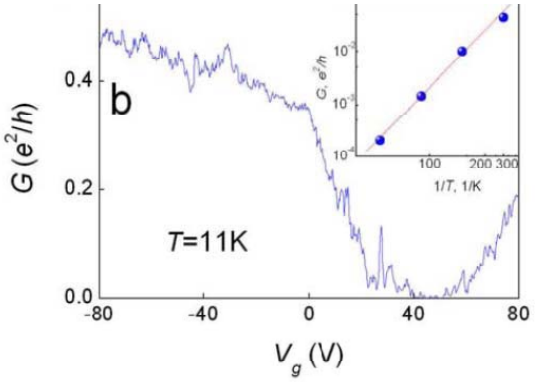
Bandgap in graphene nanoribbon

Han et al. Phys. Rev. Lett. 98, 206805 (2007)



Chemically Derived, Ultrasmooth Graphene Nanoribbon Semiconductors
Xiaolin Li, *et al.*
Science **319**, 1229 (2008);

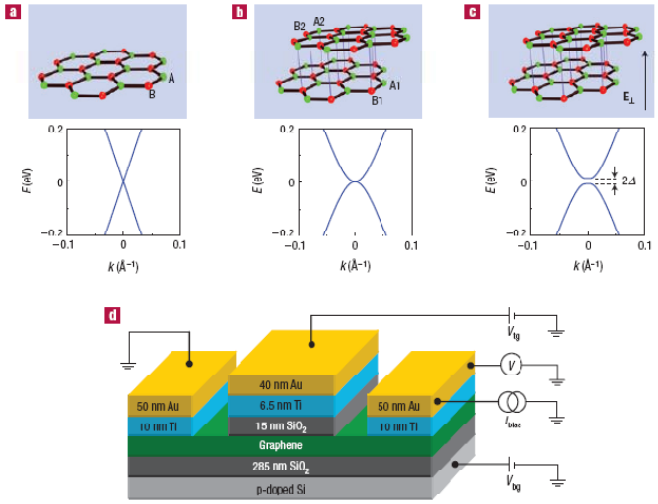




Bandgap in quantum dots

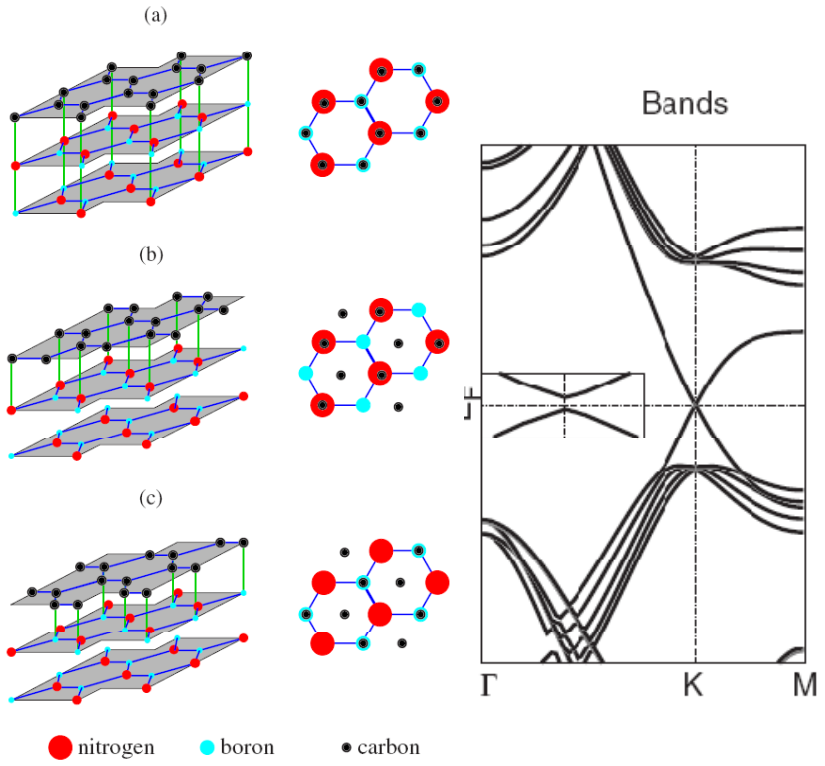
Ponomarenko et al. Science 320, 356 (2008)

Break the symmetry



Bandgap on bilayer graphene by electric field effect

Oostinga et al. Nature Materials 7, 151 (2008)
McCann et al. PRB 74,161403 (2006)
Castro et al. PRL 99,216802 (2007)

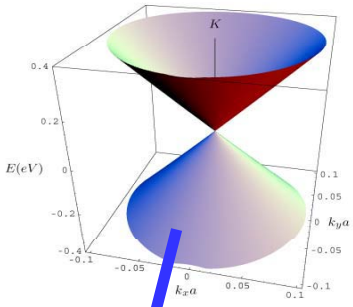


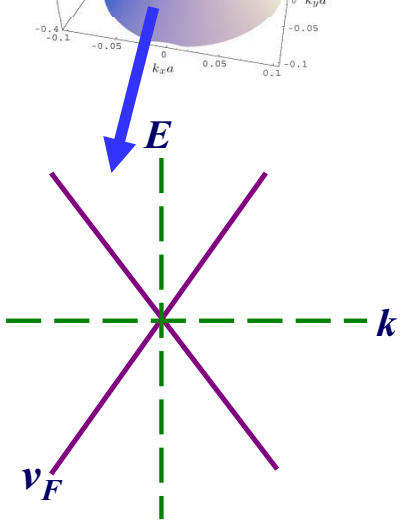
Graphene on BN substrate

Giovannetti et al. Phys. Rev. B 76, 073103 (2007)

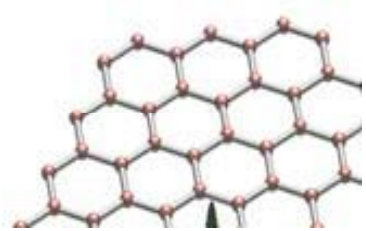
Uniaxial Strain on Graphene to open bandgap

Dirac Cone



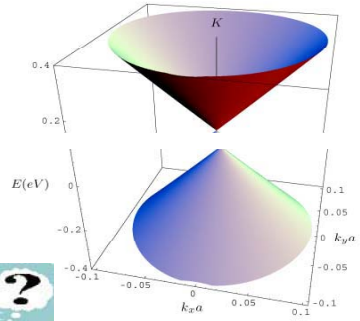


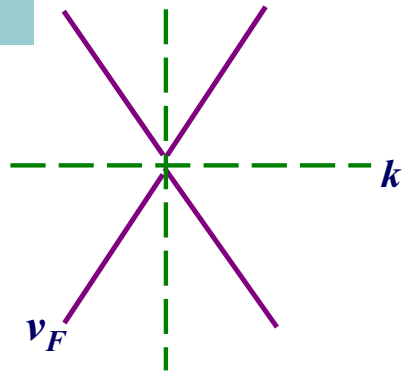
Semi-Metal



Strain

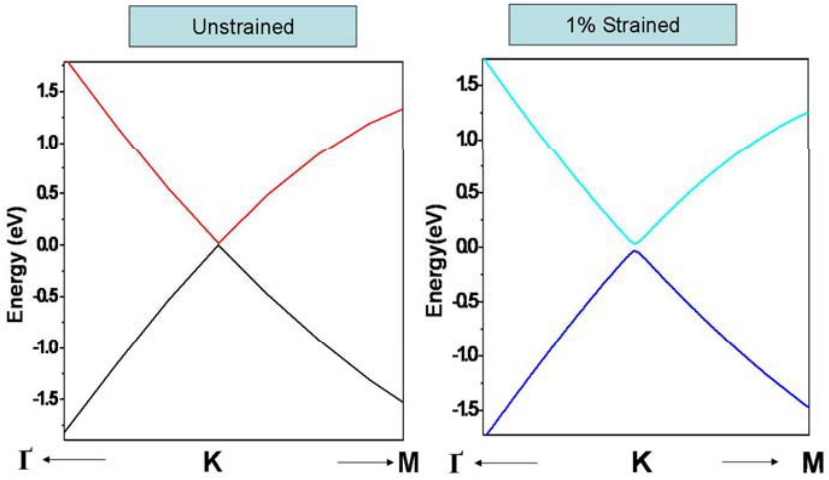
Dirac Cone



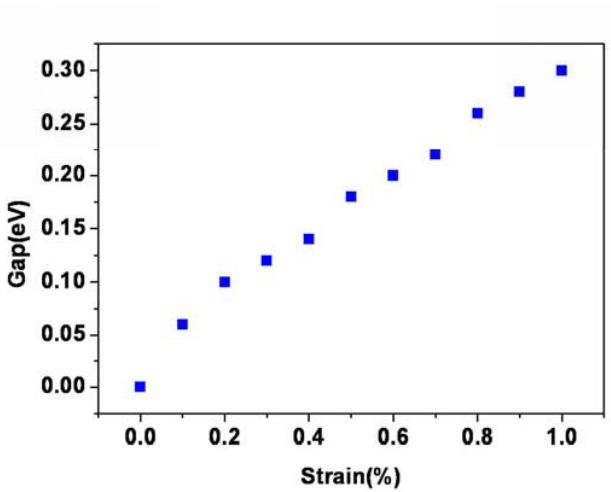


Semiconductor

Opening bandgap by strain



Electronic band structure



Band gap *vs* strain

- First-principles calculations: VASP code
- Local spin density approximation (LSDA): exchange-correlation function
- Cutoff energy: 400 eV
- The lattice constant of perfect graphene structure: 0.242nm

YP Feng, NUS
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Ni ZH, Yu T, *et al.* ACS Nano (to be published)

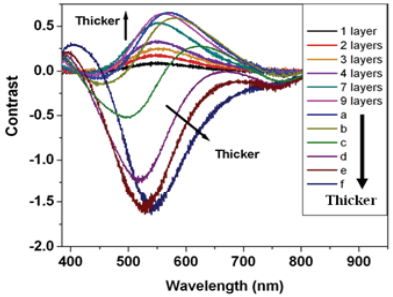
Conclusion

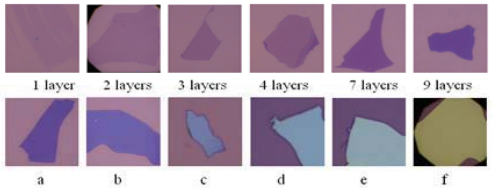
- Graphene on flexible transparent substrate
- Strain coefficient of graphene = - 27.8 $cm^{-1}/\%$
- A bandgap opening of ~300 meV for graphene under 1% uniaxial tensile strain

? Strain engineering on graphene: strained graphene

Graphene Week 2009

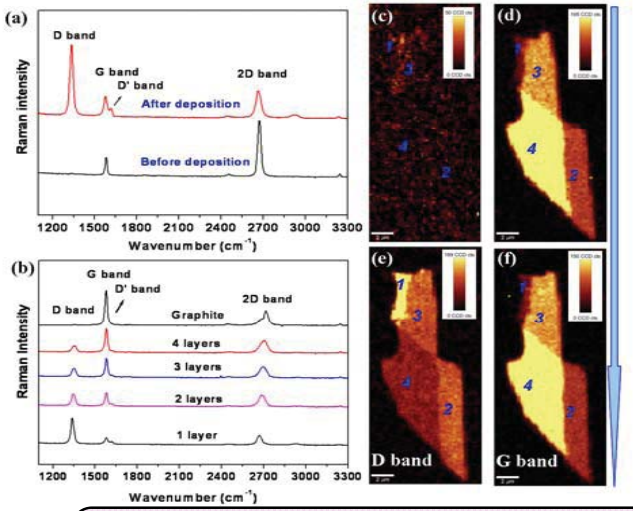
Our works





Counting layer number

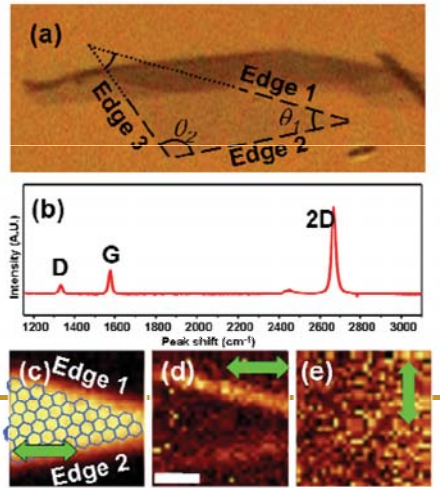
Nano Letters **7**,2758 (2007)

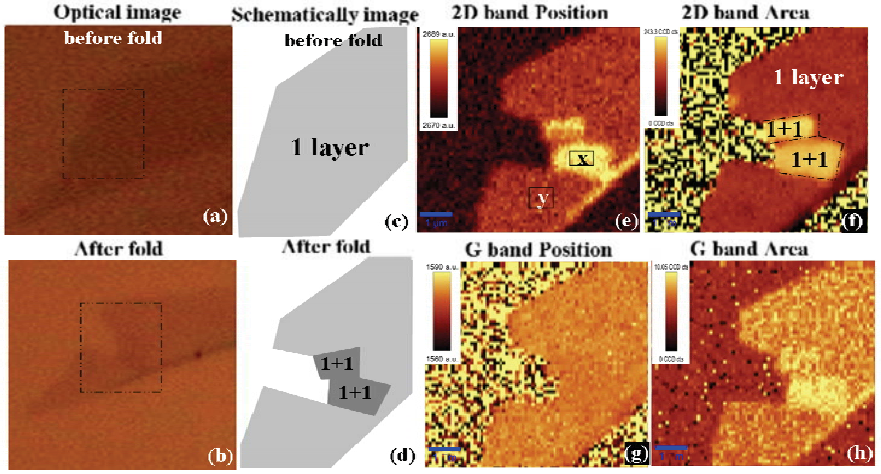


Effect of top insulator deposition

ACS Nano 2, 1033 (2008)

Edge chirality determination





Folded graphene

Phys. Rev. B 77, 235403 (2008)

AsiaNANO 2008

The 2008 Asian Conference on
Nanoscience and Nanotechnology
3rd - 7th November 2008 • Biopolis, Singapore

Symposium C: Graphene: Materials and Devices

Chair

- Ozyilmaz BARBAROS (NUS, Singapore)

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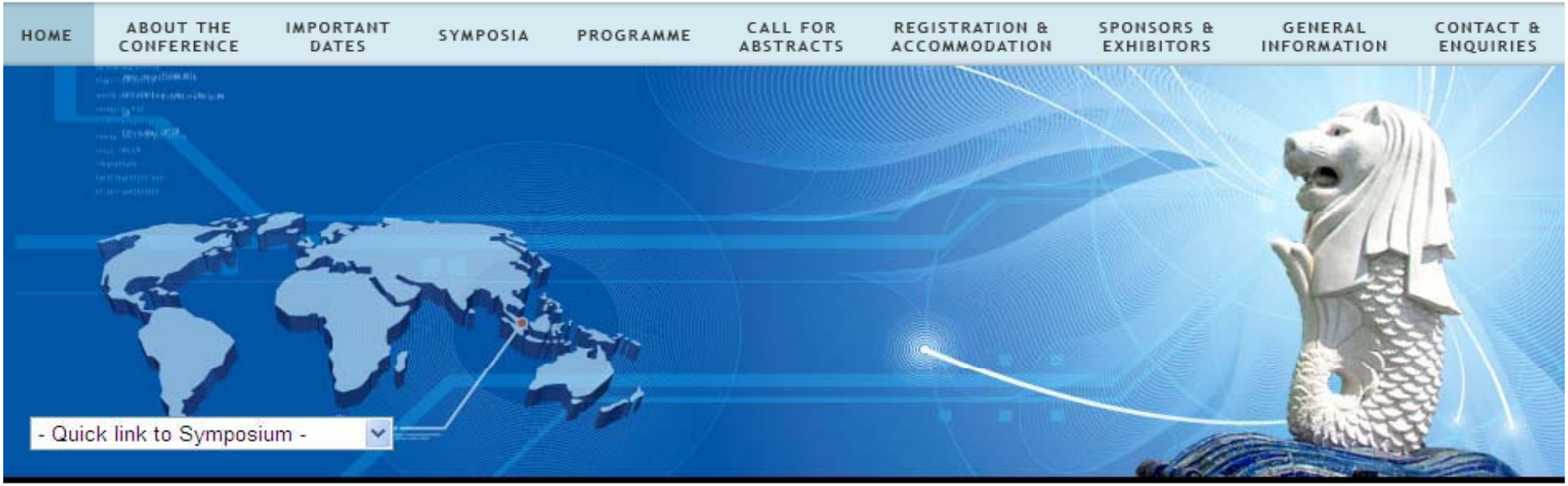
ICMAT 2009
International Conference on
Materials for Advanced Technologies

IUMRS - ICA 2009
Int'l Union of Materials Research Societies -
International Conference in Asia 2009

28 June - 3 July 2009, Singapore
Suntec Singapore International
Convention & Exhibition Centre



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