電界効果によるグラフェンの電気伝導変調

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Exciting Material, Graphene !

Electric Field Effect in Atomically Thin Carbon Films

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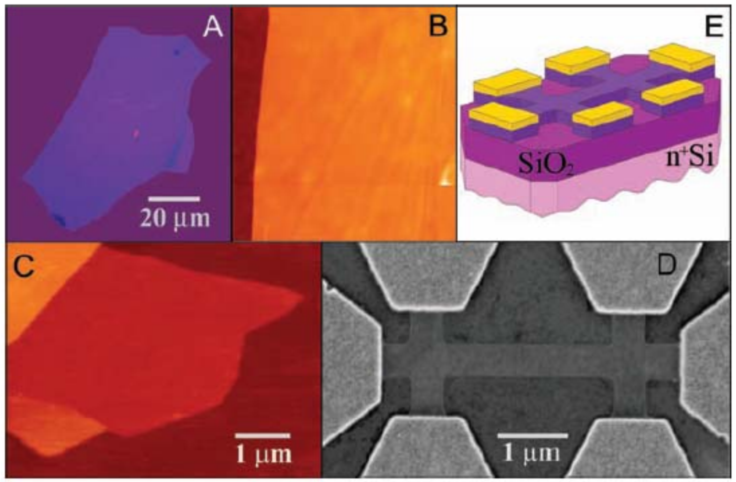
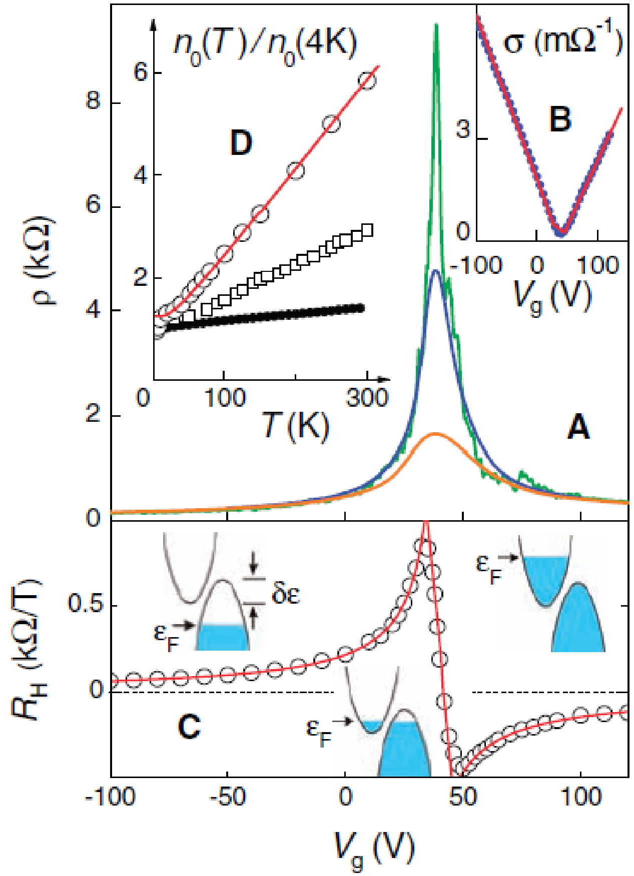
Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]





K. S. Novoselov et al. Science 306 (2004) 666.

The pioneering work in Manchester Univ.

Outline

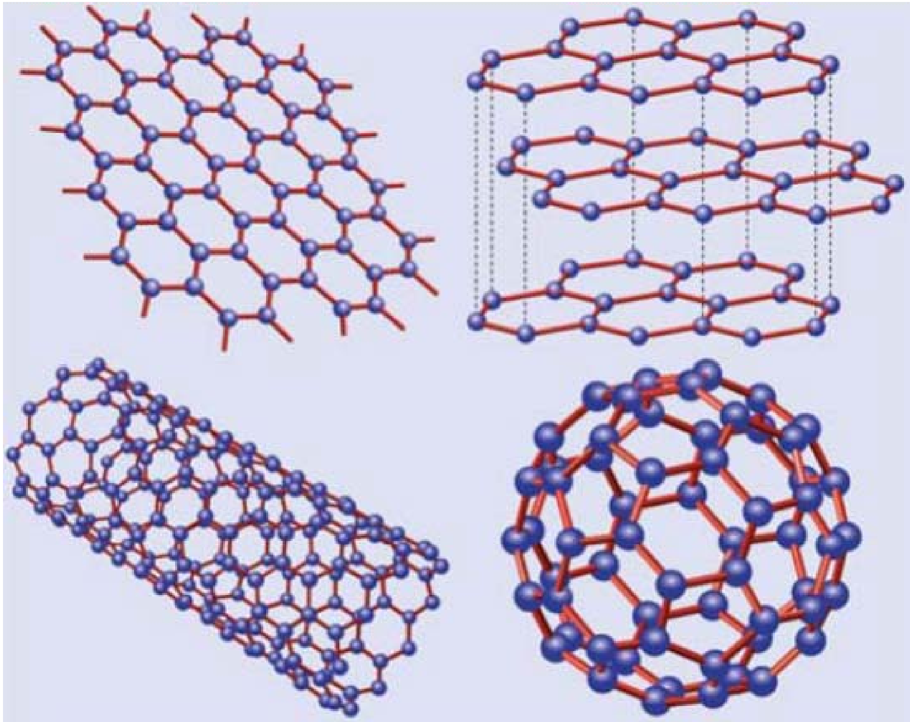
1.Graphene Introduction

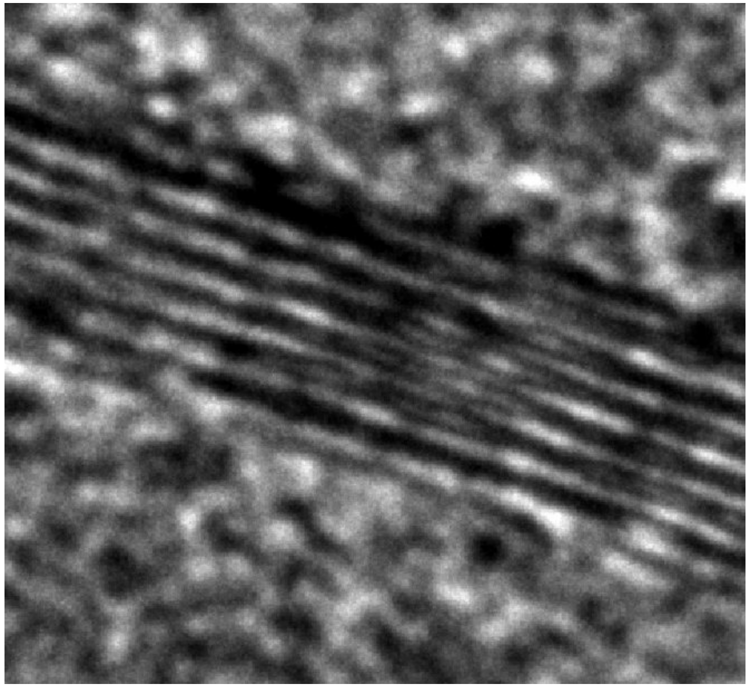
2.Electric Field Effects in Graphene

3.Possible Applications

4.Summary and Future Outlook

Graphene



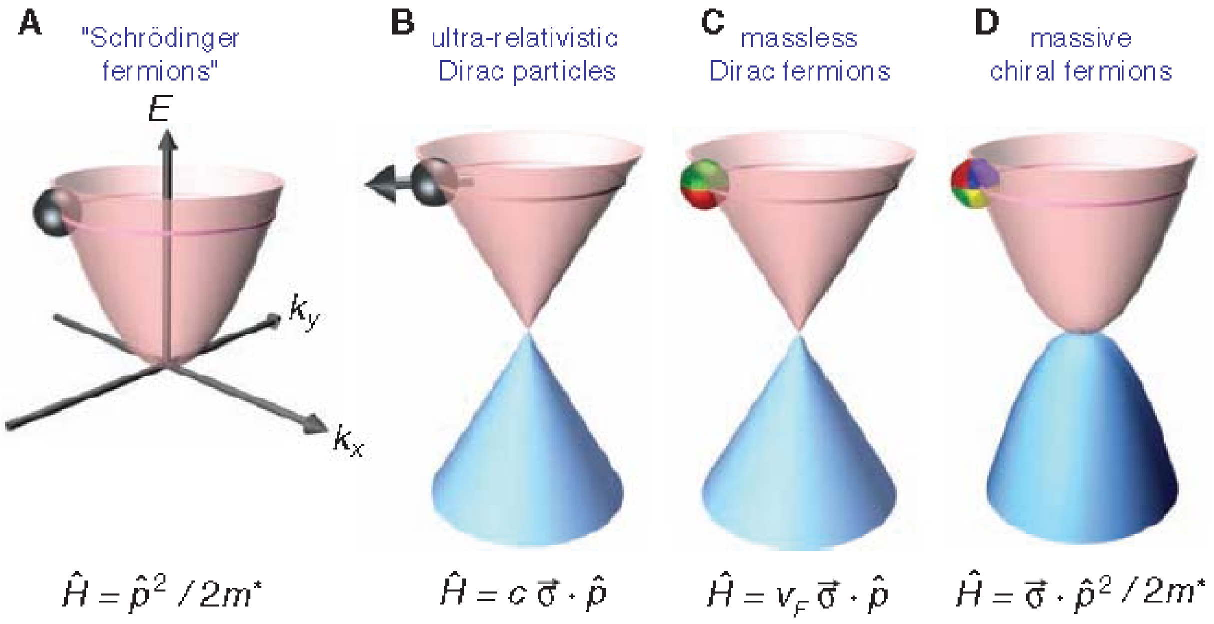


TEM on 90 nm-thick SiO_2 @Lab.

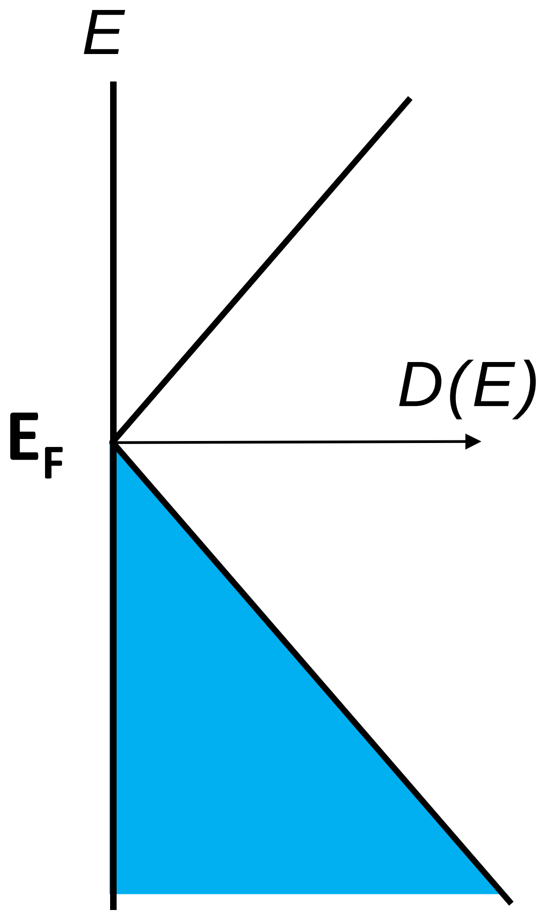
A. H. Castro Neto et al., Rev. Mod. Phys. 81(2009)109.

E - k Dispersion and Density of States

A great fun for condensed matter physicists



A. K. Geim, Science, 324 (2009)1530.



Unique E-k dispersion and density of states.

Advanced Peeling Technique !

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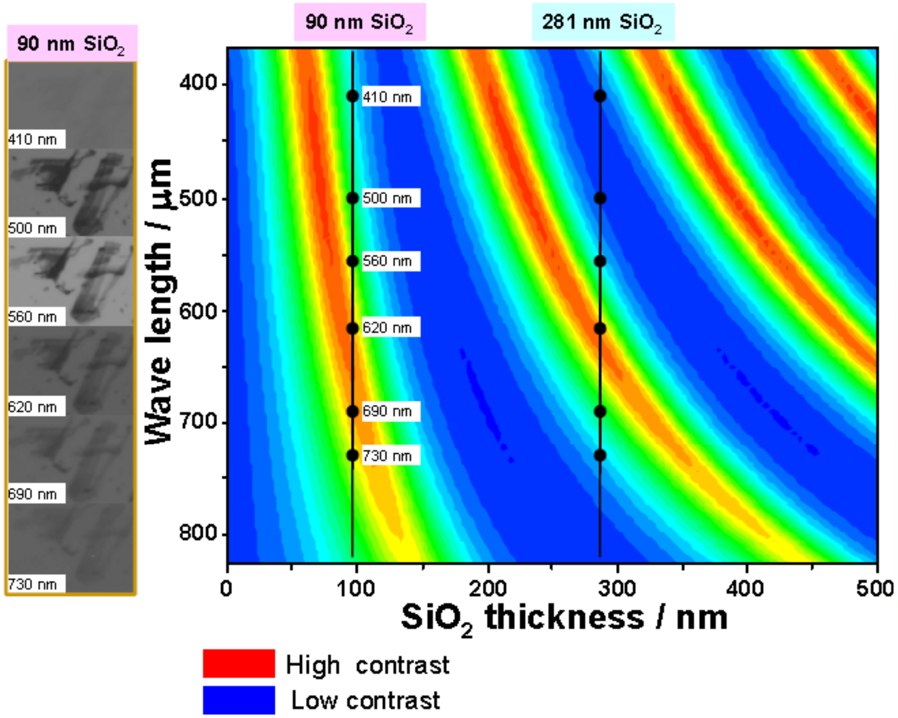
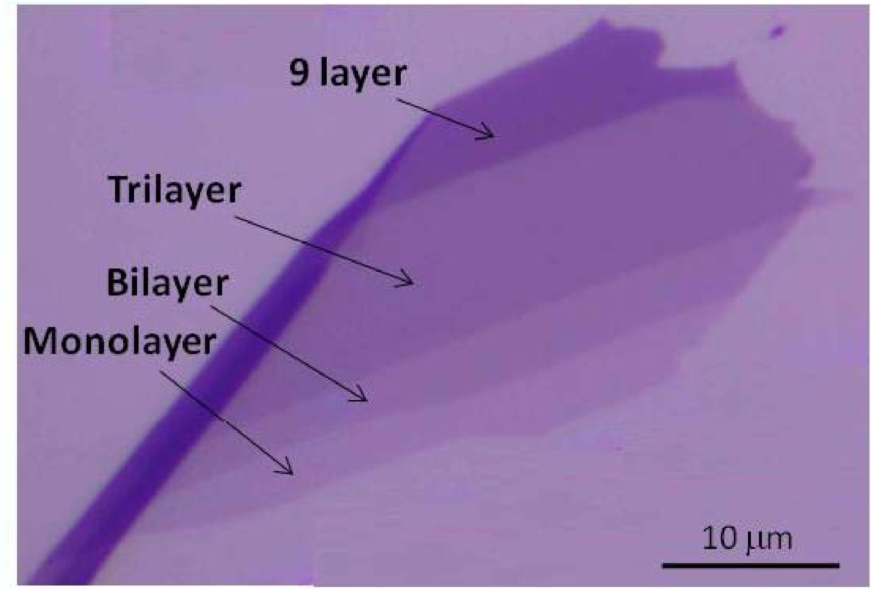
Optical Contrast of Graphene on SiO_2/Si

$$\text{contrast} = \frac{R_{oxide} - R_{gra}}{R_{oxide}}$$





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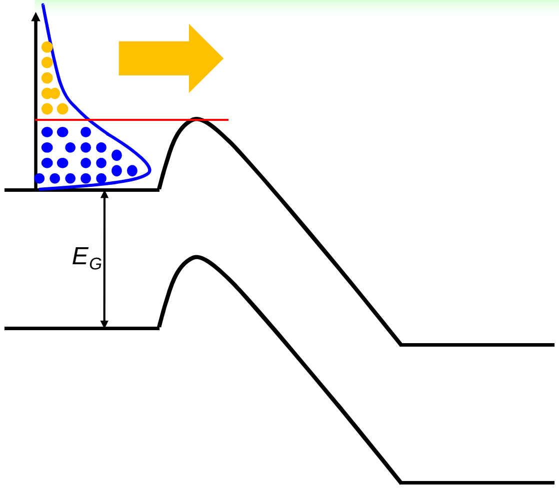
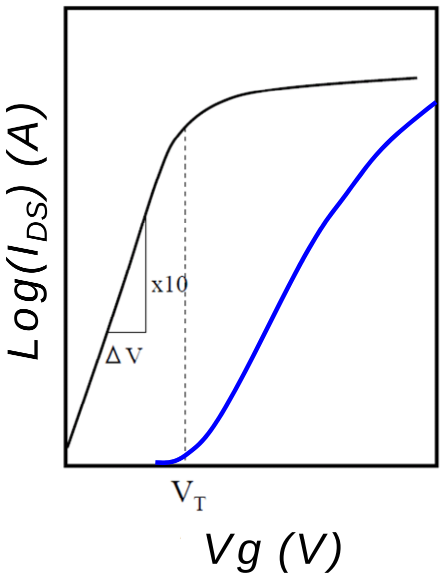
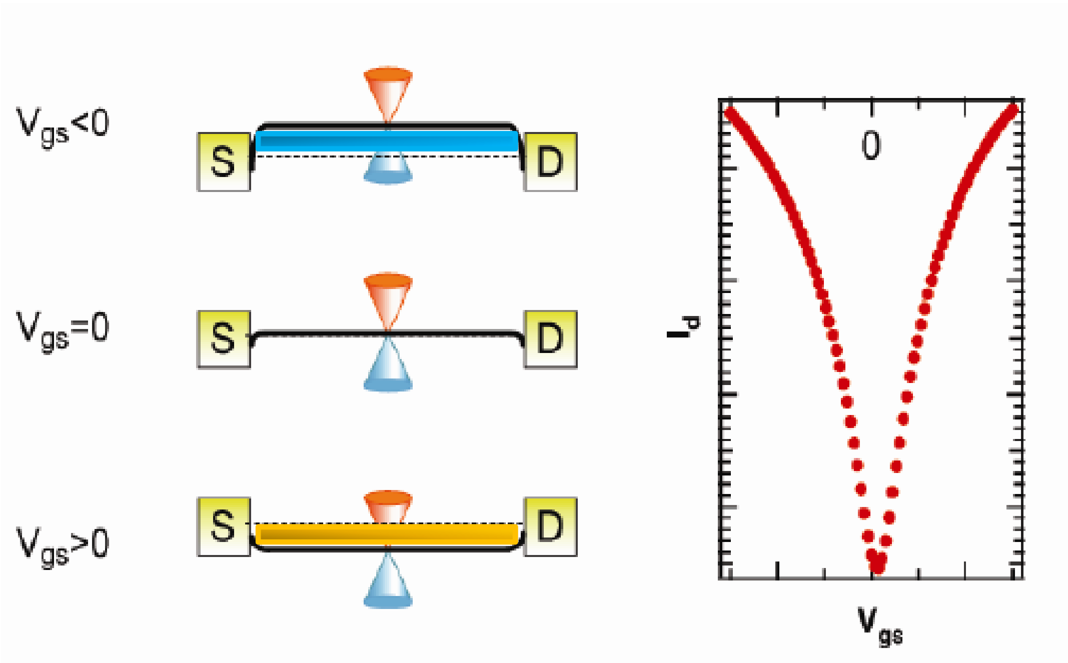
A monolayer graphene on ~90 nm SiO_2 is also visible by optical microscope.

Conventional FET and Graphene FET



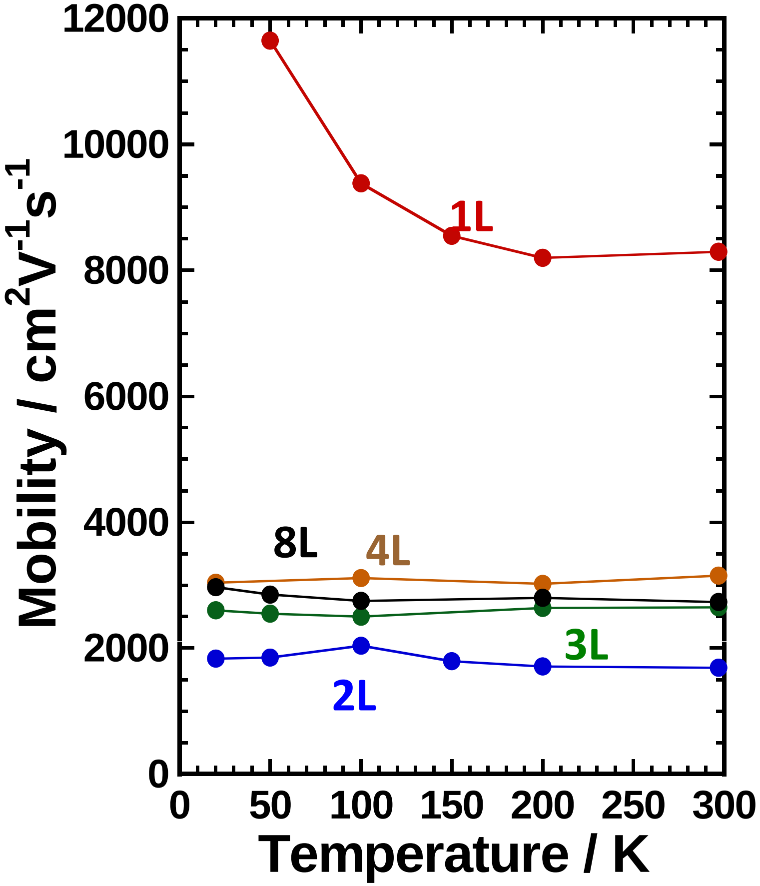


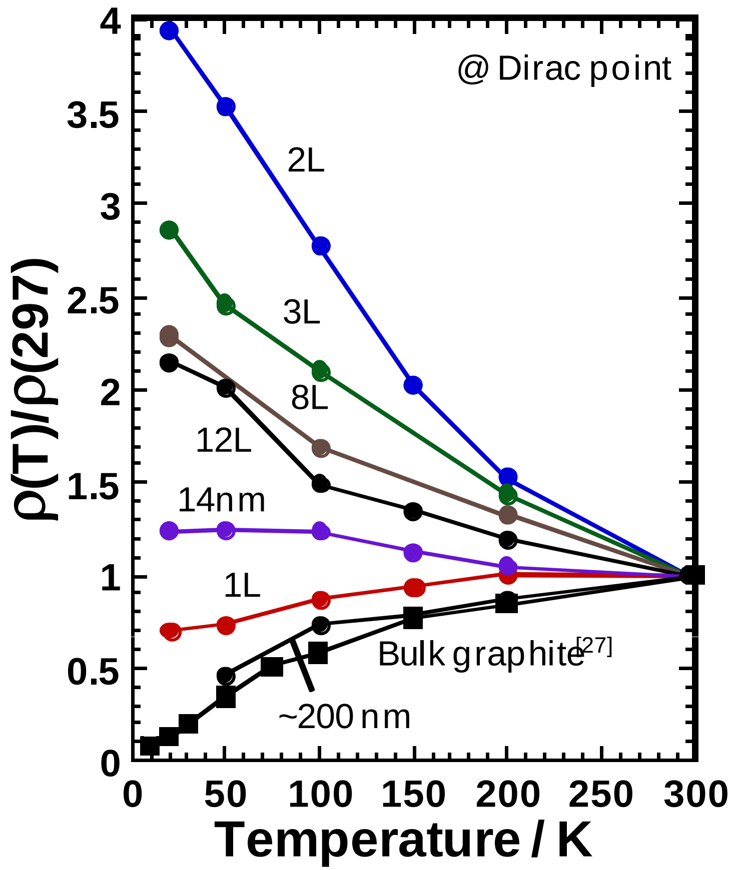


Z. Chen and J. Appenzeller, IEDM (2008).

Ambipolar Characteristics.

Graphite to Graphene on SiO_2



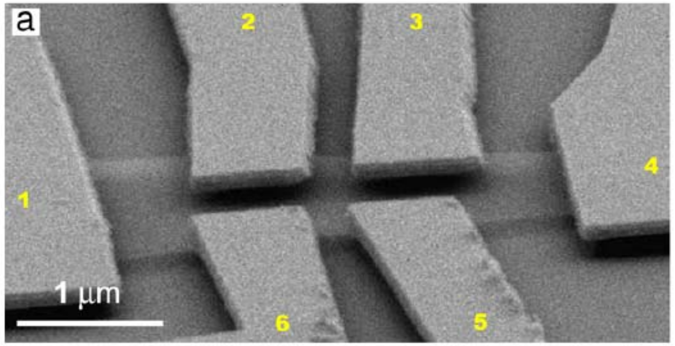


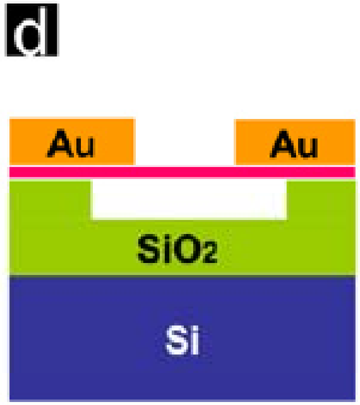
K. Nagashio et al., JJAP 49 (2010).

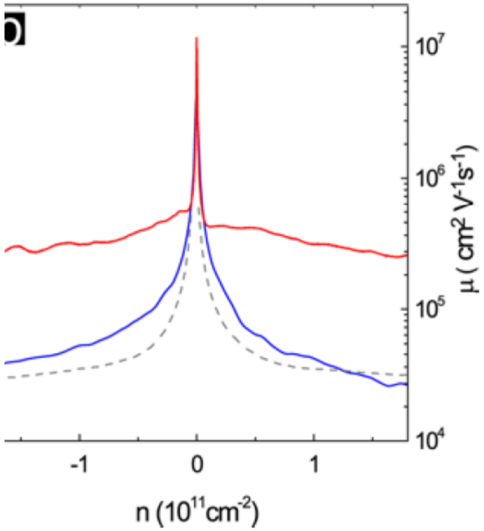
Monolayer graphene is something special.

Graphene on Nothing and on BN

Suspended

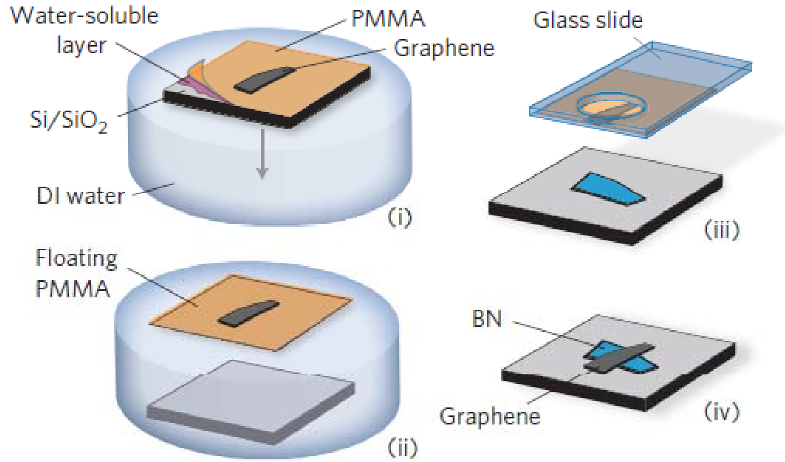




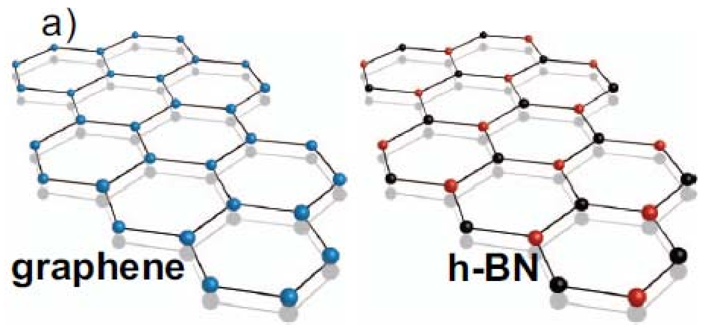


K. I. Bolotin et al., SSC 146 (2008) 351.

On BN

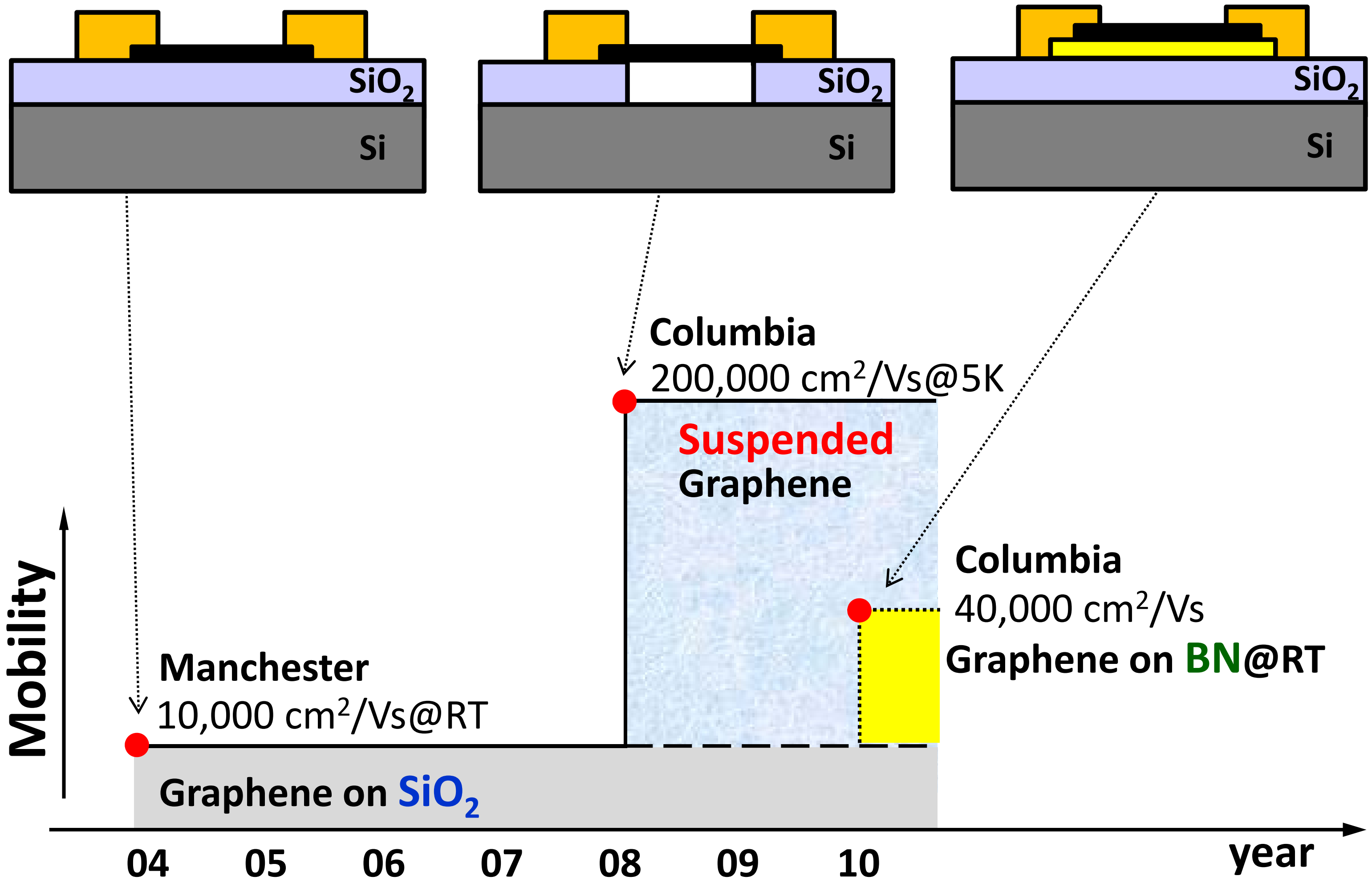


C. R. Dean et al., Nature Nano. 172 (2010) 722.

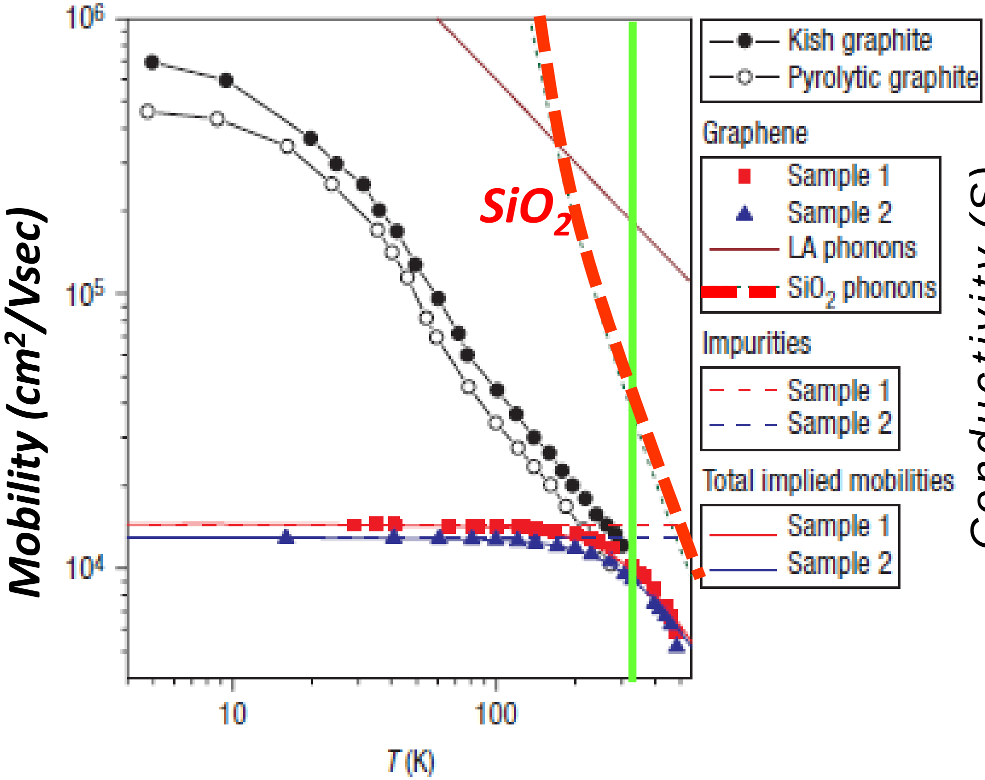


1.7% lattice mismatch

Mobility Limited by Interfacing Substrate

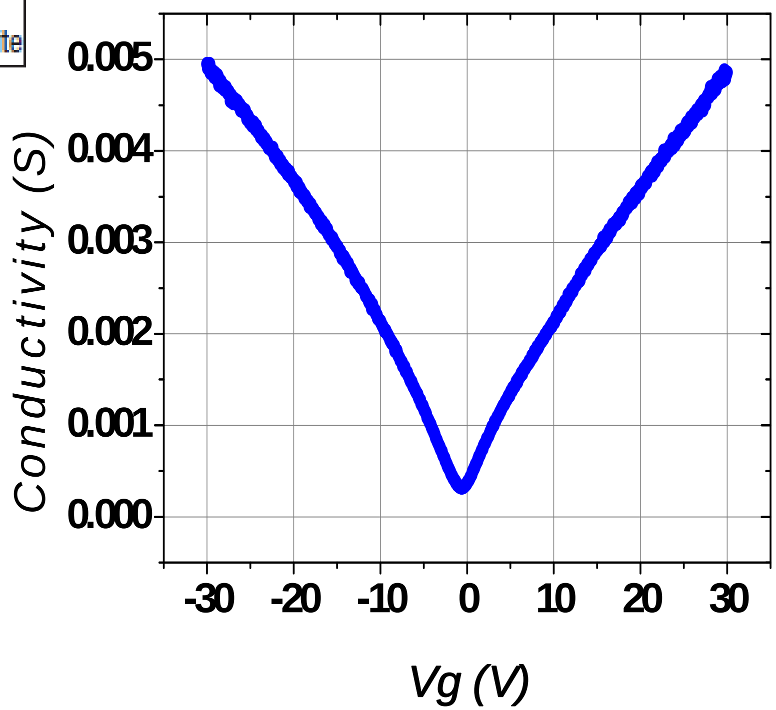


Possible Scattering Mechanisms



J-H Chen et al., Nature Nano. 3 (2008) 206.

μ=8,000cm²/Vsec



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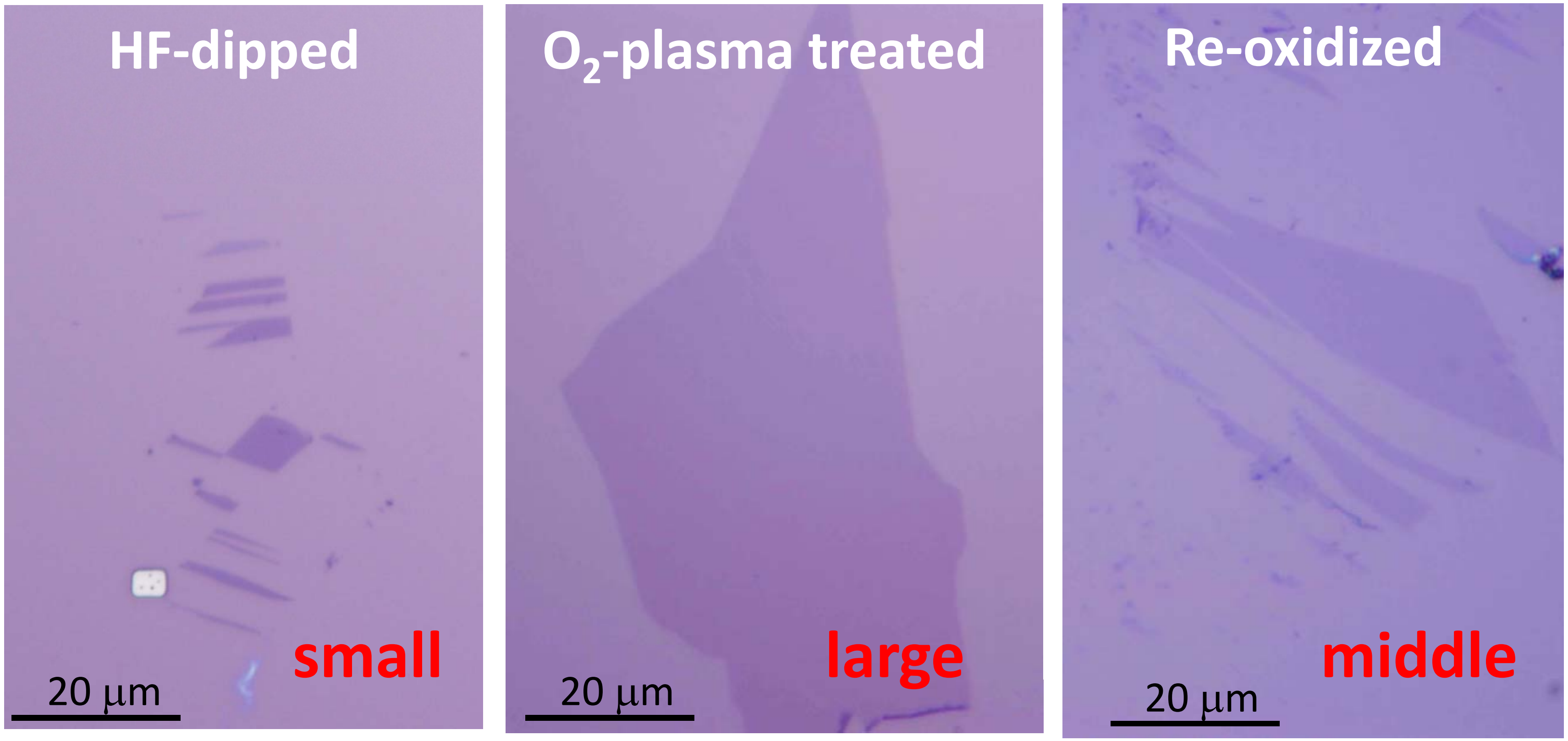
Graphene / SiO_2 Interaction



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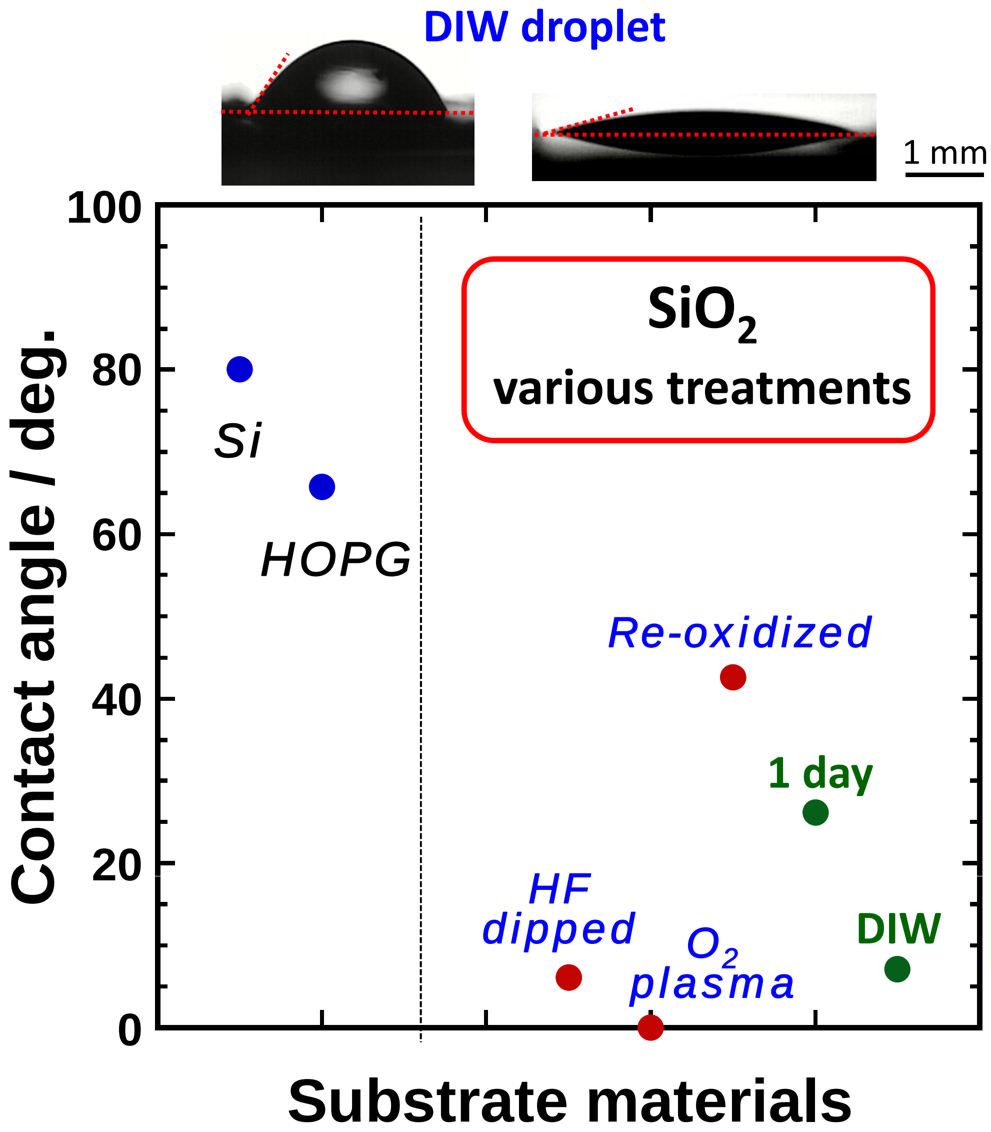
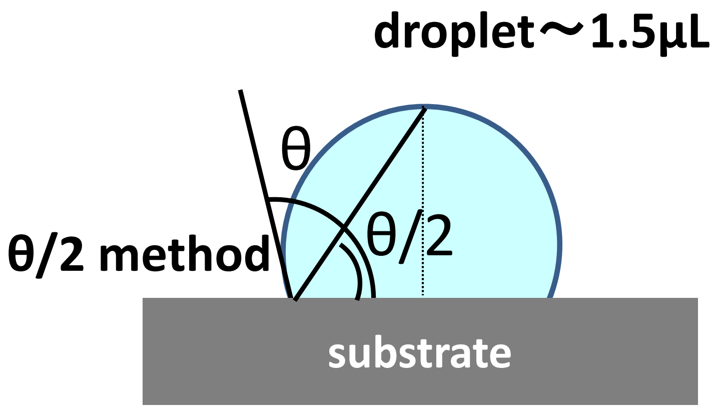
The flake size depends on SiO_2 surface treatment.

Contact Angles on Differently Treated SiO_2





Measurement Conditions

Temperature:23-27℃

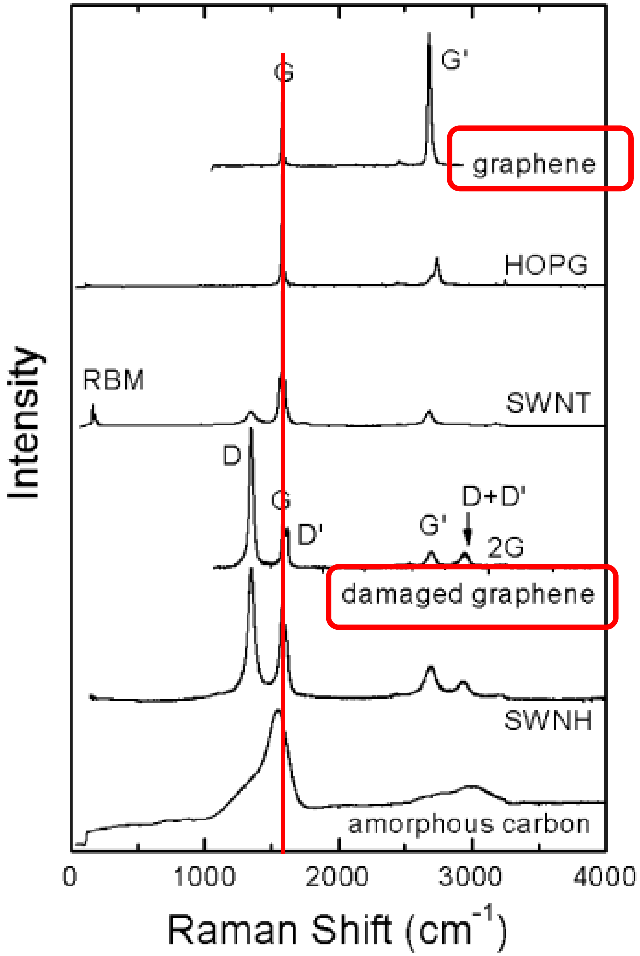
Humidity: 58-66%

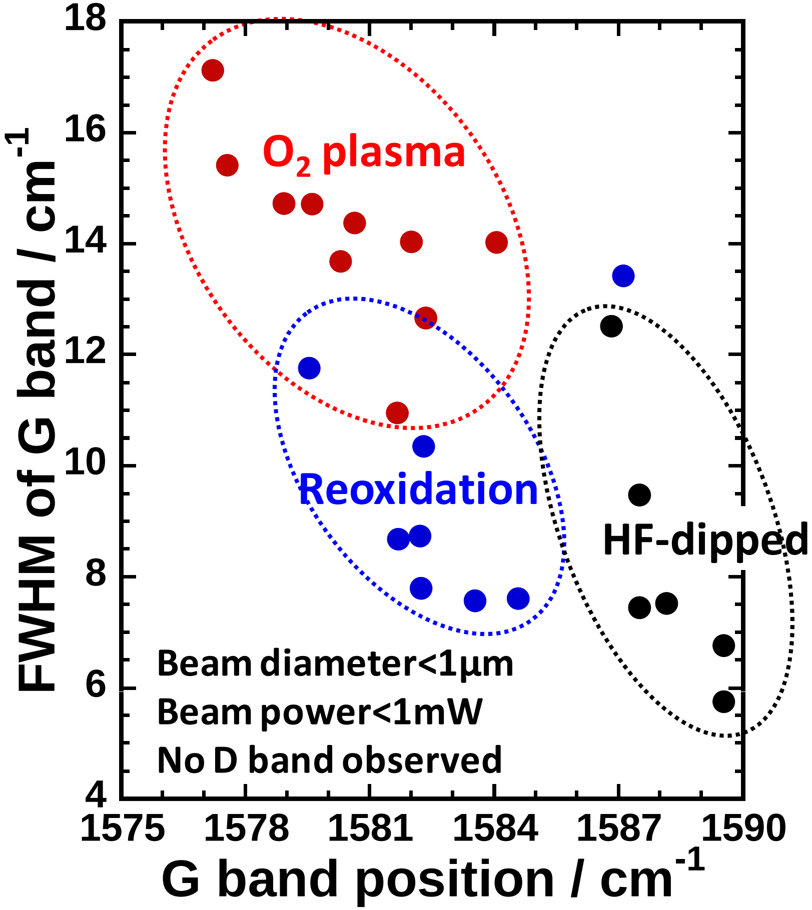
OH-termination.....hydrophilic

O-termination.....hydrophobic

T. Yamashita et al., SSDM (2010).

Effects of SiO_2 Surface on Raman G-band





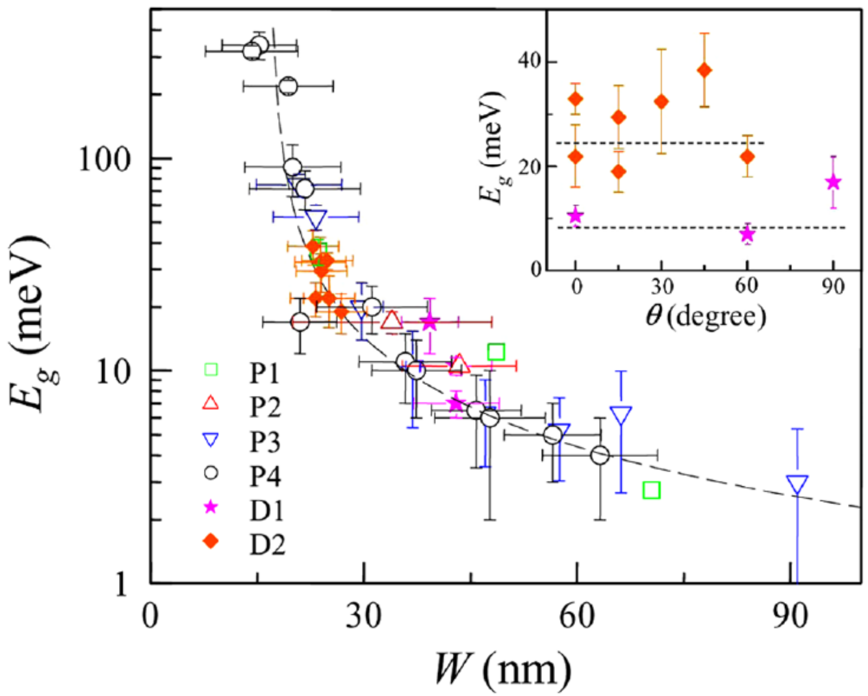
M. S. Dresselhaus et al., Nano Lett. 10(2010)751

K. Nagashio et al., IEDM (2010).

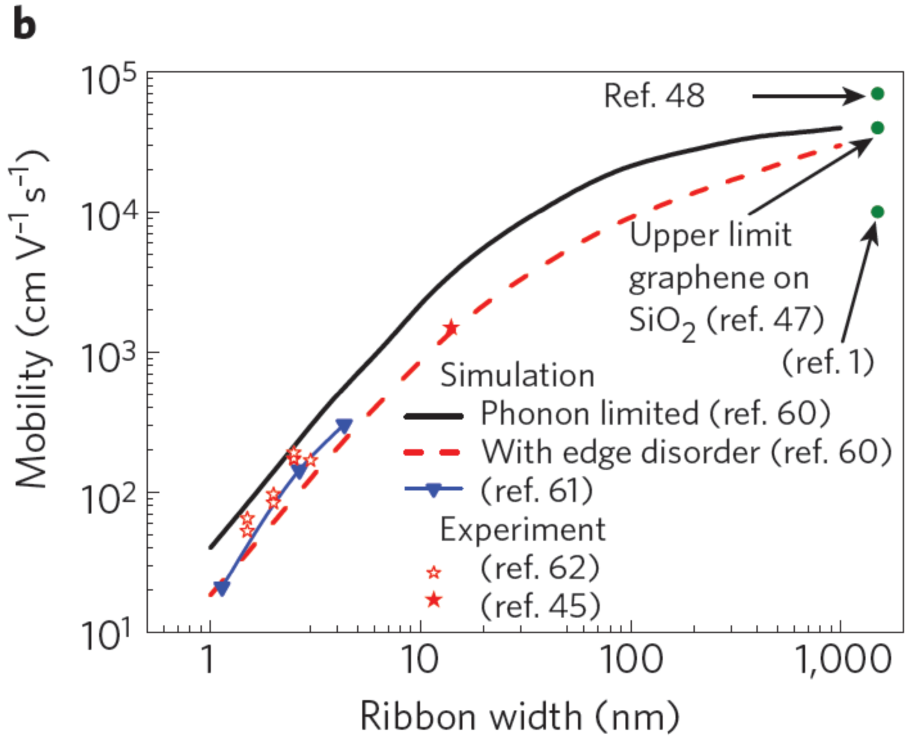
A strong interaction between graphene and SiO_2.

Intrinsic Challenges (1) - no band gap -

Nano Ribbon



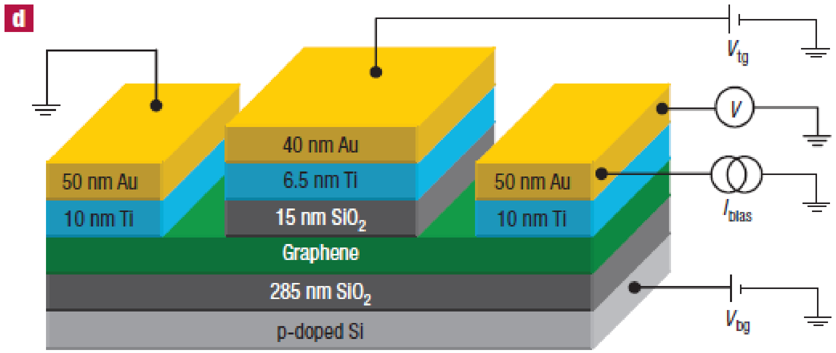
M. Y. Han et al., PRL 98(2007)206805.

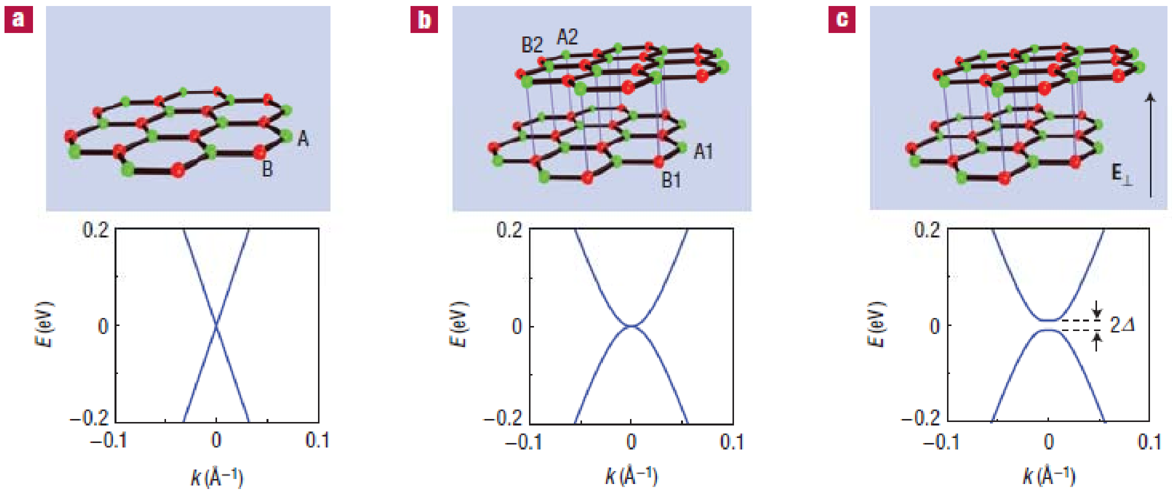


F. Schwierz, Nature Nanotech. May 2010.

Mobility is degraded as E_G is opened.

Bi-layer Graphene

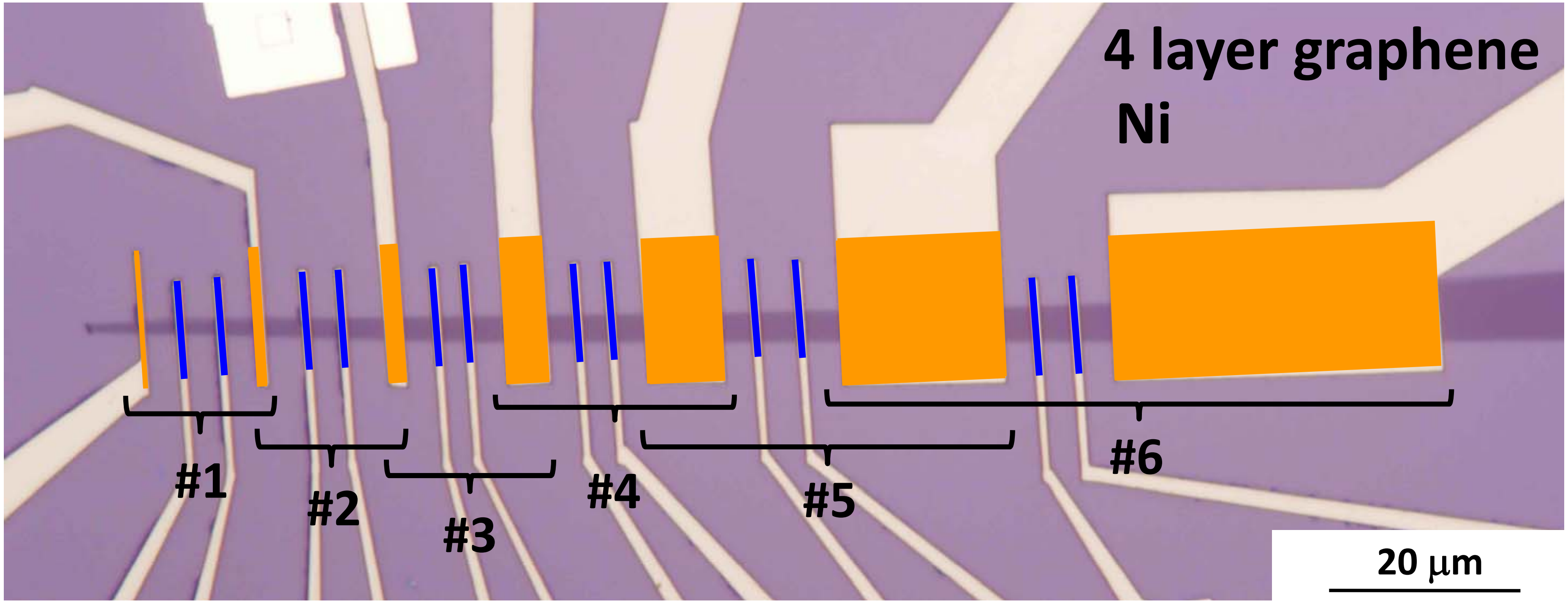




J. B. Oostinga et al., Nature Materials 7 (2008) 151.

Bi-layer graphene with double gates can open the gap!

Intrinsic Challenges (2) - contact resistance -



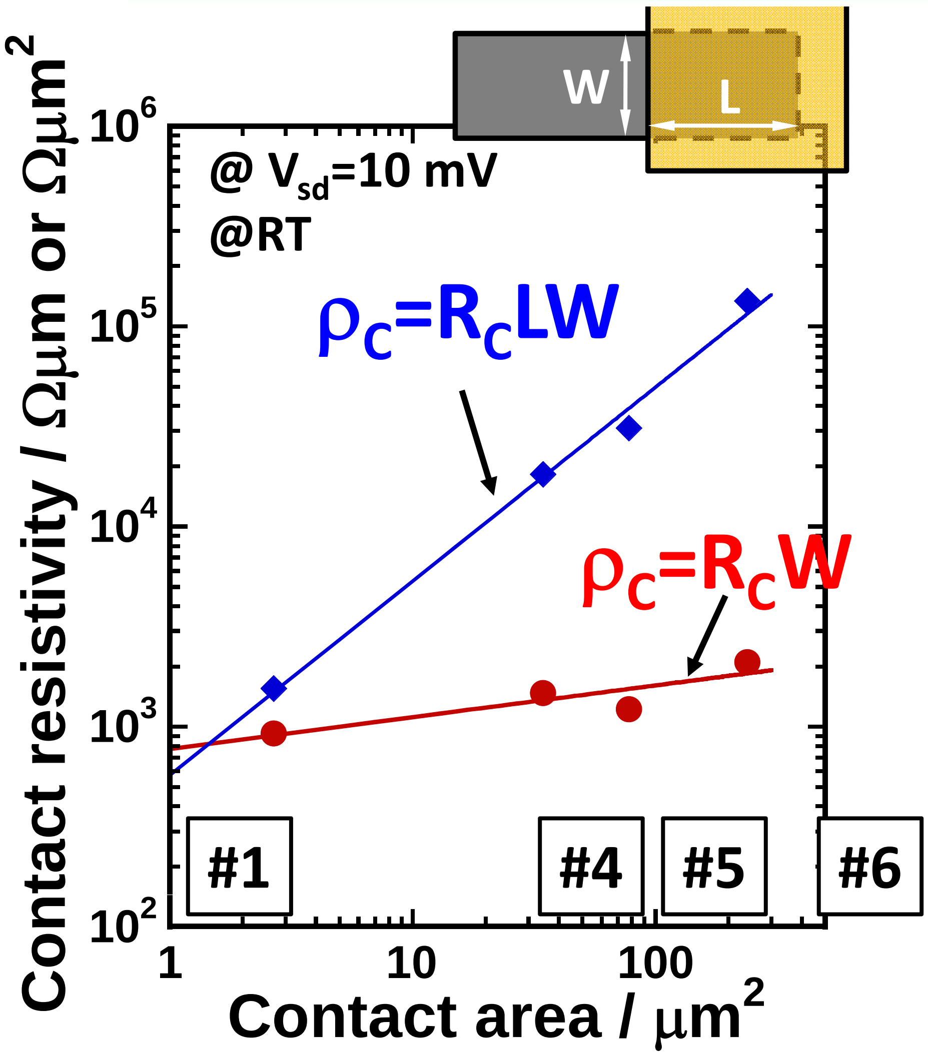
$$R_{total} = R_{ch} + 2R_{contact}$$

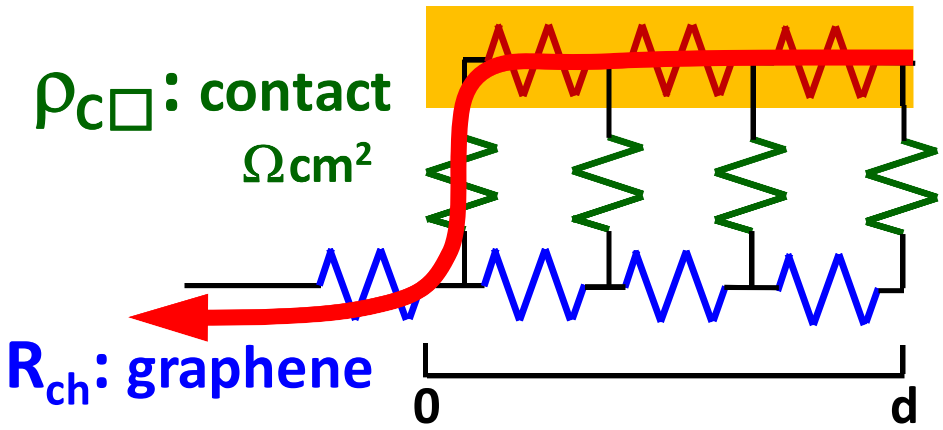
$$R_{contact} = \frac{1}{2}\left(R_{total} - \rho_{channel}\frac{L}{W}\right)$$

K. Nagashio et al., IEDM (2009).

Contact area dependence of contact resistance.

Current Crowding





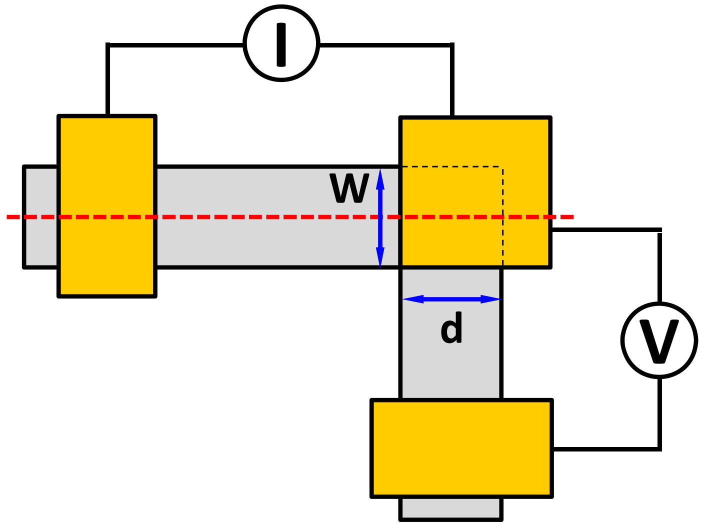
K. Nagashio et al., IEDM (2009).

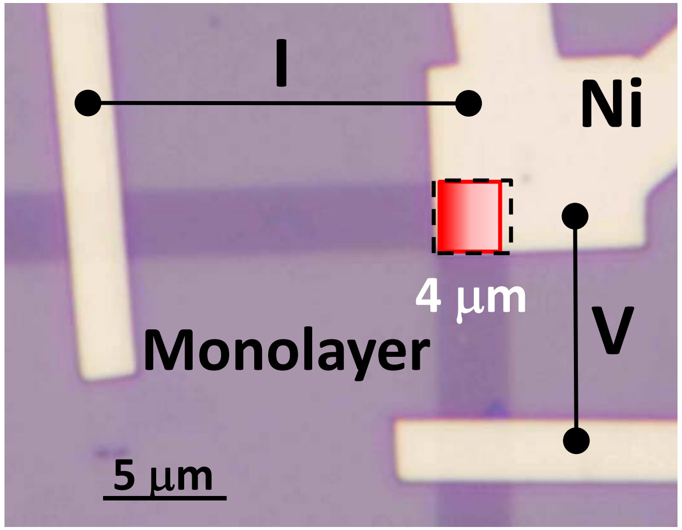
Current crowding should be considered in large contacts.

Specific Contact Resistance

Cross-bridge Kelvin

$$R_c = \frac{V}{I} = \frac{\rho_{c\square}}{dW}$$





Etched by O_2 plasma

contact resistivity

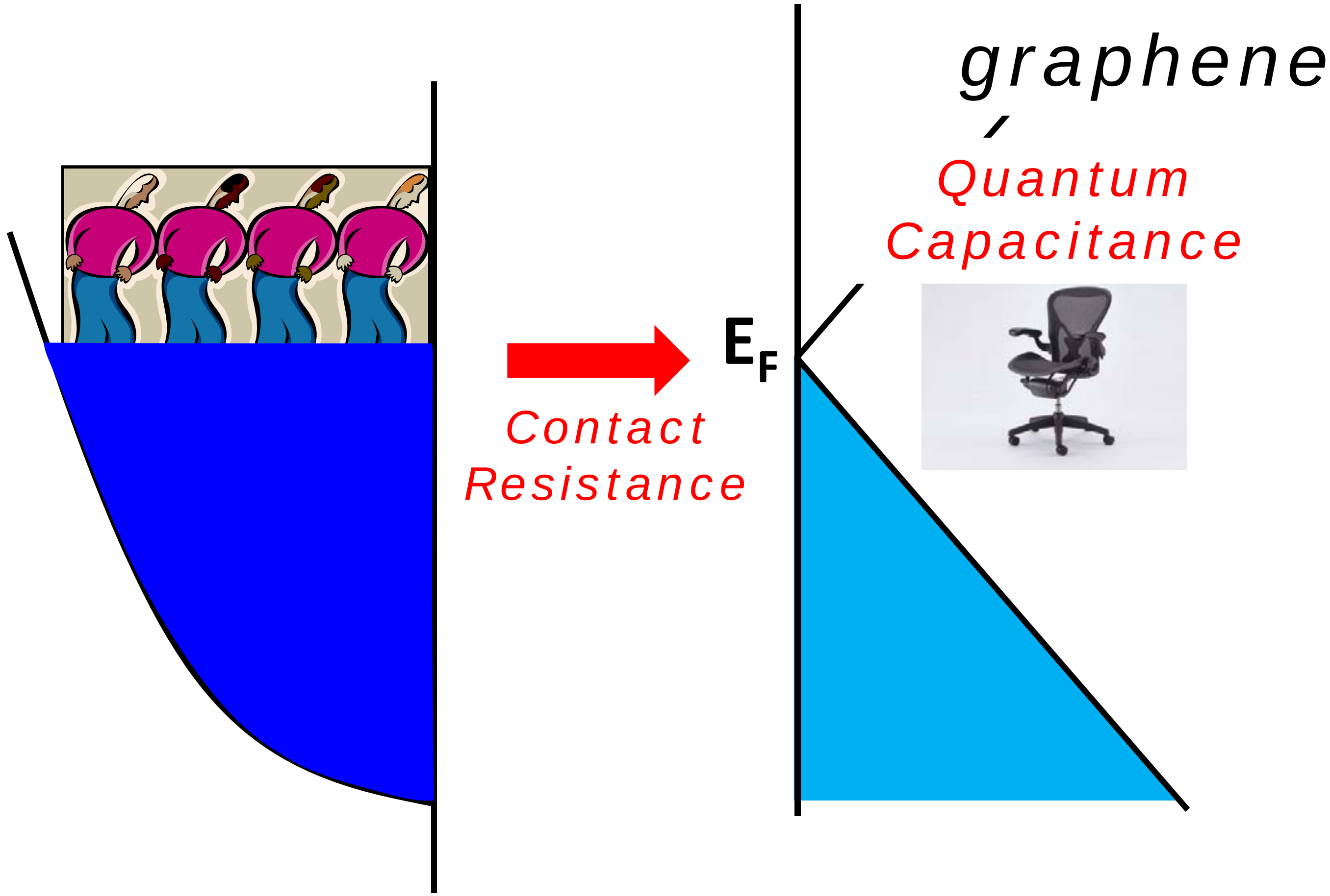
$$\rho_{c\square} =\sim 5\times 10^{-6}\,\Omega cm^2$$

Transfer length

$$d_T = \sqrt{\frac{\rho_{c\square}}{R_{sh}}} =\sim 1\mu m$$

K. Nagashio et al., APL. 97(2010) 143514.

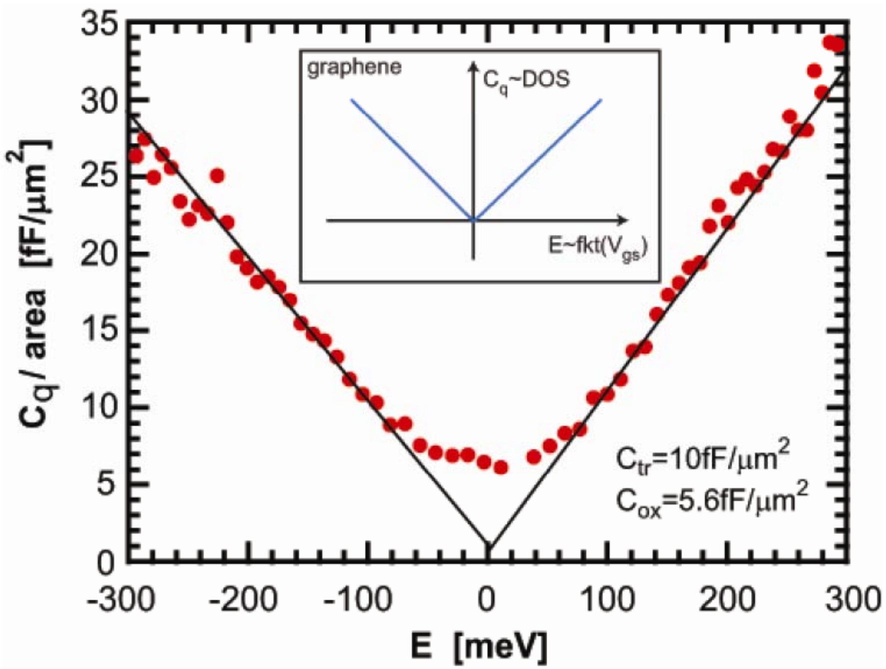
DOS Bottleneck

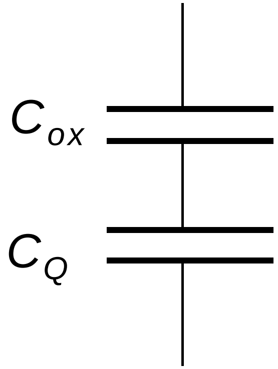


A small number of seats available in the channel.

Intrinsic Challenges (3) - quantum capacitance -

$$C_q(V_g) = e^2 D(E) = e^2 \frac{2E_F}{\pi(\upsilon_F \hbar)^2}$$



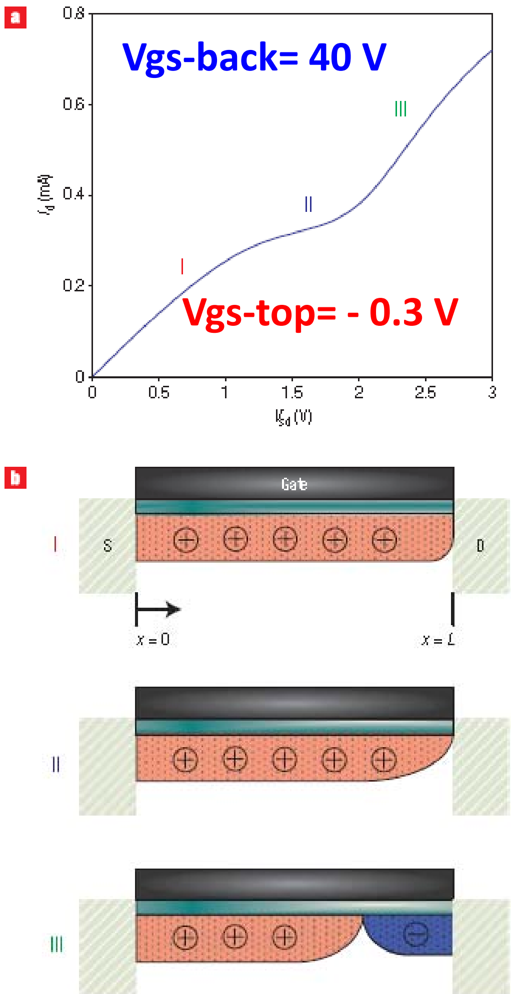


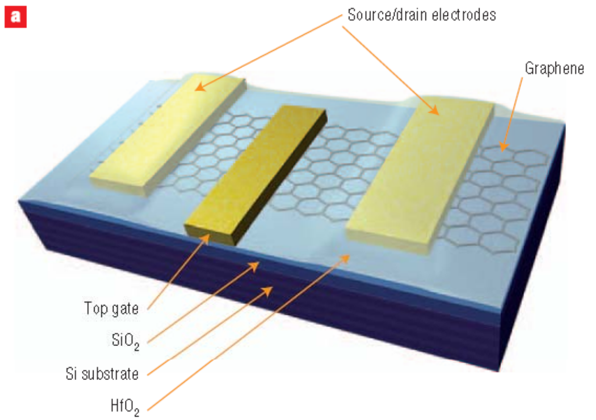
$$10[\,fF/\mu m^2\,] = 3.4nm(EOT)$$

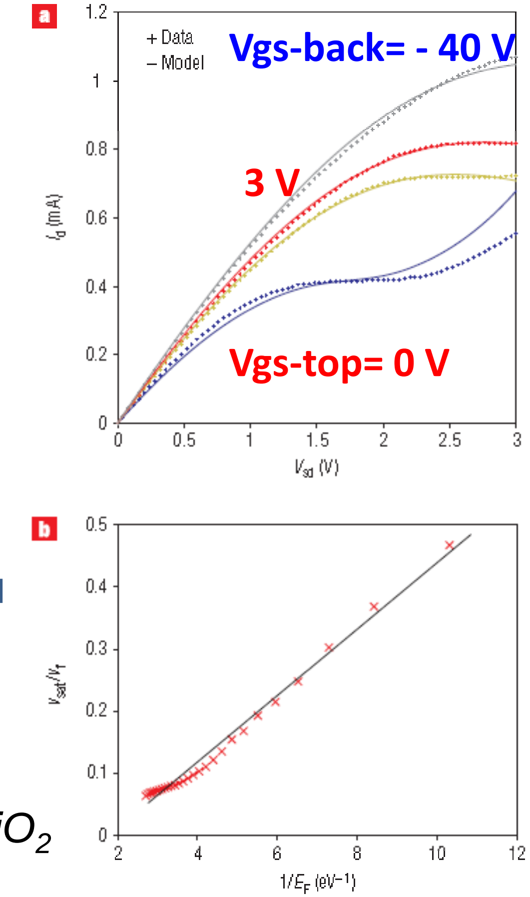
Z. Chen and J. Appenzeller, IEDM (2008)

Sub-nm CET is intrinsically difficult.

Output Characteristics







$$\upsilon_{sat} = \upsilon_F \left(\hbar\Omega / E_F \right)$$

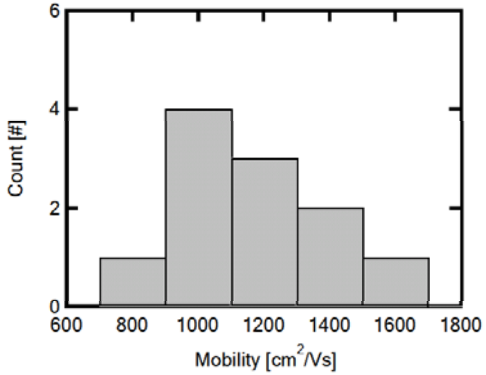
$$\hbar\Omega = 54\ meV$$

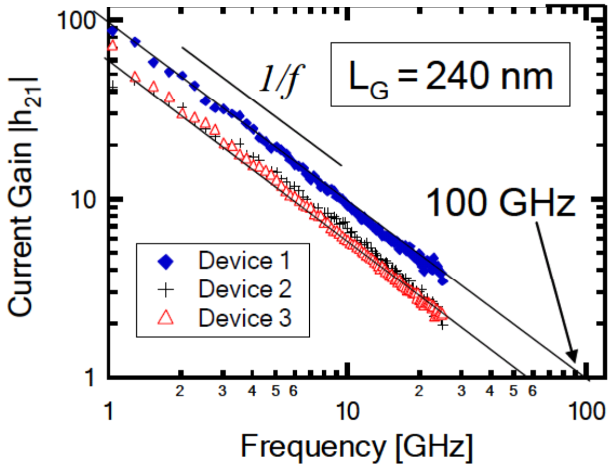
Optical phonon of SiO_2

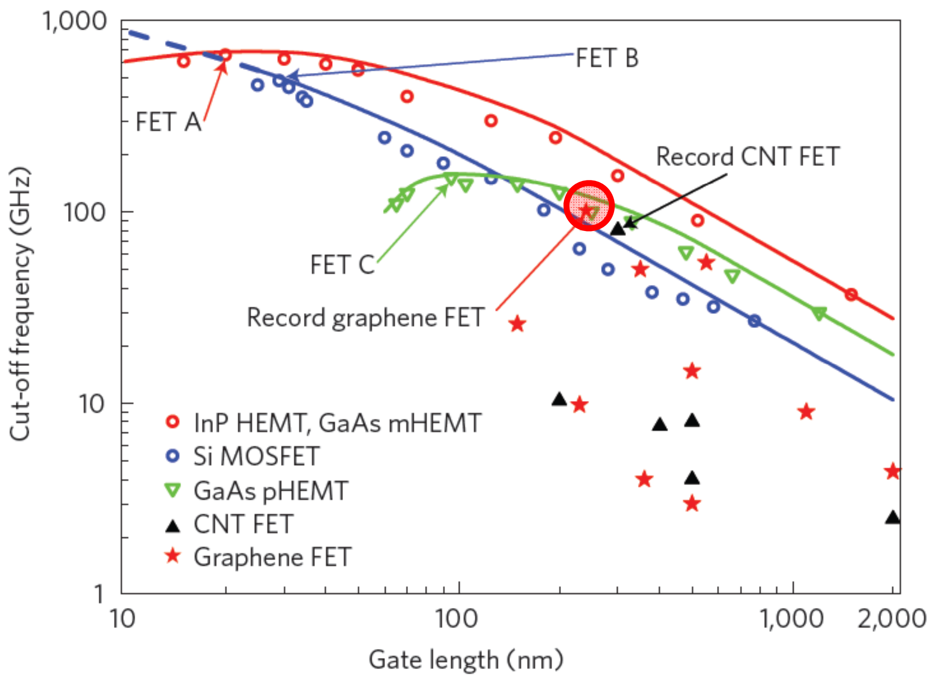
I. Meric et al., Nature Nanotech. 3 (2008)654.

Intrinsically no pinch-off due to no band-gap.

RF-Performance





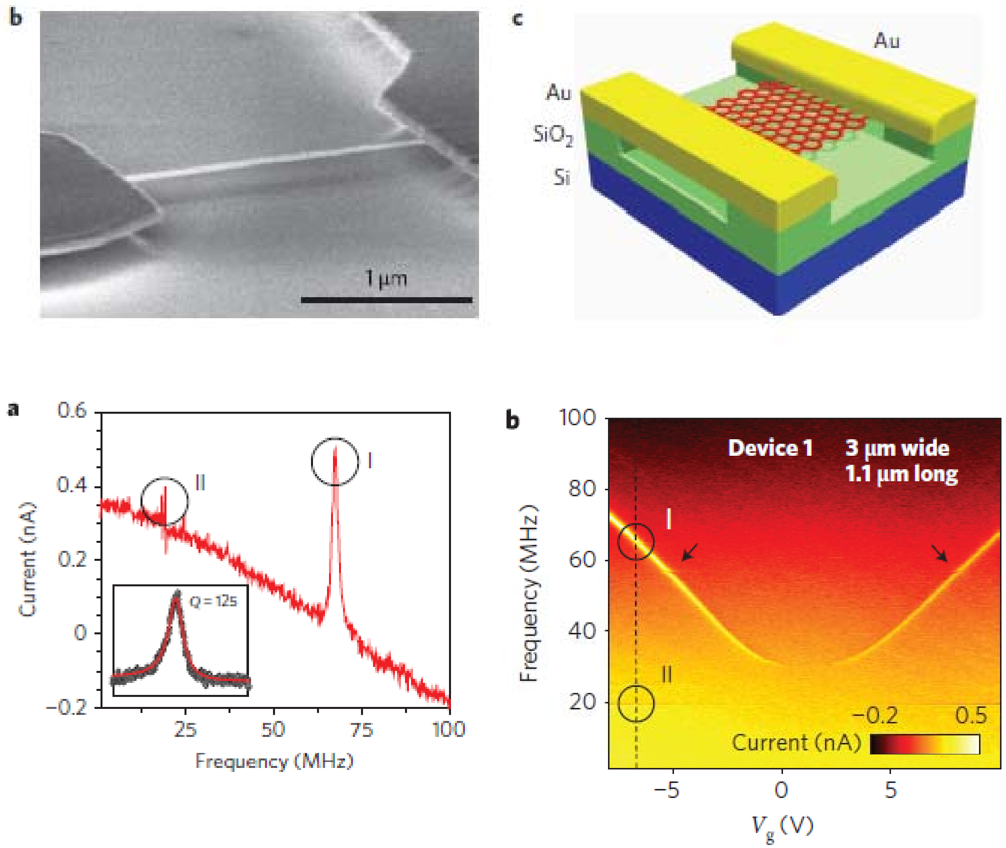


Y. M. Lin et al. Science 327(2010)662. *F. Schwierz, Nature Nanotech. May 2010.*

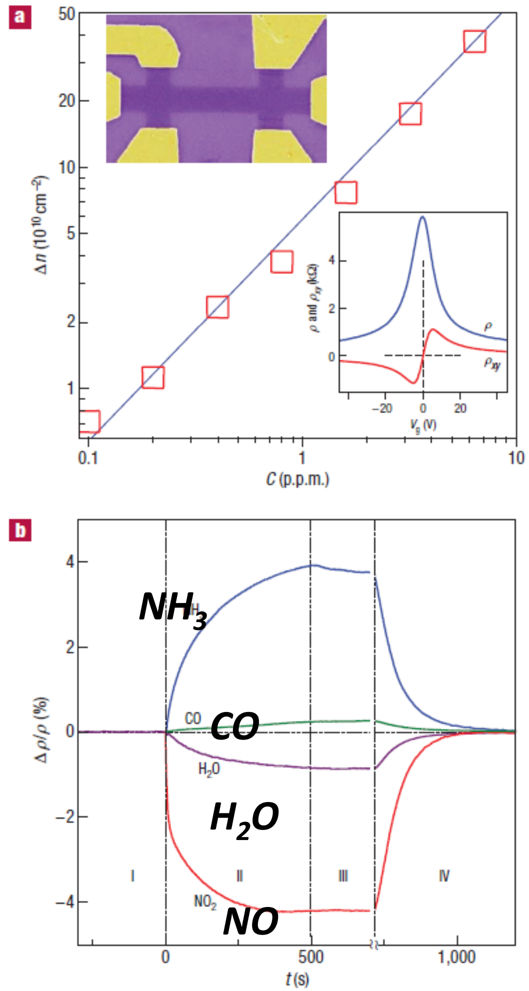
f_T is comparable to existing RF devices.

Other Applications

NEMS *Sensor*



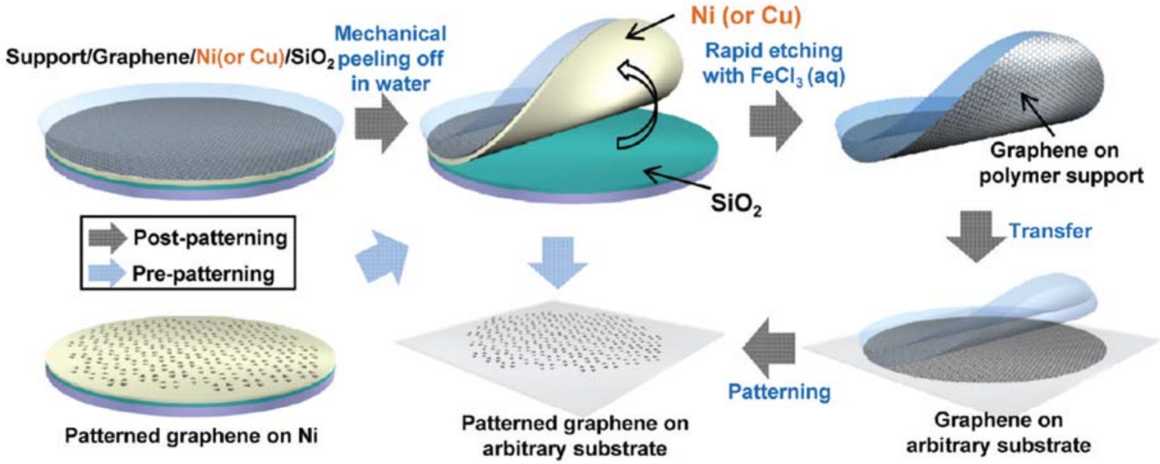
C. Chen, et al., Nature Nanotech. 4 (2009)861.



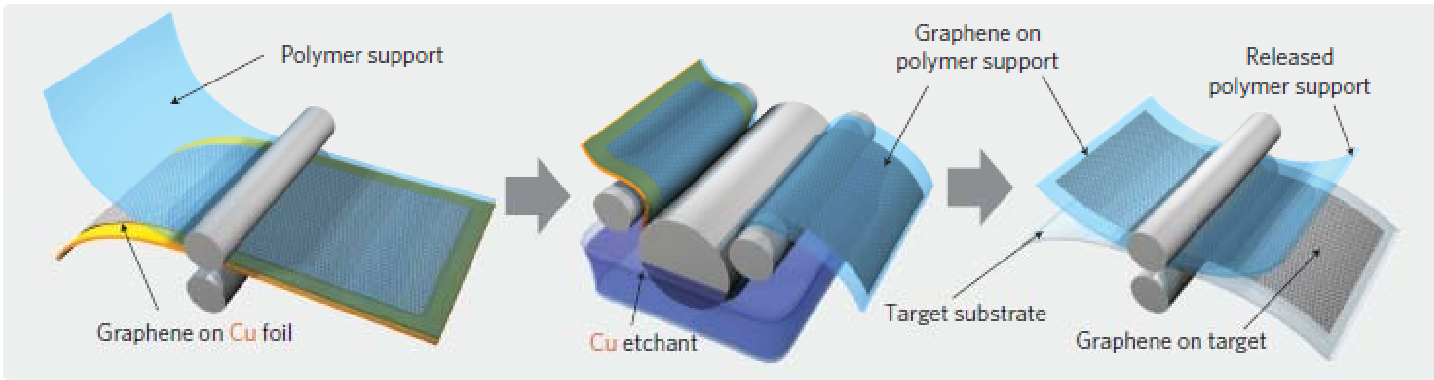
F. Schedin, et al., Nature Mater. 6 (2007)652.

Wafer Scale to Roll-to-Roll

SKKU + Samsung



Y. Lee et al., Nano Lett. ***10 (2010)*** *490.*



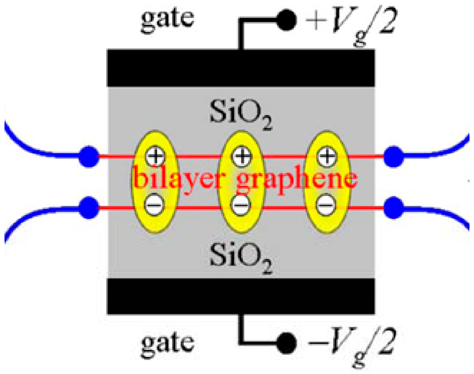
S. Bae et al, Nature Nanotech. 5 (2010)574.

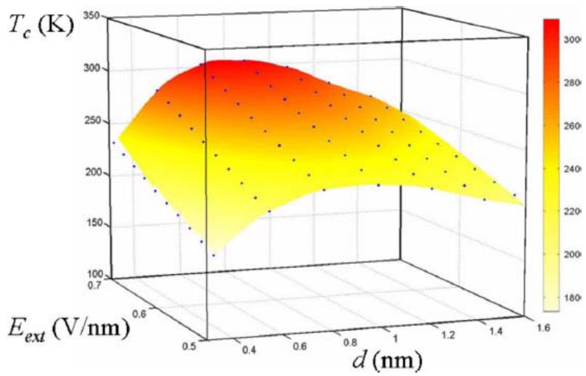
Far Beyond Conventional FETs

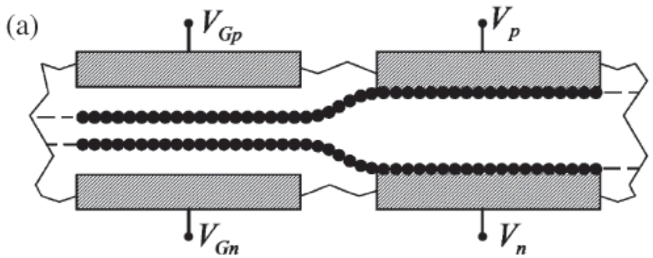
BiSFET - Bilayer Pseudo Spin Field-Effect Transistor -

H. Min et al., Phys. Rev. B78 (2007)121401.

el-hole condensation through thin insulator.







S. K. Banerjee et al. IEEE EDL 30 (2009)158.

Bose condensation *contacts*

Ultra-low Power Switching !

Summary

✓**Graphene is a really exciting material for both physicists and engineers.**

✓**Monolayer graphene shows very high mobility for both electron and hole.**

✓**High frequency application seems more promising than digital one.**

✓**No band-gap and small DOS effects such as quantum capacitance and large contact resistance should be seriously concerned.**

✓***The graphene research is just booming up, and I believe it will shows different faces in a couple of years.***

✓***Be optimistic about new materials for the present.***