


Graphene: A new Electronic Material

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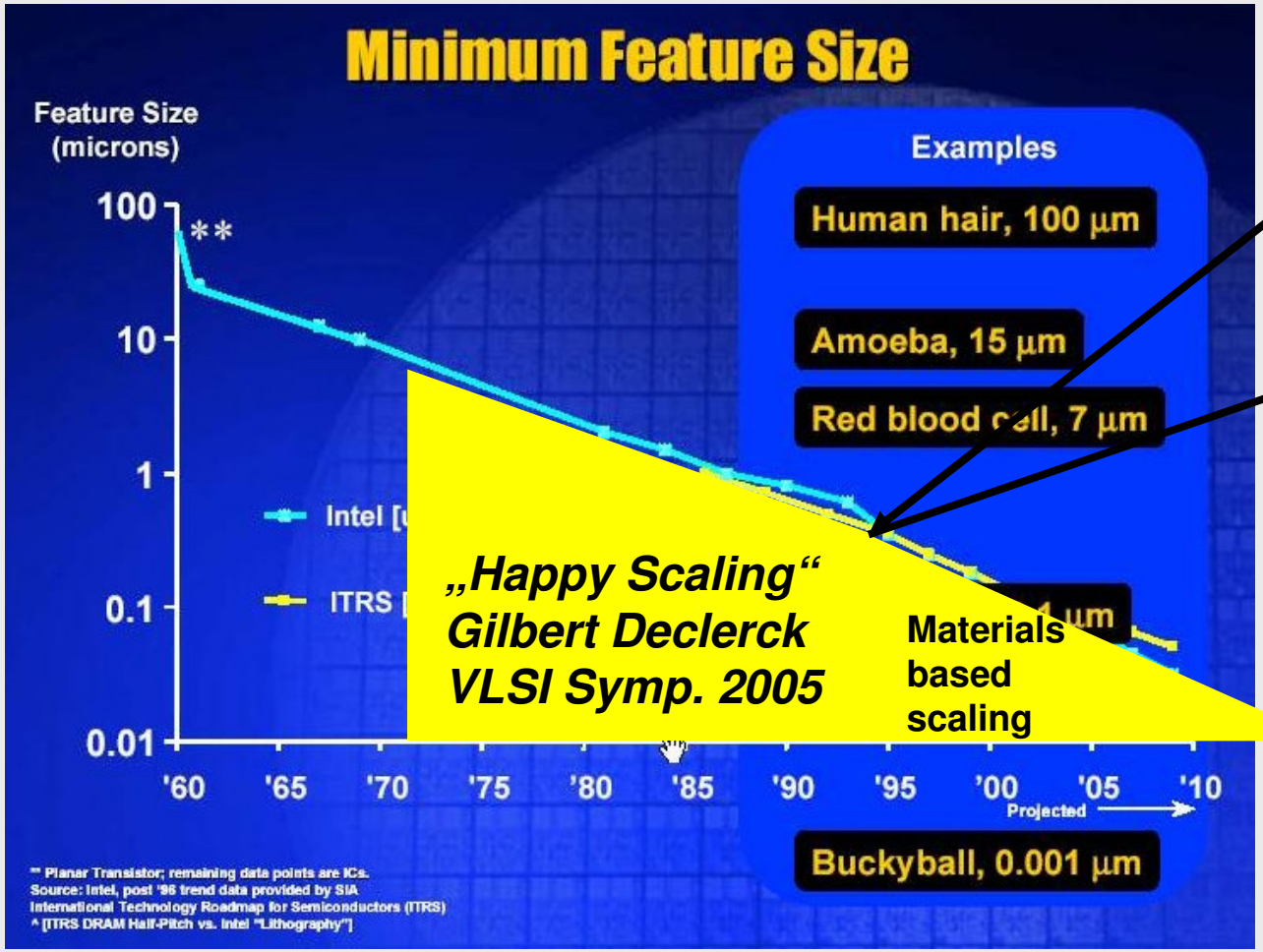
Outline

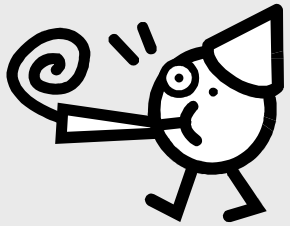
- Introduction
- Results & Discussion
- Outlook
- Summary

Motivation: Moore's Law



Industry guy

Researcher



- SOI
- High-k
- Metal Gates
- Strained Silicon
- Germanium
- Carbon…

Source: G.E. Moore, No exponential is forever…, ISSCC, February 2003

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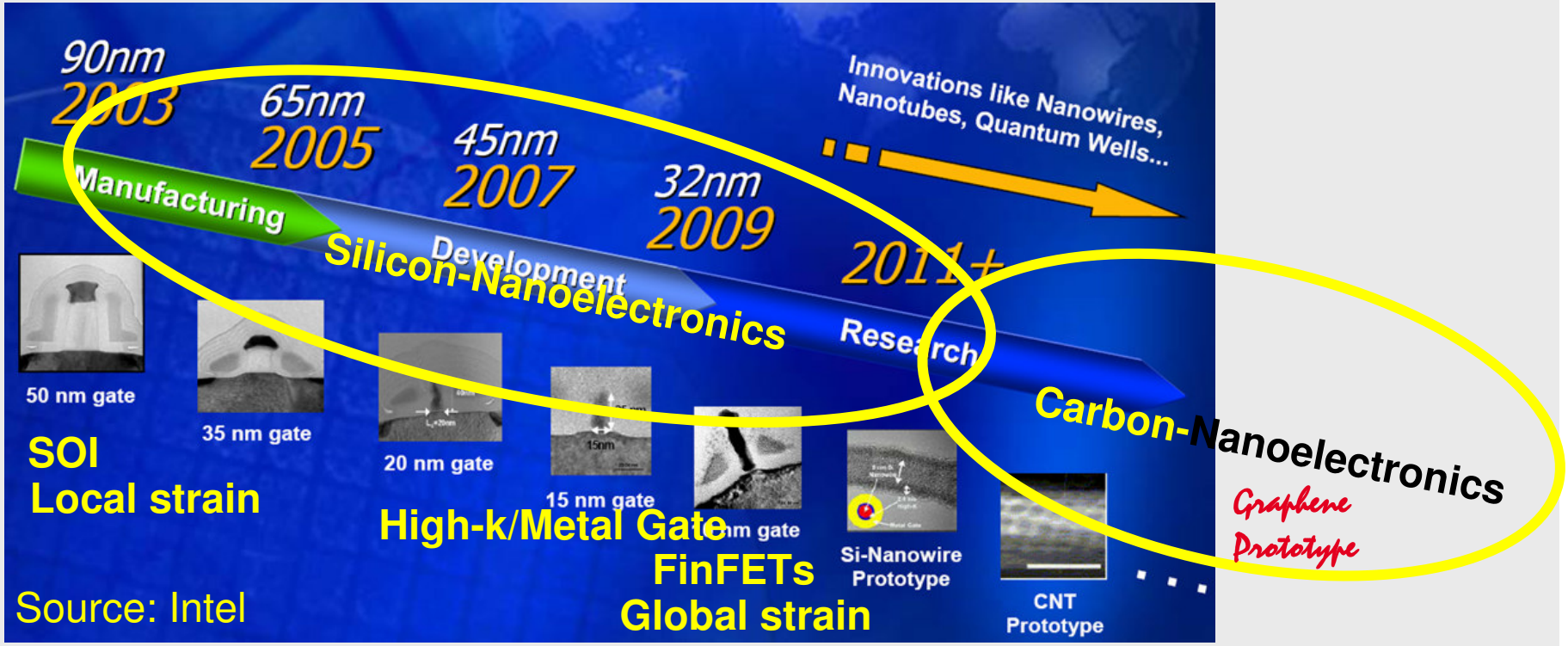
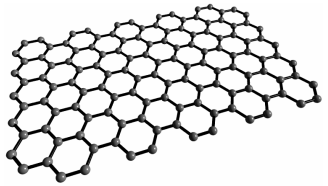
Motivation: Moore's Law





Graphene

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1]
Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

Science, Oct. 2004

Ultrathin epitaxial graphite: 2D electron gas properties and a route toward graphene-based nanoelectronics.

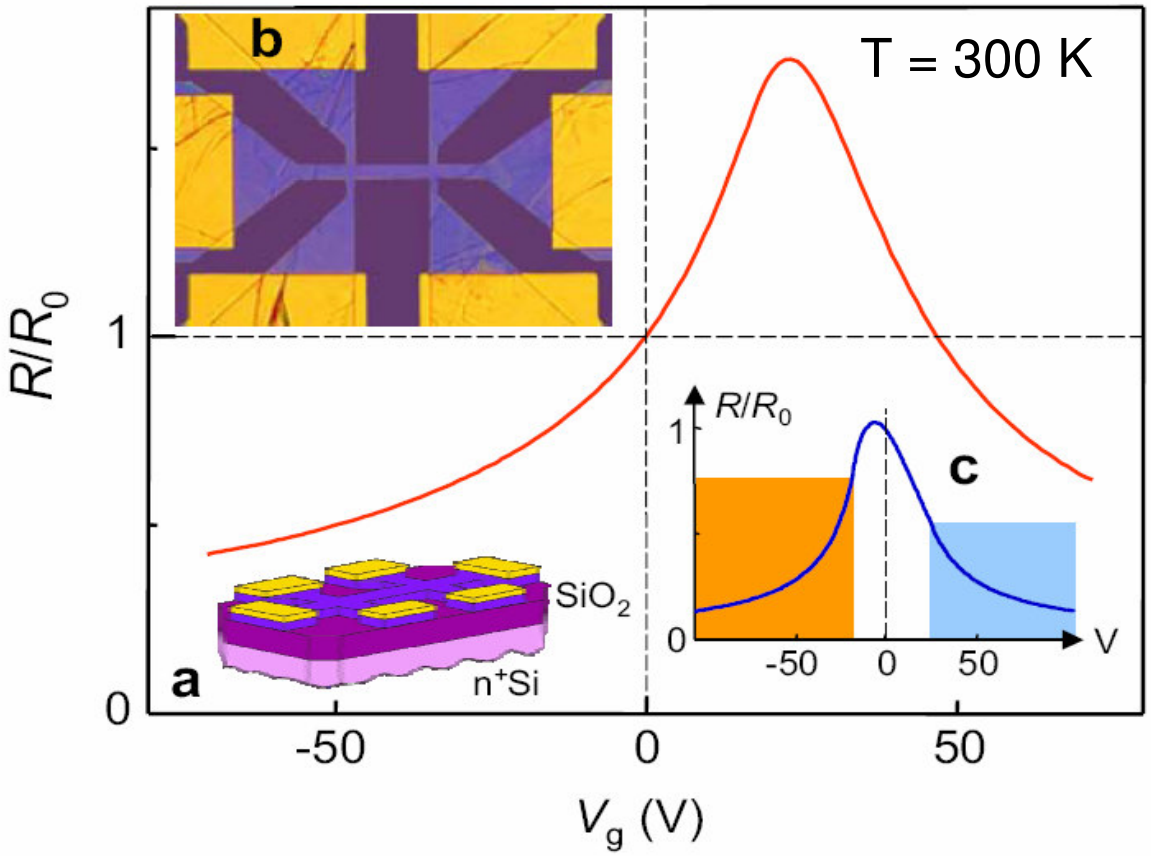
Claire Berger,* Zhimin Song, Tianbo Li, Xuebin Li, Asmerom Y. Ogbazghi, Rui Feng,
Zhenting Dai, Alexei N. Marchenkov, Edward H. Conrad, Phillip N. First, and Walt A. de Heer
School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430
(Dated: October 7, 2004)

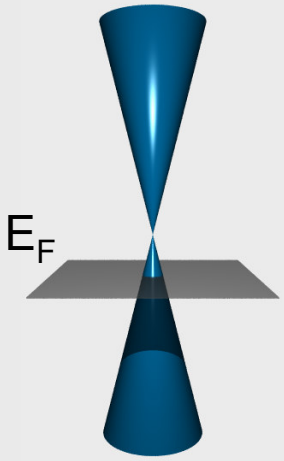
J. Phys. Chem. B., 2004

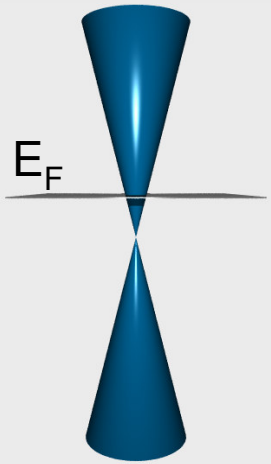
→ Route towards graphene layers

Graphene

Novoselov et al., 2005







Electric field-effect in graphene

- Ambipolar conduction
- Maximum resistivity ~ $h/4e^2$ @ charge neutrality point
- Poor I_{on}/I_{off} ratio ~ 30

→ Off-current problem

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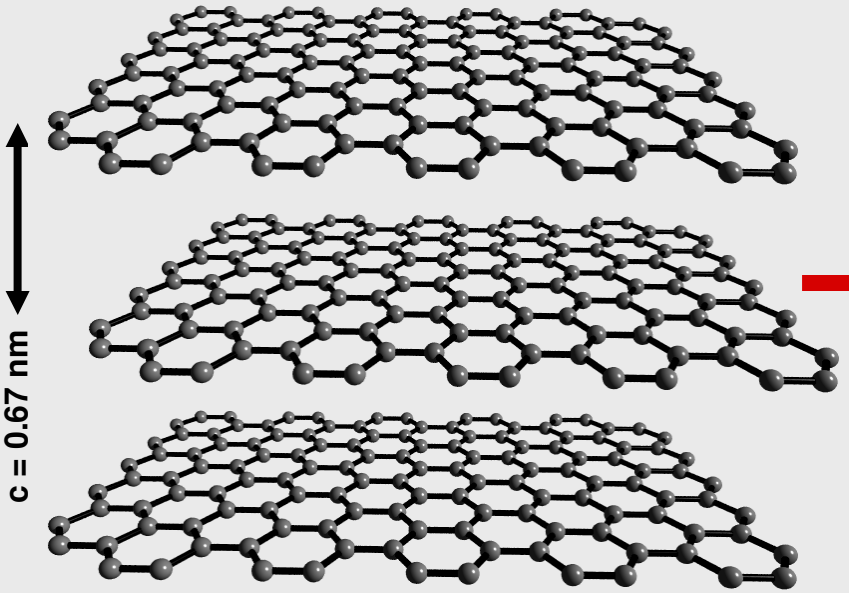
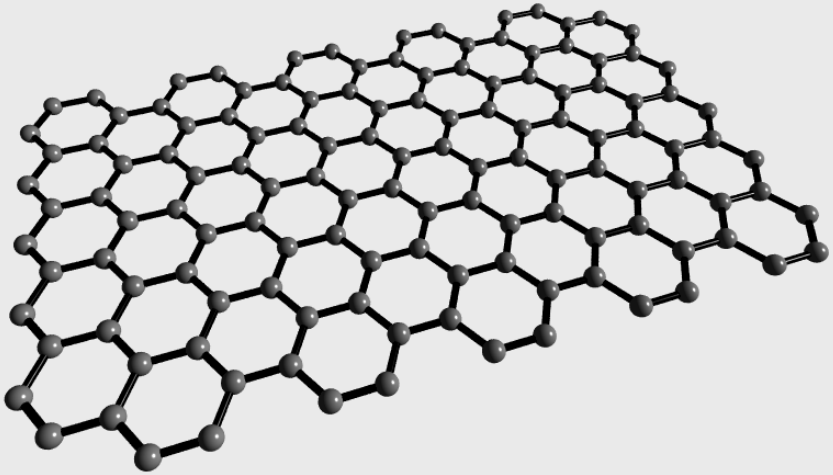
Graphene

Graphite



- In plane: sp^2 bonded carbon atoms (~4,3eV)
- Inter plane: weak v.d. Waals bonds (π-orbitals, ~0,07eV)

Graphene



- Monolayer of sp^2 bonded carbon atoms
- Two-dimensional honeycomb lattice
- Experimentally discovered by A.K. Geim in 2004 and / or R. Ruoff in 1999
- Thought to be instable due to thermodynamic fluctuations → recently solved (Meyer et al., Nature, 2007)

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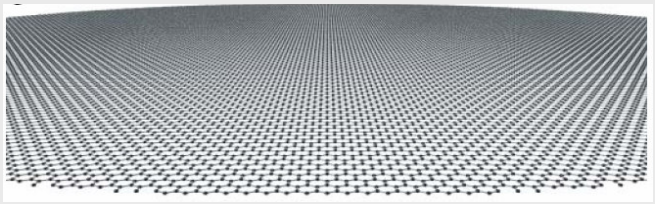
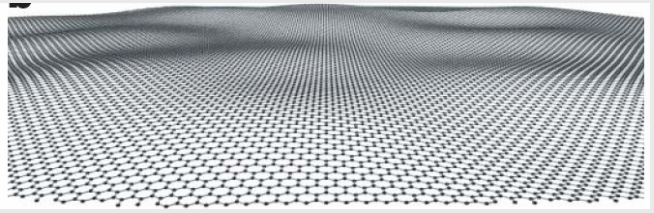
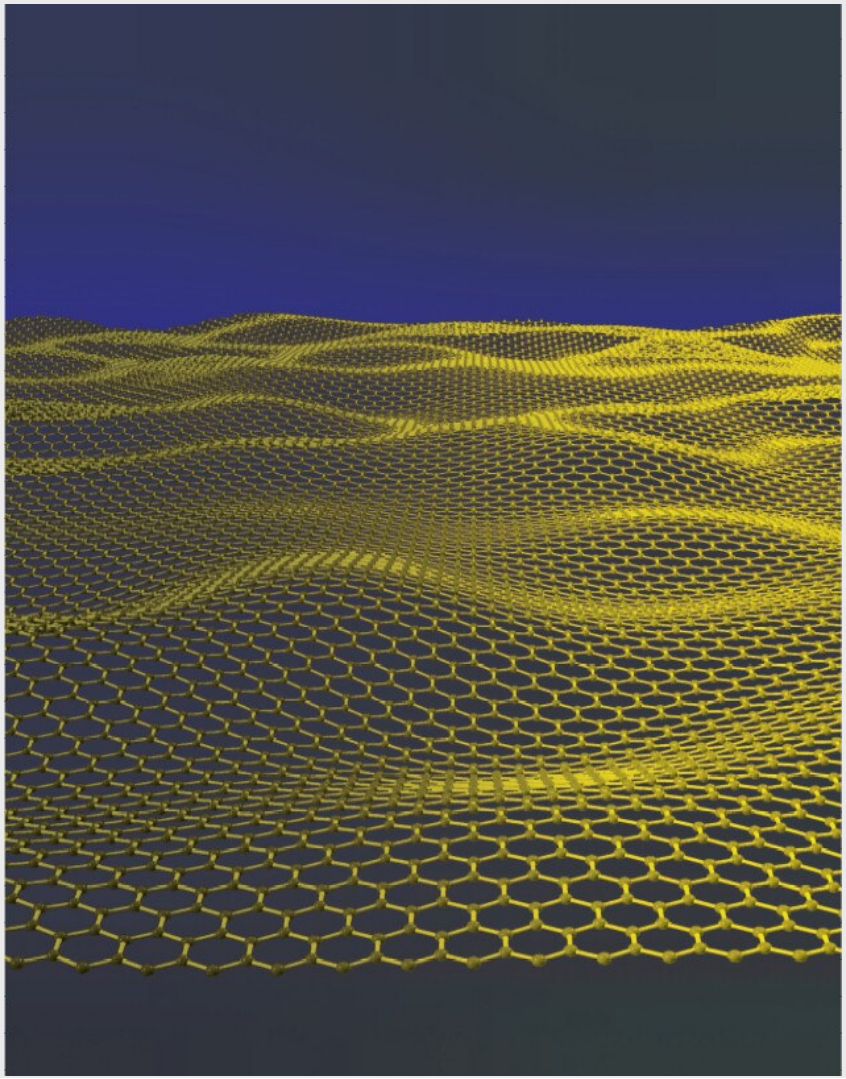
Corrugated sheet of graphene (Meyer et al., Nature, 2007)

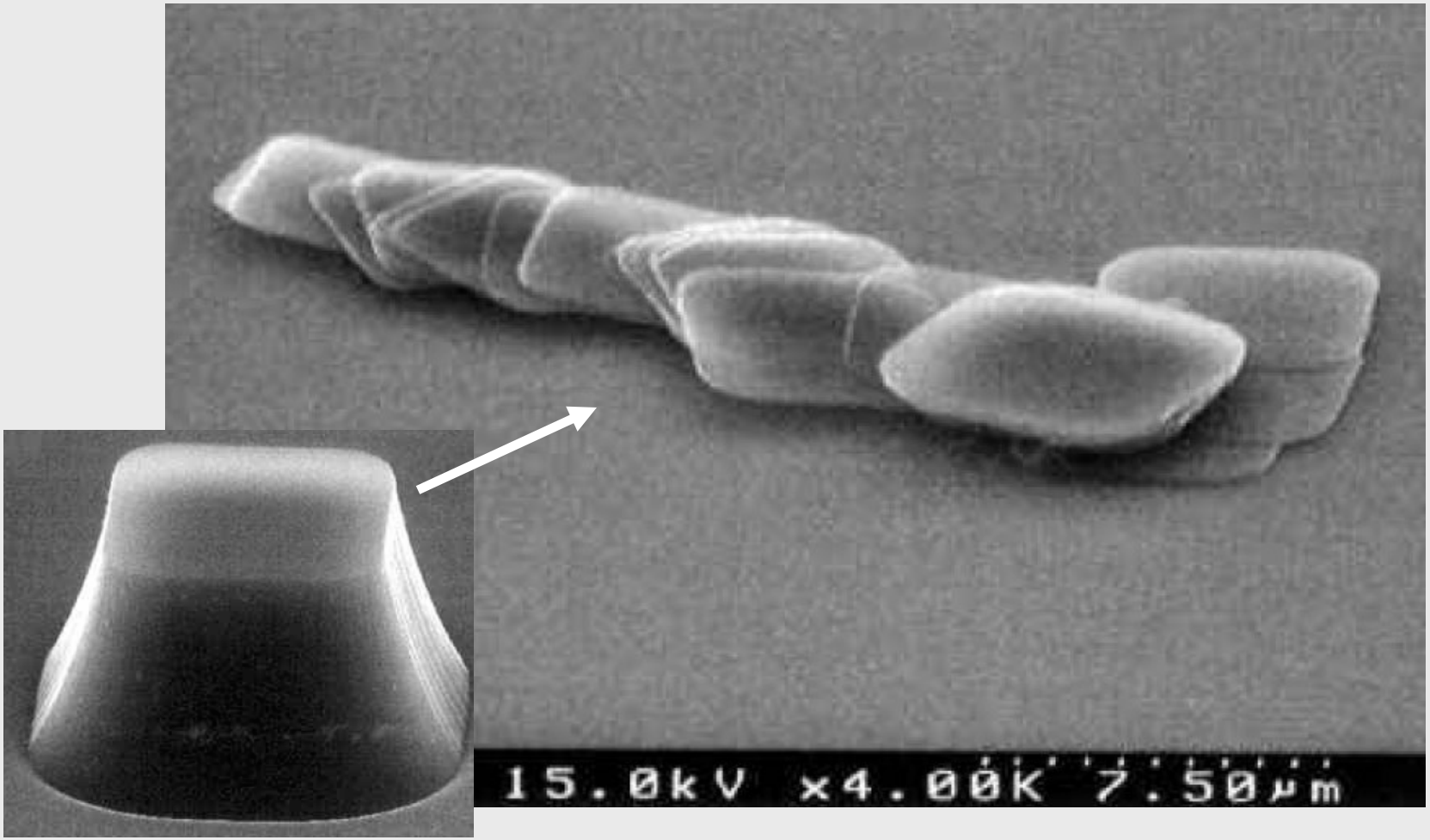




Peierls, Landau and Mermin happy as well !

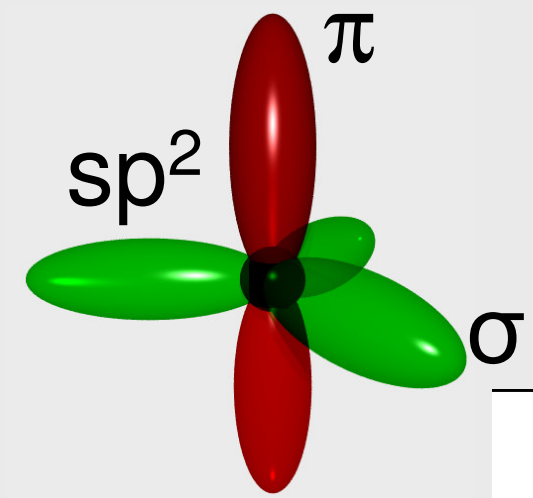


Fallen MESA of Graphite
(Lu, Ruoff et al., Nanotechnology, 1999)

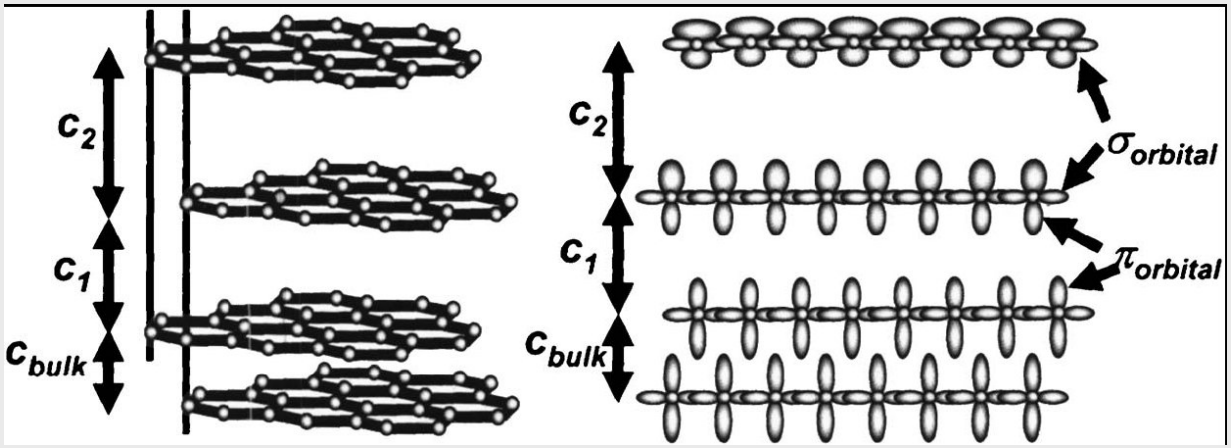


Conduction in graphene vs. graphite

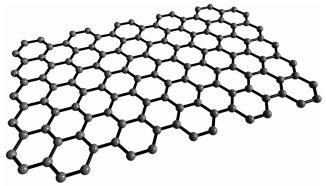
π -orbitals responsible for carrier conduction in graphene



Why is there a difference to graphite?



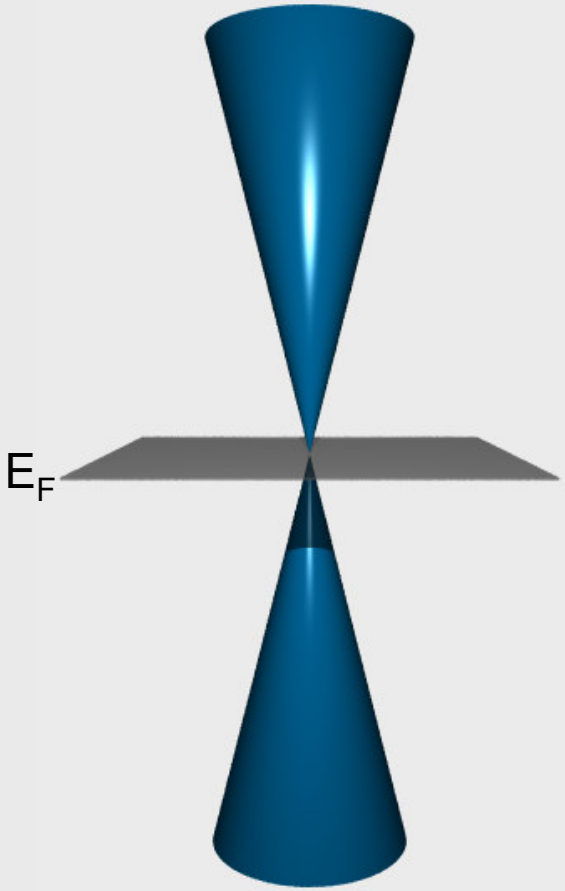
Banerjee *et al.* Appl. Phys. Lett. 88, 062111 2006



Graphene

Electronic properties of graphene

E-k diagram of graphene near K-point



- Zero-gap semimetall
- Linear dispersion relation described by Fermi-Dirac instead of Schrödinger equation
- Massless dirac fermions, v ~ c/300
- $\mu > 25.000\ cm^2/Vs$ @ 300K
- $J > 10^8\ A/cm^2$
- L_{MFP} ~ 400nm @ 300K

Potential for:

- High switching speeds
- Ballistic devices

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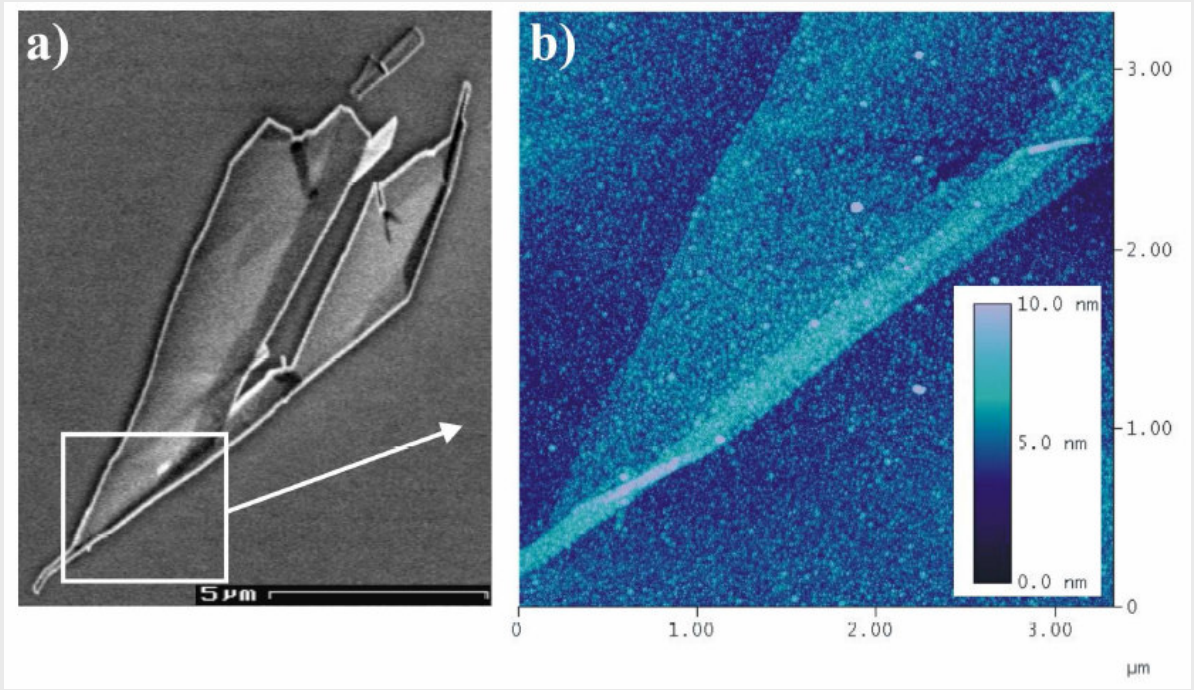
Device Fabrication / Manufacturing

- Thermal oxidation of silicon wafer
- Manual transfer of graphene layer from graphite (highly oriented pyrolitic graphite)
- Visual identification of single and few layer graphene

- AFM
- SEM
- Raman …

Characterization of graphene by AFM



- Step heights determined by AFM: 0.8-1.2 nm
- Measurements differ due to adsorbates
- → No reliable determination of layer thickness by AFM

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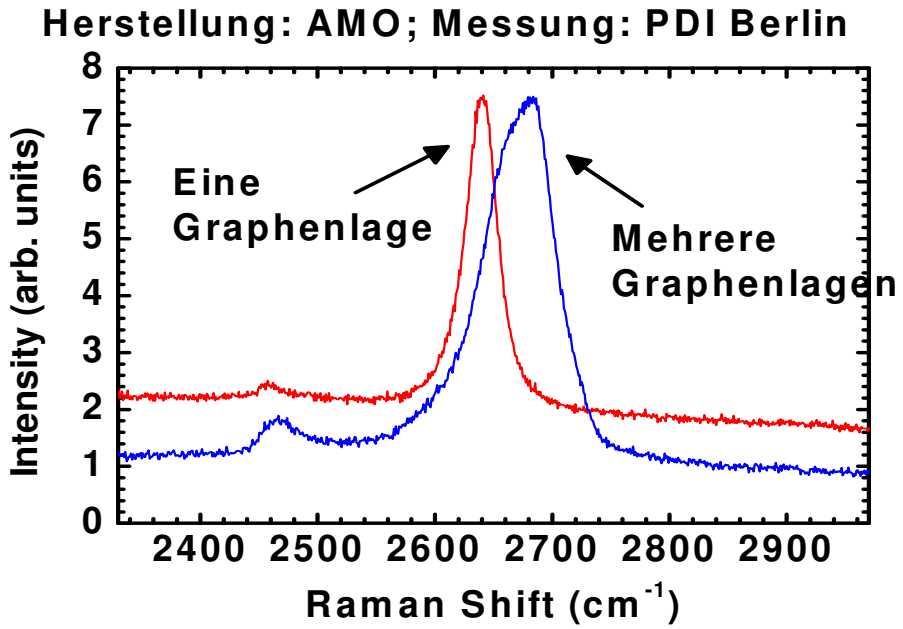
Characterization of graphene by Raman spectroscopy

Identification of monolayers by Raman spectroscopy



Echtermeyer *et al.* tbp

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Device Fabrication / Manufacturing

- Thermal oxidation of silicon wafer
- Manual transfer of graphene layer from graphite (highly oriented pyrolitic graphite)
- Visual identification of single and few layer graphene
- Optical lithography for contacts
- Evaporation of contact metals (Ti, Au, W…)

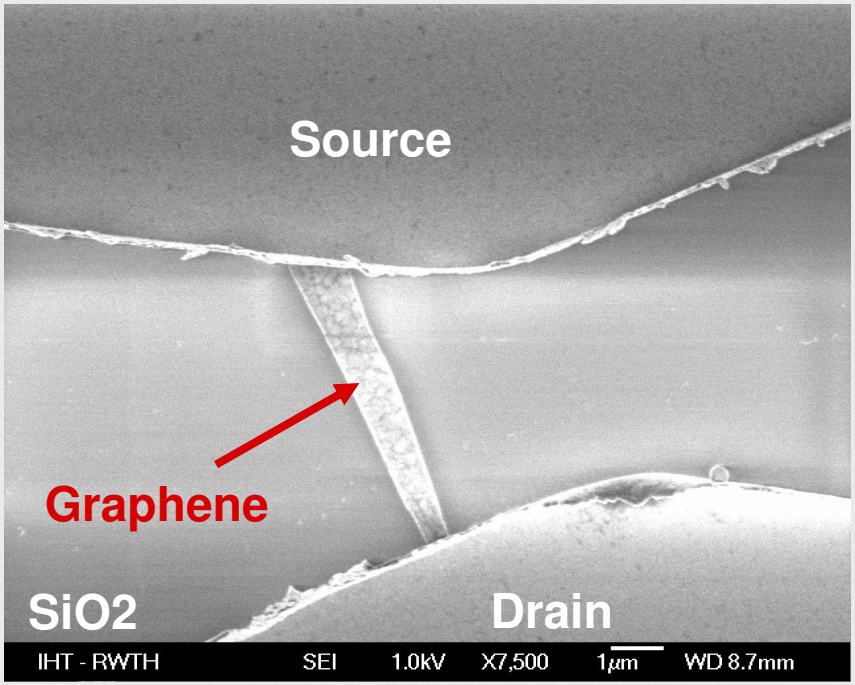
↓

- Electrical characterization

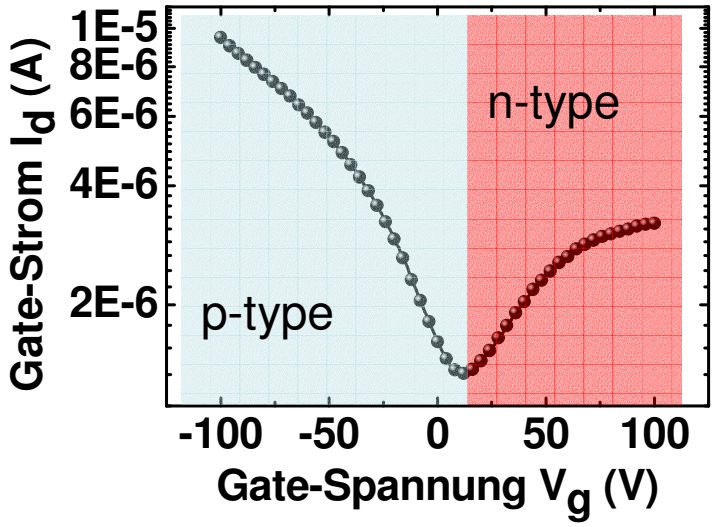
↙ ↓ ↘

- Raman
- SEM
- AFM …

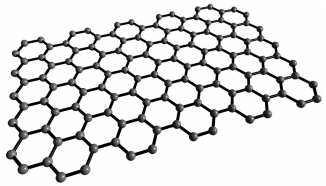
A graphene Pseudo-FED



Transfer characteristics



- N- and p-type conduction
- High off-current (=maximum resistivity)
- Minimum shifted from Vg = 0V
- → unintentional chemical doping



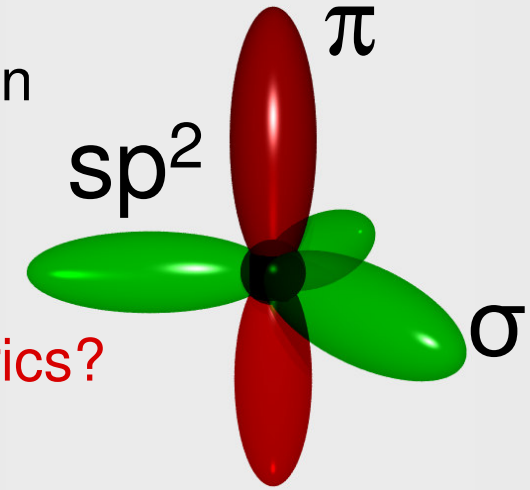
Graphene

All experimental data published until now obtained from graphene covered with SiO_2 on one side only.

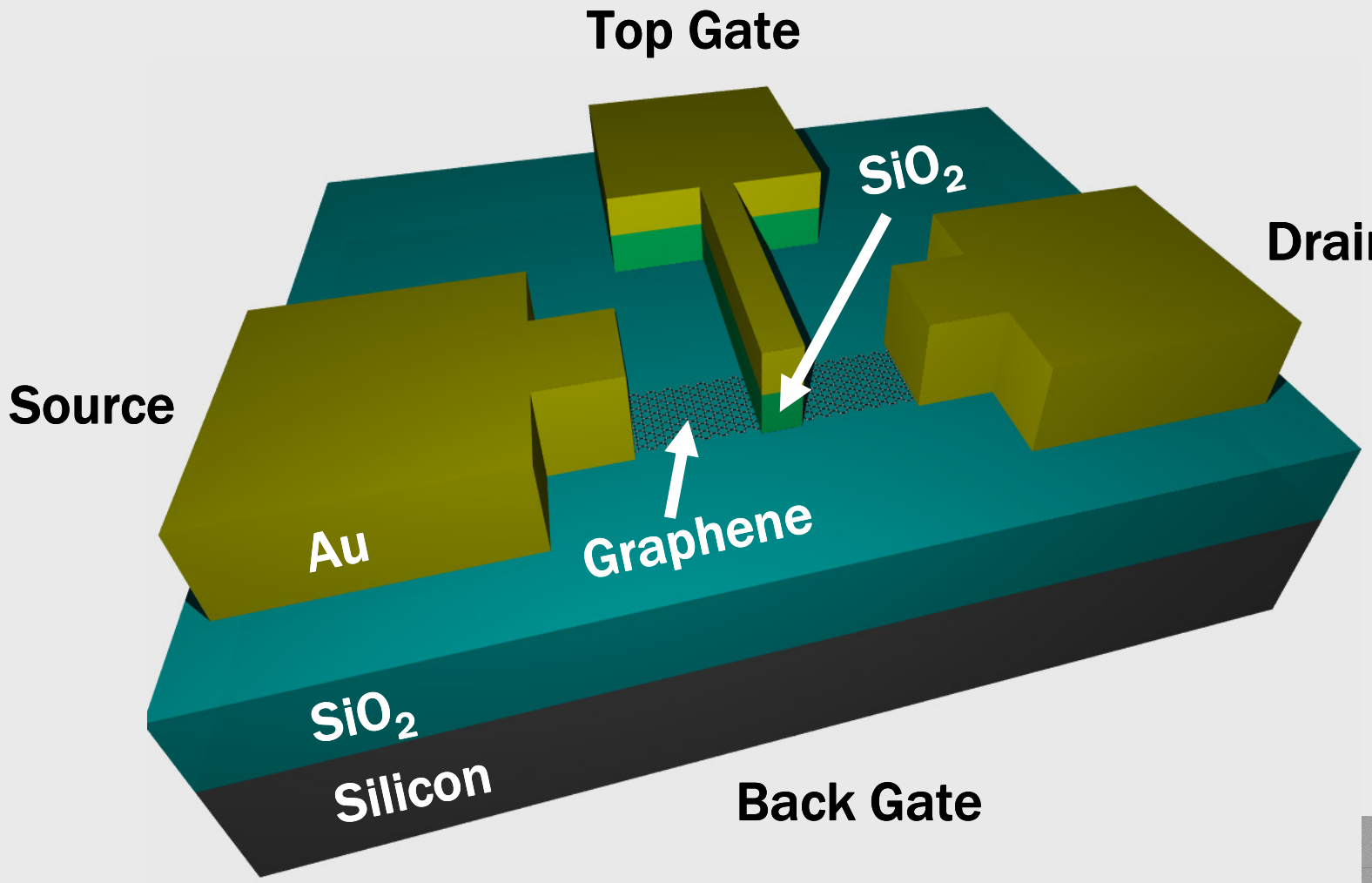
→ Unrealistic situation since graphene devices for nanoelectronics would require passivation/packaging.

π -orbitals responsible for electrical conduction in graphene

→ What happens to mobility in case of graphene "sandwiched" in between dielectrics?

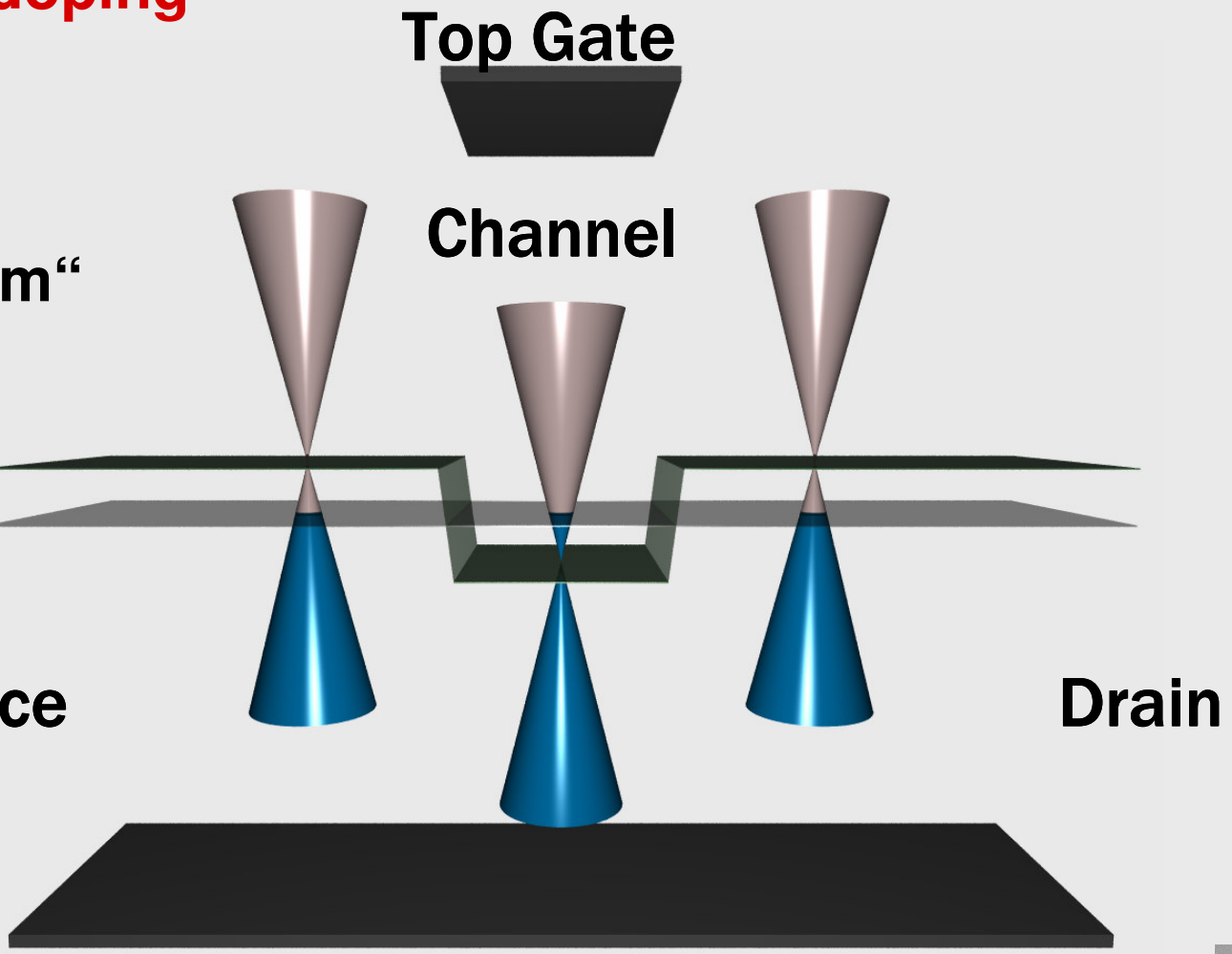


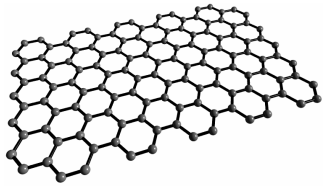
Graphene FED with top gate



Electrostatic doping

„distributed
E-k diagram“





Graphene

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- Visual identification of single and few layer graphene
- Optical lithography for contacts
- Evaporation of contact metals (Ti, Au, W…) → Electrical characterization
- E-Beam gate lithography ← Electrical characterization
- Evaporation of gate dielectric and metal

- Raman
- SEM
- AFM …

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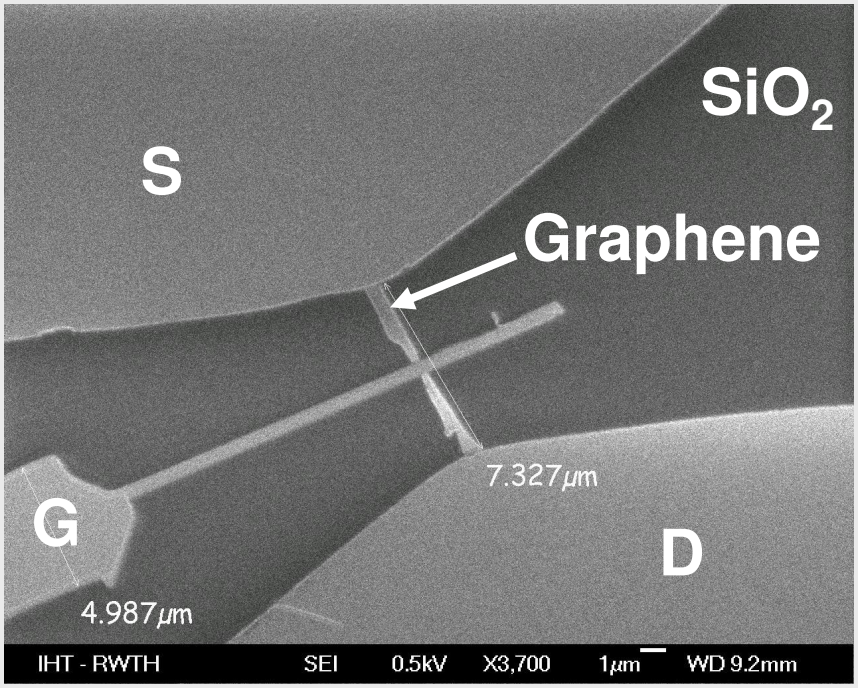
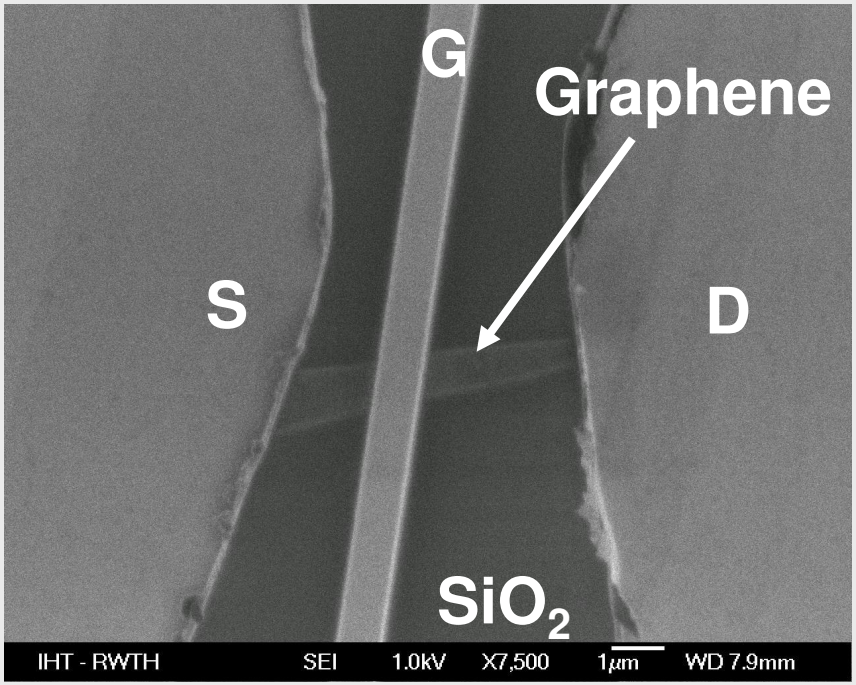
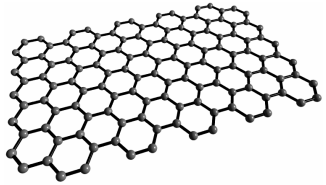
Graphene FEDs with top gate





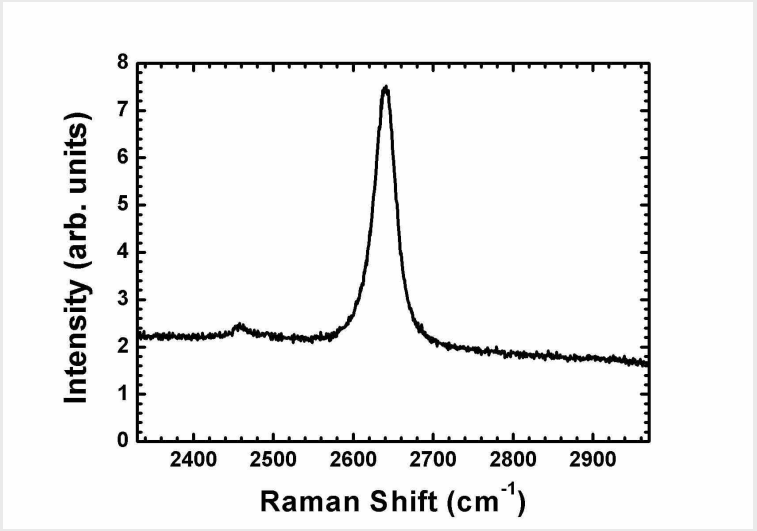
Graphene thickness by AFM: 1.5nm
→ 1-3 layers
→ Raman needed to identify exact number of layers

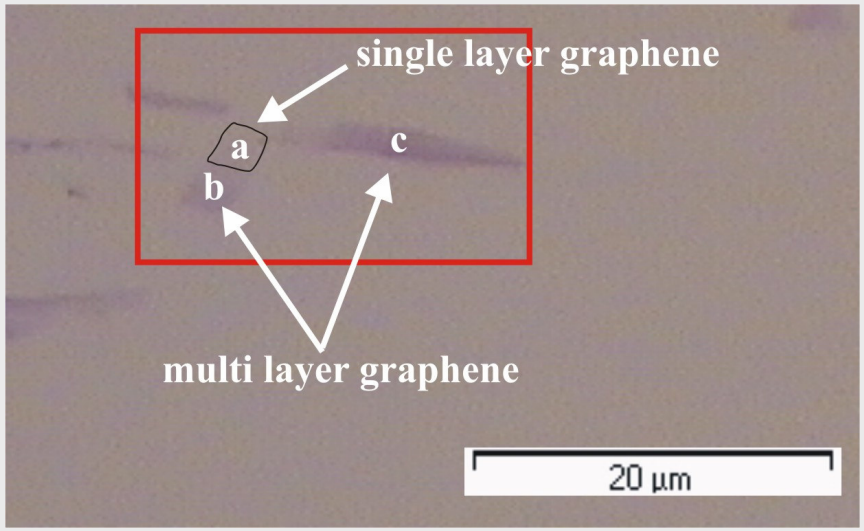
Lemme et al., IEEE EDL, April 2007

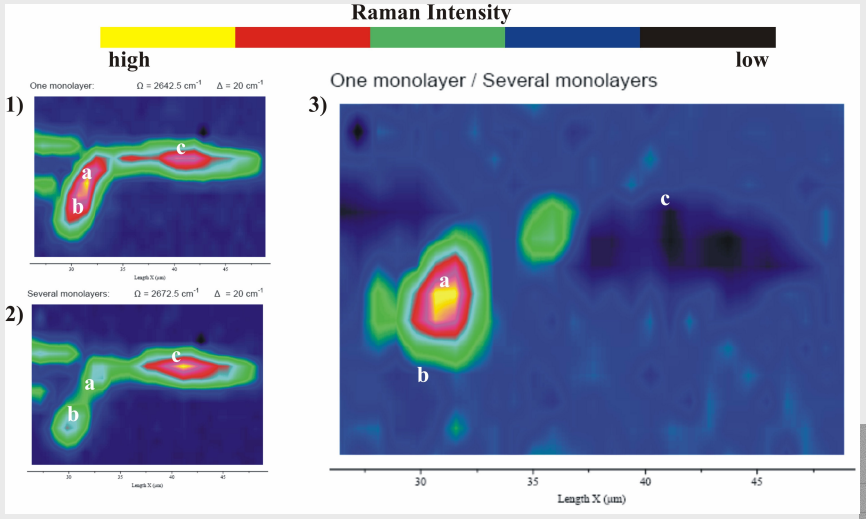


Graphene

Scanning Raman spectroscopy

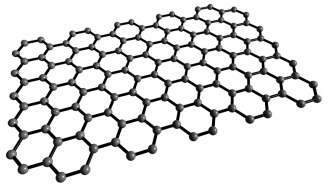






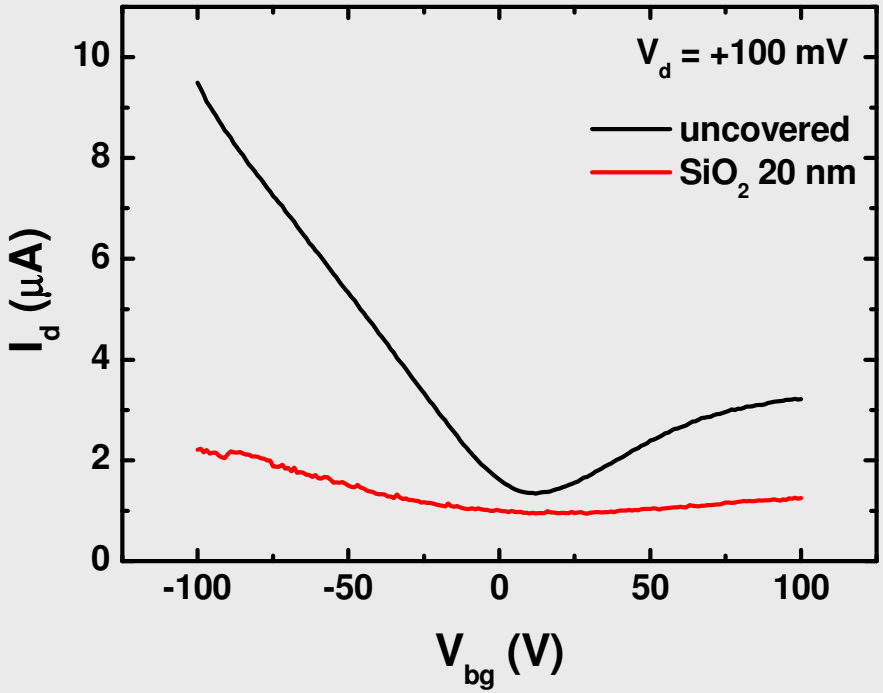
- Confocal microscope setup
- λ = 633 nm
- Raman intensity increases from blue to yellow
- Ratio of Raman intensities at ~2640 and ~2670 cm^{-1}

Echtermeyer et al.,
tbp EPJ Graphene Week Dresden, 2007

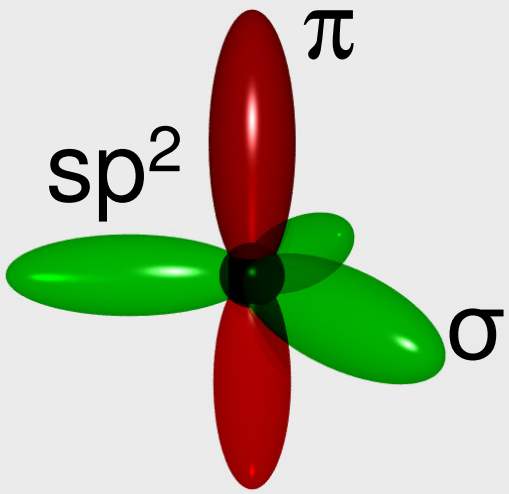


Graphene

Transfer characteristics with and without top-gate



Lemme et al., IEEE EDL, April 2007



- Unintentional chemical doping (I_{dmin} not @ V_{bg} = 0V)
- Total current decreases (~ 1/5) for graphene "sandwiched" in SiO_2

→
- Top-gate dielectric disturbs π-orbitals
- Evaporated SiOx, no annealing (high Dit, Qox)

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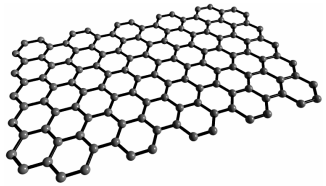
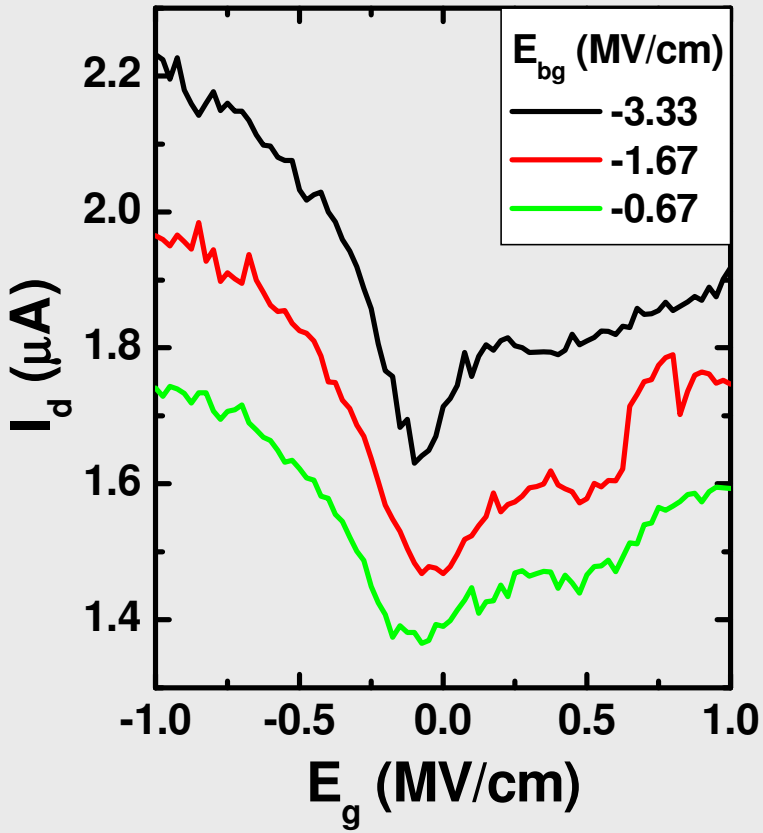


Top gate transfer characteristics



- First demonstration of a top(!)-gated field effect device / transistor
- How about mobility?

Lemme et al., ULIS 2007

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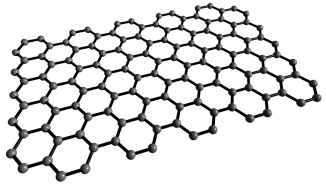
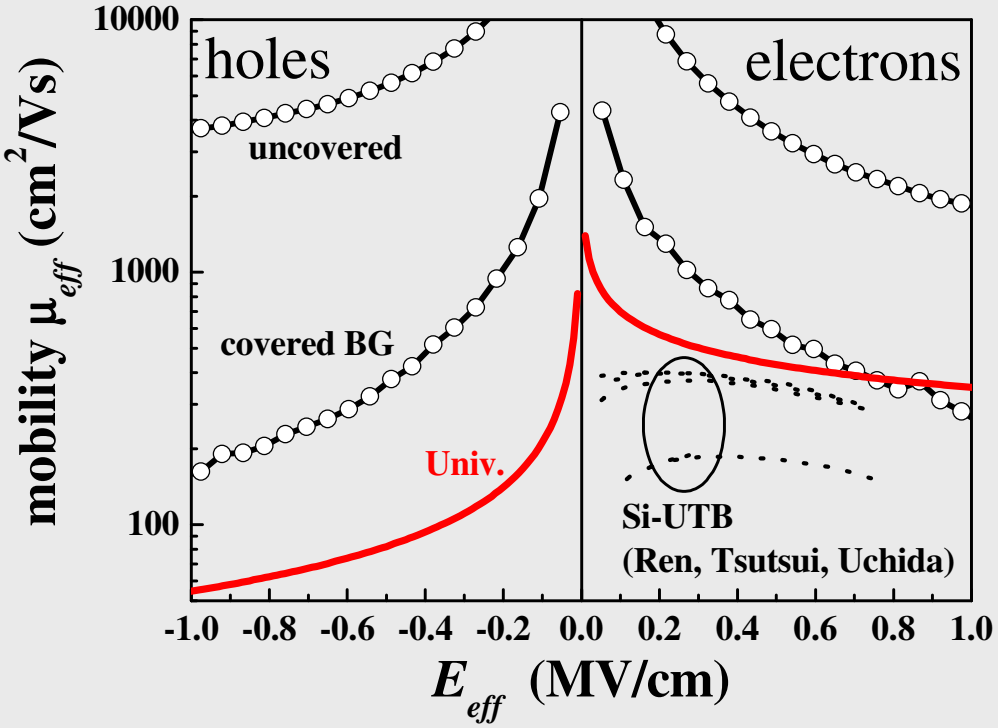


Graphene

Mobility: a first approximation



Approximation of μ:

$\mu = \sigma / (n*q)$

with

$\sigma = J/E_{ds} = I/\text{width} * \text{length}/V_{ds}$

$n = \varepsilon * E_{eff}/q$

- Mobility decreases (> 1/10) for graphene "sandwiched" in SiO_2
  → dominant scattering mechanism seems to be substrate determined
- Yet higher values than universal mobility and especially higher than Ultra Thin Body SOI MOSFETs

Lemme et al., ULIS 2007

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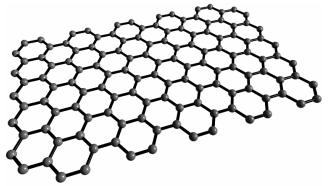
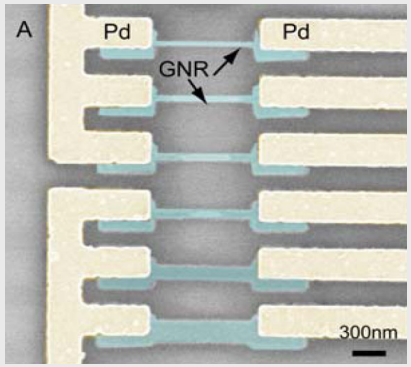


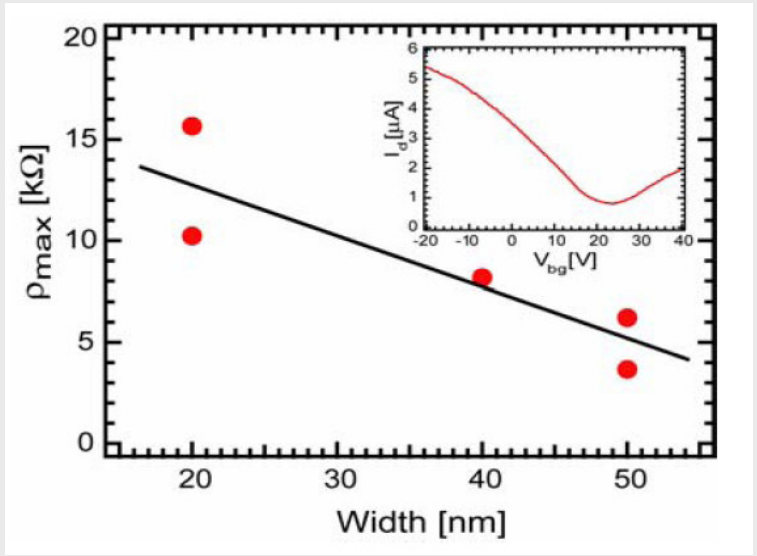
Graphene

„Engineering“ graphene for electronics

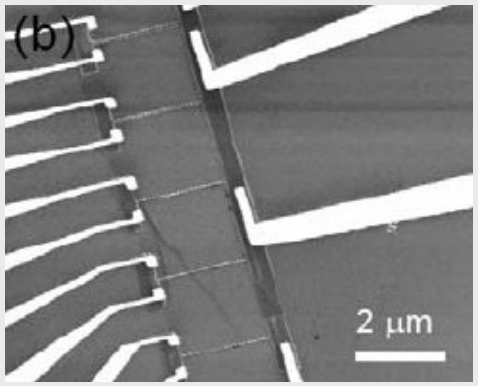
- Lateral Confinement

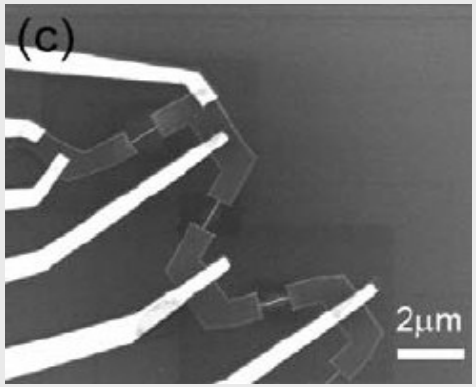
Chen et al., 2007

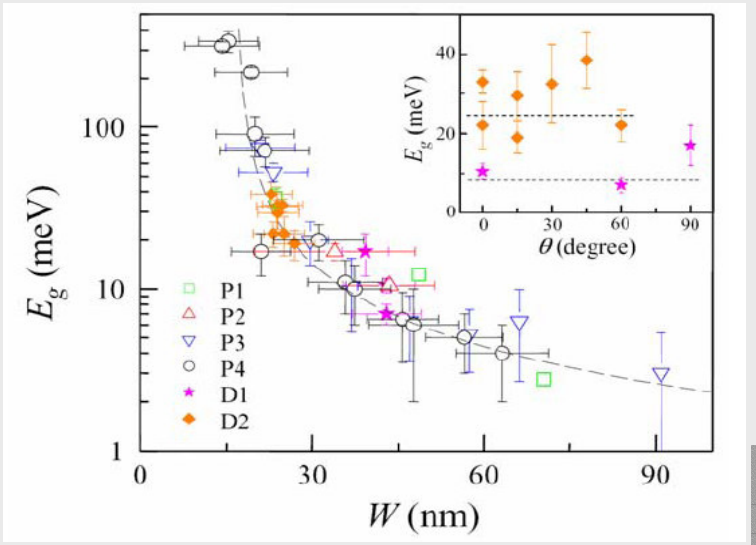


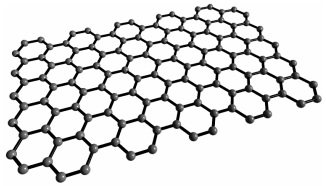


Han et al., 2007









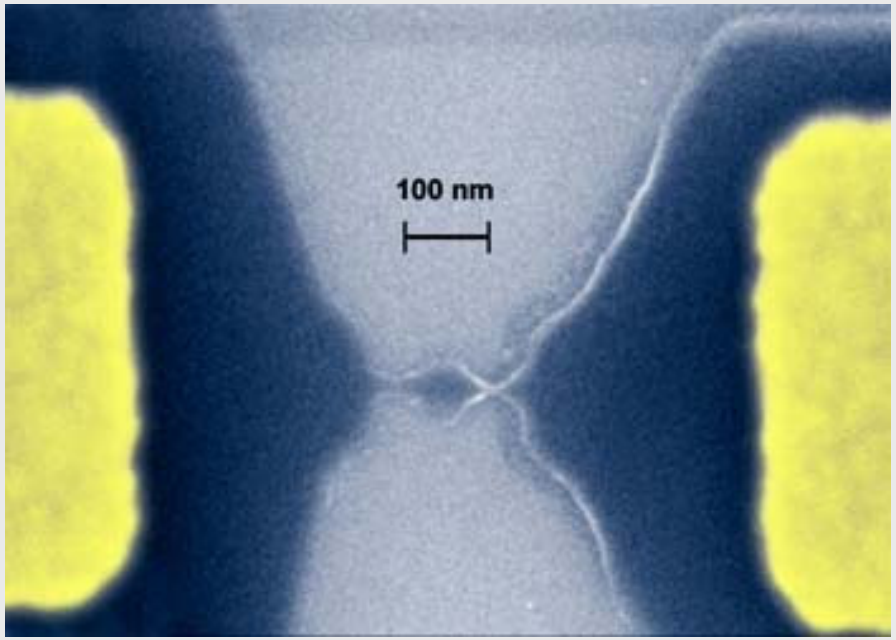
Graphene

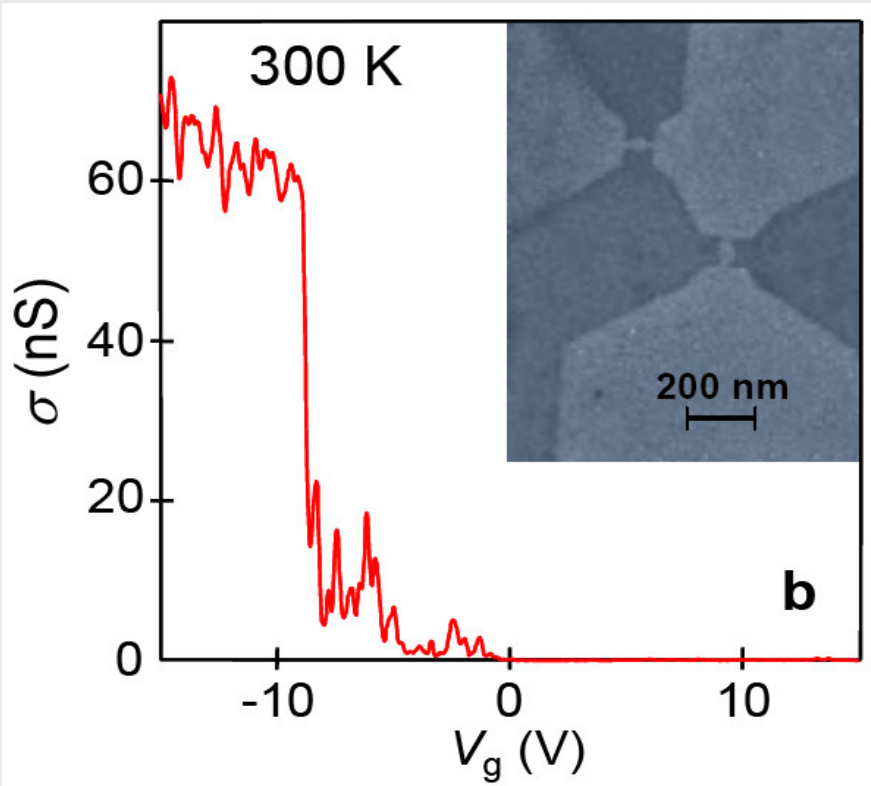
„Engineering“ graphene for electronics

- New device architectures

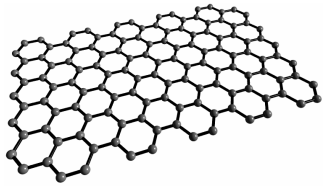
Geim et. al., 2007

Functional SET structure @ 300K





No further data published yet, but SET structure might impose on-current problems. (I_{on} < 1nA)

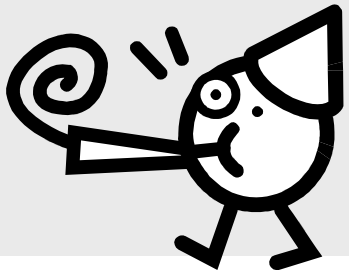


Graphene

Graphene vs. CNTs for electronics

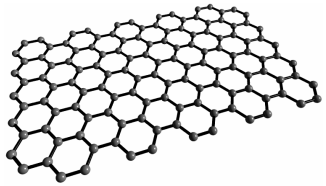
Graphene	Carbon Nanotubes
2D graphene layers → conventional lithography	Random placement
Band gap engineering by top down methods	Bottom up approach
No large scale technique today	Chirality problem

Graphene will remain a vibrant research playground as long as it can not be fabricated on large area.



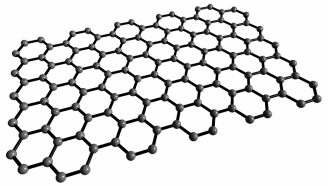
Outline

- Introduction
- Results & Discussion
- Outlook
- Summary



Summary

- Graphene is a promising option for future electronic materials
- Demonstration of the first top(!)-gated graphene field effect device
- Despite its semi-metal nature, a field effect can be observed
- Mobility in graphene is affected when a gate electrode is placed on top of the film
- Mobility clearly exceeds that of Silicon and especially UTB SOI
- Band gap engineering needed to further exploit properties
- Large area fabrication methods are needed



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- Thank YOU for your attention.

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