Graphene

In your Laptop tomorrow?

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Graphene

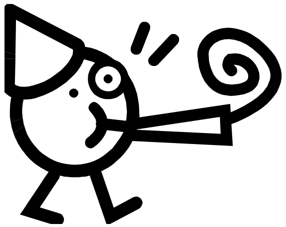
Applications of a ”Nobel” Material

- Introduction
- Graphene Fabrication
- Information Technology Applications
- Summary

Graphene – A ”Nobel” Material

The Nobel Prize in Physics 2010
Andre Geim, Konstantin Novoselov

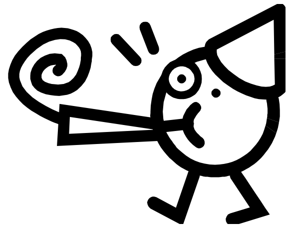
"for groundbreaking experiments regarding the two-dimensional material graphene"



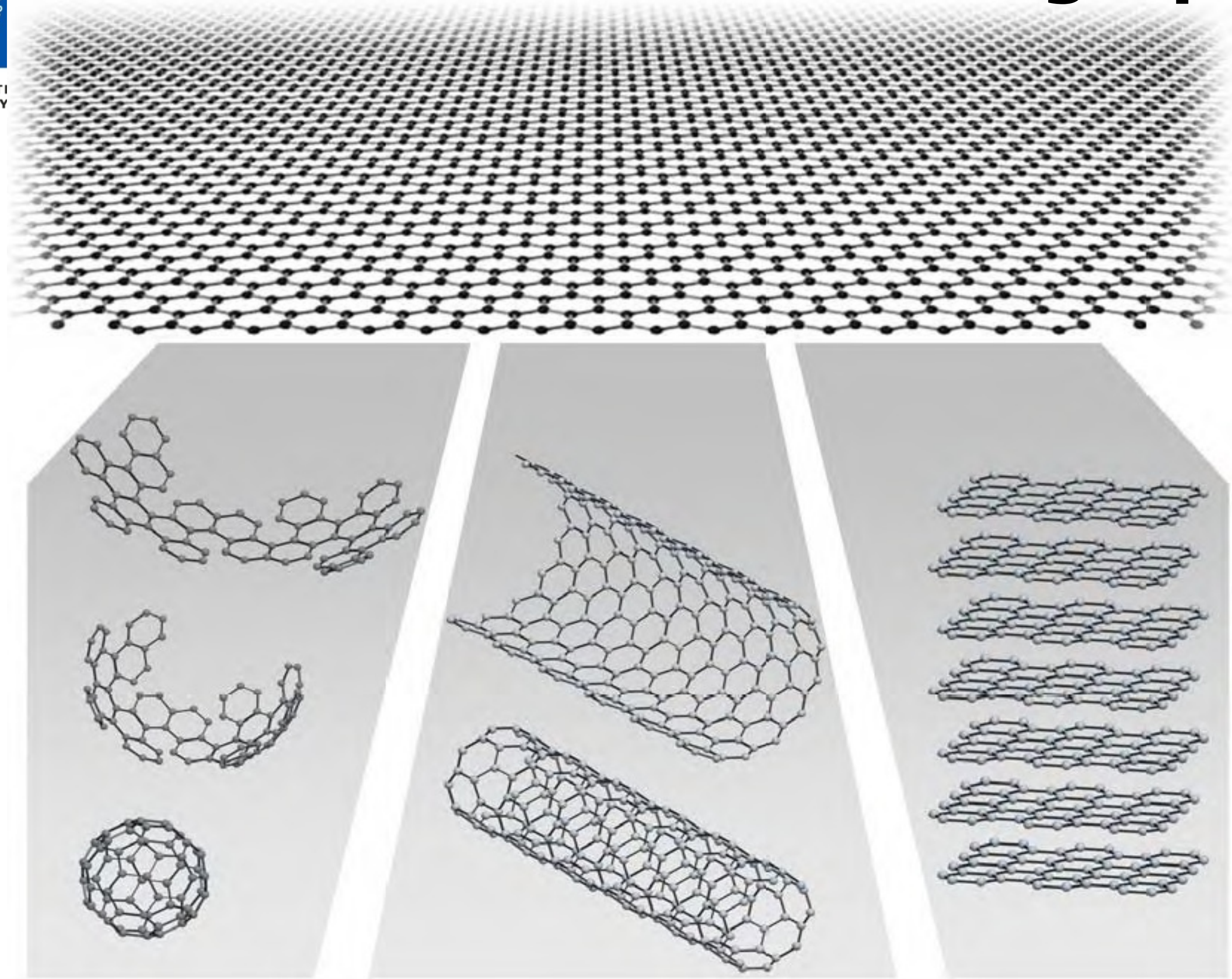
Electric Field Effect in Atomically Thin Carbon Films

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]

22 OCTOBER 2004 VOL 306 SCIENCE



"The mother of all graphitic forms"



2D: Graphene

Only one atom thick!

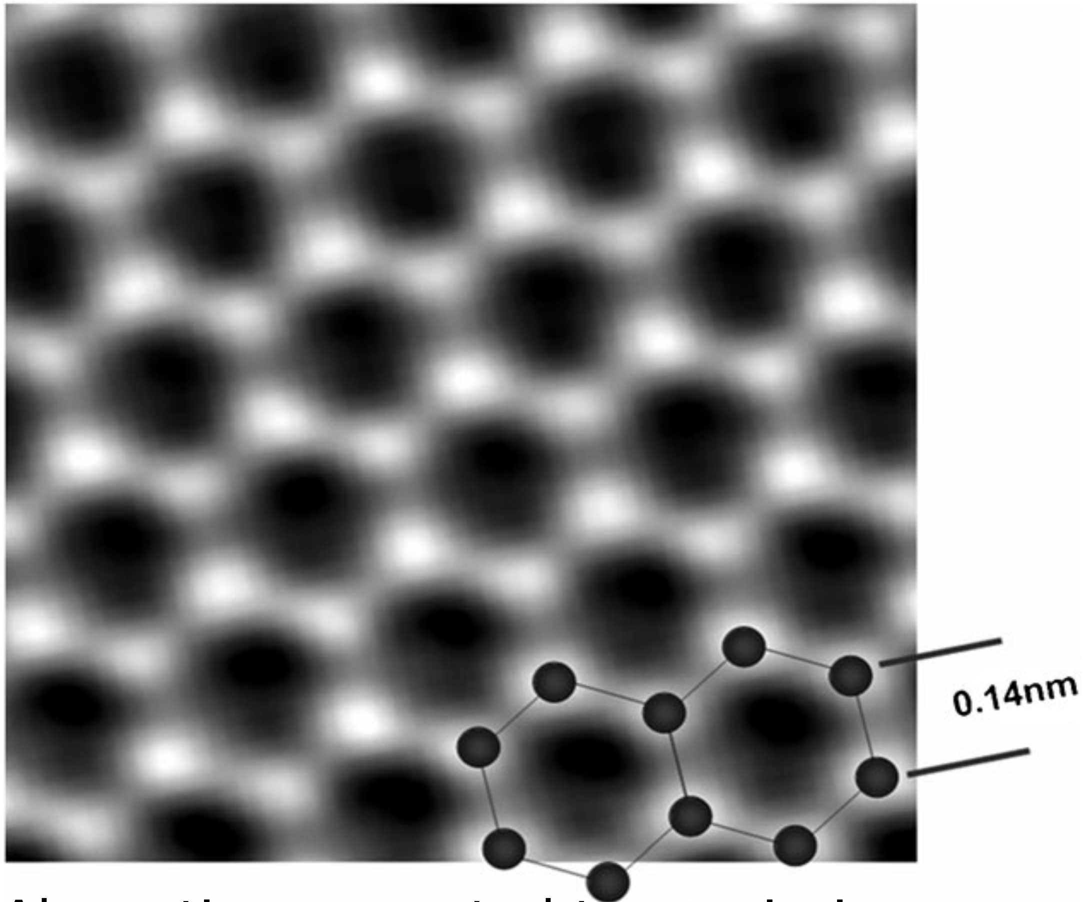
0D: Buckyballs **1D: Nanotubes** **3D: Graphite**

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

Nature Mater. 6., 183, 2007

Graphene: Nanolandscapes

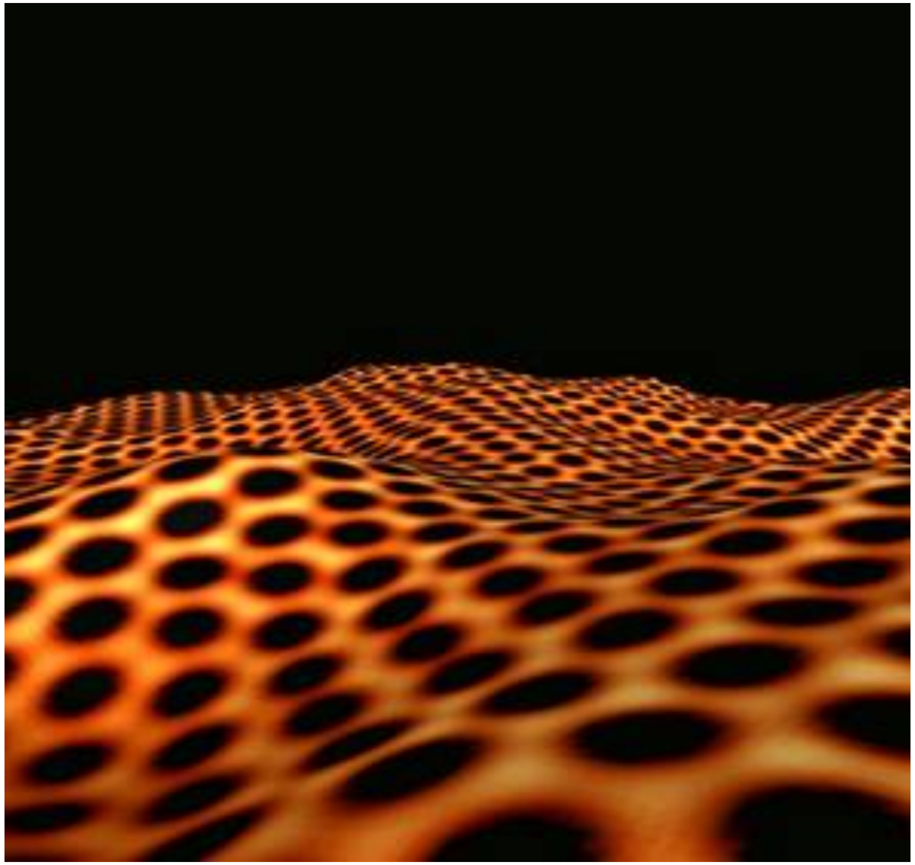
Visualization of graphene by HRTEM…



Aberration-corrected transmission electron microscope (TEAM 0.5)

Chem. Commun., 2009, 6095 - 6097

and by STM

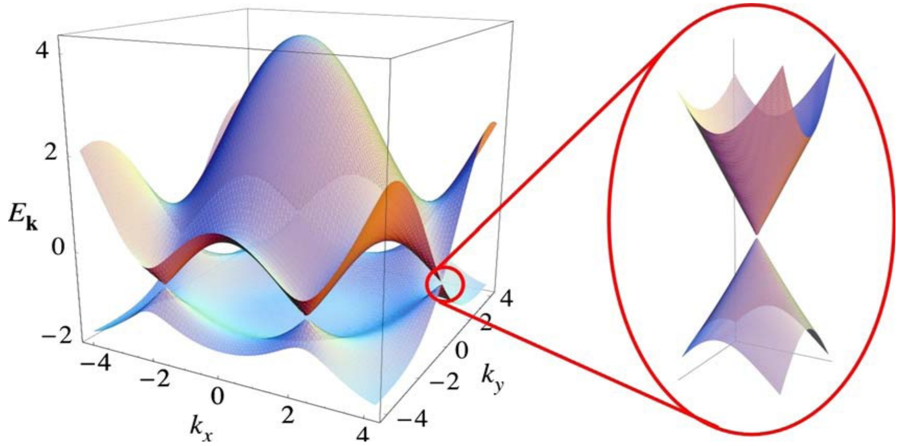


Scanning tunneling microscope image of graphene on SiO_2

Mashoff et al, Nanoletters 2010

Exceptional Properties (1/

Electronic properties



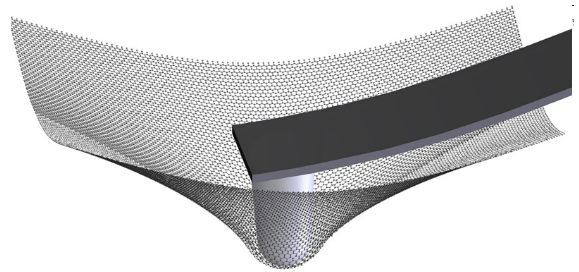
After: Wallace, Phys. Rev. **71**, 622 (1947).

- Semi-metal or zero-gap semiconductor
- Linear dispersion relation
  - Optoelectronics
- Massless dirac fermions, v ~ c/300
- Intrinsic carrier mobility (suspended graphene in vacuum)
  - 200.000 $cm^2\ V^{-1}s^{-1}$
- Carrier mobility of graphene on SiO_2 at room-temperature
  - 10.000-20.000 $cm^2\ V^{-1}s^{-1}$
- Maximum current density
  - $J > 10^8\ A/cm^2$

Exceptional Properties (2/2)

Mechanical properties

- Young's modulus: ~1.10 TPa (Si ~ 130 GPa)
- Elastically stretchable by 20%
- ”strongest material known”
- Flexible



Lee et al., Science, 385-388, 18 July 2008

Thermal conductivity

- ~5.000 W/m•K at room temperature

  Diamond: ~2000 W/m•K, 10 x higher than Cu, Al

Thinnest material possible

Transparent (only 1 atom thin)

Transparent flexible conductive electrodes

High surface to volume ratio

Sensors

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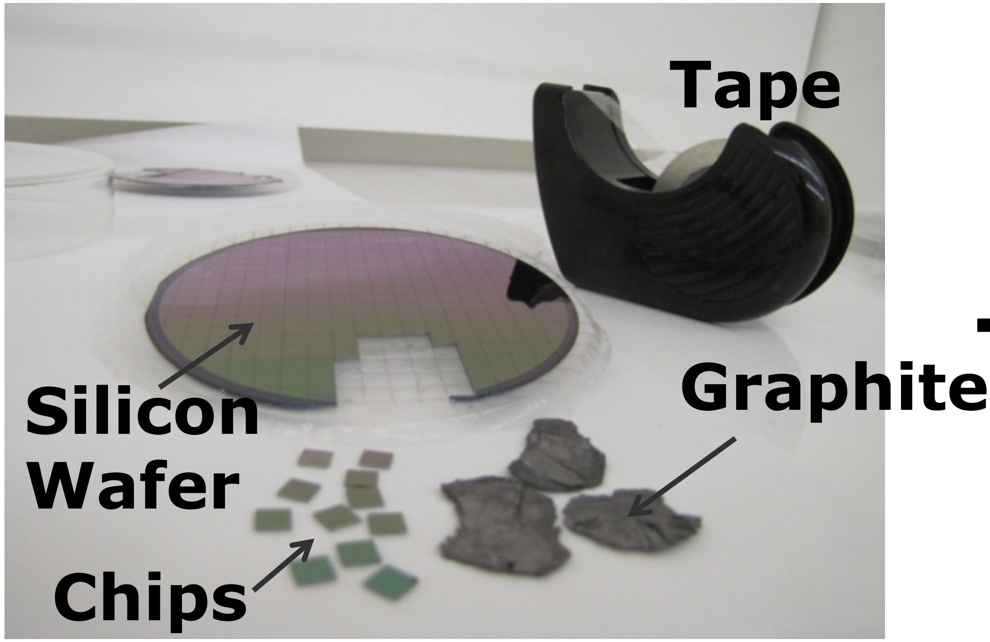
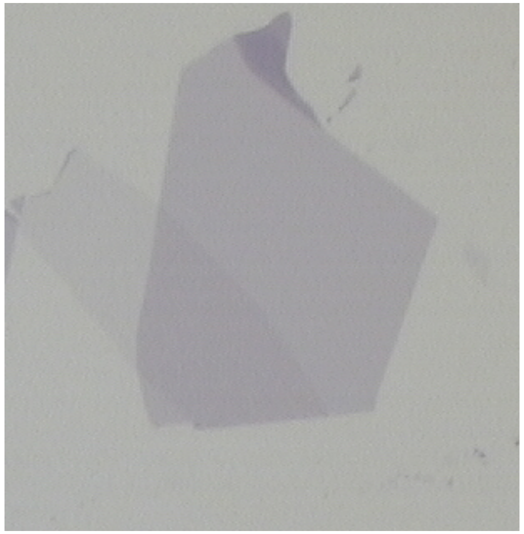
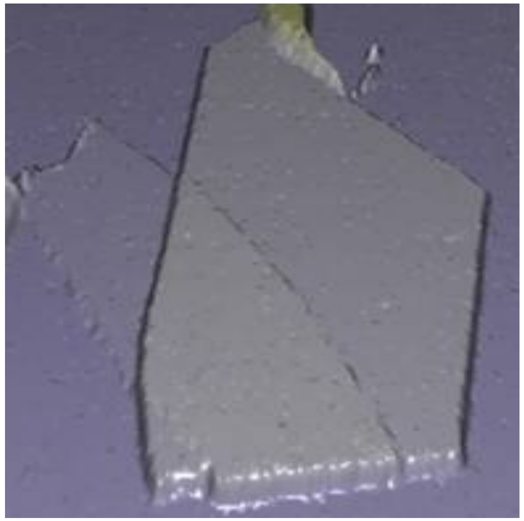
Graphene Fabrication Methods: Exfoliation (1/4)

Exfoliation with adhesive tape







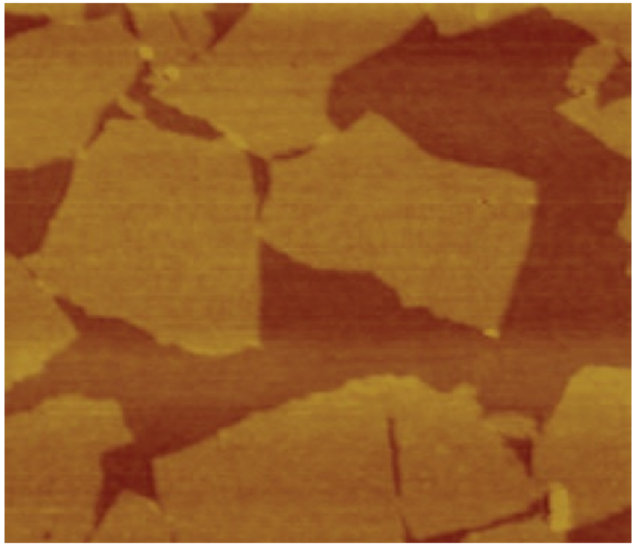
- Novoselov et al., Science 306, 666 (2004)
- flake size: 5 – 100 mm
- random location
- simple process for proof-of-concept
- ***no industrial relevance0***

Graphene Fabrication Methods: Chemical Exfoliation (2/4)

Exfoliation process
(treatment in acids)

natural graphite

Graphene solution



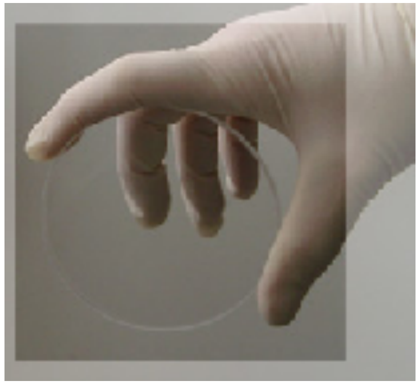
Deposition of graphene

- Process at room temperature
- Industrial scale manufacturing possible

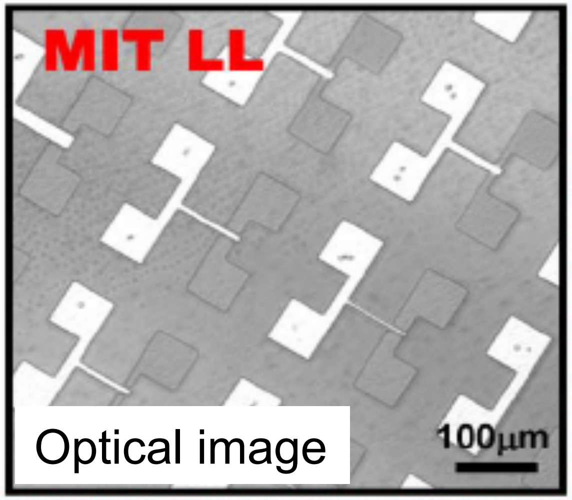
Nature Nanotech. **3,** 101, 2008

Graphene Fabrication Methods: Epitaxy (3/4)

Thermal decomposition of SiC (epitaxial graphene)



- Berger et al., J. Phys. Chem. B 108, 2004
- limited scalability
- experimentally complex (8N H2…)
- high temperatures (~1500°C)
- high cost of material



Kedzierski et al., IEEE TED, 2008

KTH approach: SiC growth on Silicon

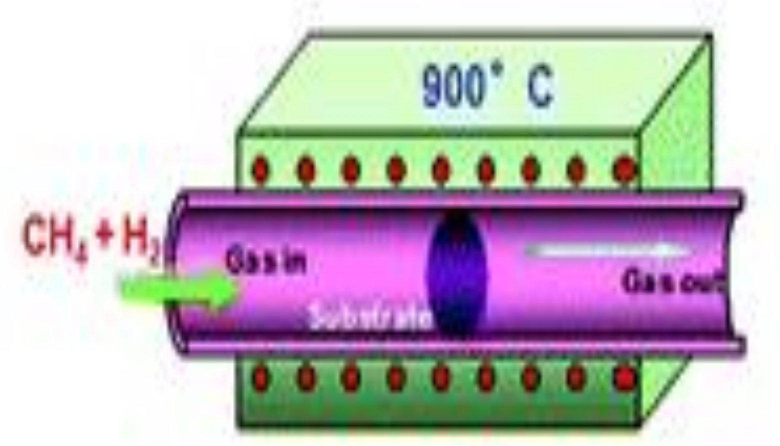
- scalable
- modest temperatures (~1000°C)
- Silicon Technology compatible (CMOS compatible)

Source: Infineon

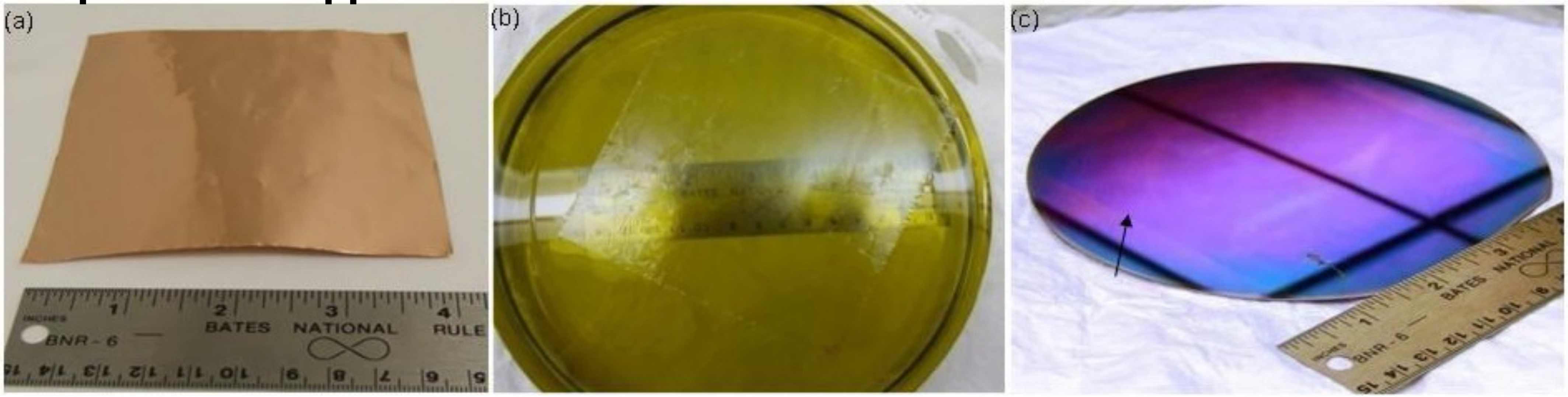
Graphene Fabrication Methods: CVD (4/4)

Chemical Vapor Deposition (CVD)

- CVD on Nickel, Copper, etc.
- High potential for large areas
- Graphene transfer to random substrates
- Monolayers vs. Multilayers?



Graphene on Copper -> PMMA -> Silicon



Cao et al, Applied Physics Letters 96, 122106 (2010)

Graphene Fabrication Methods: CVD (4/4)

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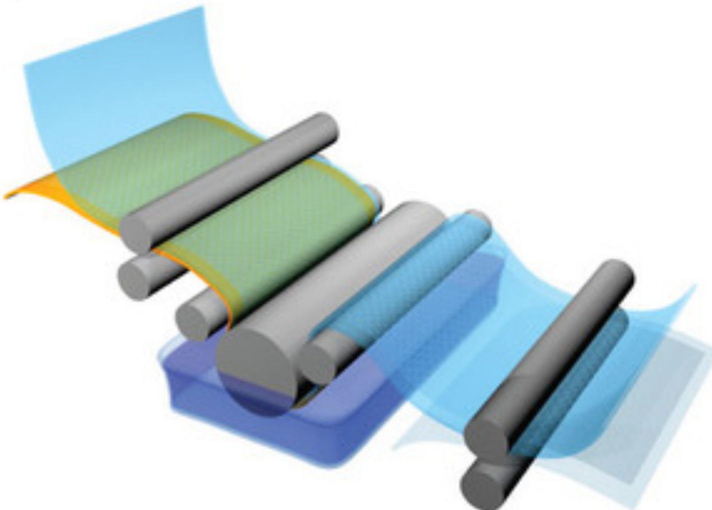
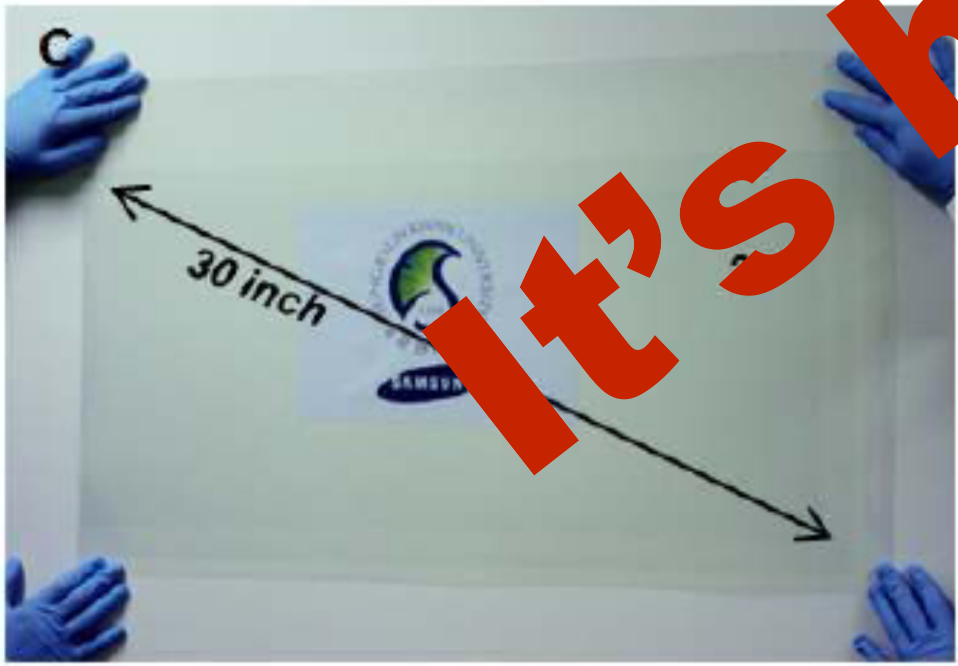
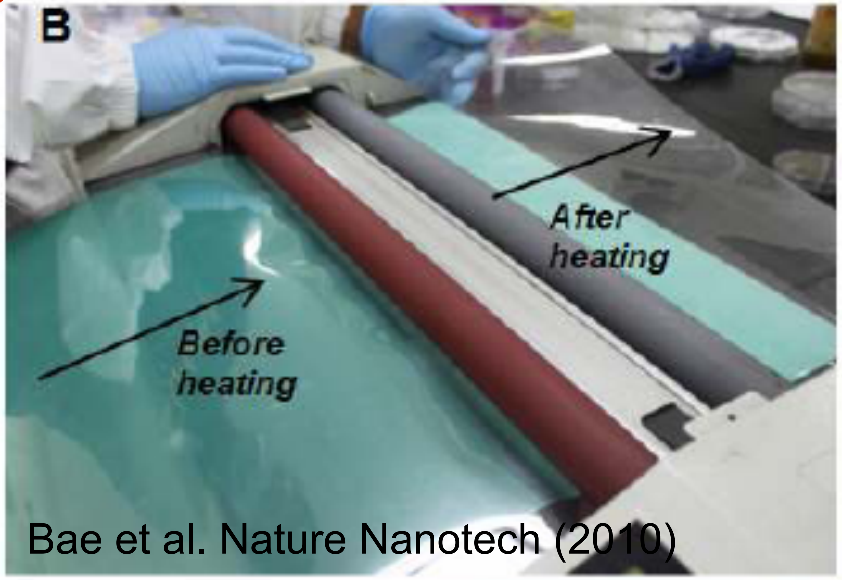
Chemical Vapor Deposition (CVD)



Chen, Nature Nanotech. 5, 559 - 560 (2010)

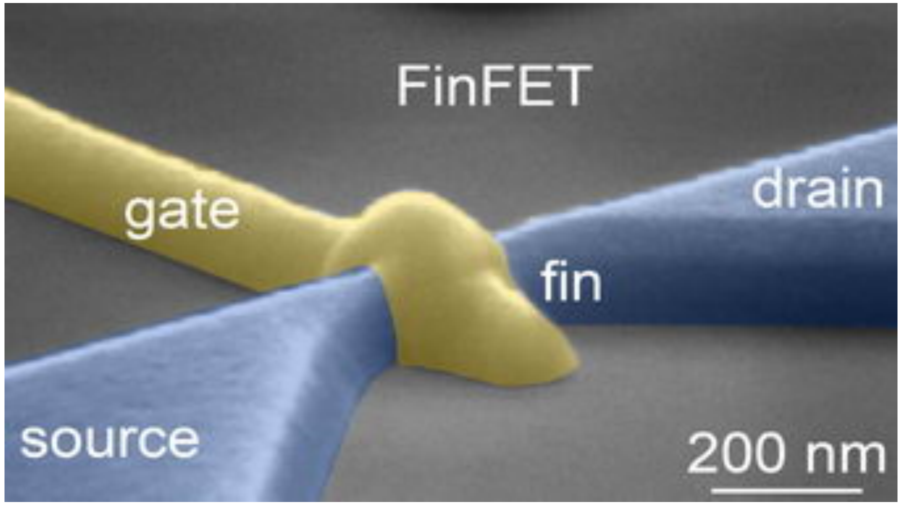




Bae et al. Nature Nanotech (2010)

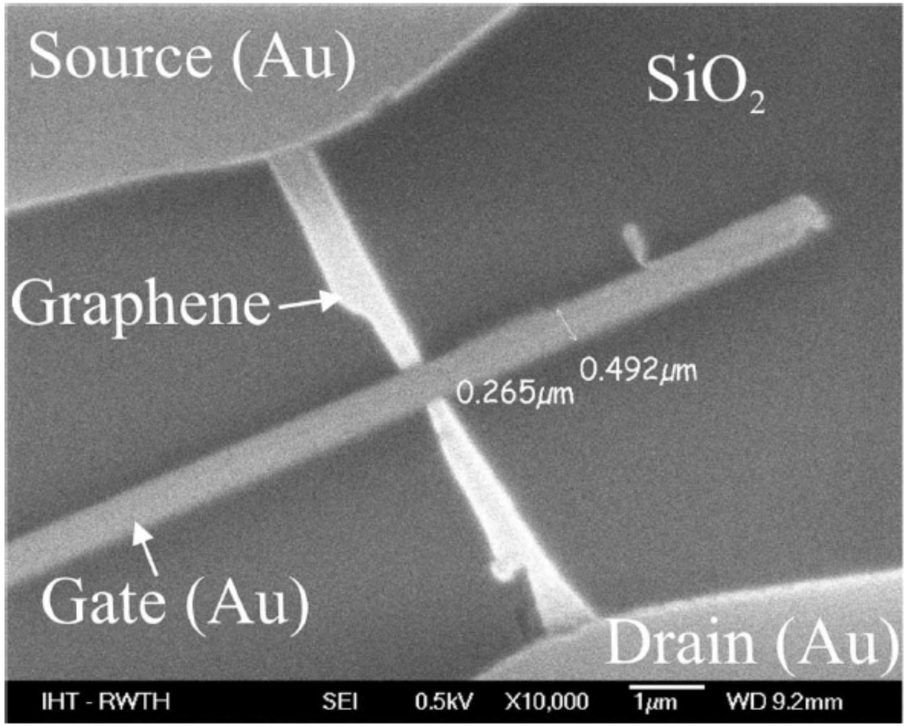
Graphene Transistors: Technology

Silicon MOSFET



Source: TU Delft

Graphene MOSFET



Lemme et al. "A Graphene Field Effect Device", IEEE Electr. Dev. Lett. 28(4), 2007.

Graphene Transistors:

- Silicon process technology can be applied („Top-Down")
- Graphene is compatible with (most) standard processes
- ...Graphene MOSFET!?

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Graphene Transistors (GFETs)

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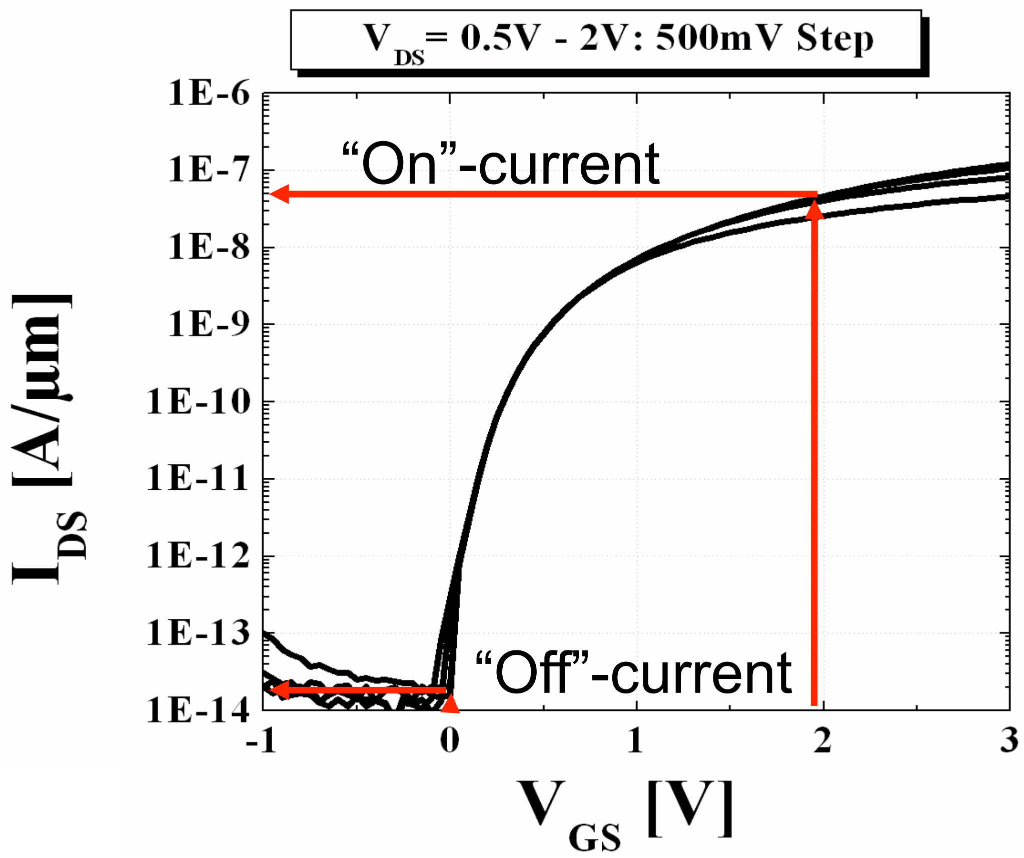
Silicon MOSFET



Schmidt et al., Sol. St. Electr., 2009

- Highly mature technology
- Billions of devices in parallel
- Near ideal switch
- I_{on}/I_{off} ratio: several decades
- Speed ~ I_{on} ~ μ_{eff} (carrier mobility)

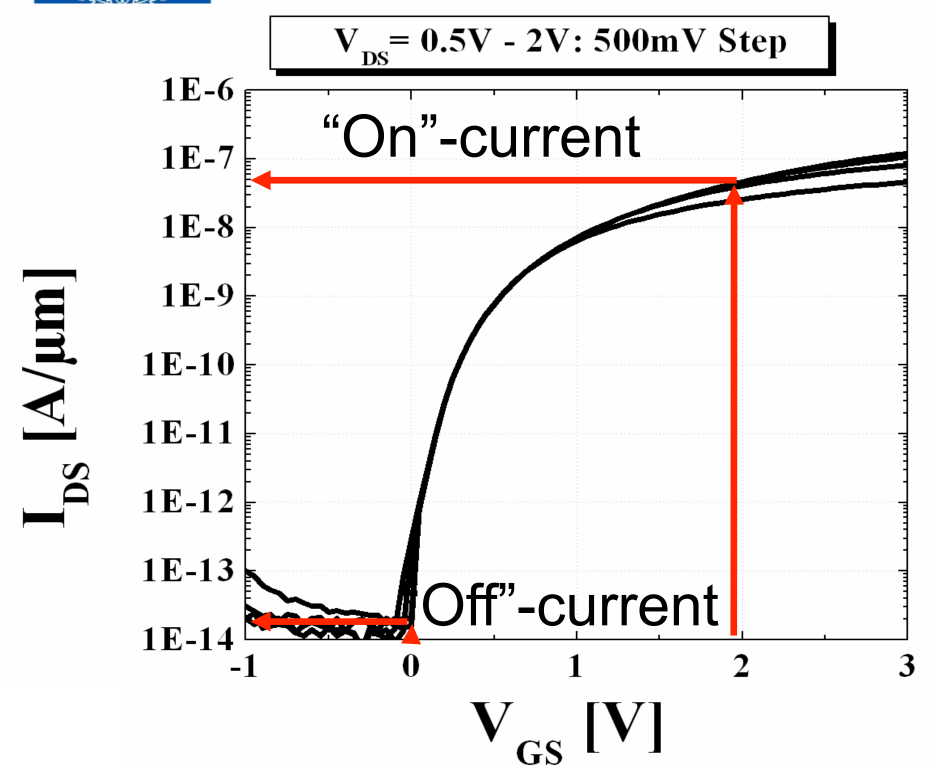
µ - Silicon: 100-450 cm^2/Vs

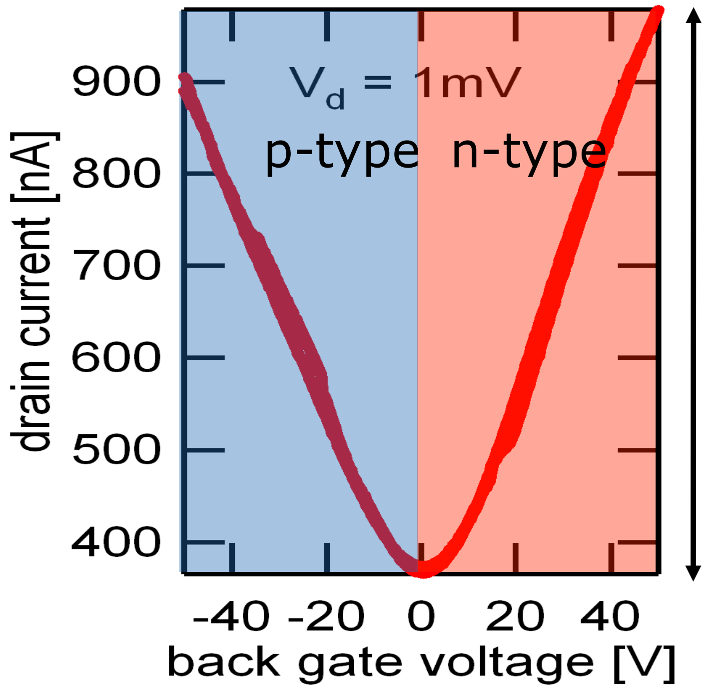
µ - Graphene: 1.0000 – 200.000 cm^2/Vs

Graphene MOSFET!?

Graphene Transistors (GFETs)

Transfer characteristics





~2 x
(compare Silicon: > 1.000.000 x)

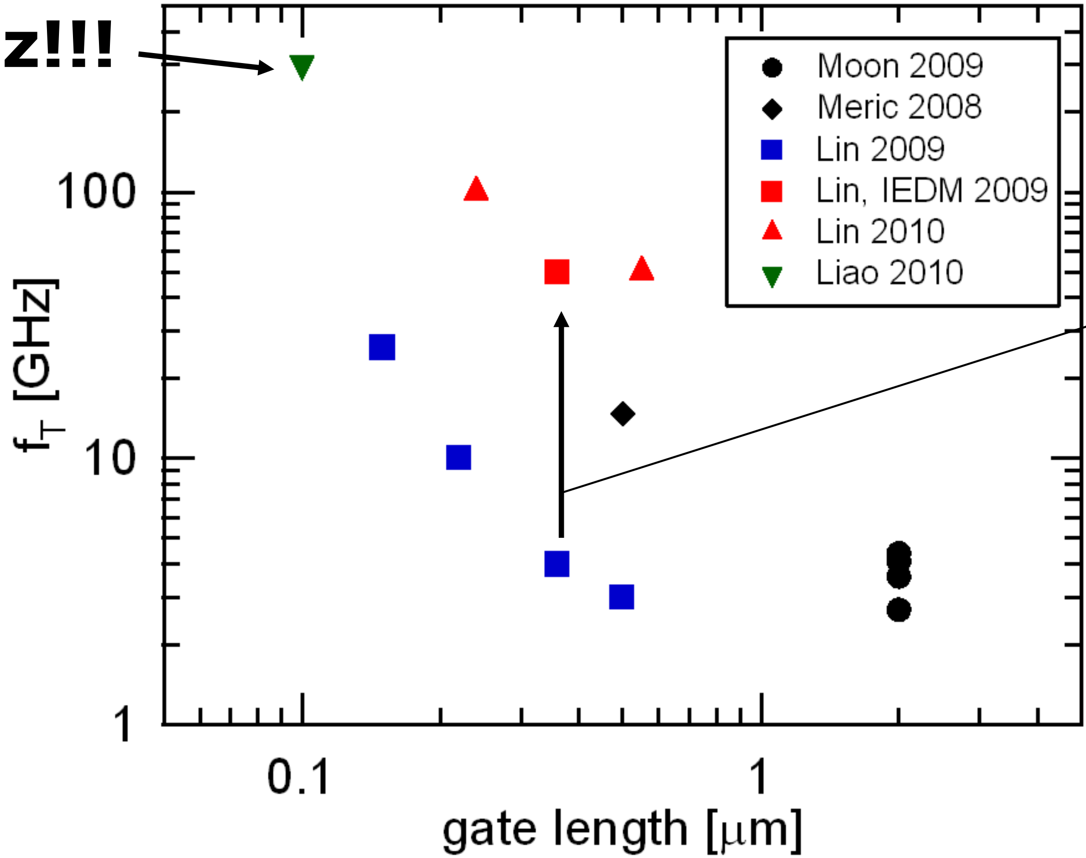
Graphene Transistors:

- Ambipolar behaviour (n- und p-type conduction)
- I_{on}/I_{off} ratio inherently limited by band structure (semimetall)
- NOT a direct replacement for Silicon logic, BUT...
- ... Higher functionality devices (e.g. frequency multipliers – Palacios)
- ... High speed analog transistors

Graphene: RF Transistors

"Historic" trend: cut-off frequency f_T

Today: 300 GHz!!!



Improvement due to interface engineering

Lemme, Sol. St. Phenom., 2010

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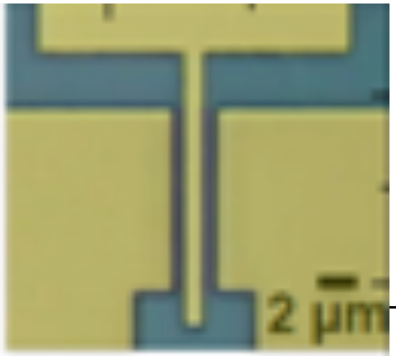
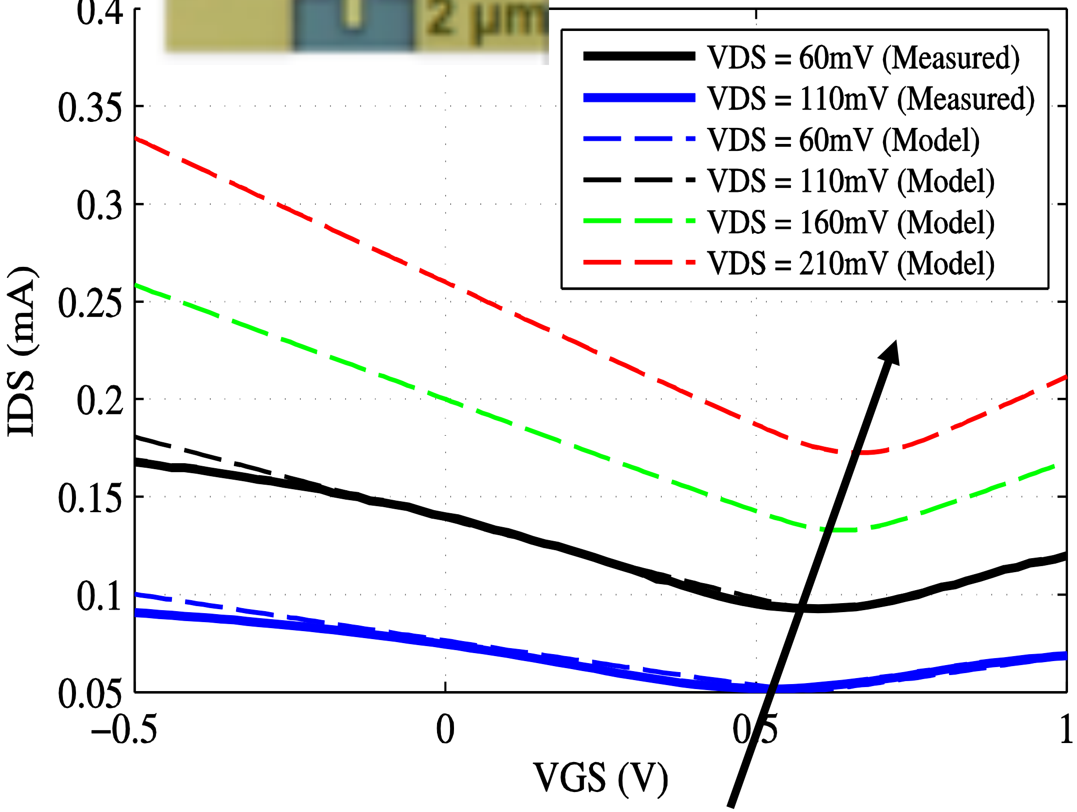
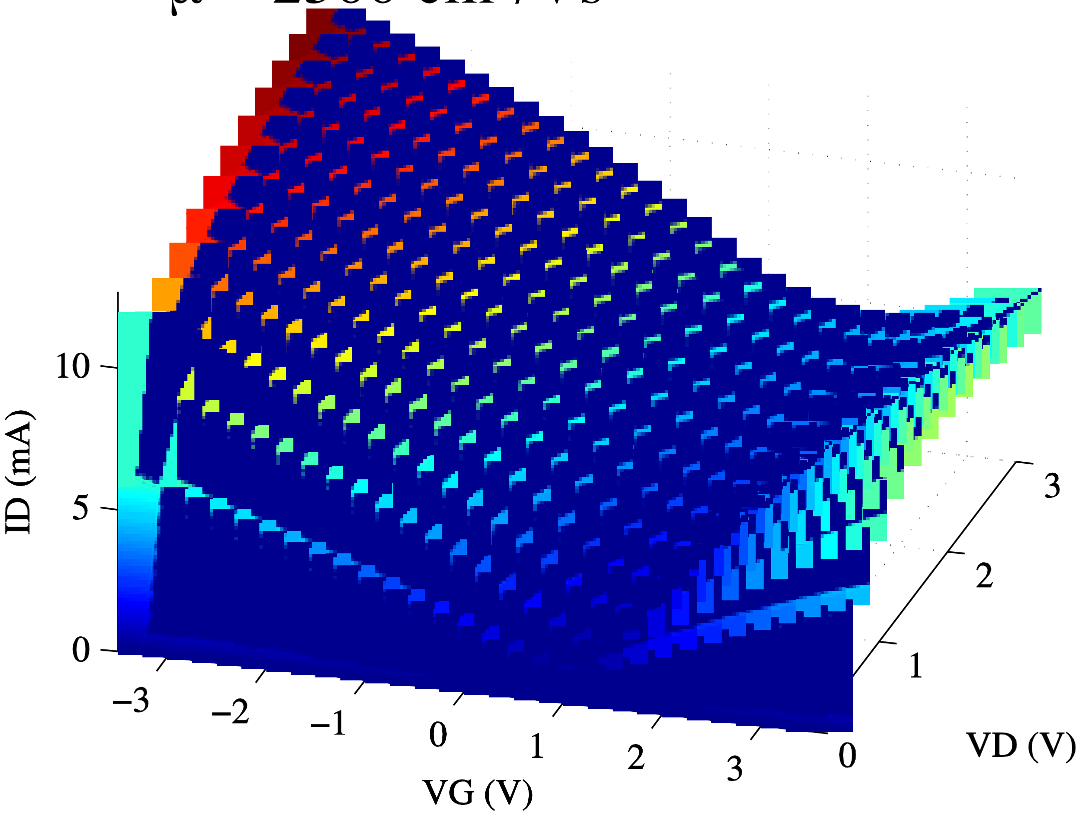
Graphene: RF Transistors Performance Projections



$L = 1\ \mu m$
$T_{ox} = 30\ nm$
$W = 10\ \mu m$
$\mu = 2500\ cm^2/Vs$

$L = 65\ nm$
$T_{ox} = 2.6\ nm$
$W = 10\ mm$
$\mu = 2500\ cm^2/Vs$





Drain Induced Dirac Shift (DIDS)

Rodriguez et al. to be published

Refined model after:
Meric et al.,Nature Nanotech 2008
Thiele et al., J. Appl. Phys., 2010

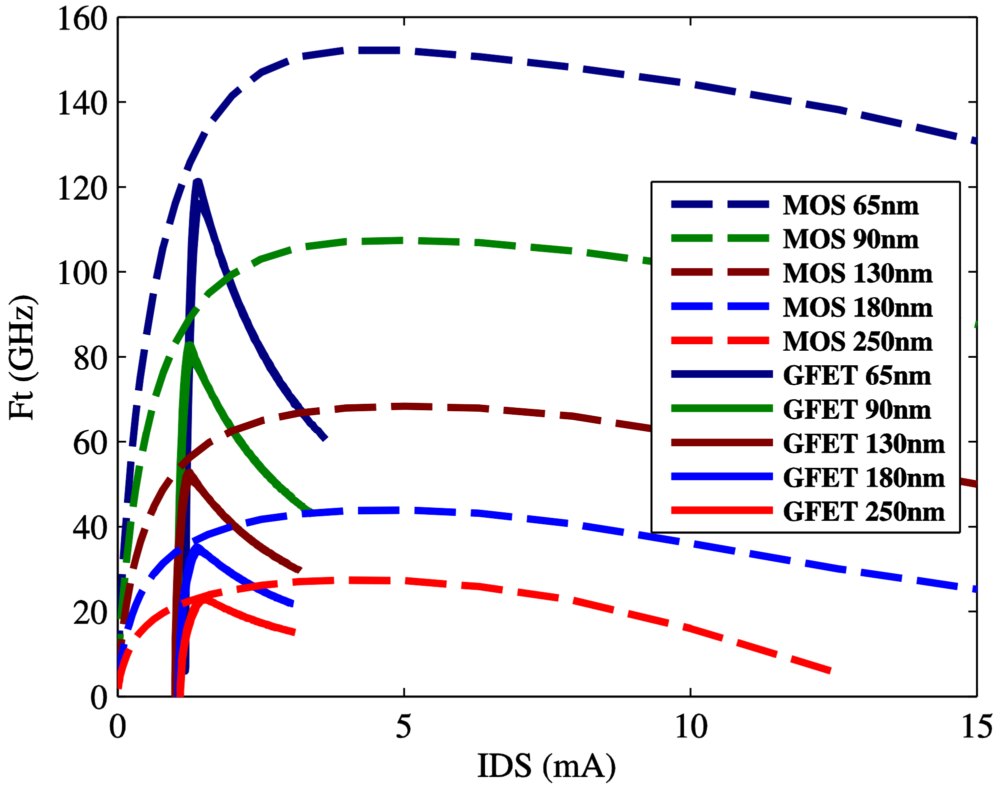
Graphene: RF Transistors

Performance Projections

$$F_T = \frac{1}{2\pi}\frac{g_m}{C_G}$$

(C_G includes $C_{t\text{-}ox}$ and C_q)

65nm GFET vs. Si-MOSFET

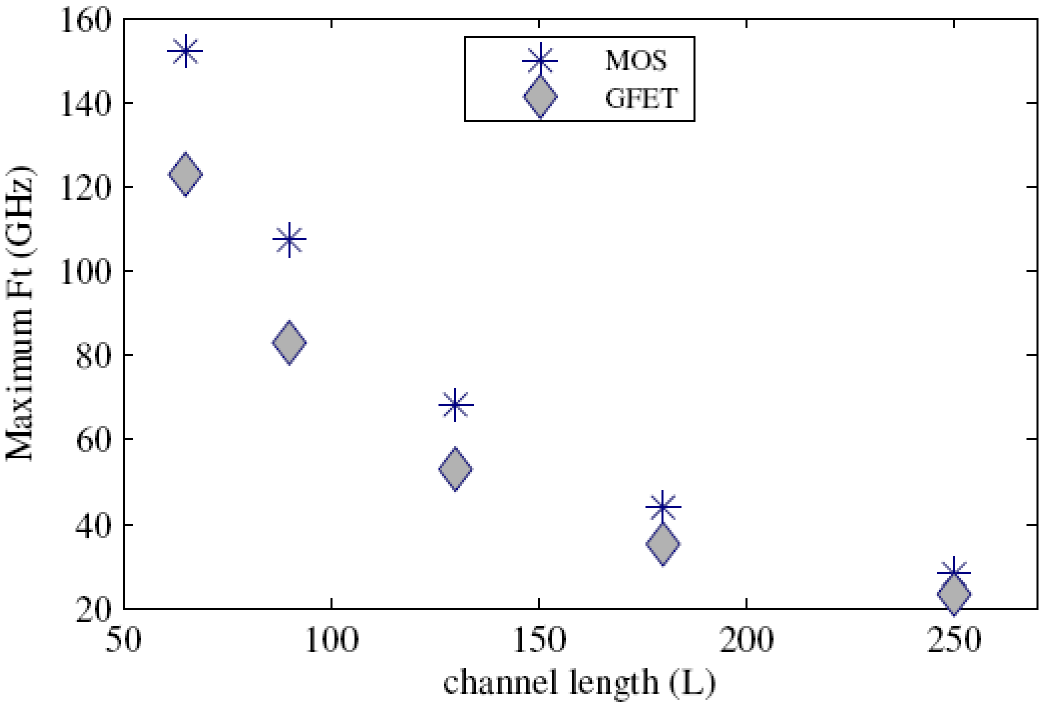


- $F_{T,MAX}$ of GFET almost as high as CMOS at I_{DS} = 1mA
- Si-MOSFET $F_{T,MAX}$ at higher current consumption than GFET $F_{T,MAX}$
- GFETs achieve their best performance in a rather narrow I_{DS} range
- "Dead zone" for GFET amplifiers

Rodriguez et al. to be published

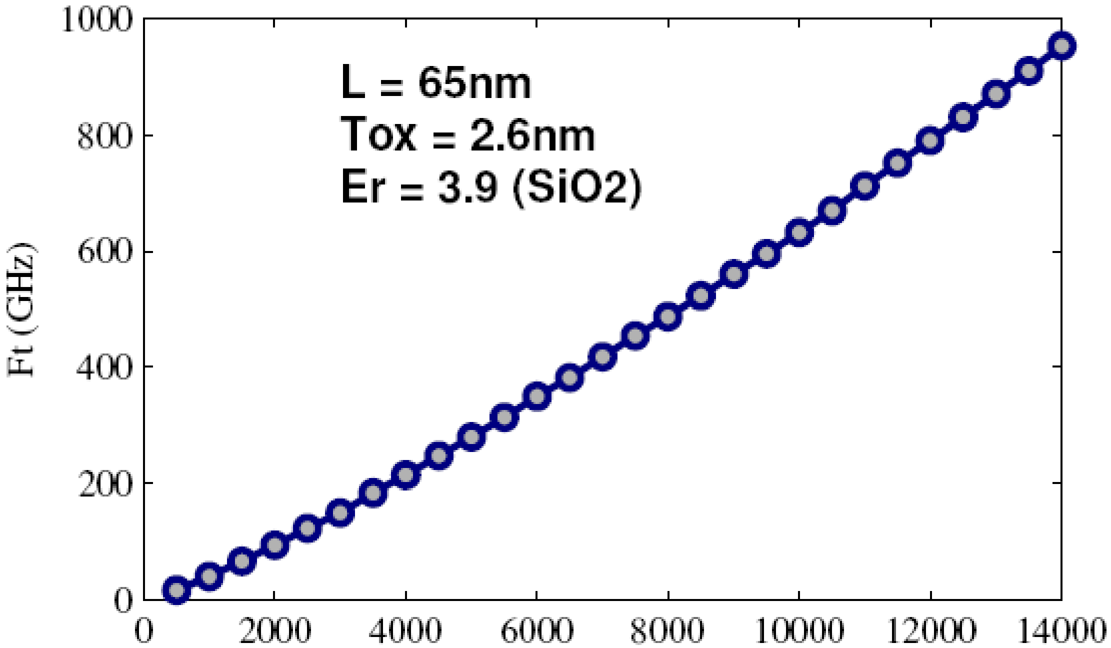
Graphene: RF Transistors Performance Projections

Gate length dependence of $F_{T,MAX}$ for Si-MOSFETs and GFETs



• Superior mobility in GFETs NOT sufficient to provide higher performance than Si-MOSFETs

$GFET_{FT,MAX}$ vs. Mobility for L=65nm, T_{OX}=2.6nm, and $\varepsilon_r = 3.9$



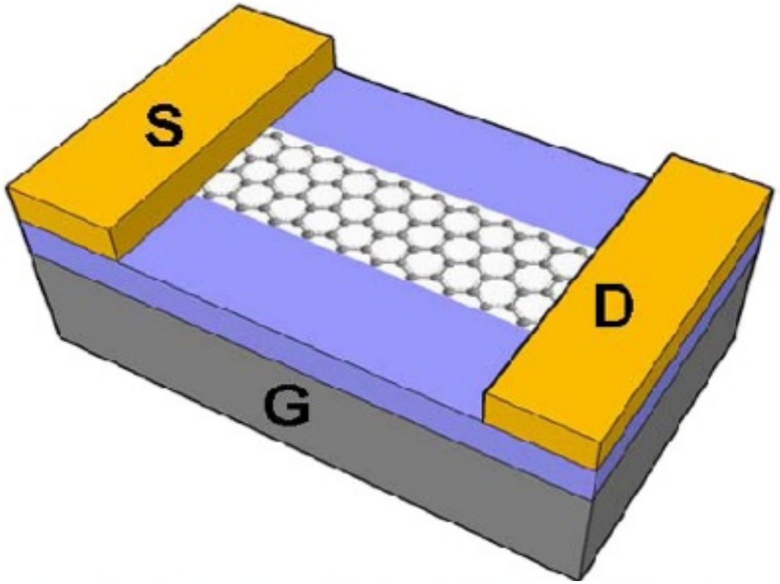
• THz operation seems feasible for high mobility graphene (→ requirements on graphene/insulator interface engineering and (CVD) growth technique)

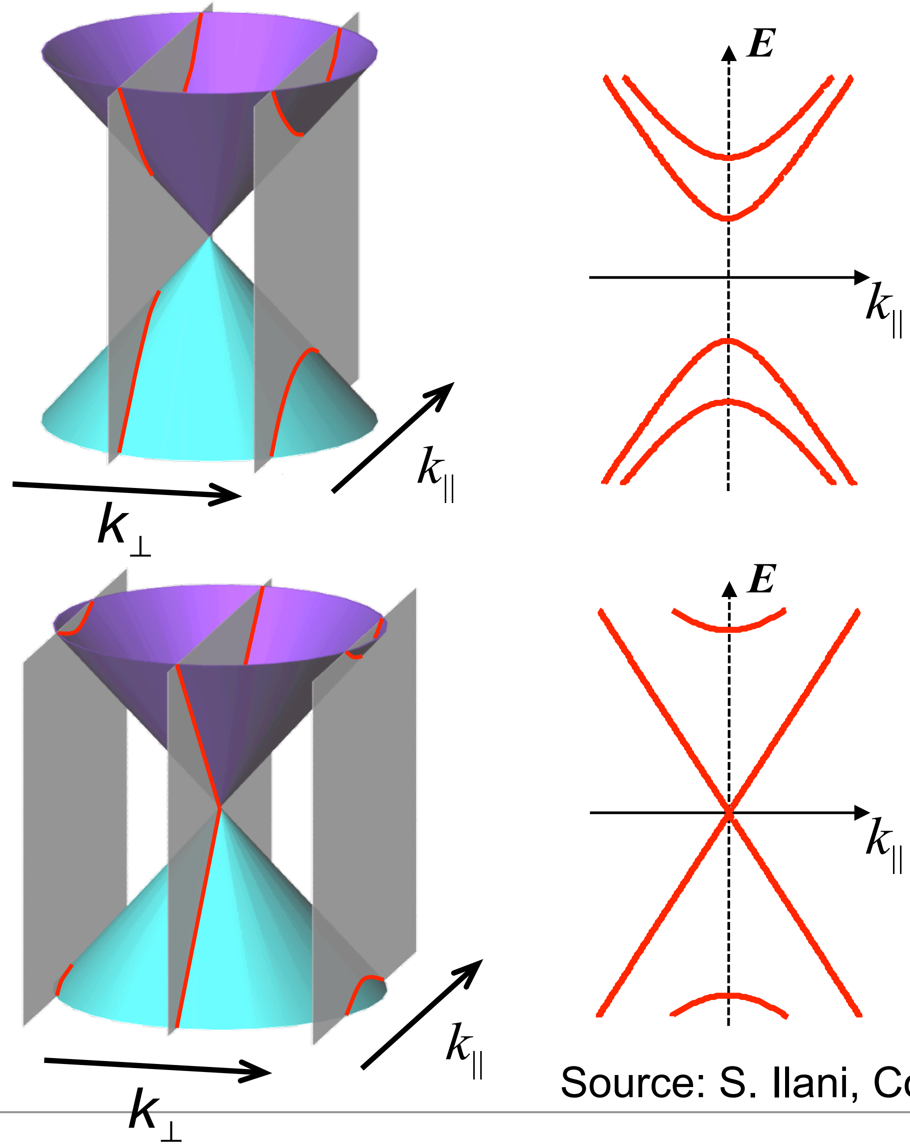
Rodriguez et al. to be published

Graphene Nanoribbon Transistors (GNR-FETs)

Graphene Nanoribbons (GNRs): lateral constrictions

- Transition from 2D to 1D material
- Geometry induced band gap
- $E_g \sim 1/W$

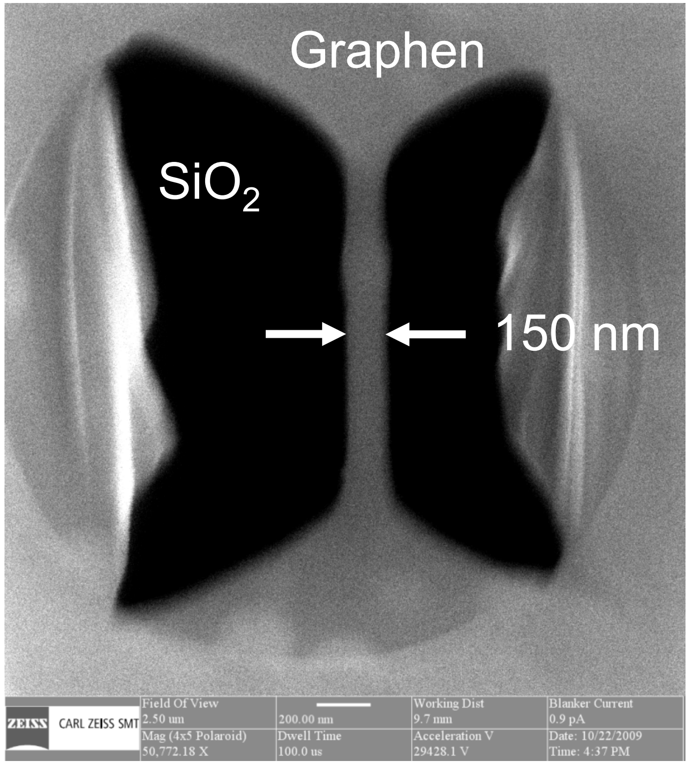




Source: S. Ilani, Cornell

Graphene Nanoribbon Transistors (GNR-FETs)

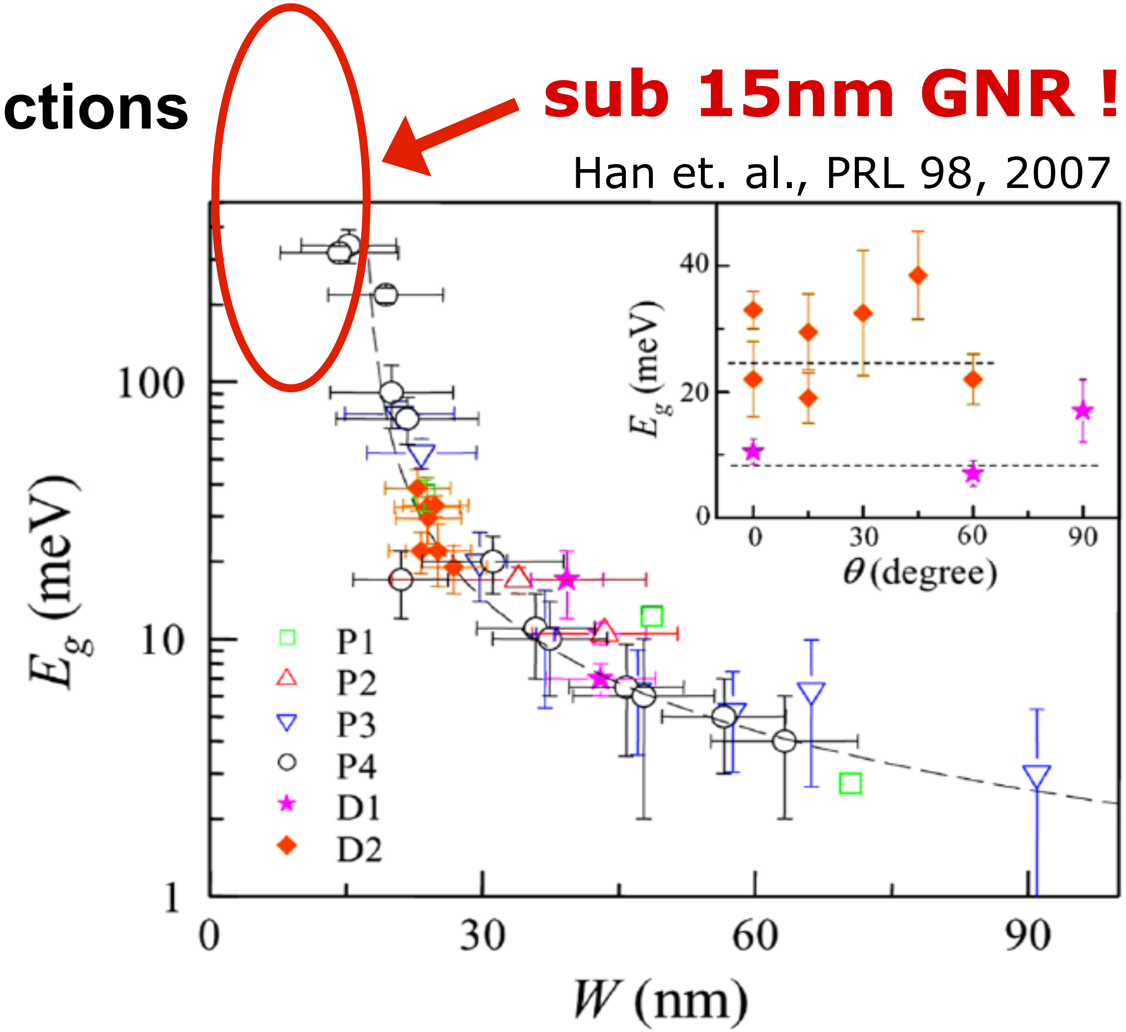
Nanoribbons: lateral constrictions



suspended GNR (unpublished)

sub 15nm GNR !

Han et. al., PRL 98, 2007



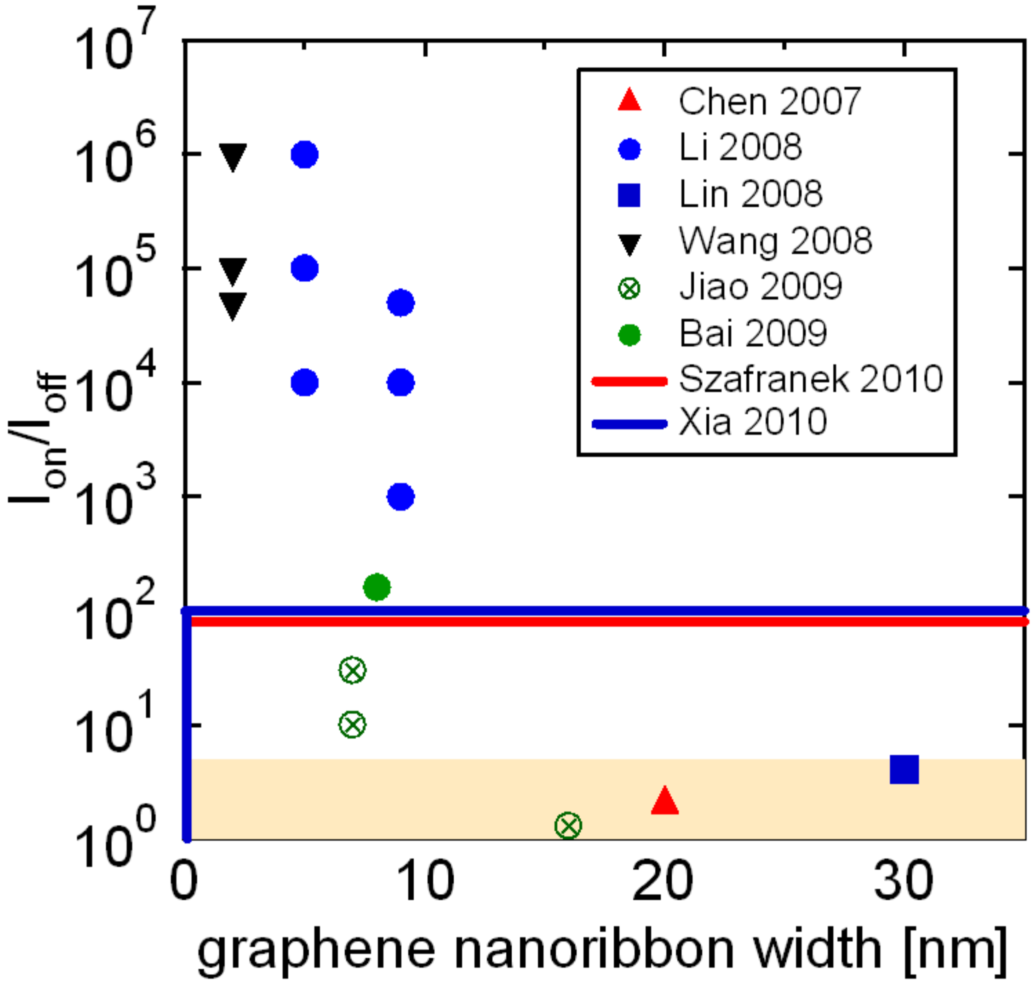
GNRs under 15 nm relevant for FETs!

Graphene Nanoribbon Transistors (GNR-FETs)

Graphene Nanoribbon FETs (GNR FETs)

Experiments confirm:

- GNRs under 10 nm relevant for logic applications
- No experimental metallic GNRs to date



Lemme, Sol. St. Phenom., 2010

Graphene Interconnects

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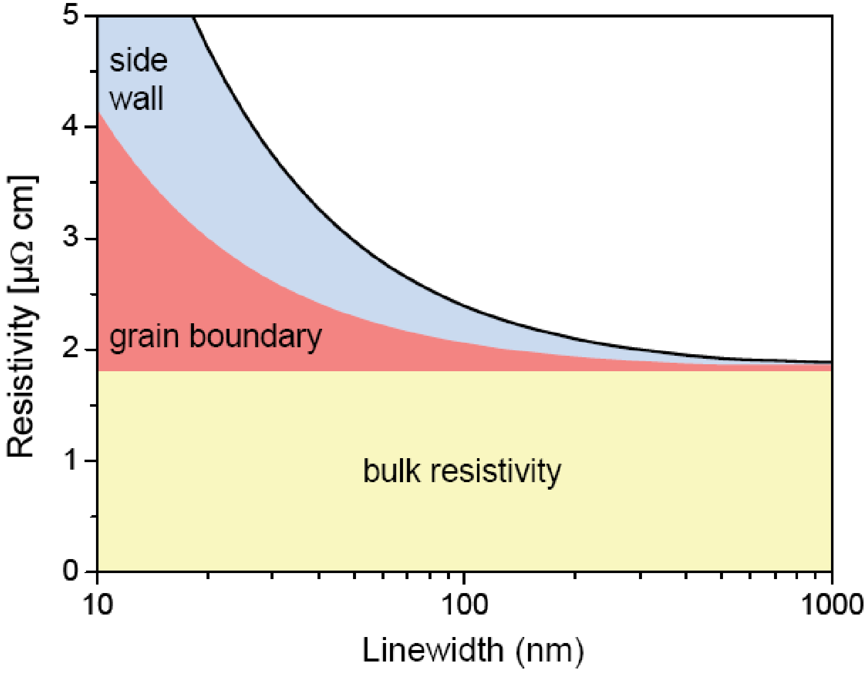
ITRS specifications

Year of Production	2016	2017	2018	2019	2020	2021	2022
MPU/ASIC Metal 1 ½ Pitch (nm)(contacted)	22	20	18	16	14	13	11
Total Metal 1 resistance variability due to CD erosion and scattering (%)	32	33	35	33	33	32	33
J_{max} (A/cm^2) – intermediate wire (at 105°C) [7] *	3.06E+06	2.97E+06	3.23E+06	3.81E+06	4.25E+06	3.65E+06	4.47E+06

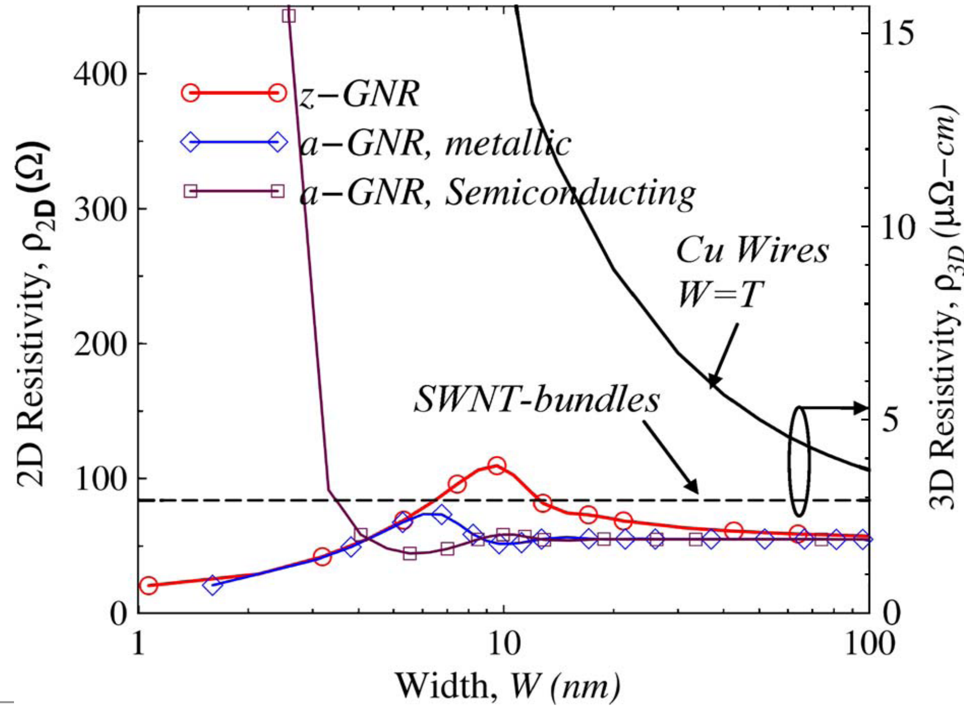
GNRs

GNRs: J > 10^8 A/cm^2

Resistivity of copper



ITRS 2007

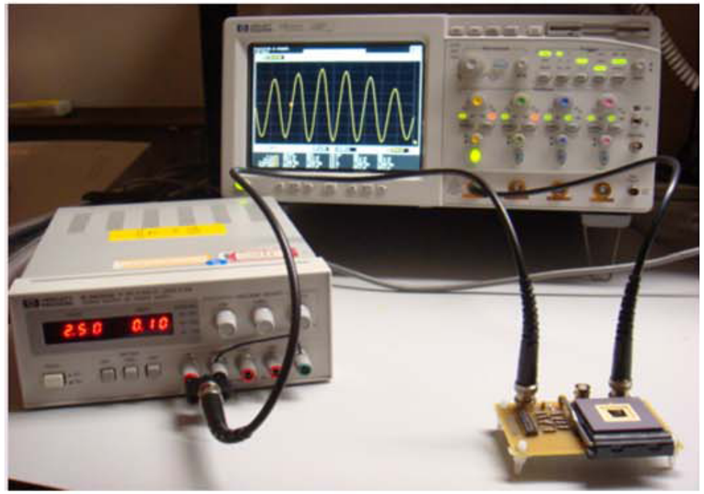


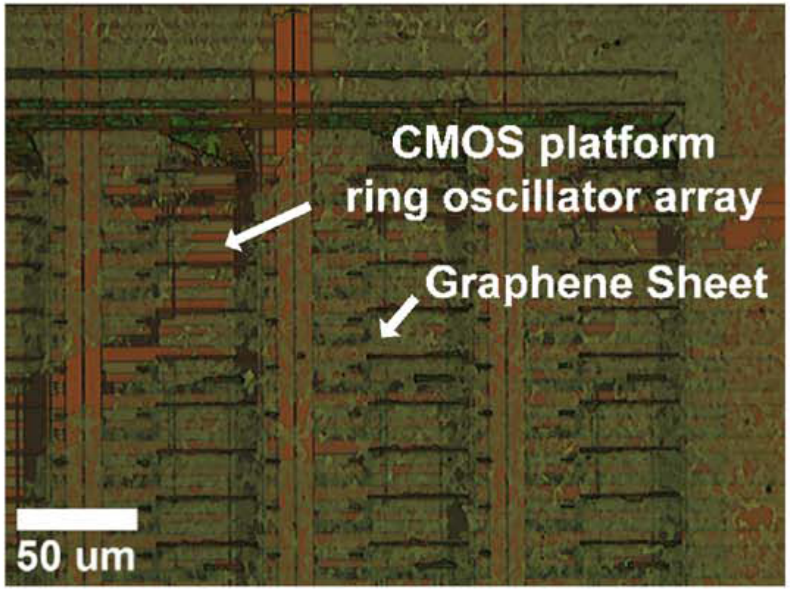
Naeemi, Meindl, IEEE TED, 56(9) 2009

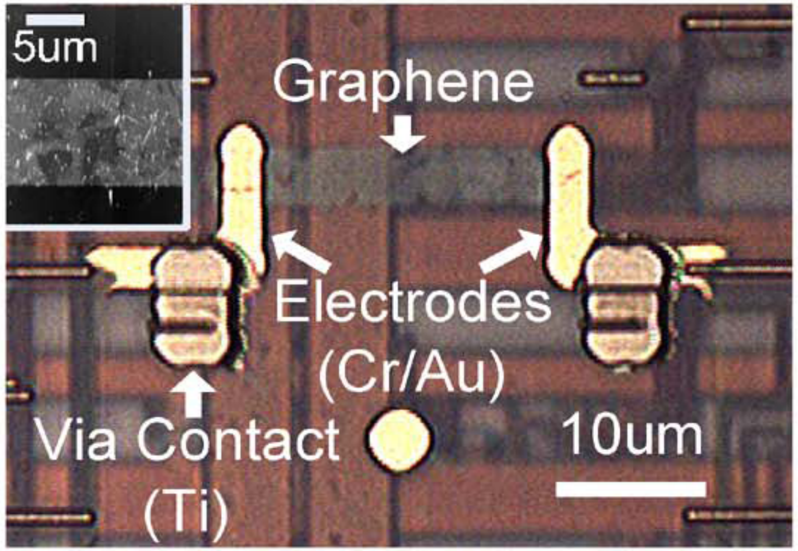
Graphene Interconnects

Graphene Interconnects

- Prediction: below 10nm, graphene outperforms copper in terms of
  - Resistivity
  - Maximum current density
- Chen et al.: Maximum frequency in graphene interconnects: 1.3 GHz







All images: Chen et al., IEEE TED, 2010

Graphene: Optoelectronics

- E-k linear up to +- 1eV
- Potential from visible spectrum to THz
- High data rates

a) Wavelength-independent absorption in single layer graphene
b) Broadband photodetection in graphene (including THz)
c) Surface plasmon generation in graphene by a dipole or a plasmon resonance

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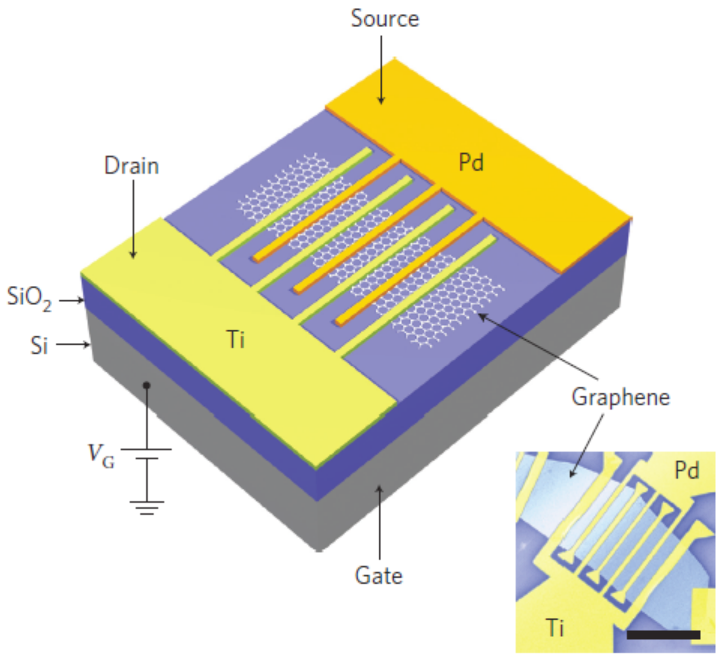
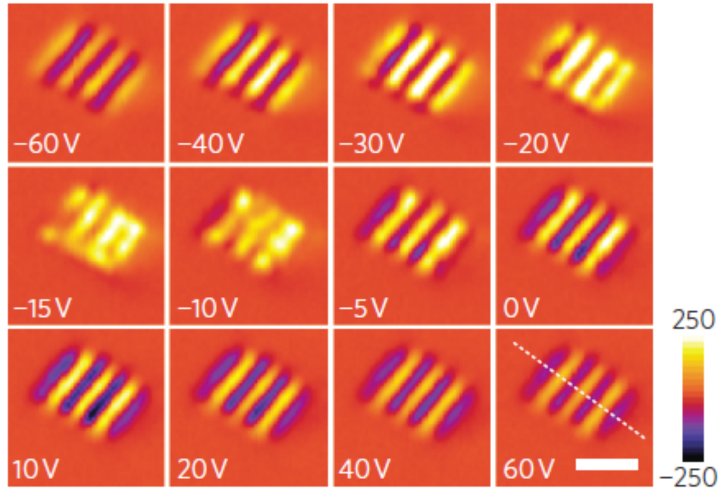
Graphene: Optoelectronics

Graphene photodetectors for high-speed optical communications

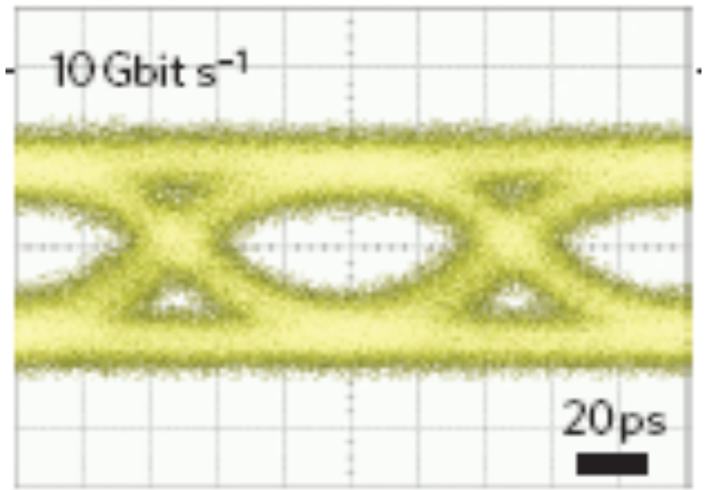
Mueller et al., Nat. Photonics 2010





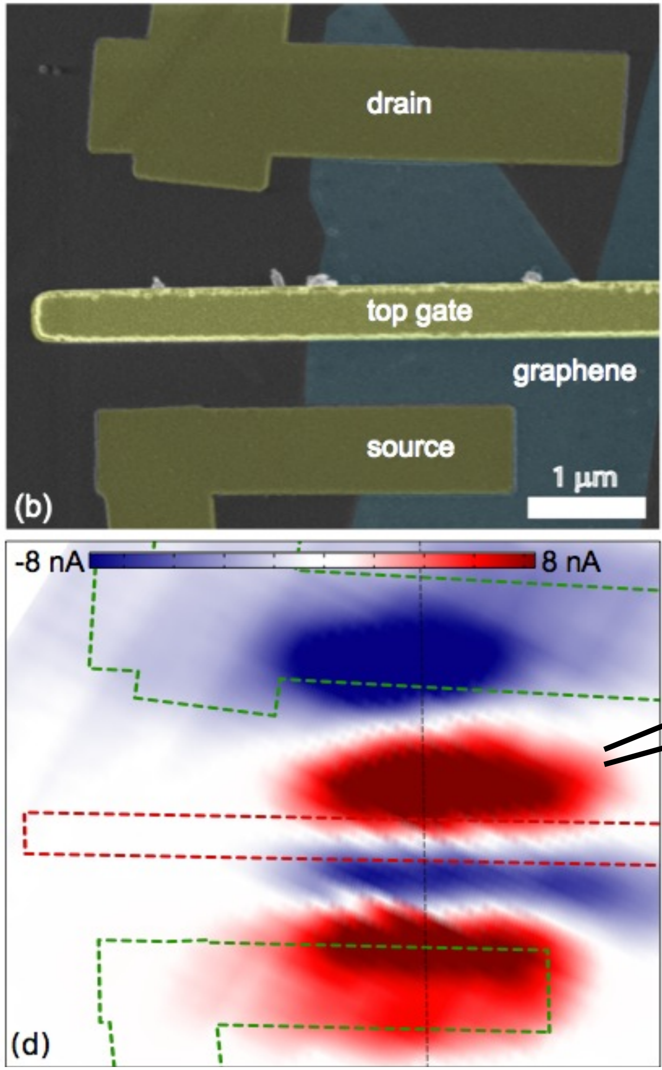
- Metal – graphene interface induces pn-junction
- Control through back gate (substrate)

- Graphene ”Eye Diagram”
- Error free optical data transmission at 10 Gbit/s

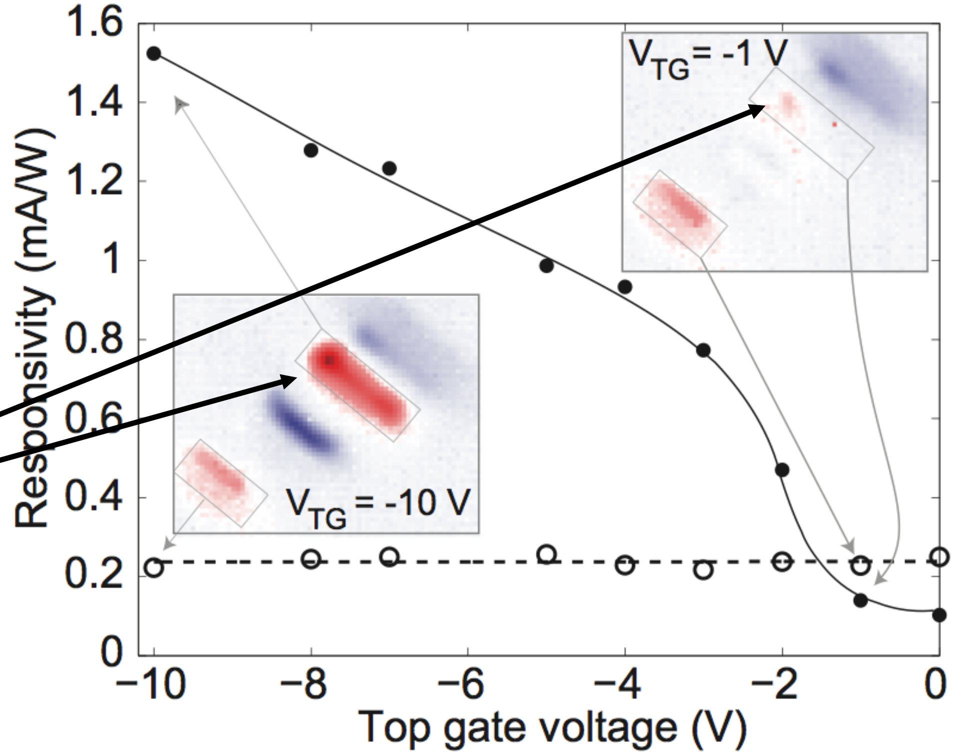


Graphene: Photodetection

Gate-Activated Photoresponse in a Graphene pn Junction

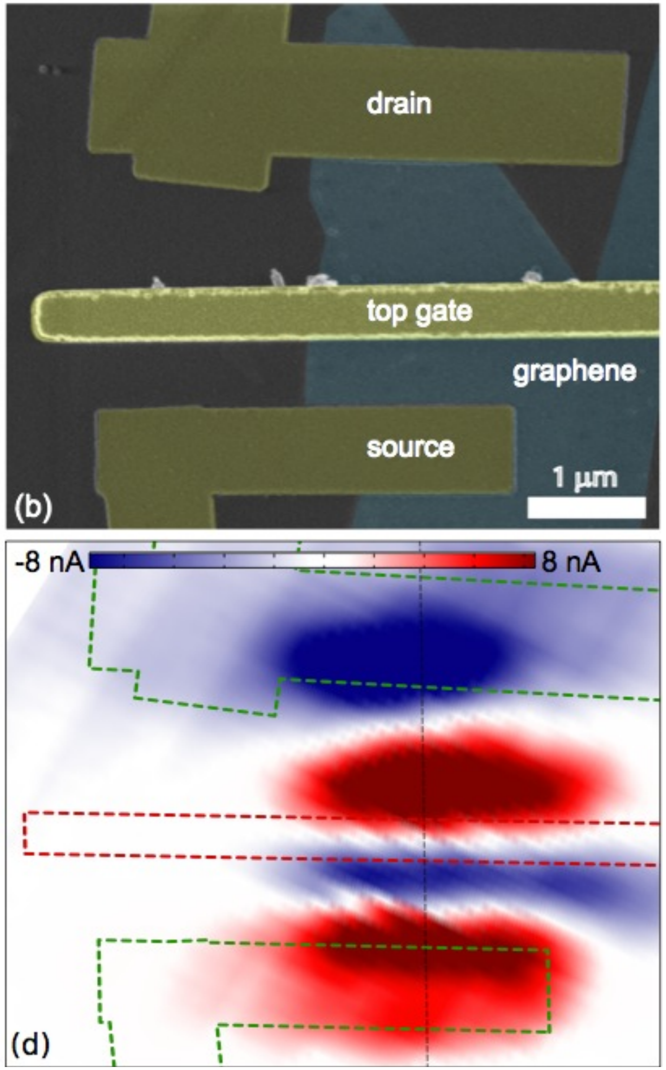


Lemme et al., Nano Lett. 2011



Local control of p-n junction allows on-off control of photodetection.

Gate-Activated Photoresponse in a Graphene pn Junction



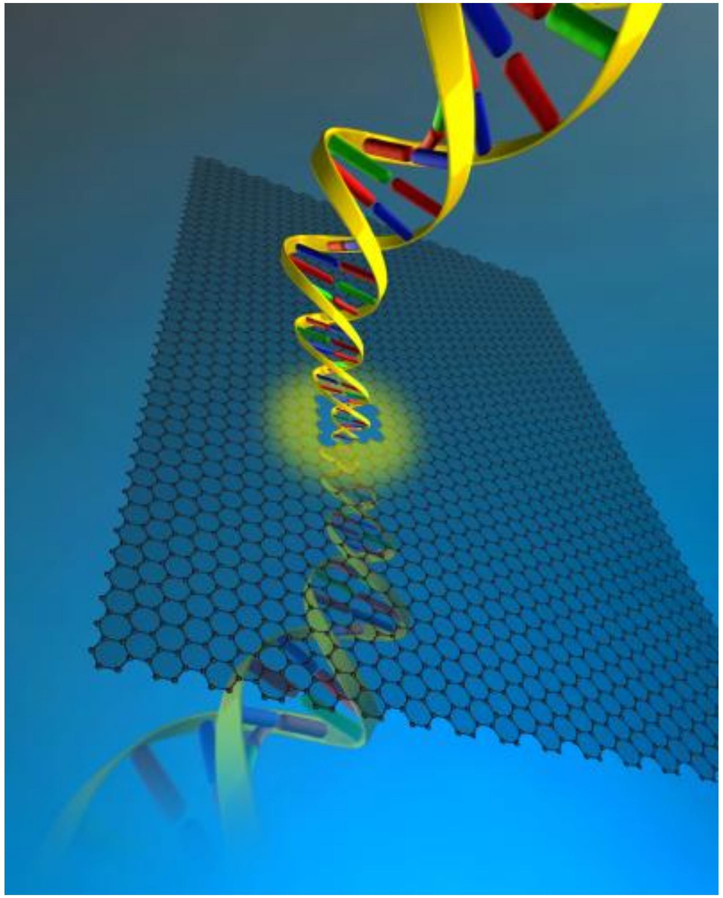
Lemme et al., Nano Lett. 2011

Strong Local Modulation of Photoresponse near a Graphene pn-Junction

- In part depending on Seebeck effect (pn-junction required)
- Local control of p-n junction allows on-off control of photodetection.
- No biasing required (no dark current)
- Scalability to submicron gates
- Potential to integrate graphene optoelectronics into existing platforms

Graphene: Biomedical / Diagnostics

DNA sequencing using nanopores in graphene



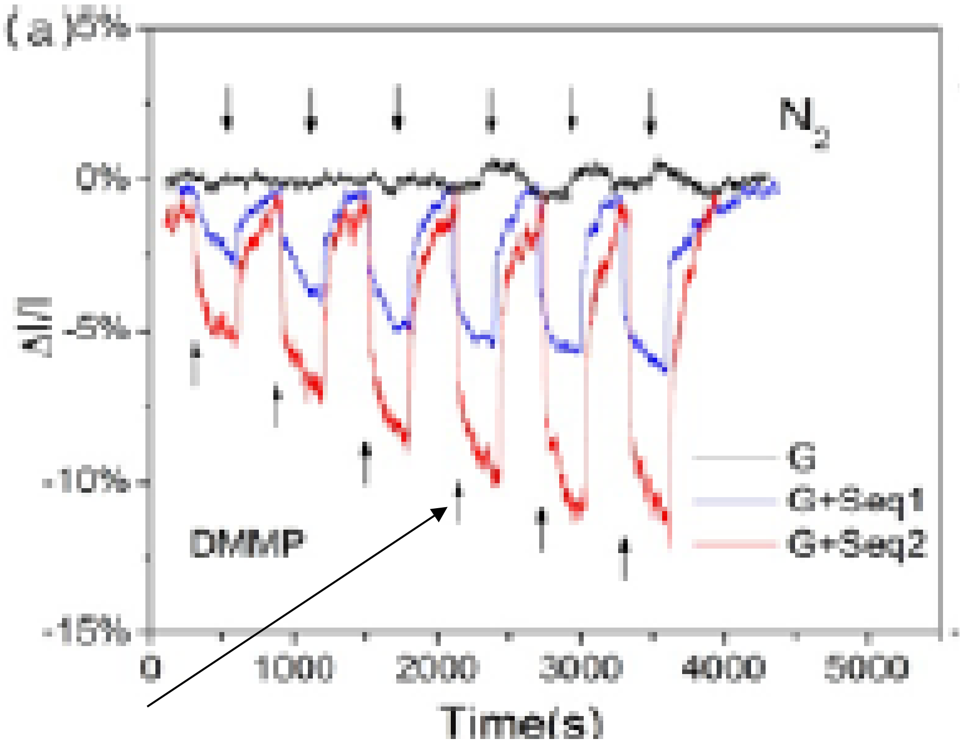
Jene Golovchenko, Harvard University.

Why graphene?

- High mechanical strength
- High electric conductivity
- Ultimately thin

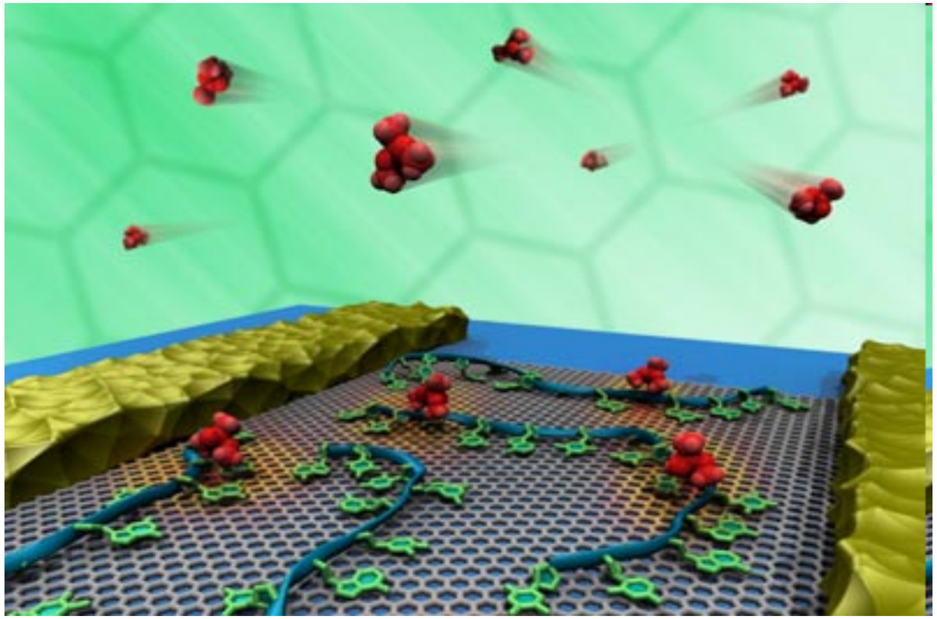
Graphene: Biomedical / Diagnostics

DNA decorated graphene chemical sensors



Introduction of analyte at progressively larger concentrations

Lu et al., Appl. Phys. Lett. 97, 083107 (2010)



- Clean graphene devices (black data) show very weak vapor responses barely above the noise floor
- Devices functionalized (red & blue data) show significant sequence-dependent responses

32

Graphene

Applications of a ”Nobel” Material

- Introduction
- Graphene Fabrication
- Information Technology Applications
- Summary

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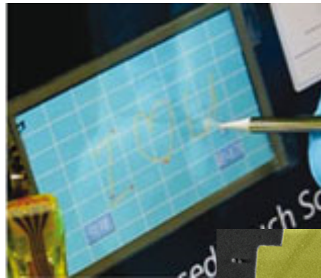
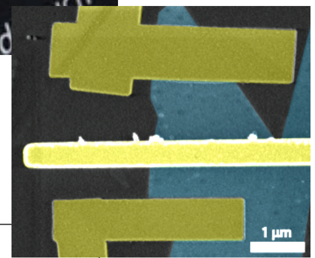
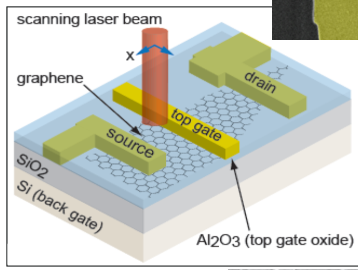
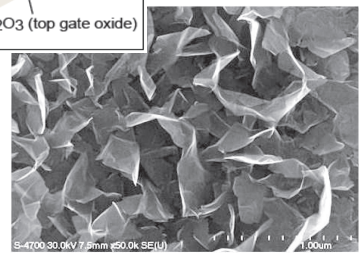
Summary

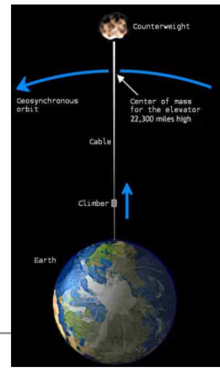
- **Graphene is indeed a "wonder material"**
- **Large Area Manufacturing Available**
- **Electronic Applications**
  - **Add on to Silicon Technology (Interconnects, Analog Devices)**
  - **Optoelectronics**
  - **Transparent electrodes (Solar, Displays)**
  - **Supercapacitors**
- **Mechanical Applications**
  - **NEMS**
  - **Space Elevator**











Graphene: Open Topics

- **Sensors (Functionalised Surfaces, Biocompatibility)**
- **Resistive Switching (Memory Applications)**
- **Ballistic Devices**
- **Spintronics (Spin-Valves, SpinMOSFET, SpinFET)**
- **Thermoelectricity (Z-Factor: el. vs. therm. conductivity)**
- **Plasmonics**
- **Solution based Applications (Inkjet Printing)**
- **And potentially more...**

Graphene - In Your Laptop Tomorrow?

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CPU / Graphics Chip:	
Replacement of CMOS logic	„Unlikely“ to „No“
Interconnects / Heat Sinks	„Probable“ (8+ years)
Energy Harvesting	„Maybe?“
Display:	
ITO replacement	„Likely“ (5+ years)
Touch screen	„Likely“ (5+ years)
Interfaces (I/O):	
Wideband Optoelectronic Coupling	„Probable“ (10+ years)
Wireless Amplifiers and Antennas	„Probable“ (8+ years)

Disclaimer: This slide is intentionally printed in **BOLD** letters