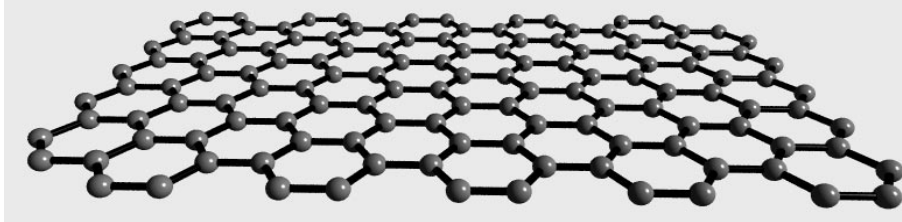
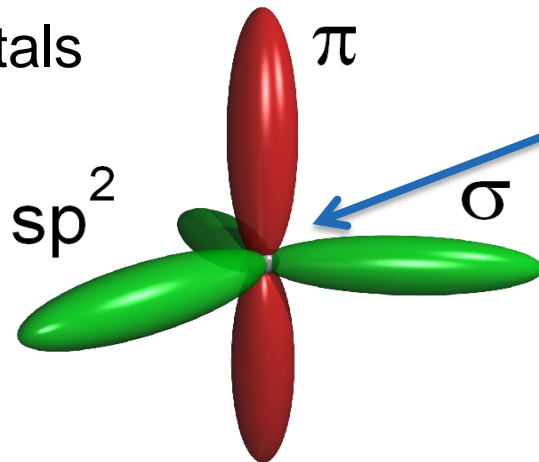


Graphene

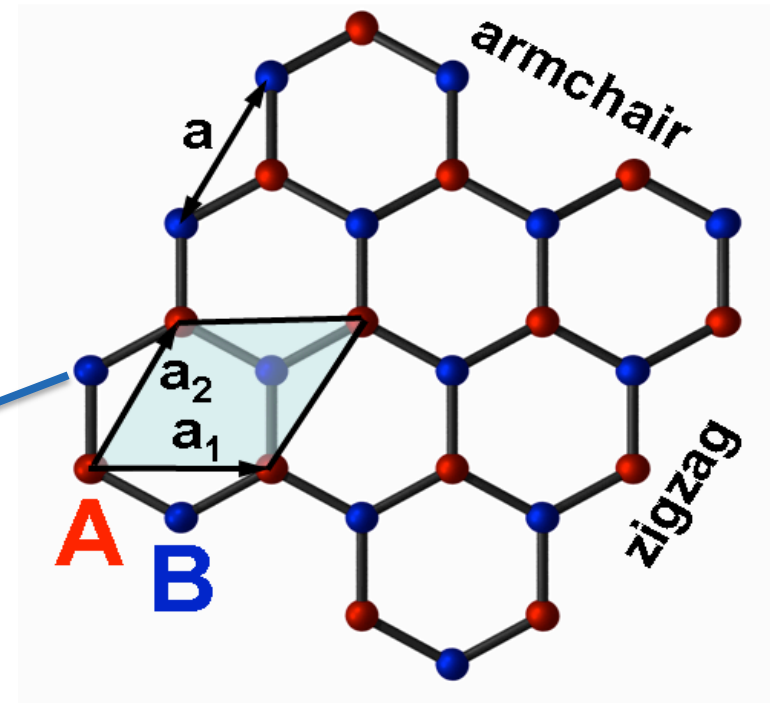


sp^2 bonded carbon atoms ($\sim 4,3\text{eV}$)

Orbitals



2D-crystal lattice

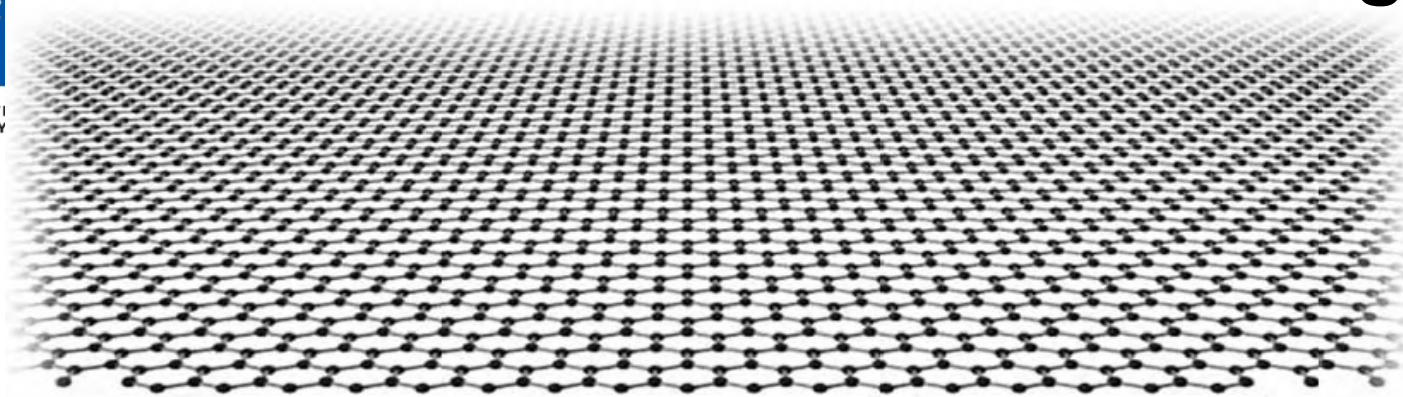


Sublattice constant: $a = 0.246 \text{ nm}$

"Thickness": $d = 0.34 \text{ nm}$

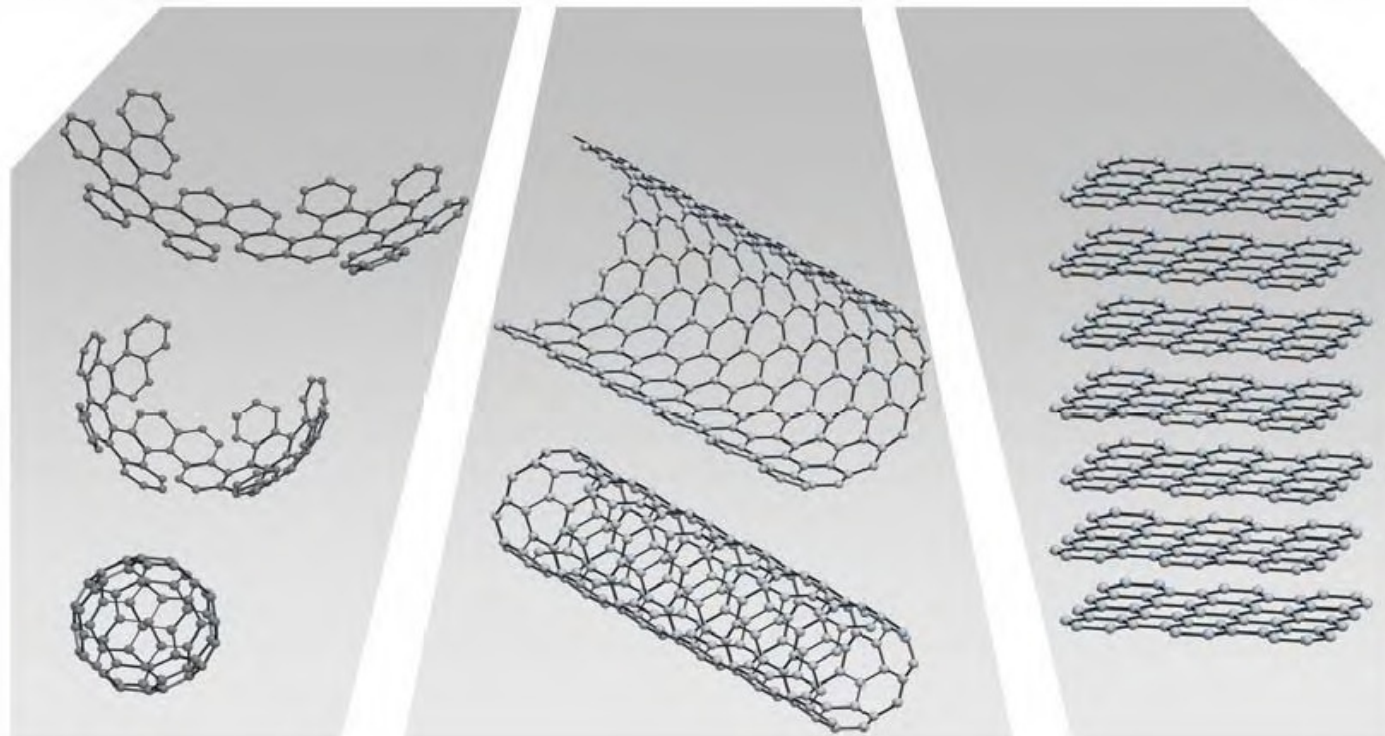
Lemme, Sol. St. Phenom., 2010

"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
($\sim 4,3\text{eV}$)

Inter plane: weak v.d.
Waals bonds
($\sim 0,07\text{eV}$)

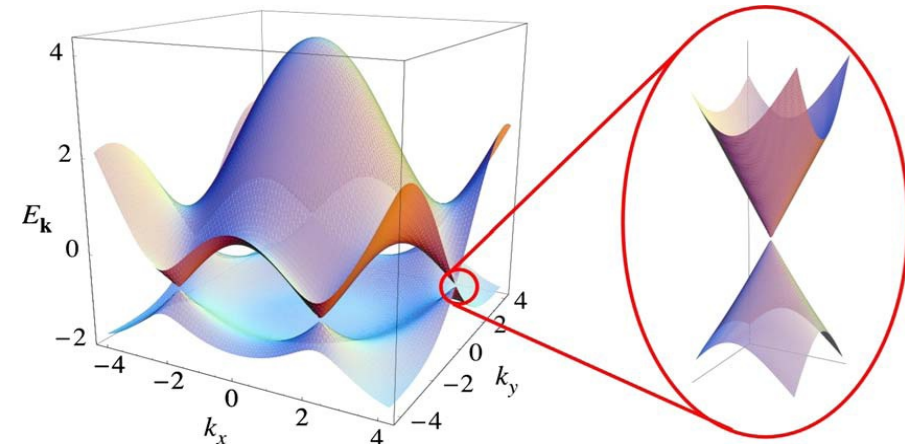
Nature Mater. 6., 183, 2007

Exceptional Properties (1/2)

Electronic properties

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

$$v_{\text{sat}} = 5 \times 10^7 \text{ cm/s (10 x Si, 2 x GaAs)}$$

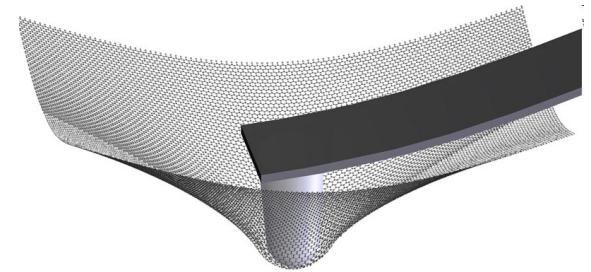


After: Wallace, Phys. Rev. **71**, 622 (1947).

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 \cdot K at room temperature
- Diamond: ~ 2000 W/m \cdot K, 10 x higher than Cu, Al

Thinnest material possible

Transparent (only 1 atom thin)

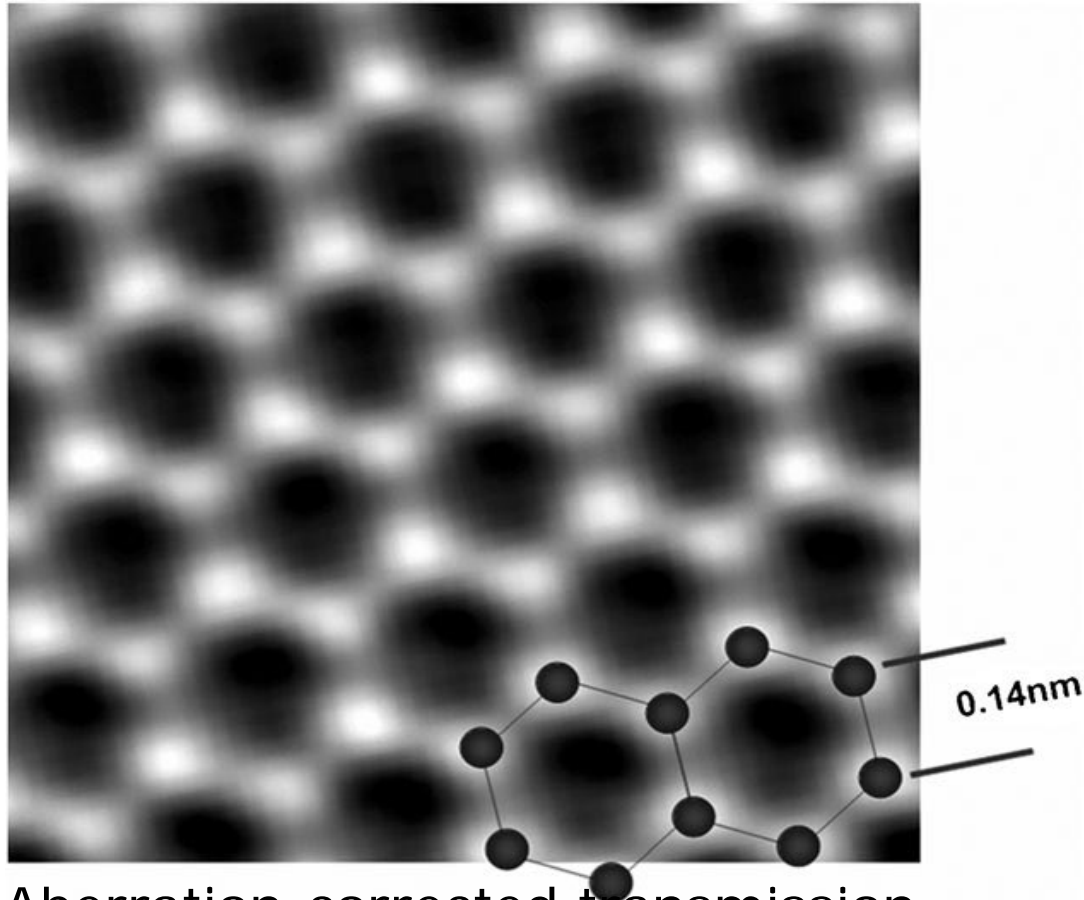
Transparent flexible conductive electrodes

High surface to volume ratio

Sensors

Graphene: Nanolandscapes

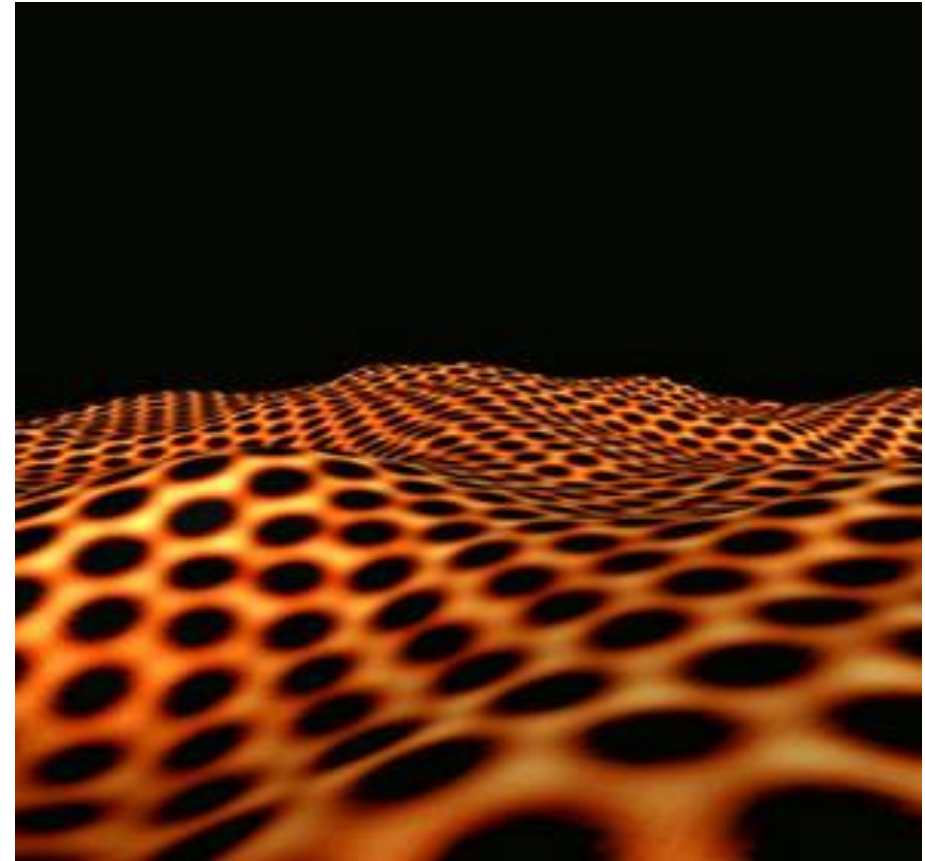
Graphene by HRTEM...



Aberration-corrected transmission
electron microscope (TEAM 0.5)

Chem. Commun., 2009, 6095 - 6097

and by STM



Scanning tunneling microscope
image of graphene on SiO₂

Mashoff et al, Nanoletters 2010

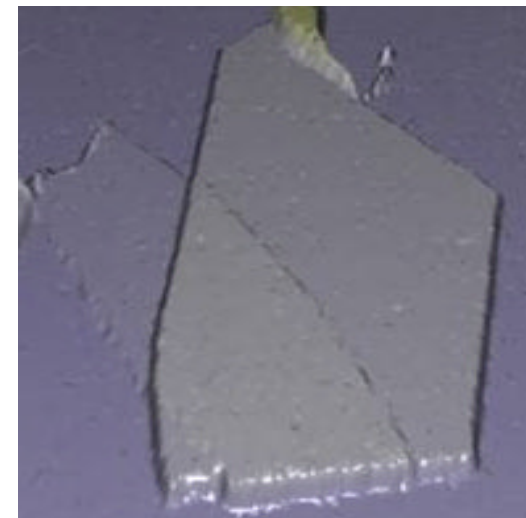
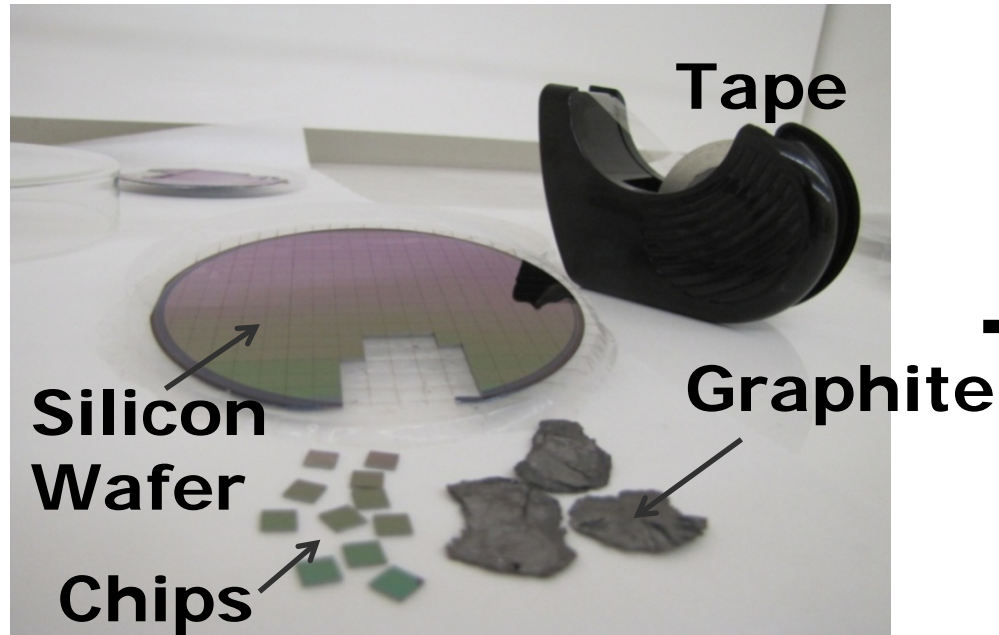
Graphene – Devices and Technology

Outline

- Introduction
- Graphene Fabrication
- Graphene-based Electronic Devices
- Applications beyond "Moore's Law"
- Summary

Graphene Fabrication Methods: Exfoliation

Exfoliation with adhesive tape

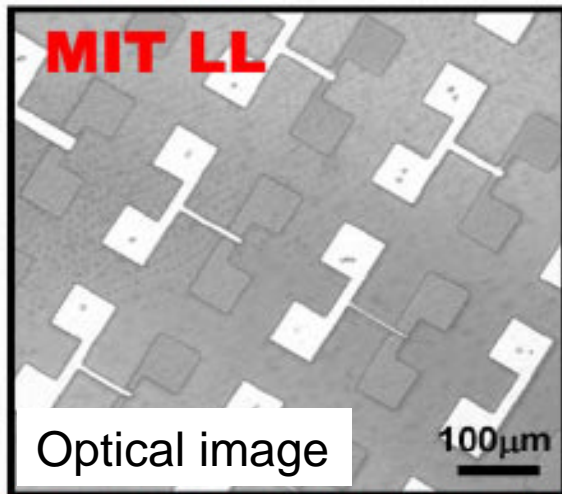


- Novoselov et al., Science 306, 666 (2004)
- flake size: 5 – 100 μm
- random location
- simple process for proof-of-concept
- ***no industrial relevance***

Graphene Fabrication Methods: Epitaxy

Thermal decomposition of SiC (epitaxial graphene)

- Berger et al., J. Phys. Chem. B 108, 2004
- limited scalability
- high temperatures ($\sim 1500^\circ\text{C}$)
- high cost of material
- monolithic integration



Kedzierski et al., IEEE TED, 2008

Alternative approach: SiC growth on Silicon
OSIRIS Project - M. Östling, M. Lemme, H. Radamson

- scalable
- modest temperatures ($< 1000^\circ\text{C}$)
- Silicon Technology compatible

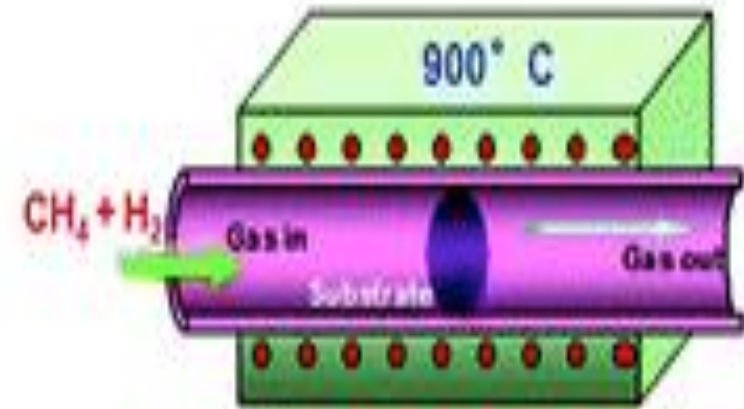


Source: Infineon

Graphene Fabrication Methods: CVD

Chemical Vapor Deposition (CVD)

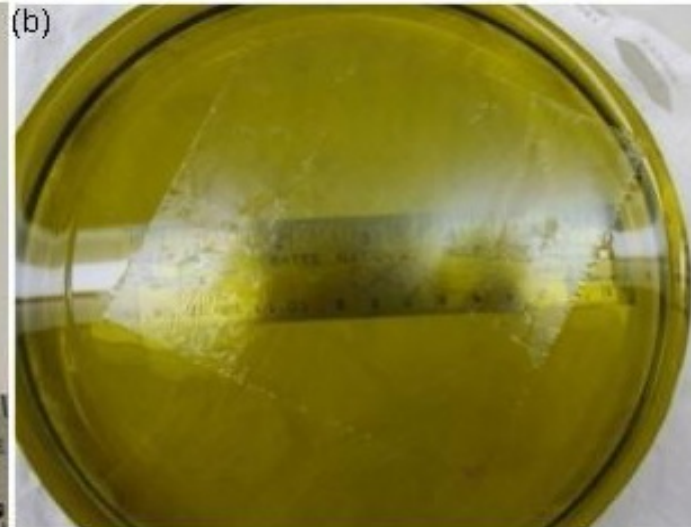
- CVD on Nickel, Copper, etc.
- High potential for large areas
- Graphene transfer to random substrates
- Monolayers vs. Multilayers?



Graphene on Copper ->

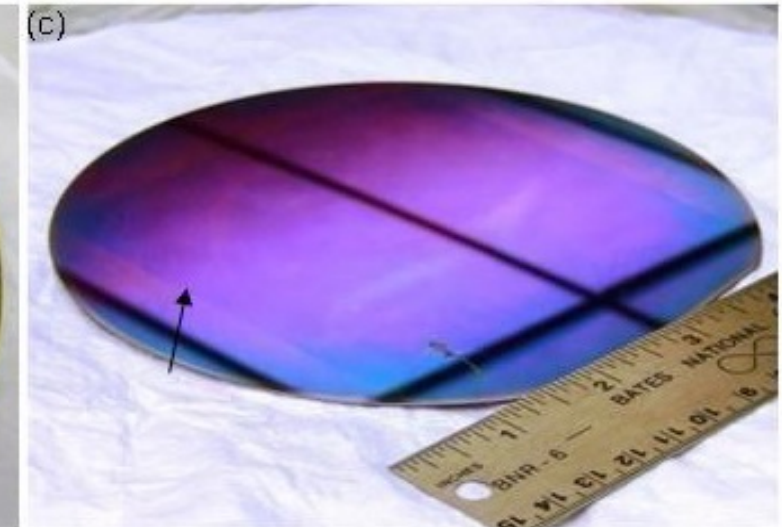


PMMA



->

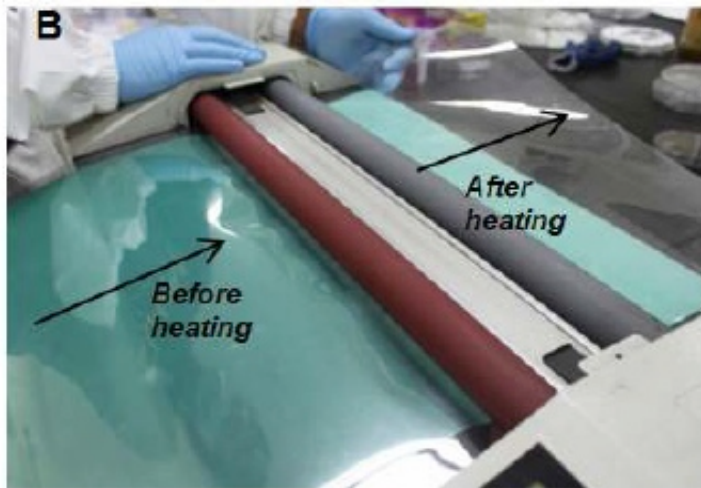
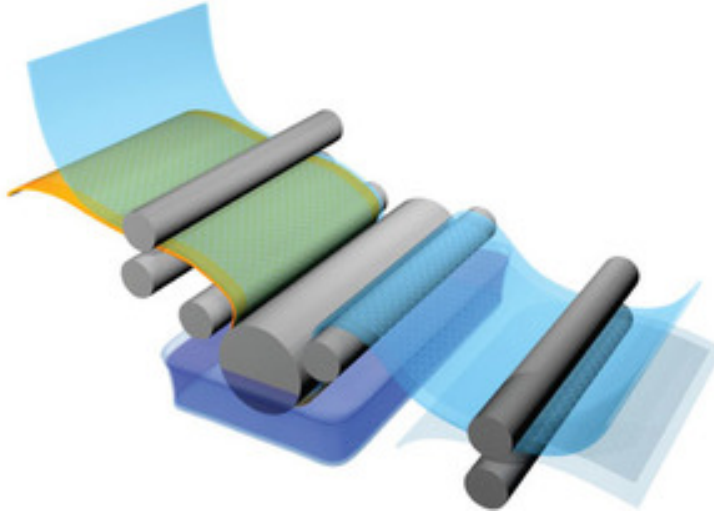
Silicon



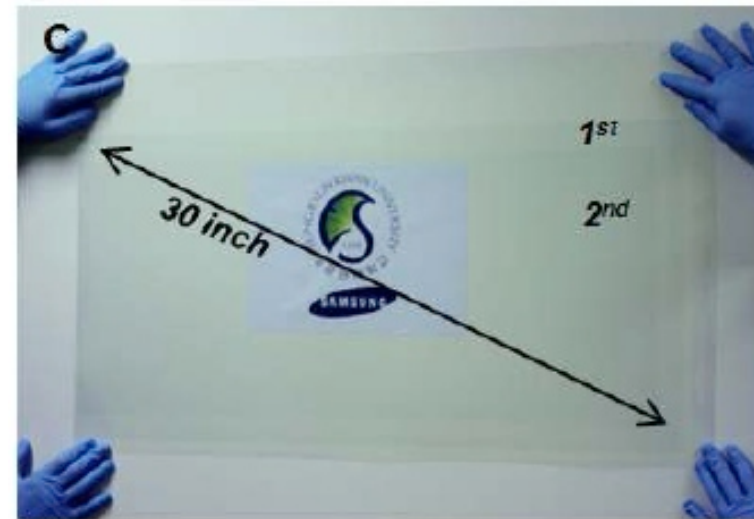
Cao et al, Applied Physics Letters 96, 122106 (2010)

Graphene Fabrication Methods: CVD

Roll-to-Roll Production



Bae et al. Nature Nanotech (2010)



In Europe: GRAFOL - Graphene Chemical Vapour Deposition: Roll to Roll Technology

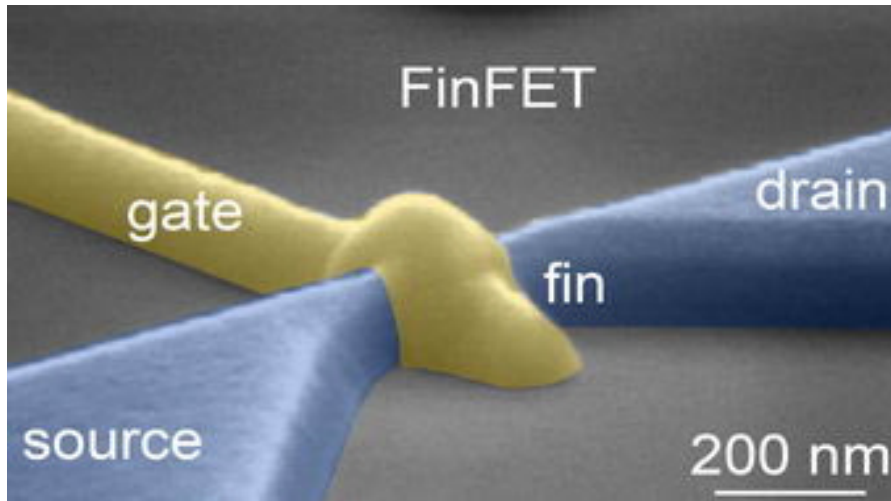
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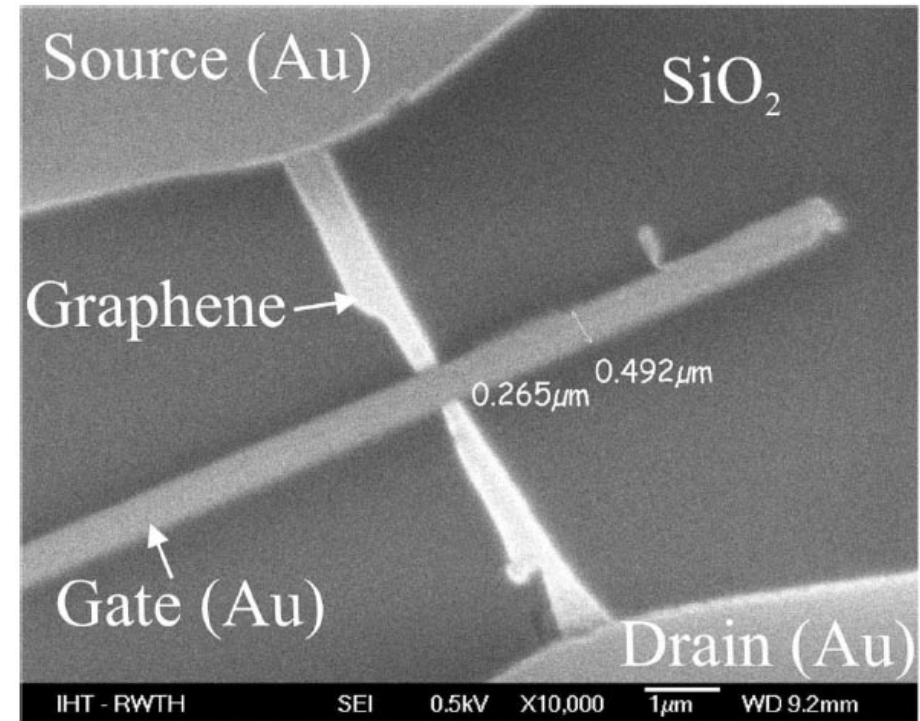
Graphene Transistors: Technology

Silicon MOSFET



Source: TU Delft

Graphene MOSFET



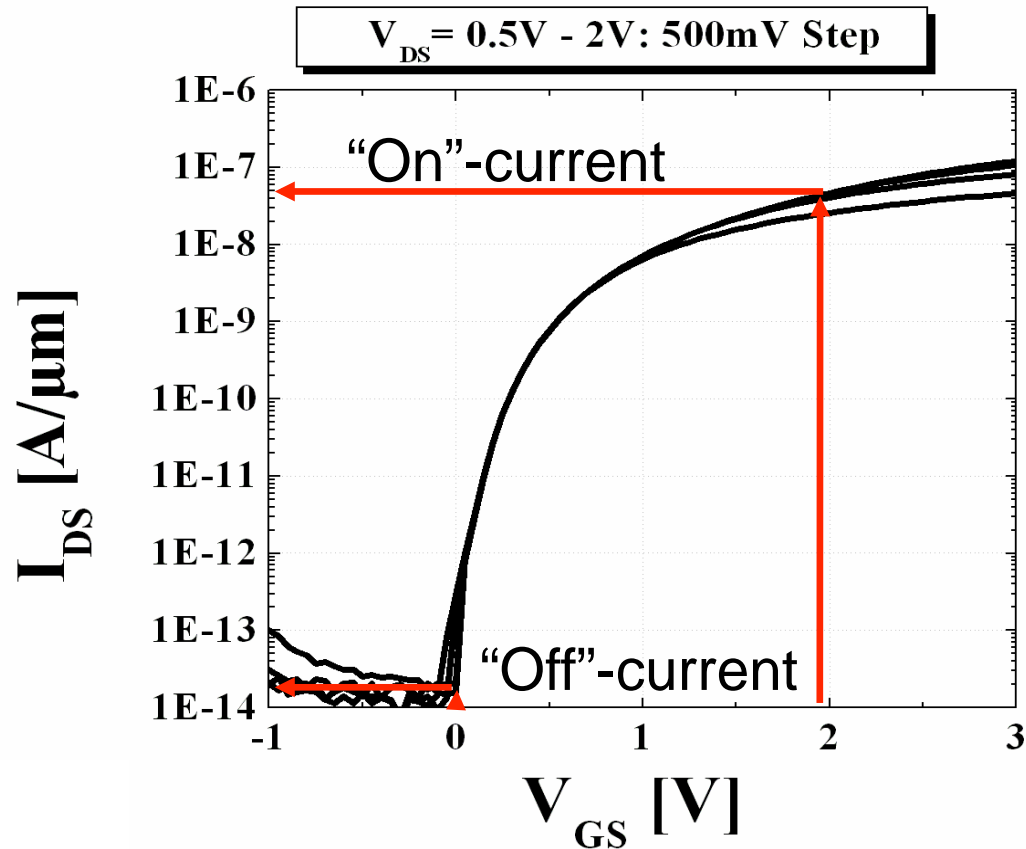
Lemme et al. "A Graphene Field Effect Device", IEEE Electr. Dev. Lett. 28(4), 2007.

Graphene Transistors:

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

Graphene Transistors (GFETs)

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 $\sim I_{on} \sim \mu_{eff}$ (carrier mobility)

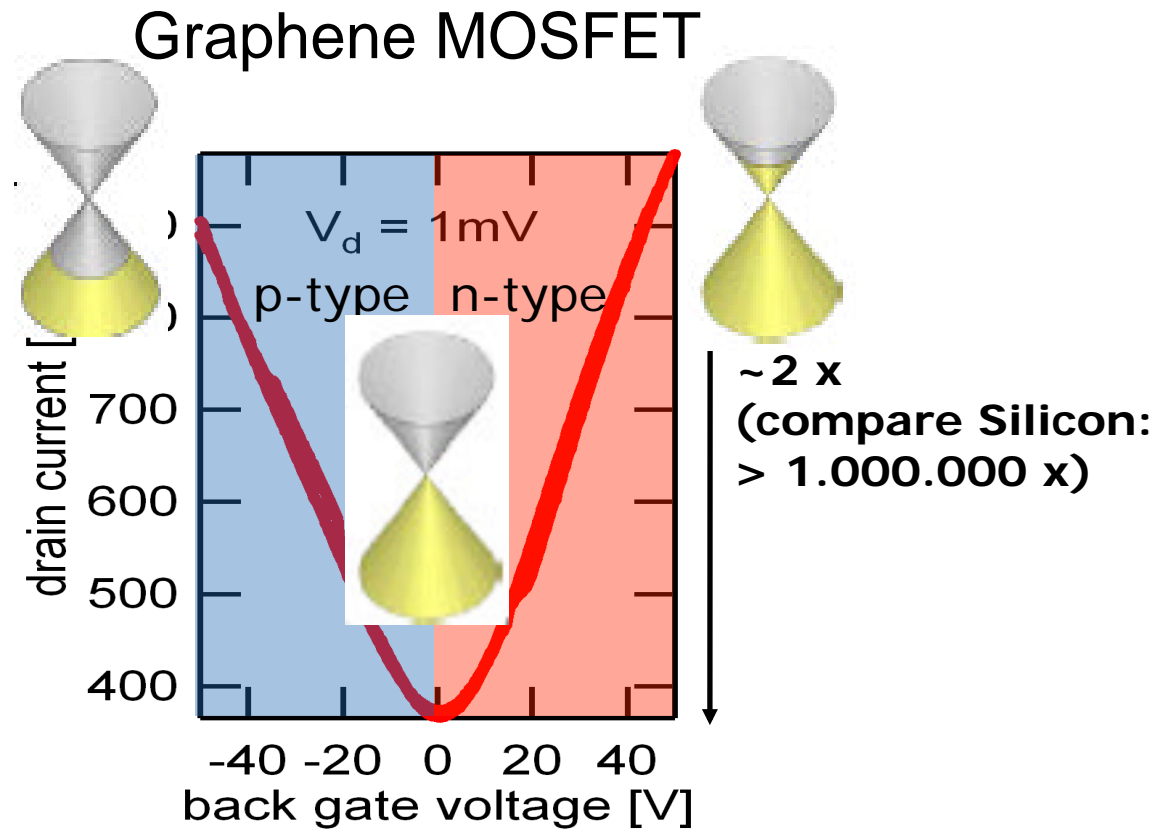
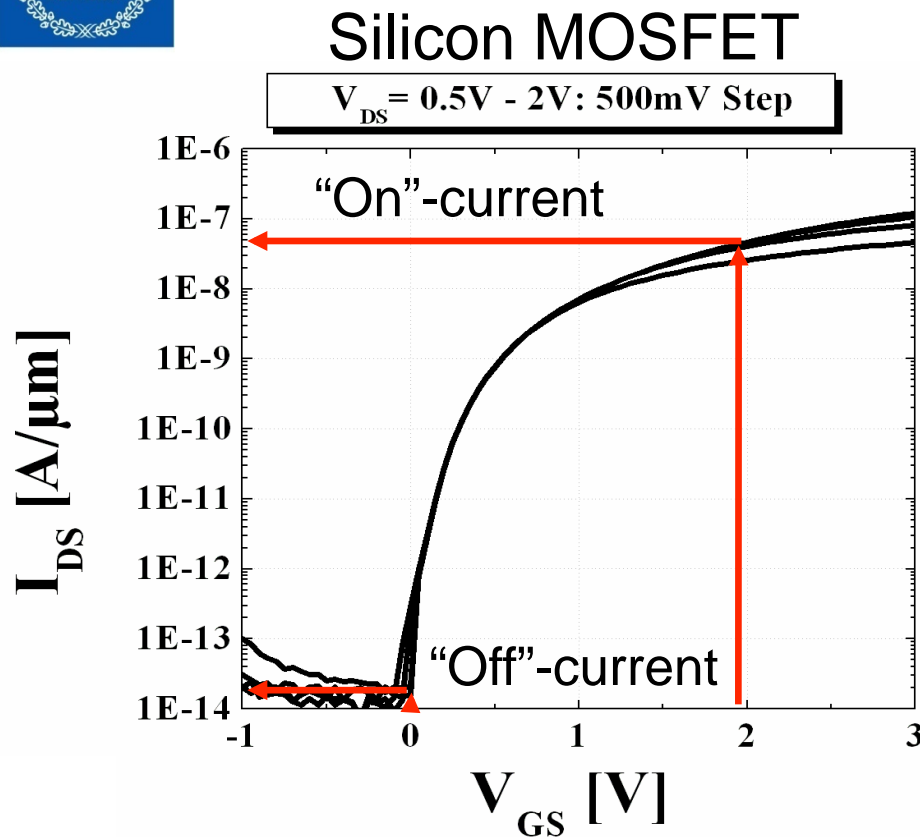
μ - Silicon: 100-450 cm^2/Vs

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



Graphene MOSFET!?

Graphene Transistors: Transfer Characteristics



Graphene Transistors:

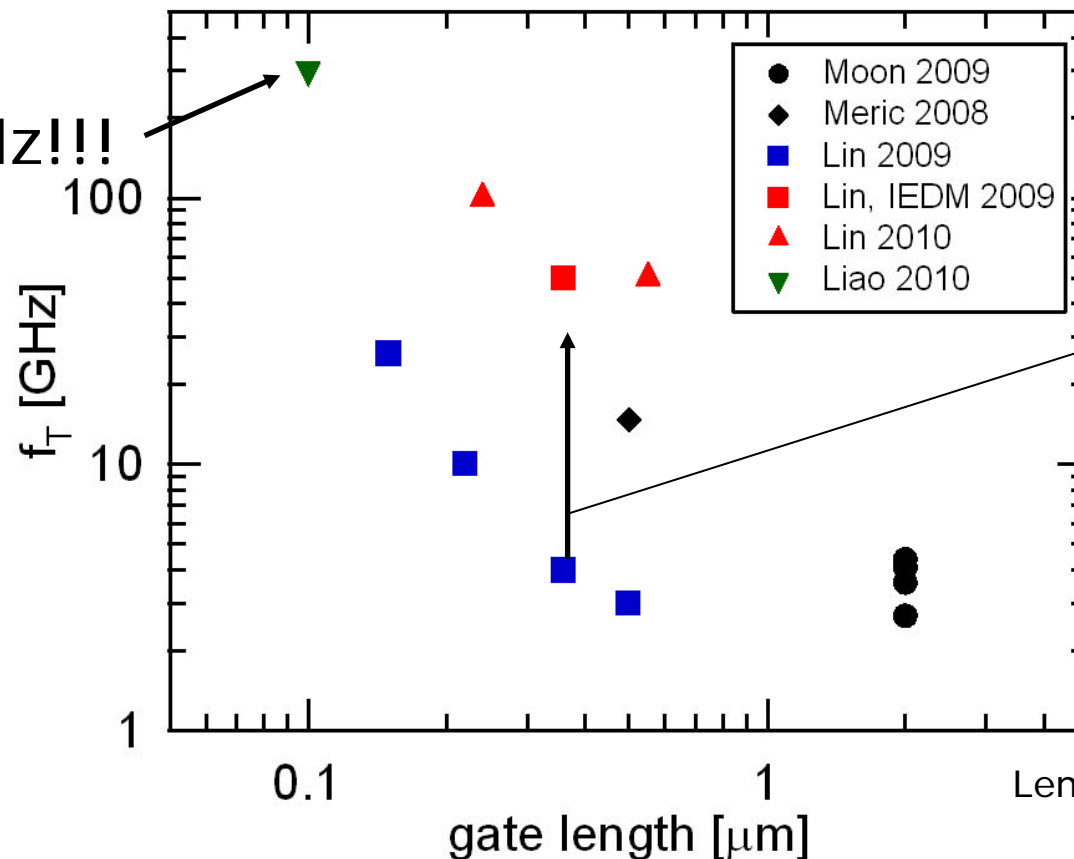
- Ambipolar behaviour (n- und p-type conduction)
- I_{on}/I_{off} ratio inherently limited by band structure (semimetal)
- NOT a direct replacement for Silicon logic, BUT...
- ... Higher functionality devices (e.g. frequency multipliers – Palacios Group)
- ... High speed analog transistors

RF Graphene Transistors

- Exploiting high carrier mobility / velocity
- High on/off ratio not required

Development of cut-off frequency f_T (12/2008-09/2010)

Today: 300 GHz!!!




Improvement due to interface engineering

Lemme, Sol. St. Phenom., 2010

Performance Projections

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

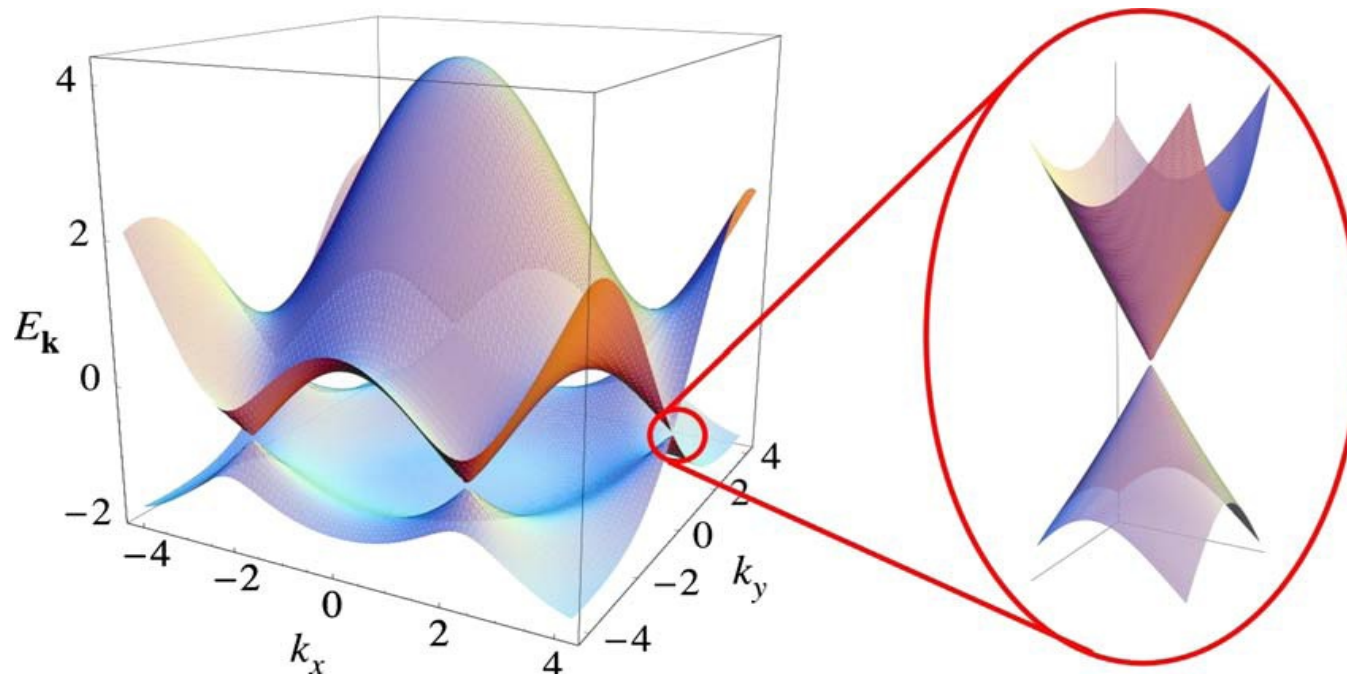
Rodriguez et al., arxiv 2011

- 
- THz operation seems feasible for high mobility graphene
 - Graphene/insulator interface engineering
 - High quality CVD (or other) growth technique

Graphene – Devices and Technology

Outline

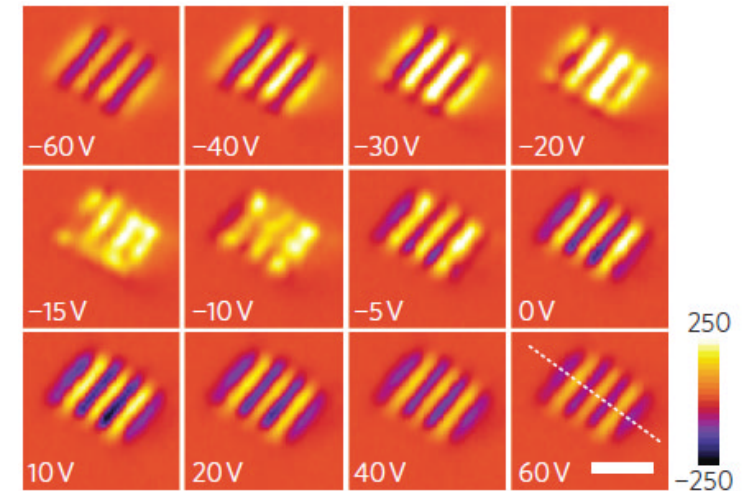
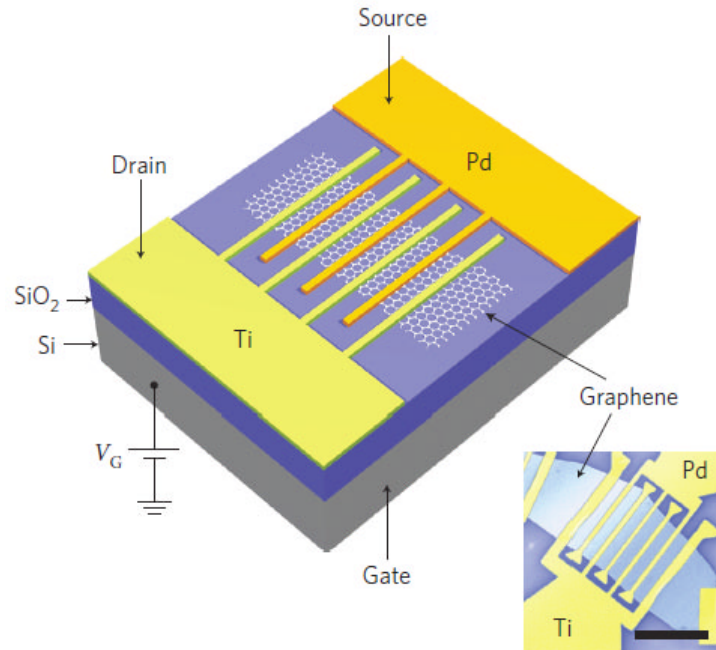
- Introduction
- Graphene Fabrication
- Graphene-based Electronic Devices
- Applications beyond "Moore's Law"
 - Photodetection
- Summary



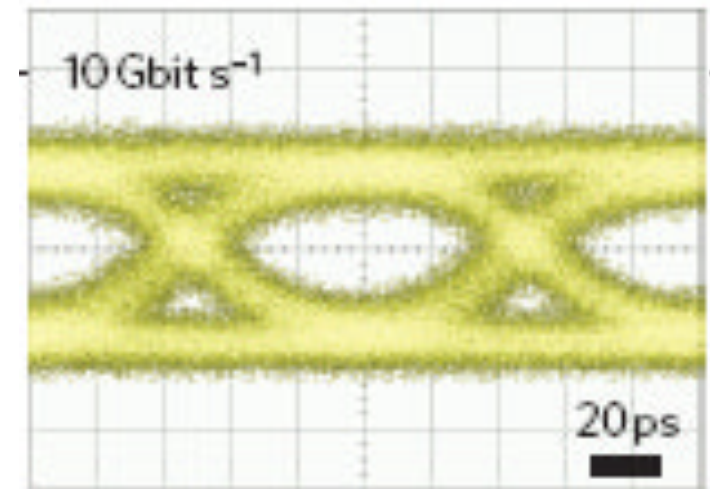
- E-k linear up to ± 1 eV
- Potential from visible spectrum to THz
- High data rates

Graphene photodetectors for high-speed optical communications

Mueller et al., Nat. Photonics 2010

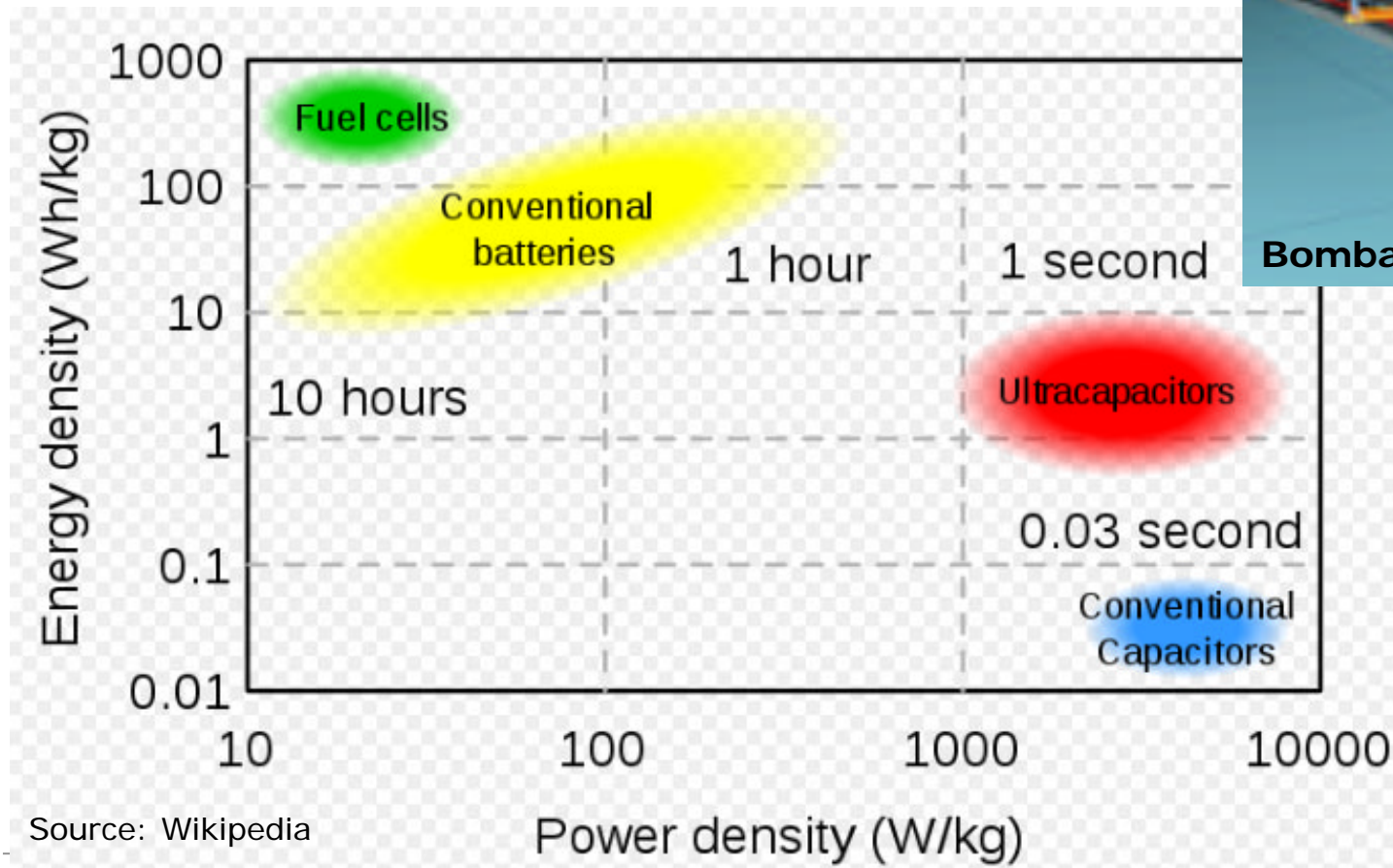


- Metal – graphene interface induces pn-junction
- Control through back gate (substrate)
- Graphene "Eye Diagram"
- Error free optical data transmission at 10 Gbit/s



Graphene Supercapacitors for Energy Storage

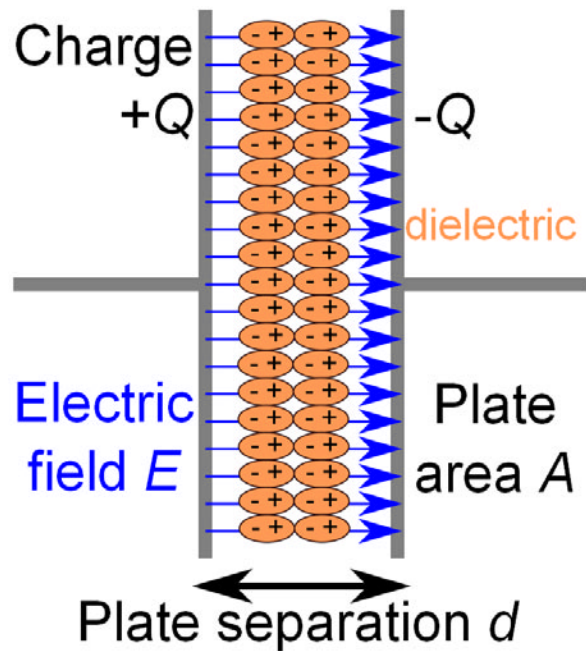
Ragone Plot



Graphene Supercapacitors for Energy Storage

Capacitor

Direct Energy Storage Non-Faradaic Process

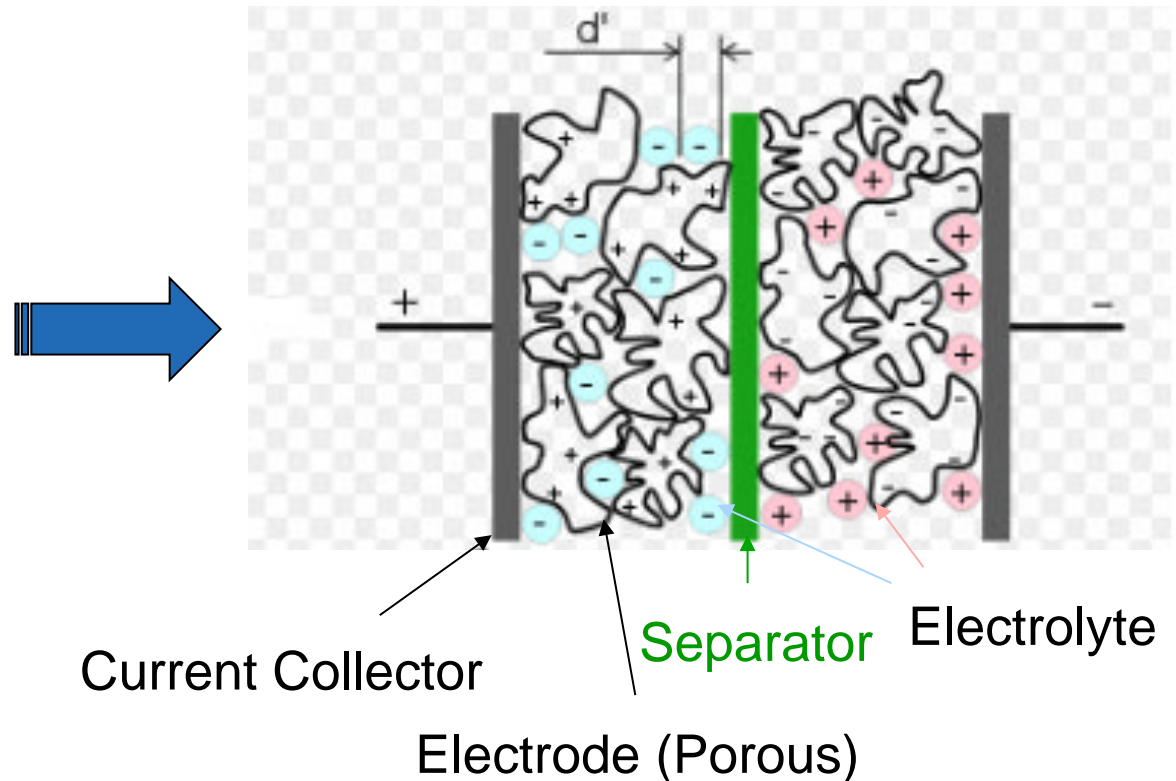


$$C = \frac{\epsilon_r \epsilon_0 A}{d}$$

Supercapacitor, Ultracapacitor

Electrochemical Double Layer Capacitor

High surface area (!)



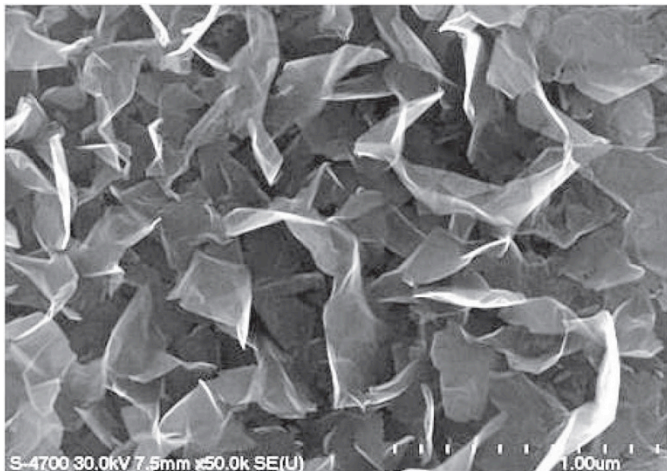
Source: Wikipedia

Graphene Supercapacitors for Energy Storage

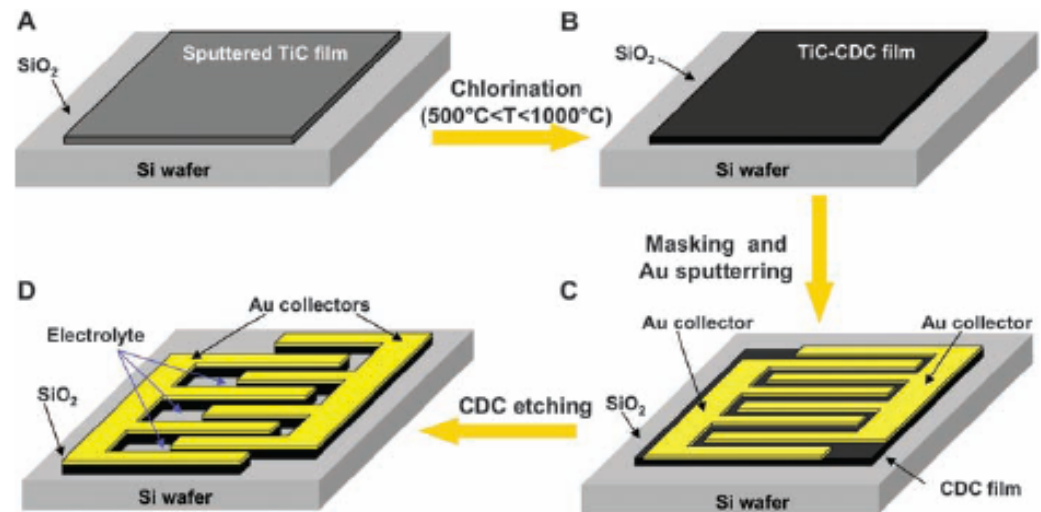
Graphene:

- comparable surface to volume ratio with porous carbon
- 10^4 - 10^5 higher conductivity

Microelectronic Integration of Supercapacitors



Graphene-based Supercapacitor,
Science 329, 1637 (2010)

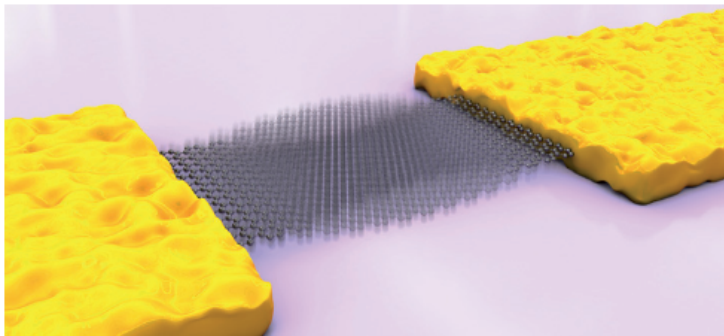
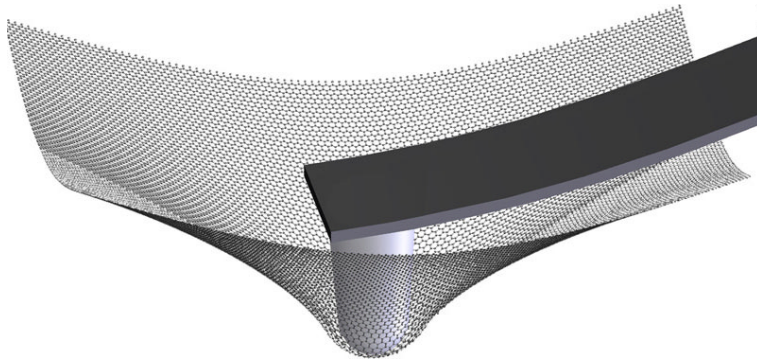


Chmiola et al., "Monolithic Carbide-Derived Carbon Films for Micro-Supercapacitors", Science **328**, 480 (2010)

Graphene Nanomechanics

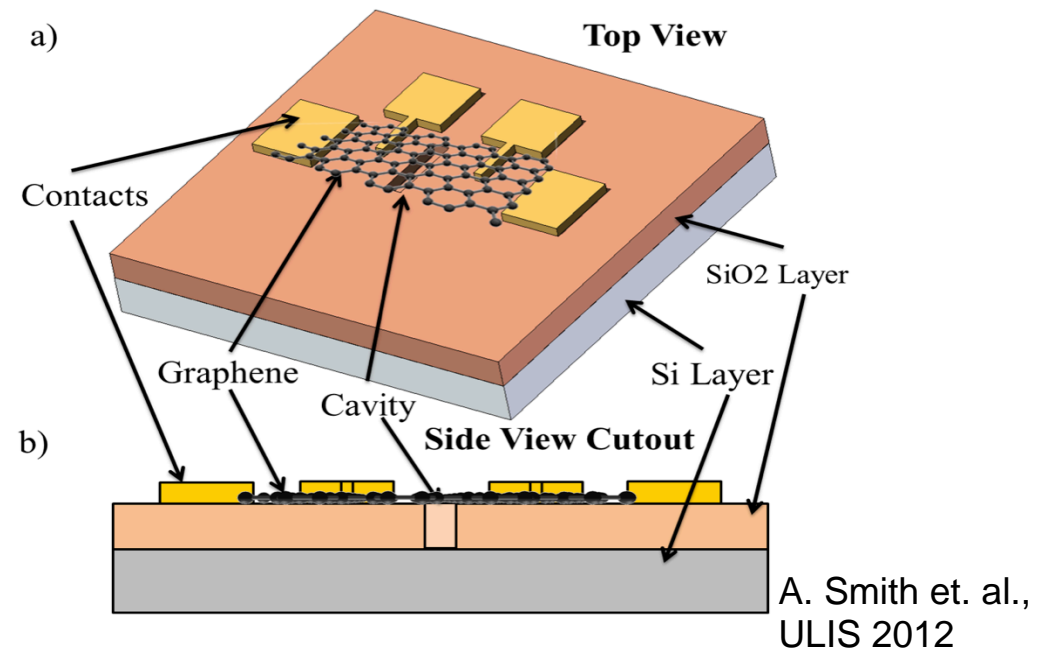
NEMS

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



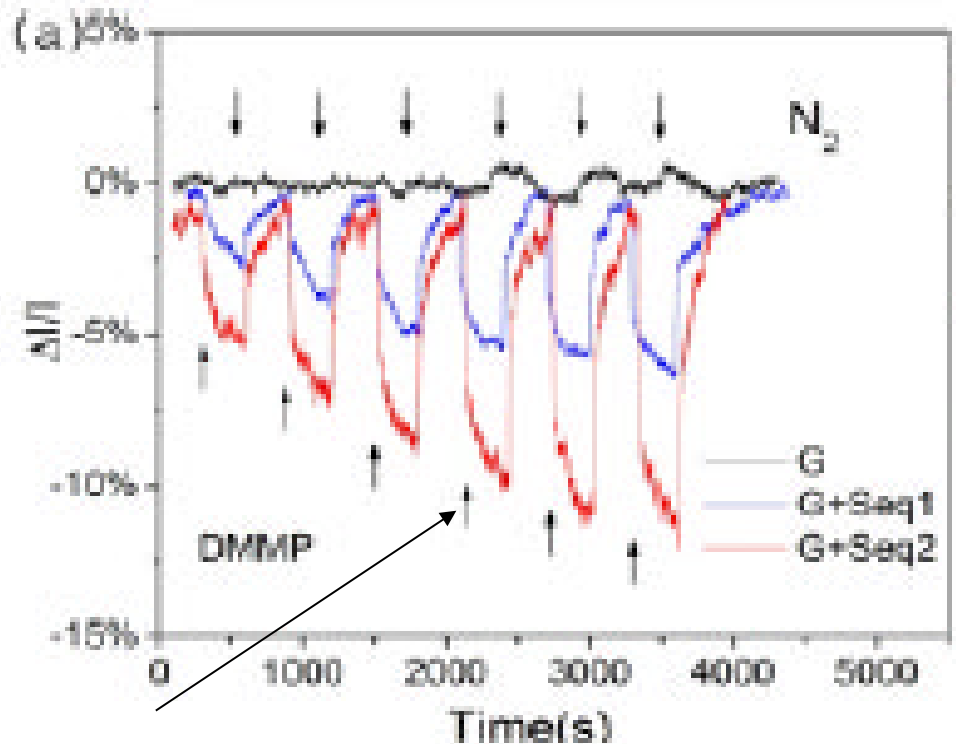
Source: A. Bachtold

- Young's modulus: ~ 1.10 TPa (Si ~ 130 GPa)
- Elastically stretchable by 20%
- High mechanical stability
- "strongest material known"
- Flexible
- Low mass



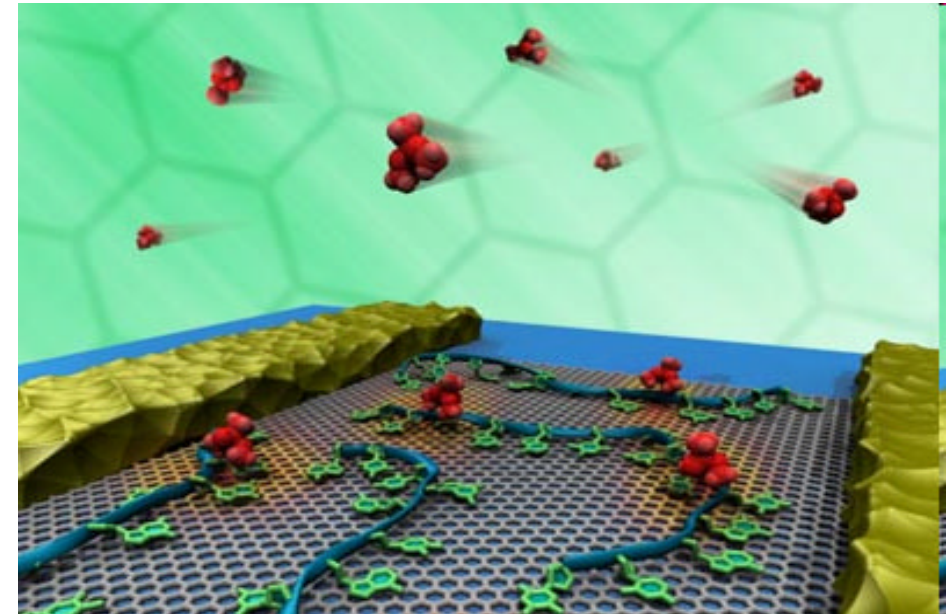
Graphene based mass, force, pressure sensors

DNA decorated graphene chemical sensors



Introduction of analyte at progressively larger concentrations

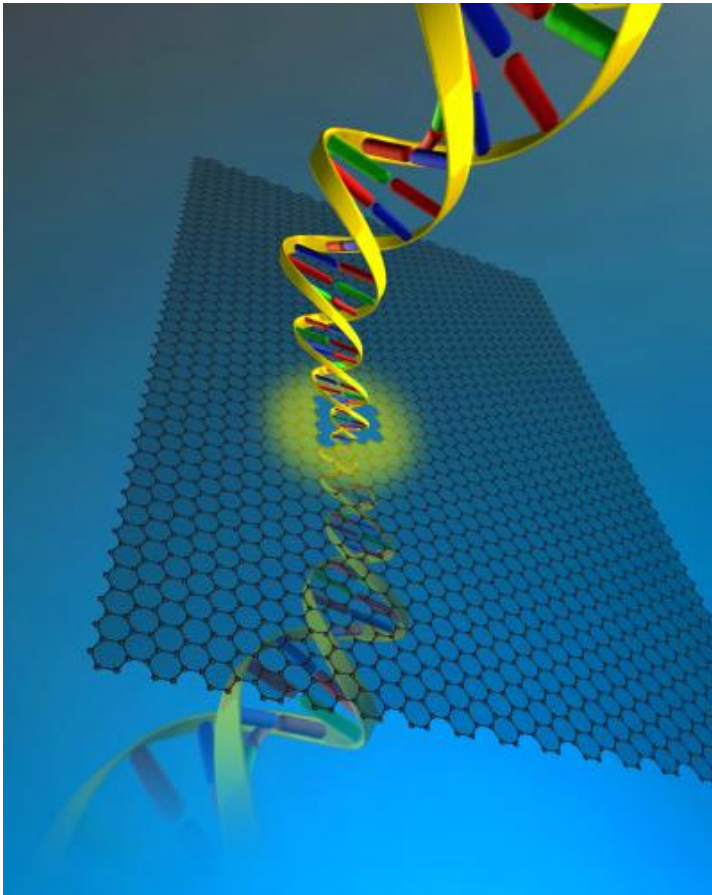
Lu et al., Appl. Phys. Lett. 97, 083107 (2010)



Source: Robert Johnson, Temple University

- Clean graphene devices show very weak vapor response
- Devices functionalized (red & blue data) show significant sequence-dependent responses

DNA sequencing using nanopores in graphene

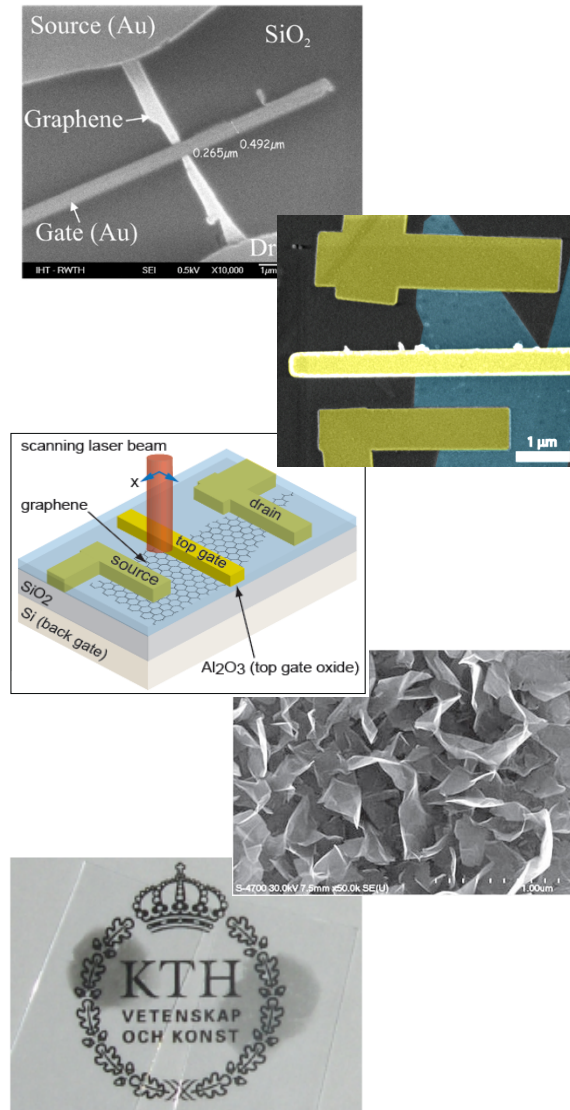


Jene Golovchenko, Harvard University.

Why graphene?

- High mechanical strength
- High electric conductivity
- Ultimately thin

- Graphene is a “Serious” Electronic Material
- Large Area Manufacturing Available
- Electronic Applications
 - Analog Transistors
 - Optoelectronics
 - Printable Electronics
 - Supercapacitors
 - Transparent Electrodes
 - Interconnects
 - Passives, Antennas



- **NEMS**
- **Mechanical Applications (Space Elevator)**
- **Sensors (Functionalized Surfaces, Biocompatibility)**
- **Resistive Switching (Memory Applications)**
- **Ballistic Devices**
- **Spintronics (Spin-Valves, SpinMOSFET, SpinFET)**
- **...other 2D Materials (h-BN, MoS2...)**

Graphene – Enabling New Gadgets?

Smart Monitoring



Wearable Electronics



Body Sensors



Guardian Angels
for a smarter life

- > 24 Universities, research institutions & industry
- Energy Harvesting
- Wireless Sensor Networks
- Health, Safety and Environmental monitoring
- Bid for 10 year, 1 billion EUR flagship project
- <http://www.ga-project.eu>