Potential Applications for Graphene Devices in Nanoelectronics

Max Lemme

KTH Royal Institute of Technology
School of Information and Communication Technology
lemme@kth.se

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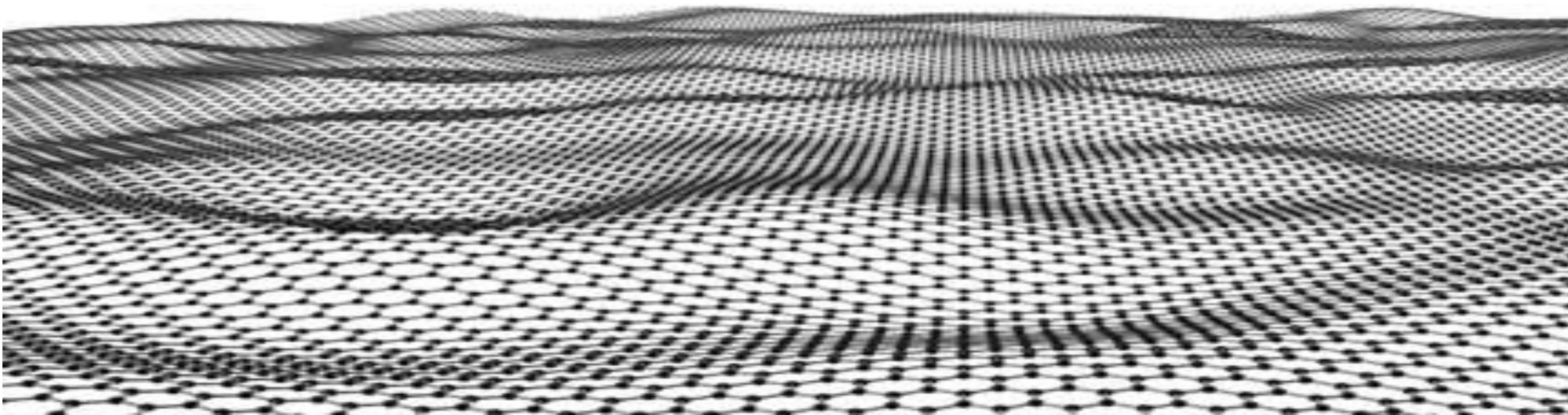

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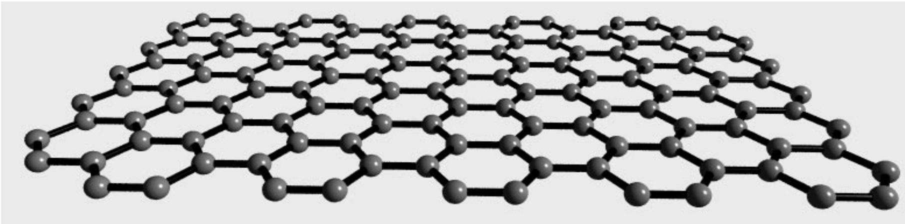
Outline

- Introduction
- Graphene Fabrication
- Graphene-based Electronic Devices
- Applications beyond ”Moore’s Law”
- Summary

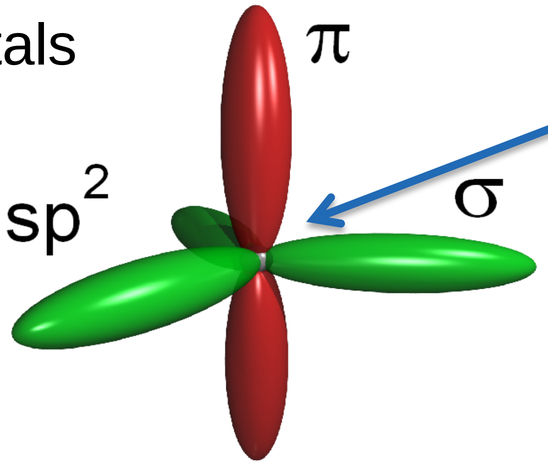
Graphene: Crystal Properties

Graphene

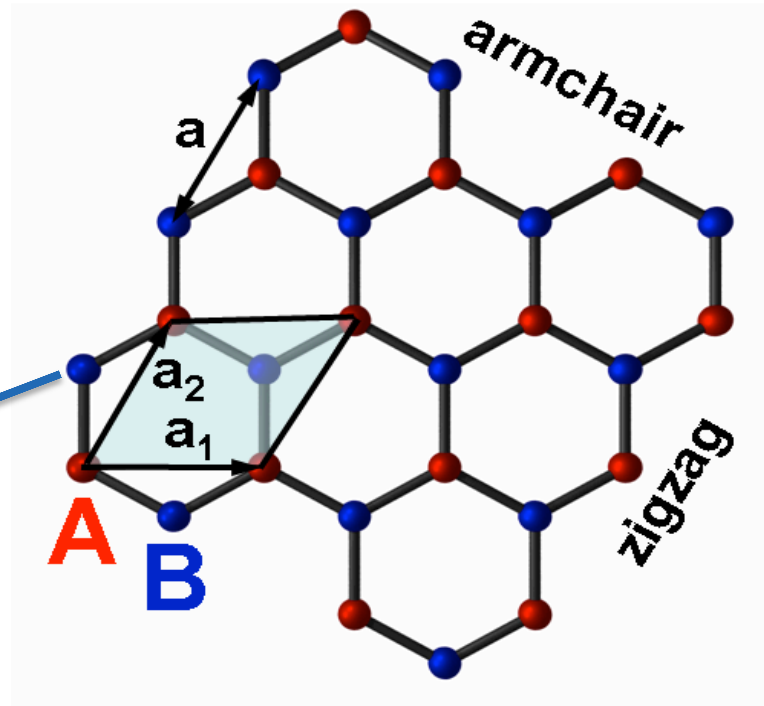


sp² bonded carbon atoms (~4,3eV)

Orbitals



2D-crystal lattice

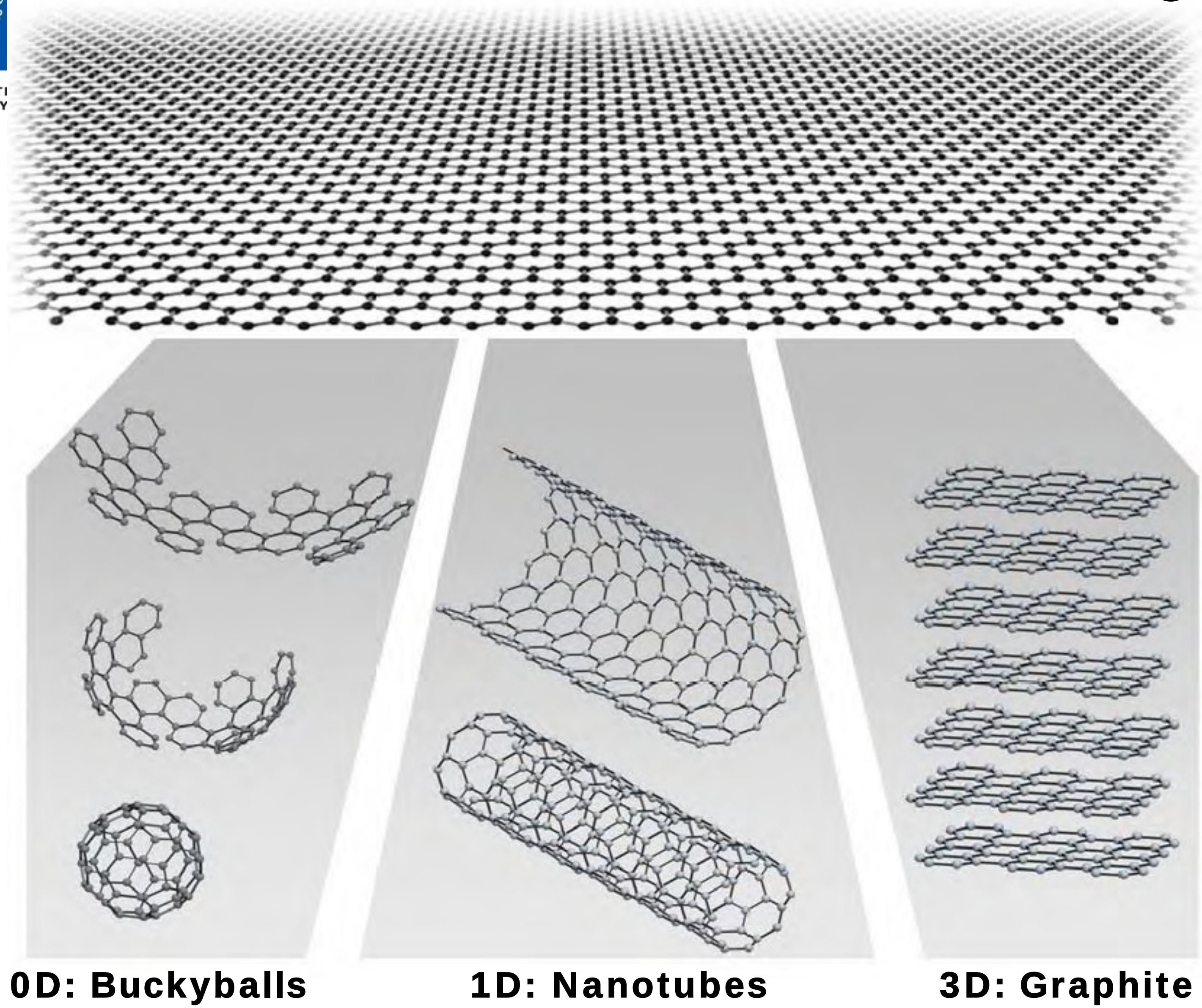


Sublattice constant: a = 0.246 nm

"Thickness": d = 0.34 nm

Lemme, Sol. St. Phenom., 2010

“The mother of all graphitic forms”



2D: Graphene

Only one atom thick!

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

Nature Mater. 6., 183, 2007

Exceptional Properties (1/2)

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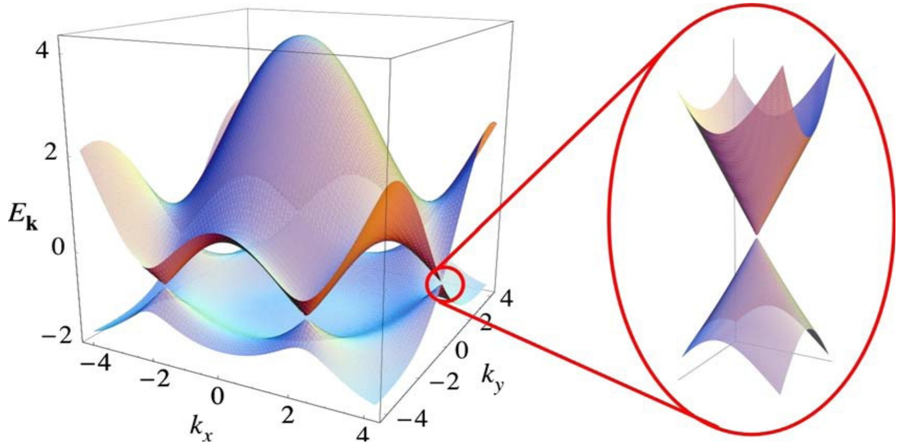
Electronic properties



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
  - $J > 10^8 A/cm^2$
- Velocity saturation
  - $v_{sat} = 5 \times 10^7$ cm/s (10 x Si, 2 x GaAs)

Exceptional Properties (2 / 2)

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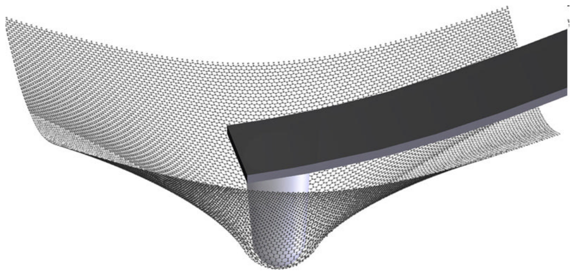
Mechanical properties

- 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

Graphene: Nanolandscapes

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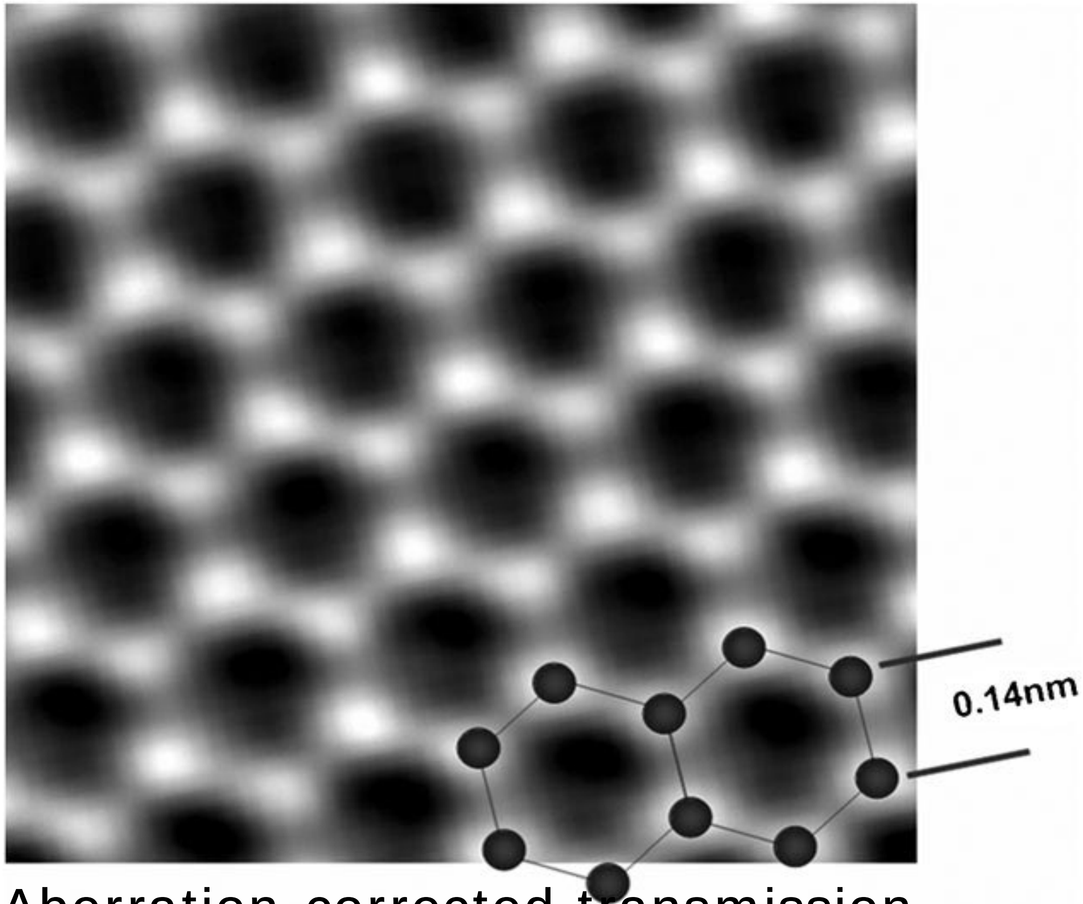
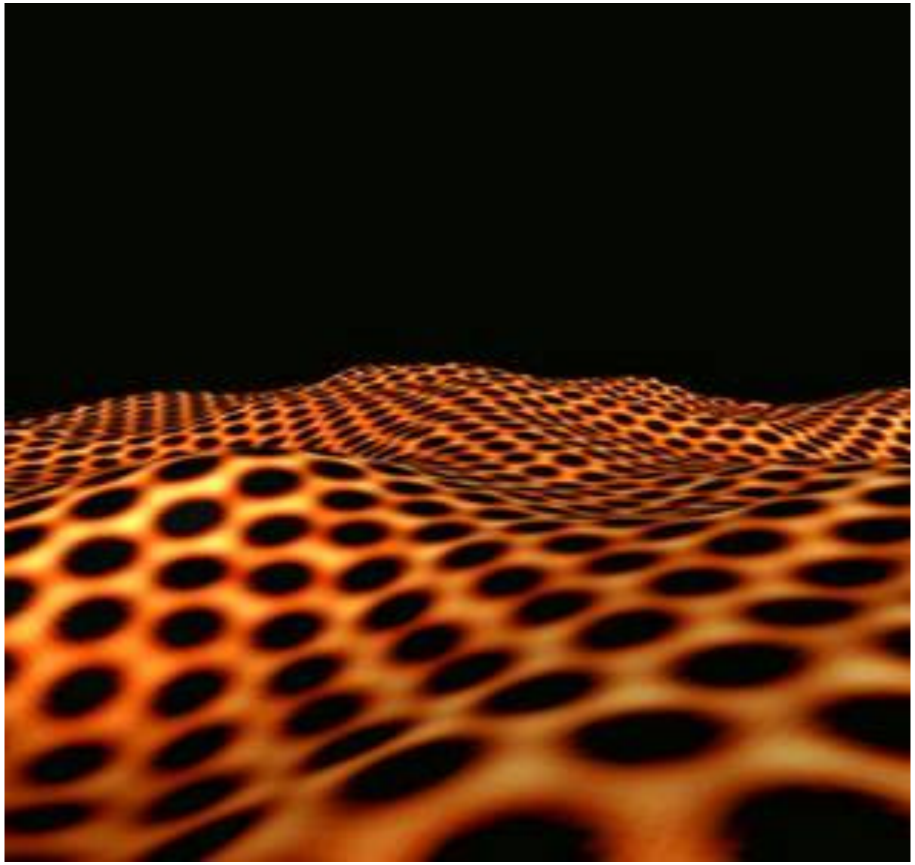
Graphene by HRTEM...



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

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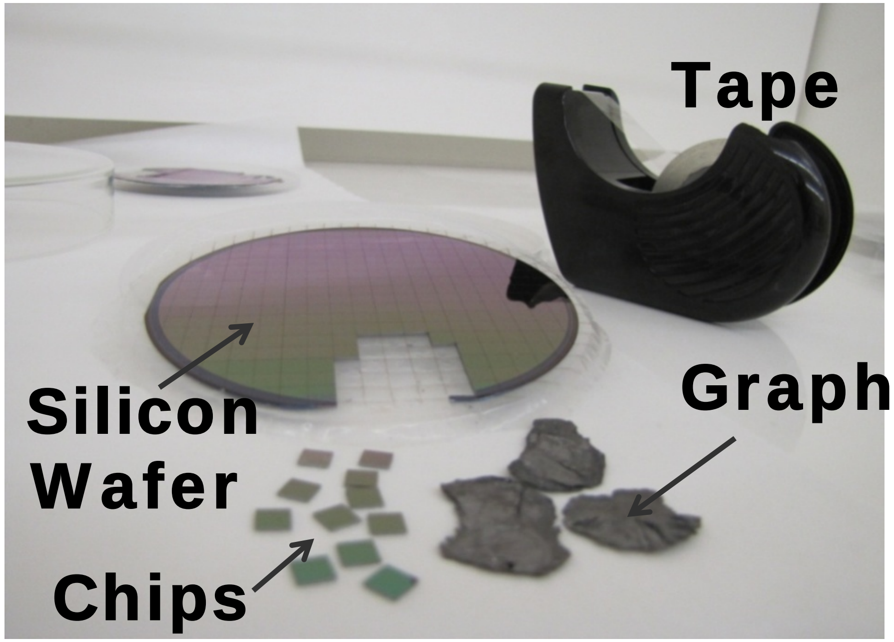
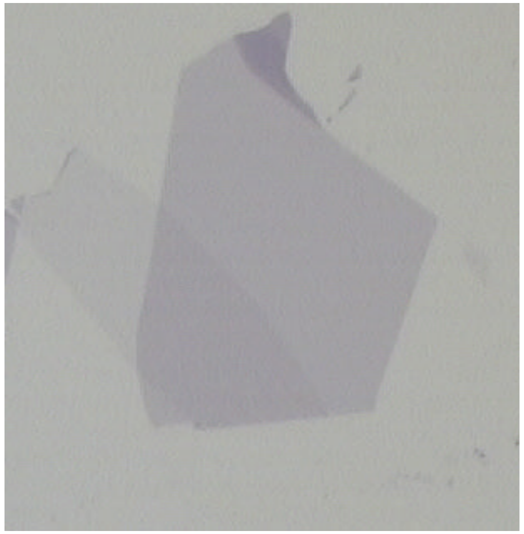
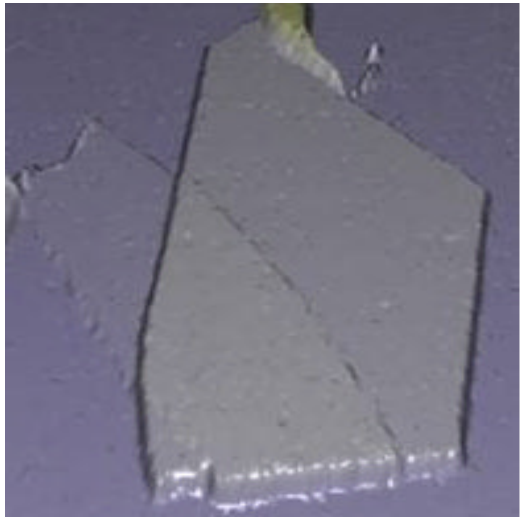
Graphene Fabrication Methods: Exfoliation

Exfoliation with adhesive tape



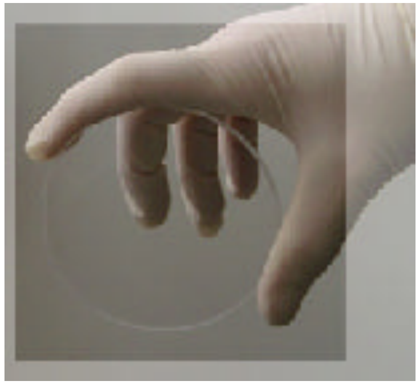




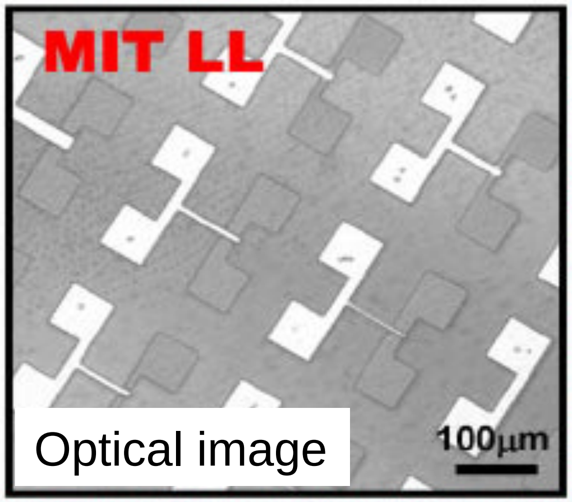
- Novoselov et al., Science 306, 666 (2004)
- flake size: 5 – 100 μm
- random location
- simple process for proof-of-concept
- ***no industrial relevance***

Graphene Fabrication Methods: Epitaxy

Thermal decomposition of SiC (epitaxial graphene)



- Berger et al., J. Phys. Chem. B 108, 2004
- limited scalability
- high temperatures (~1500°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

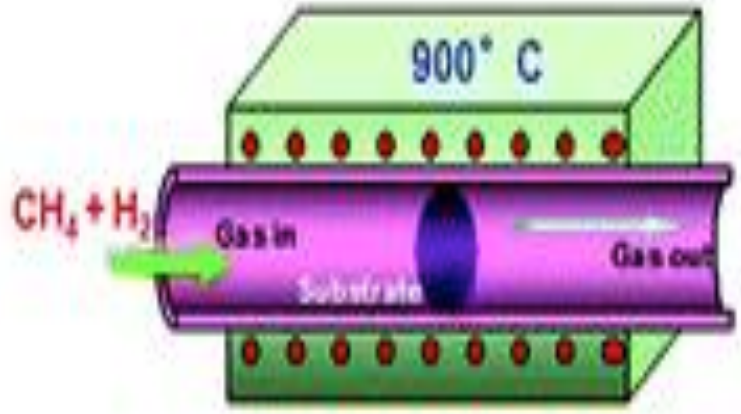
- scalable
- modest temperatures (<1000°C)
- Silicon Technology compatible

Source: Infineon

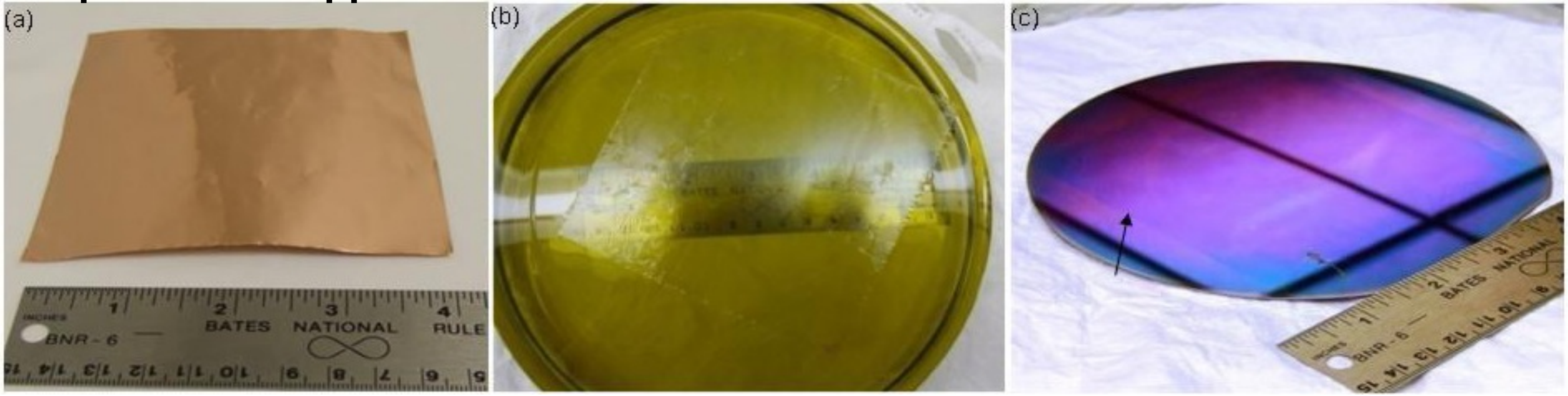
Graphene Fabrication Methods: CVD

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)

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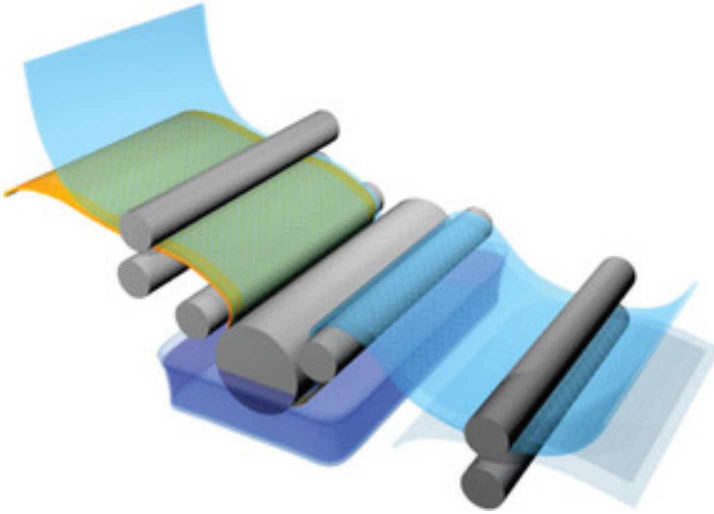
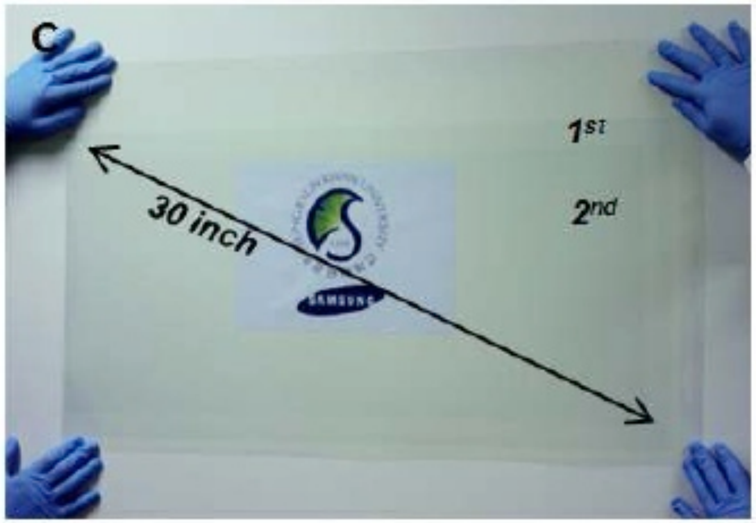
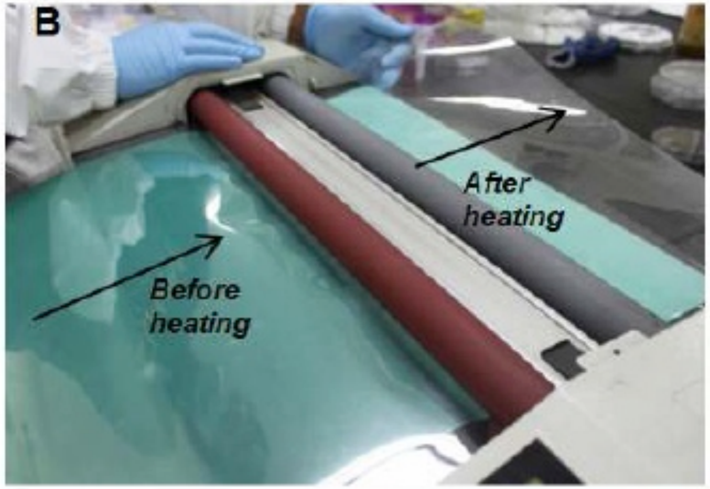
Graphene Fabrication Methods: CVD

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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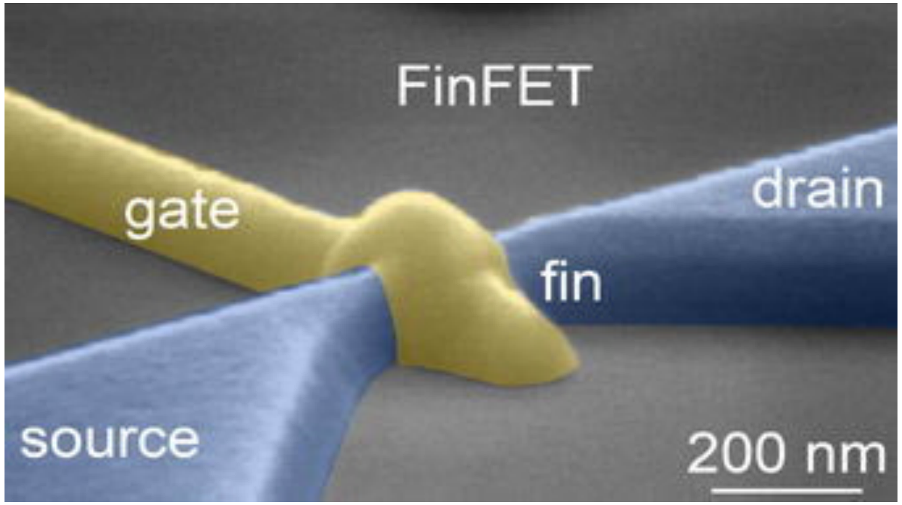
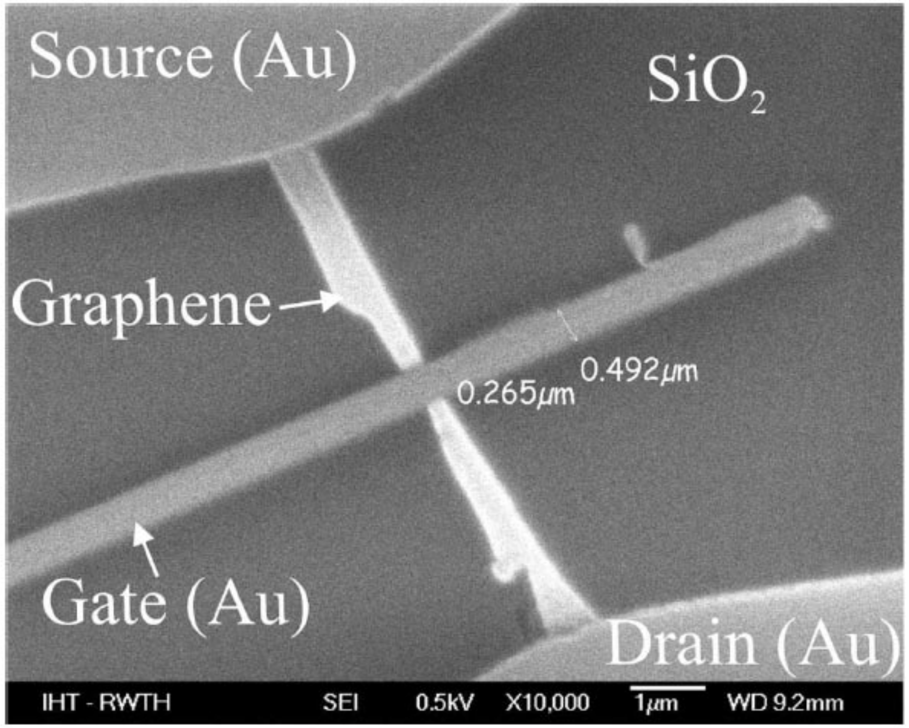
Graphene Transistors: Technology

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!?

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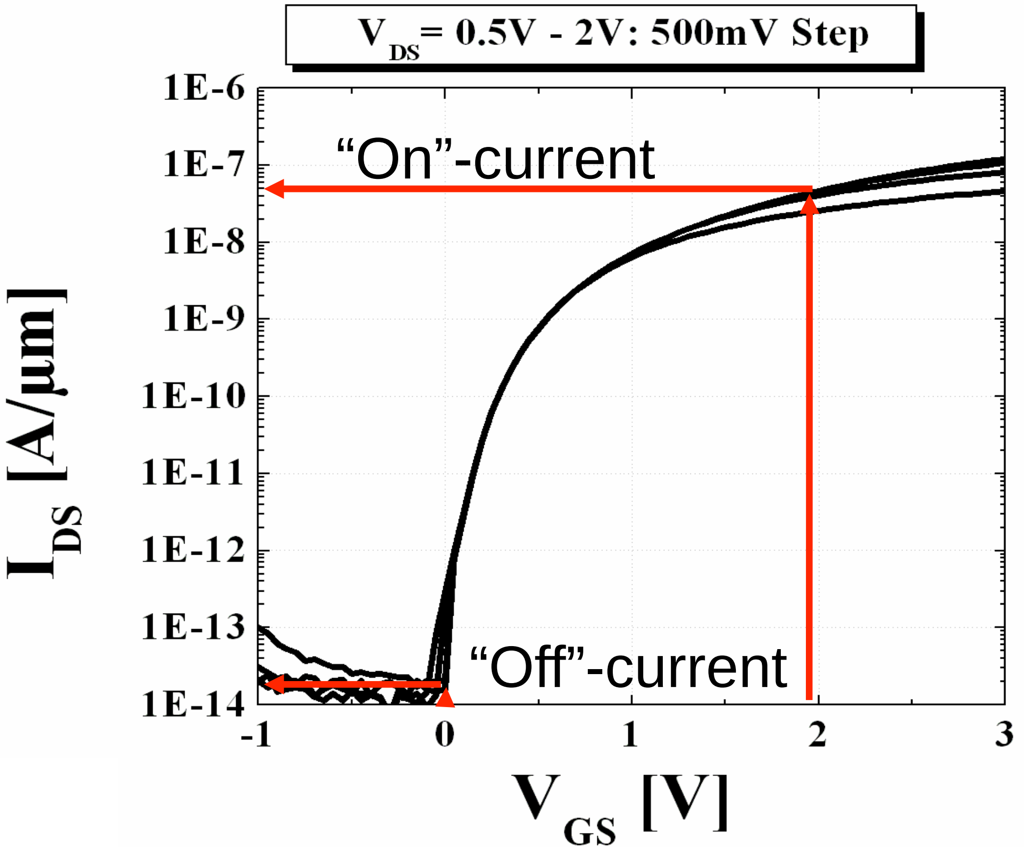
Graphene Transistors (GFETs)

Silicon MOSFET



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

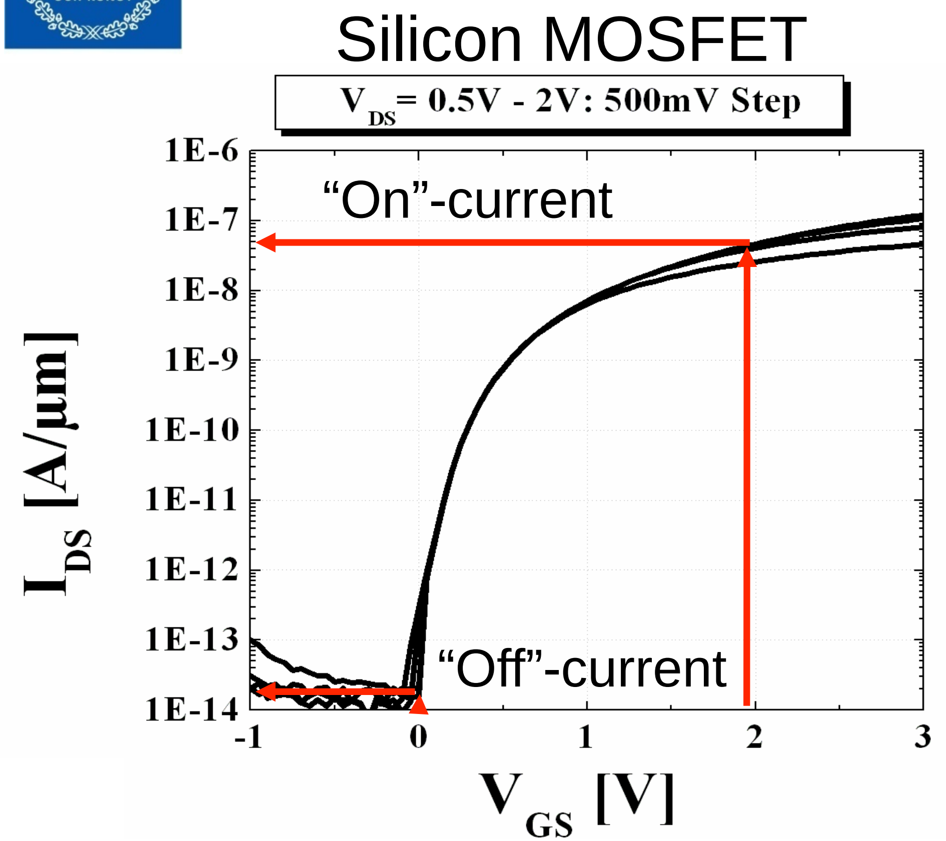
- Highly mature technology
- Billions of devices in parallel
- Near ideal switch
- I_{on}/I_{off} ratio: several decades
- Speed ~ I_{on} ~ μ_{eff} (carrier mobility)

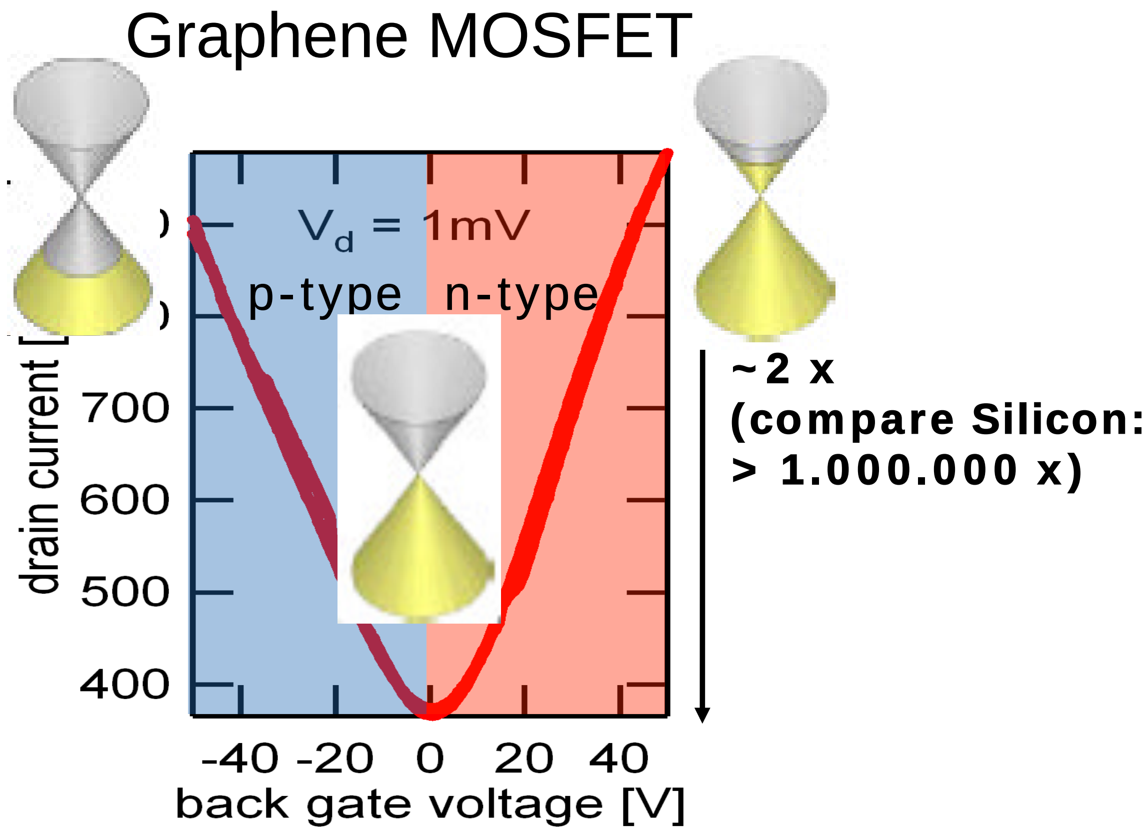
µ - Silicon: 100-450 cm^2/Vs

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

Graphene MOSFET!?

Graphene Transistors: Transfer Characteristics





Graphene Transistors:

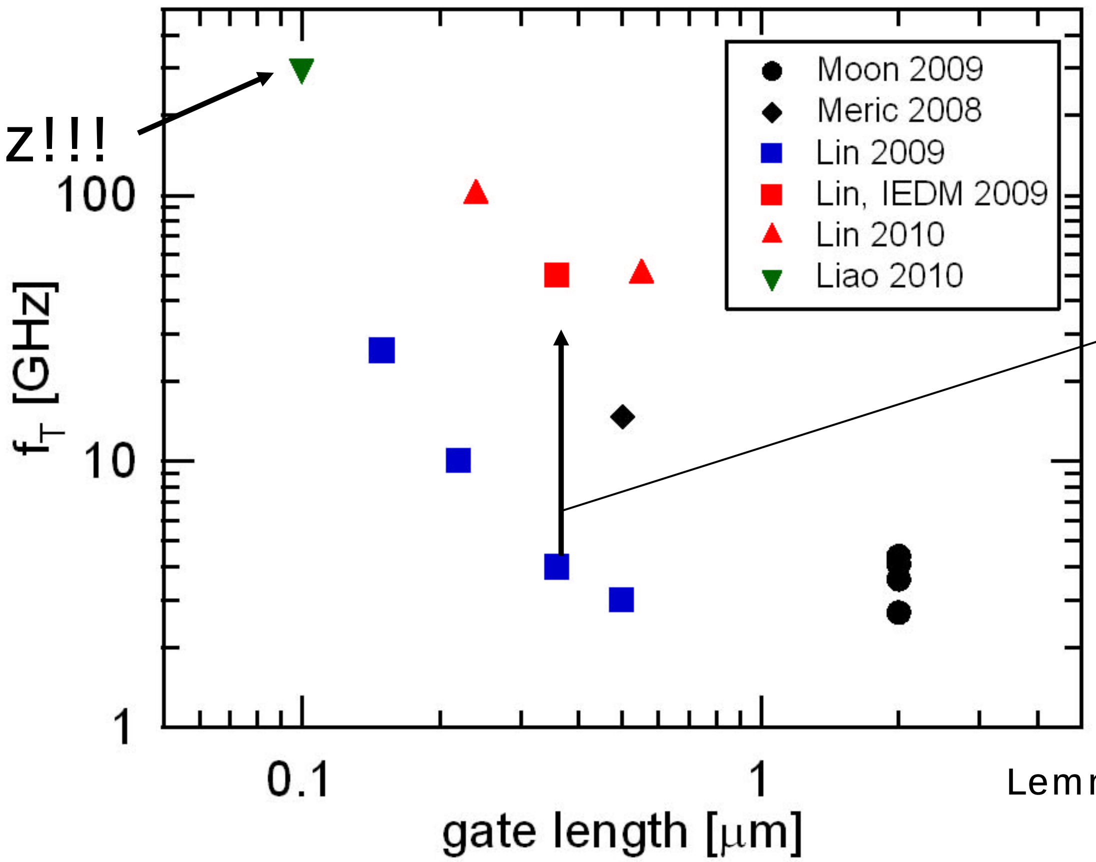
- Ambipolar behaviour (n- und p-type conduction)
- I_{on}/I_{off} ratio inherently limited by band structure (semimetall)
- NOT a direct replacement for Silicon logic, BUT...
- ... Higher functionality devices (e.g. frequency multipliers – Palacios Group)
- ... High speed analog transistors

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

$$F_T = \frac{1}{2\pi}\frac{g_m}{C_G}$$ (C_G includes $C_{t\text{-}ox}$ and C_q)

65nm GFET vs. Si-MOSFET

- $F_{T,MAX}$ of GFET almost as high as Si-CMOS at I_{DS} = 1μA
- Si-CMOS $F_{T,MAX}$ at higher current consumption than GFET $F_{T,MAX}$
- GFETs achieve best performance in rather narrow I_{DS} range
- “Dead zone” for GFET amplifiers
- Bilayer GFETs?

Rodriguez et al., arxiv 2011

Performance Projections

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

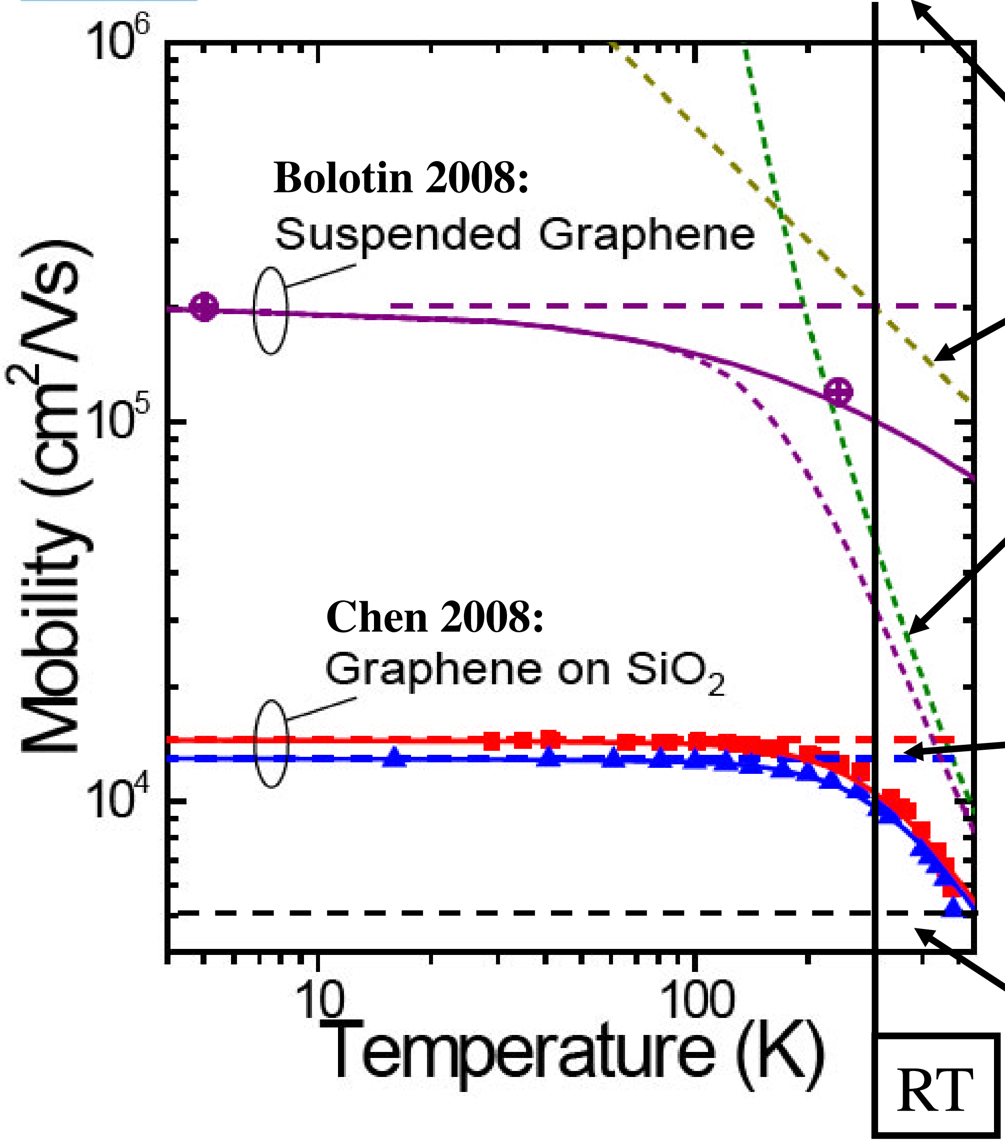
Rodriguez et al., arxiv 2011

- THz operation seems feasible for high mobility graphene

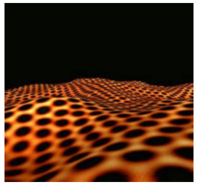
→ Graphene/insulator interface engineering

→ High quality CVD (or other) growth technique

Graphene Transistors: Fundamental Limits



Mobility limited by scattering by:

Corrugations 

Longitudinal Acoustic Phonons
($\mu_{RT,max}$ ~ 200.000 cm^2/Vs)

SiO_2 Surface Phonons
($\mu_{RT,max}$ ~ 40.000 cm^2/Vs)

Charged impurities
($\mu_{RT,max}$ ~ 10.000 cm^2/Vs)
(Oxide, interface, molecules?)

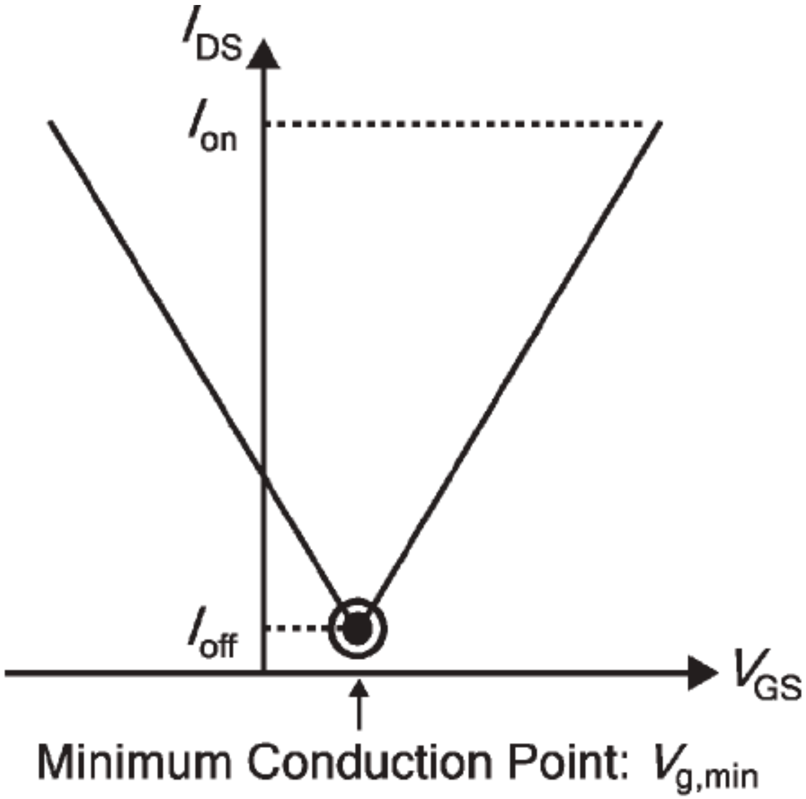
Crystal defects
CVD Graphene!

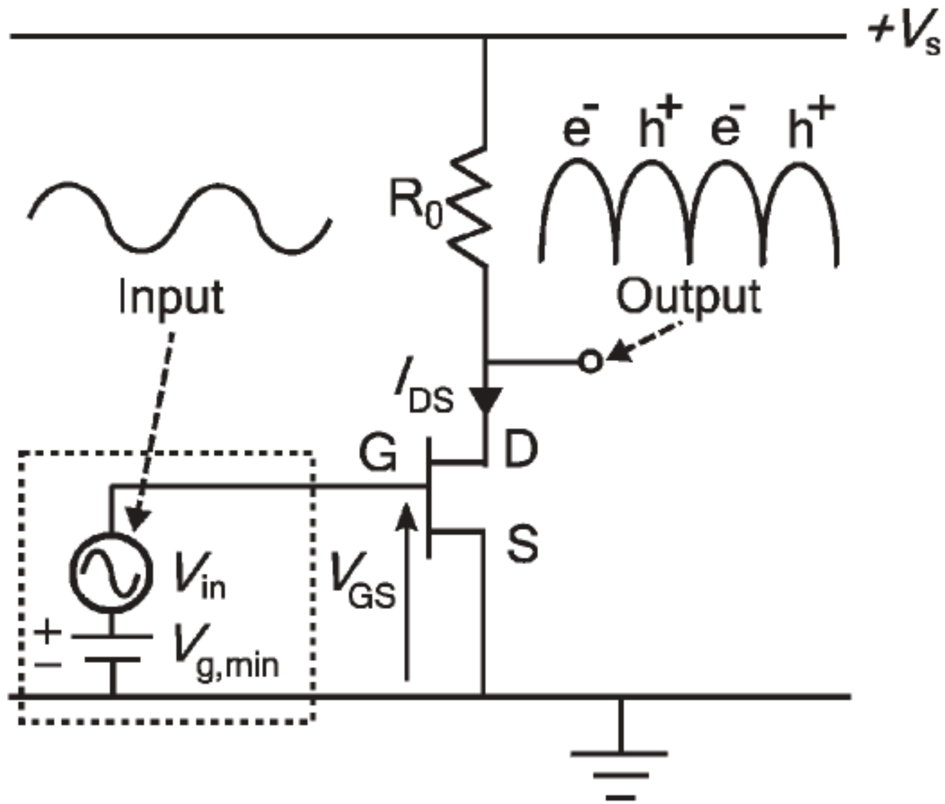
After: Chen et al. Solid State Comm., 2009

Silicon

Graphene: RF Transistors

Unconventional use of unconventional characteristics!?



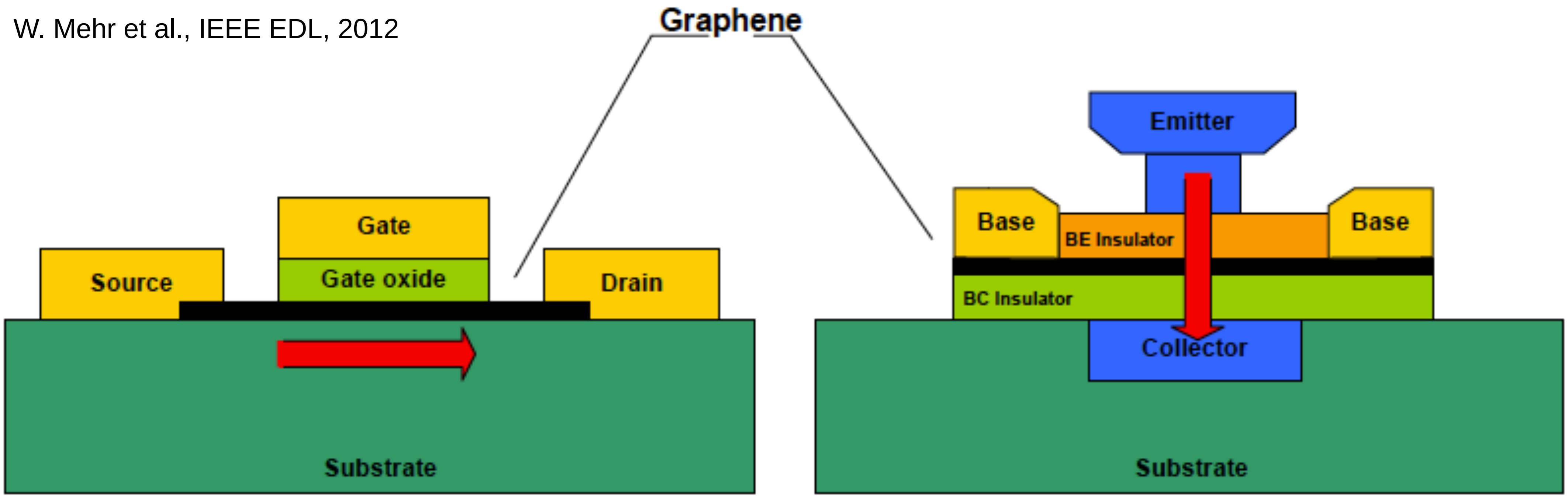


Wang et al., "Graphene Frequency Multipliers", IEEE EDL 5, 2009

- 1 Transistor Rectifier
- 1 Transistor Frequency Doubler

A new proposal: Graphene Base Transistor - GBT

W. Mehr et al., IEEE EDL, 2012

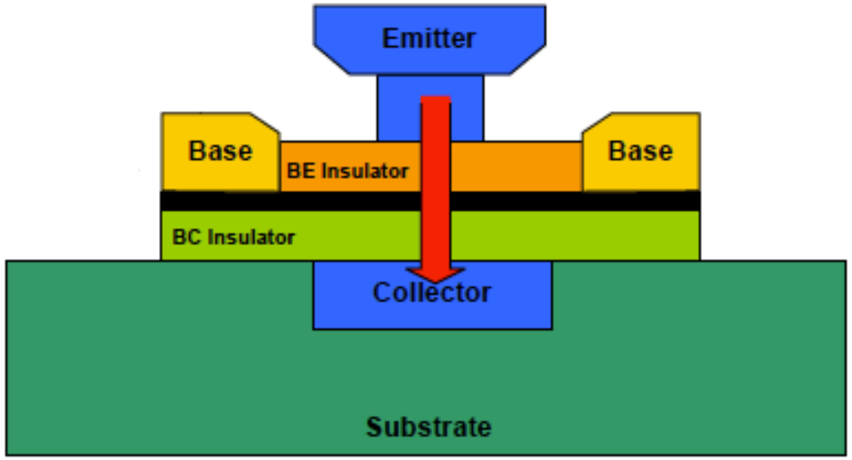


GFET GBT

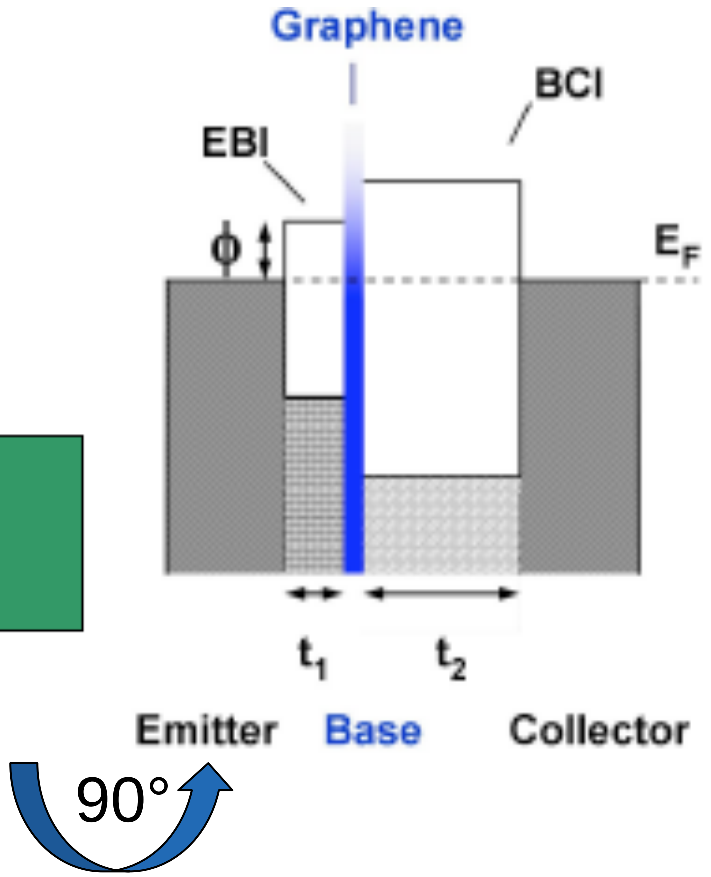
- “Hot Electron” transistor
- Charge carriers are transported perpendicular to the graphene sheet
- Operation depends on quantum mechanical tunnelling

A new proposal: Graphene Base Transistor - GBT

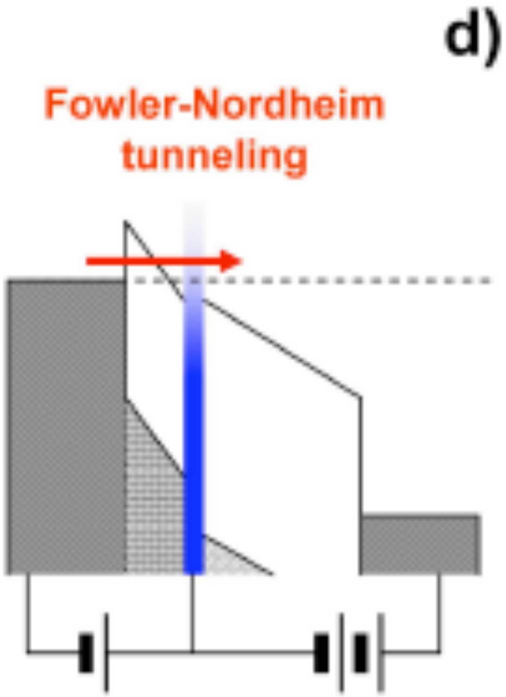
W. Mehr et al., IEEE EDL, 2012



GBT



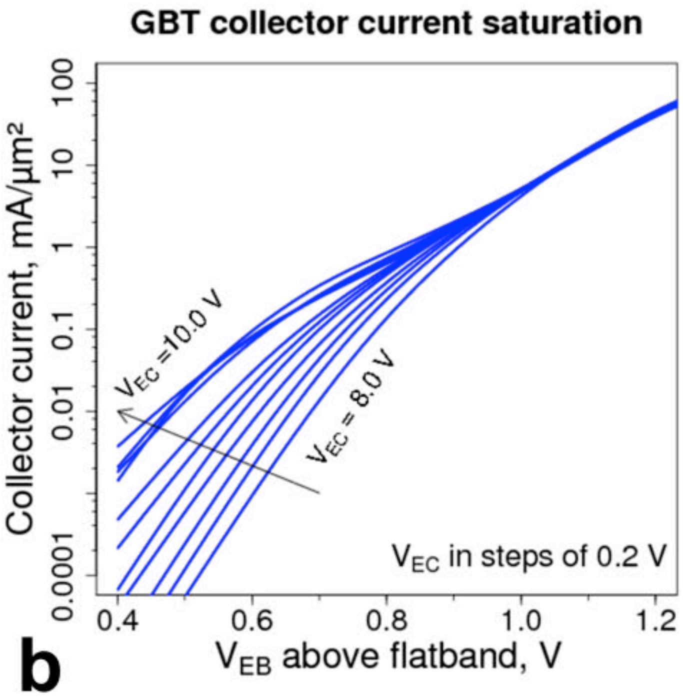
Unbiased

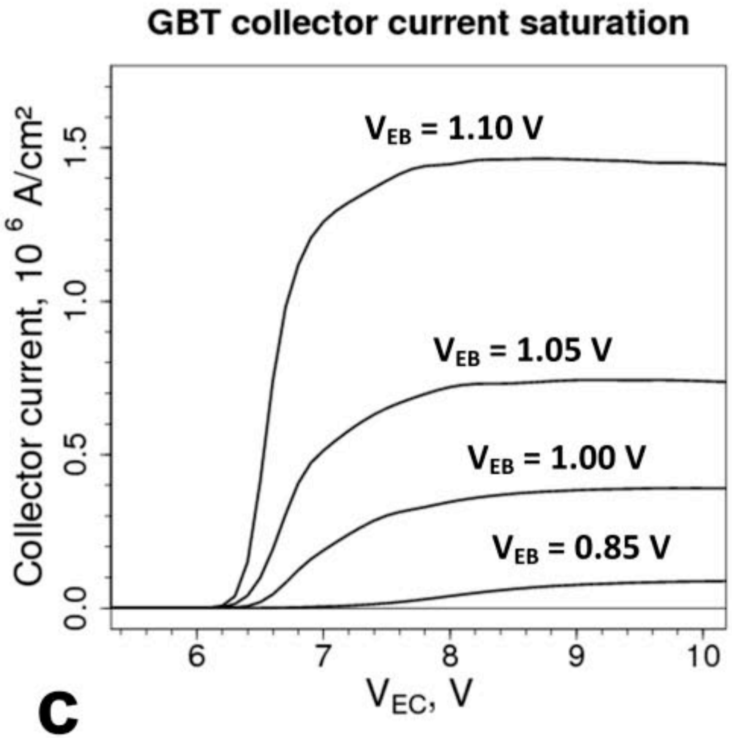


Biased

A new proposal: Graphene Base Transistor - GBT

W. Mehr et al., IEEE EDL, 2012



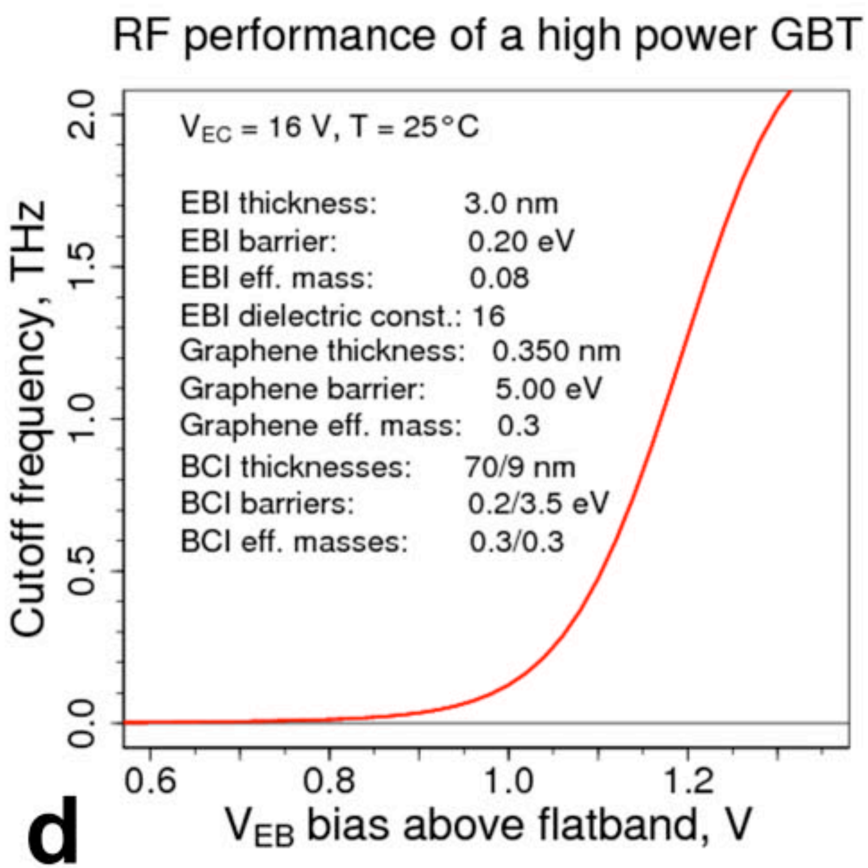


- Estimated transfer (b) and output (c) behavior
- Off-state expected to be well below on-state
- Current saturation
- Band structure needs careful engineering

Graphene Transistors: GBT

Performance Projections

W. Mehr et al., IEEE EDL, 2012



THz Operation seems feasible

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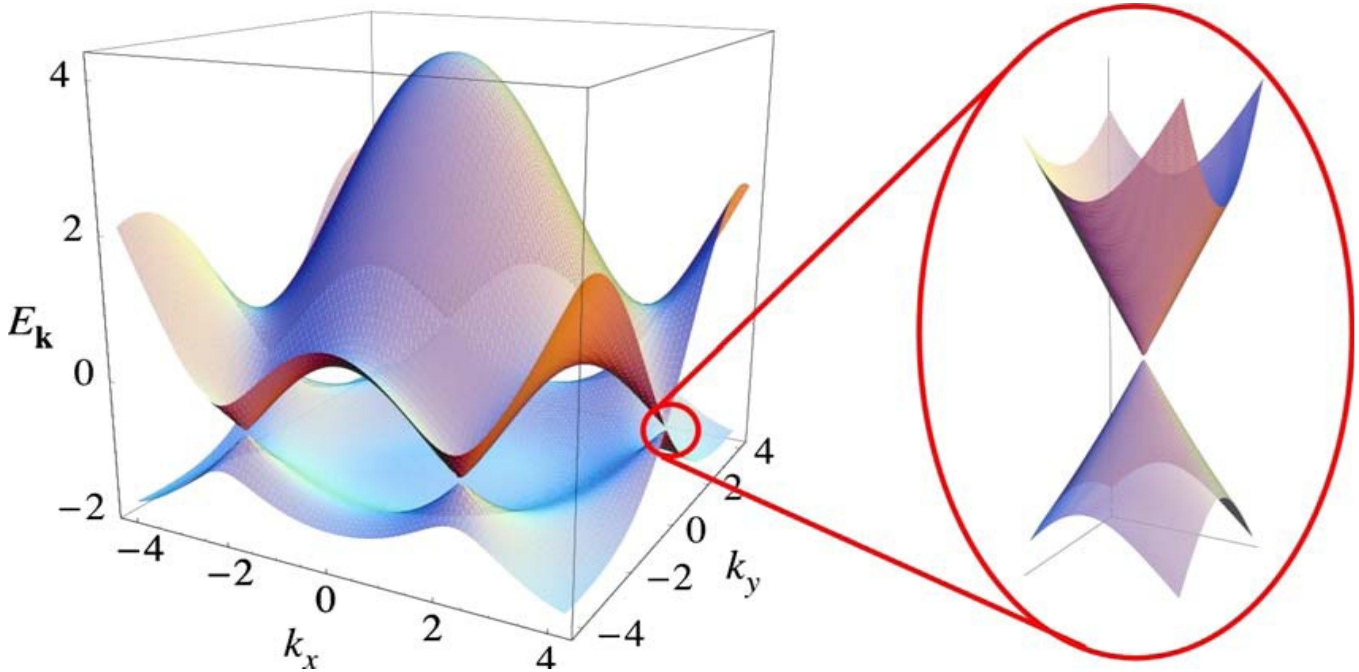
Graphene Optoelectronics

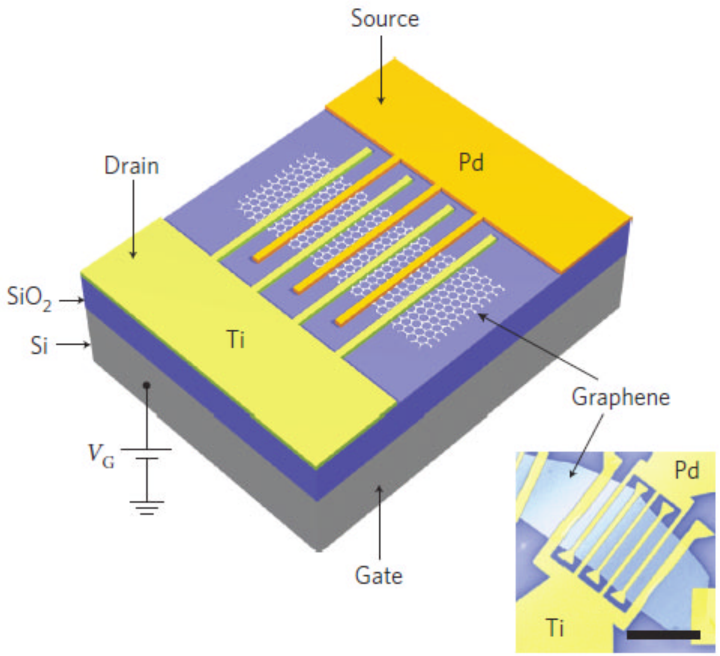


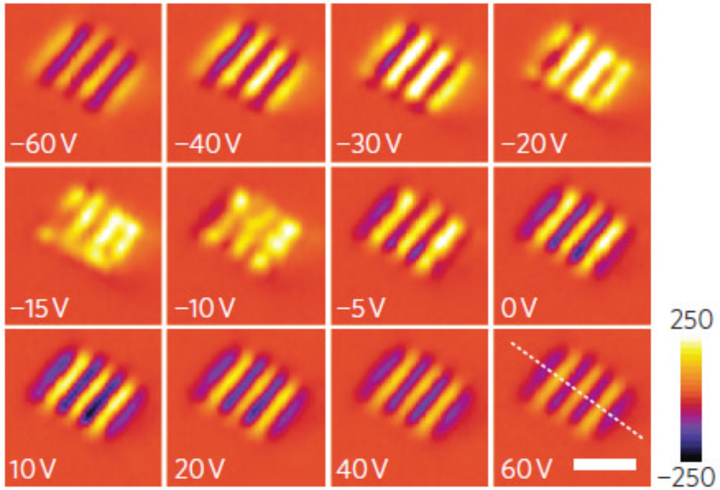
- E-k linear up to +- 1eV
- Potential from visible spectrum to THz
- High data rates

Graphene Optoelectronics

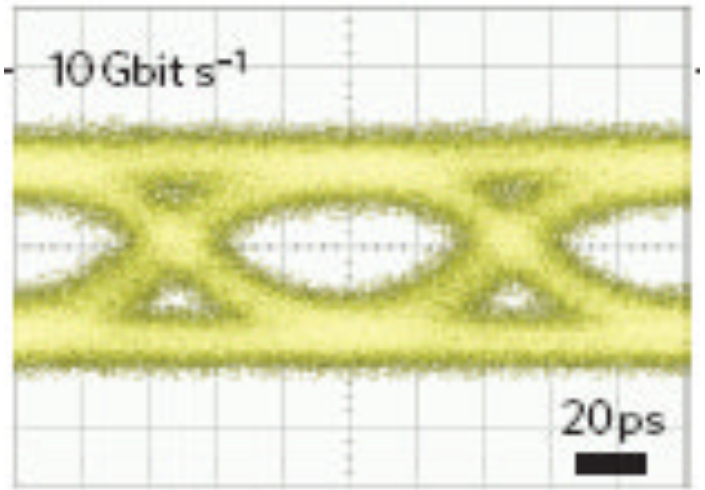
Graphene photodetectors for high-speed optical communications

Mueller et al., Nat. Photonics 2010





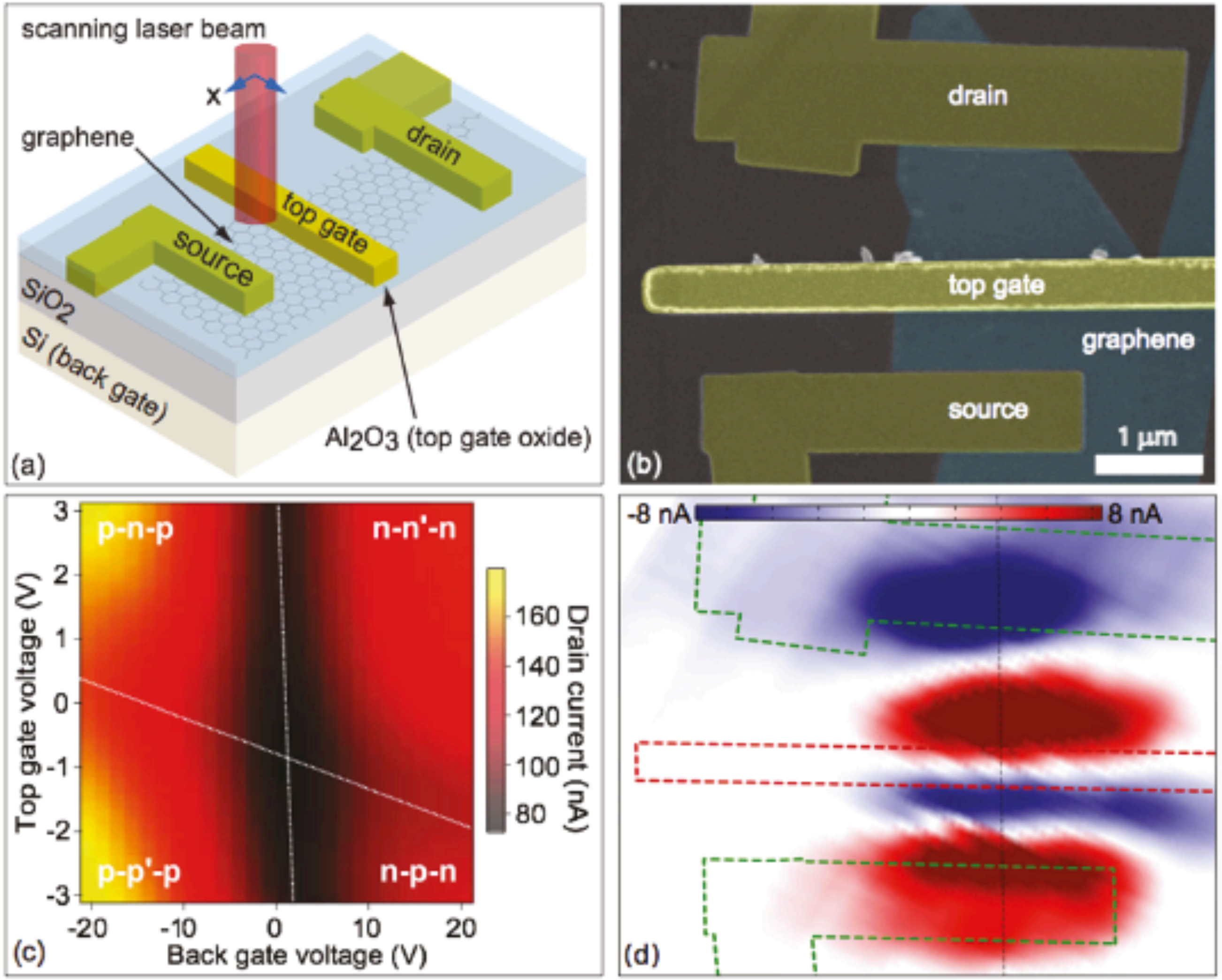
- Metal – graphene interface induces pn-junction
- Control through back gate (substrate)



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

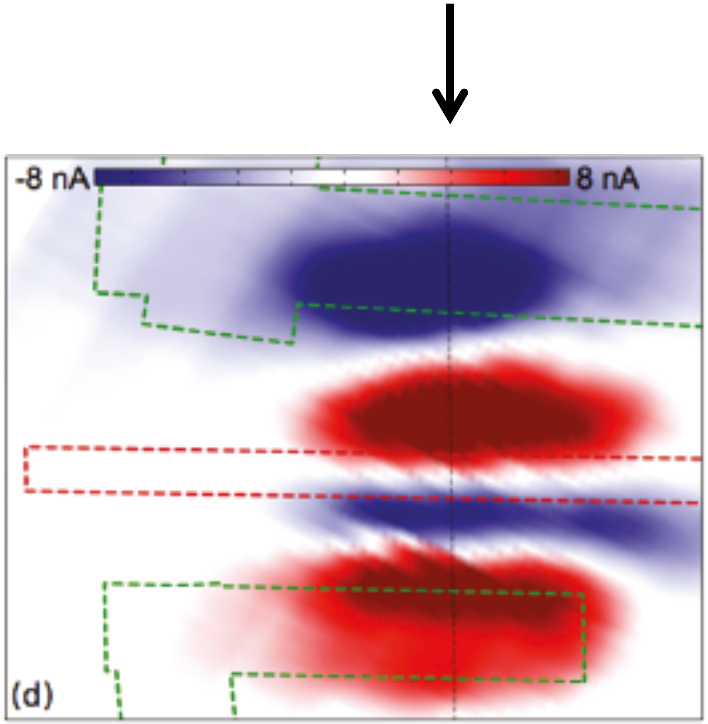
Graphene: Photodetection

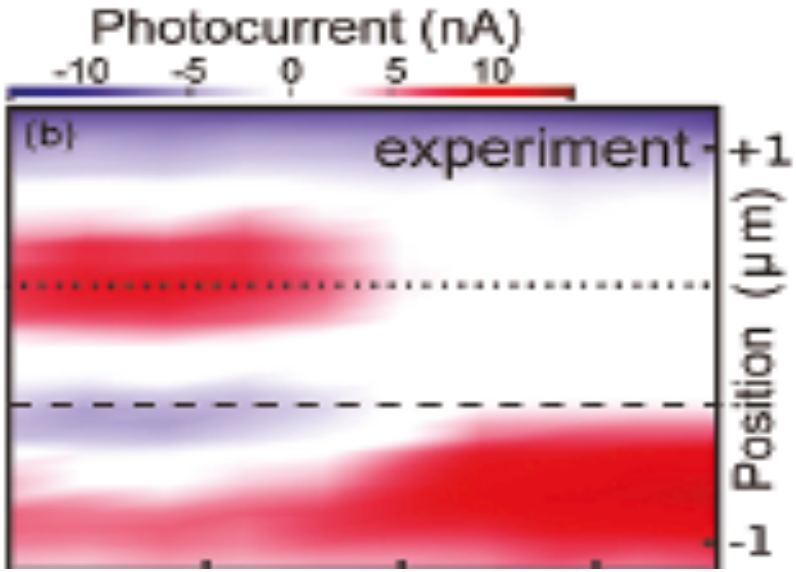
Graphene Photodetectors: Local Tunability

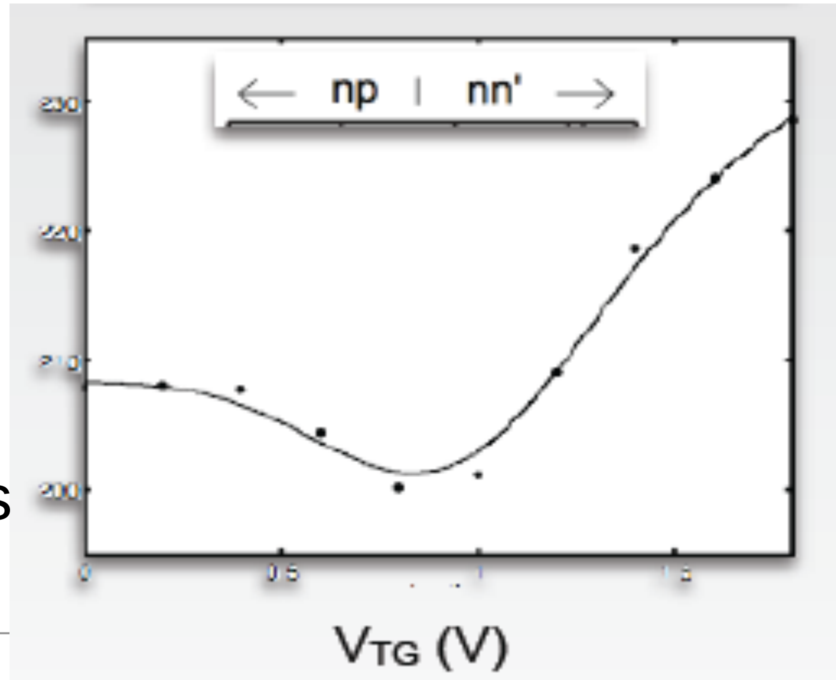


Lemme, Koppens, et al. "Gate Controlled Photocurrent in a Graphene p-n Junction", Nano Letters, 11, 2011.

Graphene: Photodetection

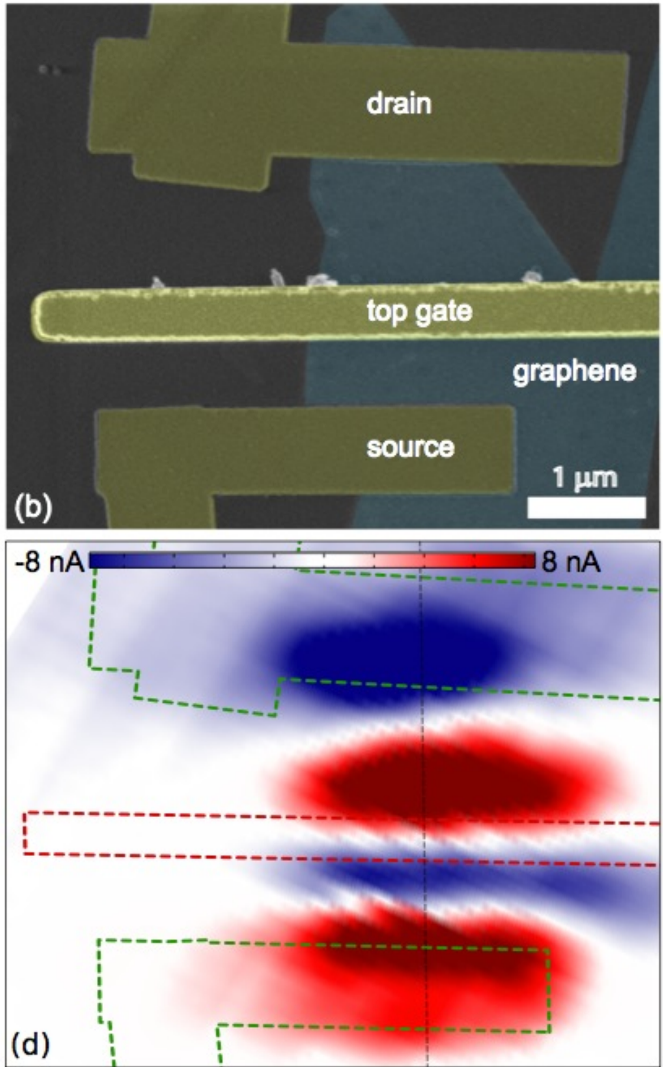






- Strong photoresponse in pn junction
- Weak photoresponse in similar carrier gradient (nn’ or pp’)
- Thermoelectric effect dominates over photovoltaic effect

Lemme, Koppens, et al. “Gate Controlled Photocurrent in a Graphene p-n Junction”, Nano Letters, 11, 2011.



Lemme et al., Nano Letters 2011

Graphene Photodetection

- Strong contribution from Seebeck effect (pn-junction required)
- Local contol 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
- Potential for UV to THz applications
- Enhanced quantum efficiency through carrier multiplication*

* Prediction: Song et al., Nano Letters 2011

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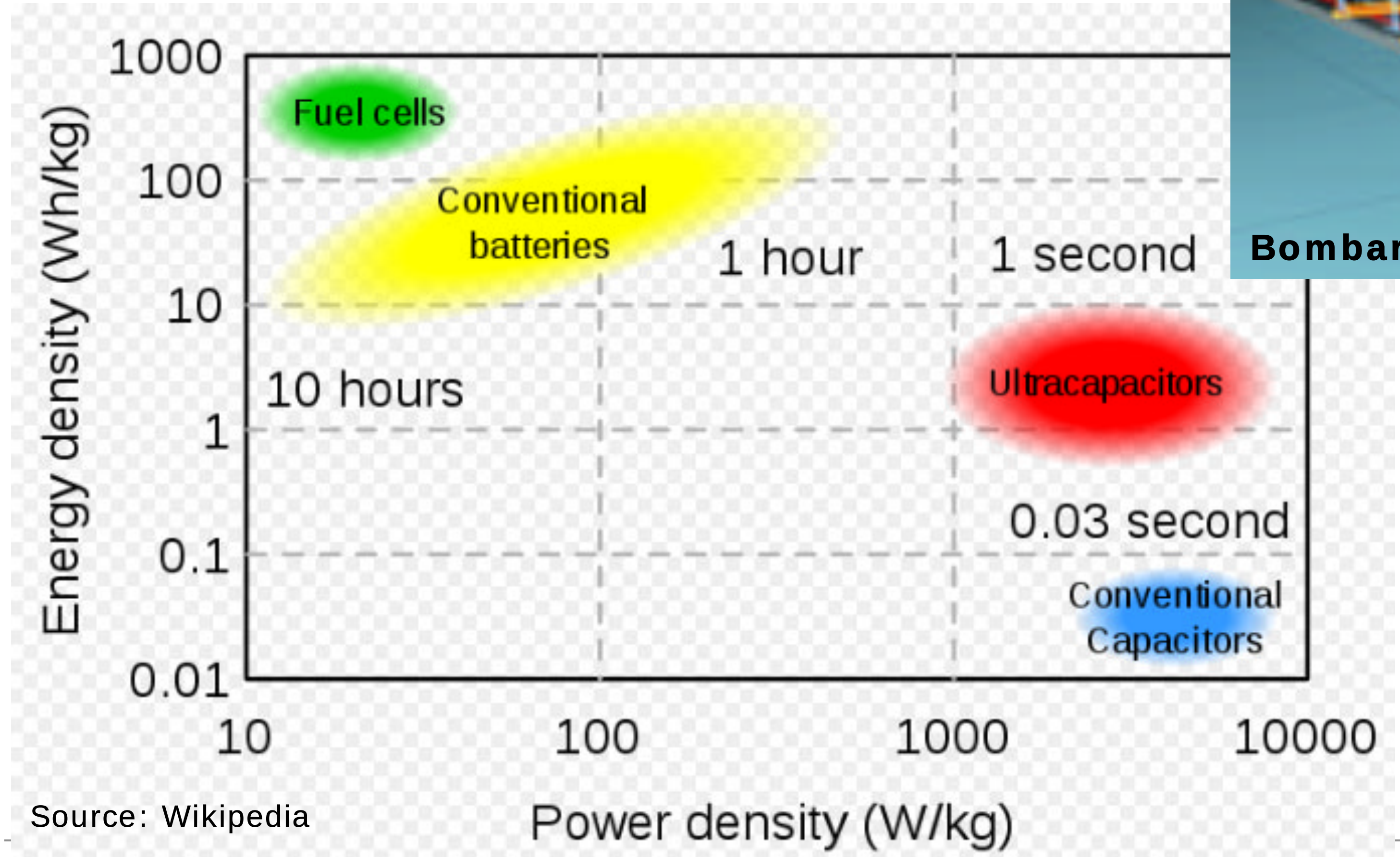
Graphene Supercapacitors for Energy Storage

Ragone Plot



Source: Wikipedia

Bombardier “Wireless” Train

Graphene Supercapacitors for Energy Storage

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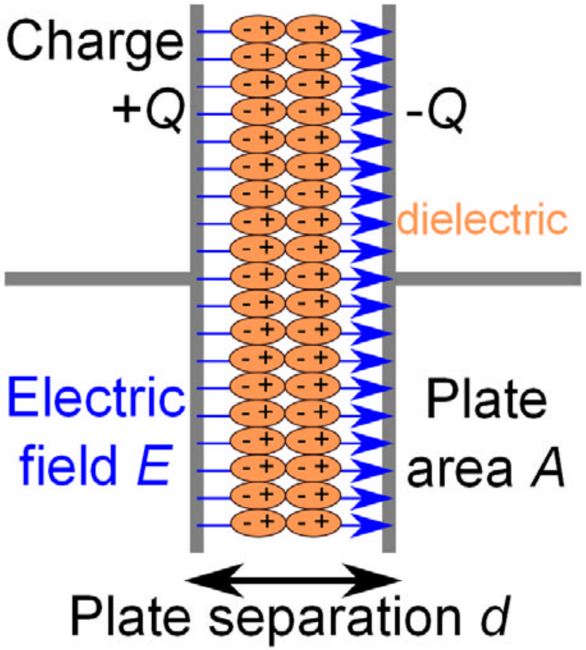
Capacitor

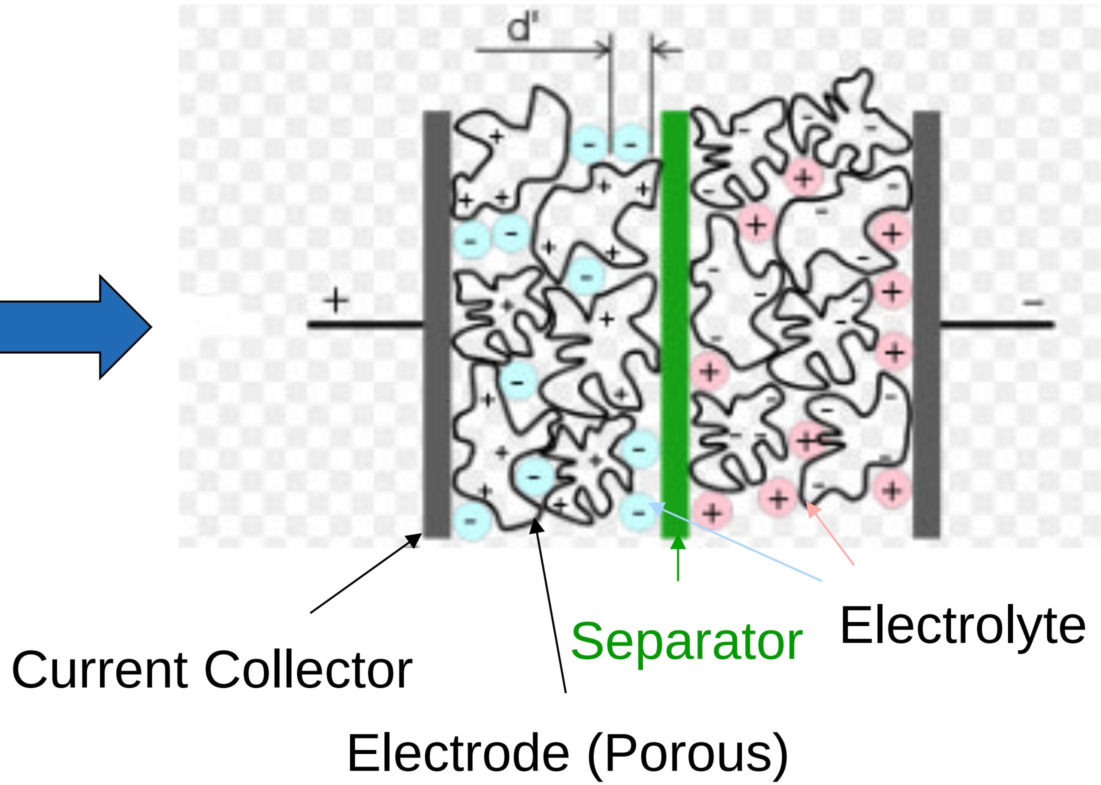
Direct Energy Storage
Non-Faradaic Process



$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

Supercapacitor, Ultracapacitor

Electrochemical Double Layer Capacitor
High surface area (!)



Source: Wikipedia

Graphene Supercapacitors for Energy Storage

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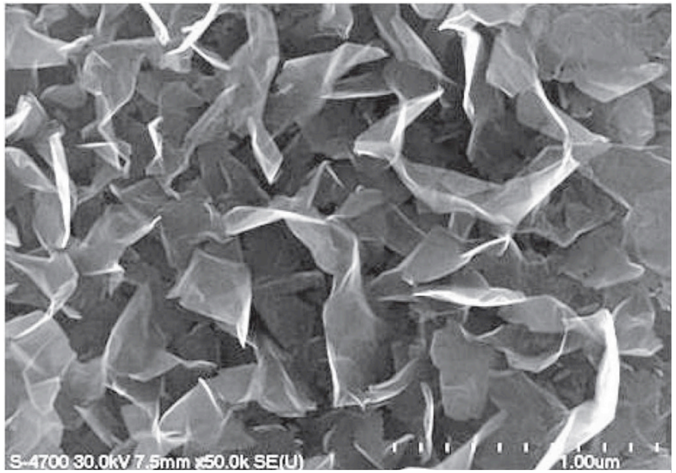
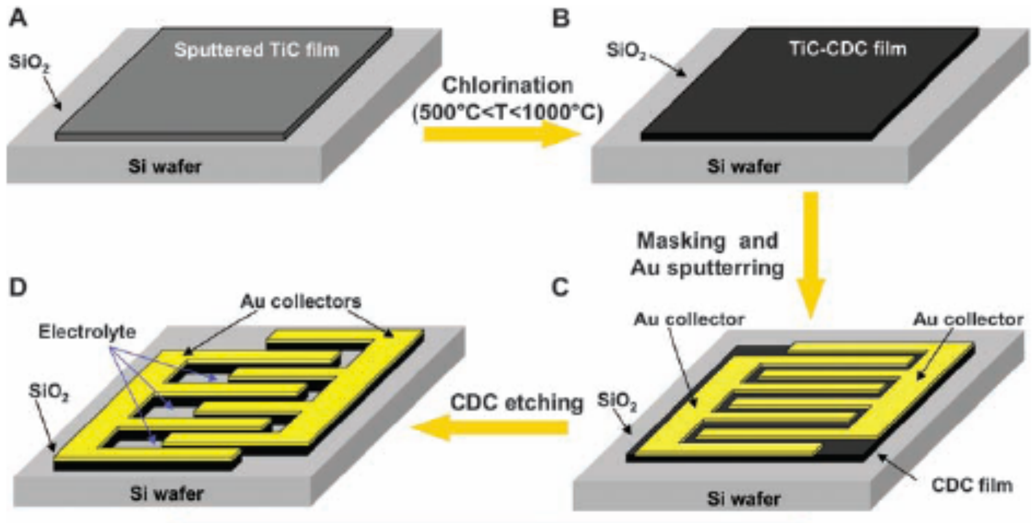
Graphene:

- 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)

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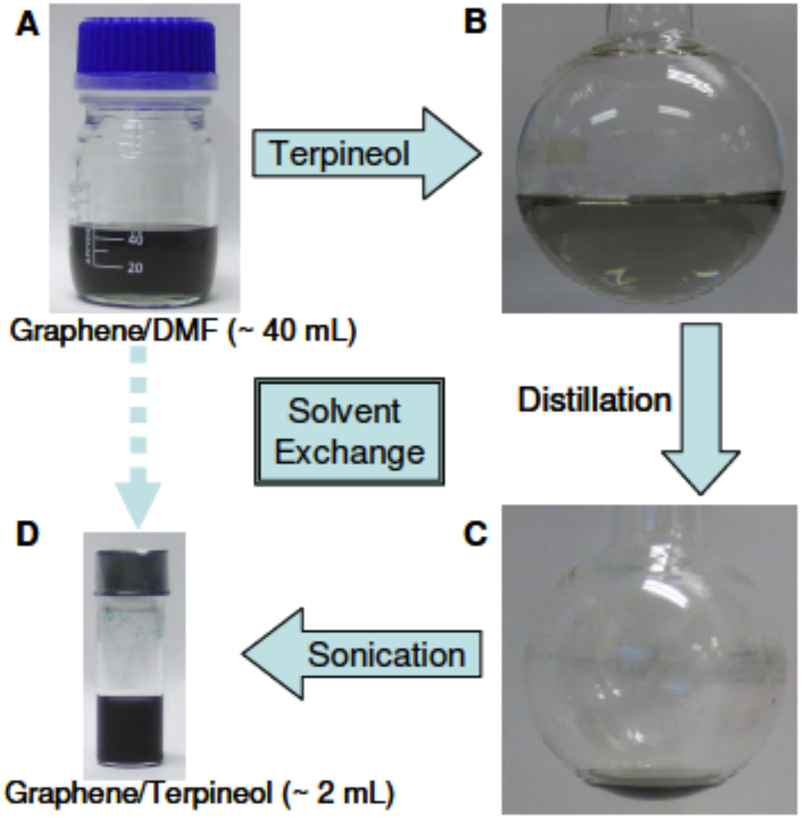
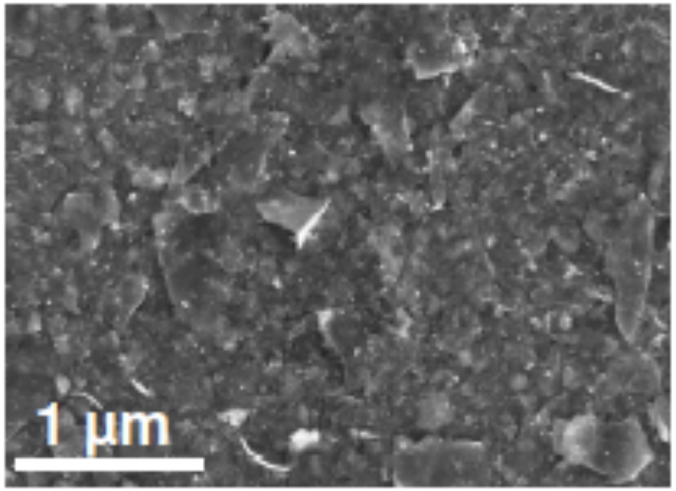
Graphene Supercapacitors for Energy Storage





- Graphene thin films from solution
- Transparent & conductive
- Inkjet-printable

Li, Lemme, Ostling, “A Simple Route towards High Concentration Surfactant-Free Graphene Dispersions“, Carbon, 2012

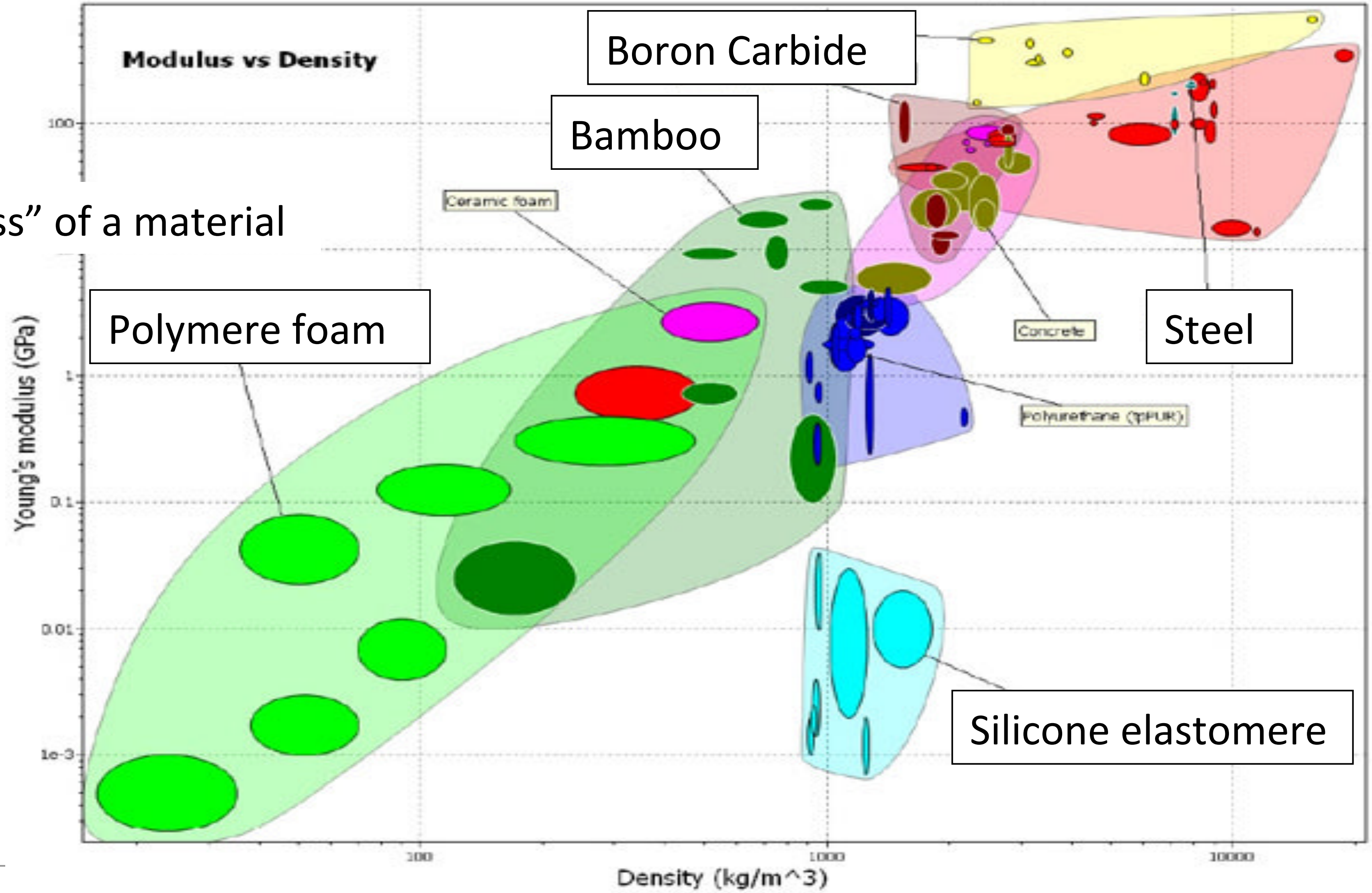
Outline

- Introduction
- Graphene Fabrication
- Graphene-based Electronic Devices
- Applications beyond ”Moore’s Law”
    - NEMS / Sensors
- Summary

Graphene Mechanics

- Graphene

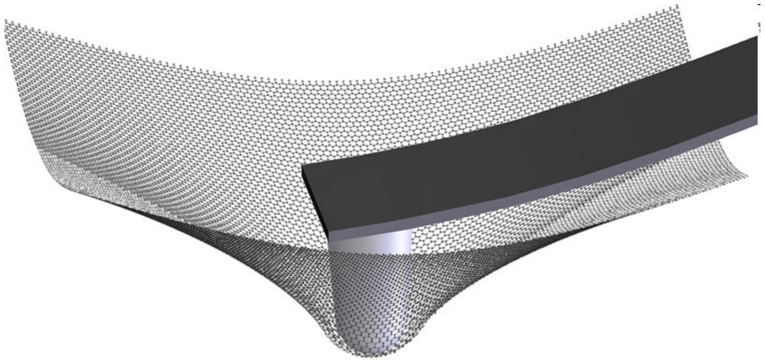
”Stiffness” of a material



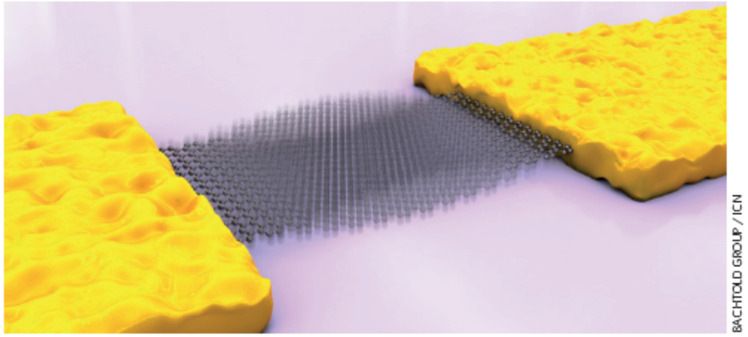
Graphene Nanomechanics

NEMS

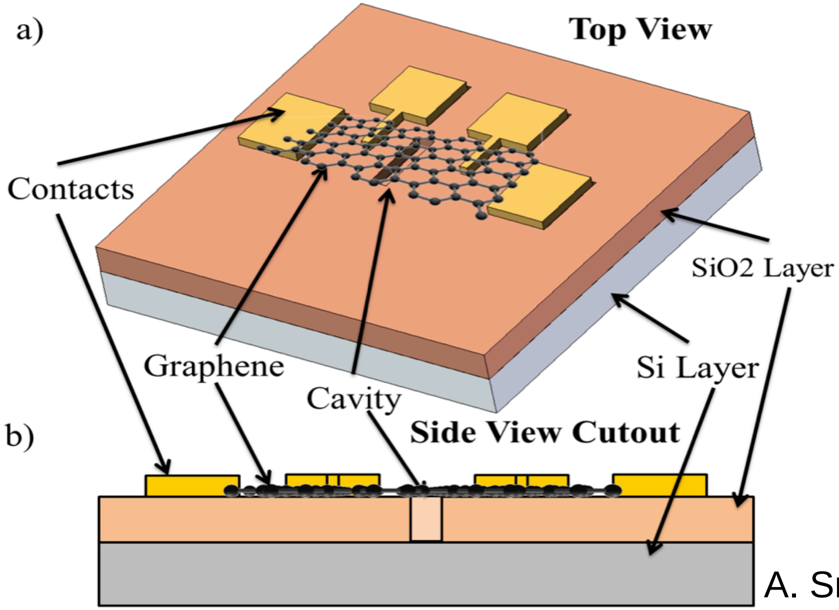
Lee et al., Science, 385-388, 18 July 2008



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



Source: A. Bachtold

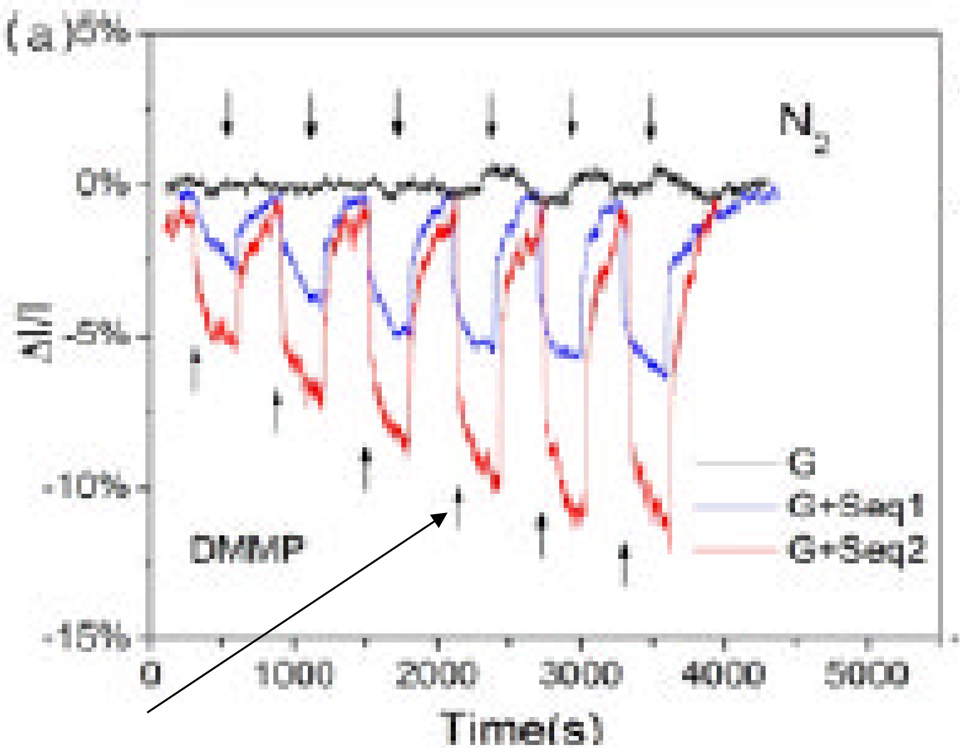


A. Smith et. al., ULIS 2012

→ Graphene based mass, force, pressure sensors

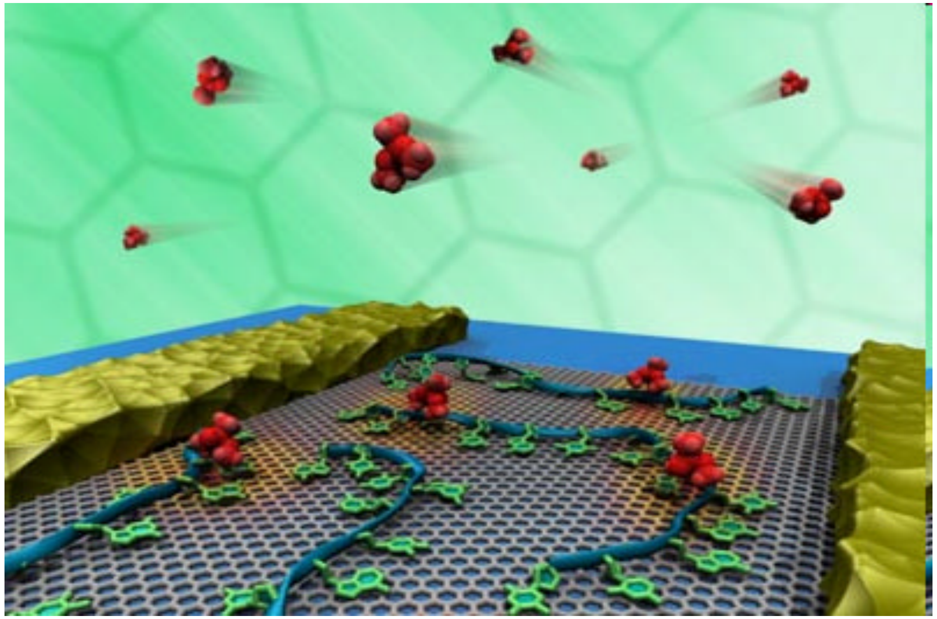
Graphene Sensors

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

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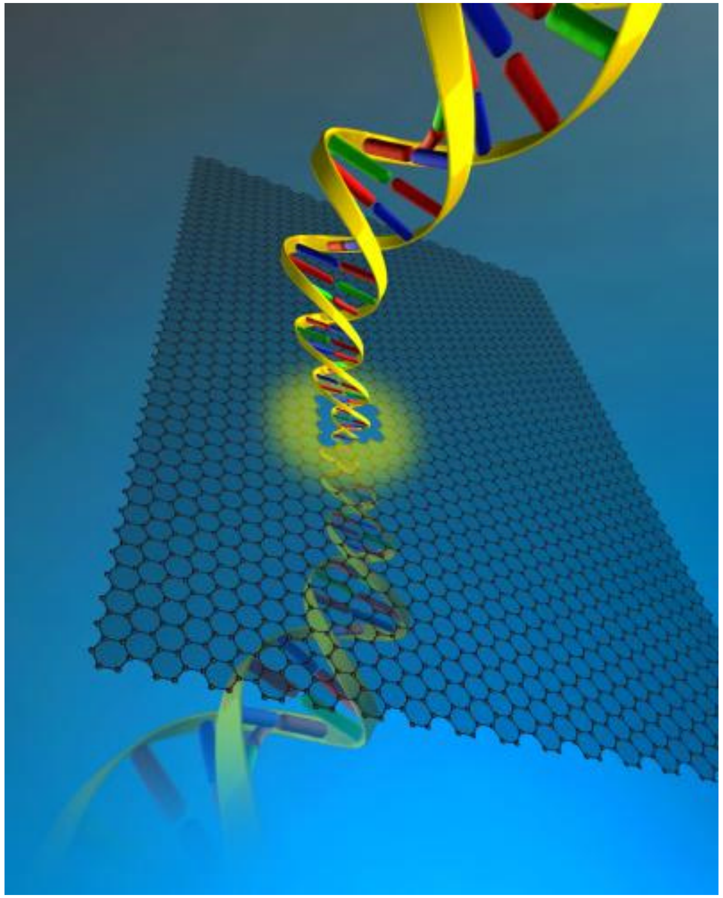
DNA sequencing using nanopores in graphene



Jene Golovchenko, Harvard University.

Why graphene?

- High mechanical strength
- High electric conductivity
- Ultimately thin

Outline

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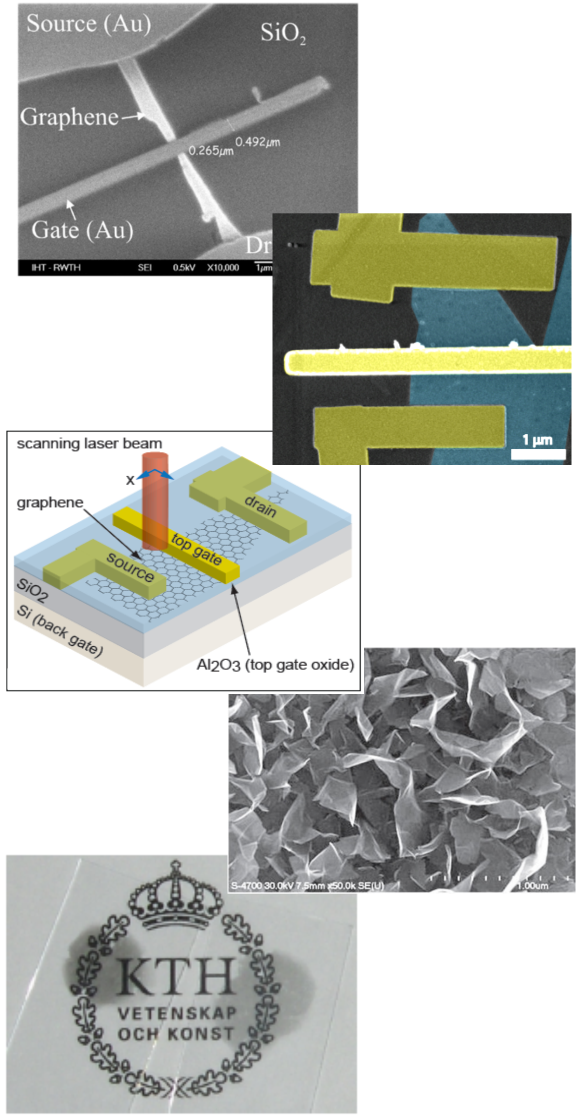
Summary

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



Graphene: Research Topics

- **NEMS**
- **Mechanical Applications (Space Elevator)**
- **Sensors (Functionalized Surfaces, Biocompatibility)**
- **Resistive Switching (Memory Applications)**
- **Ballistic Devices**
- **Spintronics (Spin-Valves, SpinMOSFET, SpinFET)**

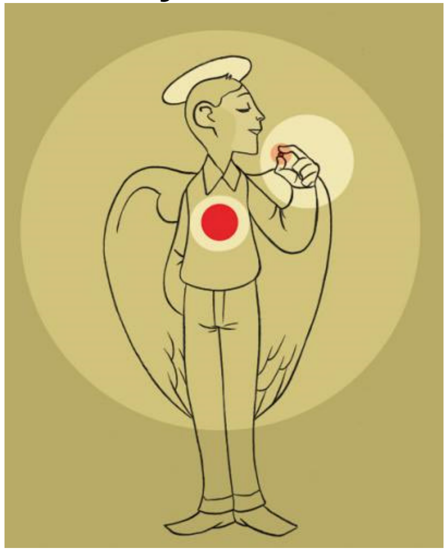
- **…other 2D Materials (h-BN, MoS2…)**

Graphene – Enabling New Gadgets?

Smart Monitoring

Wearable Electronics

Body Sensors



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- http://www.ga-project.eu