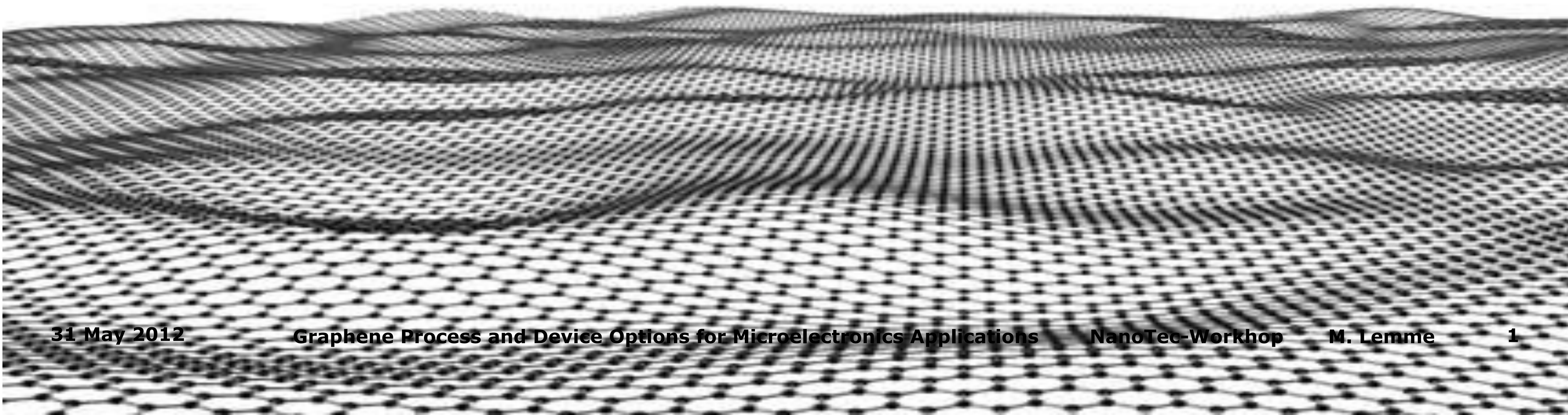
ROYAL INSTITUTE
OF TECHNOLOGY

Graphene Process and Device Options for Microelectronics Applications

Max Lemme

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



Acknowledgement / Collaborators

KTH
Jiantong Li
Mikael Östling
Saul Rodriguez
Ana Rusu
Anderson Smith
Sam Vaziri

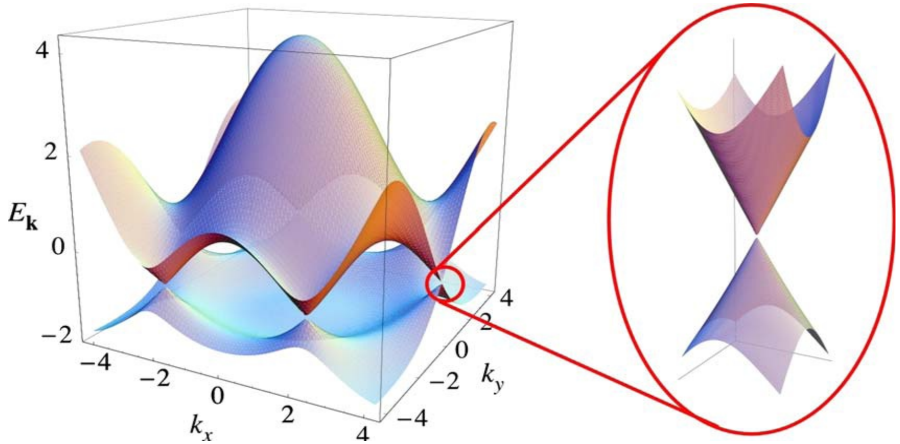
Harvard
David Bell
Frank Koppens
Charles Marcus

MIT
Leonid Levitov
Mark Rudner

UPC Barcelona
Eduard Alarcon

IHP
Jarek Dabrowski
Gunther Lippert
Grzegorz Lupina
Wolfgang Mehr
Christoph Scheytt

Graphene: Exceptional Properties (1/2)



Electronic properties

- Semi-metal or zero-gap semiconductor
- Linear dispersion relation
- Massless dirac fermions, v ~ c/300
- Intrinsic carrier mobility (suspended graphene in vacuum)

  $\mu = 200.000\ cm^2\ V^{-1}s^{-1}$
- Carrier mobility of graphene on SiO_2 at room-temperature

  $\mu = 10.000\text{-}20.000\ \ cm^2\ V^{-1}s^{-1}$ (speed ~ I_{on} ~ μ)
- Maximum current density

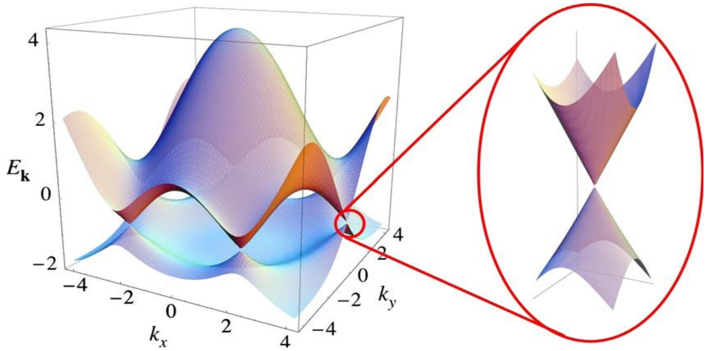
  $J > 10^8\ A/cm^2$
- Velocity saturation

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

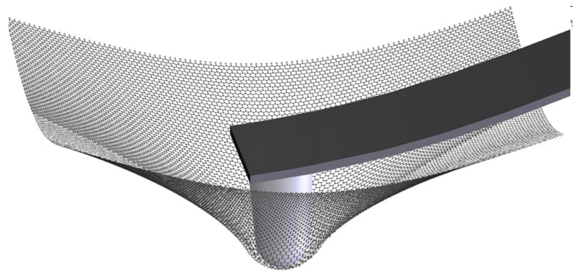
Exceptional Properties (2/2)

Optical properties

- Linear dispersion relation



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



Mechanical properties

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

Thermal conductivity

- ~5.000 W/m•K at room temperature

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

Transparent (only 1 atom thin)

Transparent flexible conductive electrodes

High surface to volume ratio

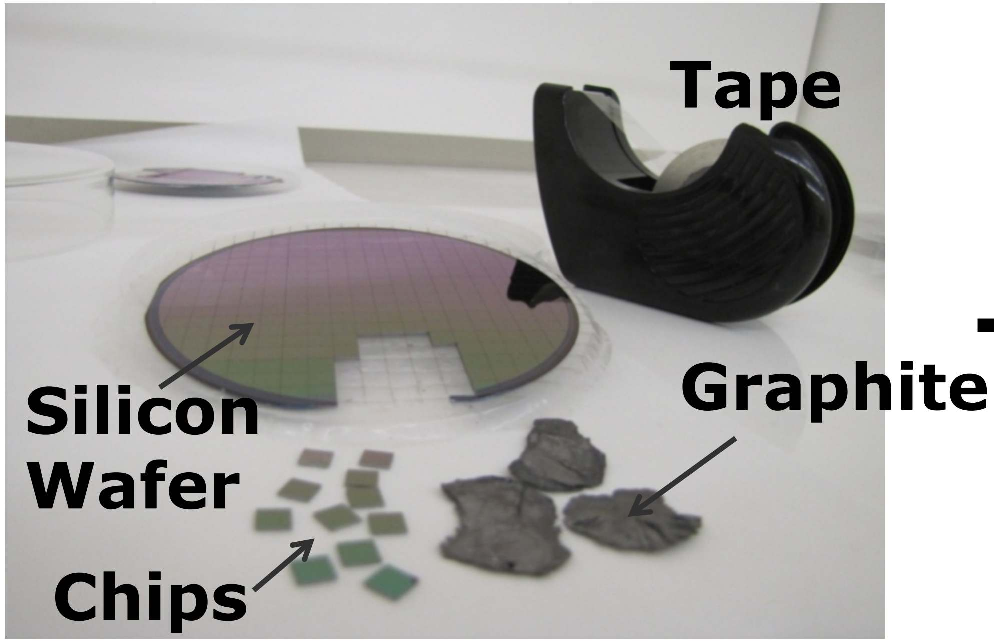
Sensors

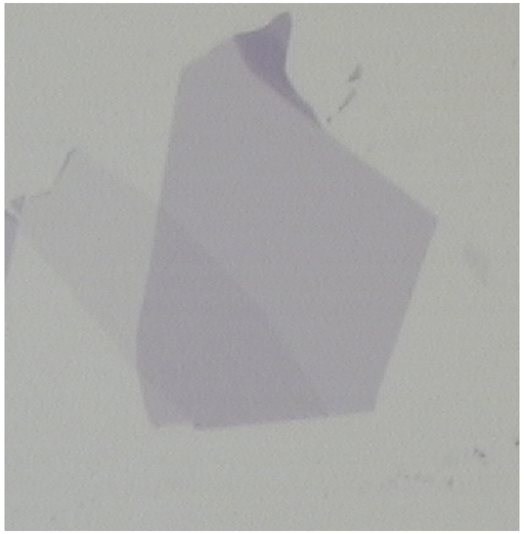
Outline

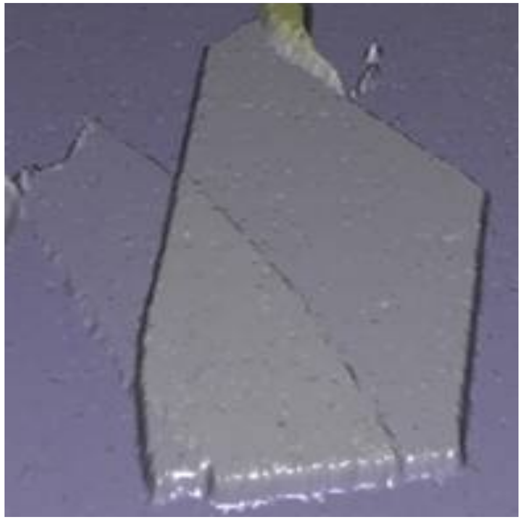
- **Process Options**
  - **Deposition & Growth**
- Graphene-based Transistors
- Applications beyond ”Moore’s Law”
- Summary

Graphene Fabrication Methods: Exfoliation

Exfoliation with adhesive tape

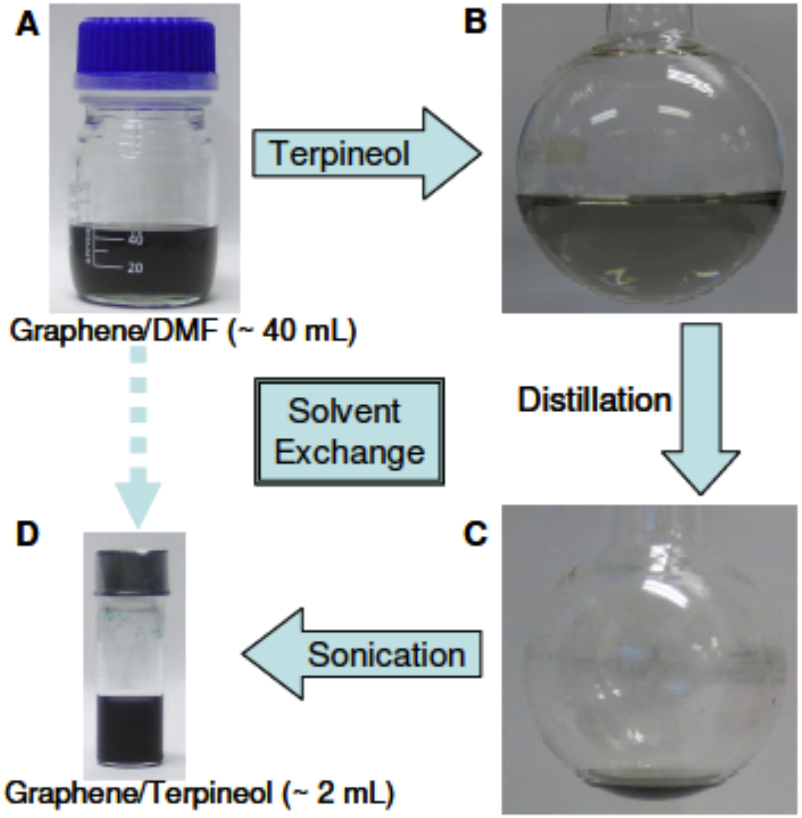


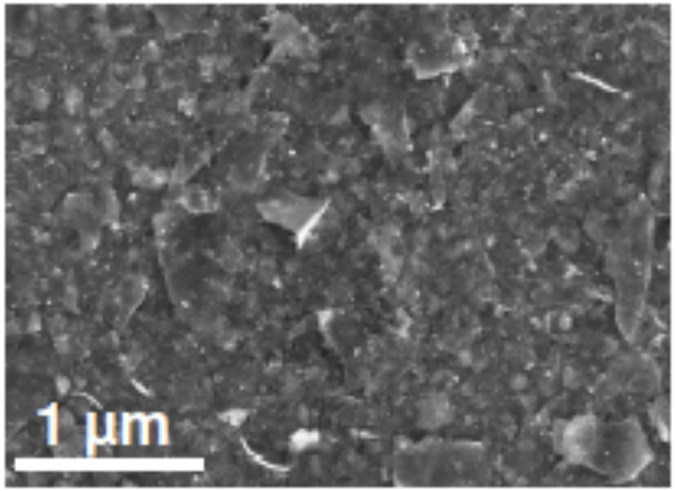




- Novoselov et al., Science 306, 666 (2004)
- flake size: 5 – 100 μm
- random location
- simple process for proof-of-concept
- ***no industrial relevance***

Graphene Fabrication Methods: Dispersions





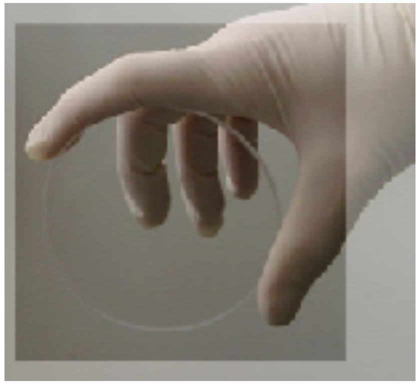
Li, Lemme, Ostling, Carbon, 2012

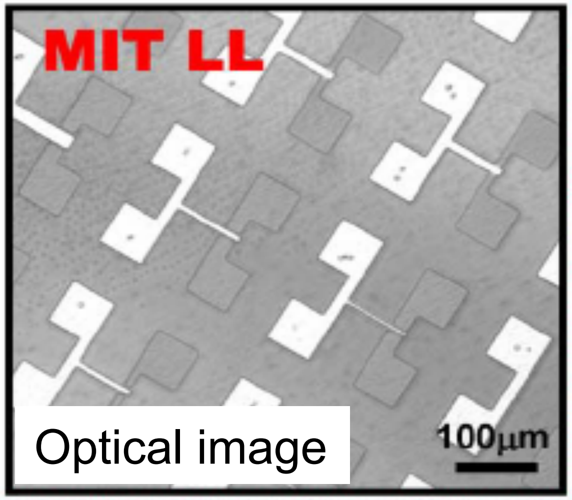
- Graphene thin films from solution
- Transparent & conductive
- Inkjet-printable

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

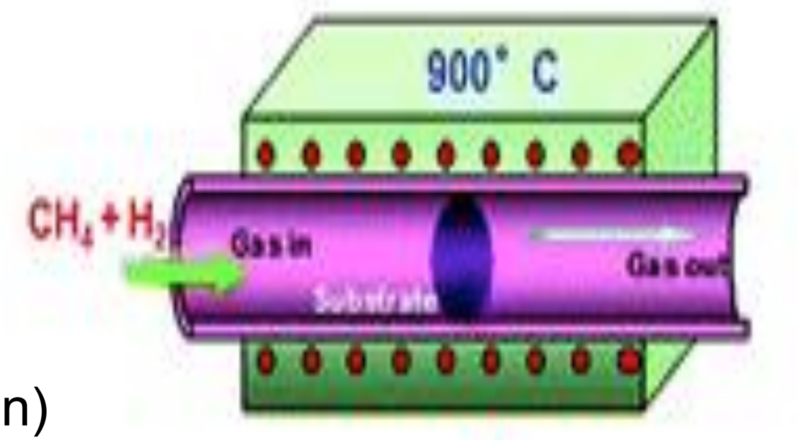
- scalable
- modest temperatures (<1000°C)
- Silicon Technology compatible

Source: Infineon

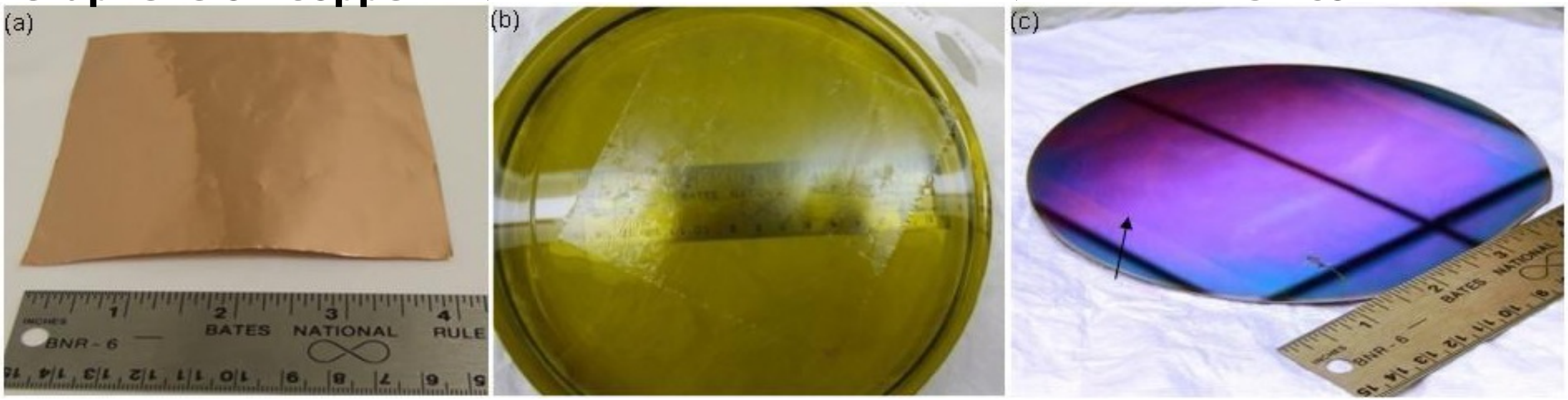
Graphene Fabrication Methods: CVD

Chemical Vapor Deposition (CVD)

- CVD on Ni, Cu, Ru, Ir, TiC, TaC, etc.
- Process Temperatures: 850-1000°C
- Graphene transfer to random substrates
- Monolayer vs. multilayer control (solubility)
- High potential for large areas (roll to roll production)



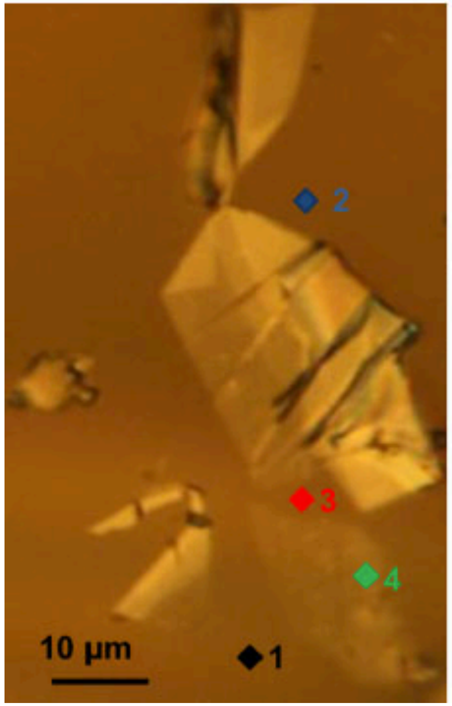
Graphene on Copper -> PMMA -> Silicon

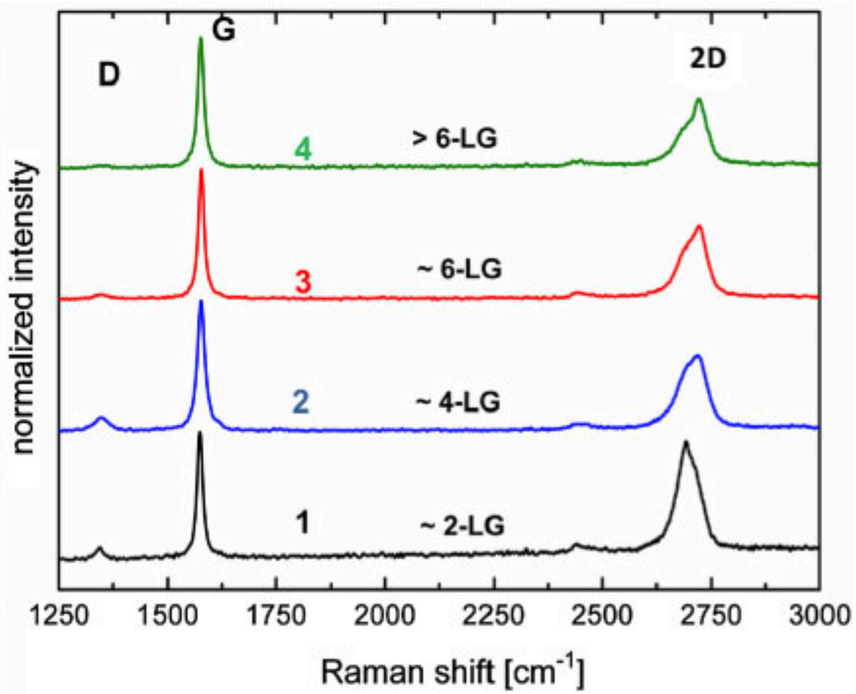


Cao et al, Applied Physics Letters 96, 122106 (2010)

Graphene Fabrication: Molecular Beam Growth

- direct deposition on anything
- „holy grail"
- to date: small flakes < 1 μm
- ***high risk – high payoff***





G. Lippert et al., "Direct graphene growth on insulator", Phys. Status Solidi B 248, No. 11, 2619–2622 (2011)

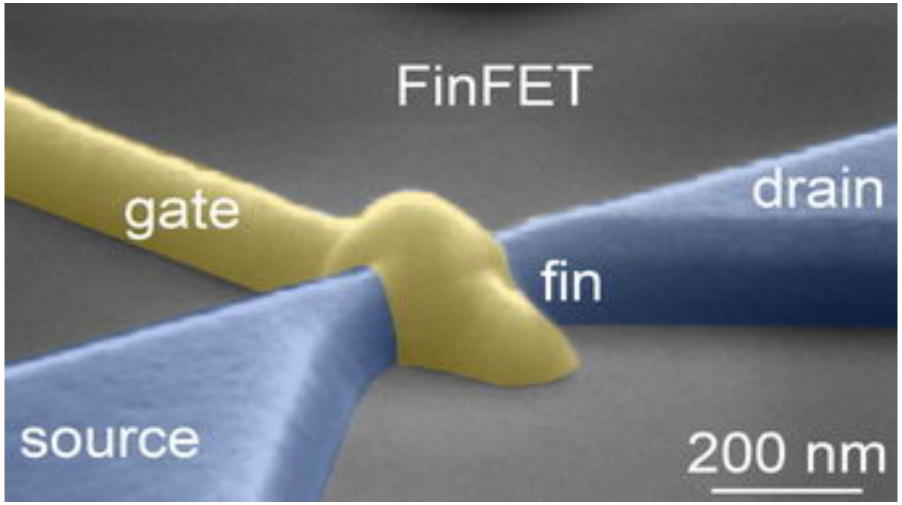
Increasing interest:

- J. Kelber et al, "Direct Graphene Growth on Oxides: Interfacial Interactions and Band Gap Formation", (2011)
- U. Wurstbauer, R. He, A. Rigosi, C. Gutierrez, A. Pasupathy, T. Schiros, C. Jaye, D. Fischer, A. Plaut, L.N. Pfeiffer, A. Pinczuk, J.; Garcia, . arXiv:1202.2905v1 (2012)
- S.K. Jerng, D. Yu, Y.S. Kim, J. Ryou, S. Hong, C. Kim, S. Yoon, D.K. Efetov, P. Kim, S. Chun, Journal Physical Chemistry C, 115, 4491–4494, (2011).

Outline

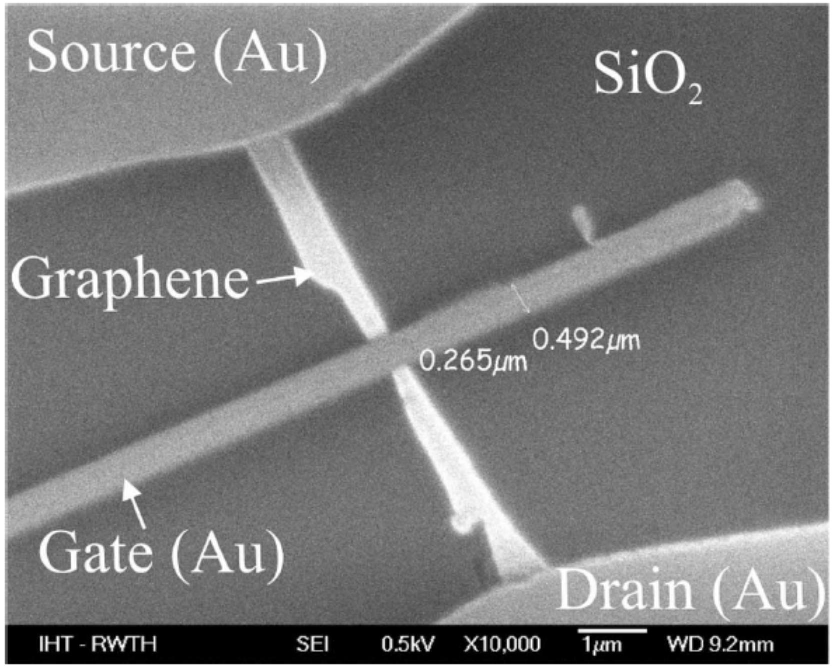
- **Process Options**
  - **Process Integration**
- Graphene-based Transistors
- Applications beyond ”Moore’s Law”
- Summary

Silicon MOSFET



Source: TU Delft

Graphene MOSFET



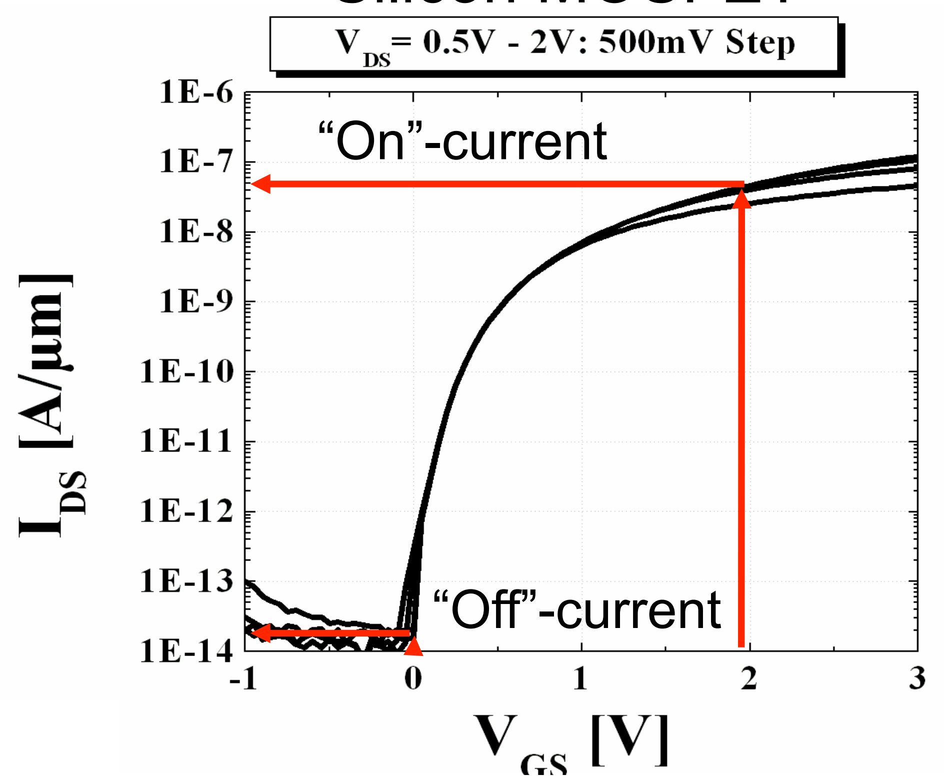
Lemme et al. "A Graphene Field Effect Device", IEEE Electr. Dev. Lett. 28(4), 2007.

Graphene Devices:

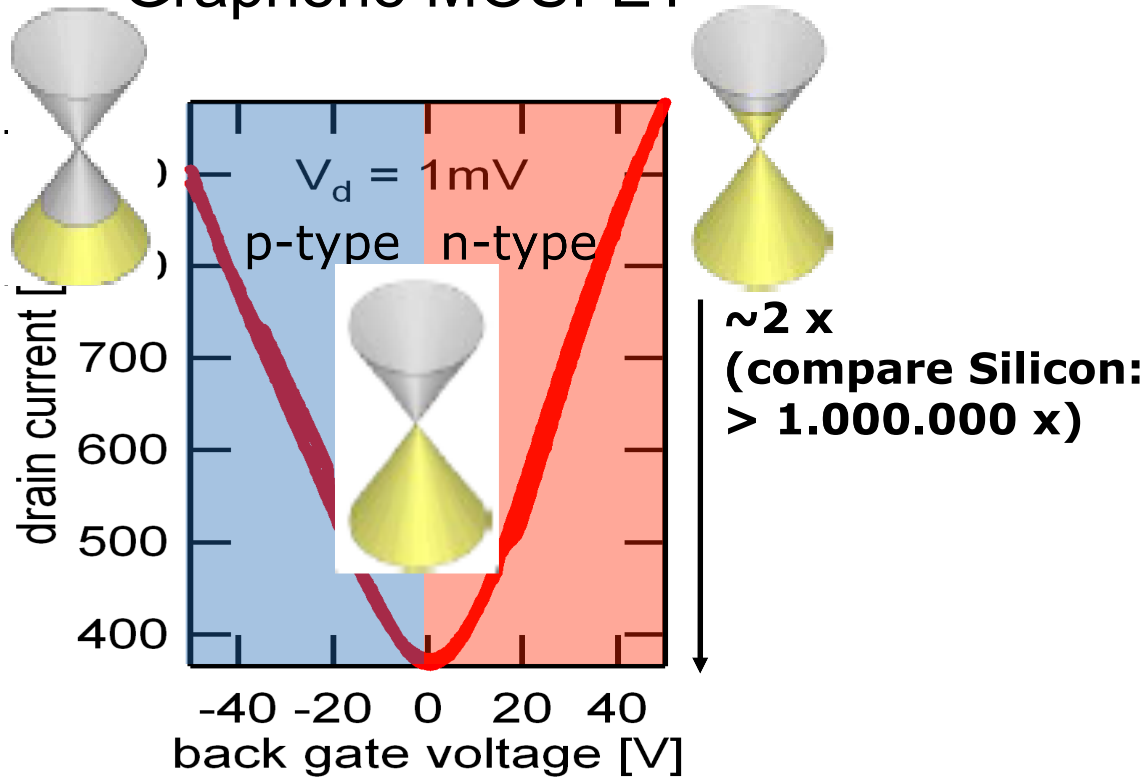
- Silicon process technology can be applied („Top-Down")
- Graphene is compatible with (most) standard processes
- Scalable graphene deposition methods emerging (CVD, epitaxy)
- …Graphene MOSFET (GFET)?

Graphene Transistors: Transfer Characteristics

Silicon MOSFET



Graphene MOSFET



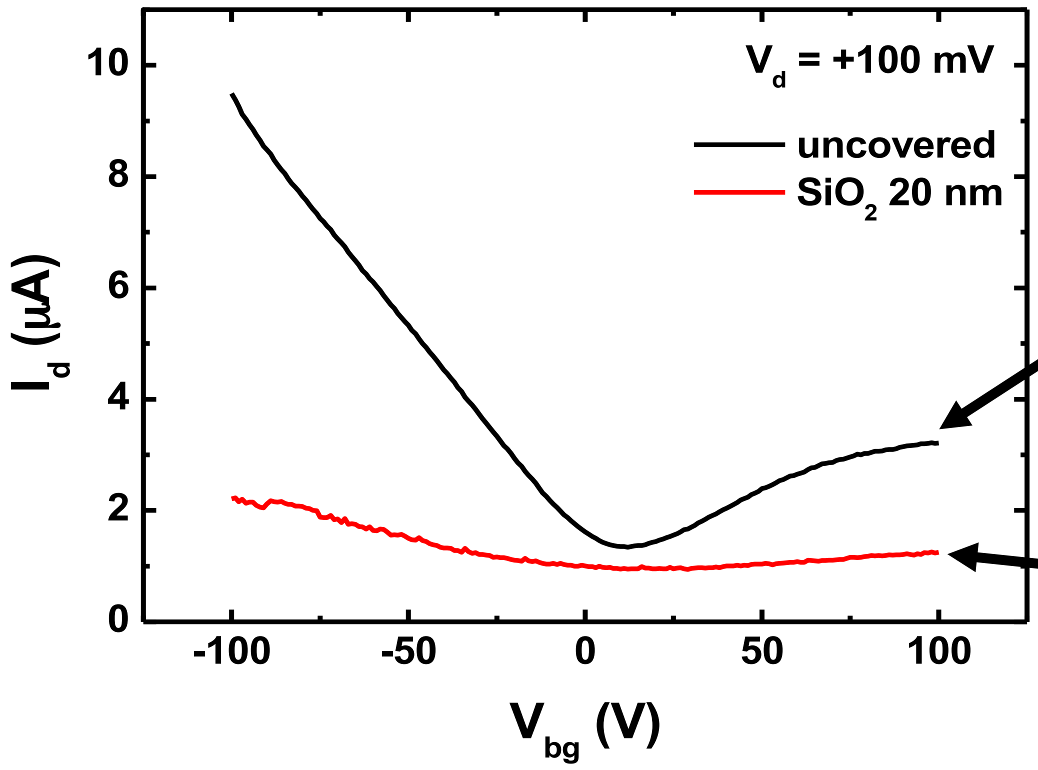
Graphene Transistors:

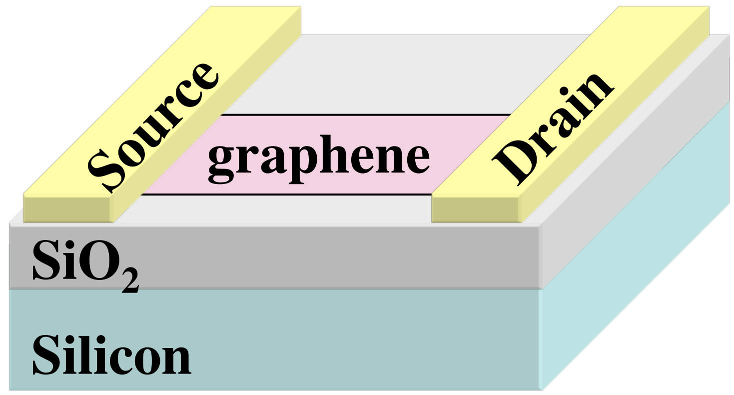
- Ambipolar behaviour (n- und p-type conduction)
- I_{on}/I_{off} ratio inherently limited by band structure (semimetall)
- NOT a direct replacement for Silicon logic, BUT...
- ... RF analog / higher functionality / new functionality?!

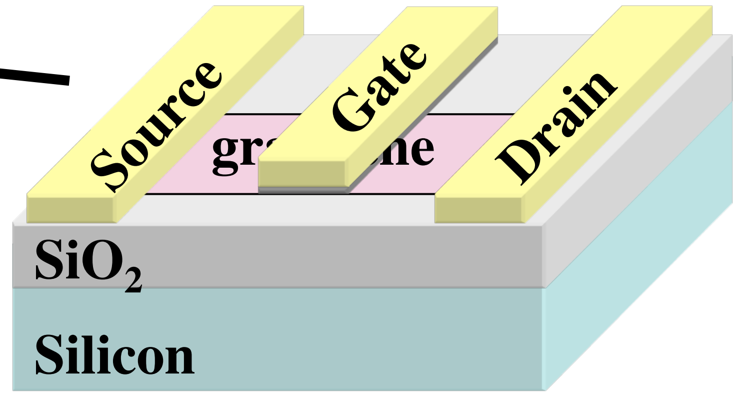
Interface Engineering

Reality check: what about gate oxides?

Lemme et al., IEEE Electr. Dev. Lett. 28(4), 2007.

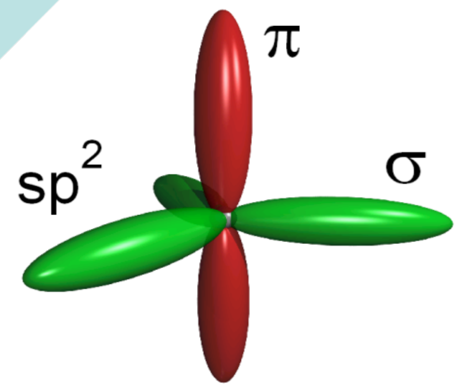




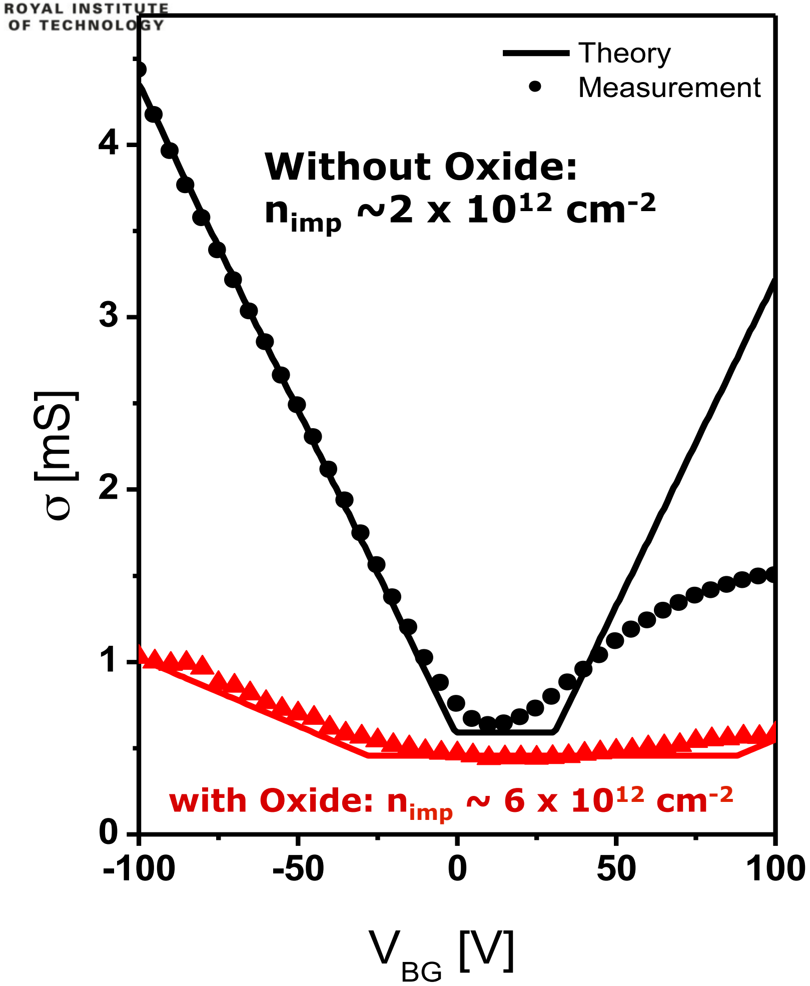


Reduction of current by factor of ~5

- Top-Gate dielectric disturbs **p**-Orbitals
- Charegd impurity scattering (Adam et al. PNAS 104(47), 2009)



Interface Engineering



Model: Adam et al. PNAS 104(47), 2009
Data: Lemme et al. IEEE EDL, 28(4), 2007

Mobility reduced by top gate oxide

„**Charged Impurity Scattering**“ Model:

Minimum conductivity and Dirac point shift through charges „near” Graphene / oxide interface

$$\mu_C = \frac{5\times 10^{15}\,Vs}{n_{imp}}$$

Electron – hole asymmetry not included in Adam-Model

"Carrier Injection" model:

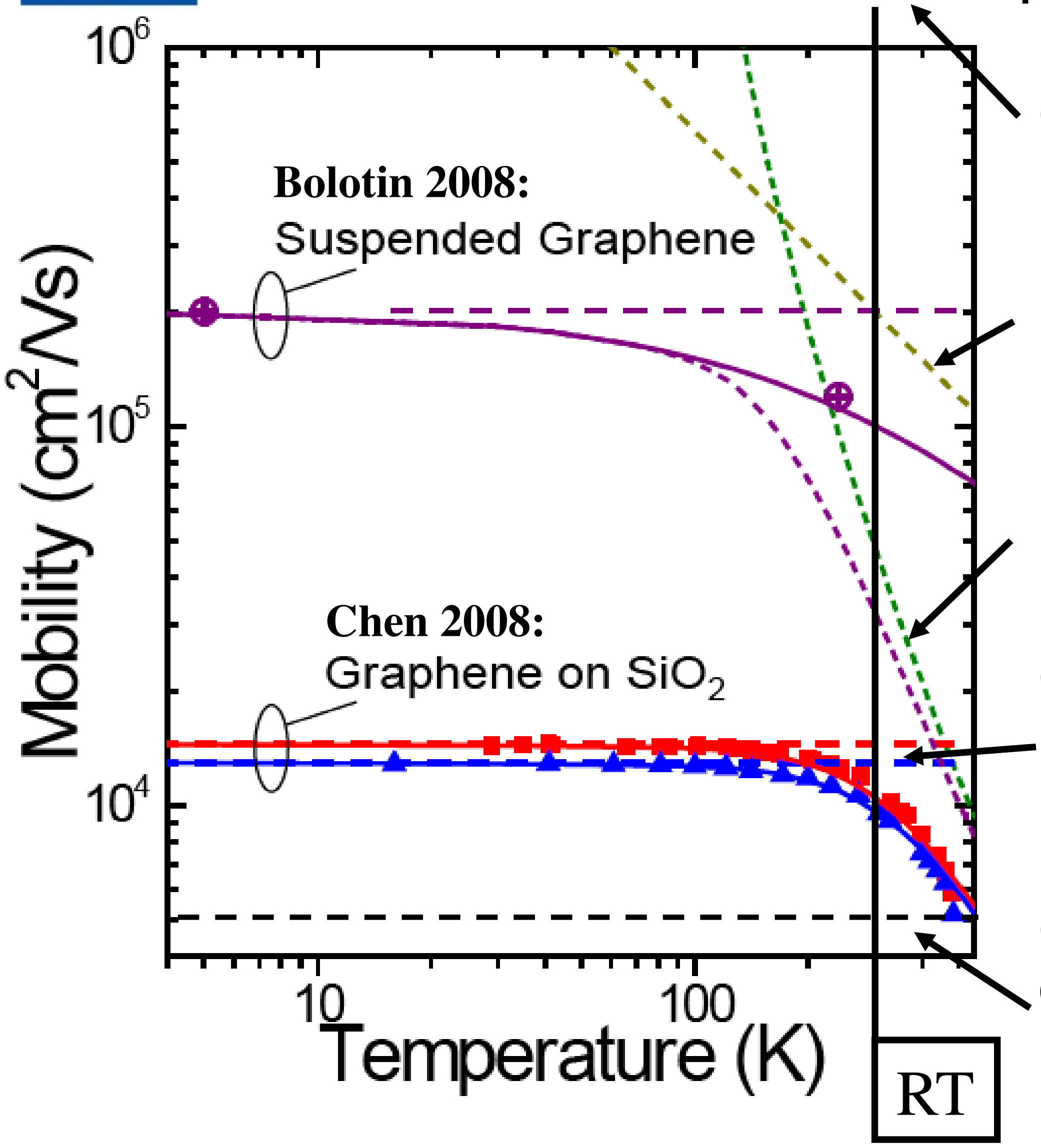
Carrier injection limited by contacts

"Long Range Scatterer" Model:

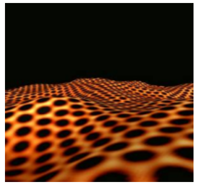
selective limit for ONE carrier type

Farmer et al. Nano Lett. 9(1), 2009

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?)

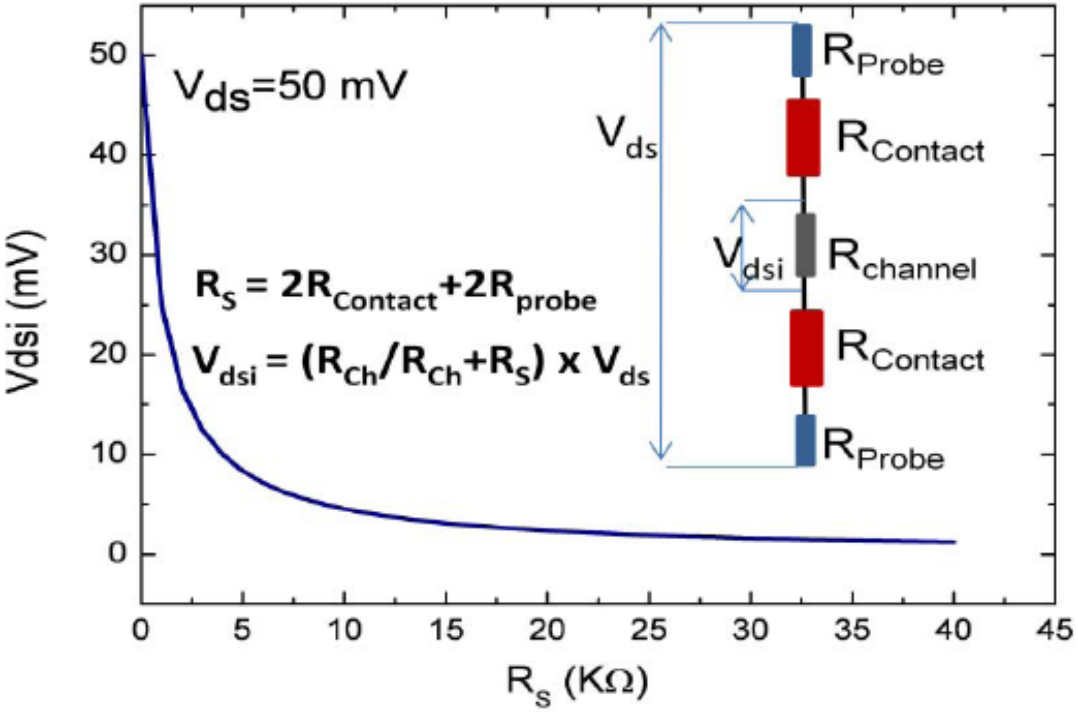
Crystal defects
CVD Graphene!

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

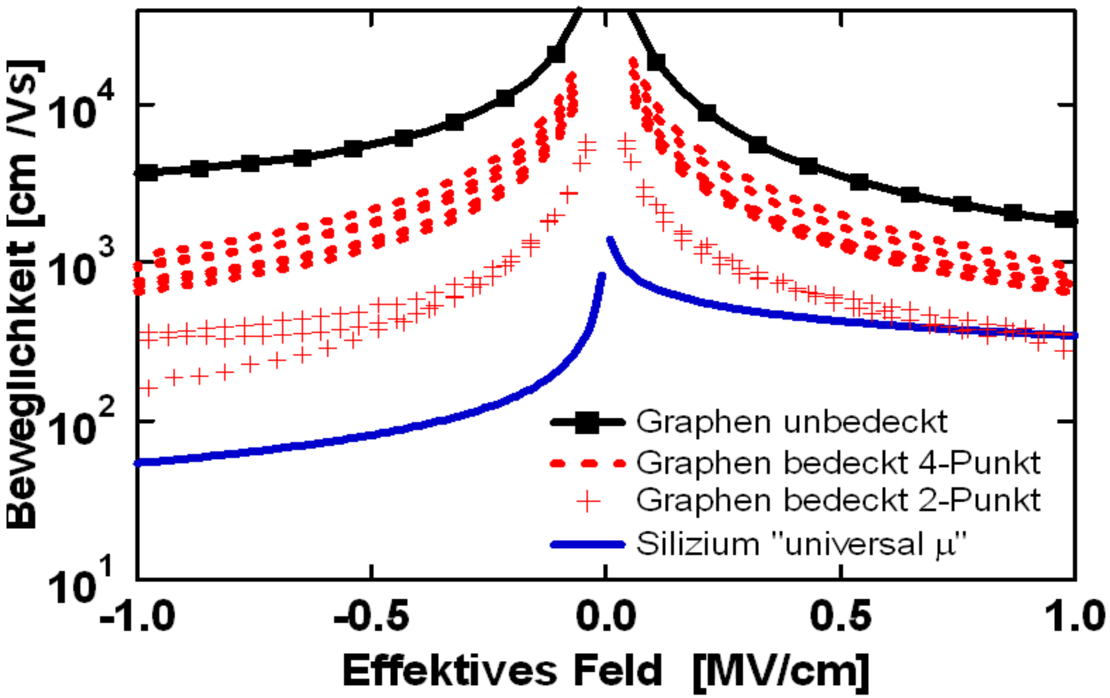
Silicon

Graphene Transistors: Contacts

Contact resistance and V_{DS}



Field Effect Mobility µ



Lemme et al. Solid St. Electr. 2008

Typical values on the order of 1 kOhm

Contact resitance needs to be improved

Outline

- Introduction
- **Graphene-based Transistors**
  - **RF Graphene FETs**
- Applications beyond ”Moore’s Law”
- Summary

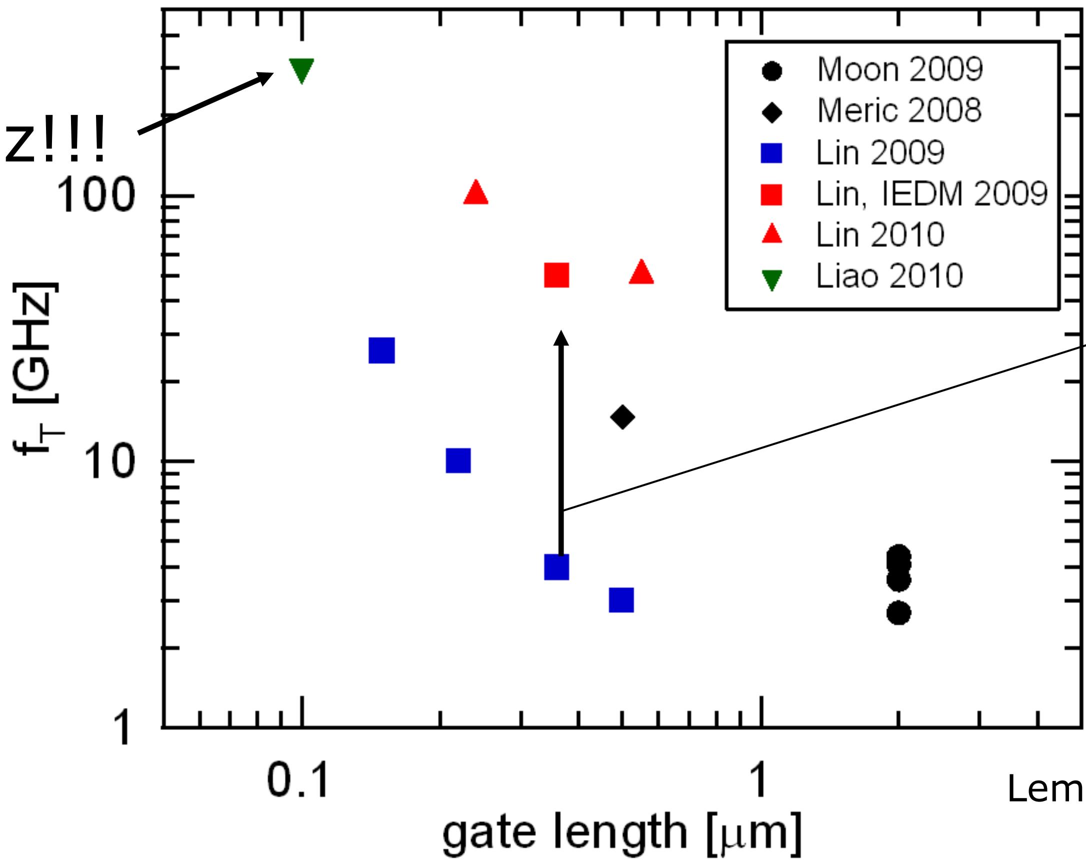
ROYAL INSTITUTE OF TECHNOLOGY

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

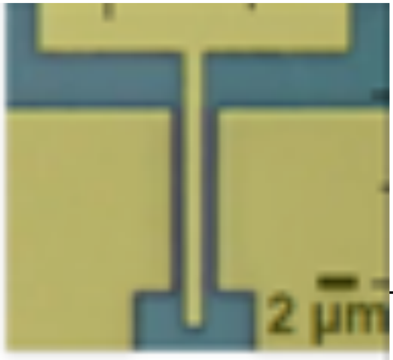
Lemme, Sol. St. Phenom., 2010

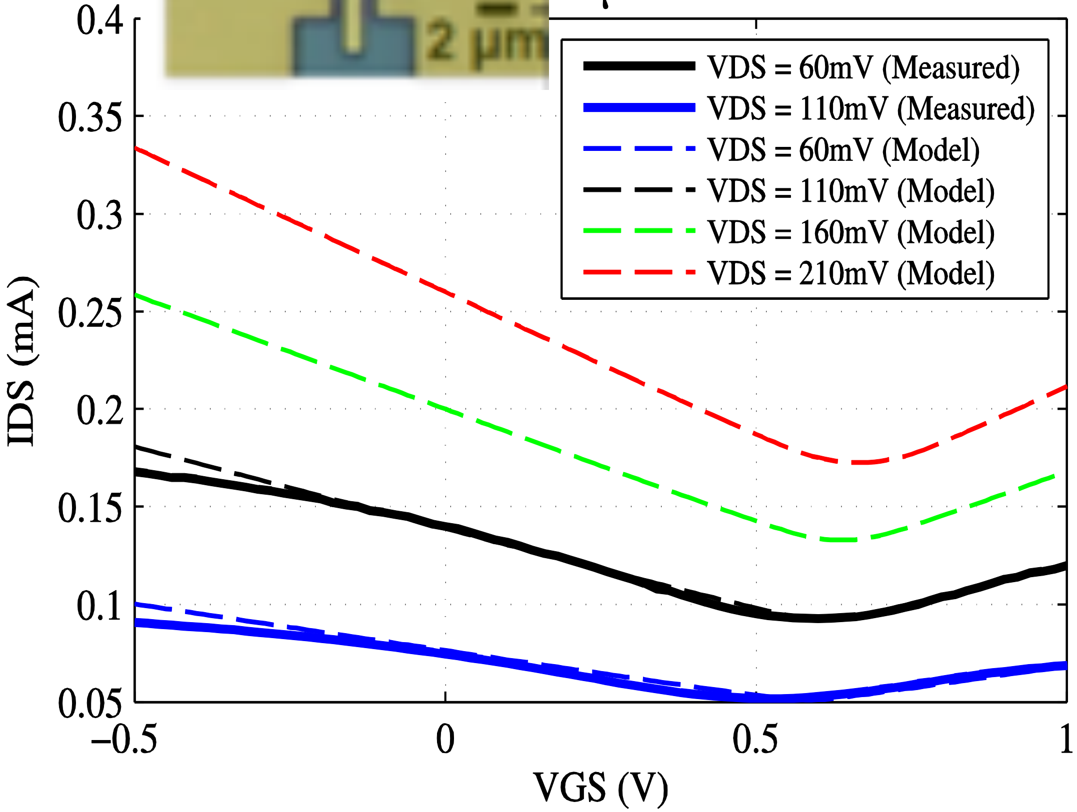
Performance Projections

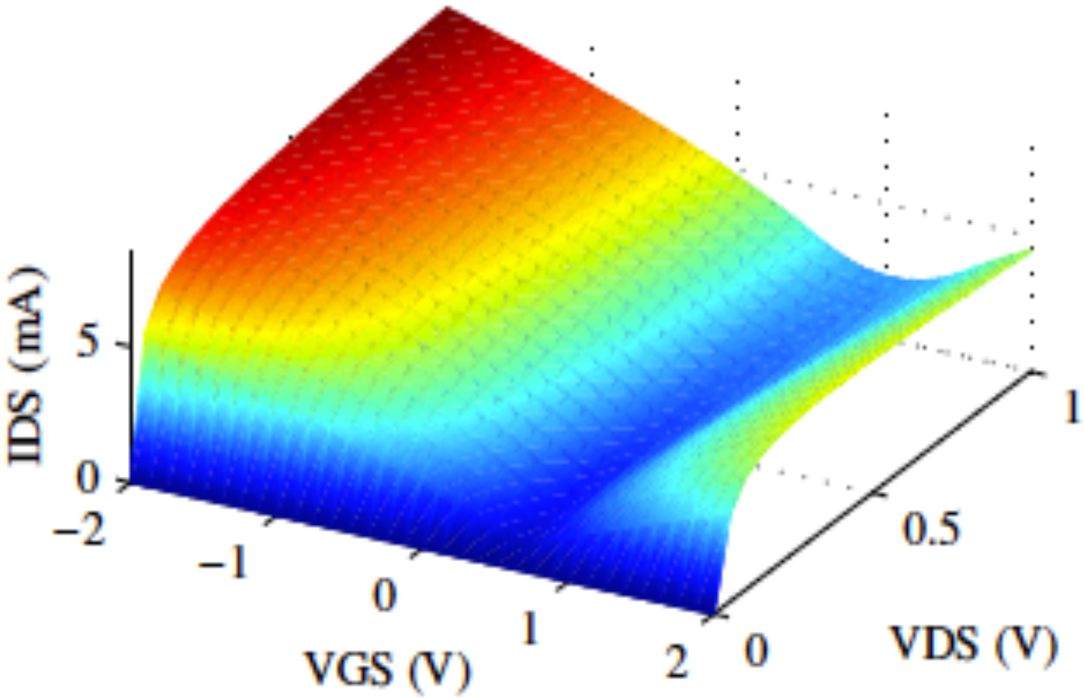
$L = 1\ \mu m$
$T_{ox} = 30\ nm$
$W = 10\ \mu m$
$\mu = 2500\ cm^2/Vs$

→

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







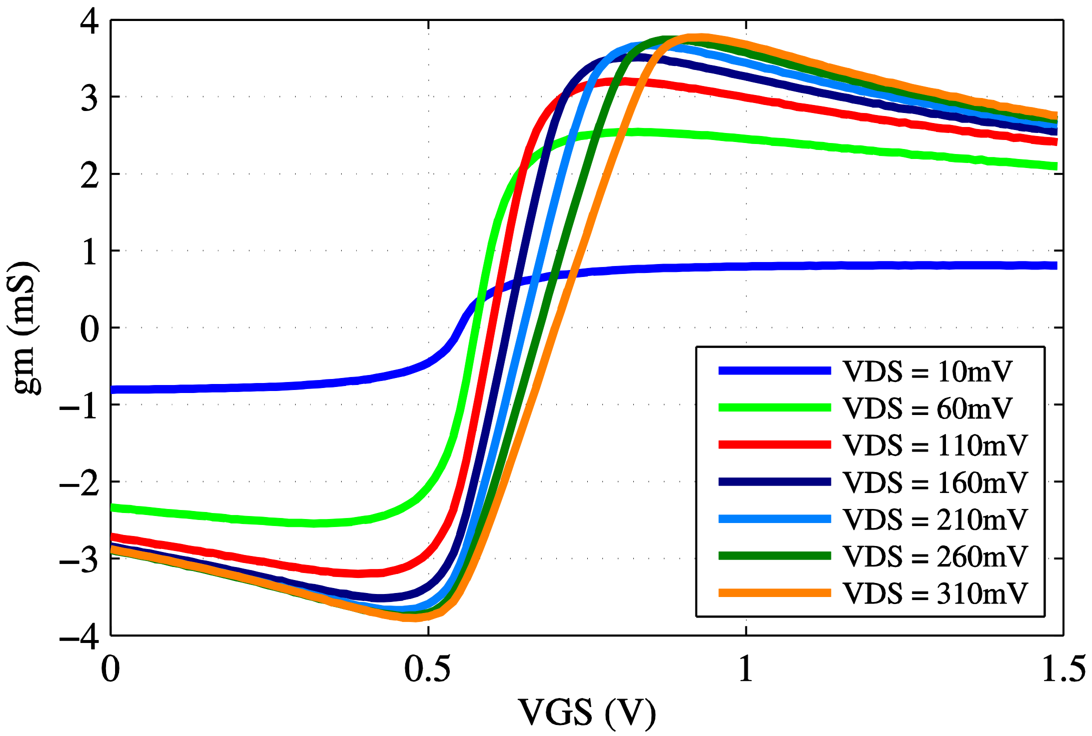
Rodriguez et al., arxiv, 2011

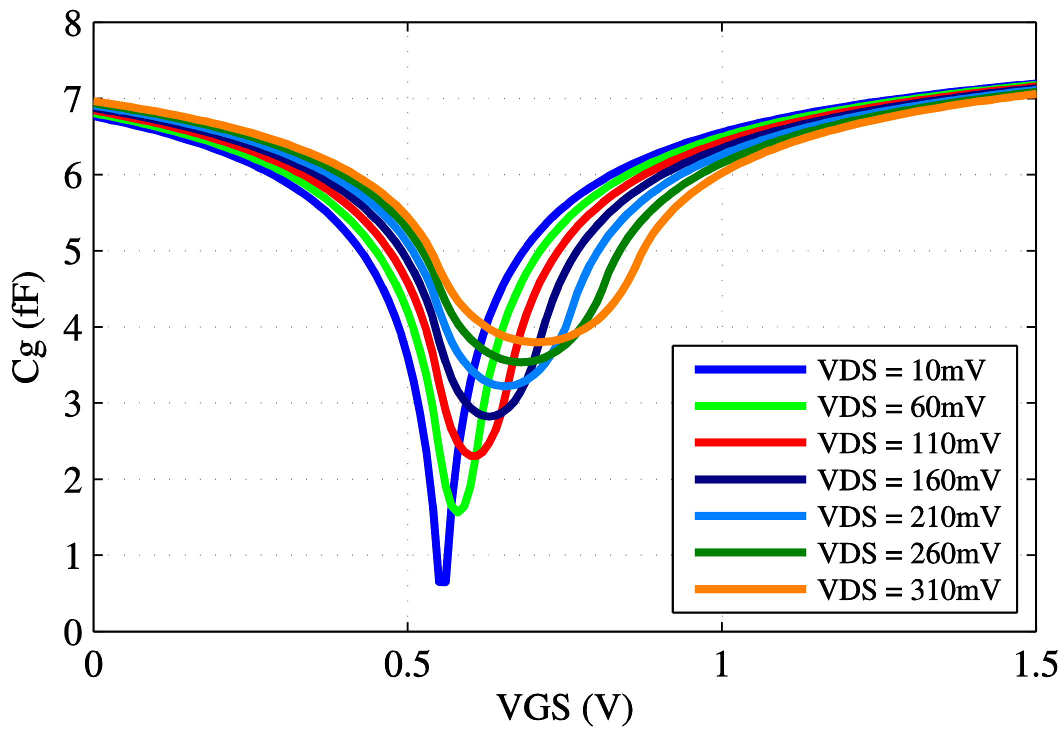
Refined model after:
Meric et al., Nature Nanotech 2008
Thiele et al., J. Appl. Phys., 2010

Performance Projections

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

$$C_G = W\int_0^{V_{DS}} \frac{C_{ox-top}\cdot C_q(V)}{C_{ox-top}+C_q(V)}\,dV$$



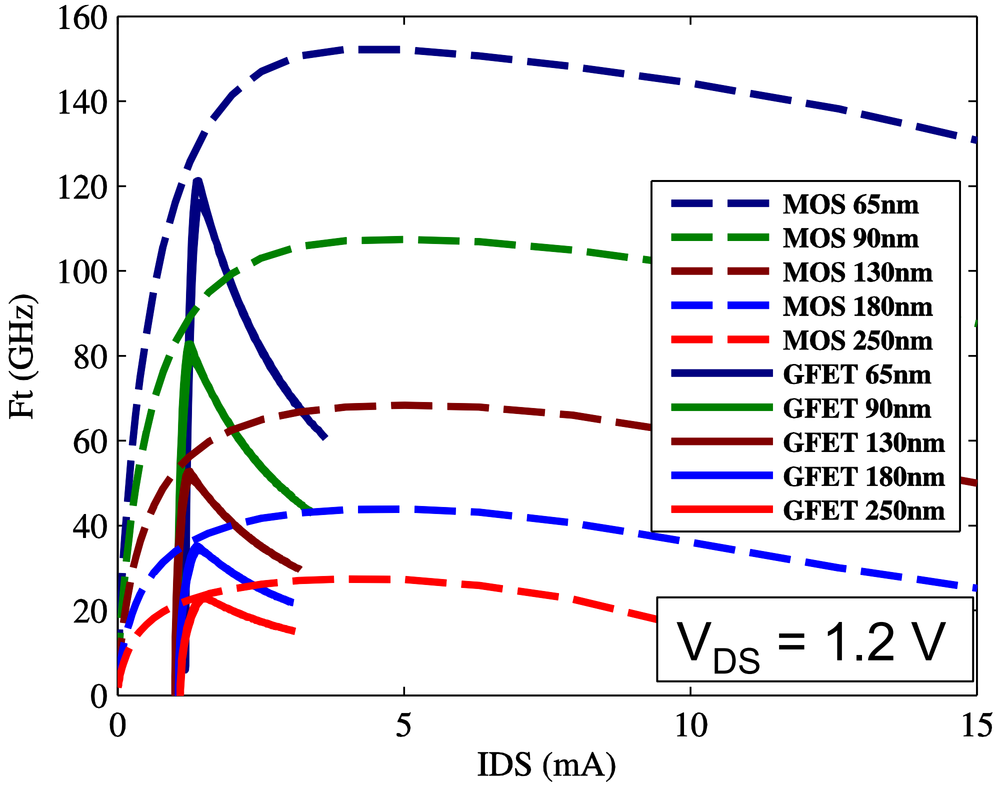


Rodriguez et al., arxiv 2011

Performance Projections

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

65nm GFET vs. Si-MOSFET

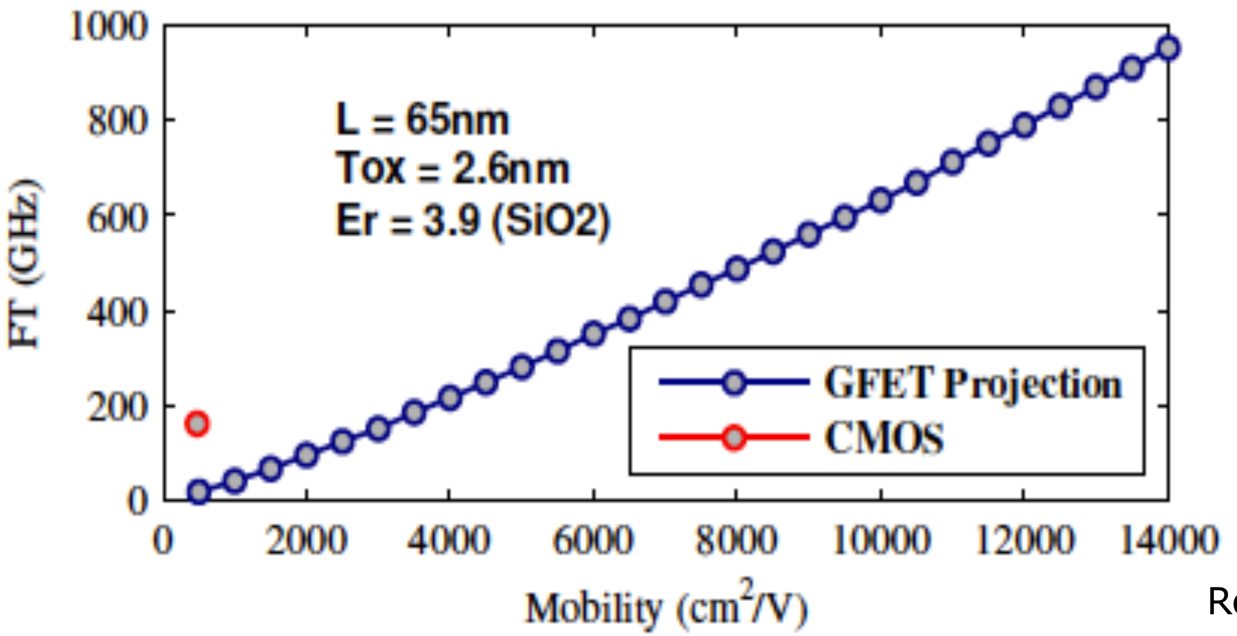


- $F_{T,MAX}$ of GFET almost as high as Si-CMOS at I_{DS} = 1μA
- Si-CMOS $F_{T,MAX}$ at higher current consumption than GFET $F_{T,MAX}$
- Superior mobility in GFETs NOT sufficient to provide higher performance than Si-MOSFETs
- GFETs achieve best performance in rather narrow I_{DS} range
- "Dead zone" for GFET amplifiers

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

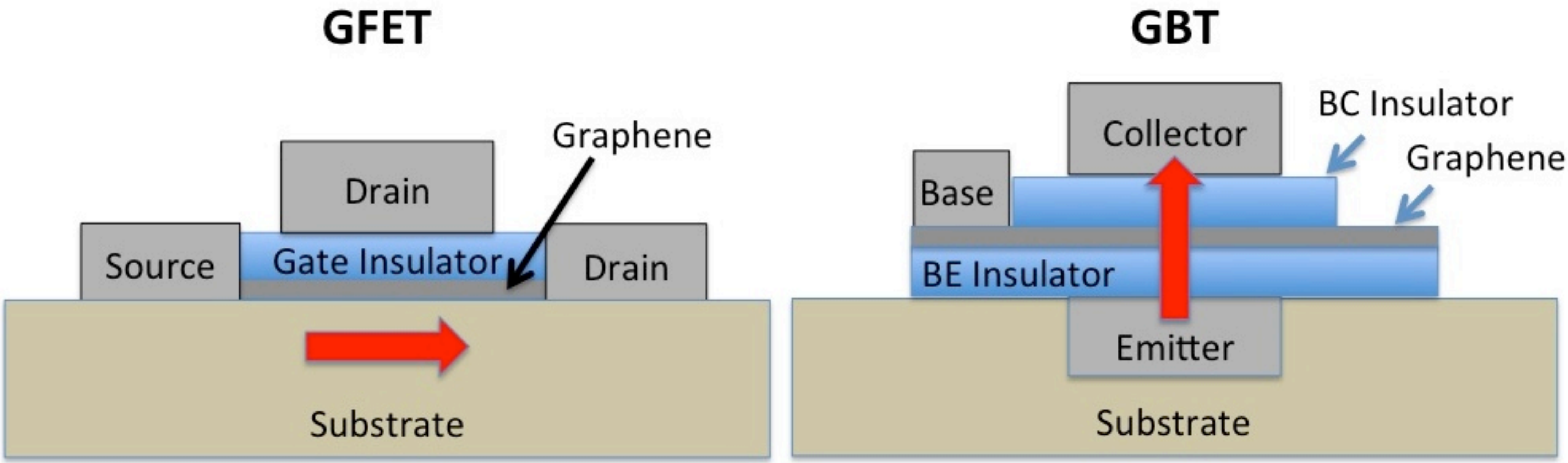
Graphene for post CMOS Applications

Outline

- Introduction
- **Graphene-based Transistors**
  - **Hot Electron Transistors**
- Applications beyond ”Moore’s Law”
- Summary

Graphene Base Transistors: GBT

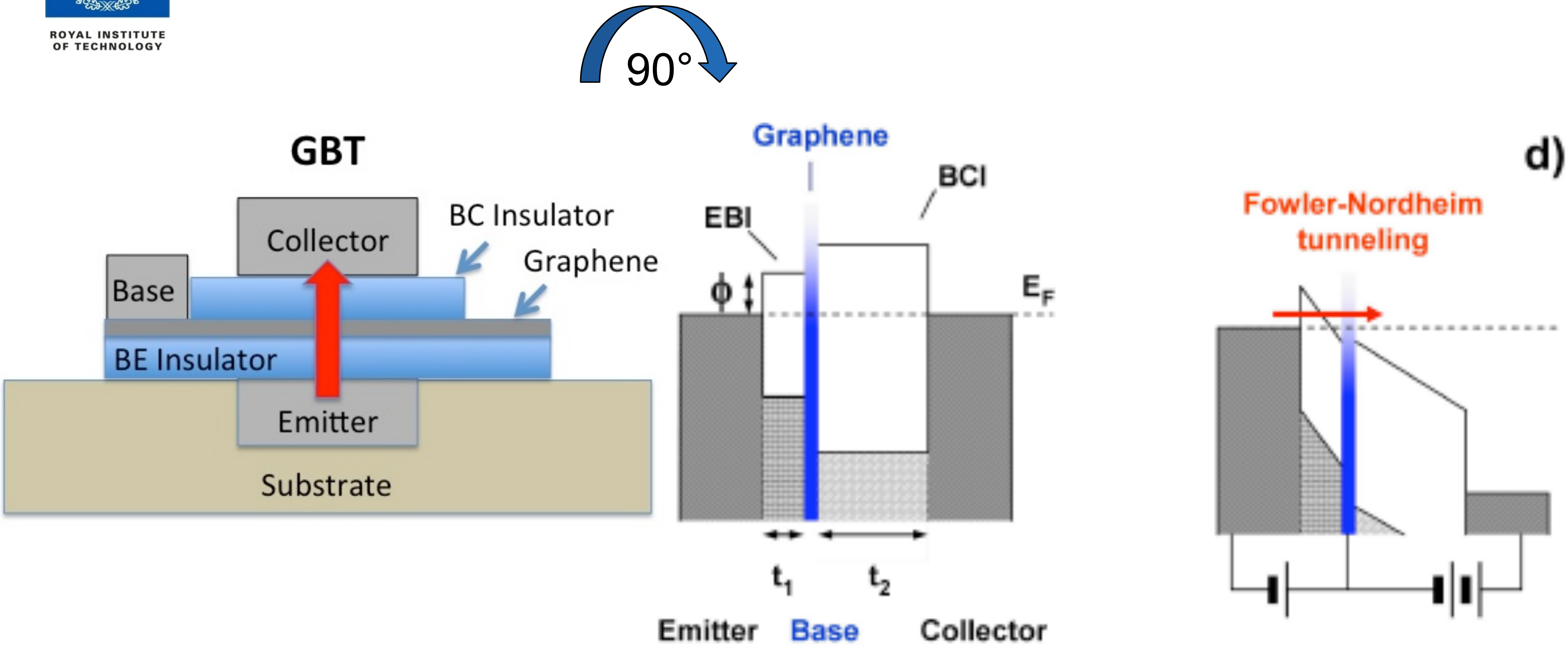
A new proposal: Graphene Base Transistor - GBT



W. Mehr et al, IEEE EDL, 33(5), 2012

- "Hot Electron" transistor
- Charge carriers are transported perpendicular to the graphene sheet
- Operation depends on quantum mechanical tunnelling
- Speed limit set by transport through base (here: 0.35nm monolayer!)

Graphene Base Transistors: GBT



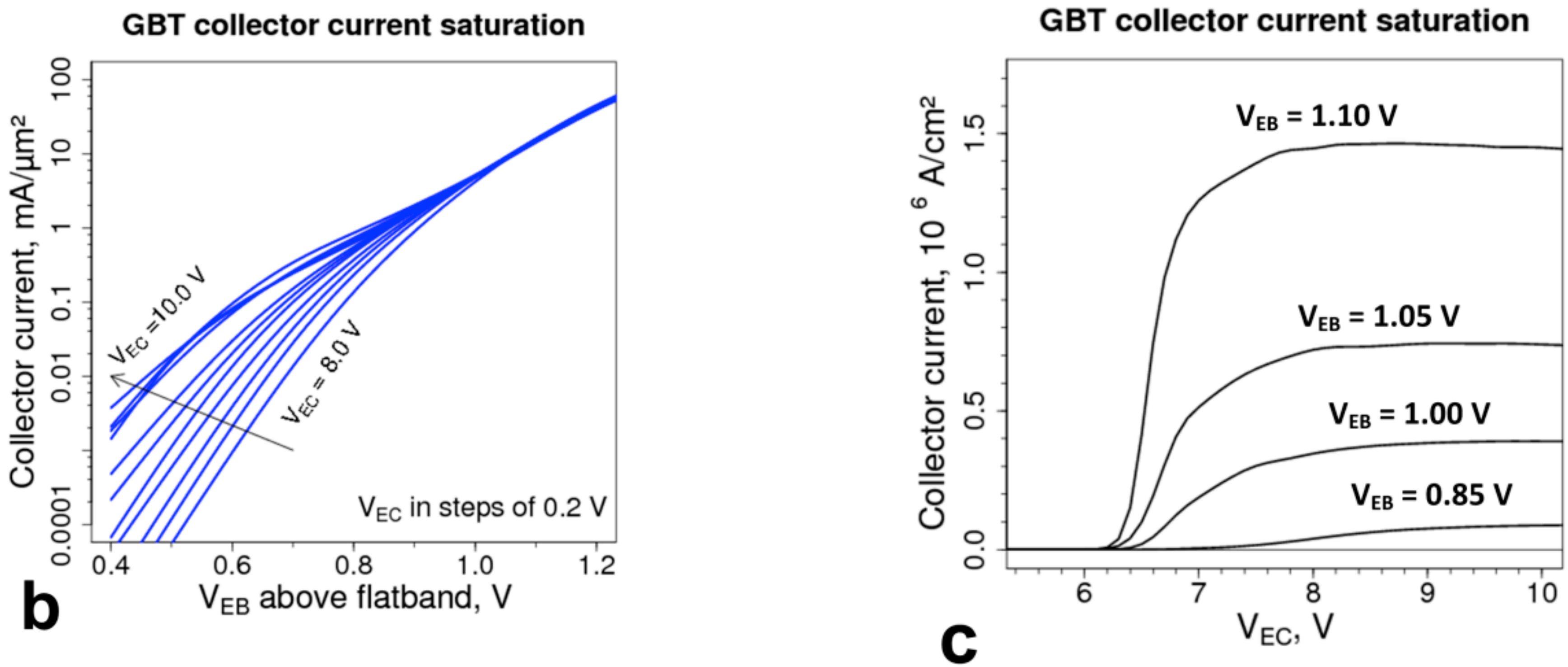
Unbiased

Biased

W. Mehr et al, IEEE EDL, 33(5), 2012

Graphene Base Transistors: GBT

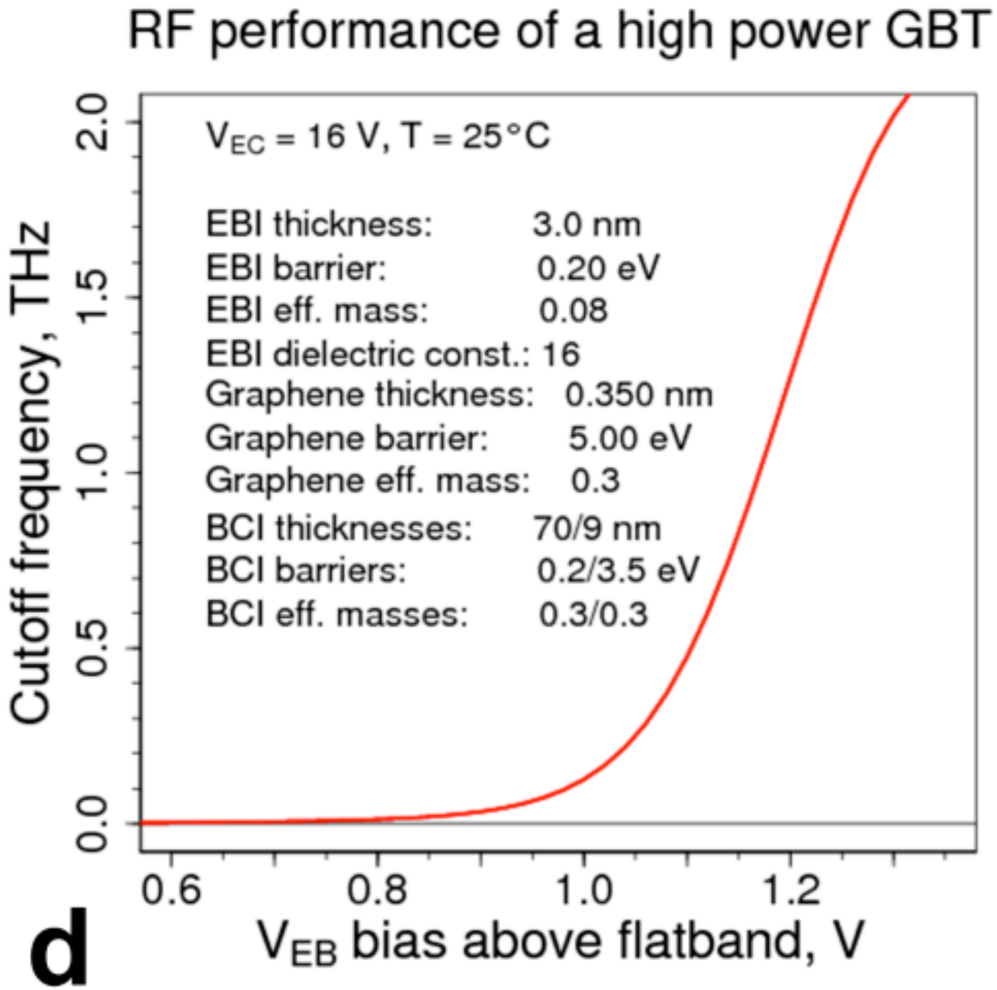
W. Mehr et al, IEEE EDL, 33(5), 2012



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

Graphene Base Transistors: GBT

Performance Projections



THz Operation seems feasible

W. Mehr et al, IEEE EDL, 33(5), 2012

Graphene for post CMOS Applications

Outline

- Introduction
- Graphene-based Transistors
- **Applications beyond ”Moore’s Law”**
  - **Optoelectronics**
- Summary

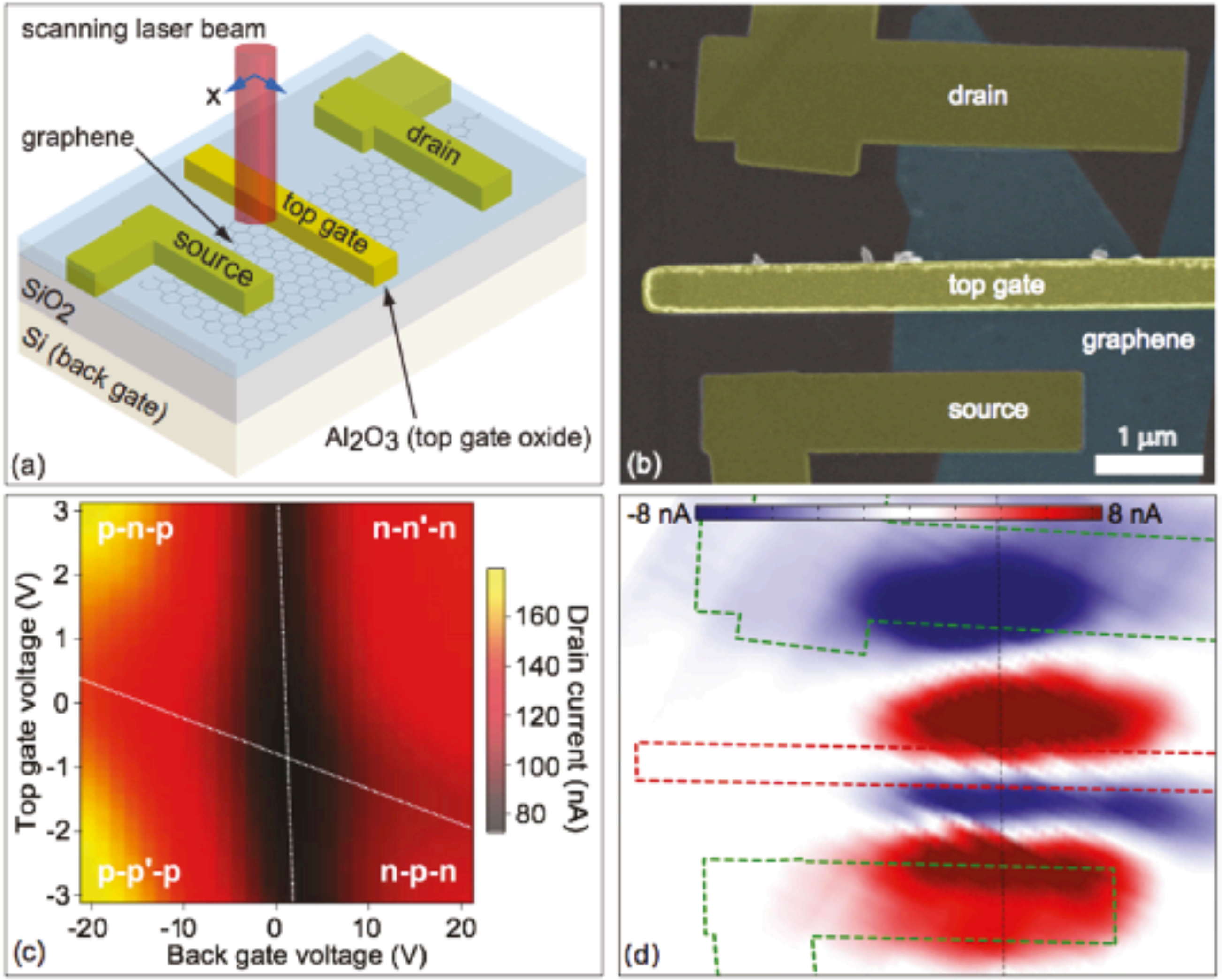
Graphene Optoelectronics

- E-k linear up to +- 1eV
- Potential from visible spectrum to THz
- High data rates (high carrier mobility)

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

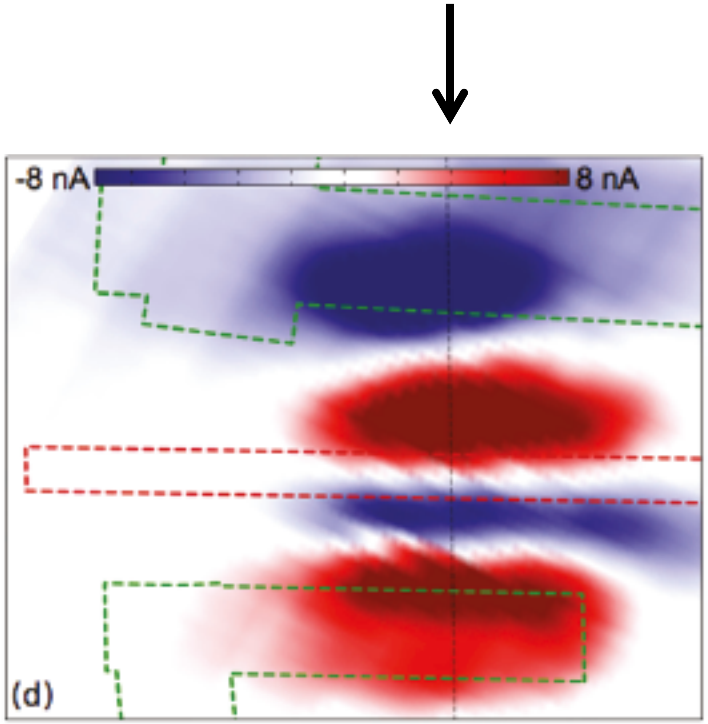
Graphene: Photodetection

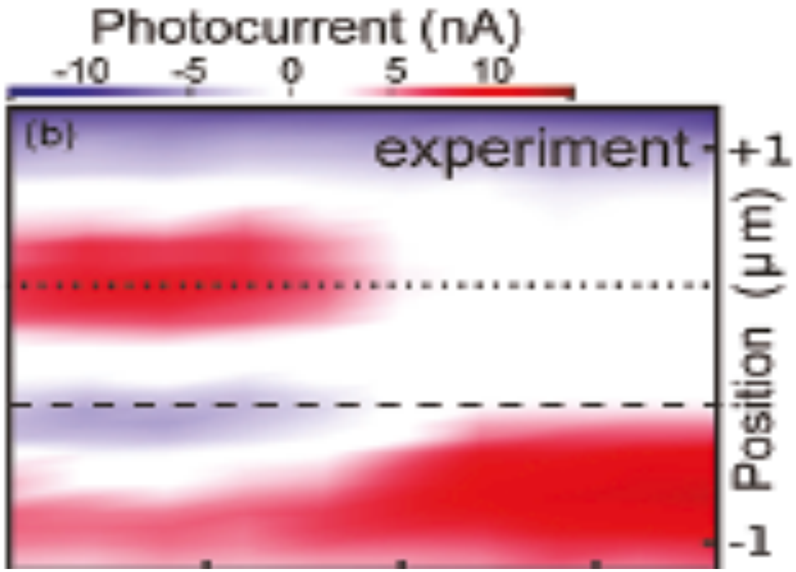
Graphene Photodetectors: Local Tunability

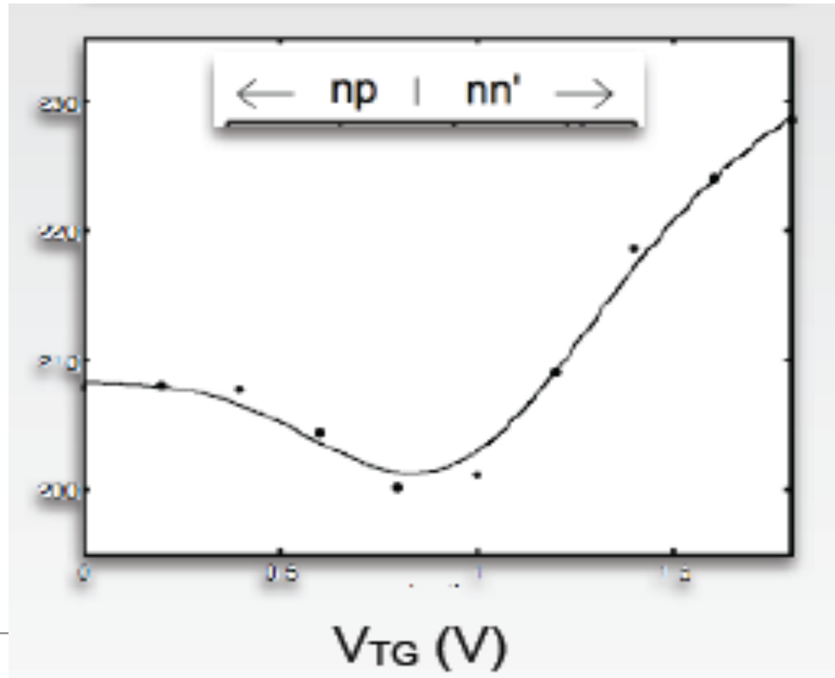


Lemme, Koppens, et al. "Gate Controlled Photocurrent in a Graphene p-n Junction", Nano Letters, 11, 2011.

Graphene: Photodetection

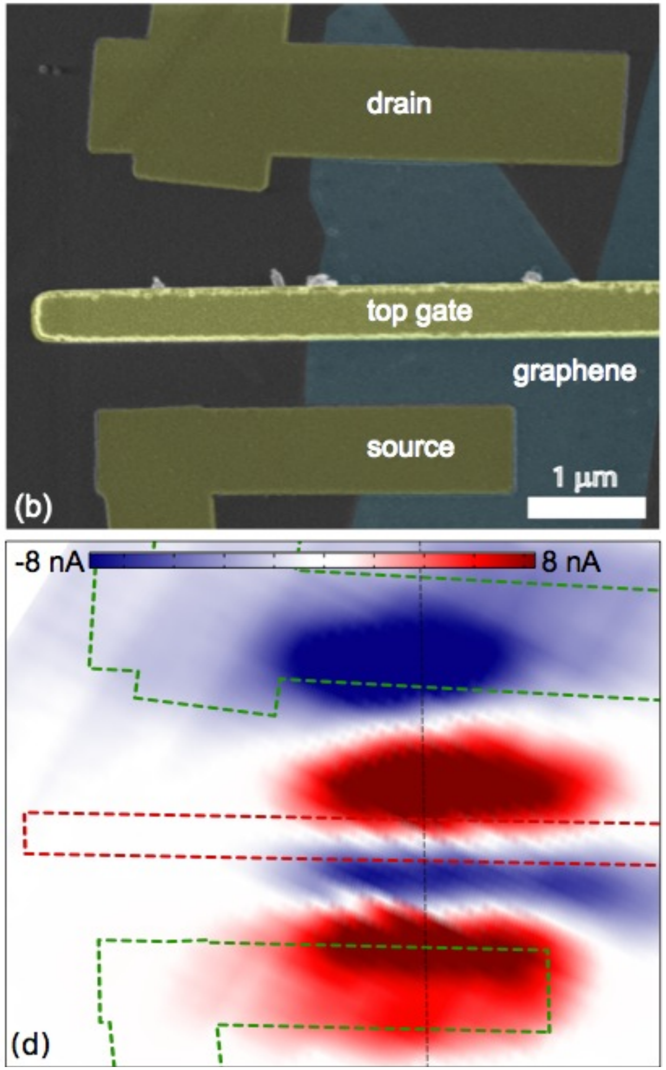






- Strong photoresponse in pn junction
- Weak photoresponse in similar carrier gradient (nn’ or pp’)

Graphene: Photodetection



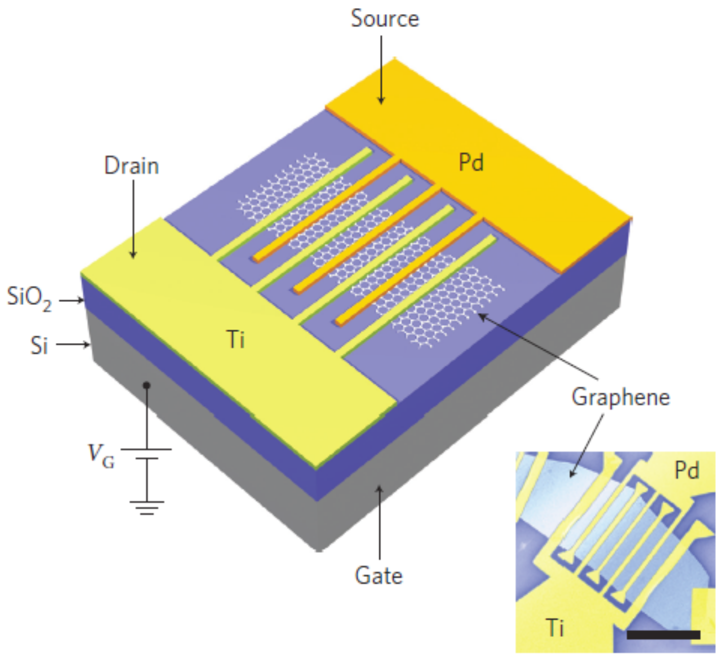
Lemme et al., Nano Letters 2011

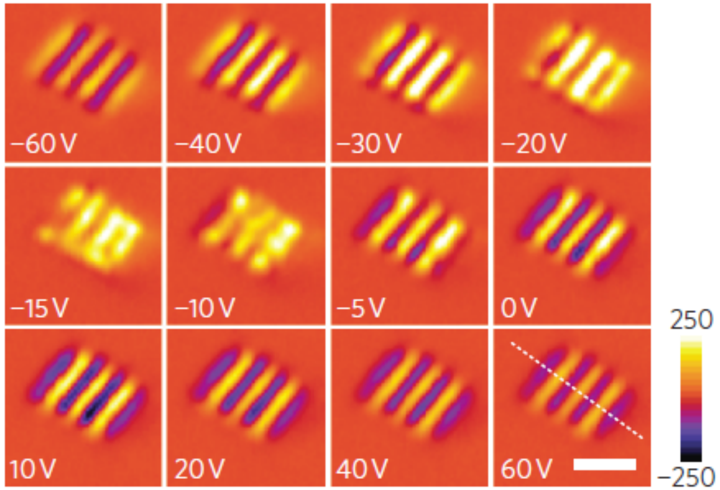
- Strong contribution from Seebeck effect (pn-junction required) -> Bolometers
- Local control of p-n junction allows on-off control of photodetection
- Scalability to submicron gates and potential to integrate into existing platforms
- Potential for UV to THz applications, but competing effects are not identified for whole spectrum
- Plasmonics:
  - Echtermeyer et al., “Strong plasmonic enhancement of photovoltage in graphene”, Nature Communications 2, 458 (2011)
  - Koppens et al., “Graphene plasmonics: a platform for strong light-matter interactions.,” Nano Letters, 11(8), 2011

Graphene Optoelectronics

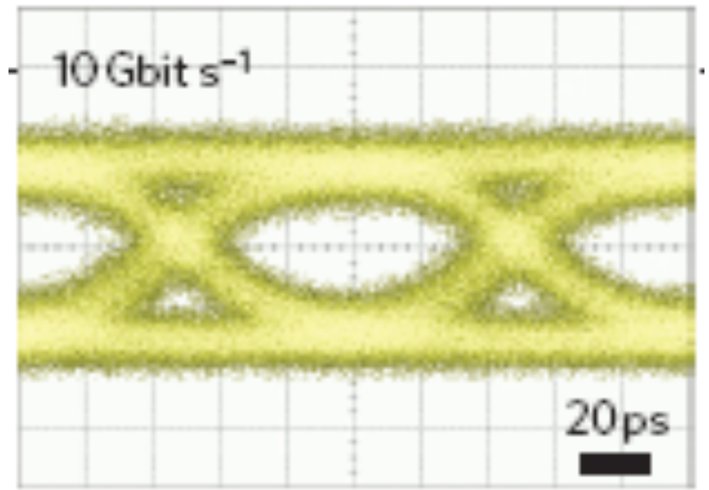
Graphene photodetectors for high-speed optical communications

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

Outline

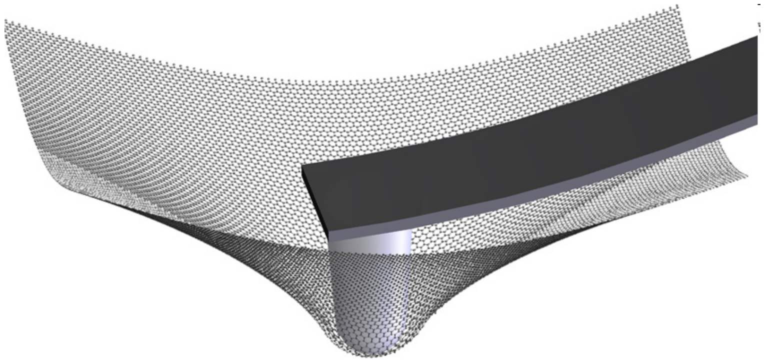
- Introduction
- Graphene-based Transistors
- **Applications beyond ”Moore’s Law”**
  - **NEMS**
- Summary

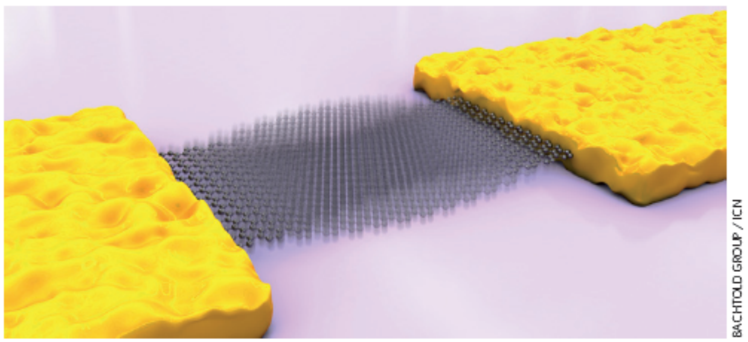
KTH VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

Graphene NEMS

NEMS

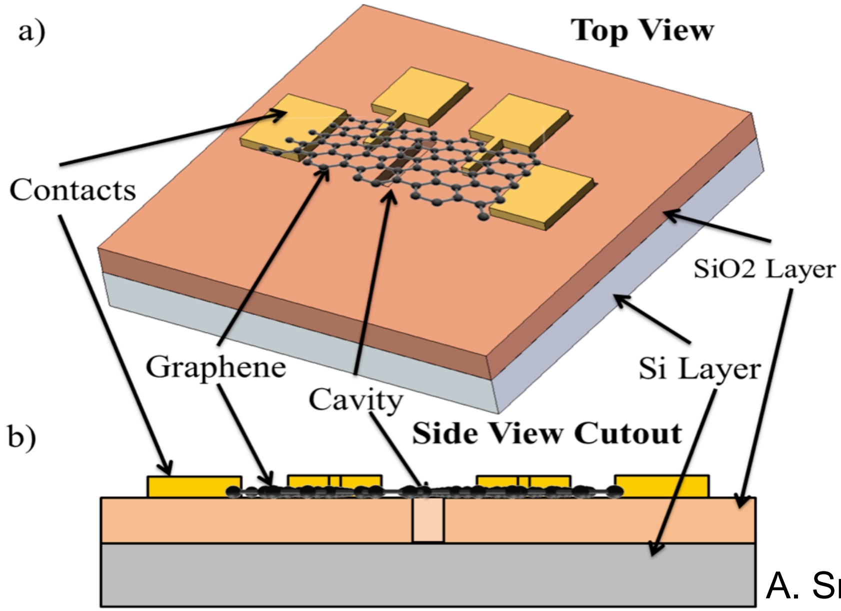
Lee et al., Science, 385-388, 18 July 2008





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



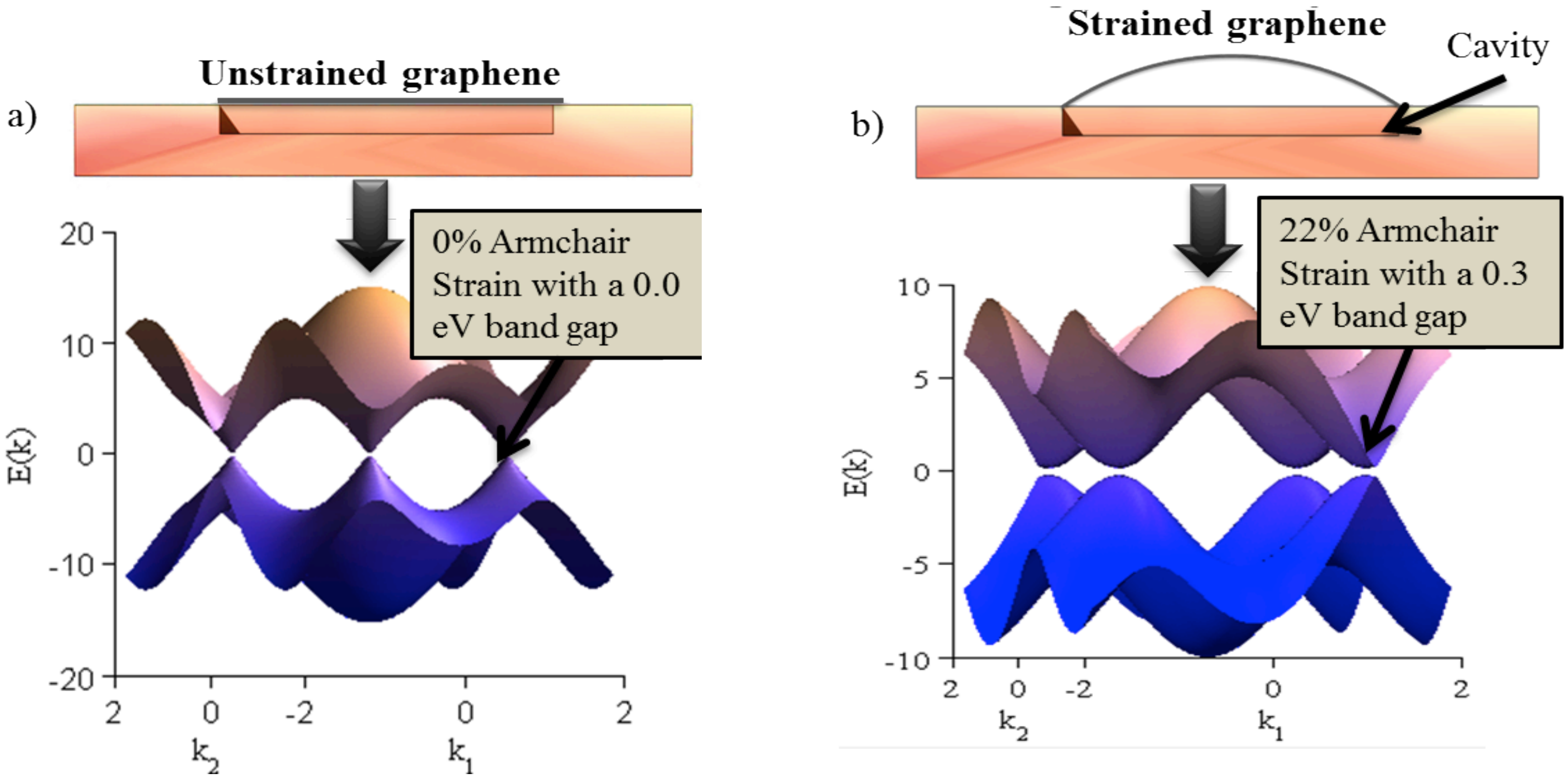
A. Smith, ULIS 2012

Graphene based mass, force, pressure sensors

Graphene NEMS

Concept: Piezoresistive Detector

A. Smith, ULIS 2012



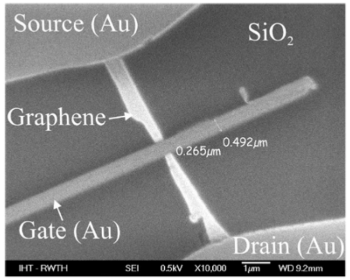
- Combinations of strain lead to band gaps up to 1 eV.
- Small strain will shift the Dirac point and therefore change the DOS
- This will in turn change the resistance
- Pressure gauge: Deflection due to pressure difference causes strain

Graphene for post CMOS Applications

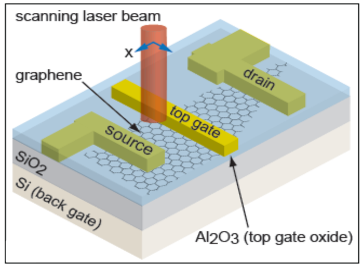
Outline

- Introduction
- Graphene-based Transistors
- Applications beyond ”Moore’s Law”
- **Summary**

Summary



- Graphene is a "Serious" Electronic Material
- Large Area Manufacturing Available
- Electronic Applications
  - Analog Transistors
  - GBTs
  - Optoelectronics (e.g. Photodetector)
  - NEMS (e.g. Pressure Sensor)
  - Printable Electronics



Graphene: Research Topics

ROYAL INSTITUTE OF TECHNOLOGY

- Interconnects
- Passives, Antennas
- Plasmonics
- Supercapacitors
- Transparent Electrodes
- Mechanical Applications (avionics, car industry)
- Chemical / Biosensors (Functionalized Surfaces)
- Resistive Switching (Memory Applications)
- Ballistic Devices
- Spintronics (Spin-Valves, SpinMOSFET, SpinFET)
- …other 2D Materials (h-BN, MoS_2…)

Thank you for your attention!