UNIVERSITY OF CAMBRIDGE
Department of Engineering

CAMBRIDGE GRAPHENE CENTRE

Graphene electronics and optoelectronics

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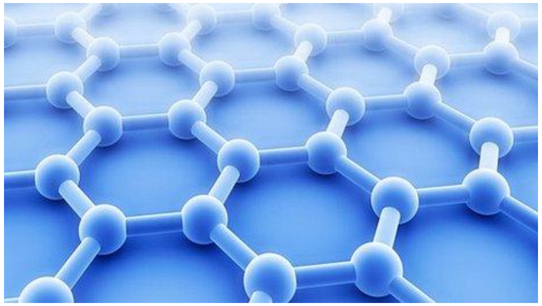
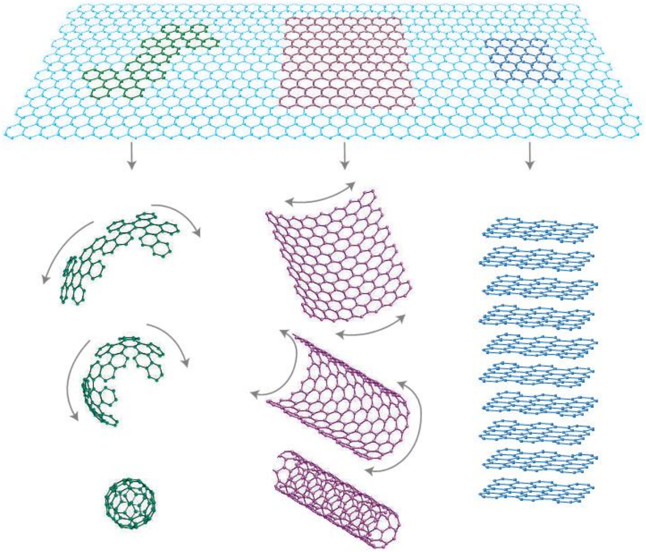
Graphene: what is that?

“Sheet” of carbon atoms arranged in an hexagonal lattice, one atom thick!



“Building block” for carbons of other dimensionalities:

- graphite
- carbon nanotubes
- fullerenes



Nature Materials 6, 183

Graphene: the groundbreaking experiment

22 OCTOBER 2004 VOL 306 SCIENCE

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]

Individual graphene layers can be extracted from 3-dimensional graphite

Stable under ambient conditions

Remarkable electronic properties: ambipolar transport, mobility ~10^3 cm^2/Vs

Nobel prize in Physics 2010

Graphene: properties & technology

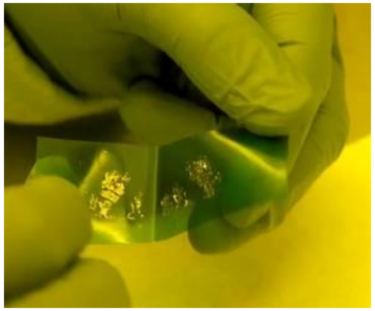
Properties:

- Charge carriers mobility: $>10^5$ cm^2/Vs (room T), $>10^6$ cm^2/Vs (low T) – high speed
- Saturation velocity: $> 10^7$ cm/s (even for fields up to 50 KV/cm) – scalability
- Thermal conductivity: > 3,000 WmK^{-1} – heat dissipation
- Current-carrying capacity: $>10^8$ A/cm^2 - interconnects
- Young modulus ~ 1TPa
- Stretchable up to 20% - flexible, wearable electronics
- Broadband optical absorption - optoelectronics
- Possibility of chemical functionalization

Technology:

- fully compatible with silicon-based planar fabrication technology
- can be integrated with practically every substrate (e.g. Si, plastic, etc.)

Graphene: production



Mechanical cleavage
- Highest quality
- Low yield

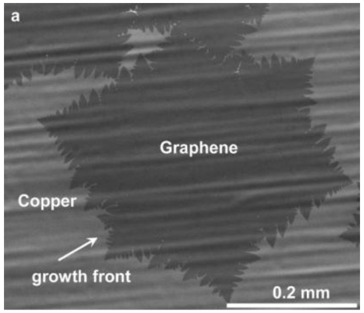
↓

- Research
- Prototyping

Liquid phase exfoliation
- Exfoliation by ultrasounds
- Cheap and scalable

↓

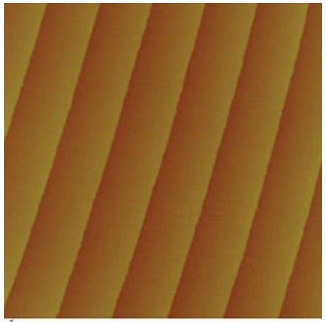
- Inks, printed electronics
- Coatings
- Composites



Chemical vapour deposition
- Growth on Cu, scalable
- Transfer

↓

- Large area
- Integrated circuits



Growth on SiC
- Thermal decomposition
- High T

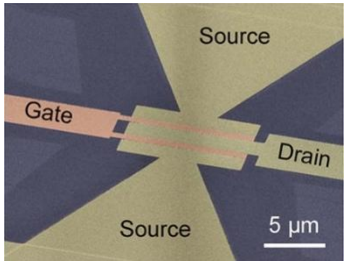
↓

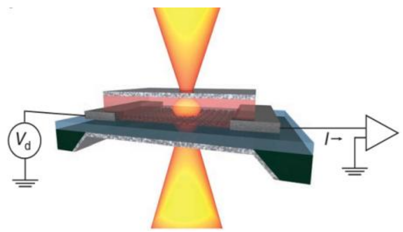
- High-frequency electronics

Graphene: a "family" of materials, very different properties

Graphene production and processing review: Bonaccorso, Lombardo et al., Materials Today 15, 564

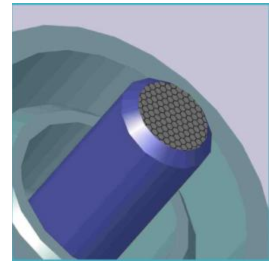
Graphene: applications



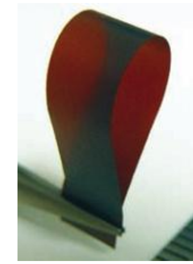


Electronics:
- High-frequency transistors
- Printed electronics

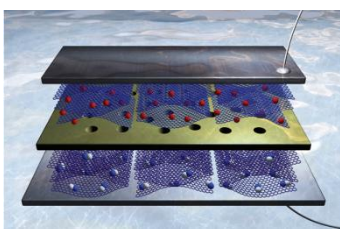
Optoelectronics
- Photodetectors
- THz detectors



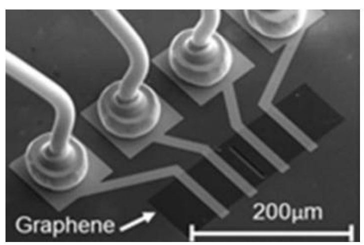
Photonics
- Optical modulators
- Mode-locked lasers



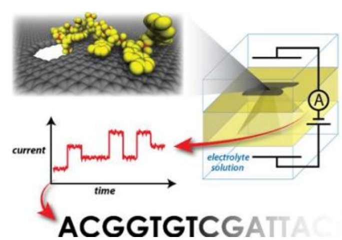
Composites & coatings
- Reinforcements
- Barriers



Energy:
- Supercapacitors
- Batteries



Sensors & metrology:
- Strain gauges
- Resistance standards (QHE)

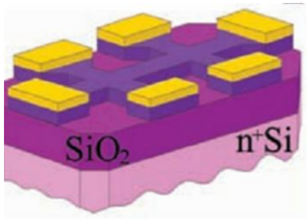


Bioapplications:
- Drug delivery
- Support for TEM
- Biosensing (e.g. DNA)

"Graphene does not just have one application, It is not even one material. It is a huge range of materials. A good comparison would be to how plastics are used"

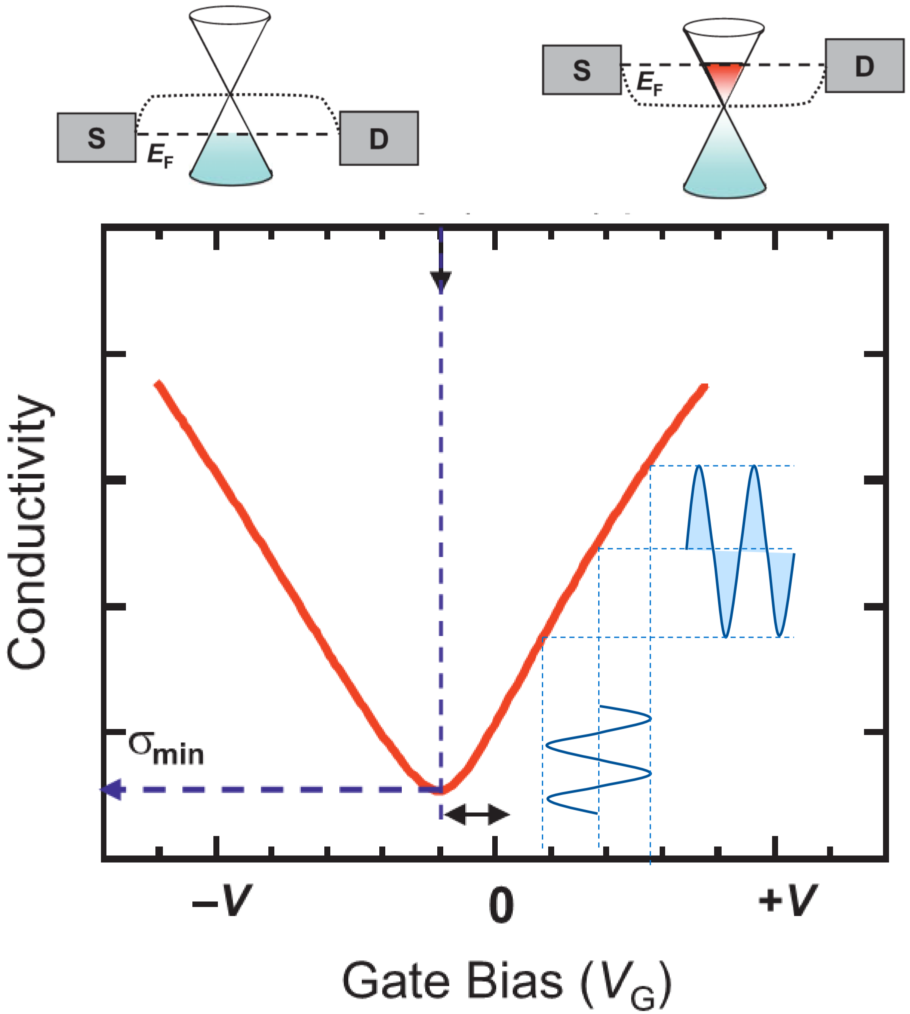
BBC News, May 2011

Graphene field effect transistors (GFETs)



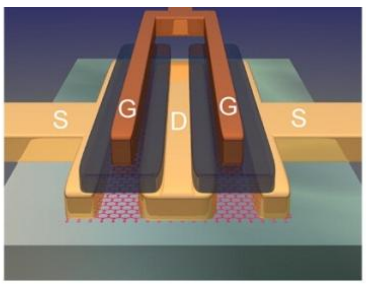
[Novoselov et al., Science 306]

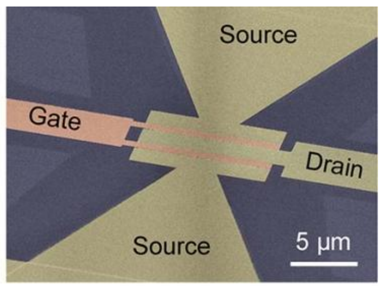
- Back gating (heavily doped Si substrate): optical visibility, easy fabrication
- **Ambipolar** field effect: charge carriers can be continuously "tuned" between electron and holes.
- Graphene FETs do not switch off completely, $I_{ON/OFF}$ ratio ~10
- In **analog RF**, switch off not essential (e.g. signal amplifiers always ON state)



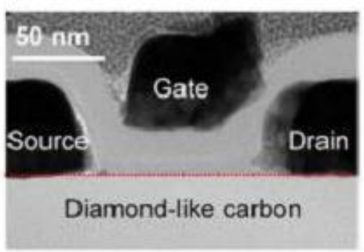
Graphene RF transistors

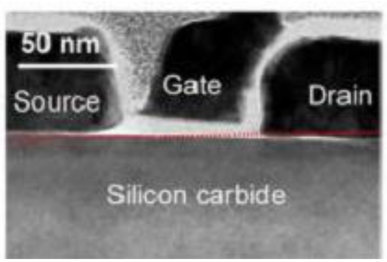
- Robustness against short channel effect
- High saturation velocity (>3x10^7 cm/s) even at high field
- Dual channel configuration

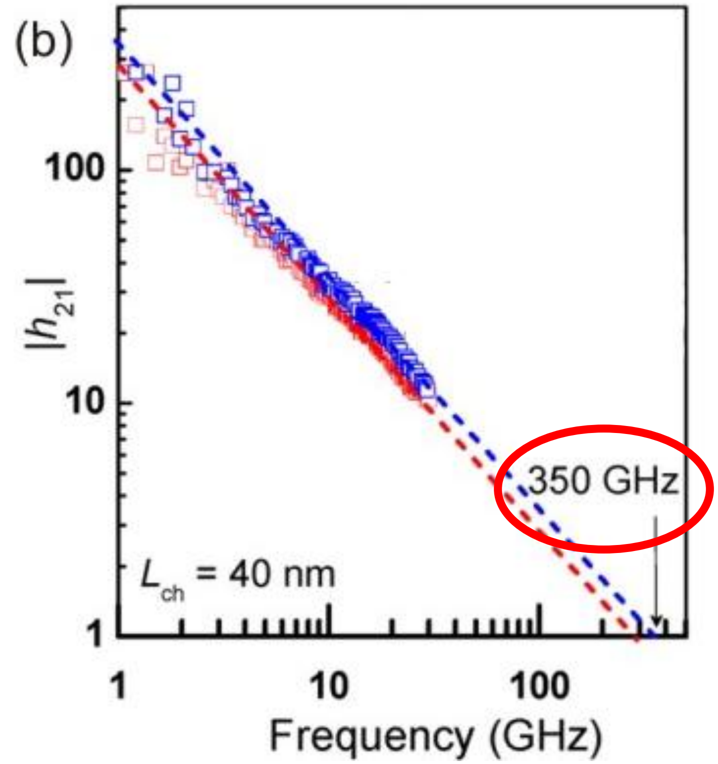




- Already scalable, operating frequencies above 300GHz both on CVD and epitaxial graphene



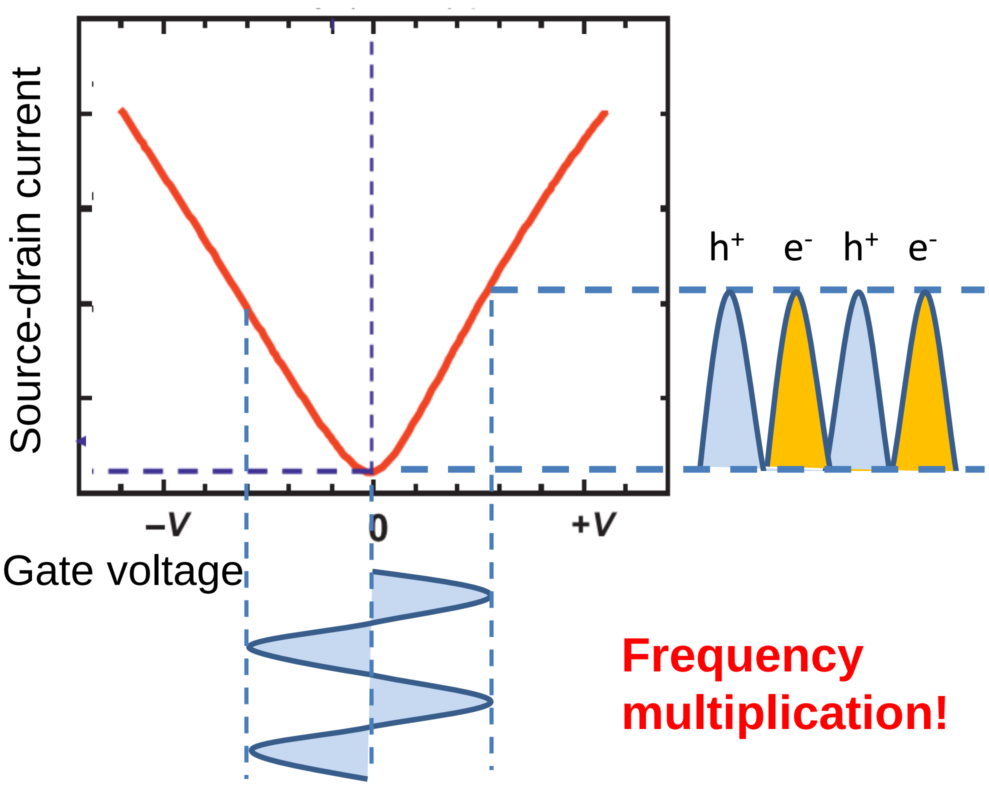




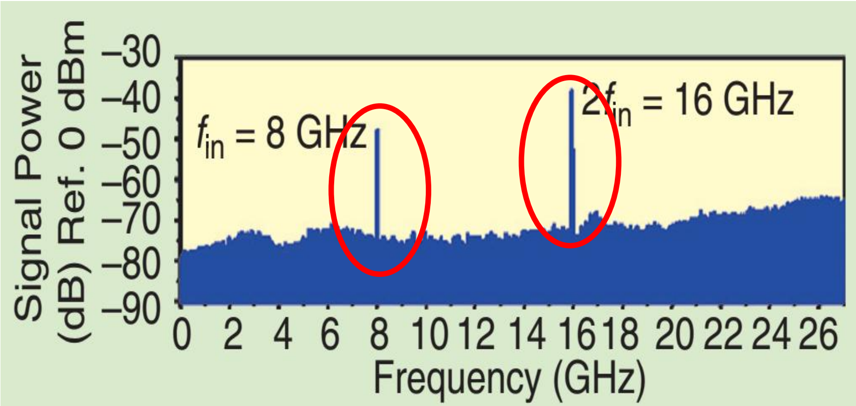
[Wu et al., Nano Lett. 12, 3062]

GFETs as frequency multipliers

- Ambipolar field effect, symmetric transfer characteristics



Frequency multiplication!



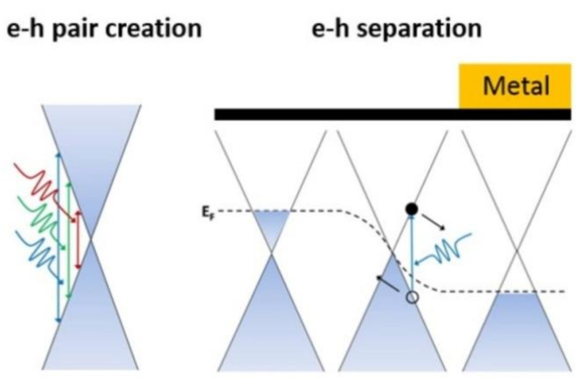
Peak @16GHz = 11dB higher than peak @8GHz → 93% of the output power is at the doubled frequency

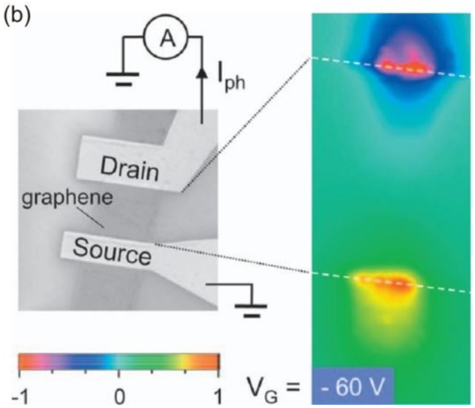
Single transistor, no filtering element!

[Wang et al., IEEE Microw. Mag. 13]

Graphene photodetectors

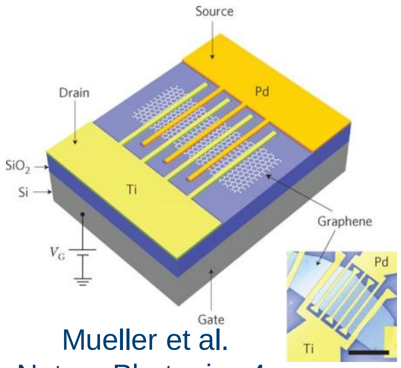
- Strong interaction with light (2.3% absoption)
- Broadband absorption
- Working principle: internal fields occurring at metal-graphene interface



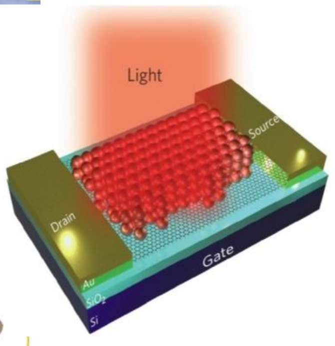


[Mueller at al., PRB 79, 245430]

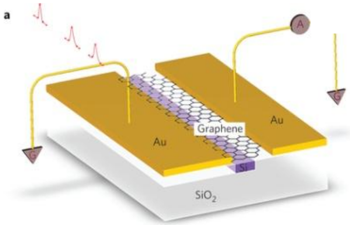
- Improvement of responsivity



Mueller et al.
Nature Photonics 4, 297

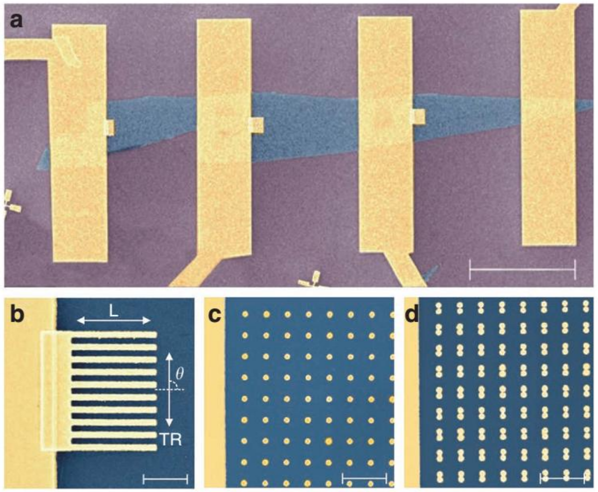


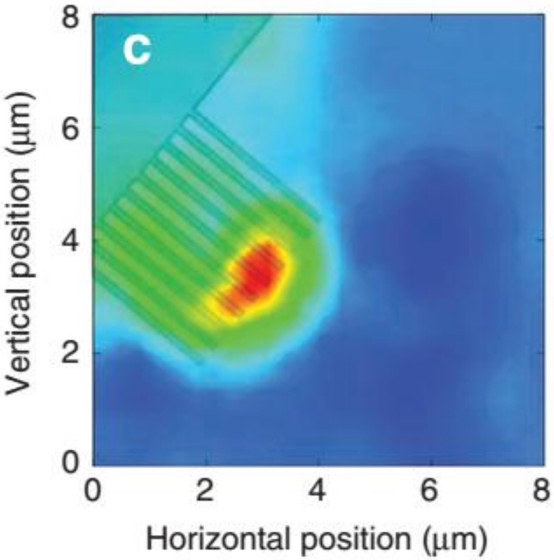
Konstantatos, et al.
Nature Nanotech. 7, 363

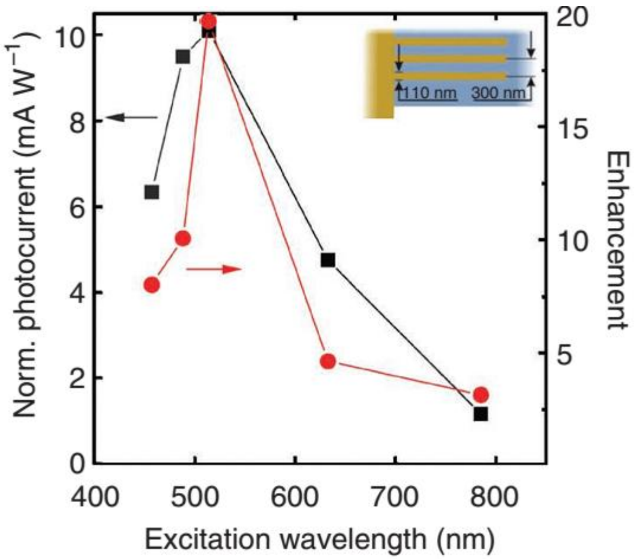


Gan, et al.
Nature Photonics 7, 883

Plasmonic-enhanced photodetectors



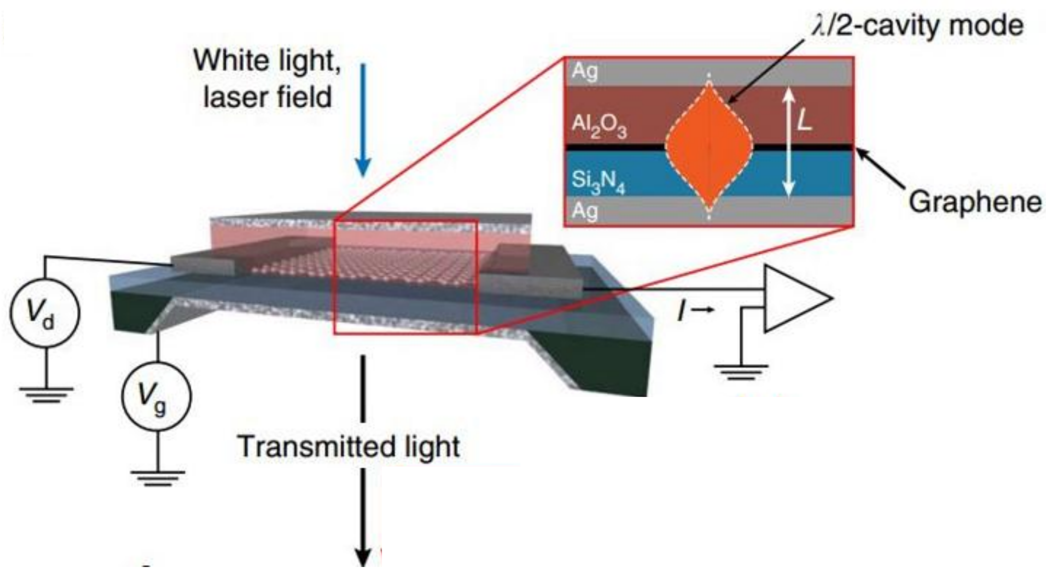


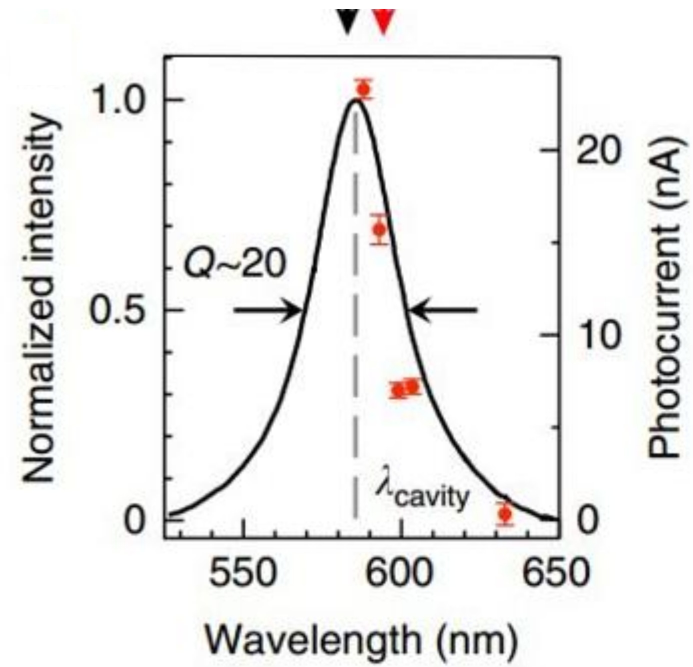


- Combination of graphene with plasmonic nanostructures
- Wavelength and polarization selectivity

[Echtermeyer, Britnell, Jasnos, Lombardo at al., Nature Comm. 2, 458]

Microcavity-controlled graphene transistor



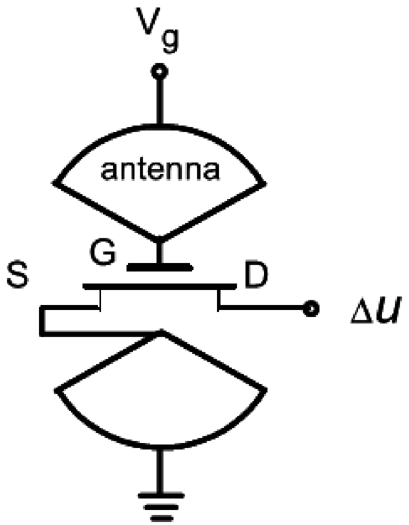


- Microcavity-induced optical confinement
- Spectrally selective light detector
- Enhanced photoresponse
- Electrically excited, narrow band thermal light emitter

[Engel, Steiner, Lombardo at al., Nature Comm. 3, 906]

FET as THz detectors

- FET (Dyakanov-Shur) detection mediated by generation of plasma waves in the channel → high sensitivity, fast response
- THz radiation coupled between gate and source (antenna coupling)
- THz field induces plasma waves propagating in the FET channel
- Resonant detection: only at specific radiation frequency
- Non resonant detection (plasma waves overdamped): broadband
- Modulation of both charge carrier density and carrier drift velocity.
- Carriers travelling towards the drain generates a DC voltage between source and drain

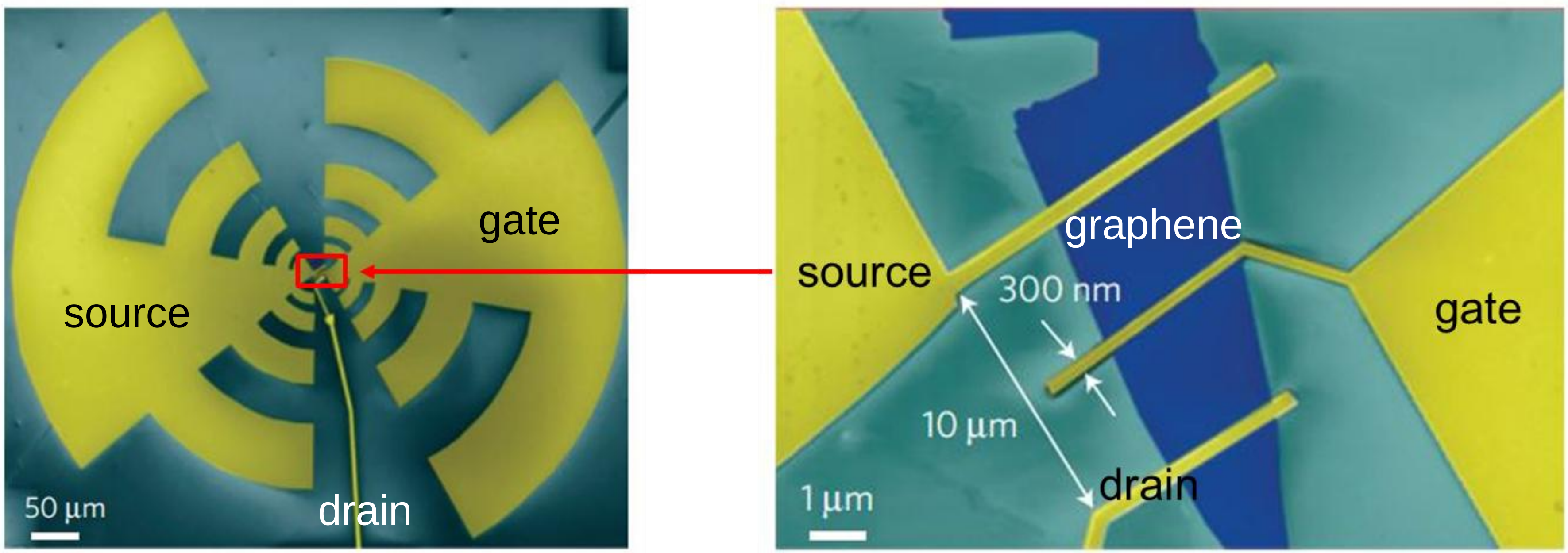


[Knap et al., Nanotech. 24]

- Key requirement: **high mobility → graphene – AT ROOM TEMPERATURE**
- Graphene supports **plasma waves** weakly damped

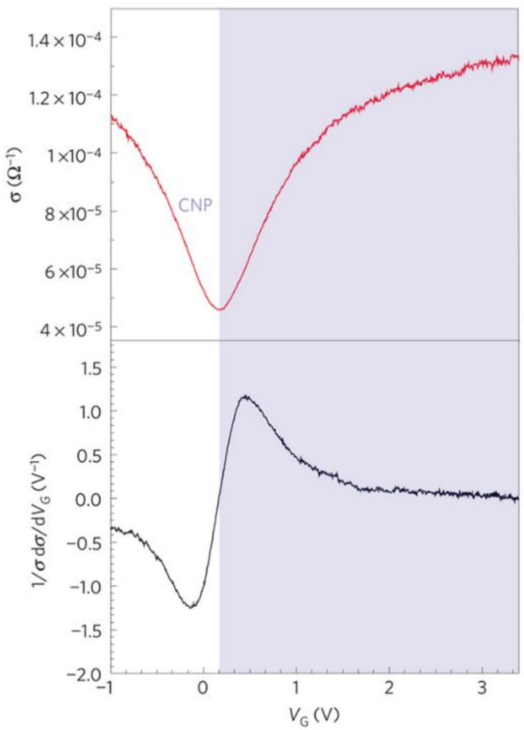
Graphene FET as THz detectors

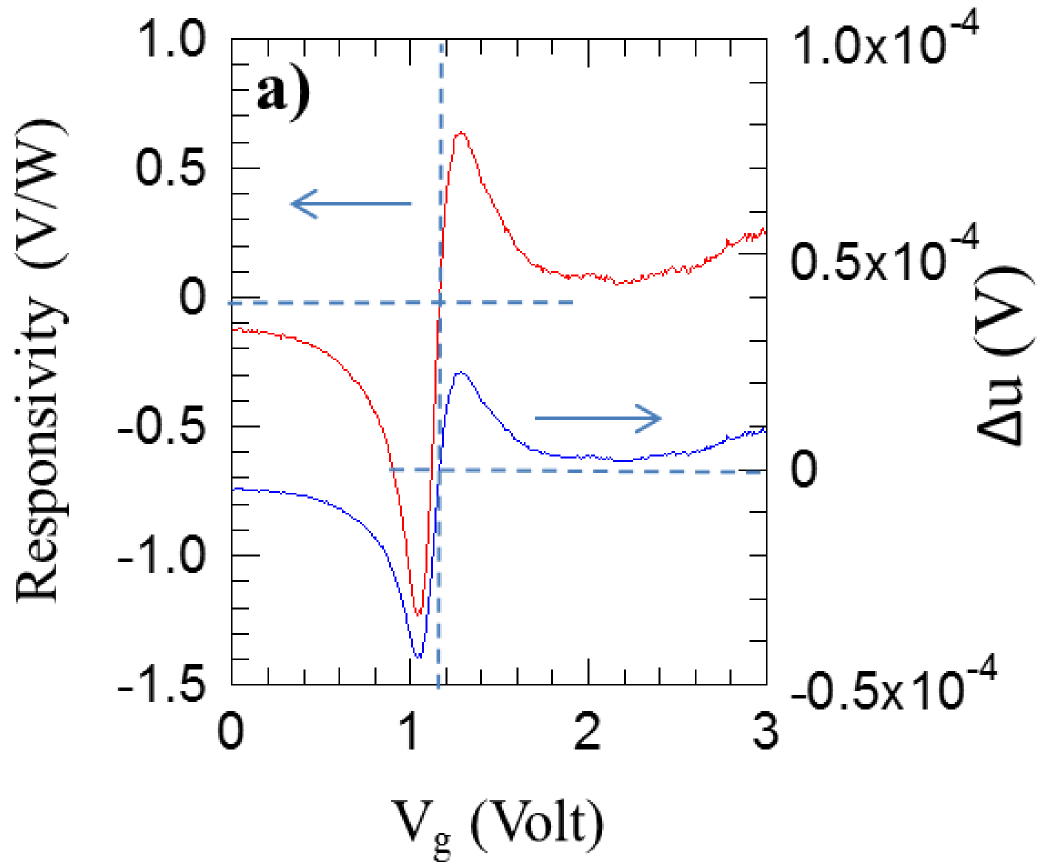
- Graphene on high-resistivity silicon
- Source (antenna lobe); drain “standard” contact
- ALD deposition of HfO2
- Gate (antenna lobe) fabrication



[Vicarelli, Vitiello, Coquillat, Lombardo et al., Nature Materials 11]

Graphene FET as THz detectors



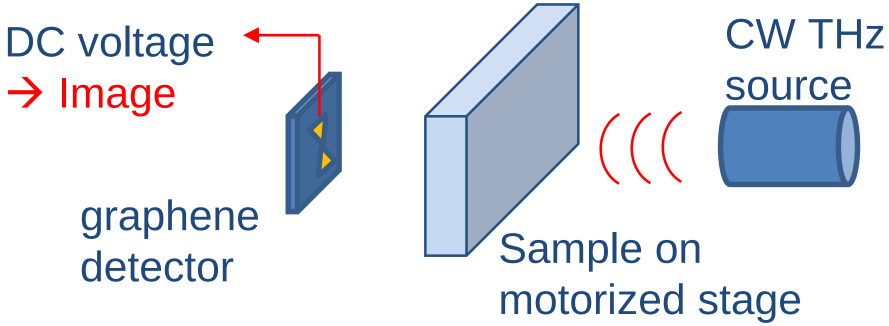


- Max responsivity > 1V/W
- Noise equivalent power (NEP) ~ 2 x 10^{-9} W/$Hz^{1/2}$

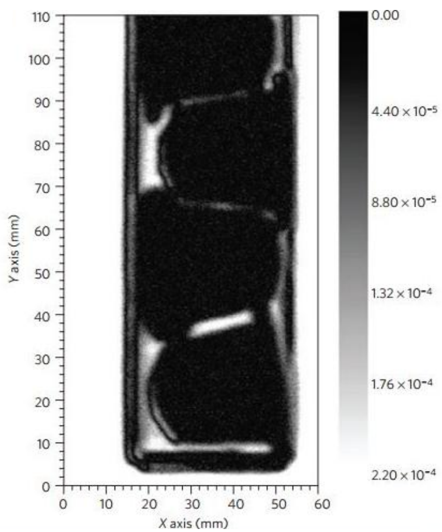
[Vicarelli, Vitiello, Coquillat, Lombardo et al., Nature Materials 11] [Spirito, Coquillat, De Bonis, Lombardo et al., Appl.Phys. Lett. 104]

THz imaging using graphene detectors

- Transmission image
- Focalized THz, spot size ~1mm
- Sample on motorized stage
- Integration time 20ms

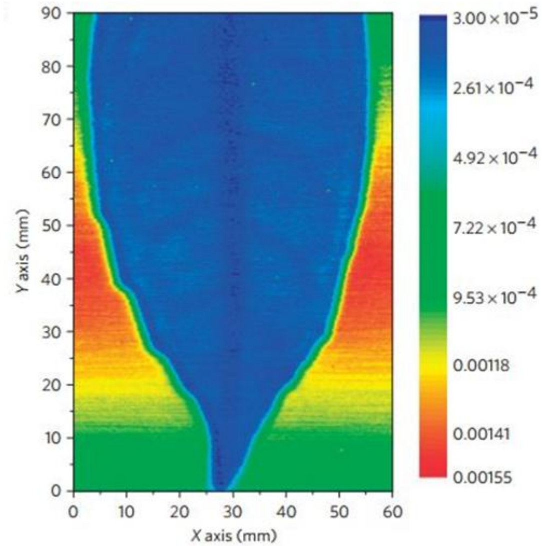


Cardboard box (closed)



THz image

Open box



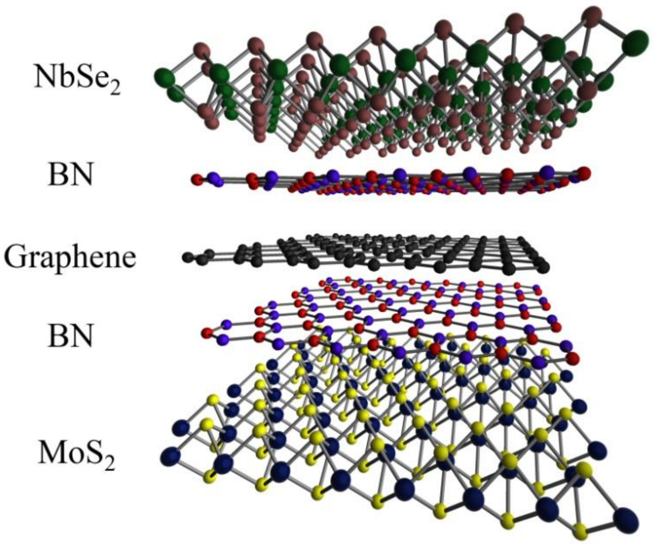
Fresh leaf

[Vicarelli, Vitiello, Coquillat, Lombardo et al., Nature Materials 11]

Beyond graphene: layered materials

Layered materials: solids with strong in-plane chemical bonds but weak out-of-plane Van der Waals bonds.

- Hexagonal boron nitride (h-BN)
- Transition metal dichalcogenides (TMDC): MoS_2, WSe_2, …
- Transition metal trichalcogenides (TMTC): TiS_3, $TaSe_3$, …
- Metal halides: PbI2, $MgBr_2$, …
- Metal oxides: MnO_2, $LaNb_2O_7$, …
- III-VI semiconductors: GaS, InSe,…
- Double hydroxides (LDHs):
- Clays (layered silicates)
- …



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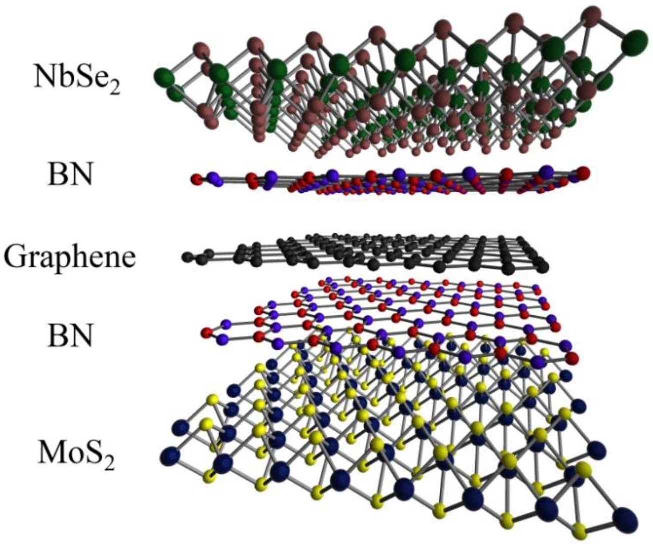
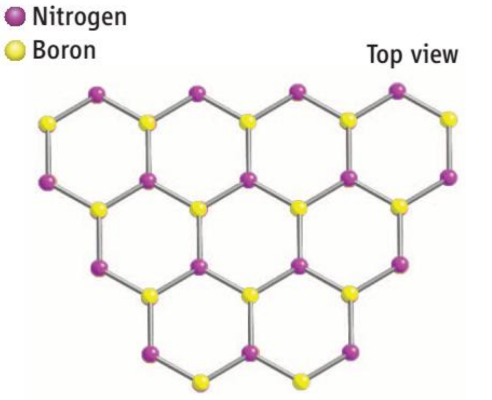
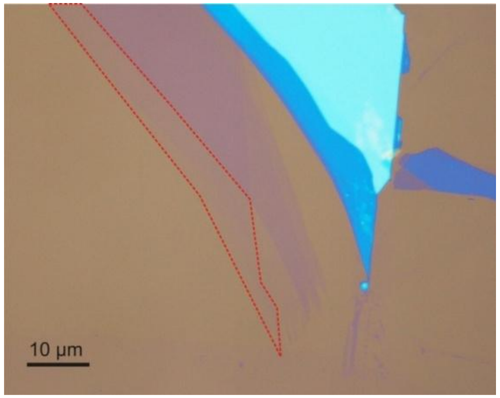


Hexagonal boron nitride

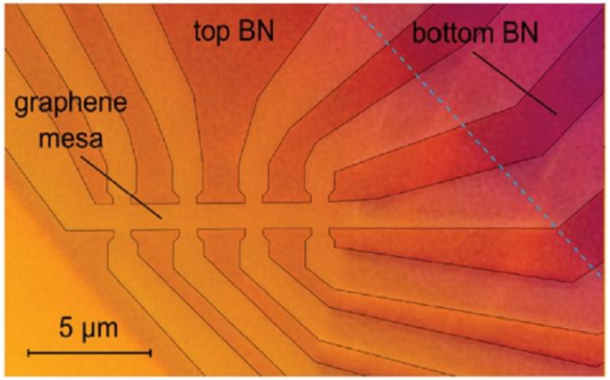
- Isomorph of graphite
- Insulator, bandgap: 5.97 eV
- Dielectric constant ~ 3.9, breakdown field ~ 0.7V/nm^{-1}
- Inert , free of dandling bonds and surface charge traps



[Nicolosi et al., Science 340, 1420]



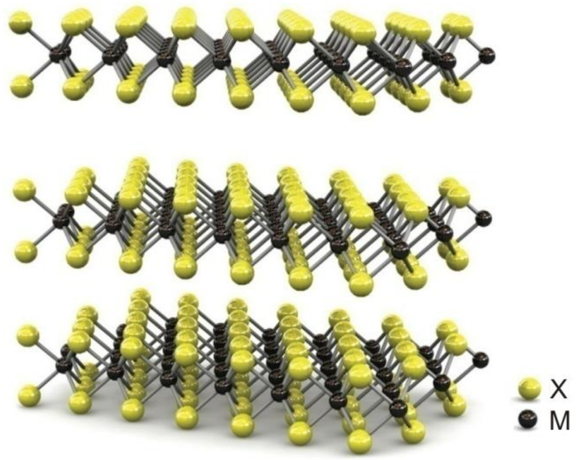
- Support and/or encapsulate graphene: room-temperature, micrometric scale ballistic transport, mobility > 10^5 cm^2/Vs



[Mayorov et al., Nano Lett. 11, 2396]

Transition metal dichacogenides

- Compound formed by a transition metal element (M) and a chalcogen (X), generalized formula MX_2
- Layered structure, planes of the form XMX coupled by Van der Walls forces
- Very different electronic properties: insulators (HfS_2), semiconductors (e.g. MoS_2), metals (NbS_2)
- Bandstructure changes significantly with the number of layers: MoX2 and WX2 indirect as bulk, direct (and larger) as single layer

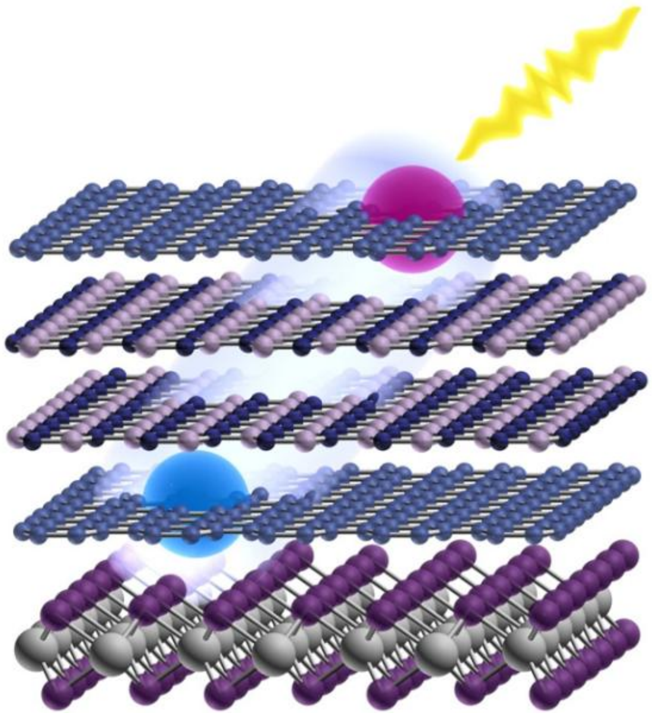


[Wang et al., Nature Nanotech. 7, 699]

Heterostructures

- Stacks of two-dimensional materials
- Not only combination of individual properties, but result of interaction between layers
- Tailored properties

Materials “on demand”



[Novoselov et al., Phys. Scripta T146, 14006]

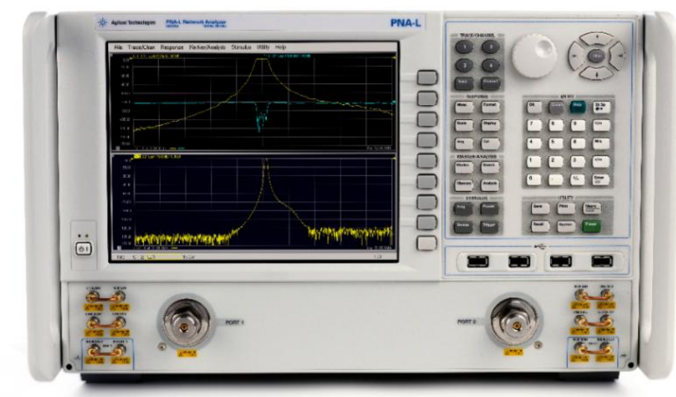
RF and microwave measurements at the nanoscale

- Spatially-resolved high-frequency measurements
- there is *still* room at the bottom: scanning microwave microscopy

Atomic Force Microscope (AFM)

High spatial resolution (nm)

+



Vector Network Analyser (VNA)

Quantitative broadband measurement at RF and microwave frequencies

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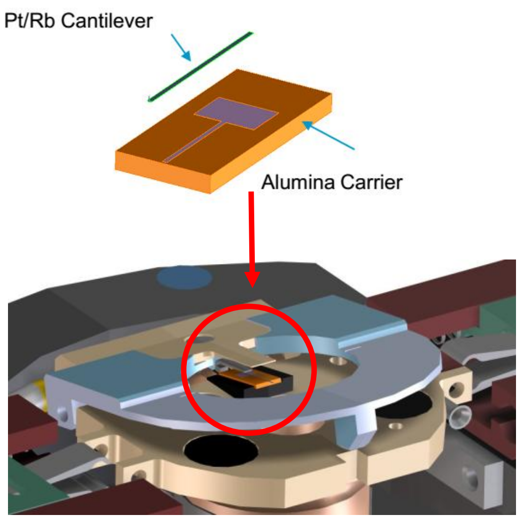
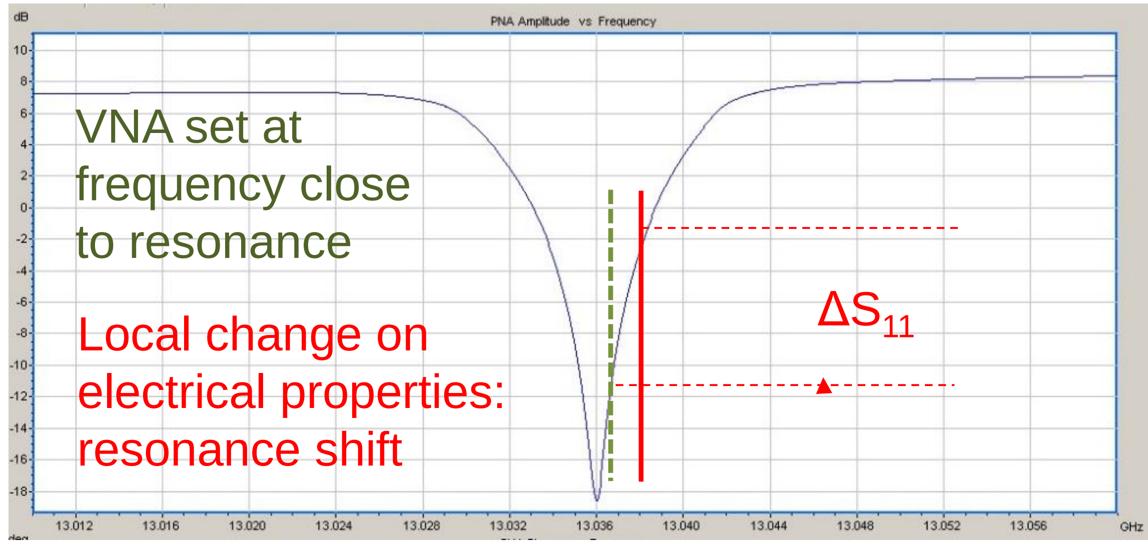
Scanning Microwave microscopy (SMM)



Metallic tip

Changes in S_{11} parameter (reflected signal)

Tip+network: resonator



Agilent Technologies

Conclusions

- Graphene exhibits unique combination of properties
- Graphene: “family” on materials, very different properties according to production method
- Applications: high frequency electronics and optoelectronics
- Not simple “replacement” for other materials, but novel material with specific properties (and also specific challenges)
- Two-dimensional materials, similar structure but very different properties
- Heterostructrures, materials “on demand”
- Scanning microwave microscopy: investigation of high-frequency properties at the nanoscale

Acknowledgements

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- M. Vitiello

Nokia
- Alan Colli

IBM
- P. Avouris
- M. Engel
- M. Steiner

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