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

Individual graphene layers can be extracted from 3-dimensional graphite

Stable under ambient conditions

Remarkable electronic properties: ambipolar transport, mobility $\sim 10^3 \text{ cm}^2/\text{Vs}$

Nobel prize in Physics 2010
Graphene: properties & technology

Properties:
- Charge carriers mobility: $>10^5 \text{ cm}^2/\text{Vs}$ (room T), $>10^6 \text{ cm}^2/\text{Vs}$ (low T) – high speed
- Saturation velocity: $>10^7 \text{ cm/s}$ (even for fields up to 50 KV/cm) – scalability
- Thermal conductivity: $>3,000 \text{ WmK}^{-1}$ – heat dissipation
- Current-carrying capacity: $>10^8 \text{ A/cm}^2$ - 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

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)

- 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 $\sim 10$
- In **analog RF**, switch off not essential (e.g. signal amplifiers always ON state)

[Novoselov et al., Science 306]
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

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% absorption)
- Broadband absorption
- Working principle: internal fields occurring at metal-graphene interface

- Improvement of responsivity

[Mueller at al., PRB 79, 245430]

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

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

[Knap et al., Nanotech. 24]
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 > 1 V/W
- Noise equivalent power (NEP) \( \sim 2 \times 10^{-9} \) W/Hz\(^{1/2}\)

THz imaging using graphene detectors

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

CW THz source

Sample on motorized stage

DC voltage → Image

graphene detector

Cardboard box (closed)

Open box
[Vicarelli, Vitiello, Coquillat, Lombardo et al., Nature Materials 11]
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: PbI$_2$, MgBr$_2$, …
- Metal oxides: MnO$_2$, LaNb$_2$O$_7$, …
- III-VI semiconductors: GaS, InSe,…
- Double hydroxides (LDHs):
- Clays (layered silicates)
- …
Beyond graphene: layered materials

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Hexagonal boron nitride

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

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

[Nicolosi et al., Science 340, 1420]

[Mayorov et al.,Nano Lett. 11, 2396]
Transition metal dichacogens
dides

- 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
Scanning Microwave microscopy (SMM)

Metallic tip

Changes in $S_{11}$ parameter (reflected signal)

Tip+network: resonator

VNA set at frequency close to resonance

Local change on electrical properties: resonance shift

$\Delta S_{11}$
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
- Heterostructures, materials “on demand”
- Scanning microwave microscopy: investigation of high-frequency properties at the nanoscale
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