Graphene based mid-infrared and THz devices and their potential application in astronomical instruments

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About MackGraphe

(Graphene and Nanomaterials Research Center)

- A center dedicated to the science and industrial application of graphene and other 2D materials
- Began its activities in 2013
- Headquarters building opened on 2 march 2016
    - 9-storey building
    - Class 1000 clean room
    - Photonics, chemistry, materials labs
    - Space for spin off companies
- 3 areas of interest: Photonics, Energy, Composite Materials

Talk outline

- Graphene
  - Basics
  - Fabrication
  - Electronic/optoelectronic/plasmonic properties

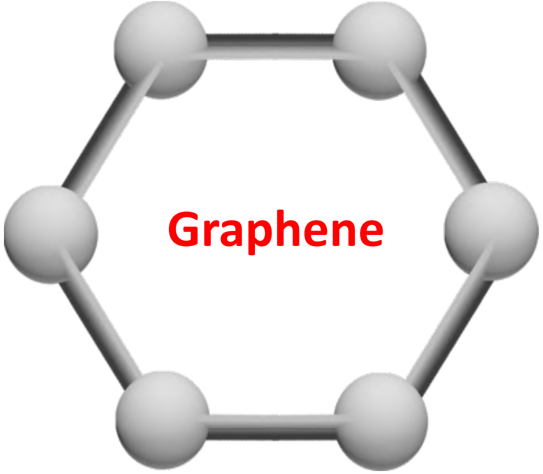
- Graphene devices for THz technologies
  - Antennas
  - Detectors
  - Filters/polarizers

- Conclusions and outlook

What is graphene?

- A 1 atom thick sheet composed of sp^2 carbon atoms assembled in a hexagonal crystal lattice
- The world's first (**but not only**) 2D material

Graphene:
a superlative material



Graphene

The thinnest material

A million times thinner than a human hair and, therefore, flexible.

The lightest material

3 gram of graphene covers a football field.

The highest thermal conductivity

10 times higher thermal conductivity than in copper.

Transparent

Graphene absorbs only 2.3% of incident light. It is, therefore, almost invisible to naked eye.

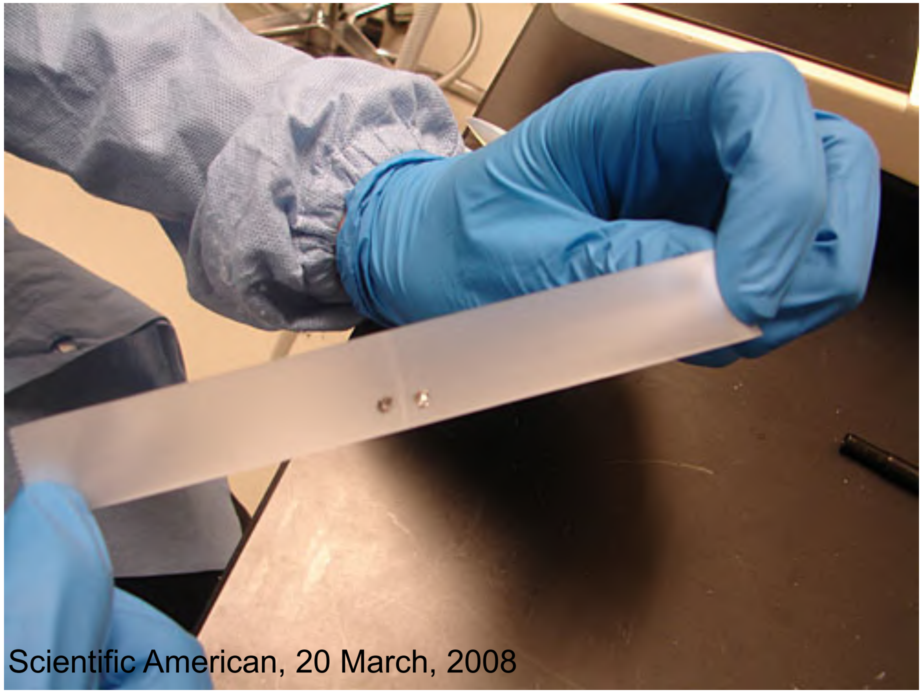
The best electricity conductor

The best known electricity conductor.

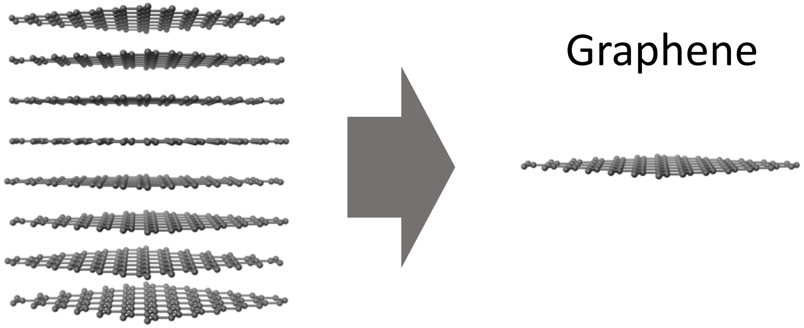
The strongest material

>200 times stronger than steel.

Obtaining graphene from graphite: mechanical exfoliation

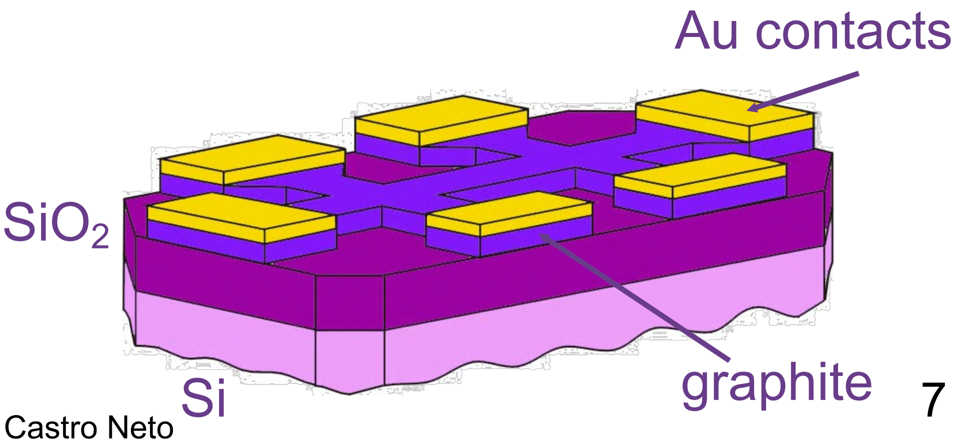


Scientific American, 20 March, 2008



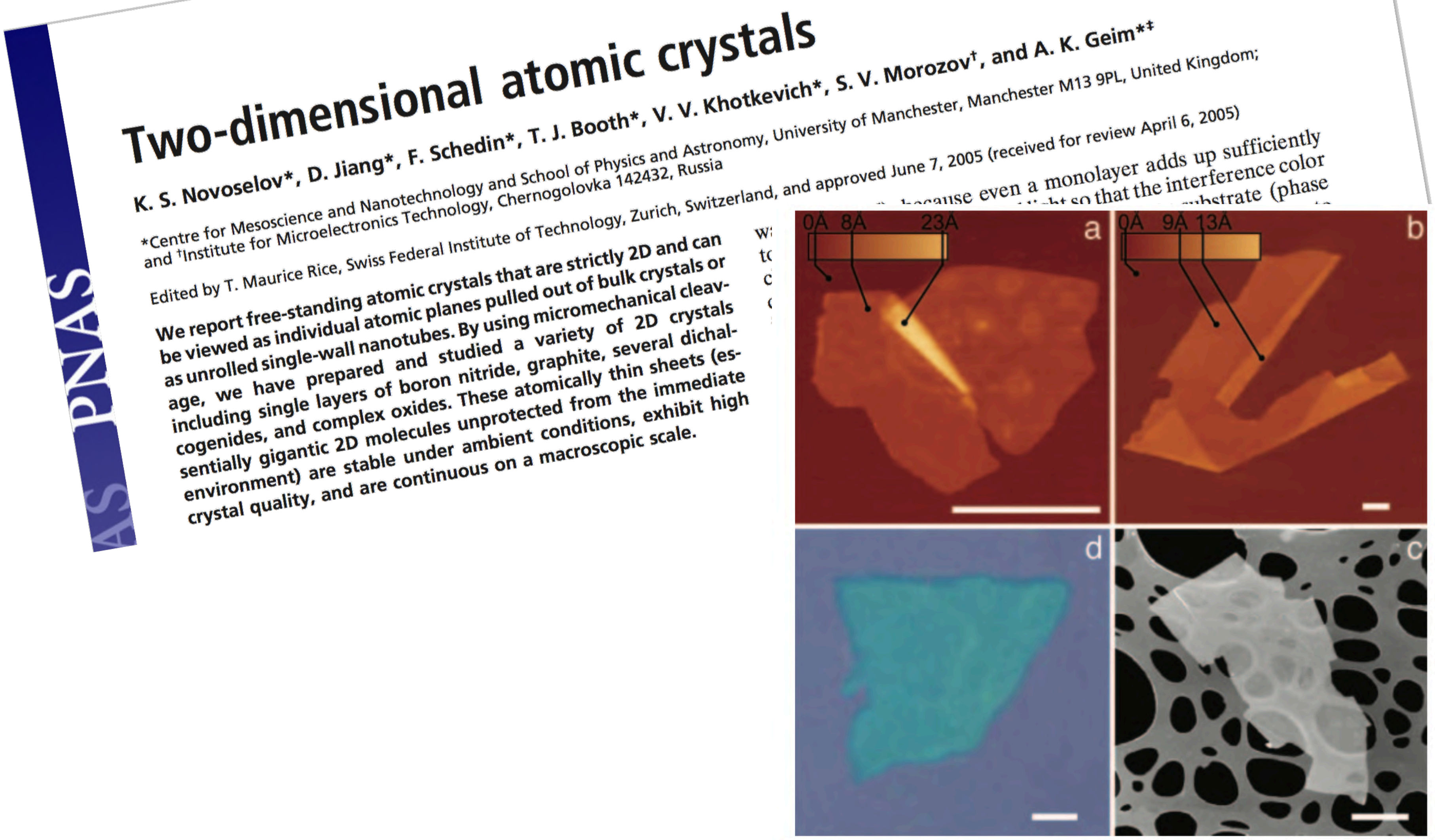
The first electronic circuits

- optical image
- SEM image
- design
- contacts and mesa



Courtesy: Prof. Castro Neto

Other 2D materials



PNAS

Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡

*Centre for Mesoscience and Nanotechnology and School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom; and †Institute for Microelectronics Technology, Chernogolovka 142432, Russia

Edited by T. Maurice Rice, Swiss Federal Institute of Technology, Zurich, Switzerland, and approved June 7, 2005 (received for review April 6, 2005)

We report free-standing atomic crystals that are strictly 2D and can be viewed as individual atomic planes pulled out of bulk crystals or as unrolled single-wall nanotubes. By using micromechanical cleavage, we have prepared and studied a variety of 2D crystals including single layers of boron nitride, graphite, several dichalcogenides, and complex oxides. These atomically thin sheets (essentially gigantic 2D molecules unprotected from the immediate environment) are stable under ambient conditions, exhibit high crystal quality, and are continuous on a macroscopic scale.

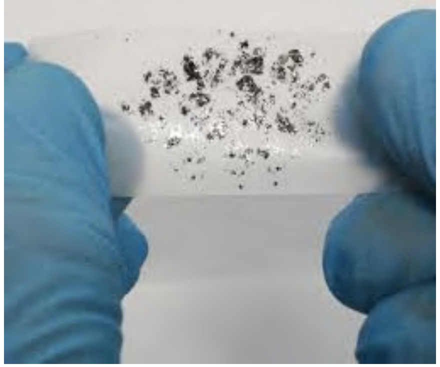
because even a monolayer adds up sufficiently that the interference color (phase

Fig. 1. 2D crystal matter. Single-layer crystallites of $NbSe_2$ (*a*), graphite (*b*), $Bi_2Sr_2CaCu_2O_x$ (*c*), and MoS_2 (*d*) visualized by AFM (*a* and *b*), by scanning

K. S. Novoselov et al., PNAS 102, 10451 (2005)

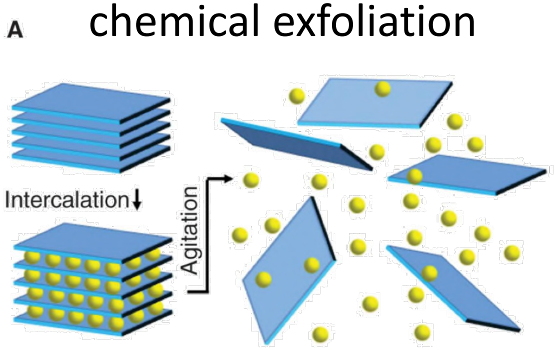
Ways to obtain graphene

Mechanical exfoliation



Crystal quality: highest
Scalability: low
Continuous area: small
Total area: small
Interaction w/ environment: low

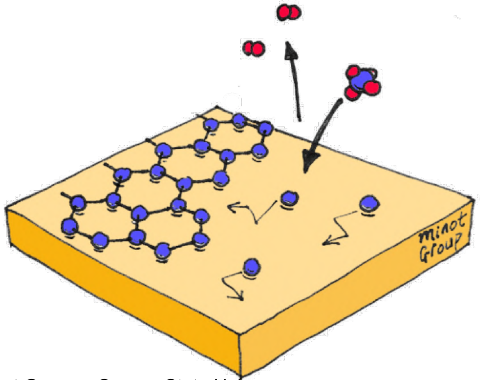
Chemical/liquid assisted chemical exfoliation



Nicolosi et al., Science 340, 419, 1226419 (2013)

Crystal quality: low/medium
Scalability: high
Continuous area: small
Total area: large
Interaction w/ environment: high

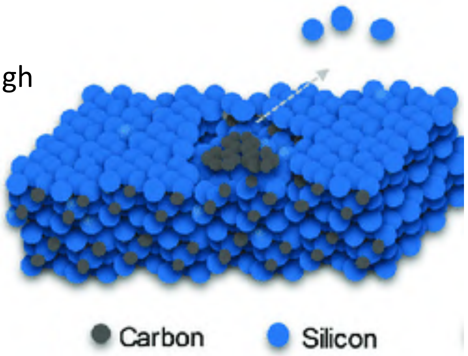
Chemical vapor deposition



From Minot Group – Oregon State Univ.

Crystal quality: medium/high
Scalability: medium
Continuous area: large
Total area: small/medium
Interaction w/ environment: low

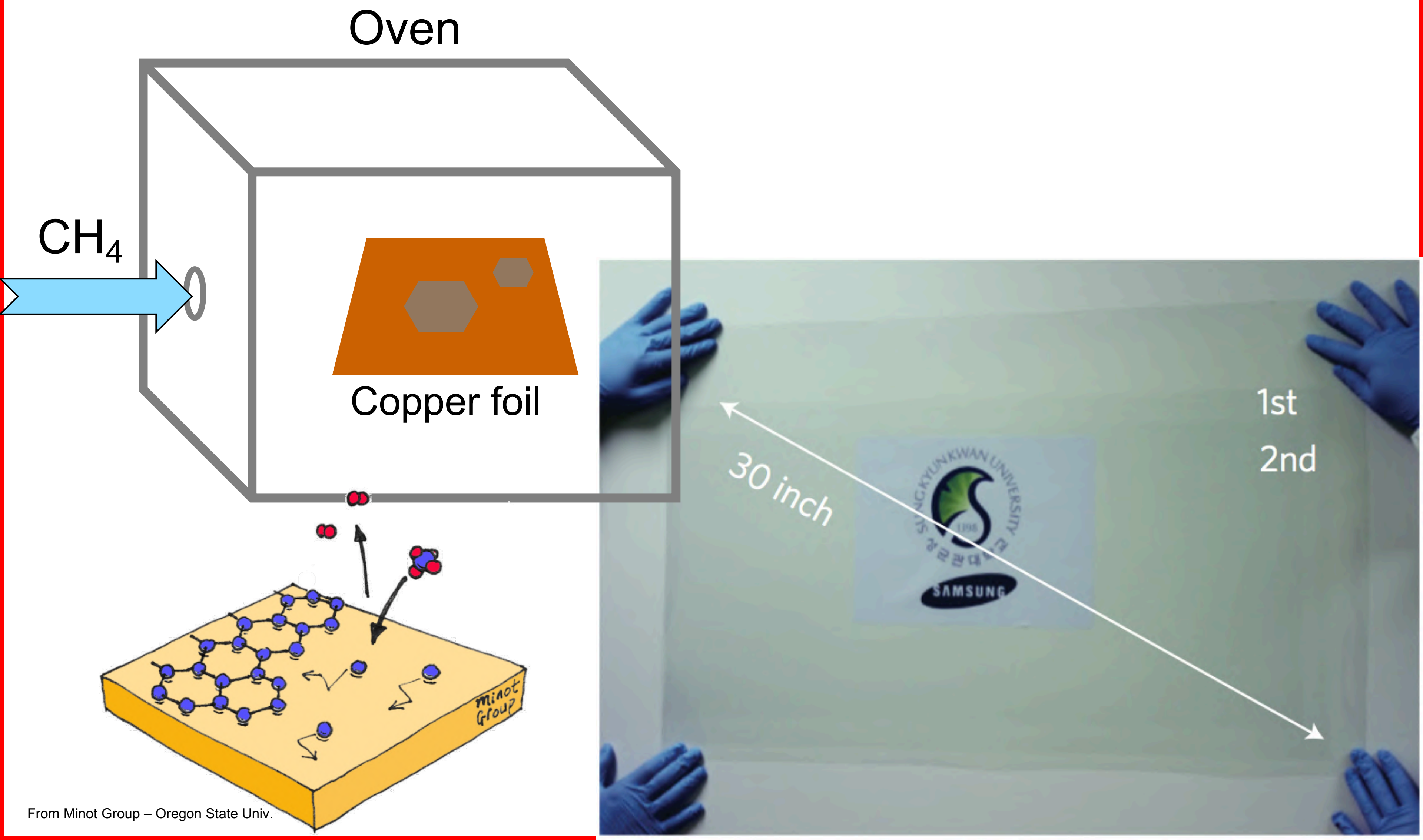
Epitaxial growth



Zhao et al., Chem Soc Rev 46, 4417 (2017)

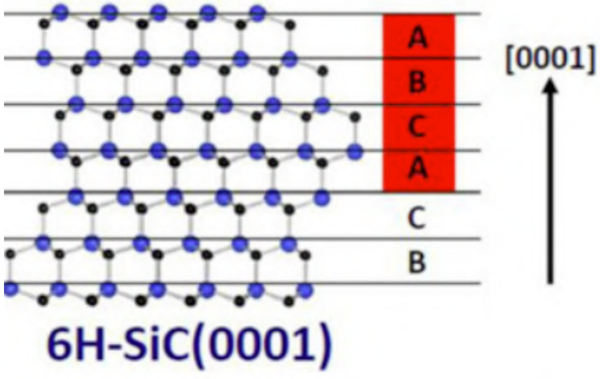
Quality: high
Scalability: medium/high
Continuous area: large
Total area: small
Interaction w/ environment: low

Obtaining graphene in a larger scale: chemical vapor deposition



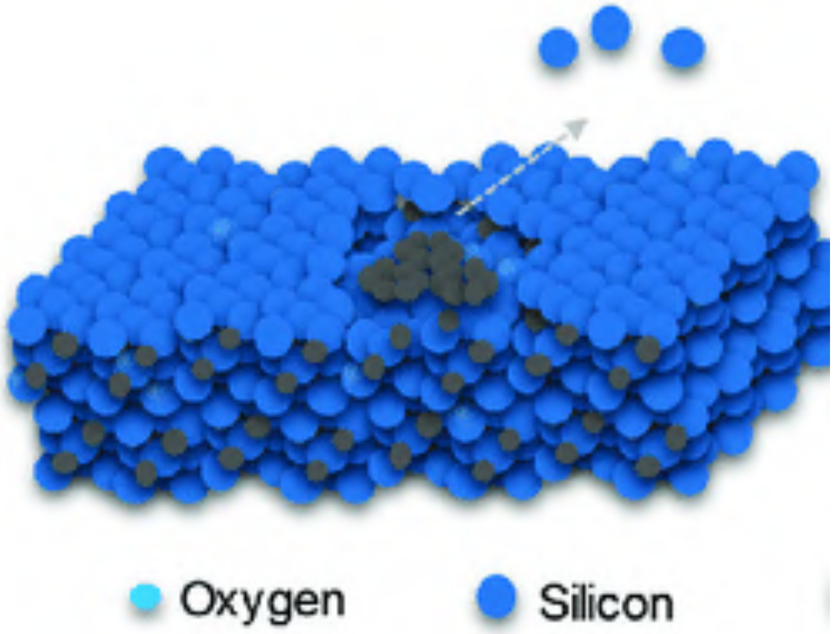
From Minot Group – Oregon State Univ.

Obtaining graphene in a larger scale: epitaxial growth



Otsuji et al., J. Phys D 45, 303001 (2012)

~1000°C

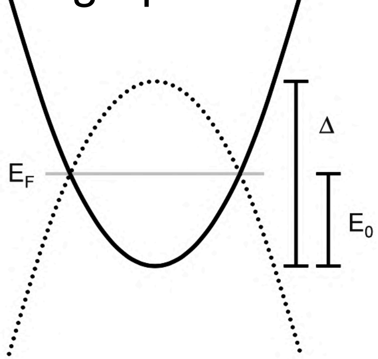


Zhao et al., Chem Soc Rev 46, 4417 (2017)

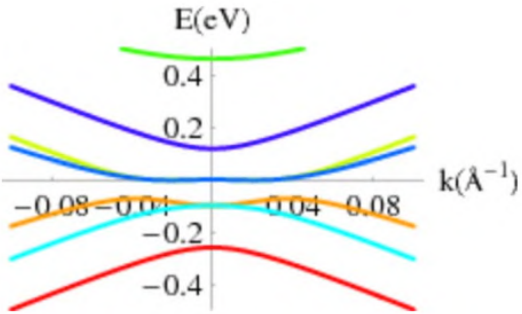
Dimensionality reduction: consequences to electrons

Changes in the band structure

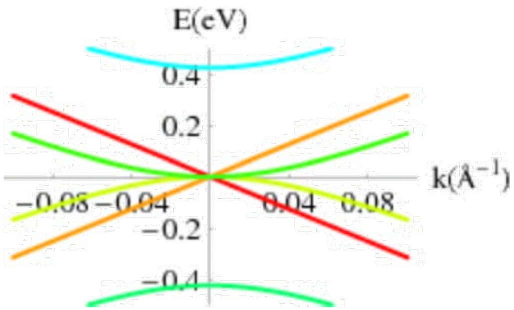
graphite



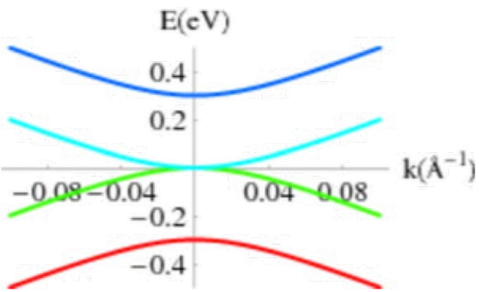
4 layers



3 layers



2 layers



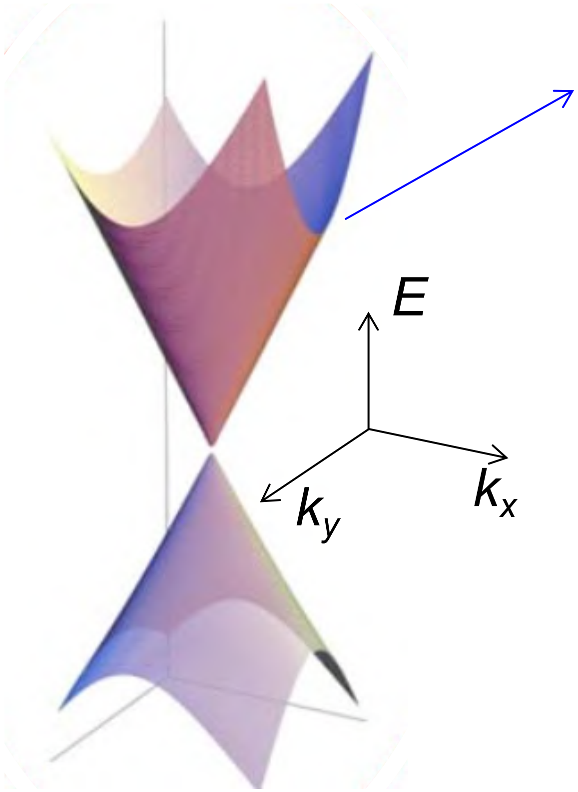
graphene

D. Nezich, Nanotechnology 23, 015701 (2012)

A. C. Castro Neto, Rev. Mod. Phys. 81, 109 (2009).

Dimensionality reduction: consequences to electrons

Linear (conical) dispersion relation, instead of parabolic



$$E(k) = \hbar v_F k$$

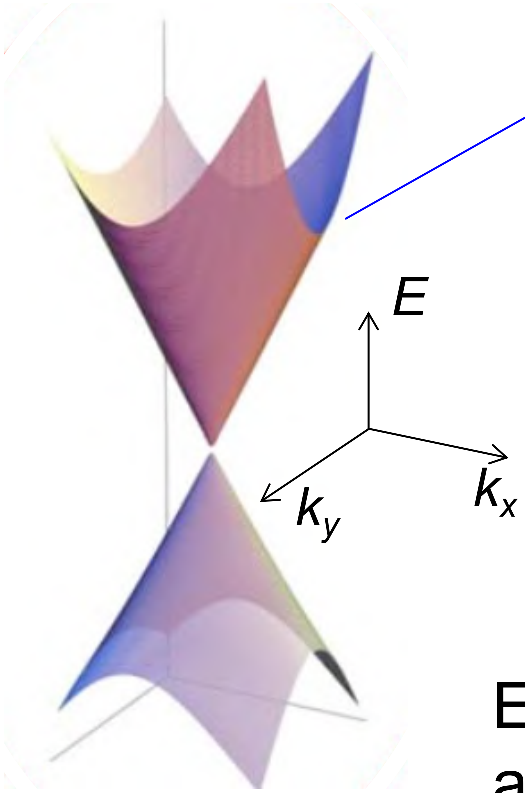
v_F (electron’s phase velocity) is independent of E

In a material with an usual (parabolic) dispersion

$$v = \sqrt{\frac{2E}{m}}$$

Conical dispersion: consequences to electrons

Linear (conical) dispersion relation, instead of parabolic



$$E(k) = \hbar v_F k$$

In which other situation fermions exhibit *E* proportional to *k*?

Relativistic dispersion with *m* = 0

$$E(k) = \sqrt{\hbar^2 k^2 c^2 + \left(mc^2\right)^2} = \hbar c k$$

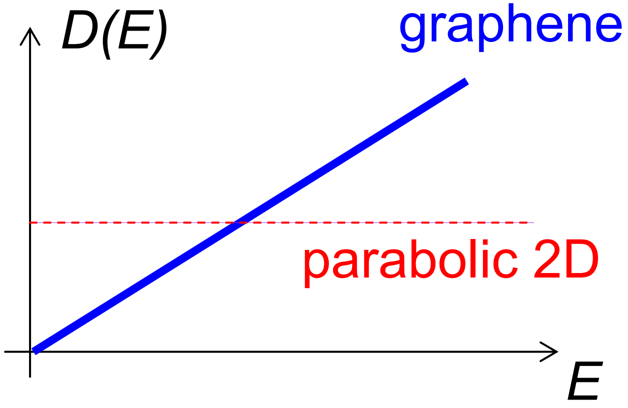
Equations are identical if $v_F \rightarrow c$ and $m^* = 0$ (zero effective rest mass)

Conical dispersion: consequences to electrons

- One consequence of the conical dispersion:

  density of states

$$D(E)=\frac{k(E)}{\pi}\frac{dk}{dE}=\frac{E}{\pi\hbar v_F}\frac{1}{\hbar v_F}=\frac{E}{\pi\left(\hbar v_F\right)^2}$$



Electron surface density in the conduction band

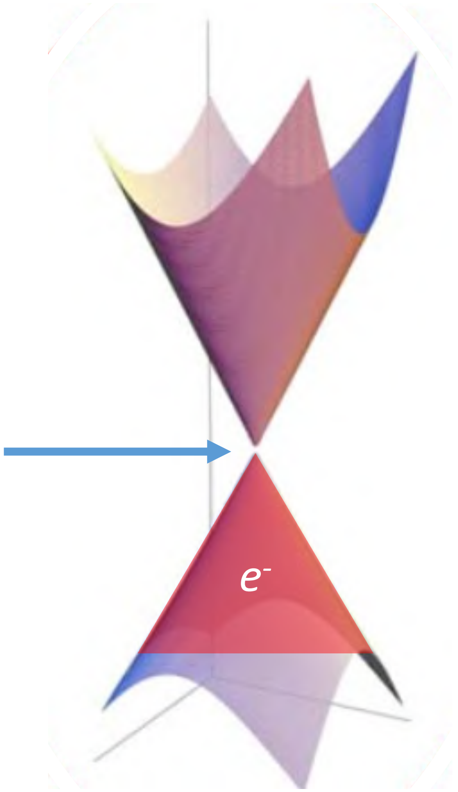
$$n_q(E_F)=2\int_0^{E_F}D(E)\,dE=2\int_0^{E_F}\frac{E}{\pi\left(\hbar v_F\right)^2}dE=\frac{E_F^2}{\pi\left(\hbar v_F\right)^2}=\frac{k_F^2}{\pi}$$

(factor 2 accounts for 2 1BZ points contributing)

$$E_F=\hbar v_F\sqrt{\pi n_q}$$

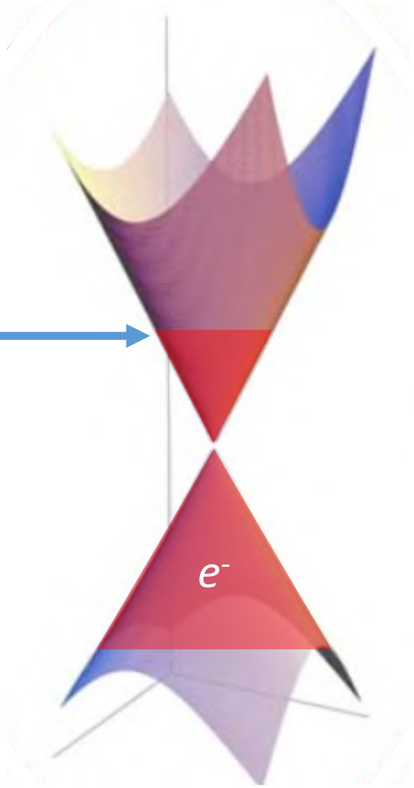
Electrical doping of graphene

- Doped graphene versus neutral graphene



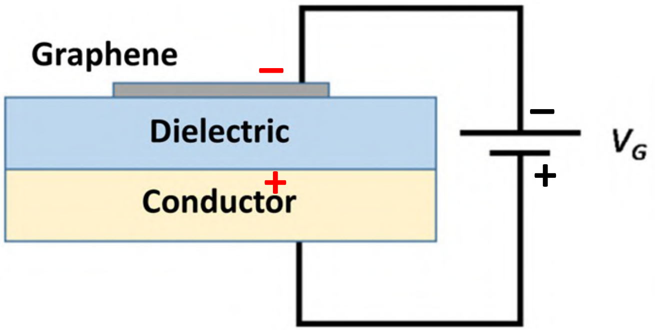
Electrical doping of graphene

- Doped graphene versus neutral graphene



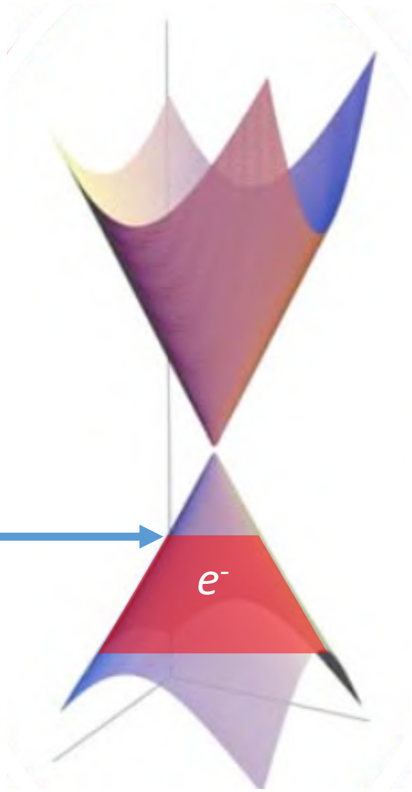
Electron doped graphene

$E_F > 0$

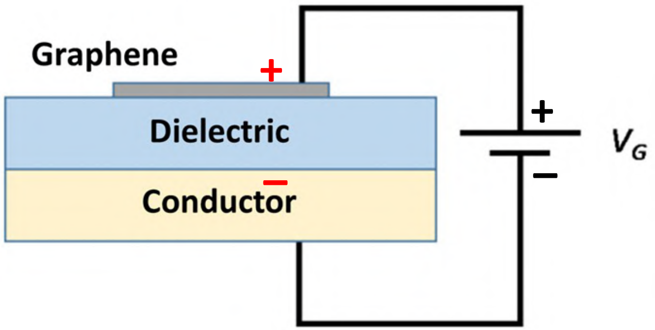


Electrical doping of graphene

- Doped graphene versus neutral graphene

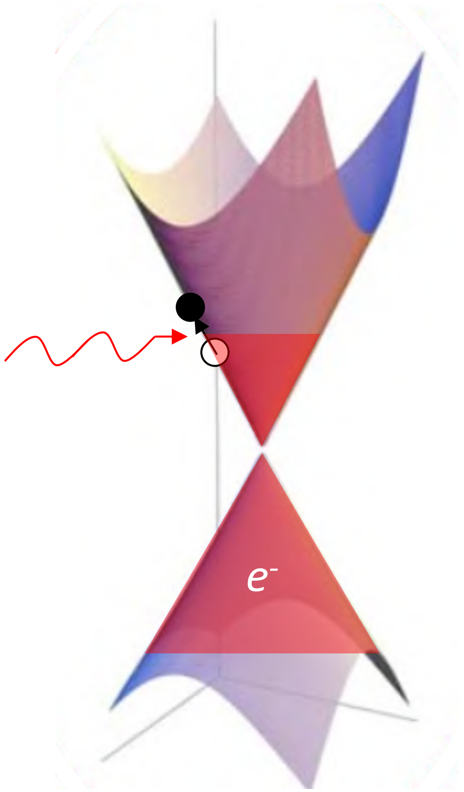


Hole doped graphene
$E_F < 0$

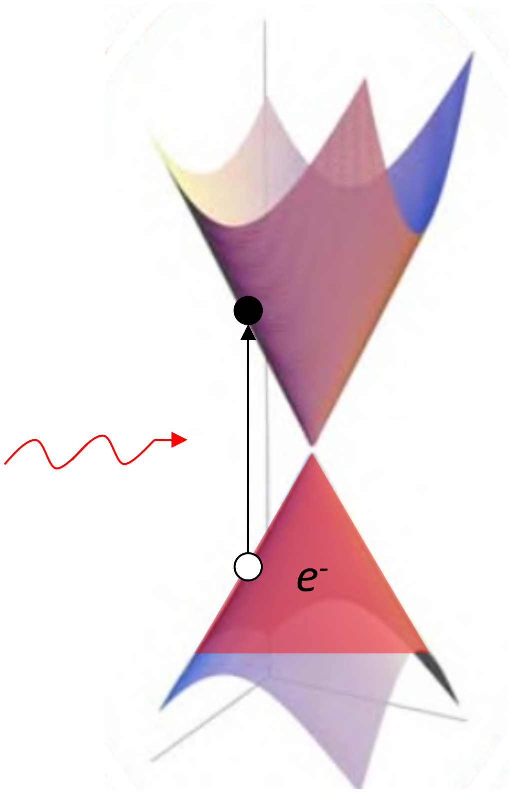


Intraband transition versus interband transition

intraband transition



interband transition



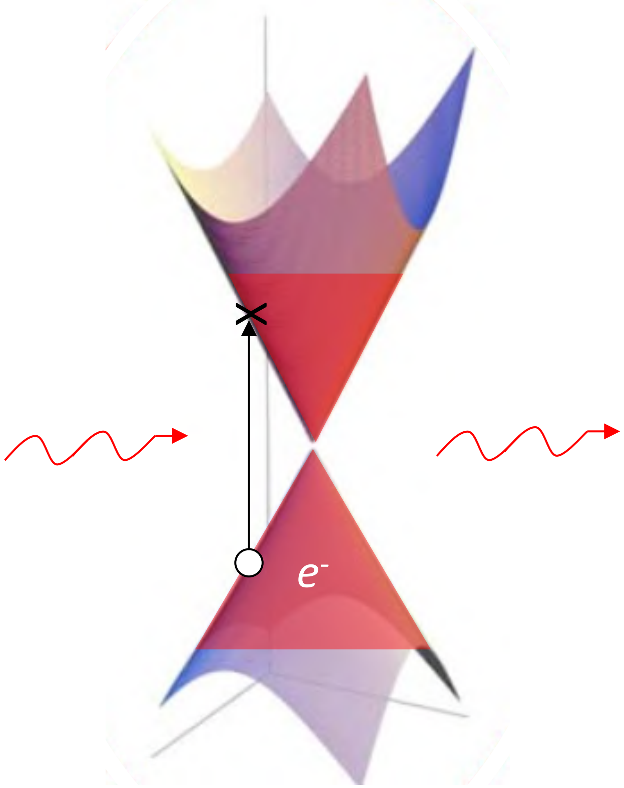
Intraband transition versus interband transition

- We can, therefore, see that there will be an intraband and an interband optical conductivity:

$$\sigma(\omega) = \sigma_{intra}(\omega) + \sigma_{inter}(\omega)$$

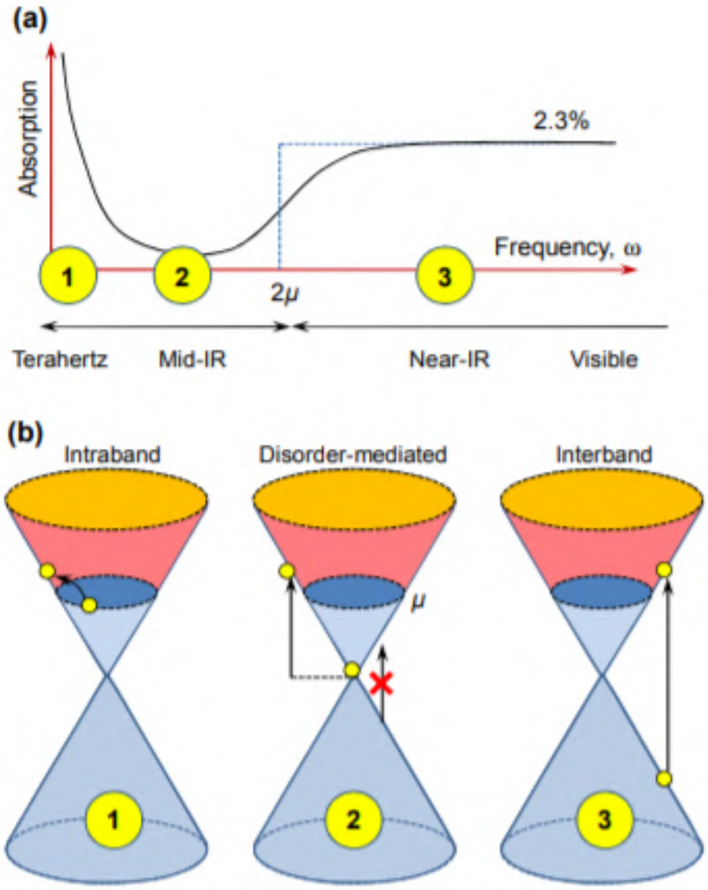
Interband transition: Pauli blocking

- When $\hbar\omega < 2E_F$: the Pauli exclusion principle prevents interband transsition ➔ $\sigma_{inter} \longrightarrow 0$



interband transition

Dielectric tunability



Low and Avouris, *ACS Nano* 8, 1086 (2014)

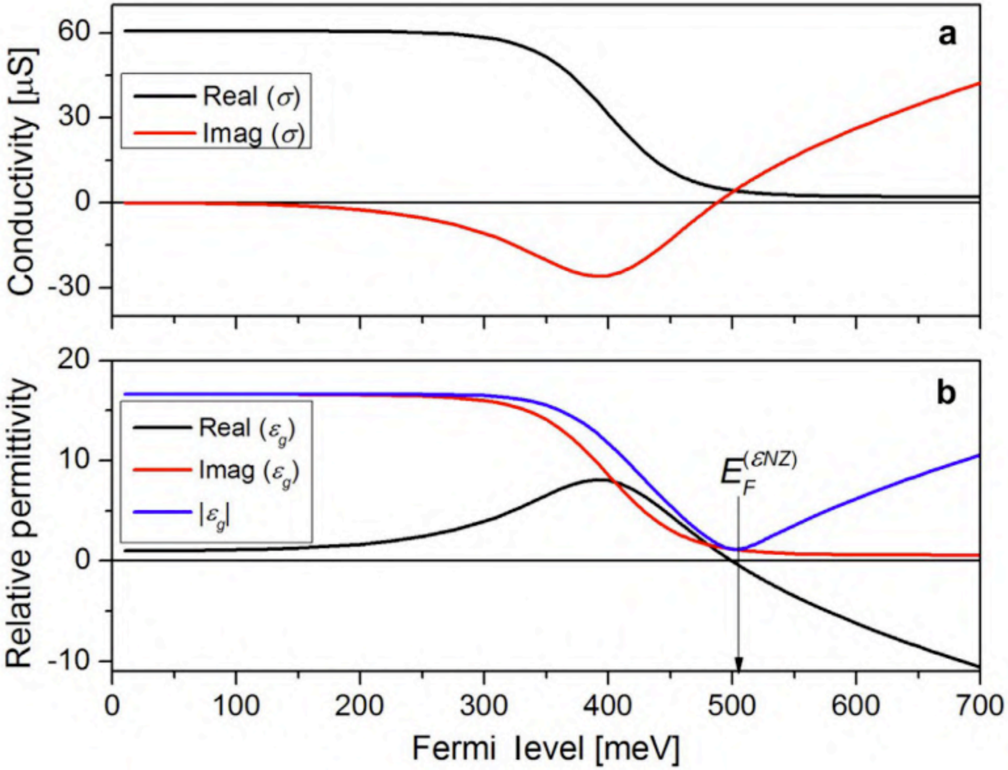
Dielectric tunability

- $\varepsilon_g = 2.5 + i\sigma/\left(\omega\epsilon_0 t_g\right)$
- Drastic dielectric function tunability

σ_{inter} dominates

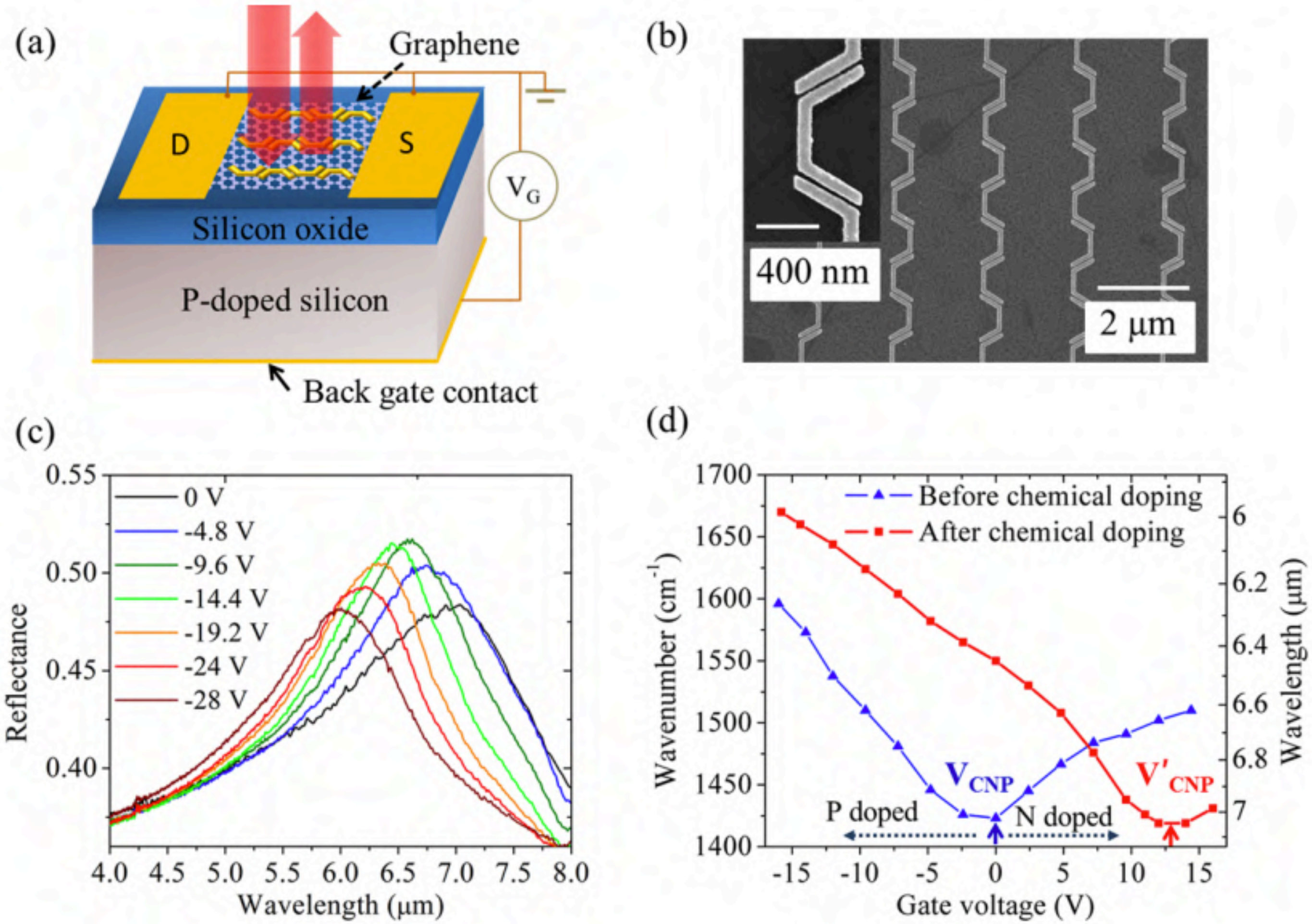
σ_{intra} dominates

$\hbar\omega = 800$ meV



de Oliveira and de Matos, Sci. Rep. 5, 16949 (2015)

Spectral tunability in graphene loaded antennas



Yao et. al, Nano Lett. 14, 214 (2004).

- Bias induced changes in graphene's dielectric function in the metal gaps tune the spectral response

Intraband conductivity

- σ_{intra} gives graphene its conductive character, and it can be approximated by the Drude conductivity.
- The (intraband) Drude conductivity is given by

$$\sigma(\omega) = \frac{n_q e^2 \tau}{m(1 - i\tau\omega)}$$

  - For graphene, we can write

$$m = \frac{\hbar k}{v_F} = \frac{E_F}{v_F^2} = \frac{\hbar\sqrt{\pi n_q}}{v_F}$$

  - So that:

$$\sigma(\omega) = \frac{v_F e^2 \tau \sqrt{n_q}}{\hbar\sqrt{\pi}\left(1 - i\tau\omega\right)}$$

Intraband conductivity

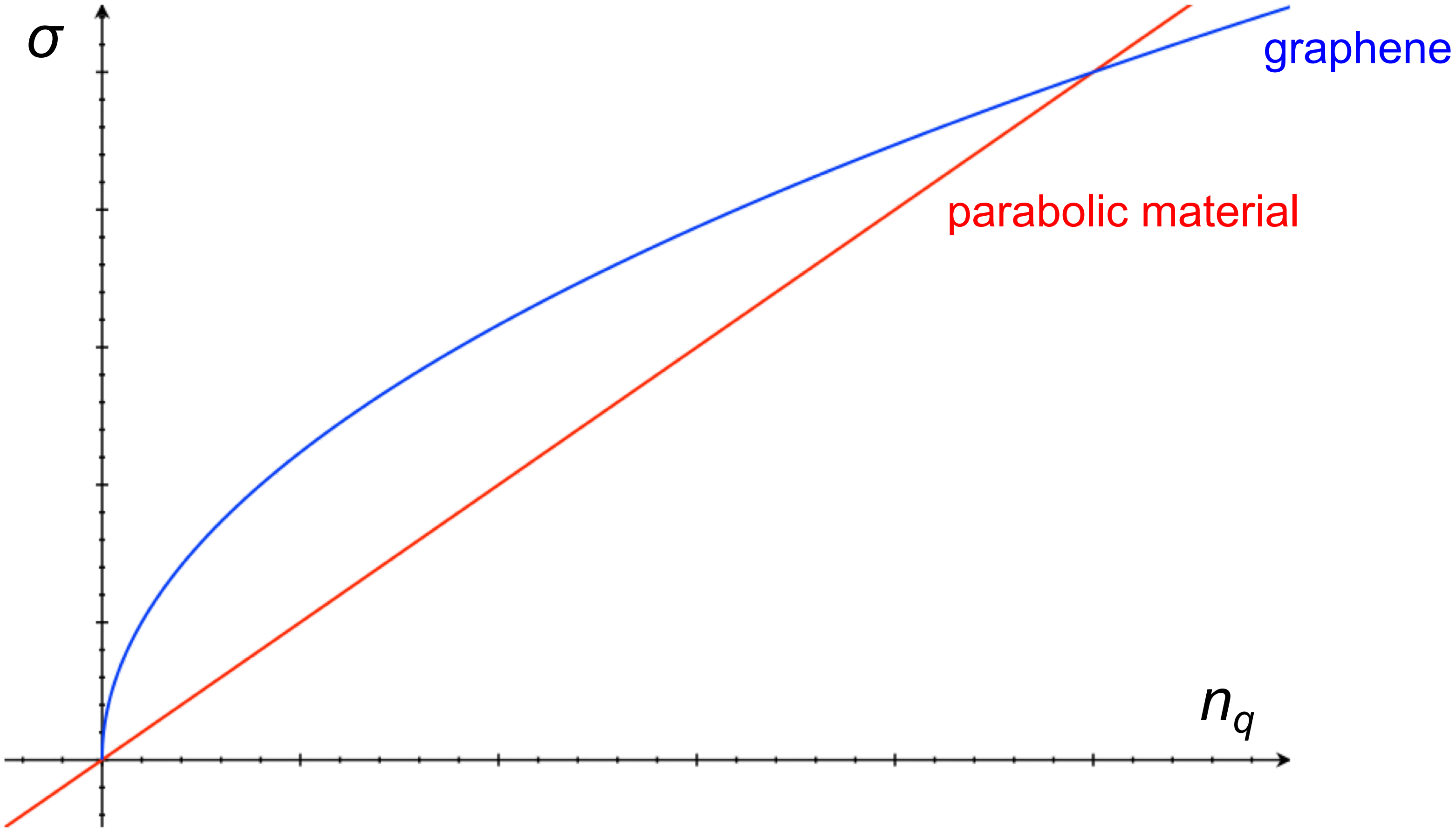
- In a **parabolic dispersion** 2D material:

$$m = \left(\frac{d^2E}{dp^2} \right)^{-1} = \underset{\substack{\nwarrow \\ \text{constant}}}{c_1}\hbar^2$$

- And therefore

$$\sigma(\omega) \propto \frac{e^2 \tau n_q}{\hbar^2 \left(1 - i\tau\omega\right)}$$

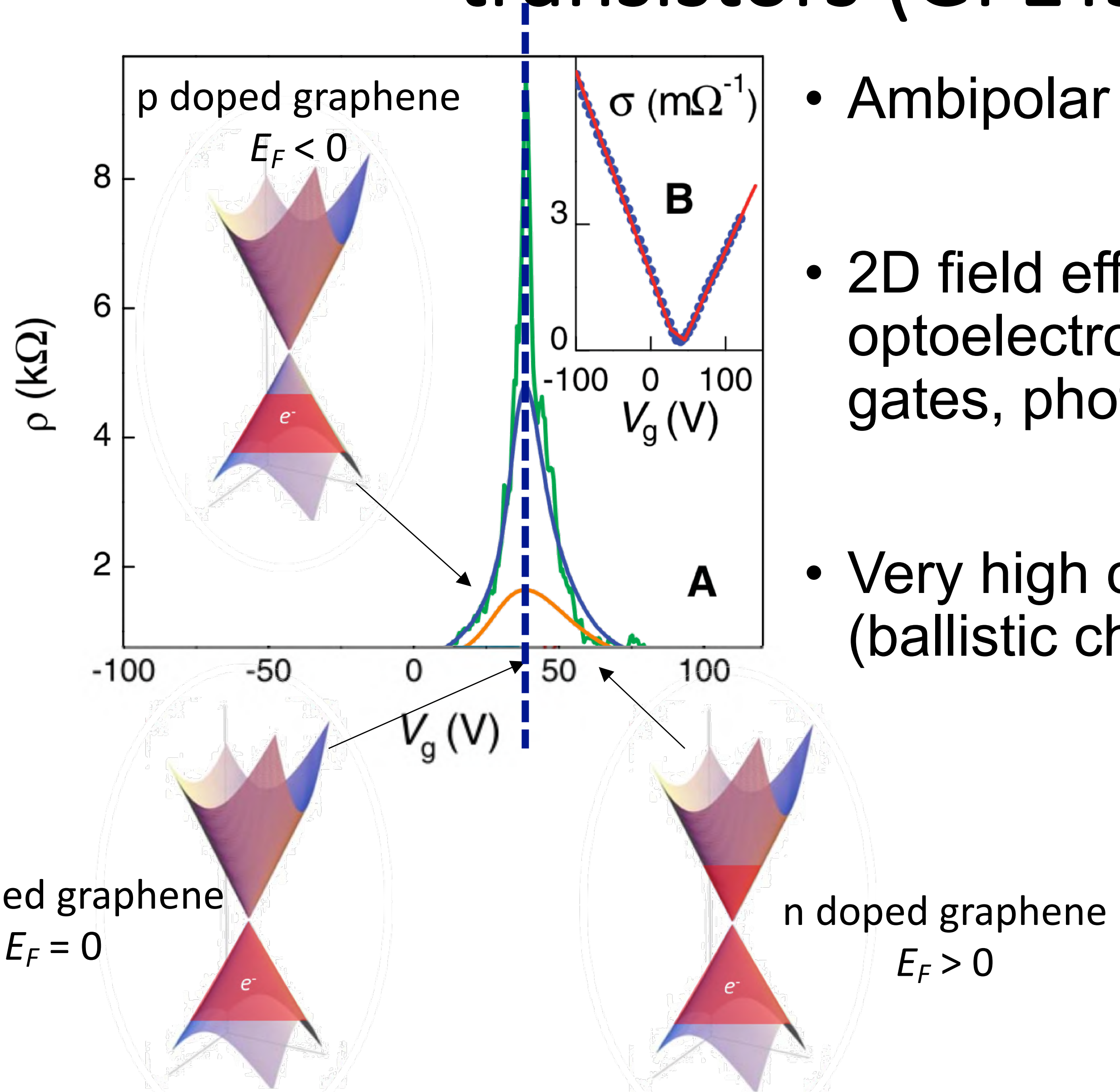
Intraband conductivity



- Over relevant n_q values, graphene’s conductivity tunes much more than that of parabolic 2D materials

Graphene field effect transistors (GFETs)

Novoselov et. al, Science 305, 666 (2004).

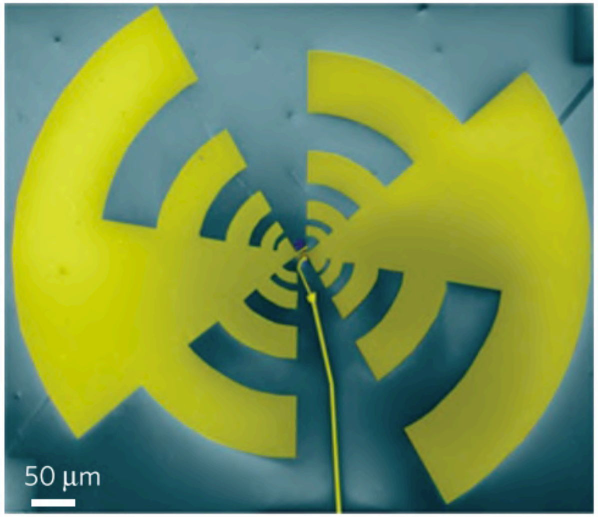


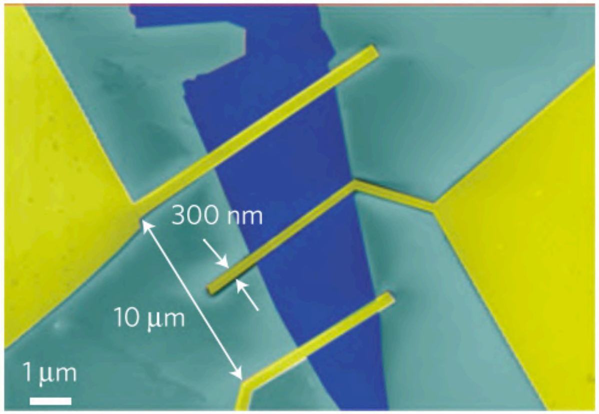
Undoped graphene
$E_F = 0$

n doped graphene
$E_F > 0$

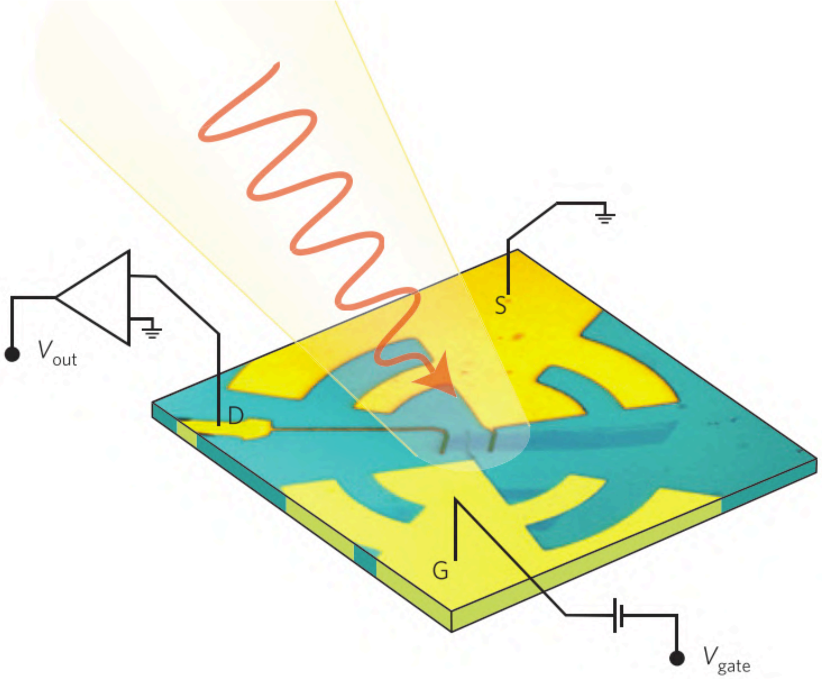
- Ambipolar behavior
- 2D field effect electronic and optoelectronic devices (logic gates, photodetectors, …)
- Very high charge mobility (ballistic charge movement)

GFETs as room temperature THz detectors



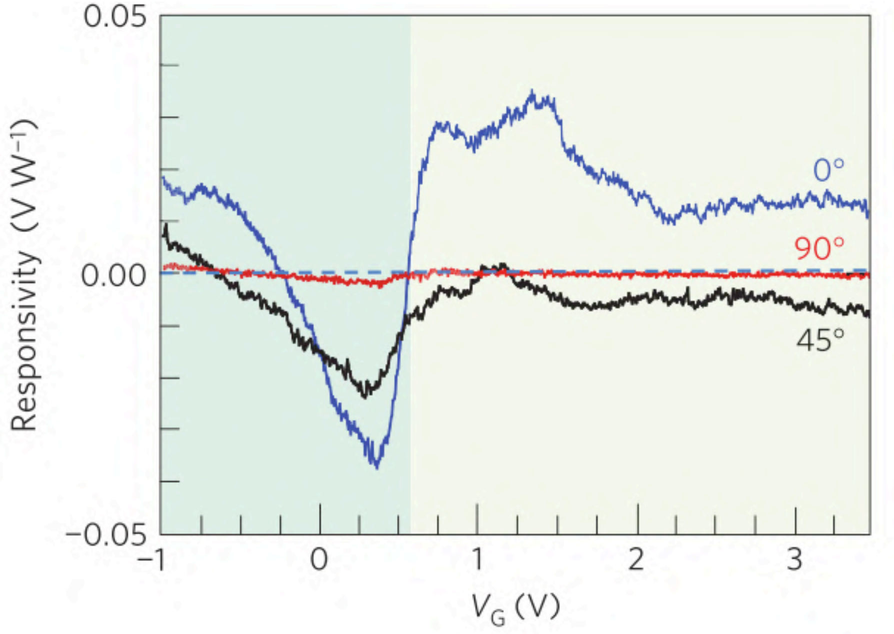


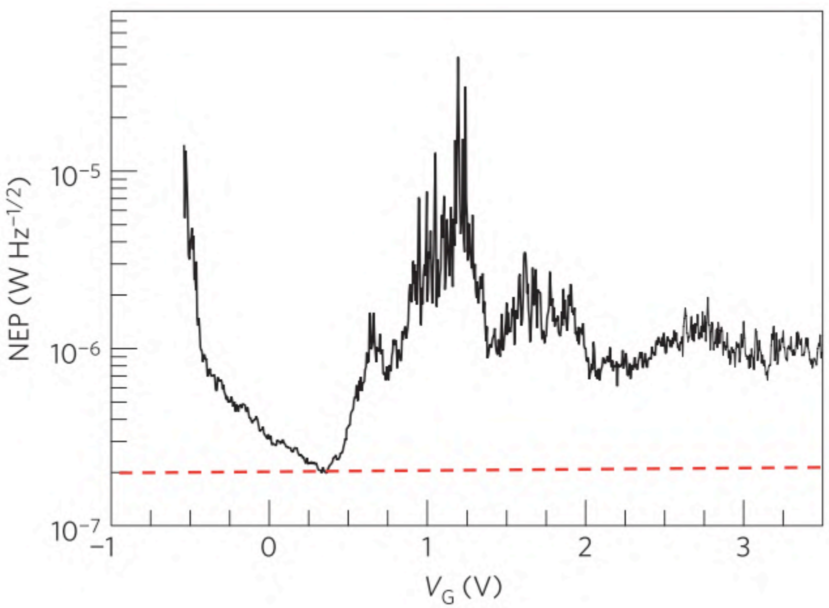
Vicarelli et. al, Nature Mat. 11, 865 (2012).



- 2 lobes of a log-periodic circular toothed antenna connected to the source and top gate
- Incoming fields modulate charge density
- Non-resonant response
- A nonlinearly rectified V_{sd} generated the detected signal

GFETs as room temperature THz detectors



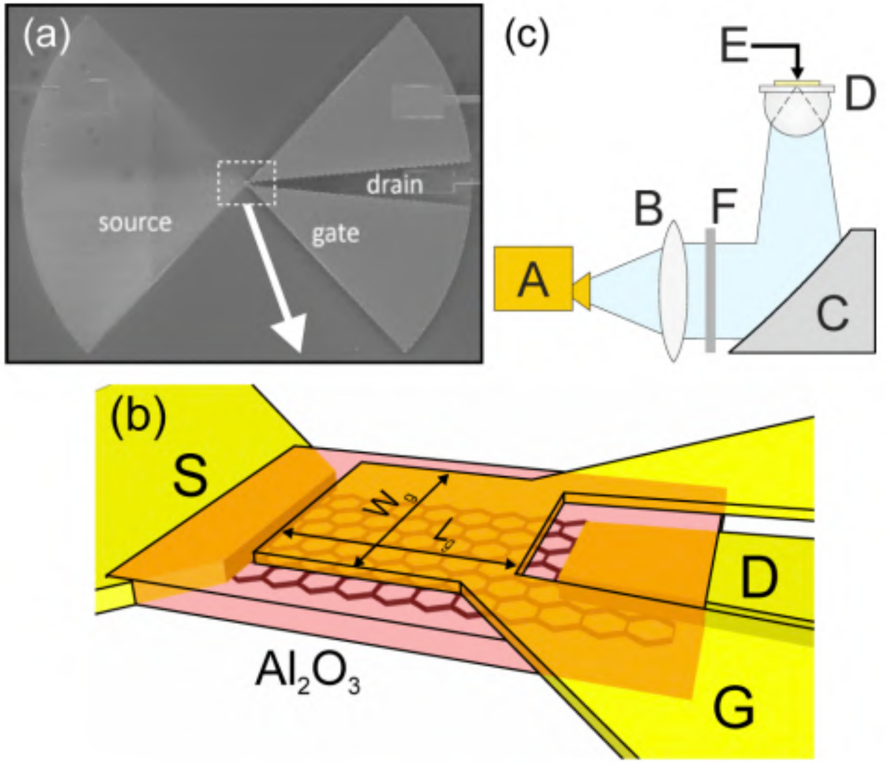


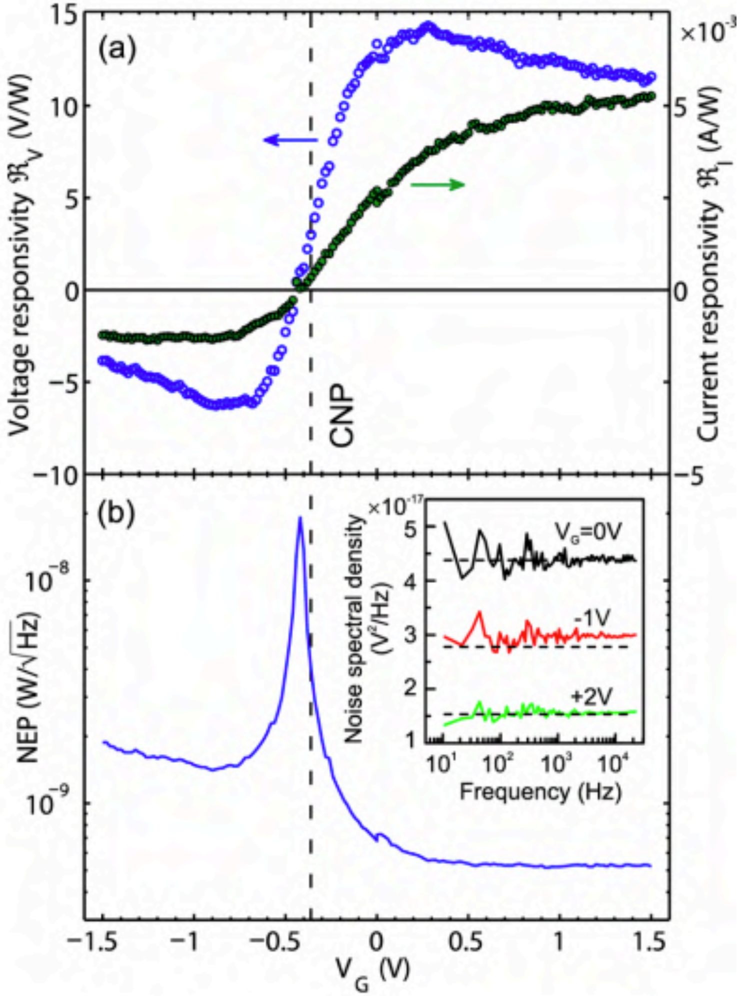
Vicarelli et. al, Nature Mat. 11, 865 (2012).

- Tests @ 0.3 THz, but broadband operation expected
- Noise equivalent power limited by the (improvable) charge mobility in the device
- A device based on bilayer graphene also shown

GFETs as room temperature THz detectors

- A somewhat better performance with CVD graphene

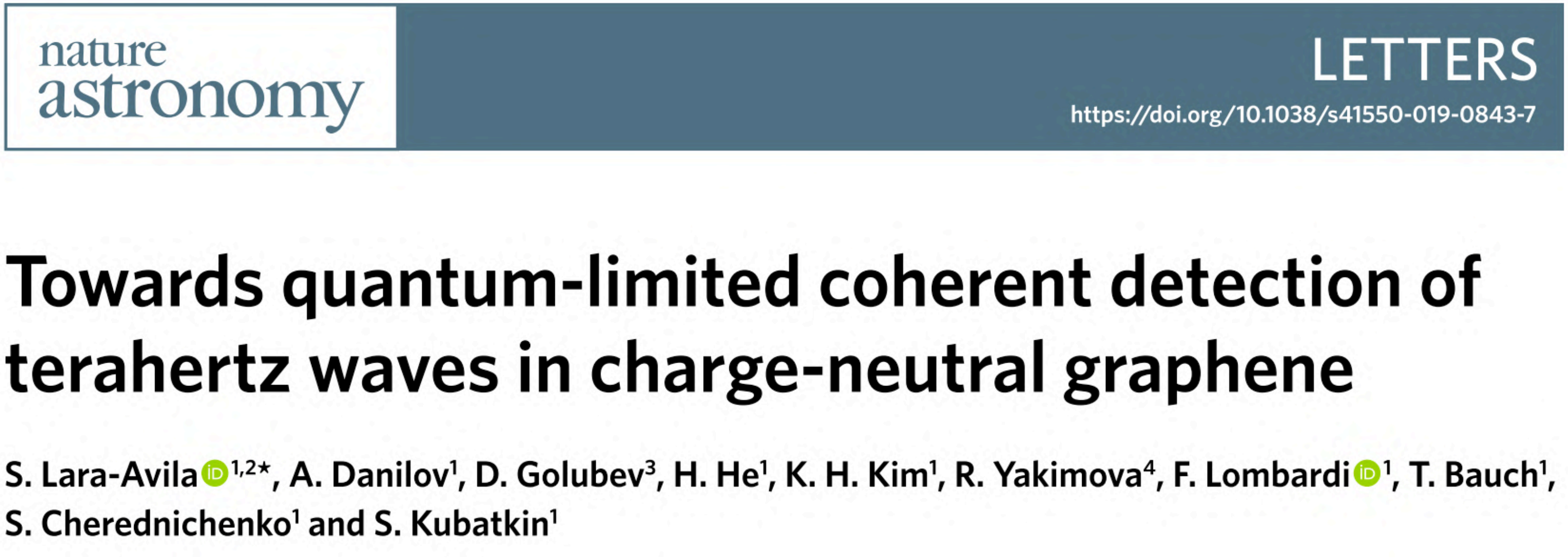




Zak et. al, Nano Lett. 14, 5834 (2014).

- Tests at 0.6 THz
- R_v up to 14 V/W, NEP as low as 515 $pW.Hz^{1/2}$

Heterodyne detection with a graphene bolometric mixer



nature astronomy

LETTERS

https://doi.org/10.1038/s41550-019-0843-7

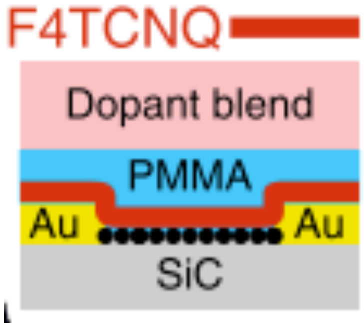
Towards quantum-limited coherent detection of terahertz waves in charge-neutral graphene

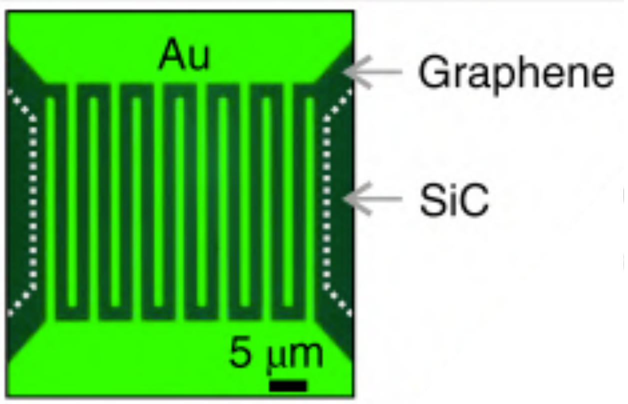
S. Lara-Avila[1,2]*, A. Danilov[1], D. Golubev[3], H. He[1], K. H. Kim[1], R. Yakimova[4], F. Lombardi[1], T. Bauch[1], S. Cherednichenko[1] and S. Kubatkin[1]

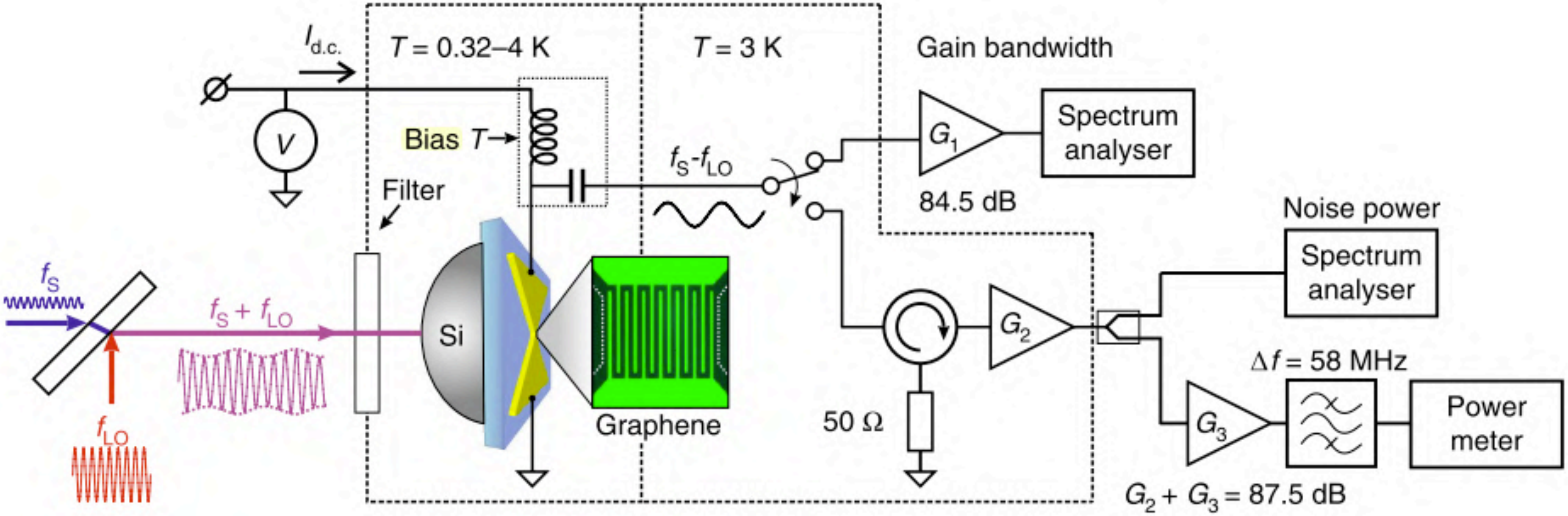
Lara-Avila et. al, Nature Astronomy (2019).

- For high quality graphene, quantum effects emerge and alter the intraband conductivity of graphene, adding a temperature dependent term: $\sigma_{intra} = \sigma_{Drude} + \sigma_1 ln(T/1K)$
- The 2nd term is relatively small except for when $n_q \rightarrow 0$ $(\sigma_{Drude} \rightarrow 0)$
- This requires high control over spurious graphene doping

Heterodyne detection with a graphene bolometric mixer

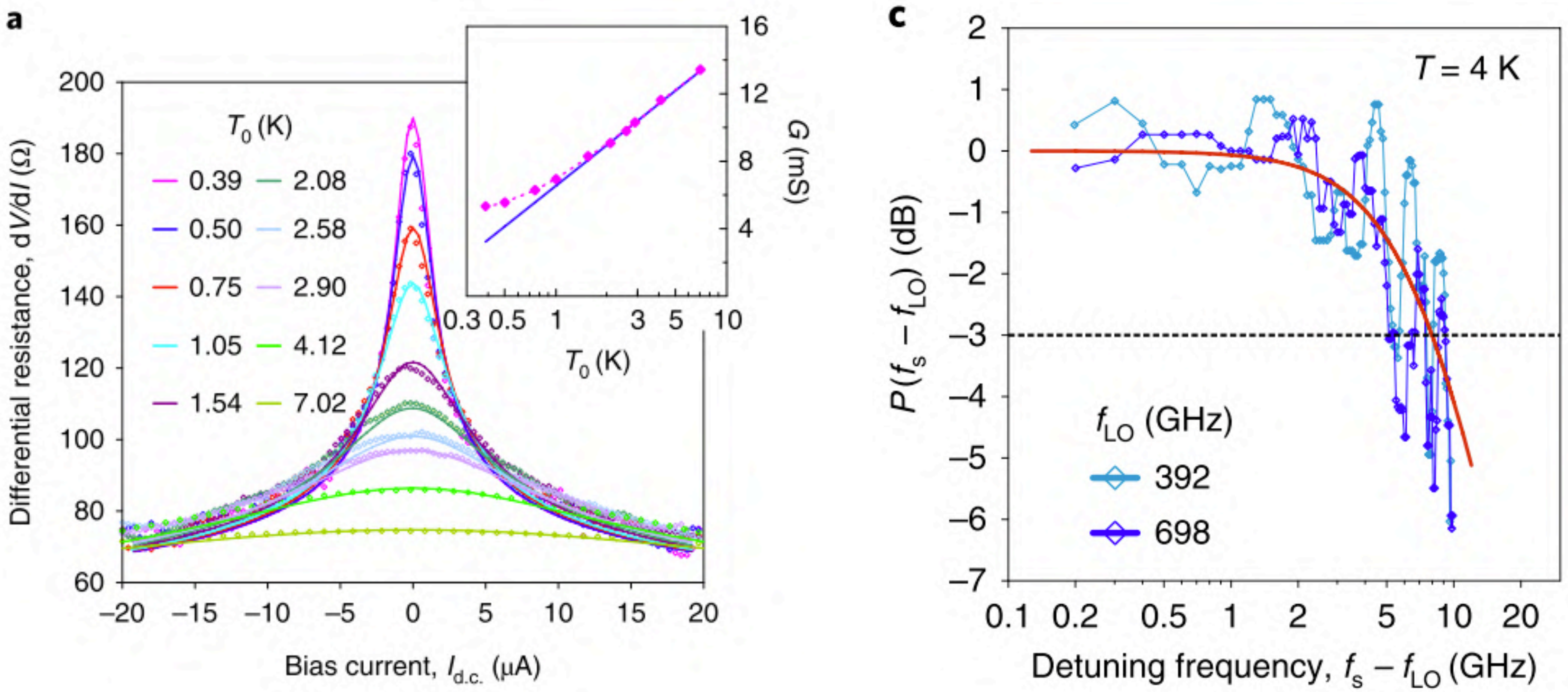






Lara-Avila et. al, Nature Astronomy (2019).

Heterodyne detection with a graphene bolometric mixer



Lara-Avila et. al, Nature Astronomy (2019).

- Ultrafast (~20 ps) heat dissipation via hot electron diffusion into the gold leads lead to 8 GHz bandwidth

Heterodyne detection with a graphene bolometric mixer

- Background radiation limits the performance in the lab. Performance in space (~0 background) can be predicted:

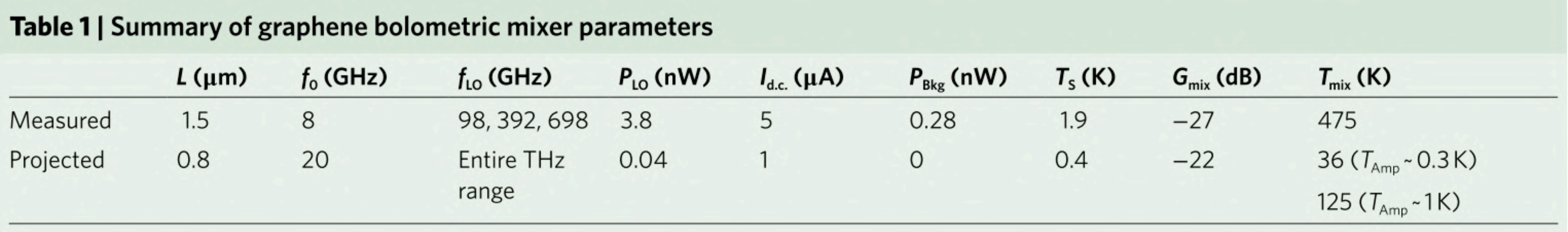


Table 1 | Summary of graphene bolometric mixer parameters

	L (μm)	f_0 (GHz)	f_{LO} (GHz)	P_{LO} (nW)	$I_{d.c.}$ (μA)	P_{Bkg} (nW)	T_S (K)	G_{mix} (dB)	T_{mix} (K)
Measured	1.5	8	98, 392, 698	3.8	5	0.28	1.9	−27	475
Projected	0.8	20	Entire THz range	0.04	1	0	0.4	−22	36 (T_{Amp} ~ 0.3 K) 125 (T_{Amp} ~ 1 K)

Lara-Avila et. al, Nature Astronomy (2019).

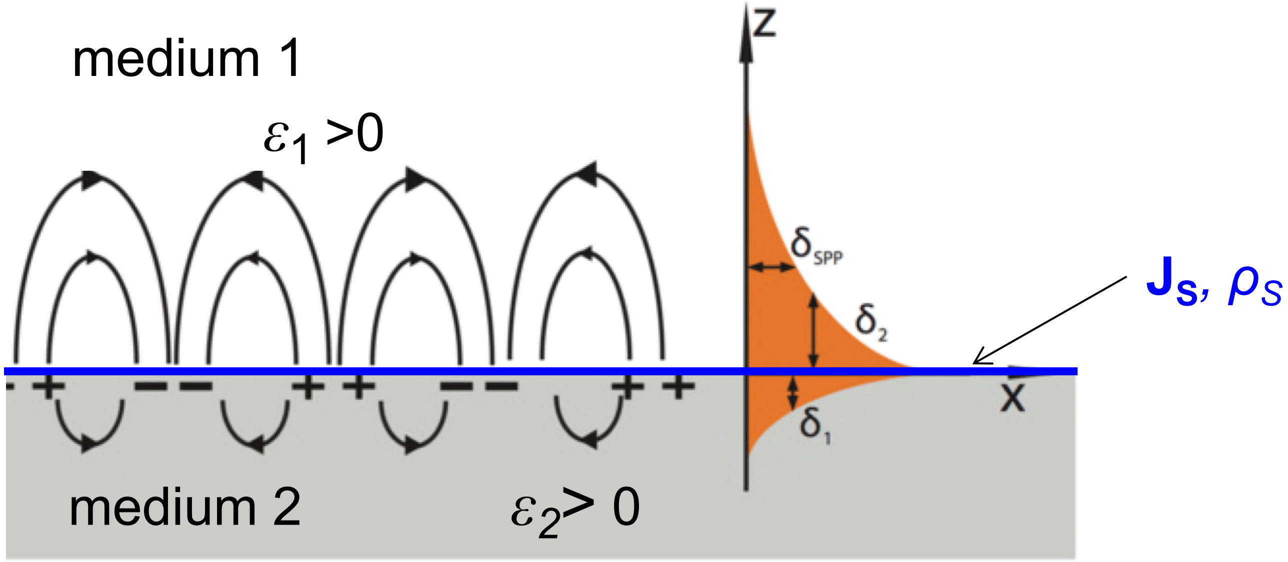
Surface plasmon polaritons in graphene

- Results presented so far assume that plasma oscillation in graphene is overdamped.

- When electron scattering rate $(1/\tau)$ is low, **surface plasmon polatitons** may be excited, significantly improving interaction with radiation

Surface plasmon polaritons in graphene

- Collective surface charge oscillations coupled to light



- TM mode with exponentially decaying fields along *z*
- Boundary conditions:

$$E_{1x} = E_{2x}$$

$$H_{1y} - H_{2y} = -J_x = -\sigma E_{2x}$$

Surface plasmon polaritons in graphene

- Boundary conditions yield:

$$\frac{\varepsilon_1}{\sqrt{\beta^2-k_0^2\varepsilon_1}}+\frac{\varepsilon_2}{\sqrt{\beta^2-k_0^2\varepsilon_2}}+\frac{i\sigma}{\omega\varepsilon_0}=0$$

$$\boxed{\sigma(\omega)=\frac{v_F e^2\tau\sqrt{n_q}}{\hbar\sqrt{\pi}\left(1-i\tau\omega\right)}}$$

- For $\omega\tau >>1$

$$\frac{\varepsilon_1}{\sqrt{\beta^2-k_0^2\varepsilon_1}}+\frac{\varepsilon_2}{\sqrt{\beta^2-k_0^2\varepsilon_2}}=\frac{e^2E_F}{\pi\varepsilon_0\left(\hbar\omega\right)^2}$$

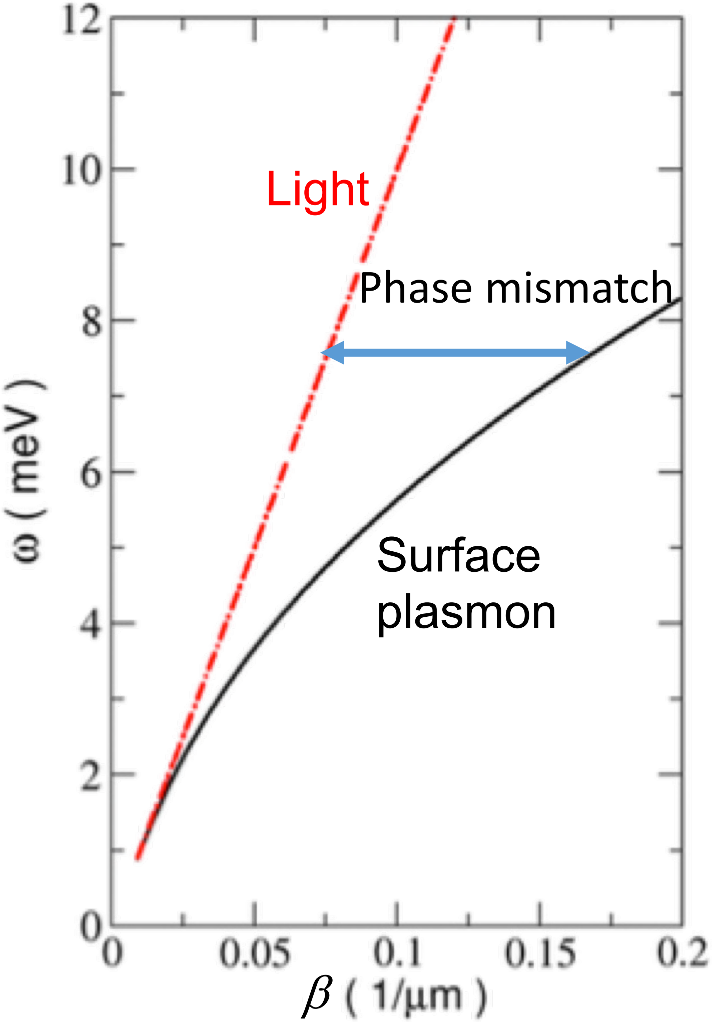
- In the electrostatic limit ($\beta^2 >> k_0^2\varepsilon_{1,2}$)

$$\hbar\omega_{pl}=\sqrt{\frac{e^2E_F\beta}{2\pi\varepsilon_0\bar{\varepsilon}}}$$

$$\bar{\varepsilon}=\frac{\varepsilon_1+\varepsilon_2}{2}$$

Surface plasmon polaritons in graphene

$$\hbar\omega_{pl} = \sqrt{\frac{e^2 \boxed{E_F} \beta}{2\pi\varepsilon_0 \bar{\varepsilon}}}$$

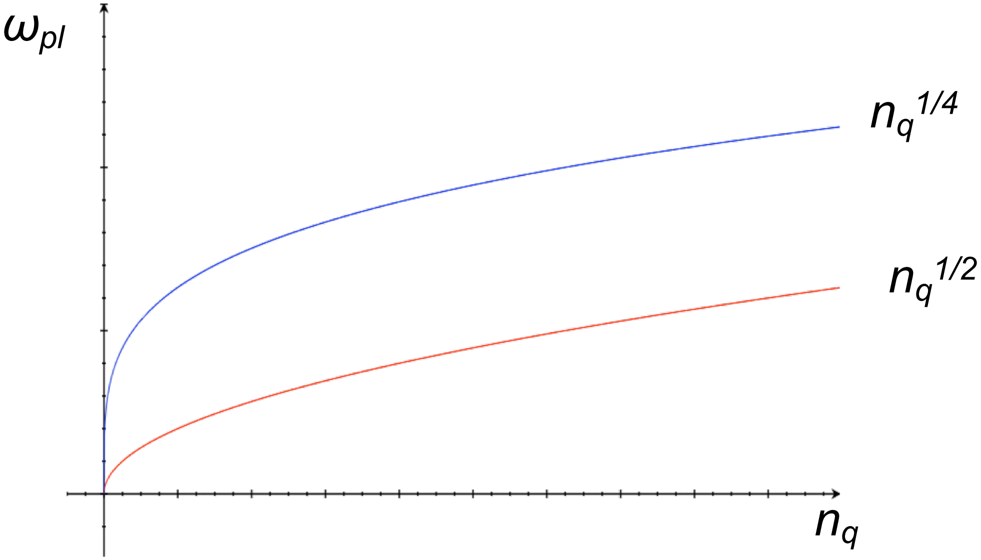


Y. Bludov *et al.*, Int. J. Mod. Phys. B 27, 1341001 (2013)

Surface plasmon polaritons in graphene

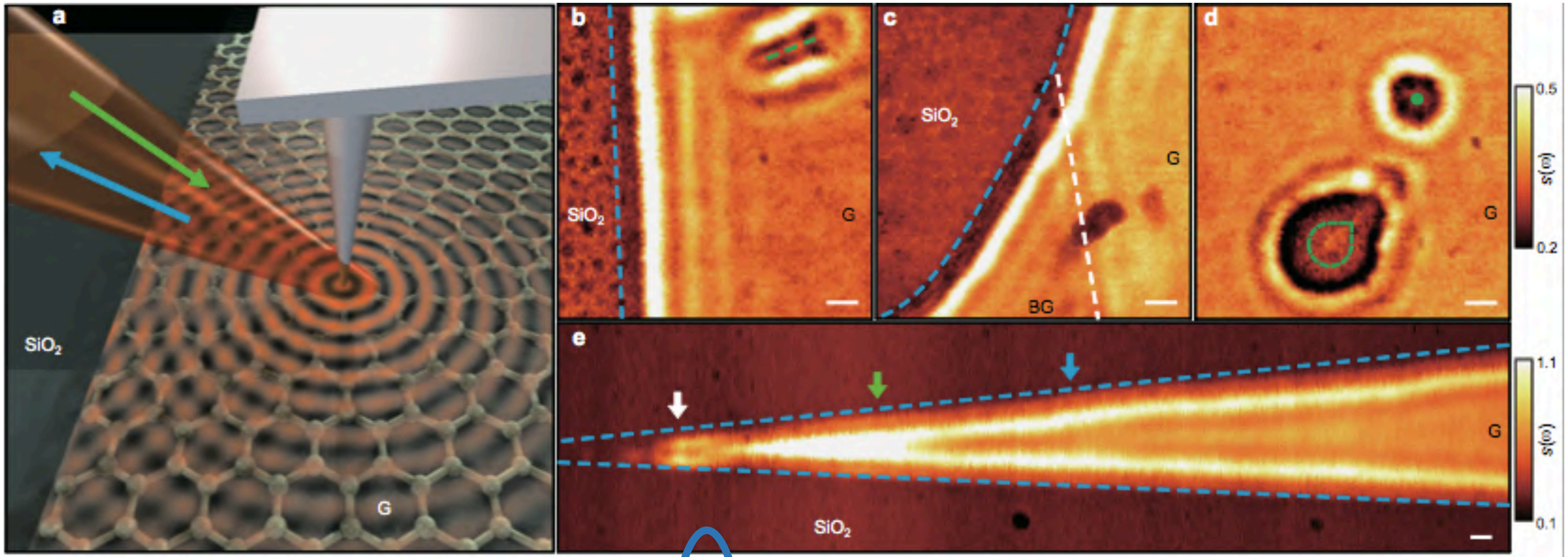
- For graphene: $E_F \propto \sqrt{n_q}$
- For parabolic materials: $E_F \propto n_q$
- ➔ $\omega_{pl} \propto n_q^{1/4} \beta^{1/2}$ (graphene)

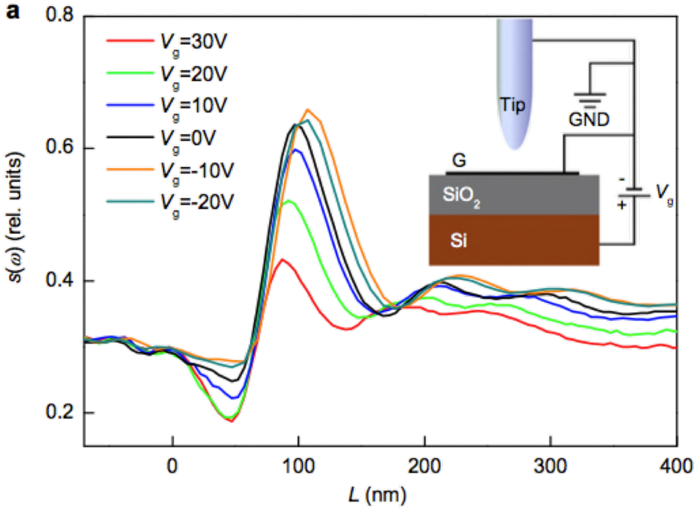
  $\omega_{pl} \propto n_q^{1/2} \beta^{1/2}$ (parabolic 2D)

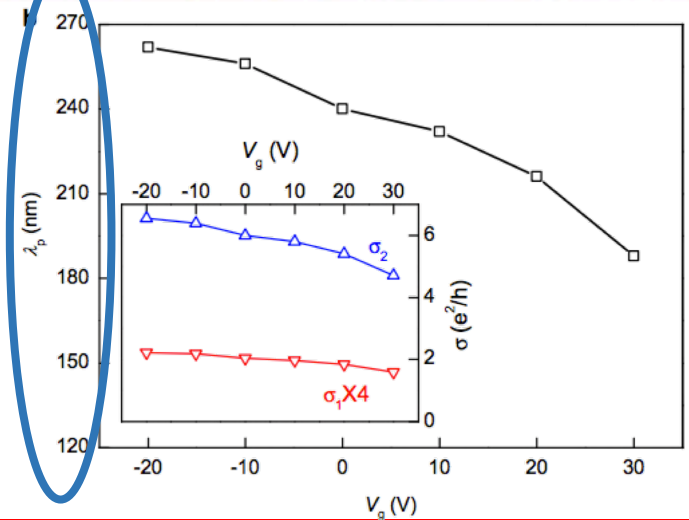


Much more ω_{pl} tunability in graphene

Surface plasmon polaritons in graphene



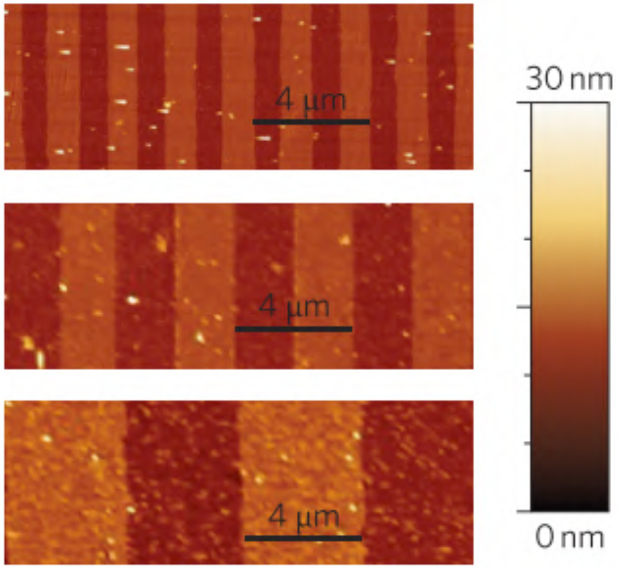




λ_{IR}/λ_p = 50-60

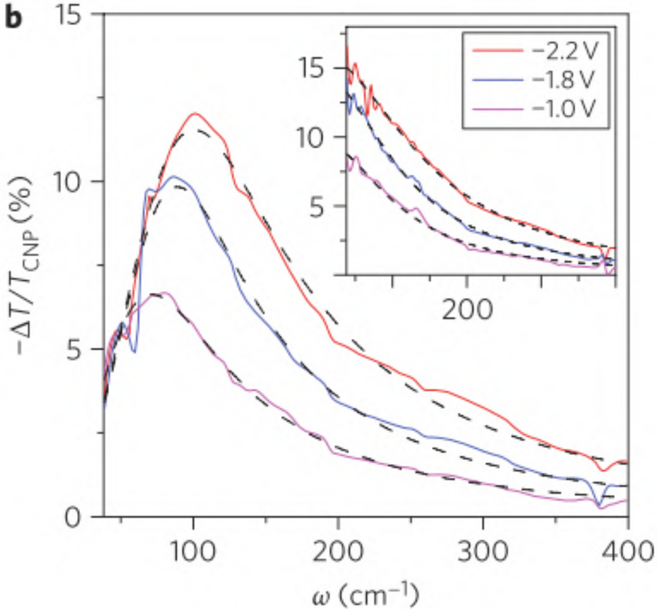
Z. Fei *et al.*, Nature (2012).

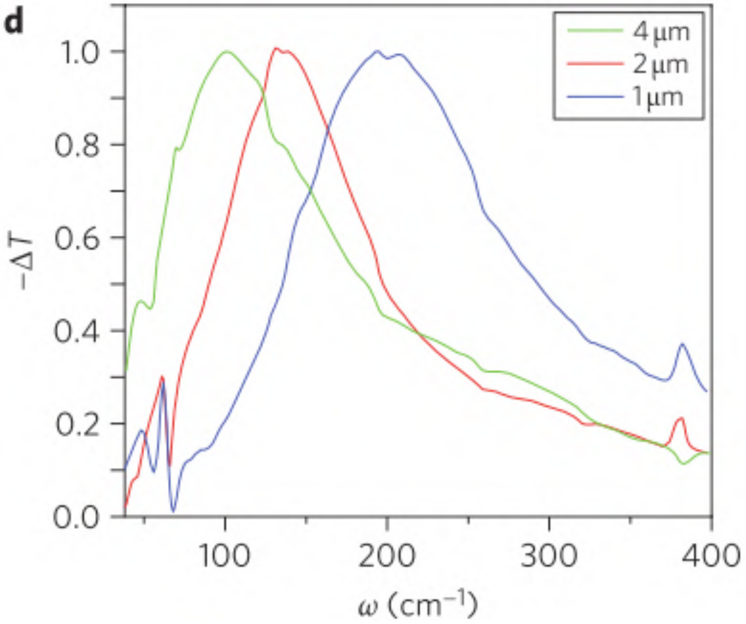
Localized surface plasmons in graphene



- The other way to overcome phase mismatch is to excite localized plasmons in micro/nanostructured graphene

1.5 – 12 THz

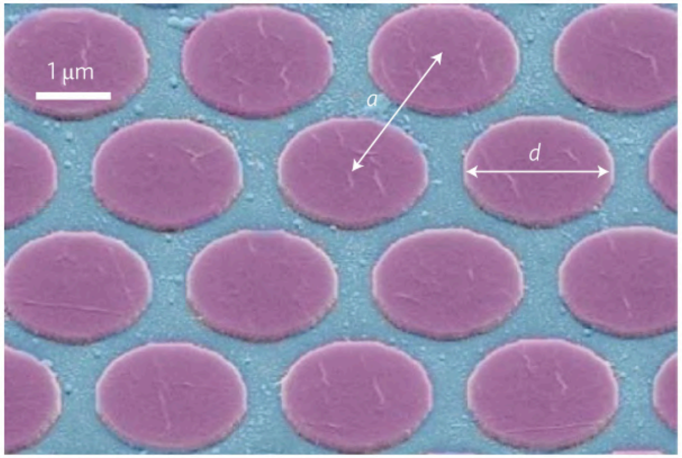


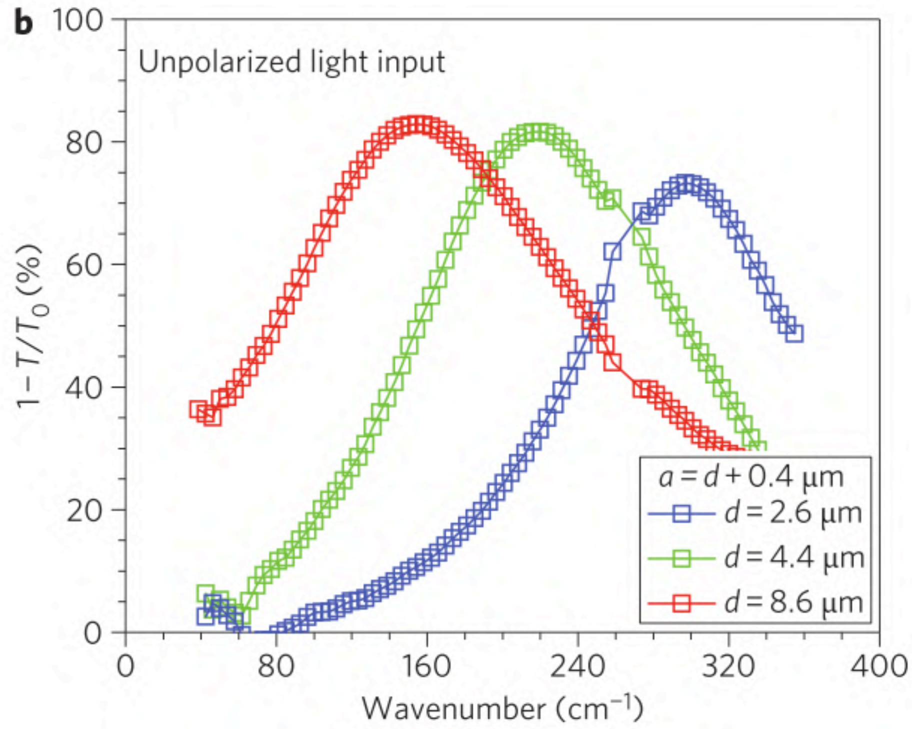


Ju *et al.*, Nature Nanotechnol. 6, 630 (2011).

Filters/polarizers based on localized surface plasmons

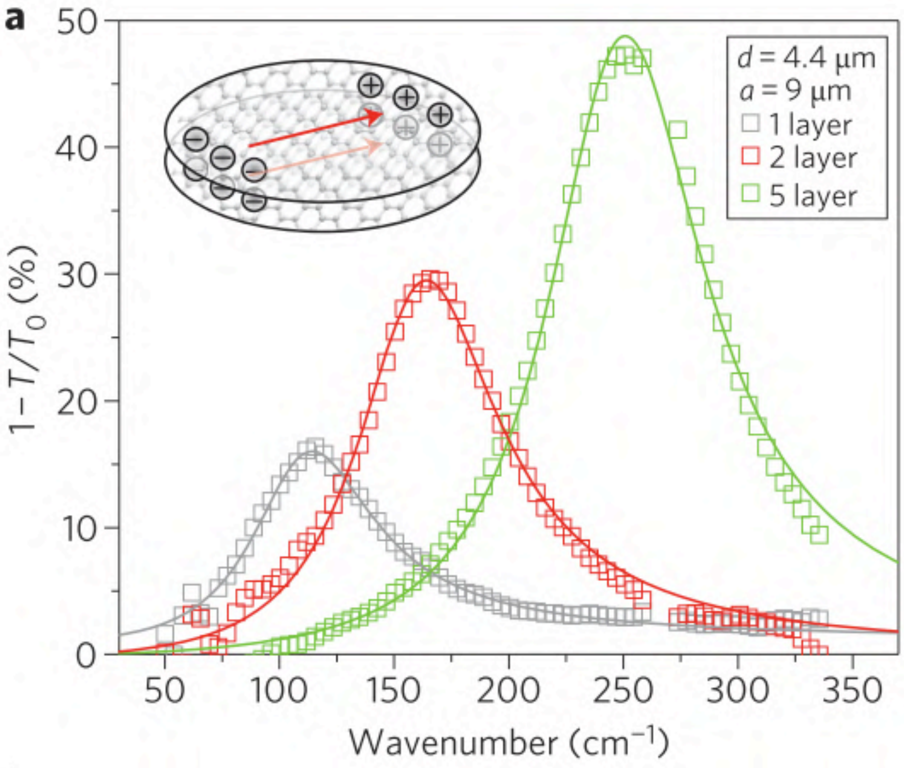
- Multiple doped graphene monolayers
- 8.2 dB polarization indep. rejection



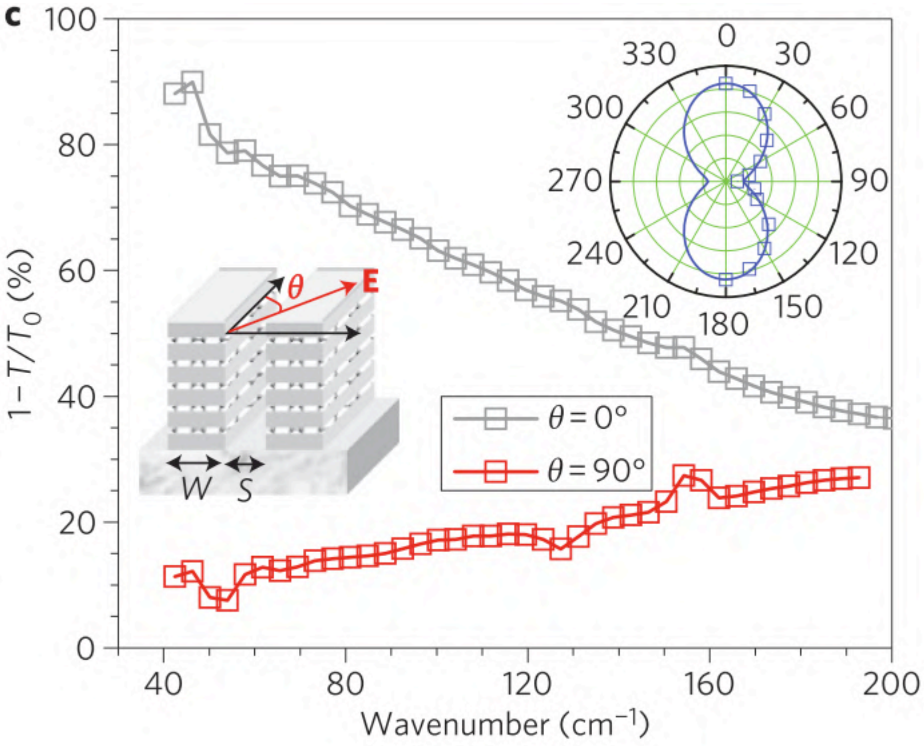


Yan *et al.*, Nature Nanotechnol. 7, 330 (2012).

Filters/polarizers based on localized surface plasmons



- Interlayer Coulomb interaction tunes filter

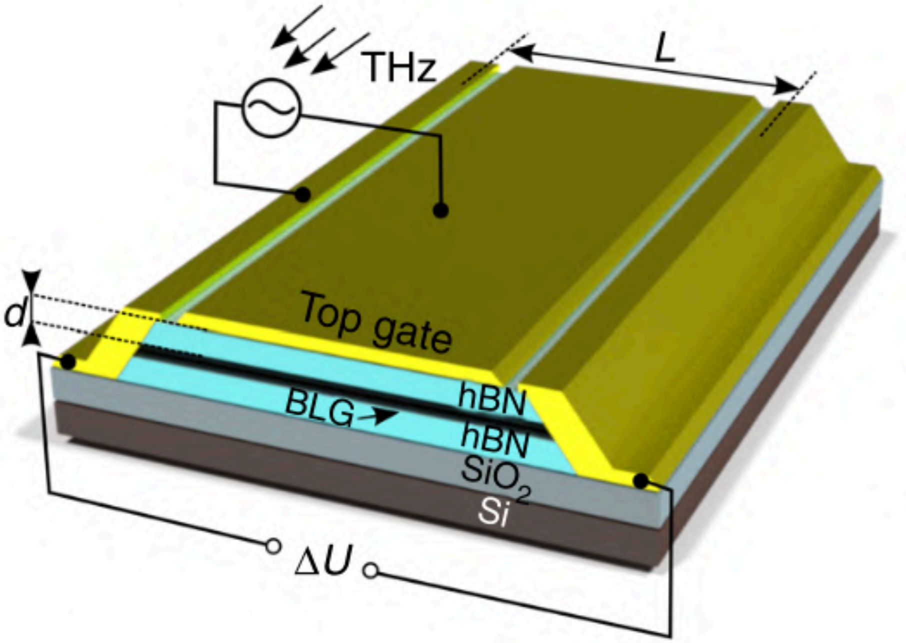


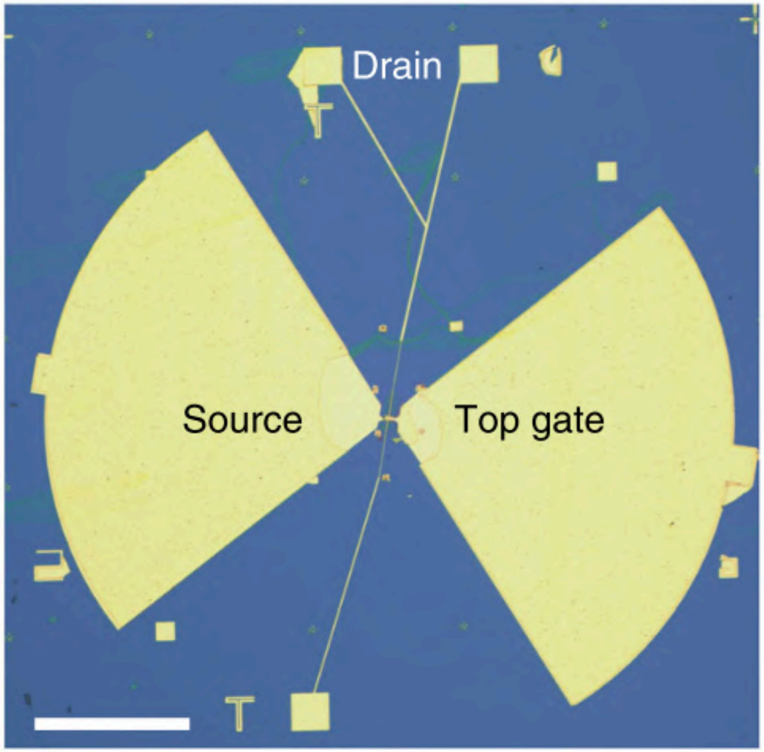
- 9.5 dB polarization extinction ratio

Yan *et al.*, Nature Nanotechnol. 7, 330 (2012).

A resonant plasmonic detector

- Graphene bilayer FET
- FET acts as a plasmonic cavity and a rectifying element

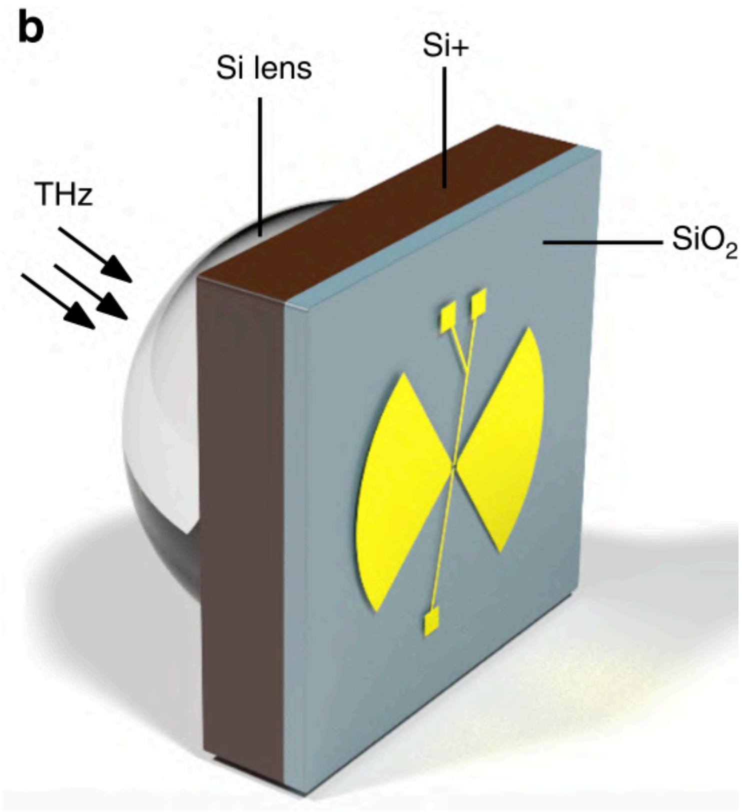


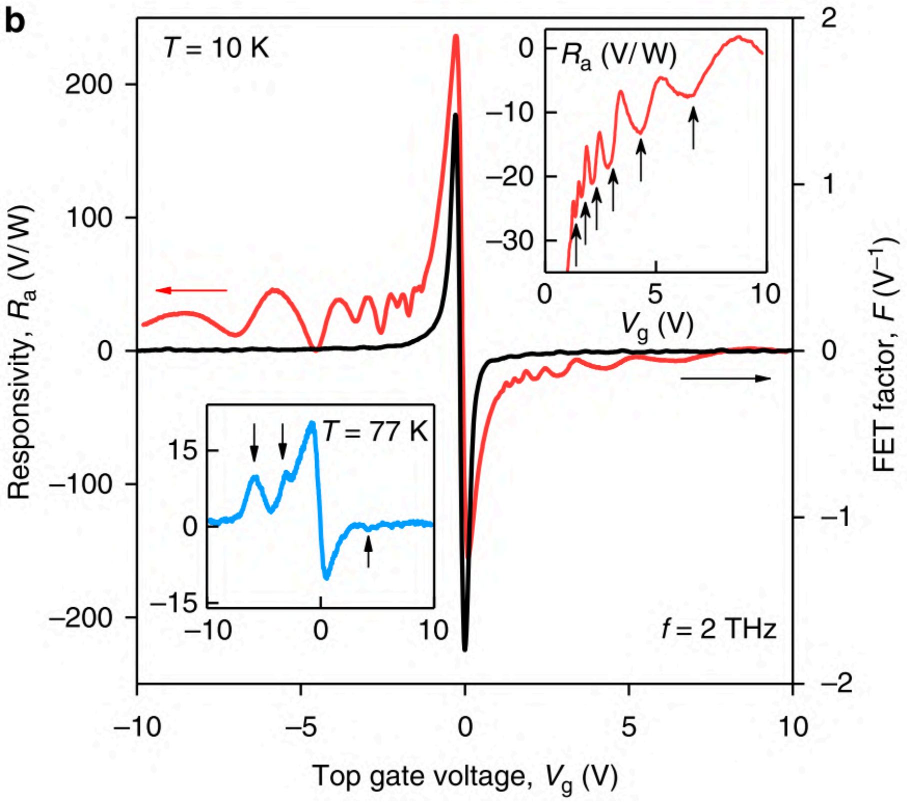


Bandurin *et al.*, Nature Comm. 9, 5392 (2018).

A resonant plasmonic detector

- Resonant peaks:
  - correspond to plasmonic Fabry-Perot modes
  - can be exploited to obtain spectral resolution





Bandurin *et al.*, Nature Comm. 9, 5392 (2018).

Conclusions and outlook

- Graphene present electronic, optoelectronic and plasmonic properties that make it attractive for THz applications
- The high charge mobility, electrical tunability and low temperature dependence are attractive features for use in astronomical instruments
- For space-bourne applications susceptibility to the space environment (e.g. cosmic rays, radiation) is yet to be further tested.

MackGraphe

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