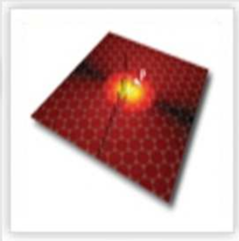
Magneto-plasmonic effects in epitaxial graphene

Alexey Kuzmenko

University of Geneva

Graphene Nanophotonics
Benasque, 4 March 2013



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www.graphene-flagship.eu
GRAPHENE FLAGSHIP

Collaborators

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J. Chen, F. Huth, R. Hillenbrand
CIC nanoGUNE, San Sebastian

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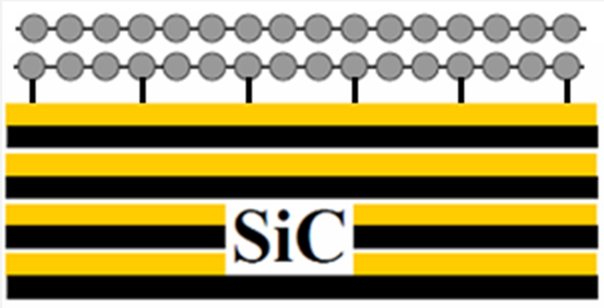
CNRS, Grenoble

Different types of epitaxial graphene (EG)

Si–face

Growth at ~ 1500 ºC in Ar

monolayer on buffer layer

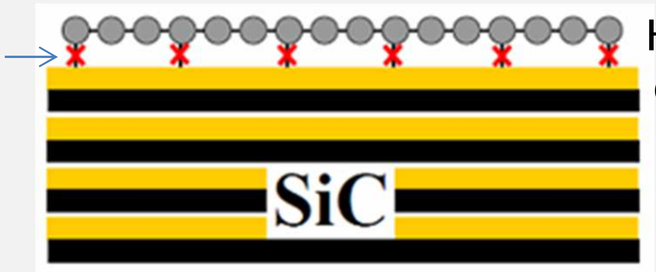


Highly doped

K. Emtsev, Nature Materials, **8**, 203 (2009)

Quasi-freestanding monolayer
(hydrogenated dangling bonds)

H

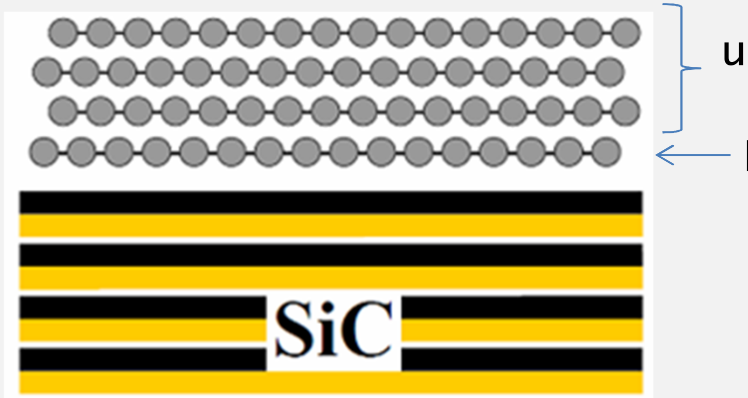


Highly doped

C. Riedl *et al.* PRL **103**, 246804 (2009)

C–face

twisted multilayer



undoped

Highly doped

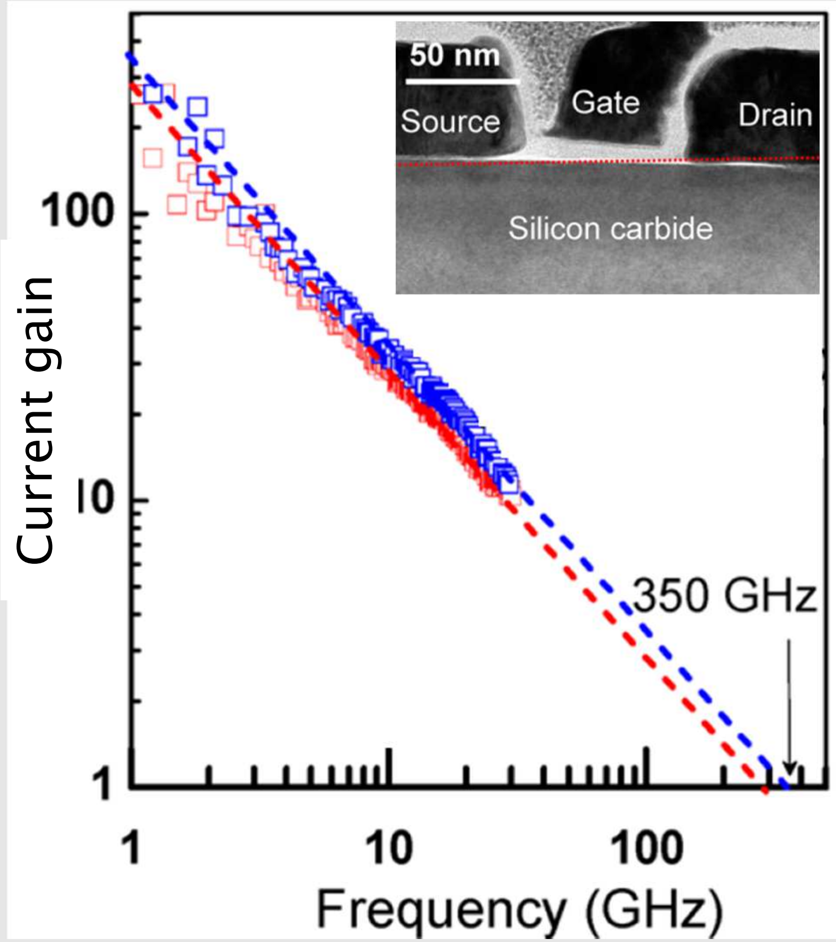
C. Berger *et al.* J. Phys. Chem. B **108**, 19912 (2004)

Defect free-regions
of several micron size

Single layer graphene on Si-face of SiC

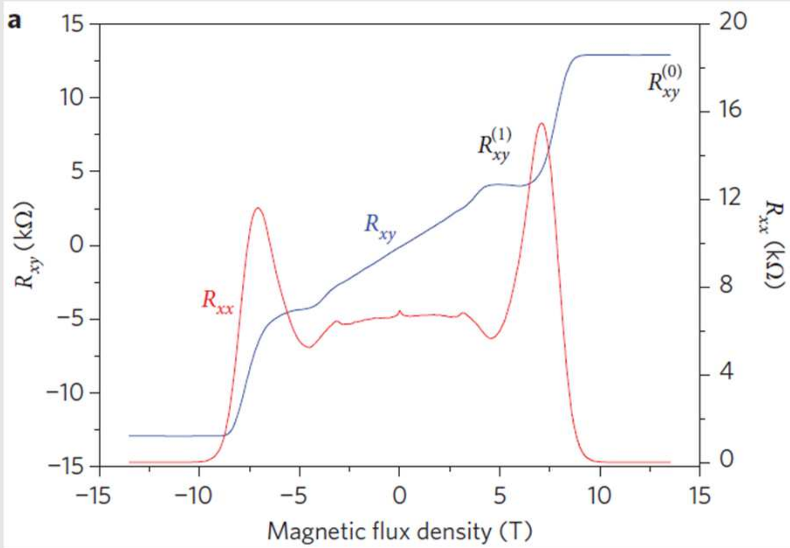
Ultrafast graphene transistors

Mobility $\mu \approx 3000 \frac{\mathrm{cm}^2}{\mathrm{V\,s}}$

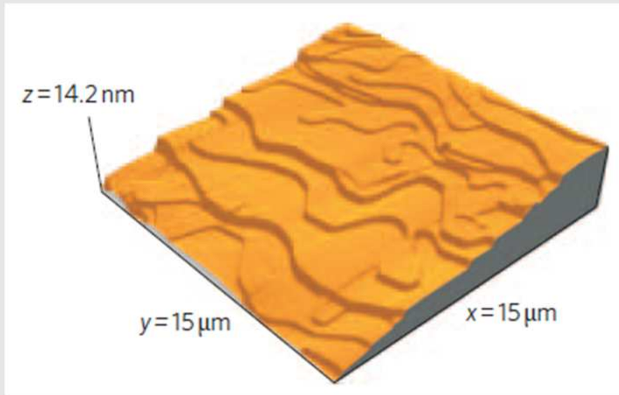


IBM group: Wu *et al.* Nano Letters (2012)

QHE resistance standard

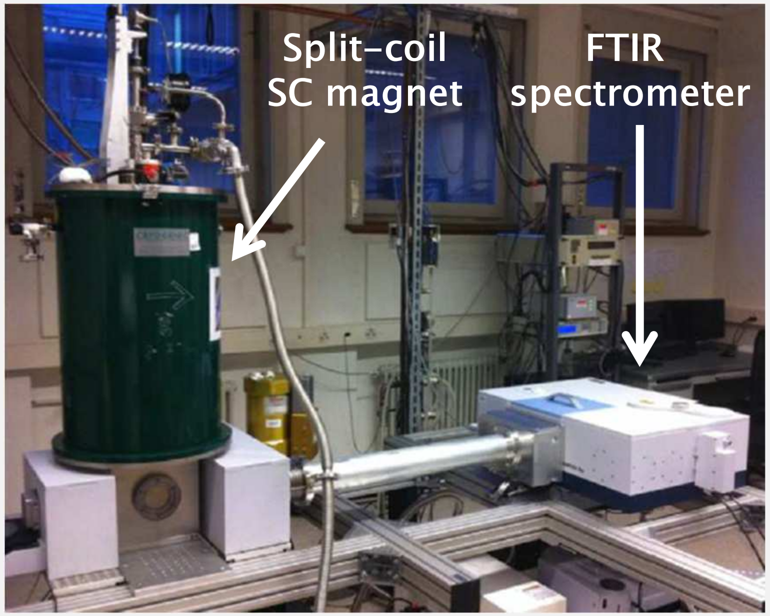


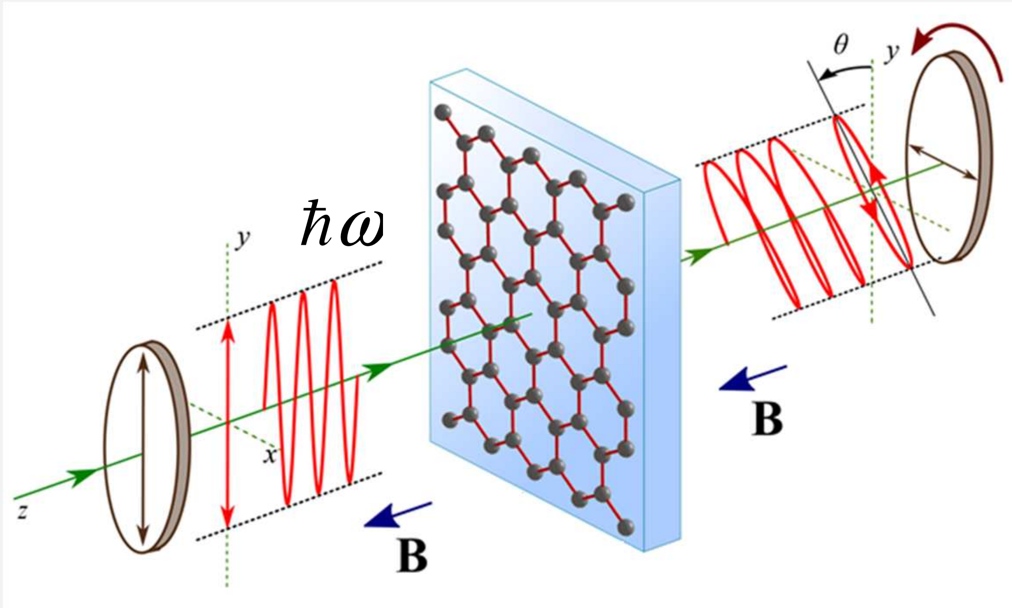
Terrace steps



A. Tzalenchuk *et al.* Nature Nano. (2010)

Infrared/THz magneto-optical setup





- $\hbar\omega$ from to 1 meV - 0.5 eV
- B from -7 to +7 T
- Linear polarization
- Far-field / large spot

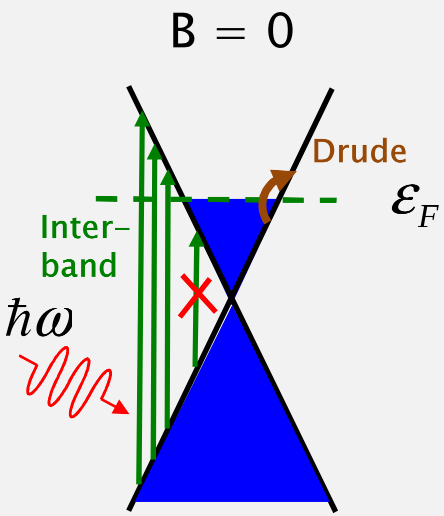
Absorption ➜ Optical conductivity $\sigma_{xx}(\omega)$

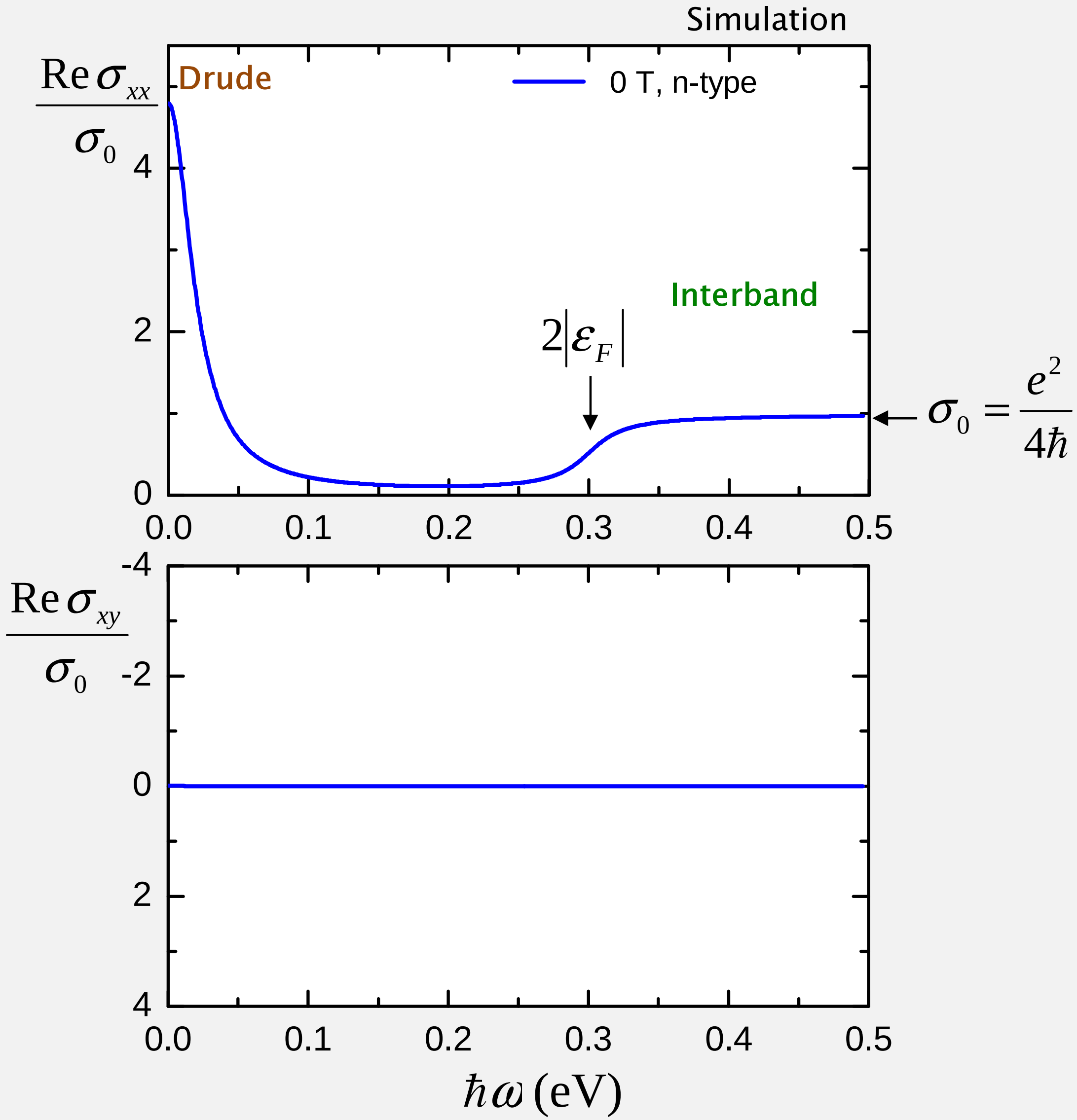
Faraday rotation ➜ Optical Hall conductivity $\sigma_{xy}(\omega)$

Finally we extract: (+) (−)

$$\sigma_{\pm}(\omega) = \sigma_{xx}(\omega) \pm i\sigma_{xy}(\omega)$$

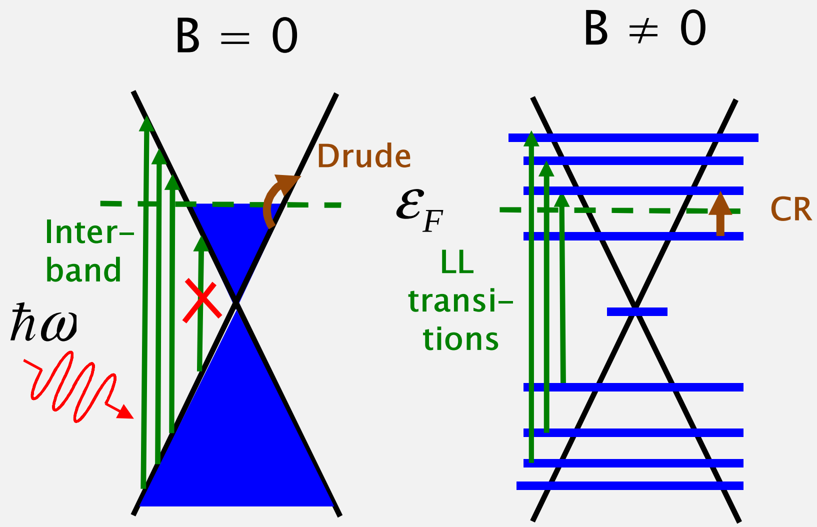
Optical conductivity of one monolayer (theory)



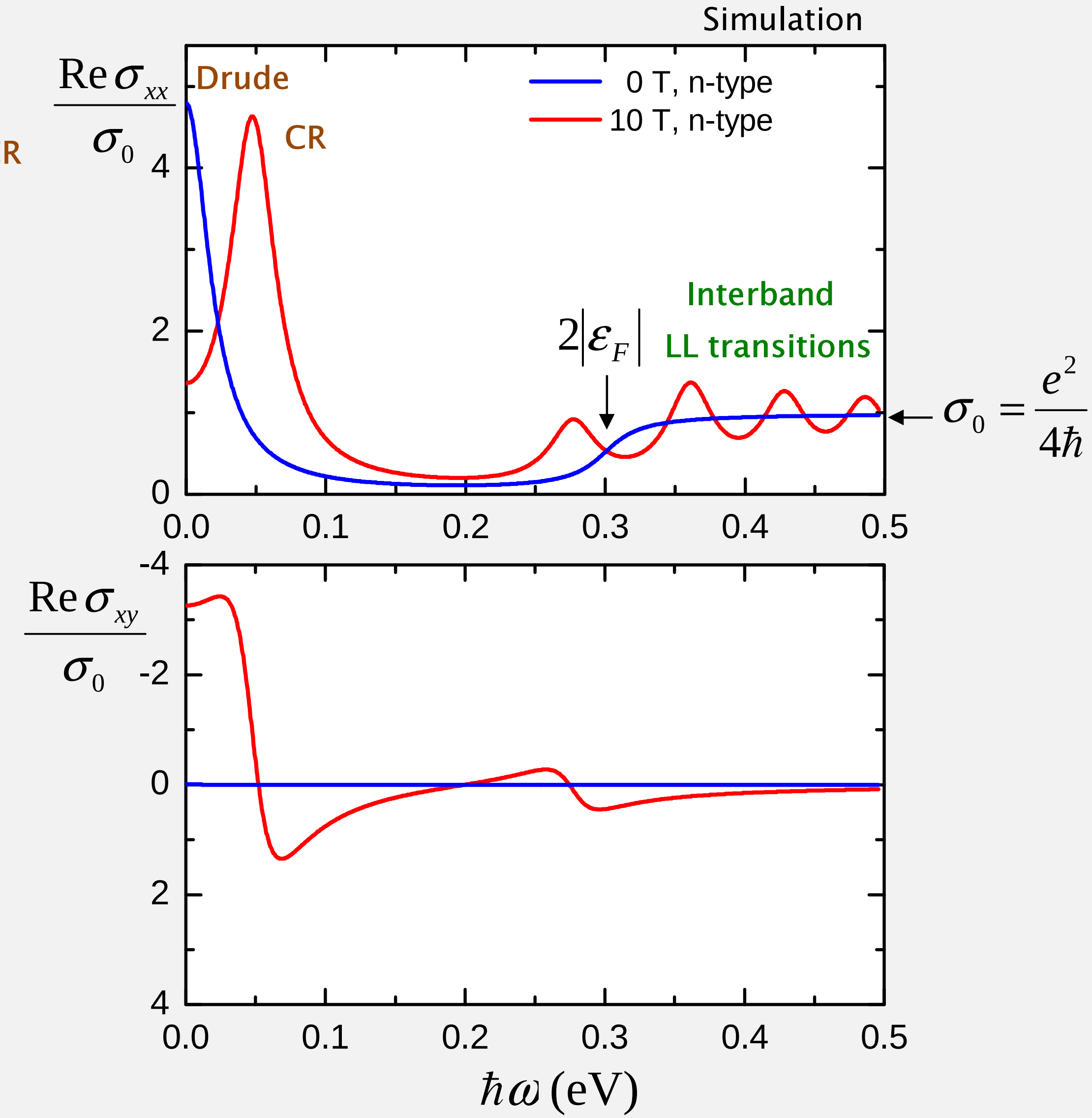


T. Ando JPSJ, 71, 1318 (2002)

Optical conductivity of one monolayer (theory)



$$E_n = \pm v_F \sqrt{2e\hbar nB}$$



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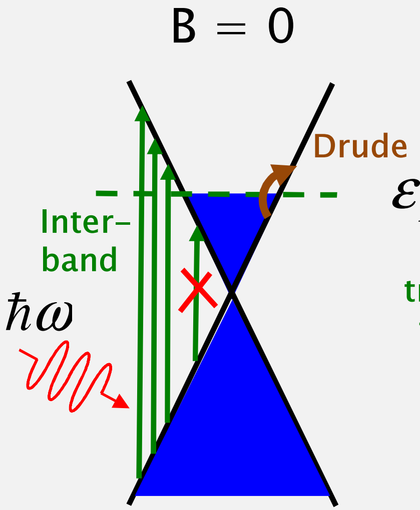
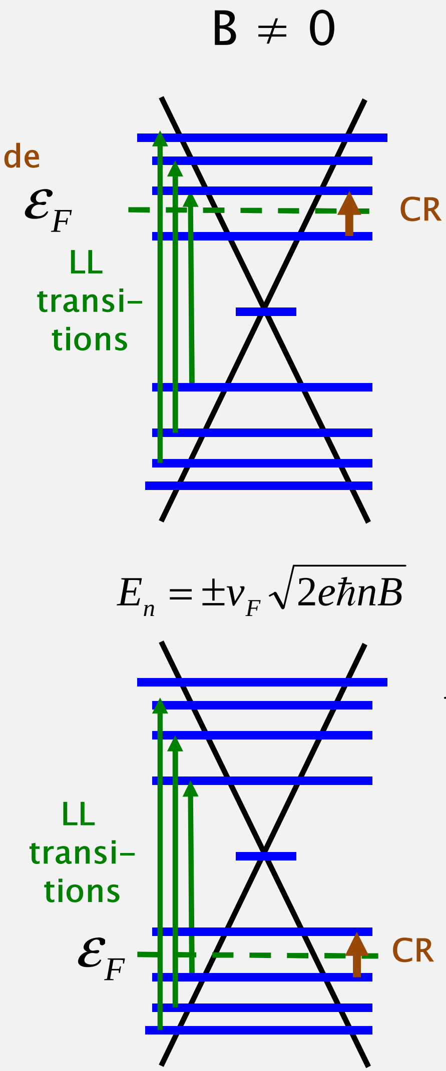
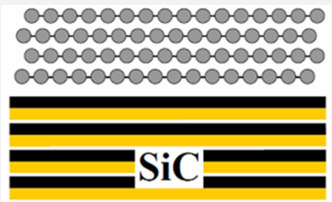
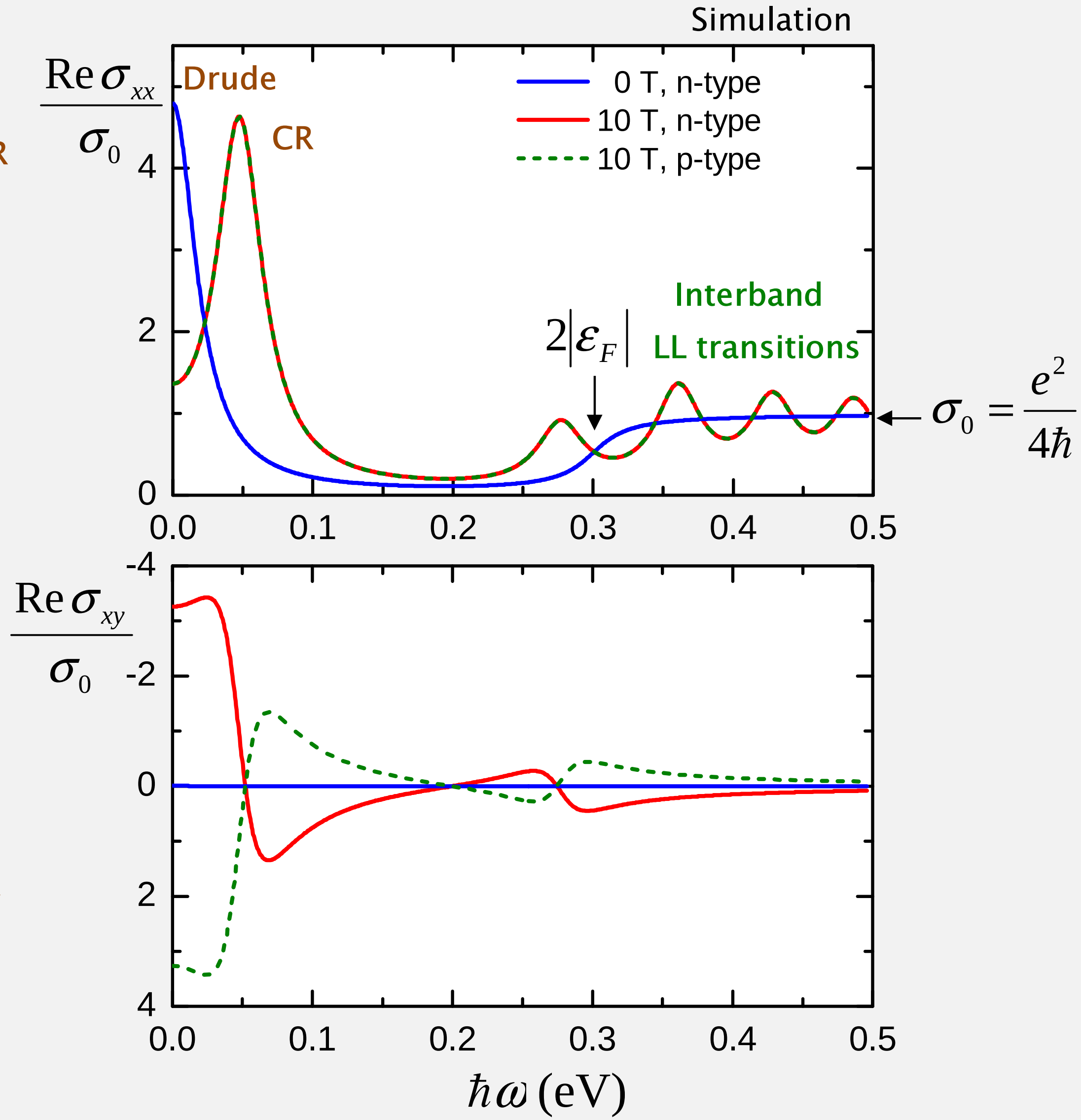






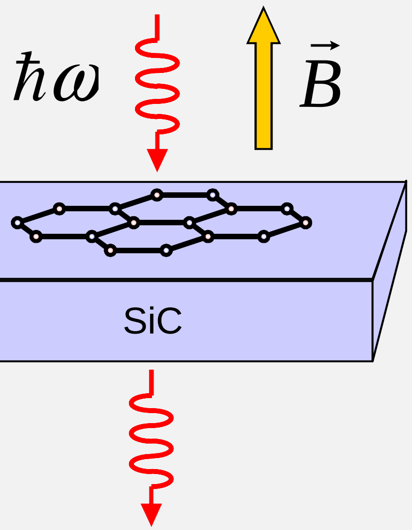


In reality:

- all layers add to the signal
- doping changes across layers
- stacking and grains may invalidate simple theory

T. Ando JPSJ, 71, 1318 (2002)

What magneto-optics can tell about graphene ?



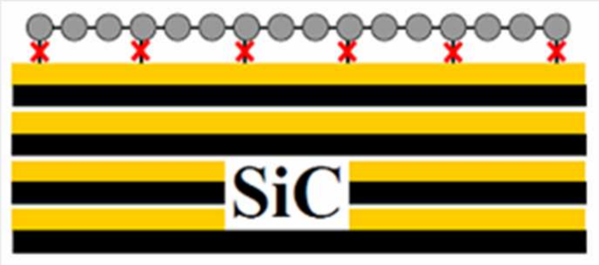
- Thickness / homogeneity
- Doping level
- Doping type (p or n)
- Doping homogeneity
- Mobility
- Fermi velocity
- Cyclotron mass
- Electron–hole asymmetry
- Stacking
- Grains boundaries
- ...

- Sees all layers
- No contacts/resist
- No UHV needed
- Done routinely

useful for routine characterization

Extracting physical parameters

Quasi-free standing monolayer



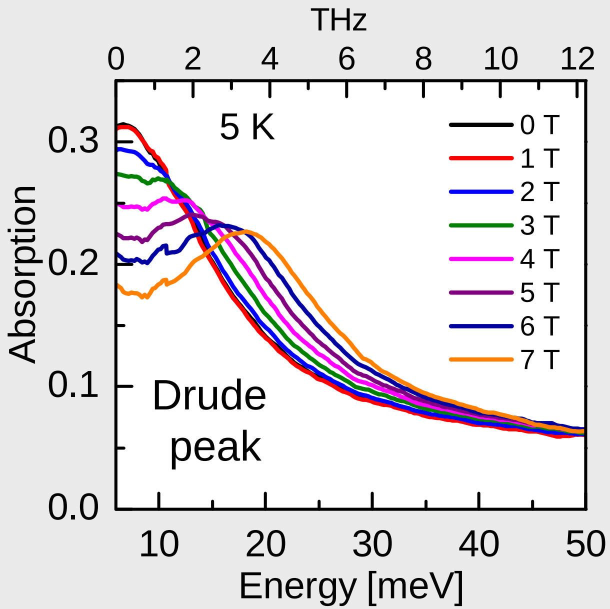
$$|\varepsilon_F| \approx 0.35\,\mathrm{eV}$$

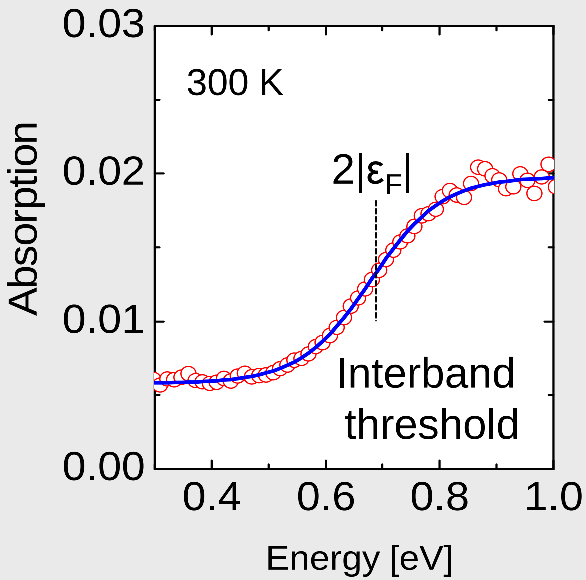
$$n \approx 8\cdot 10^{12}\ \mathrm{cm}^{-2}$$

$$m_{CR} \approx 0.055\, m_e$$

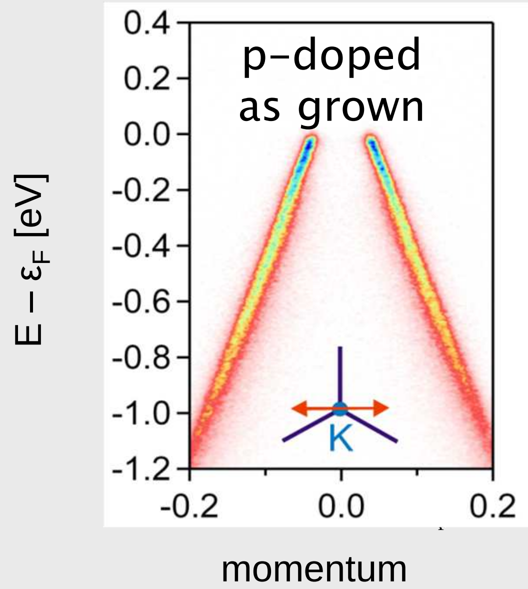
$$v_F = 1.05\cdot 10^{6}\ \mathrm{m/s}$$

$$\mu \approx 2500\,\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$$





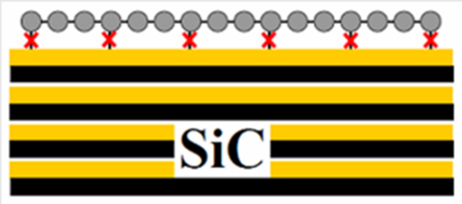
ARPES



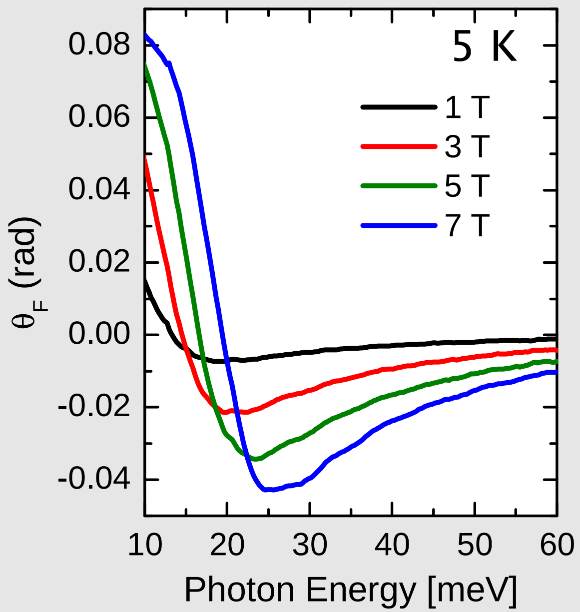
I. Crassee *et al.* Nature Physics **7**, 48 (2011)

Electrons or holes ?

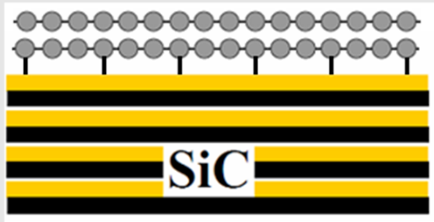
Quasi-free standing monolayer



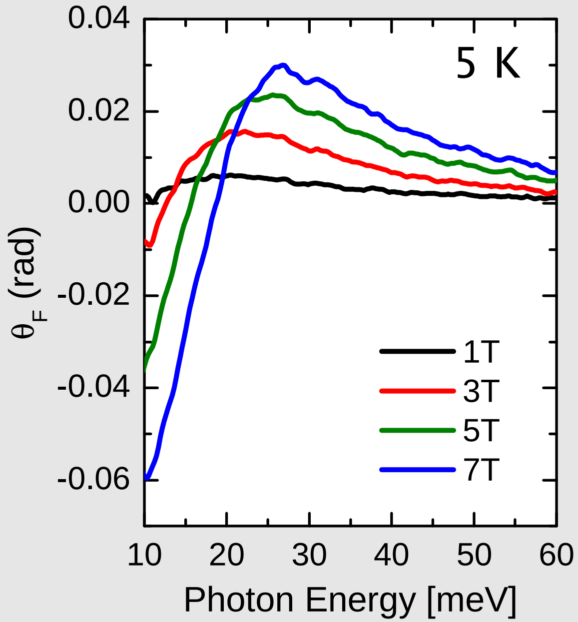
p-doped

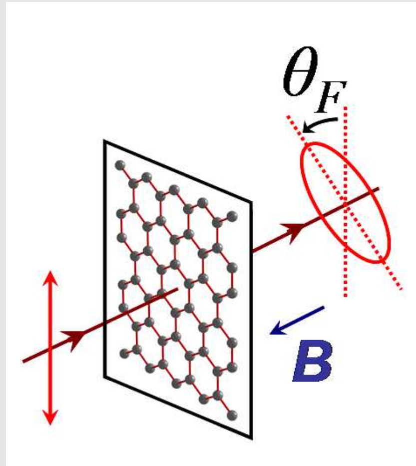


Monolayer on buffer layer



n-doped



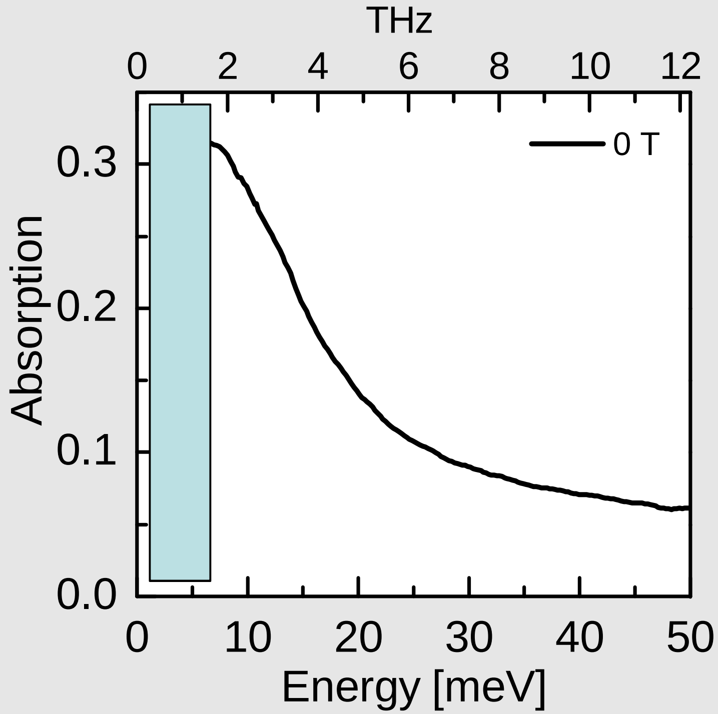


Faraday rotation is sensitive to the doping type

I. Crassee *et al.* Nature Physics **7**, 48 (2011)

N. Ubrig et al., in preparation

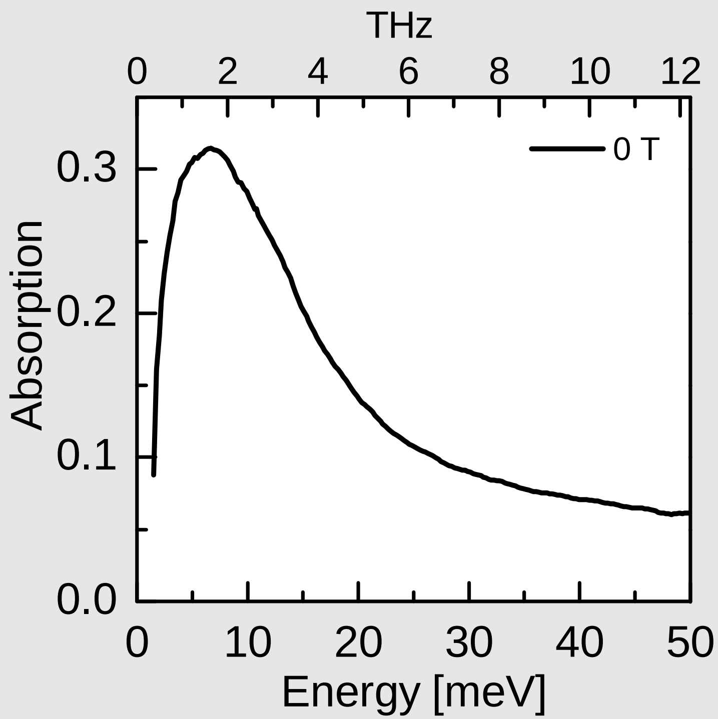
Drude peak



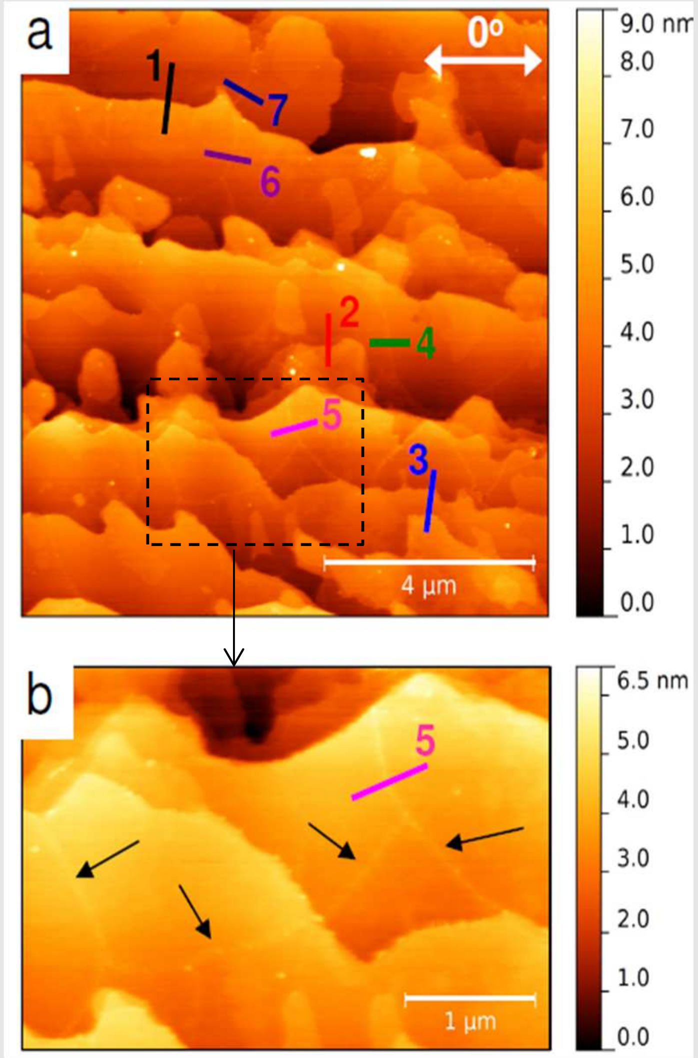
QFS monolayer

I. Crassee *et al.* Nano Lett. **12**, 2470 (2012)

Drude peak … is not a Drude peak !



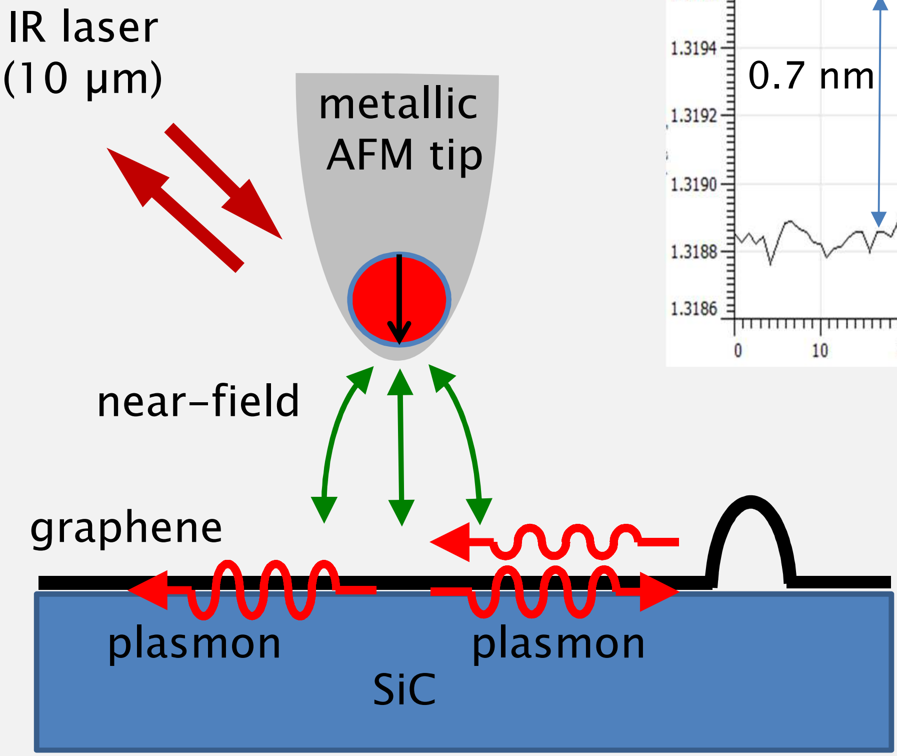
Quasi-freestanding monolayer

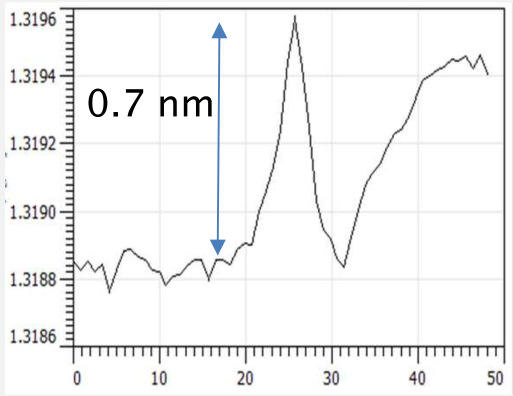


- Plasmon excitation
- Caused by steps (and wrinkles)
- Edge resistance should be big

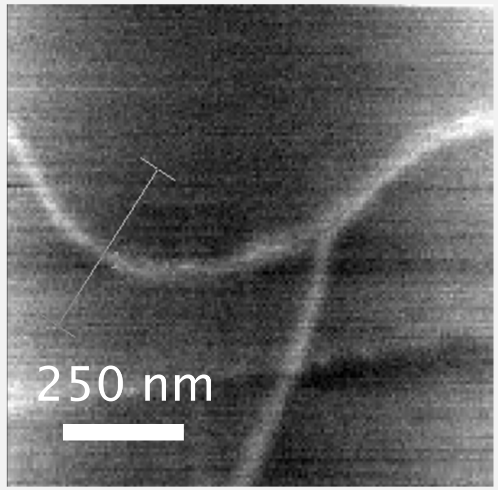
I. Crassee *et al.* Nano Lett. 12, 2470 (2012)

AFM–near field optical plasmon imaging

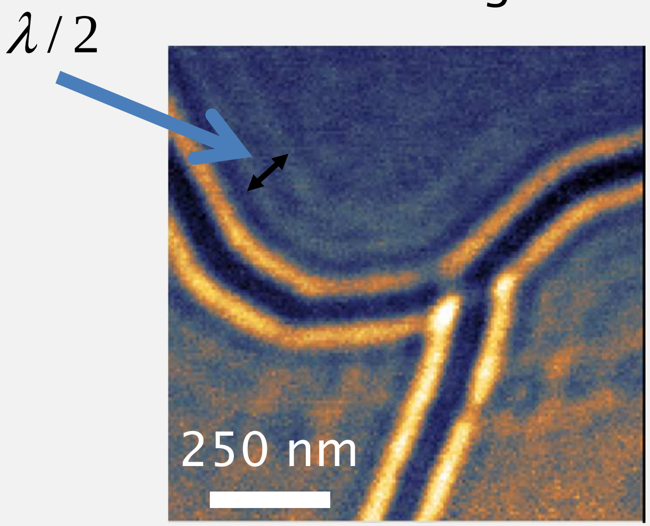




AFM topography



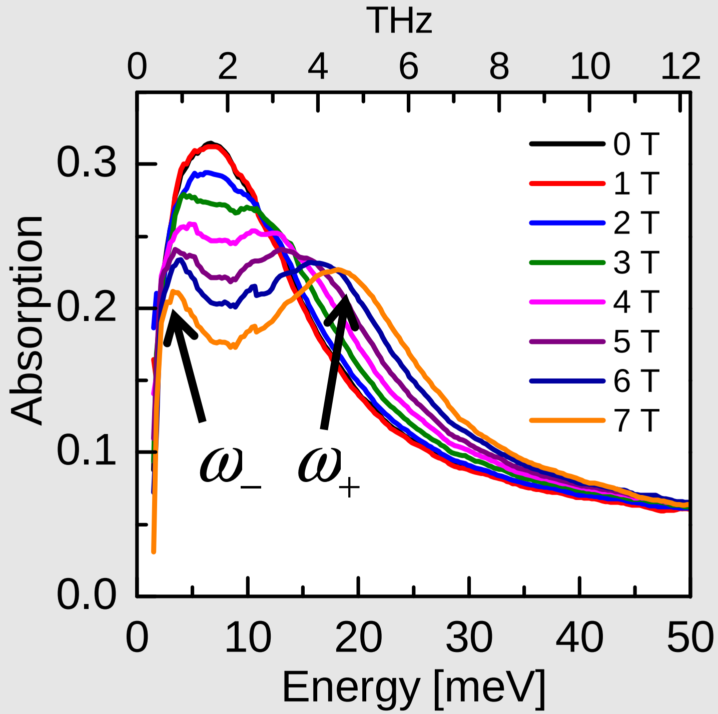
Near field signal

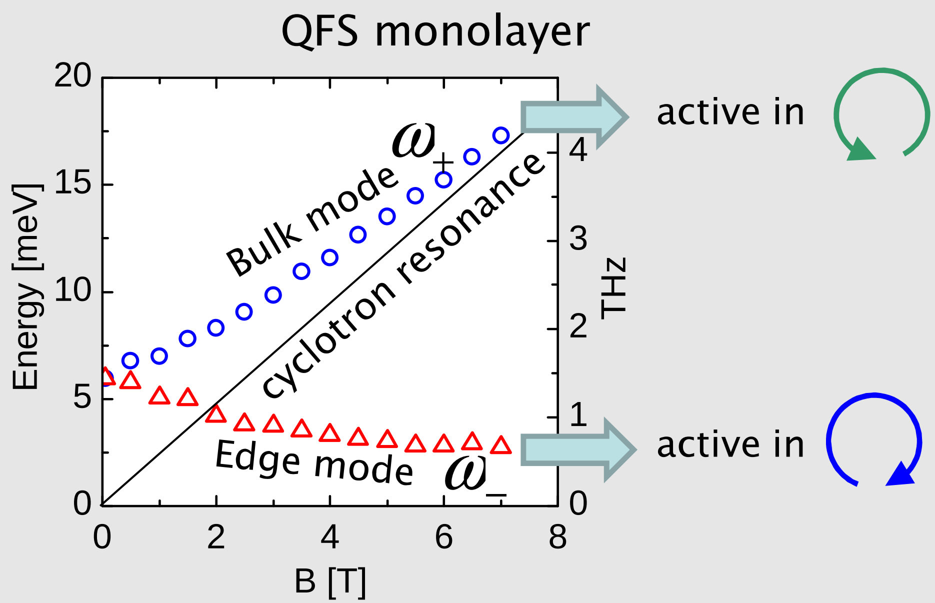


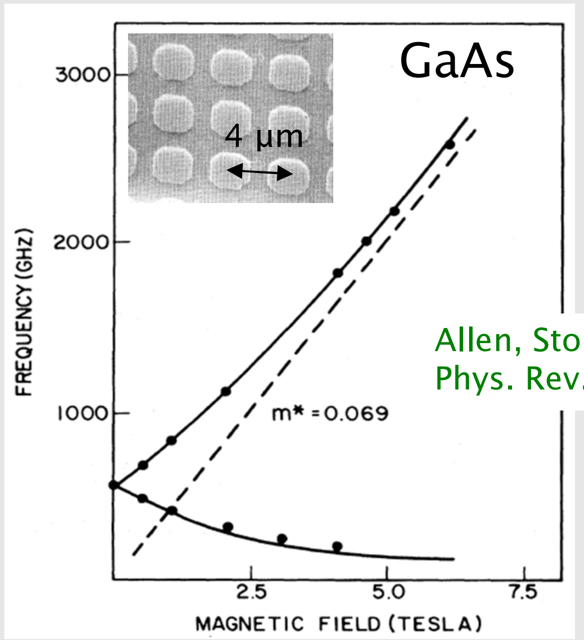
- SiC terraces and graphene wrinkles are strong plasmon scatterers

Details: talk of R. Hillenbrand on Tuesday
See also: J. Chen *et al*, Nature 487, 77 (2012); Fei *et al*, *ibid*, p. 82.

Magnetoplasmons in graphene







Allen, Stormer and Hwang,
Phys. Rev. B 28, 4875 (1983)

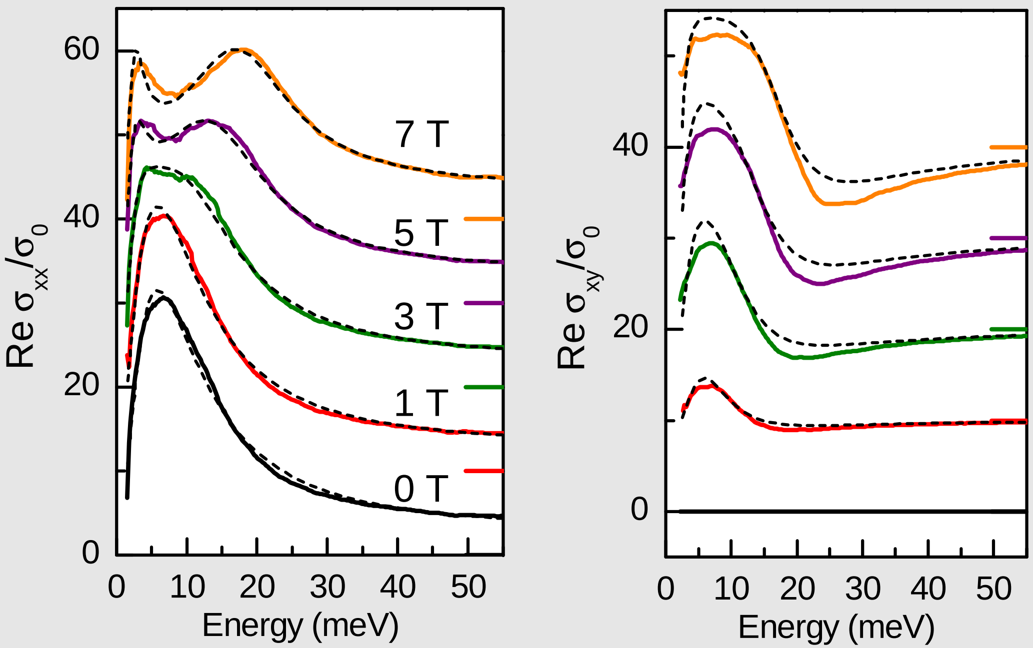
- Plasmon splits in two magnetoplasmons
- Bulk and edge modes
- similar to classical works on 2DEGs

I. Crassee *et al.* Nano Lett. 12, 2470 (2012)

Effective medium approximation

$$\sigma_{\pm}(\omega) = \frac{ne^2}{m} \frac{i}{\omega \pm \omega_c + i\gamma - \omega_0^2 / \omega} \qquad \omega_{\pm} = \sqrt{\omega_0^2 + \frac{\omega_c^2}{4}} \pm \frac{\omega_c}{2}$$

S. Mikhailov, PRB **54**, 10335 (1996)

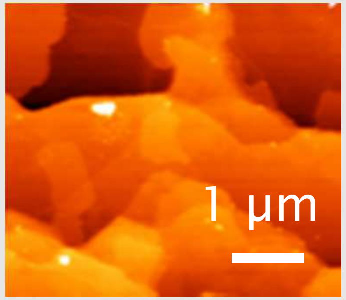


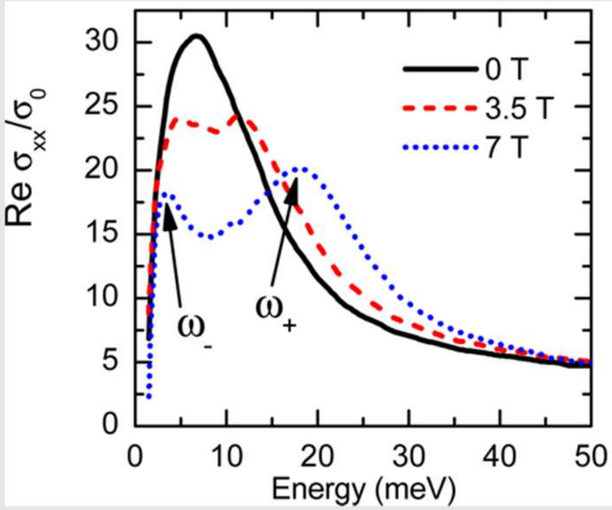
EMA works surprisingly well !

I. Crassee *et al.* Nano Lett. **12**, 2470 (2012)

Magnetoplasmons in graphene

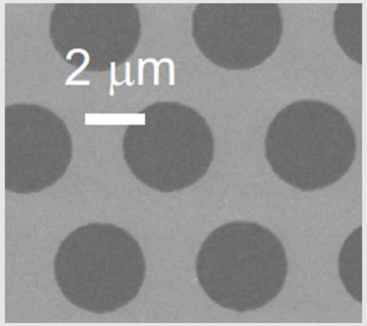
epitaxial graphene

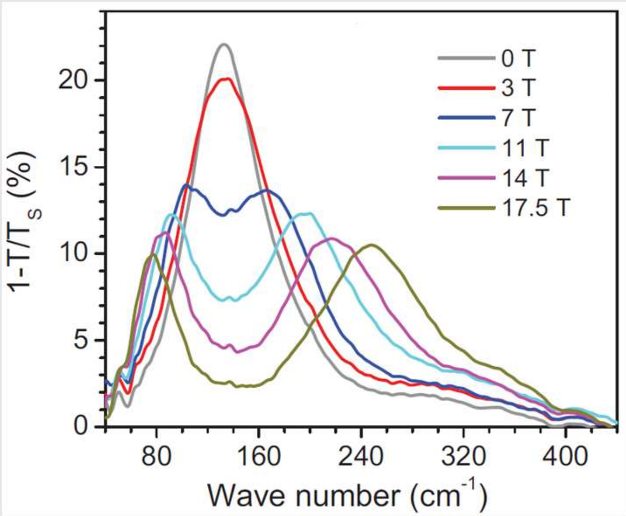




I. Crassee *et al.* Nano Lett. **12**, 2470 (2012)

CVD graphene disks





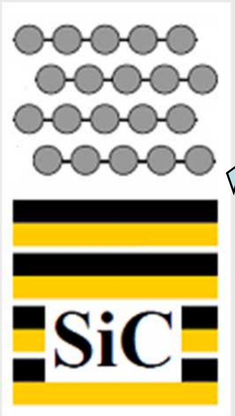
H. Yan *et al.* Nano Lett. **12**, 3766 (2012)

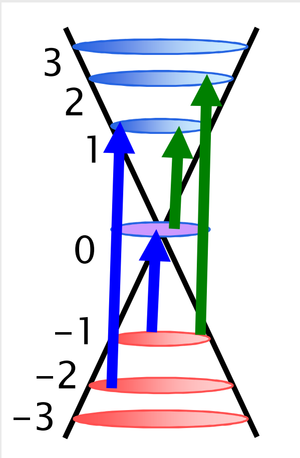
Also magnetoplasmons observed in the QHE regime

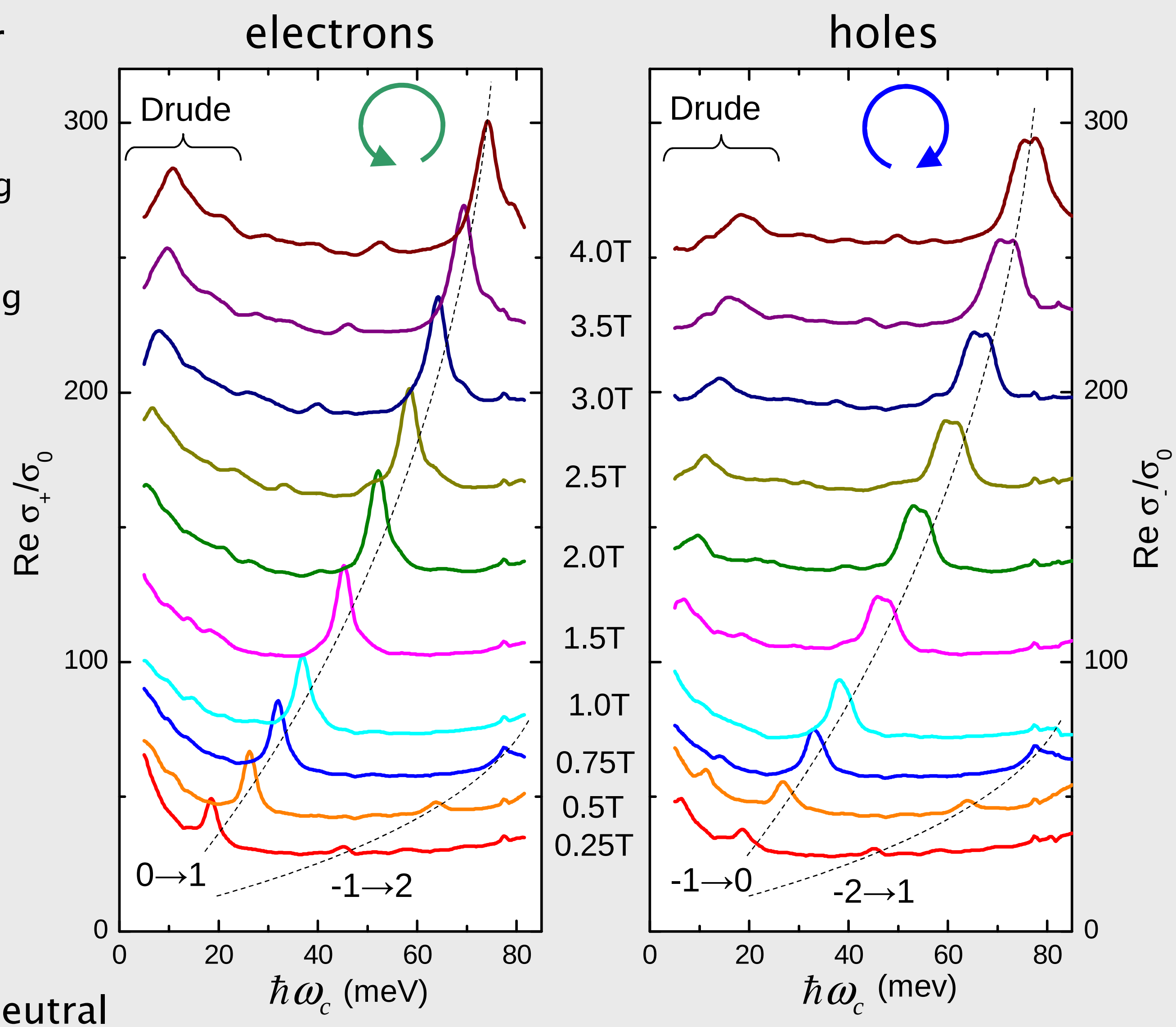
I. Petkovic et al. PRL **110**, 016801 (2013)

Multilayer epitaxial graphene on C-side of SiC

twisted multilayer
(10-15 layers)







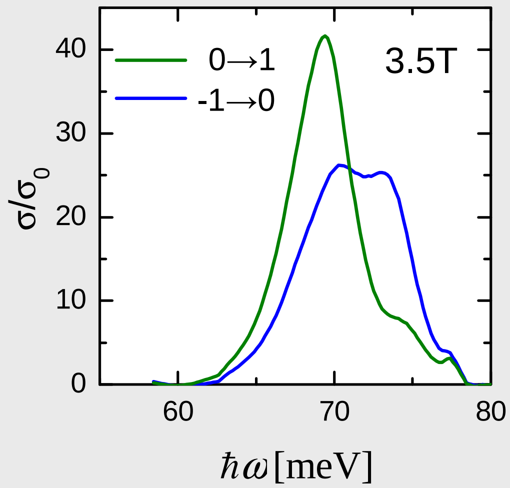
- approximately charge-neutral
- $\propto \sqrt{B}$
- electron-hole asymmetry
- stacking effects

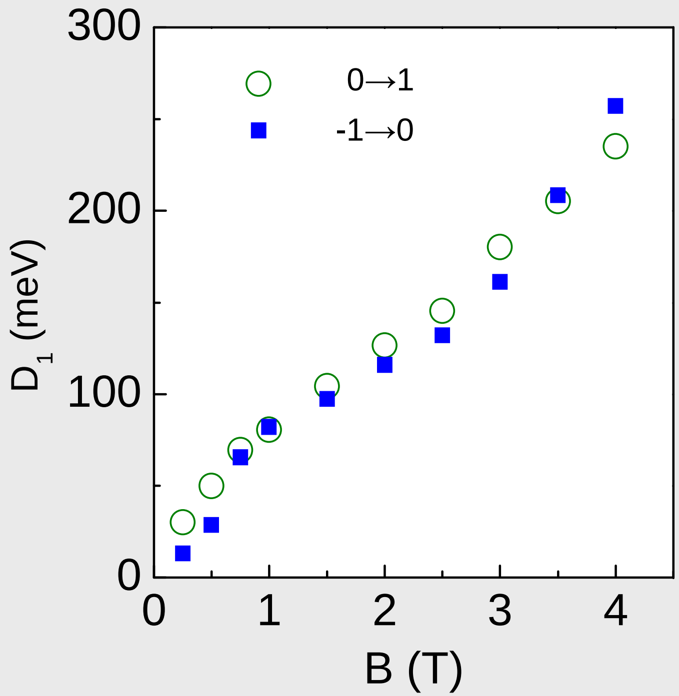
$$\varepsilon_1 = v_F \sqrt{2e\hbar B}$$

I. Crassee *et al.* Phys. Rev. B **84**, 035103 (2011)

Optical LL transition intensities

twisted multilayer
(15-20 layers)



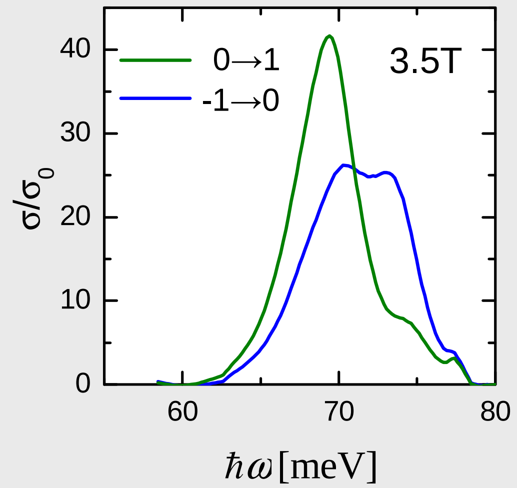


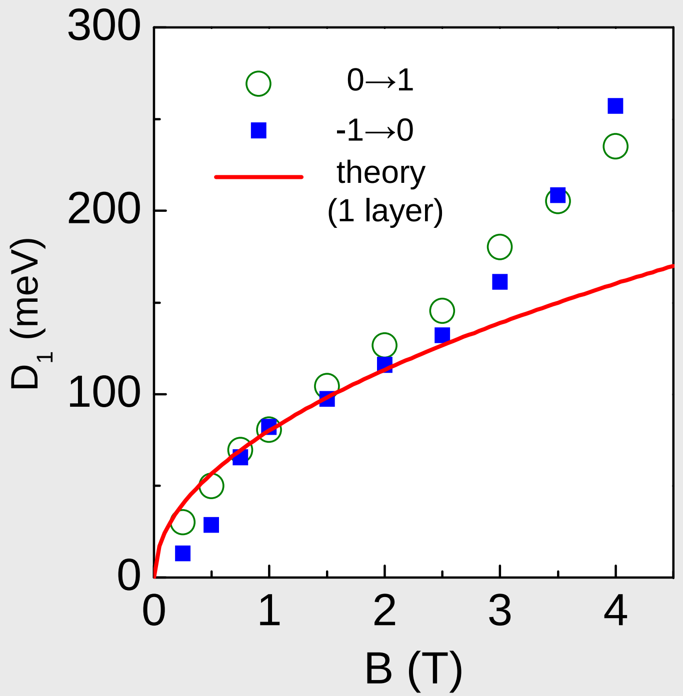
$$D_1 = \int \frac{\sigma(\omega)}{\sigma_0} d(\hbar\omega)$$

I. Crassee *et al.* Phys. Rev. B **84**, 035103 (2011)

Optical LL transition intensities

twisted multilayer
(15–20 layers)





$$D_1 = \int \frac{\sigma(\omega)}{\sigma_0}\, d(\hbar\omega)$$

theory for
Dirac fermions

1 layer:

$$D_1 = 2\varepsilon_1$$

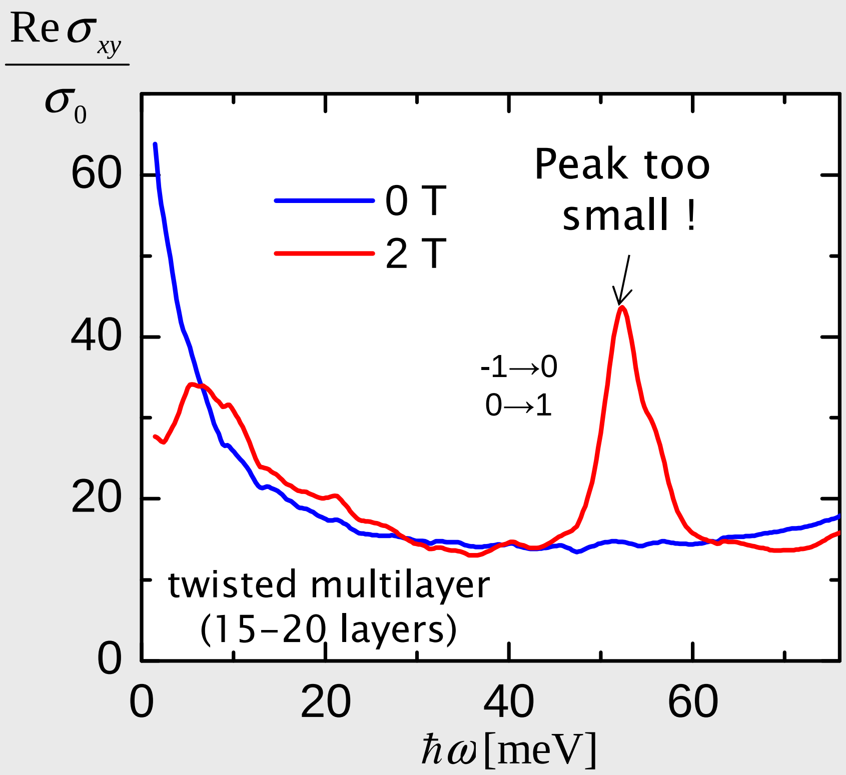
N layers:

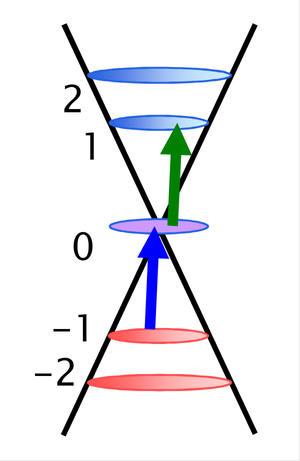
$$D_1 = 2\varepsilon_1 N$$

- NO $B^{1/2}$ dependence
- Intensity catastrophically lower than expected !!!

I. Crassee *et al.* Phys. Rev. B 84, 035103 (2011)

Optical LL transition intensities

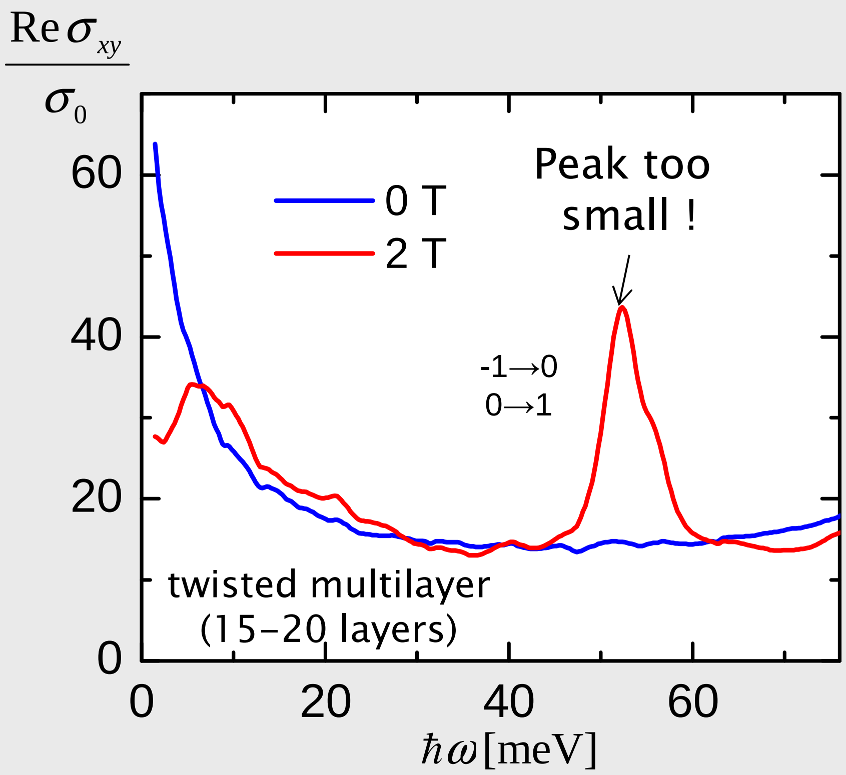


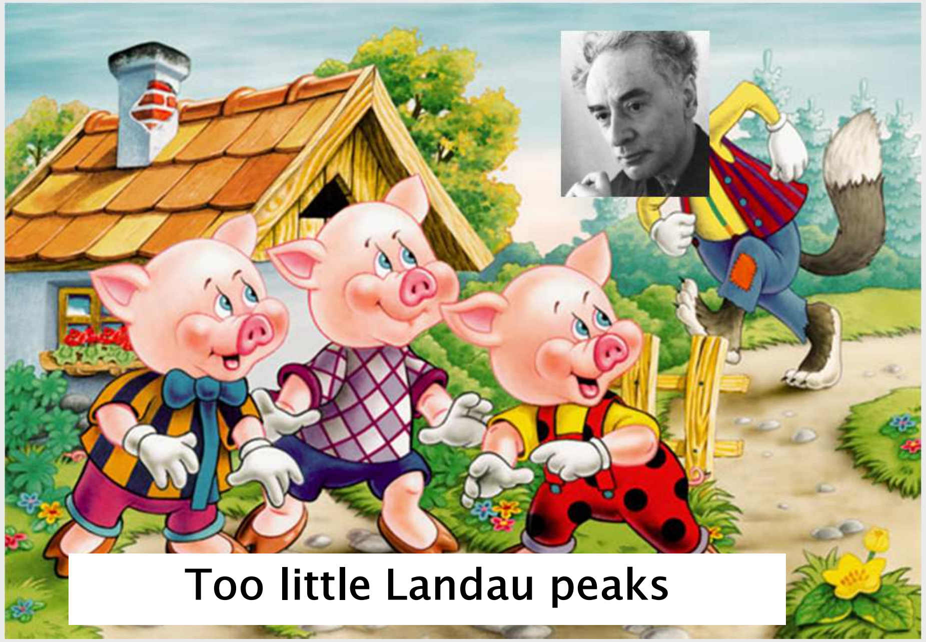


- only 1–2 layers (out of 15–20) contribute to Landau peaks
- A stacking effect ?
- Most layers overdamped?

I. Crassee *et al.* Phys. Rev. B **84**, 035103 (2011)

Optical LL transition intensities

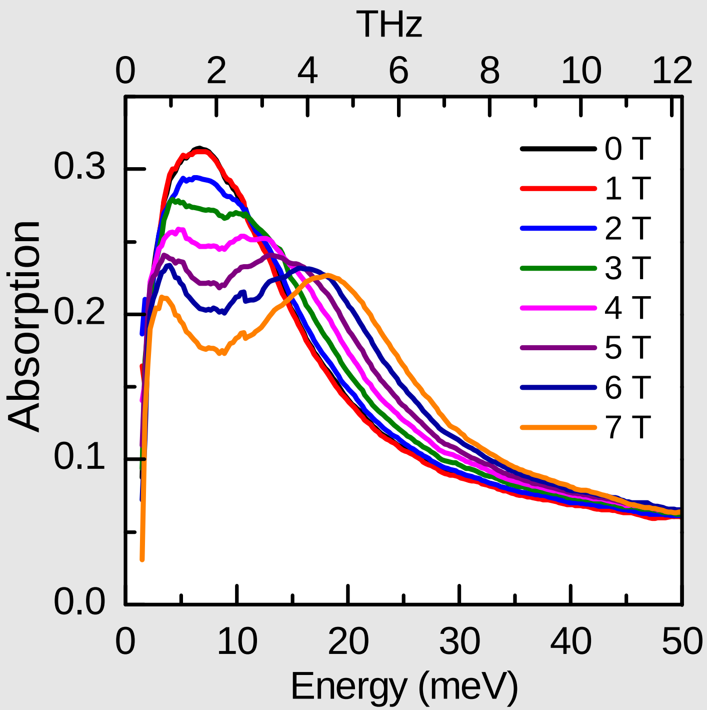


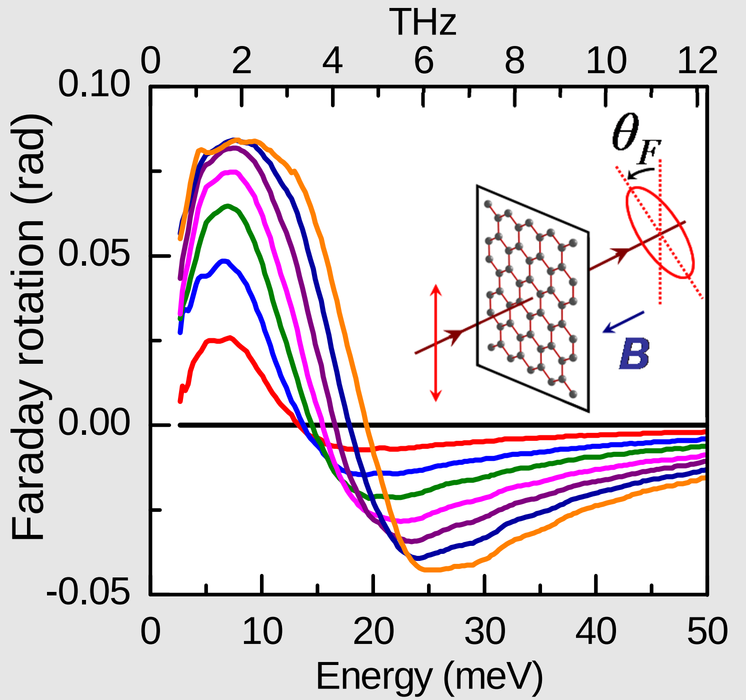


- only 1–2 layers (out of 15–20) contribute to Landau peaks
- A stacking effect ?
- Most layers overdamped?

I. Crassee *et al.* Phys. Rev. B **84**, 035103 (2011)

Graphene for magneto-optical applications



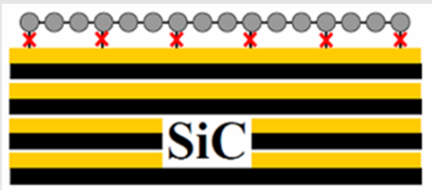


Absorption coefficient* $\approx 70 \dfrac{\%}{\mathrm{nm}}$

Verdet constant* $\approx 15 \dfrac{\mathrm{degrees}}{\mathrm{T}\cdot\mathrm{nm}}$

*provided that layers can be stacked without affecting their properties

QFS monolayer

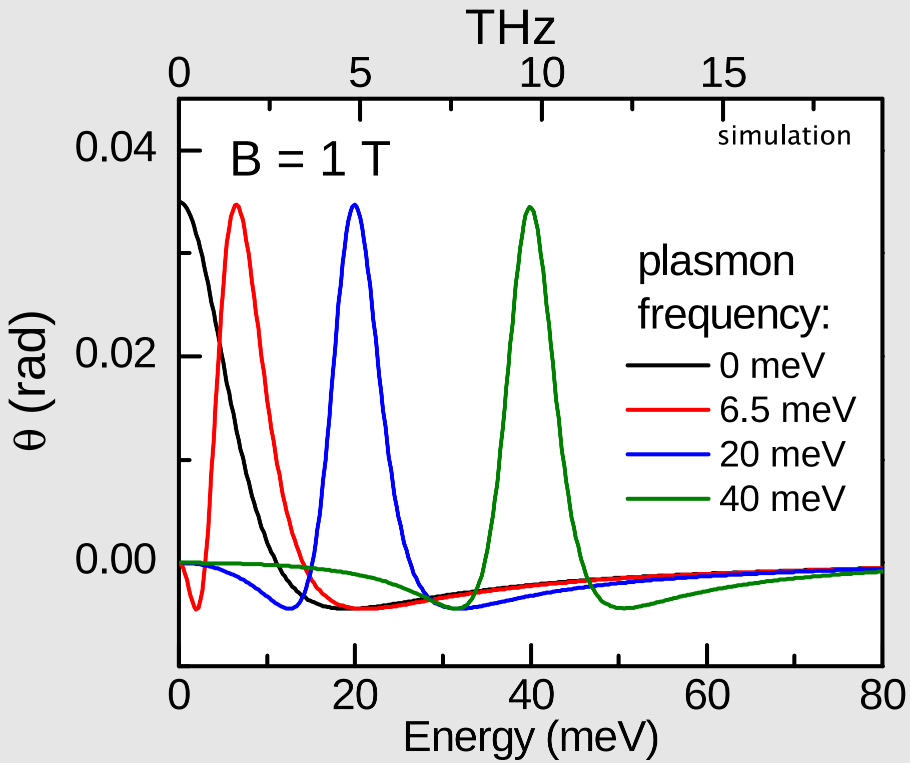


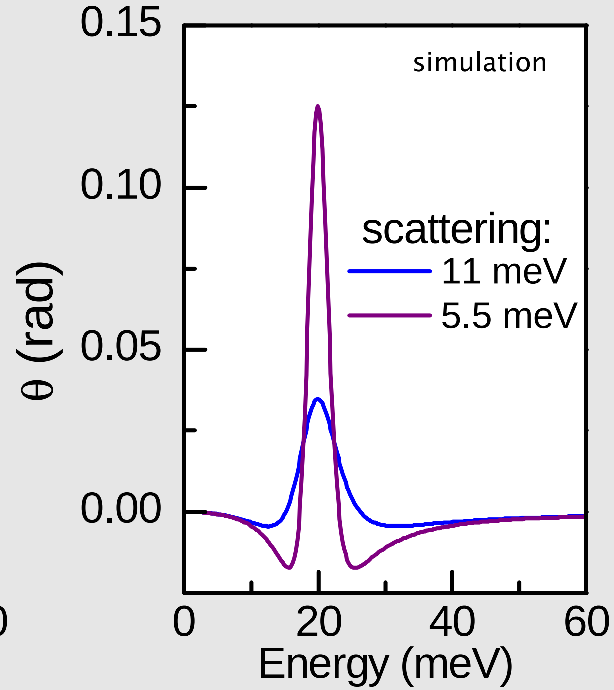
Potentially tunable by gate !

Ultrafast control !

I. Crassee *et al.* Nature Physics **7**, 48 (2011); Nano Lett. **12**, 2470 (2012)

Faraday rotation affected by magneto-plasmons





- rotation can be controlled by the plasmon frequency
- higher-mobility samples produce larger rotation
- defects are useful !

I. Crassee *et al.* Nano Lett. **12**, 2470 (2012)

Graphene-based magneto-optical applications

Types of devices

- Absorption modulators
- Polarization modulators
- Faraday isolators (valves)…

Spheres of application

- Telecommunications
- Biosensing
- Security
- Astronomy…

Advantages of epitaxial graphene

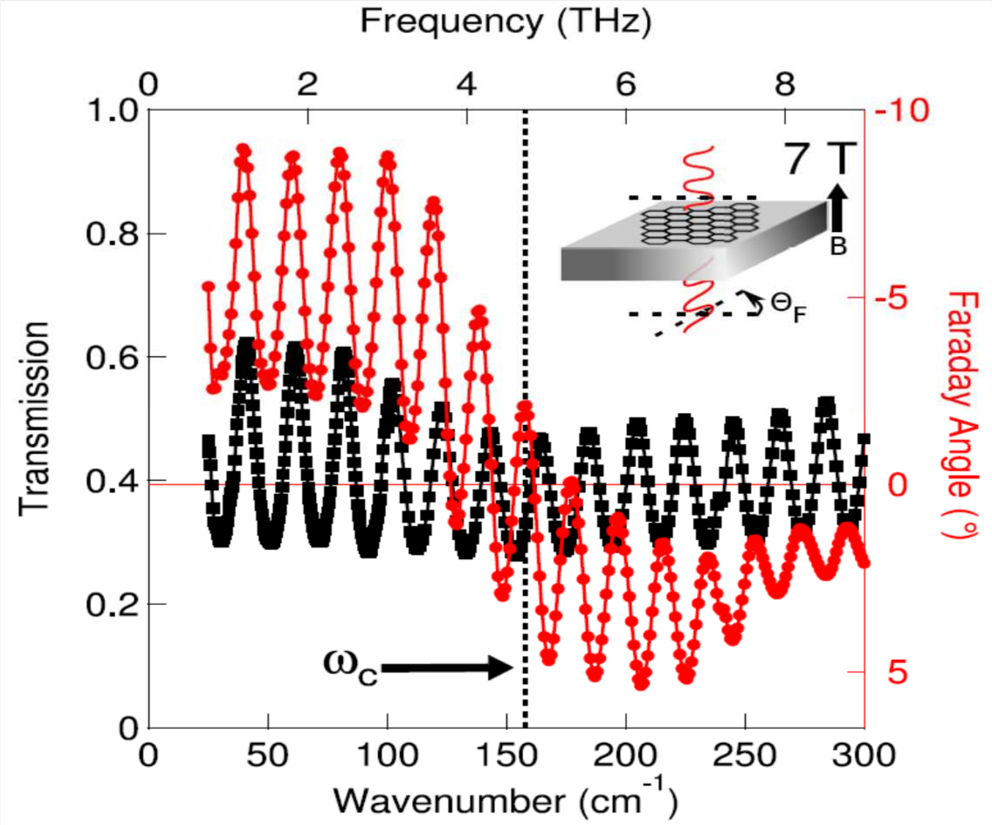
- Samples very large
- Chemical potential homogeneous
- SiC is transparent

Disadvantages of epitaxial graphene

- Gating is relatively difficult
- Controlled multilayer growth is tricky

H. Da & C.W.Qiu, APL **100**, 241106 (2012)
A. Fallahi & Perruisseau-Carrier, APL **101**, 231605 (2012)
D. L. Sounas & C. Caloz, IEEE Trans. Microw. Theory Tech. **60**, 901 (2012)
Y. Zhou *et al*, Phys.Chem. Chem. Phys. (2013)
…

Fabry–Perot enhanced Faraday rotation in graphene



- interference in the substrate
- Rotation up to 9°
- Rotation and transmission increase simultaneously

Theory of FR in graphene in a cavity:
A. Ferreira *et al*, PRB 84, 235410 (2011)

For details: Nicolas Ubrig, poster on Wednesday

Summary and outlook

- Magneto-optics (MO) is useful for routine characterization
- Giant THz Faraday rotation (present record is 9°)
- Robust (magneto-)plasmons due to nanoscale defects (i.e. steps and wrinkles)
- Strong interplay between MO and plasmonic effects (cyclotron mass about 10^2 smaller than in noble metals)
- Graphene is promising for MO applications