Graphene Nanophotonics
Centro de Ciencias de Benasque Pedro Pasqual
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PLASMON DAMPING IN GRAPHENE

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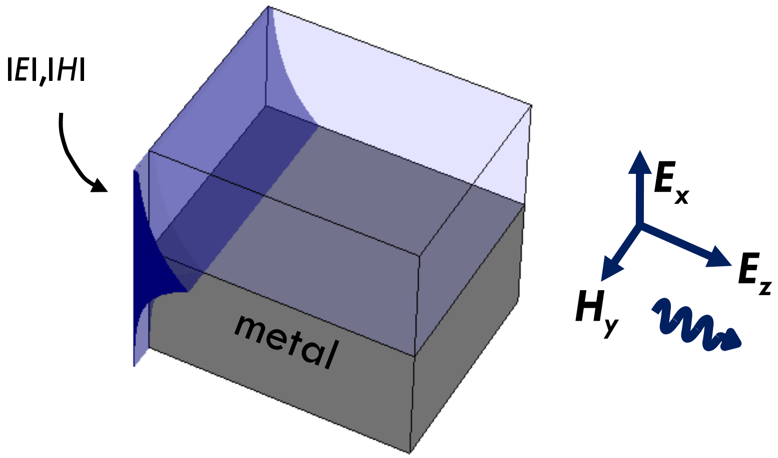
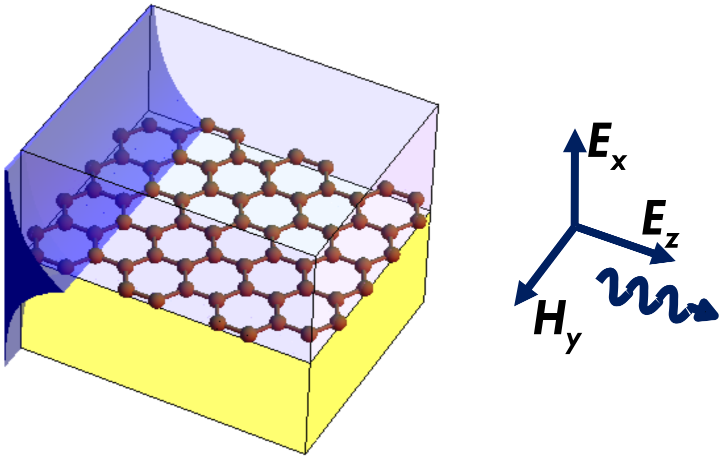
Outline

- Problem and motivation
- Relaxation time approximation – figure of merit: $\Gamma = \frac{1}{\tau}$
- Optical conductivity:
  - ➢ Experiment
  - ➢ Theory (damping channels)
- Experiments: plasmon dispersion and linewidth
- Conclusion
- P.S. Near field heat transfer & thermo-photovoltaics using graphene’s plasmons

Problem and motivation

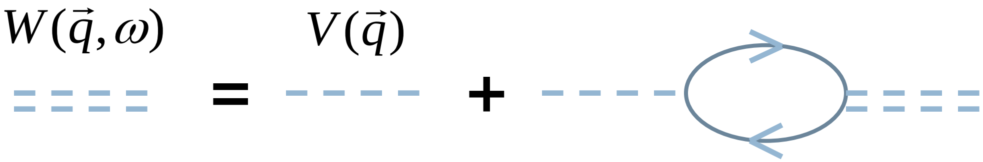
- **Plasmonics –** surface plasmons
- Exciting technological applications
  - ➢ Metamaterials
  - ➢ Nonlinear phenomena SERS
  - ➢ **Merging electronics and photonics**
- Subwavelength: $\lambda_{sp} << \lambda_{air}$
- Trade-off: small propagation lengths
- Plasmons in **graphene**
- **Plasmon damping?**
- Jablan et al., PRB 80, 245435



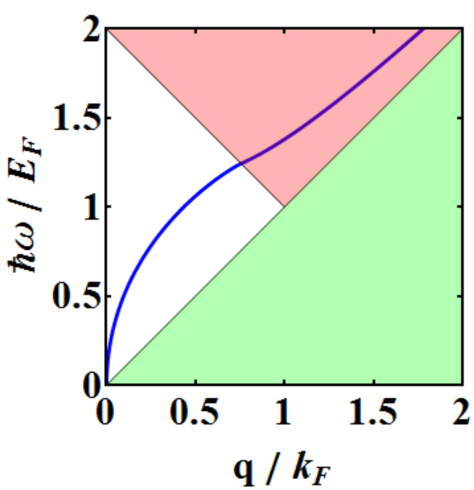


Random phase approximation

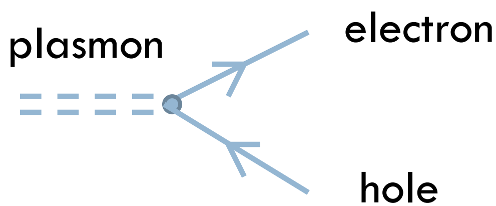
- Coulomb interaction:
  - Bare: $V(\vec{q}) = \dfrac{e^2}{2\varepsilon_0\bar{\varepsilon}_r} \cdot \dfrac{1}{q}$
  - Screened: $W(\vec{q},\omega) = \dfrac{V(\vec{q})}{\varepsilon(\vec{q},\omega)}$

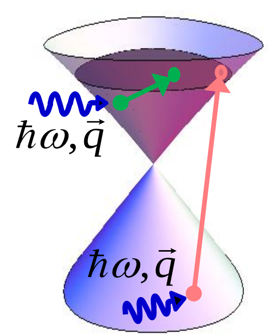


- Plasmon dispersion: $\varepsilon(\vec{q},\omega) = 0$



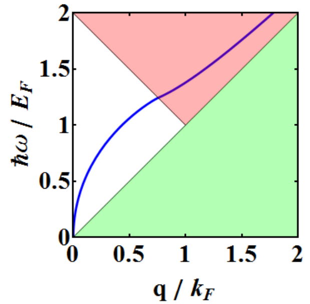
- Plasmon damping: $\mathrm{Im}\,\varepsilon(\vec{q},\omega) > 0$
- **Landau damping**





Relaxation time approximation

- Damping channels (outside of Landau damping region)



- ➢ **impurites, defects, edges**
- ➢ **phonons** (acoustical, optical, surface polar)
- ➢ **e-e correlation** beyond RPA

} phenomenological relaxation time τ

- **Relaxation time approximation:** $$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H,\rho] - \frac{1}{\tau}(\rho - \rho_0)$$

- Mermin, Phys. Rev. B 1, 2362 (1970)

- **Figure of merit:** $$\Gamma = \frac{1}{\tau} \quad [\mathrm{cm}^{-1}]$$

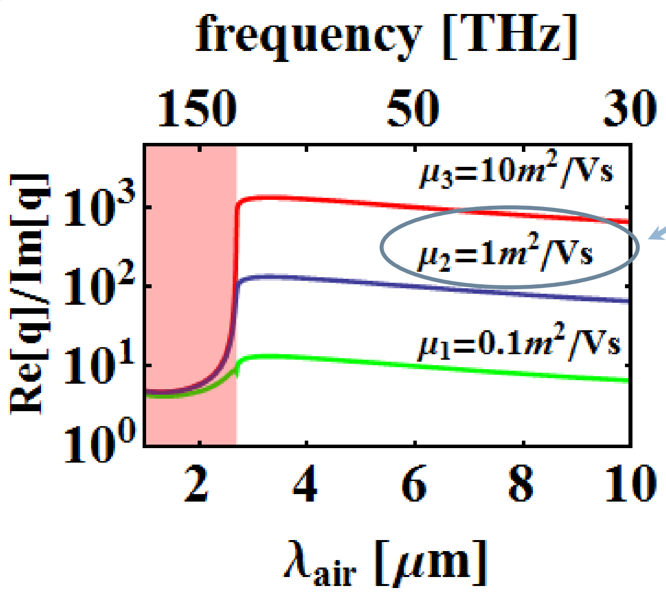
- Drude model: $$\sigma(\omega) = \frac{e^2 E_F}{\pi\hbar^2} \frac{i}{\omega + i\cdot\Gamma}$$ $$\omega \to \omega + i\cdot\Gamma$$

DC scattering rate

- DC scattering rate: $\Gamma_{DC} \propto \mu^{-1}$
- Typical measured values:

$$n = 10^{13}\,\mathrm{cm}^{-2}$$
$$\mu = 10000\,\mathrm{cm}^2/\mathrm{Vs}$$

$$\tau_{DC} \approx 370\,\mathrm{fs} \approx 0.4\,\mathrm{ps}$$
$$\Gamma_{DC} \approx 15\,\mathrm{cm}^{-1}$$

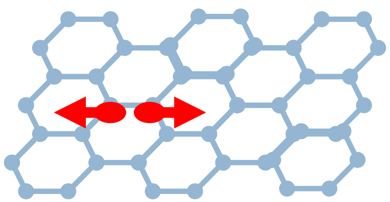


- Jablan et al., PRB 80, 245435

- How good is this Γ_{DC} approximation?

Optical phonon scattering

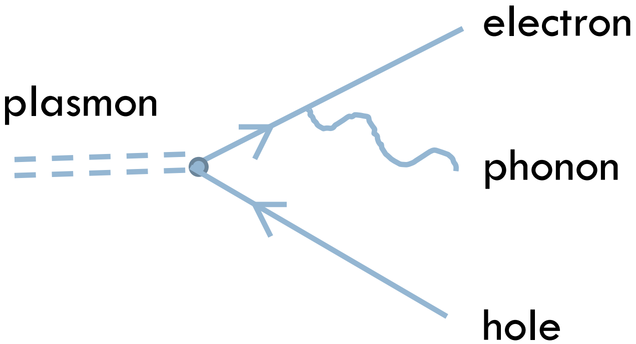
- Optical phonon: $\Omega_{OP} = 200\,\text{meV}$

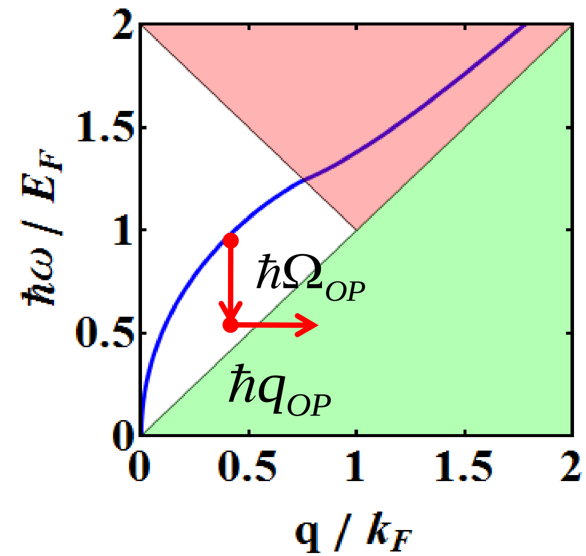


- Room temperature DC measurements:

$kT \approx 25\,\text{meV}$

- Plasmon energy: $\hbar\omega_{pl} > \hbar\Omega_{OP}$





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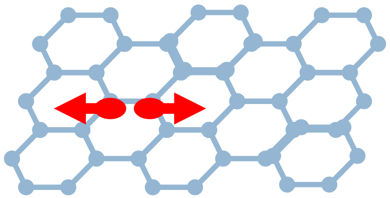

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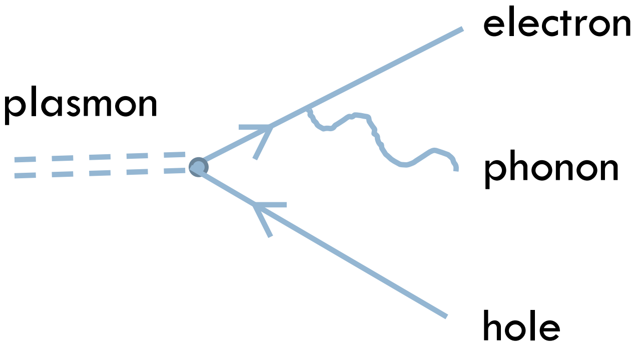
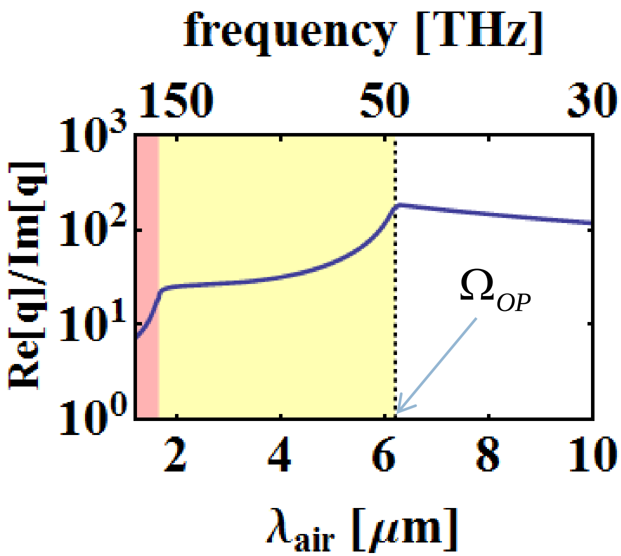
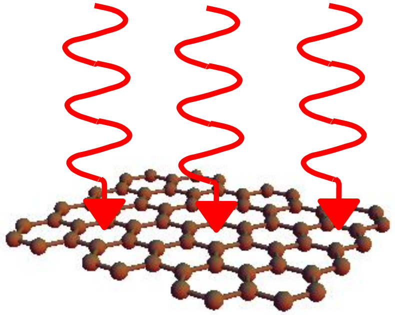


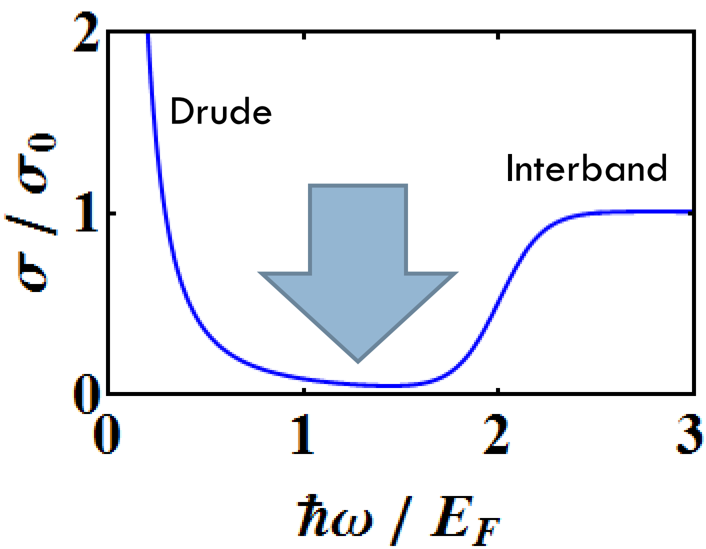


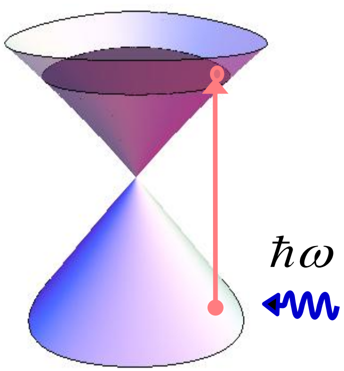
- Jablan et al., PRB 80, 245435

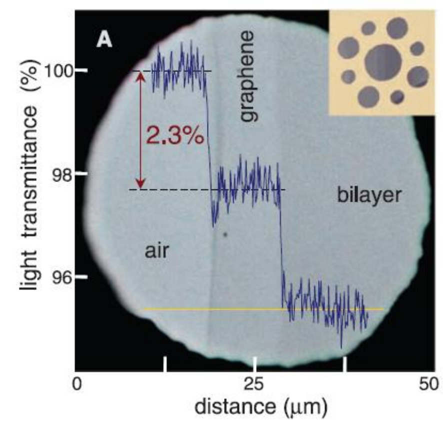
Conductivity

- Losses: $\mathrm{Im}\,\varepsilon(\vec{q},\omega) \propto \mathrm{Re}\,\sigma(\vec{q},\omega)$
- Case: $q = 0$
- **Optical experiment** (normal incidence light scattering)
- Typical conductivity profile



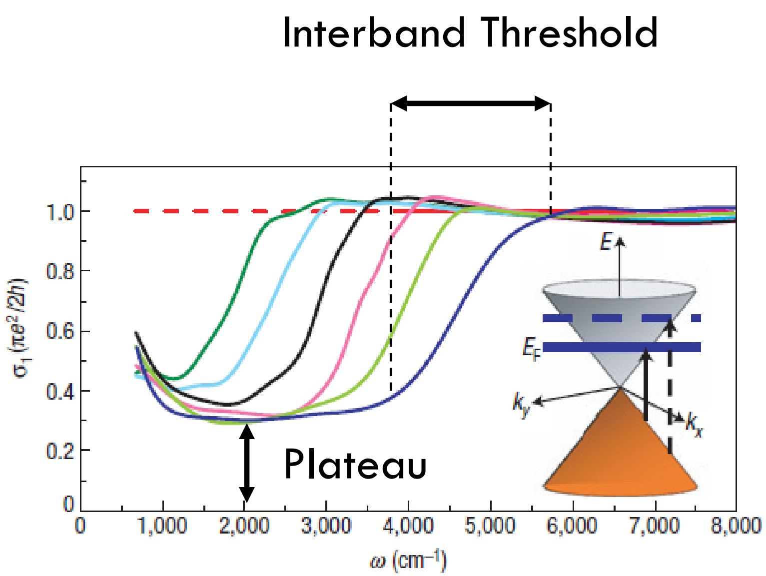






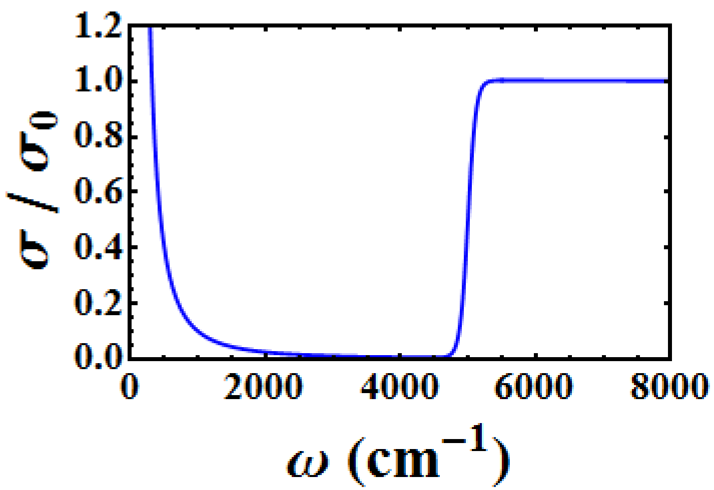
- Nair *et al.*, Science **320**, 1308 (2008)

Conductivity (experiment)



- Li et al., Nature Phys. 4, 532 (2008)

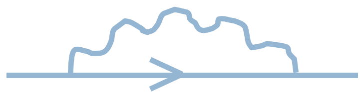
$$\Gamma(2000\,\mathrm{cm}^{-1}) \approx 400\,\mathrm{cm}^{-1}$$

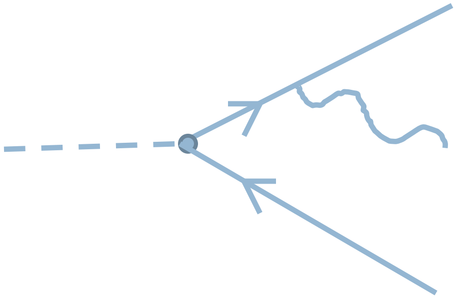


$$\Gamma_{DC} = 30\,\mathrm{cm}^{-1}$$

Optical phonon

- Phonon scattering

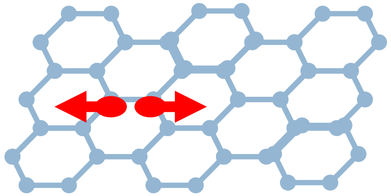


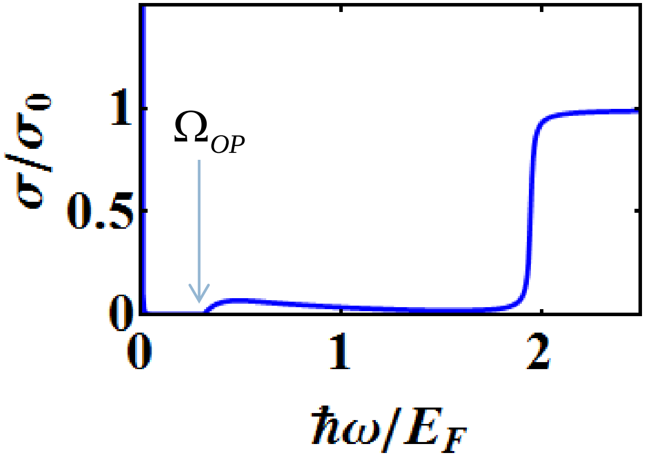


- Electron self-energy:

- Optical phonon:

$$\Omega_{OP} = 200\,\mathrm{meV} = 1600\,\mathrm{cm}^{-1}$$

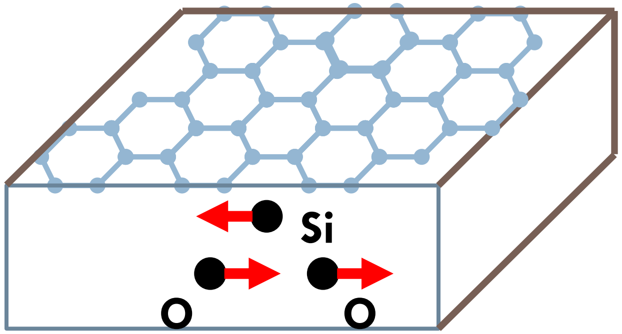


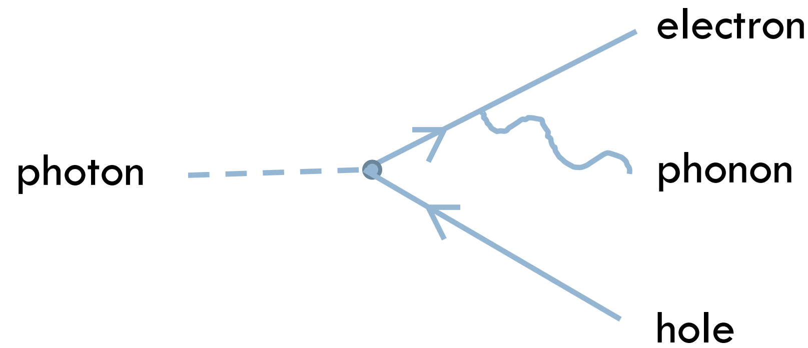


- Acoustical phonon – negligible

- Stauber et el. PRB 78, 085418 (2008)

Surface polar phonon

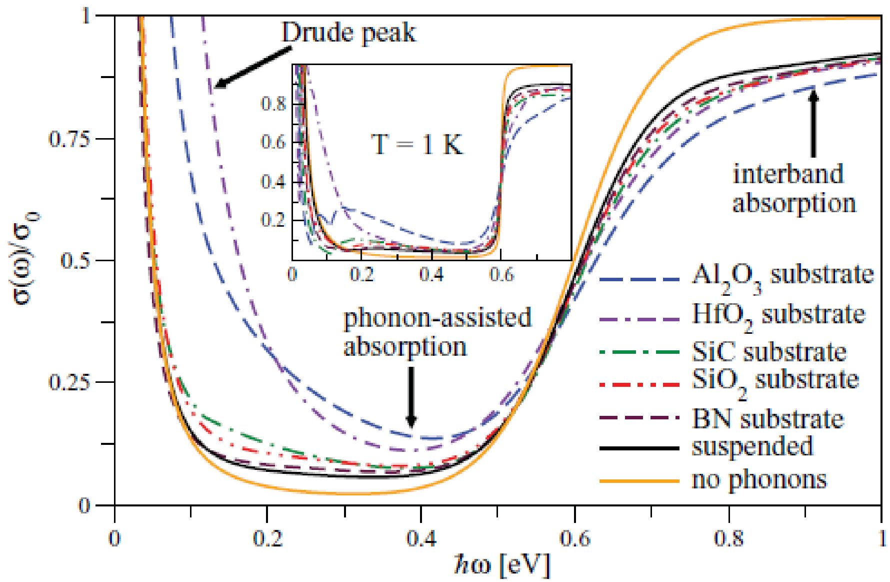




- Surface polar phonon (SiO_2):

$$\Omega_{SP1} = 59\,\text{meV} = 470\,\text{cm}^{-1}$$

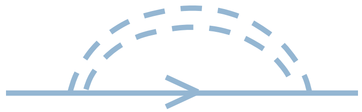
$$\Omega_{SP2} = 156\,\text{meV} = 1260\,\text{cm}^{-1}$$



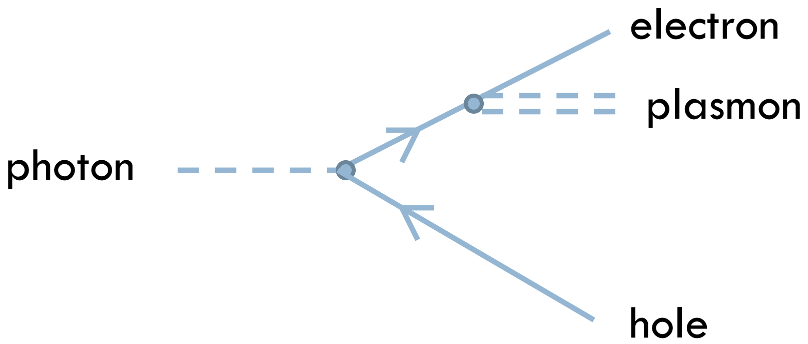
- Scharf et el. PRB 87, 035414 (2013)

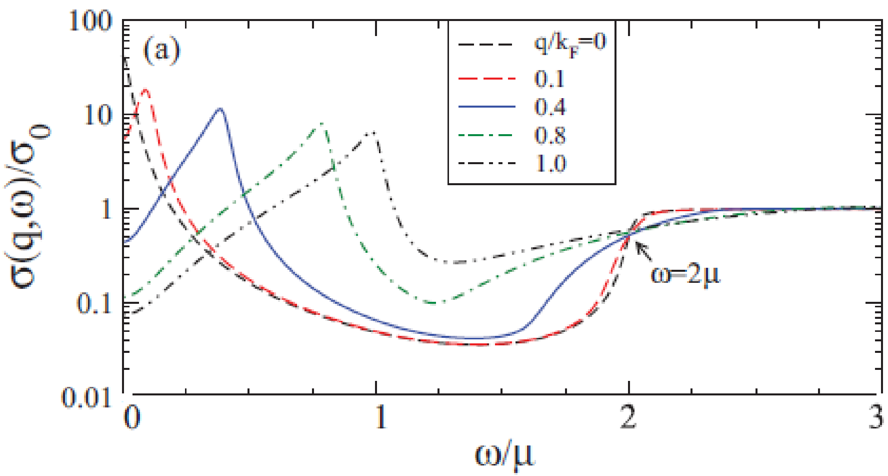
e-e correlation

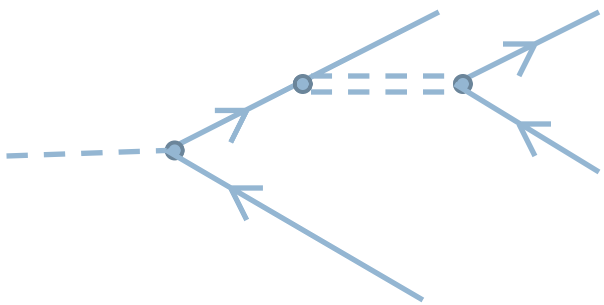
- Screened Coulomb interaction



- Electron self energy:



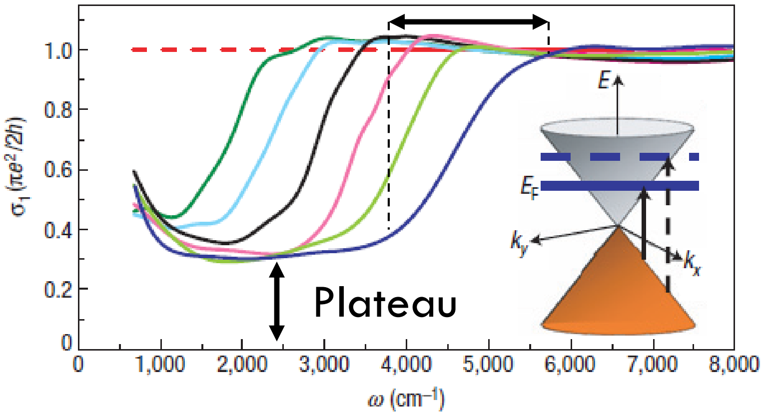




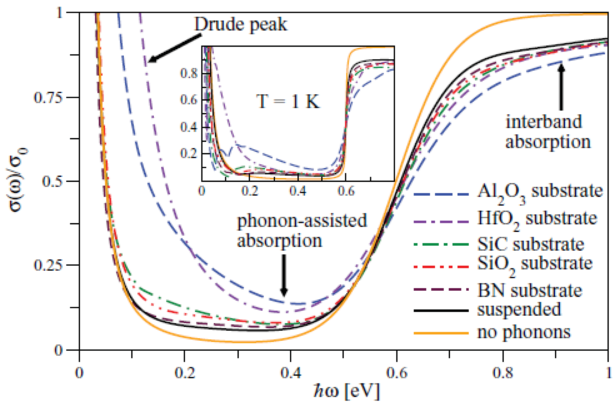
- Carbotte el. PRB 85, 201411 (2012)

Conductivity

- **Experiment**



- **Theory**



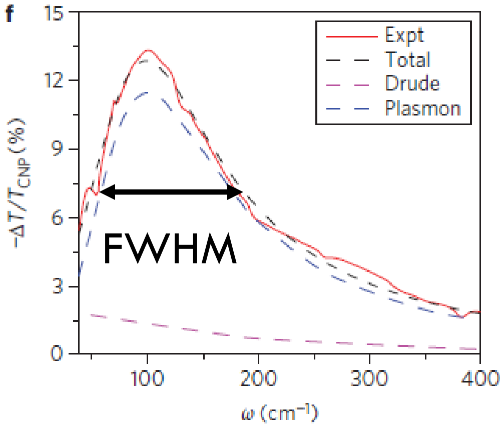
- Li et al., Nature Phys. 4, 532 (2008)

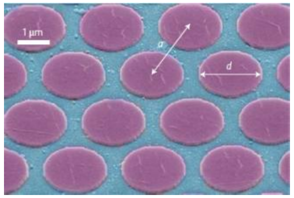
- Experiment ↔Theory
  - ➢ Quantitative difference (plateau hight – interband threshold)
  - ➢ Qualitative difference (doping dependence)

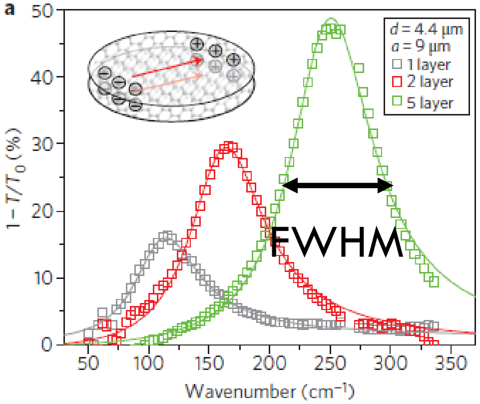
- Scharf et el. PRB 87, 035414 (2013)
- **Impurity (charged) scattering**
- Phonon scattering:
  - ➢ **Optical phonon**
  - ➢ **Surface polar phonon**
  - ➢ **Acoustical phonon (small)**
- **e-e correlation (small)**

Plasmons in far IR

- Plasmon excitation
- Patterned graphene: breaking translation symmetry
- Micron size
- Far IR (THz) regime: $\nu = 5\,\mathrm{THz} \approx 170\,\mathrm{cm}^{-1} \quad (\lambda_{air} = 60\ \mu\mathrm{m})$







- Ju et al., Nature Nanotech. 6, 630 (2011)
- Linewidth: $\Gamma \approx \Gamma_{DC} = 120\,\mathrm{cm}^{-1}$

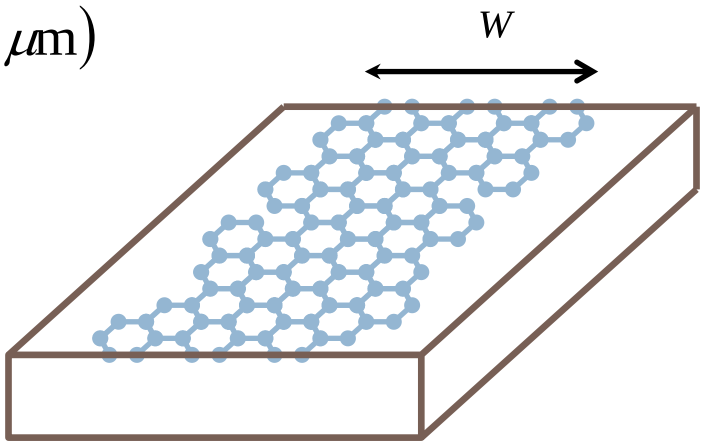
$$\tau_{DC} \approx 45\,\mathrm{fs}$$

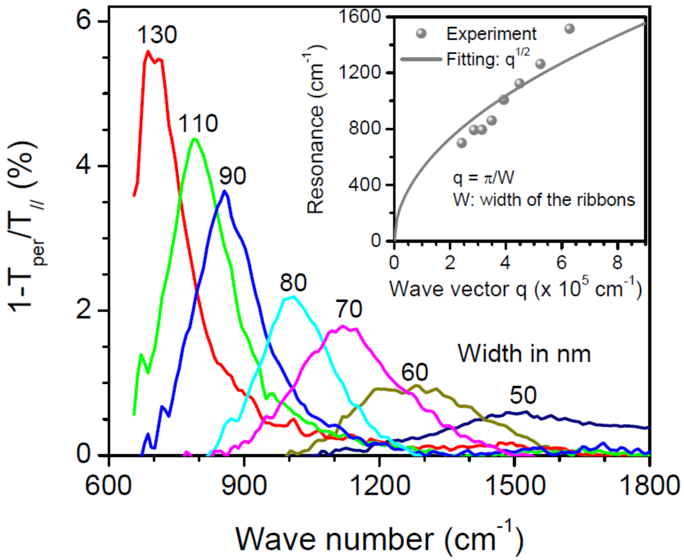
- Yan et el., Nature Nanotech. 7, 330 (2012)
- Linewidth: $\Gamma \approx \Gamma_{DC} = 50\,\mathrm{cm}^{-1}$

$$\tau_{DC} \approx 100\,\mathrm{fs}$$

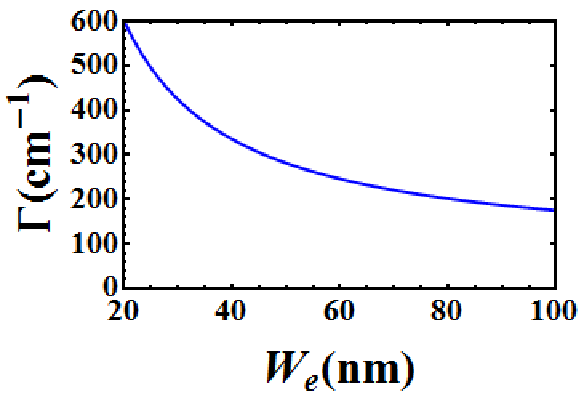
Plasmons in mid IR

- Mid IR : $\nu = 50\,\text{THz} \approx 1700\,\text{cm}^{-1}$ $(\lambda_{air} = 6\,\mu\text{m})$
- Ribbon size: $W \approx 100\,\text{nm}$
- DLC substrate





- Edge scattering? $\Gamma_{DC} \approx \Gamma_{UNI} + \frac{2v_F}{W_e}$

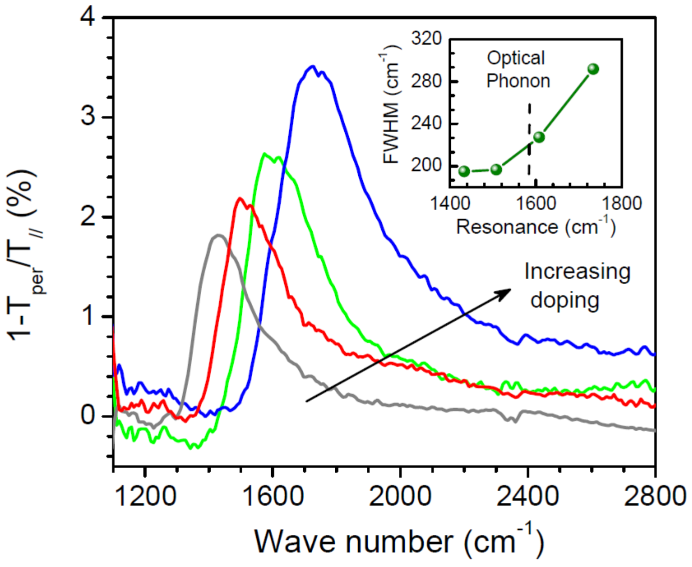


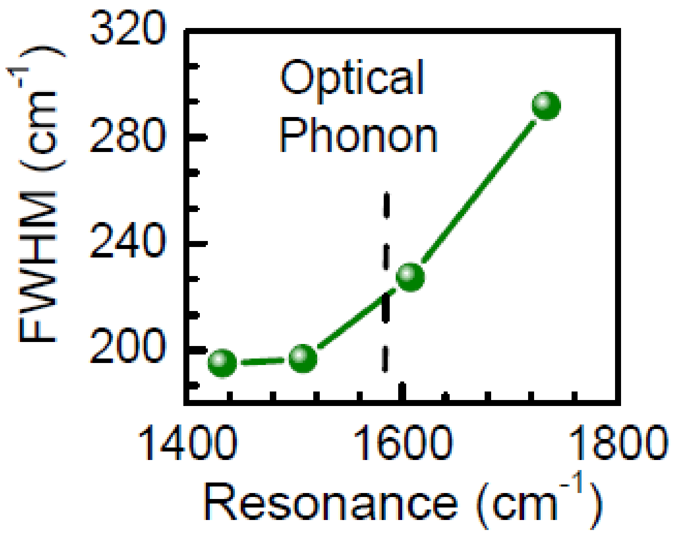
$\Gamma_{UNI} = 70\,\text{cm}^{-1}$

- Yan et al., arXiv:1209.1984

Mid IR

- Fixed ribbon width $W = 100\,\mathrm{nm}$

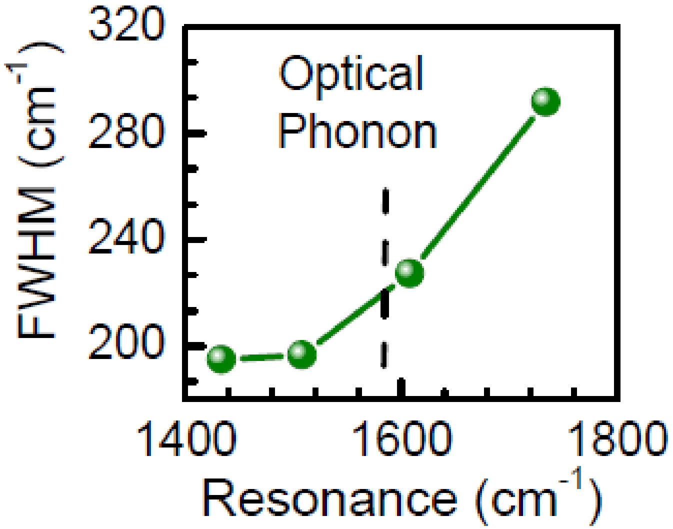




- Yan et al., arXiv:1209.1984
- DC scattering $\Gamma_{UNI} = 70\,\mathrm{cm}^{-1}$
- SiO_2 substrate

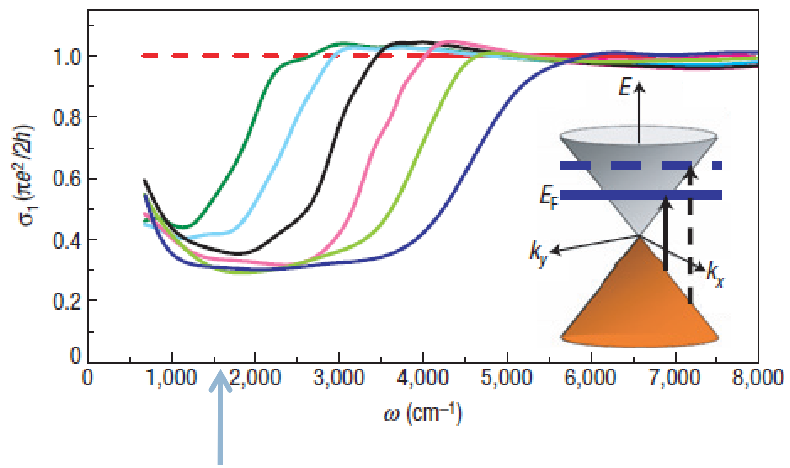
Mid IR

- Plasmon linewidth
- Plasmon momentum: $q \approx \frac{\pi}{100\,\text{nm}}$
- Yan et al., arXiv:1209.1984



- DC scattering: $\Gamma_{HOM} = 69\,\text{cm}^{-1}$

- Optical experiment
- Photon momentum: $q = 0$
- Li et al., Nature Phys. 4, 532 (2008)

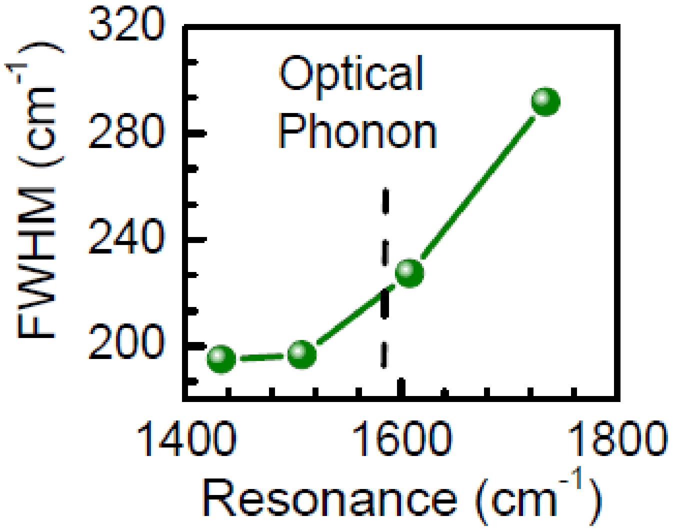


$\Gamma(1600\,\text{cm}^{-1}) \approx 260\,\text{cm}^{-1}$

- DC scattering: $\Gamma_{DC} = 30\,\text{cm}^{-1}$

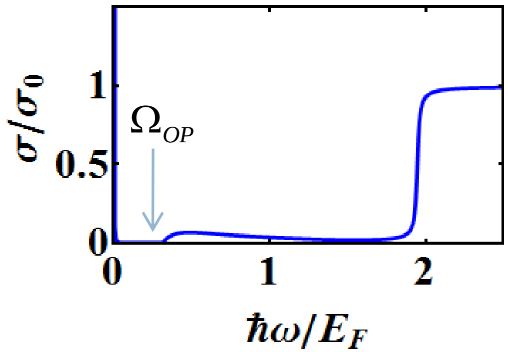
Optical phonon scattering?

- Plasmon linewidth
- Plasmon momentum: $q \approx \frac{\pi}{100\,\mathrm{nm}}$
- Yan et al., arXiv:1209.1984

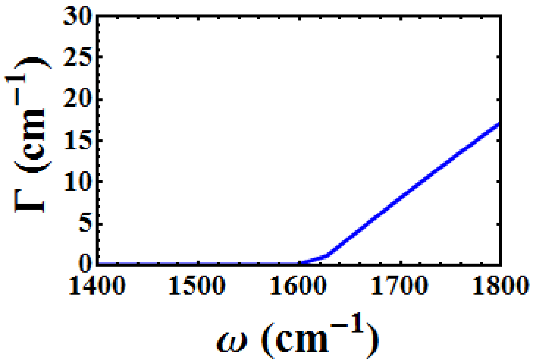


- DC scattering: $\Gamma_{HOM} = 69\,\mathrm{cm}^{-1}$

- Optical conductivity
- Stauber et el. PRB 78, 085418 (2008)

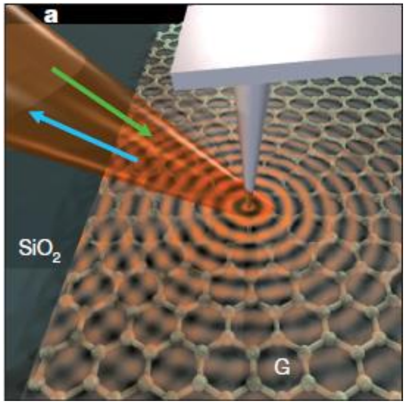


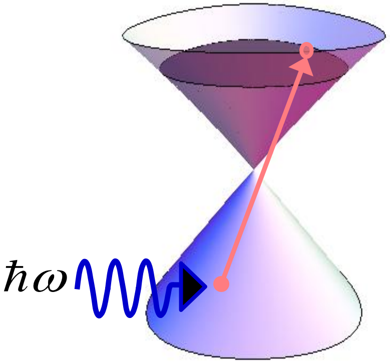
- Phonon scattering rate
- Jablan et al., PRB 80, 245435

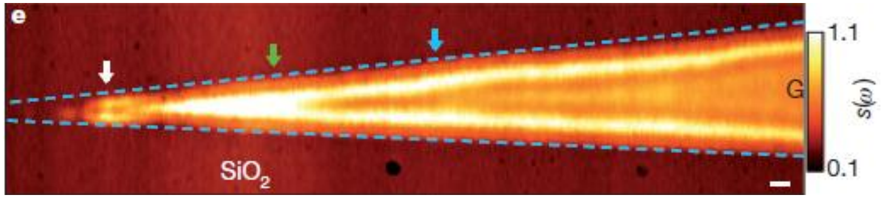


Nanoscopy

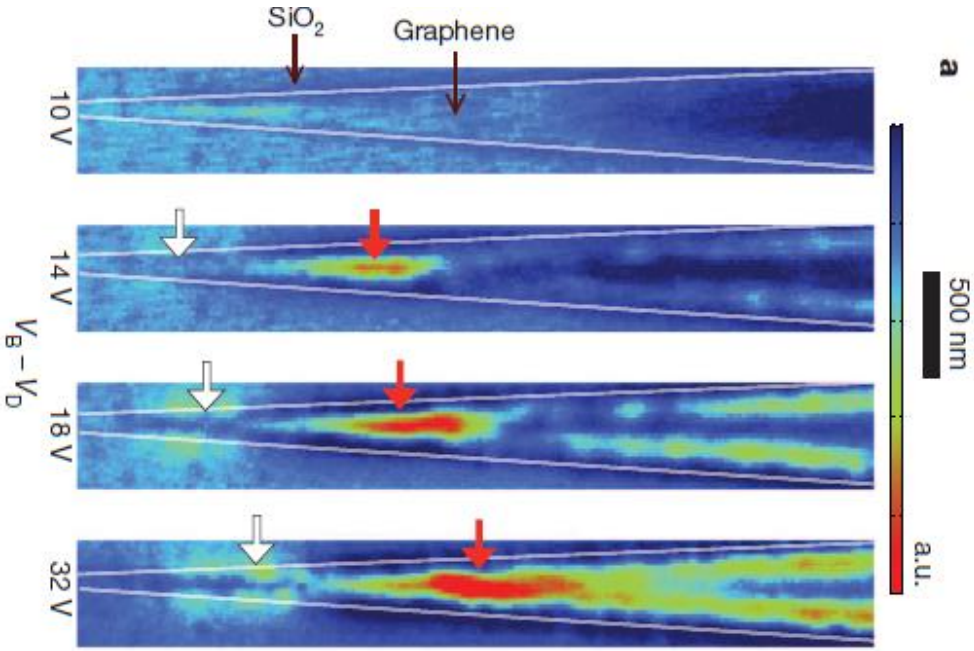
- Optical nanoimaging





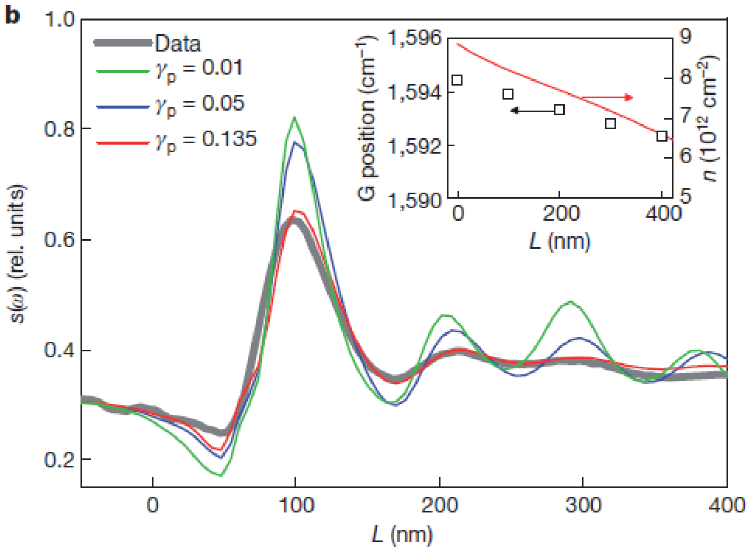


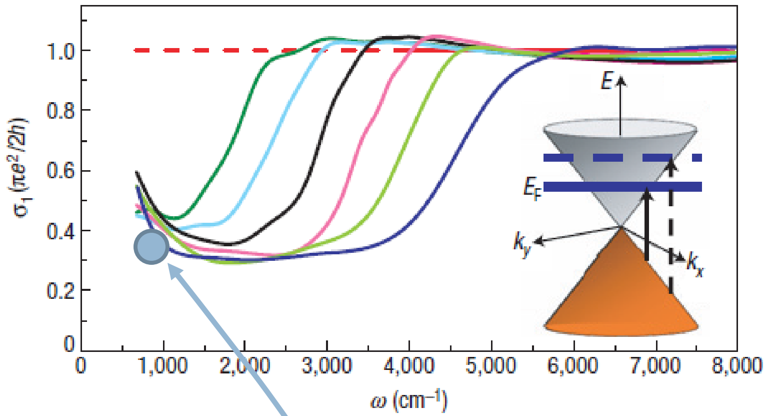
- Fei et al., Nature 487, 82 (2012)



- Chen et al., Nature 487, 77 (2012)

Nanoscopy





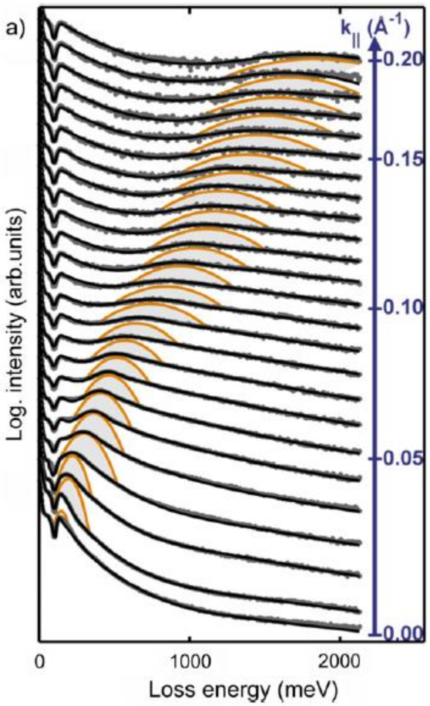
- Li et al., Nature Phys. 4, 532 (2008)

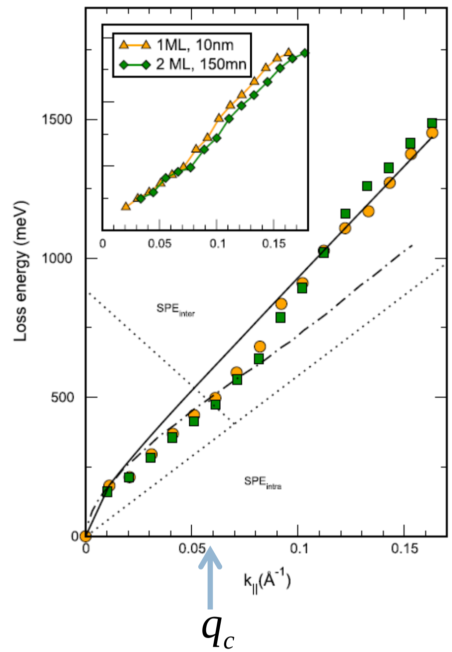
- Fei et al., Nature 487, 82 (2012)

$$\frac{\mathrm{Re}\, q}{\mathrm{Im}\, q} = \frac{1}{\gamma_p} = 7.4$$

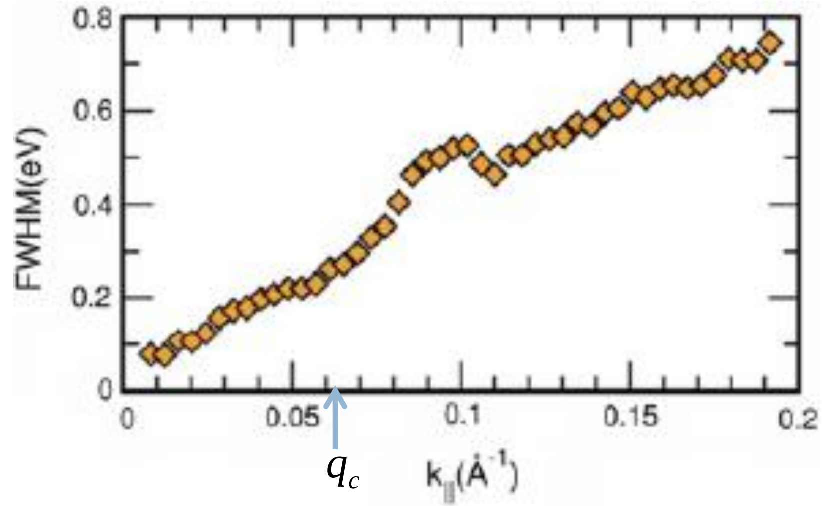
- Operating frequency $\lambda_{air} = 11.2\ \mu\mathrm{m}$ $\omega = 892\ \mathrm{cm}^{-1}$
- Plasmon linewidth: $\Gamma = 75\ \mathrm{cm}^{-1}$ $\Gamma_{DC} = 20\ \mathrm{cm}^{-1}$

EELS





- Dispersion



- Linewidth

$$\Gamma = 3.8 \frac{v_F}{\lambda_{pl}}$$

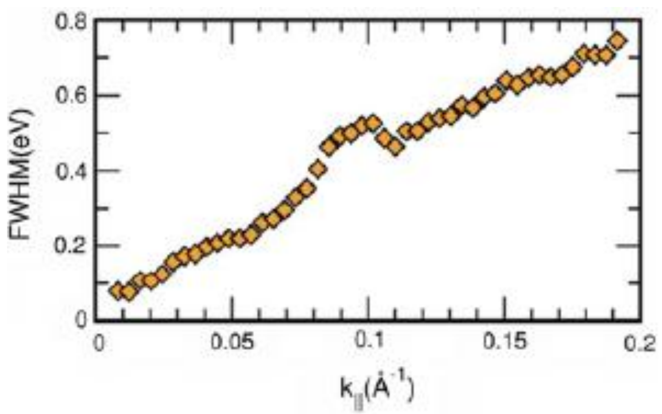
$$\Gamma(2000\,\text{cm}^{-1}) \approx 1000\,\text{cm}^{-1}$$

- Tegenkamp et al., JPCM 23, 012001 (2011)

- Liu et al., PRB 78, 201403 (2008) $\Gamma = 10.6 \frac{v_F}{\lambda_{pl}}$

EELS

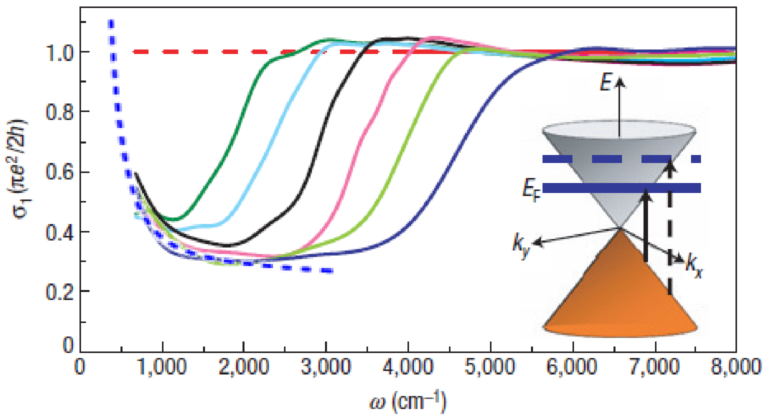
- EELS



- Tegenkamp et al., JPCM 23, 012001 (2011)

$$\Gamma = 3.8 \frac{v_F}{\lambda_{pl}}$$

- Optical conductivity



- Li et al., Nature Phys. 4, 532 (2008)

$$\Gamma = \Gamma_{DC} + 2.5 \frac{v_F}{\lambda_{pl}} \qquad \lambda_{pl} \propto \frac{E_F}{\omega^2}$$

- Plateau (doping independent)

Conclusion

- **Plasmon linewidth**

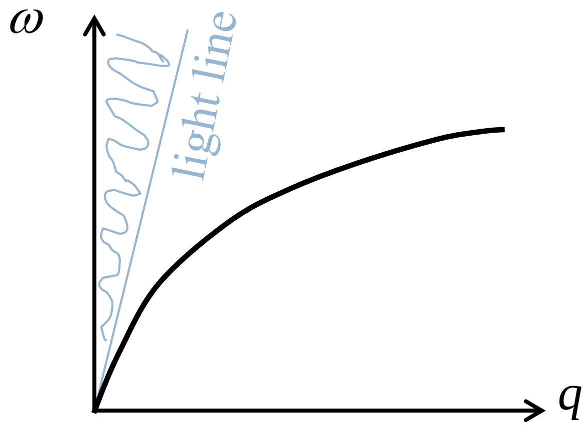
- Far IR: $\Gamma \approx \Gamma_{DC}$ ➢ Optical (Micro-ribbons)

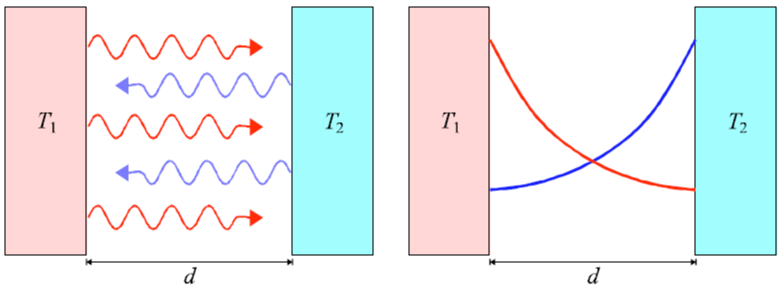
- Mid IR & Near IR: $\Gamma >> \Gamma_{DC}$
  - ➢ Optical (Uniform)
  - ➢ Optical (Nano-ribbons)
  - ➢ Nanoscopy
  - ➢ EELS

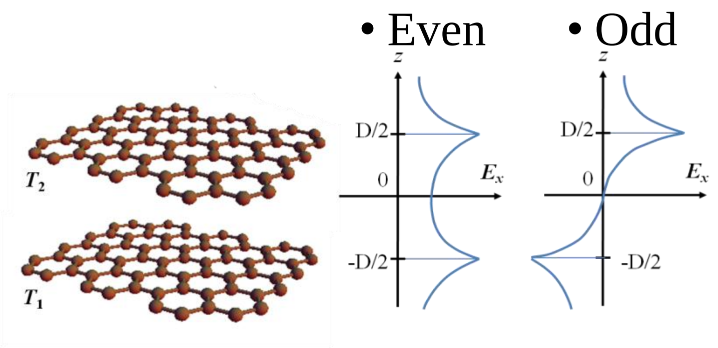
- Optical conductivity
  - ➢ Experiment
  - ➢ Theory

Near field heat transfer

- **Plasmons – heat channels**
- Large DOS



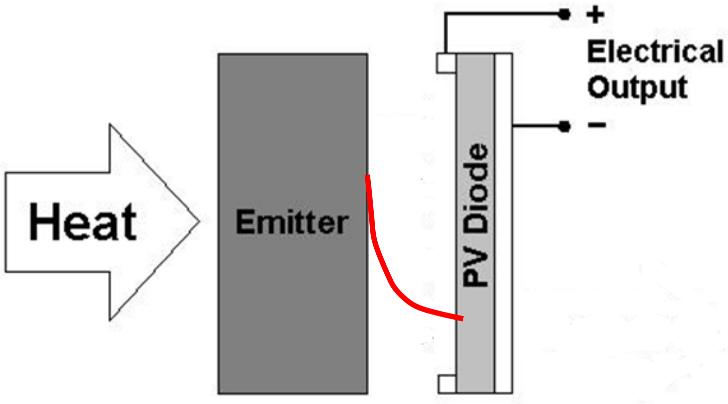


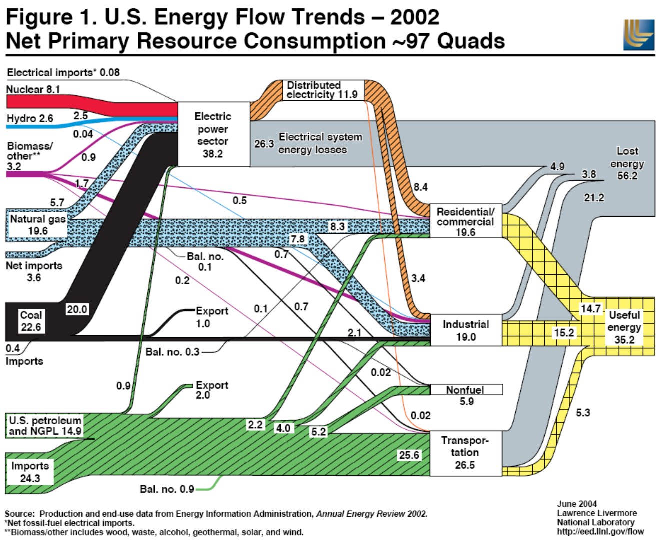


- O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, H. Buljan, M. Soljacic, Phys. Rev. B 85, 155422 (2012).

Thermo-photo-voltaics

- **Heat to electricity**





- O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, M. Soljacic, Optics Express 20, A366 (2012).

Thank you for your attention!