Coupling light into graphene plasmons with the help of surface acoustic waves

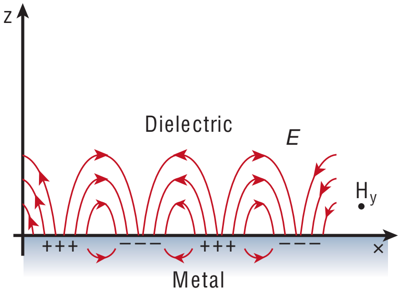
- Jürgen Schiefele (ESR) – UCM
- Jorge Pedrós – UPM
- Fernando Sols – UCM
- Fernando Calle – UPM
- Francisco Guinea – ICMM-CSIC

See arXiv:1309.0767.

Universidad Complutense Madrid | Universidad Politécnica de Madrid | Campus de Excelencia Internacional (Moncloa UCM-UPM) | ICMM (CSIC) Madrid

Plasmons: photons + conduction electrons

Plasmon oscillation at dielectric/metal interface:



From [Barnes *et al.*, Nature 2003]

Surface Plasmon Polariton

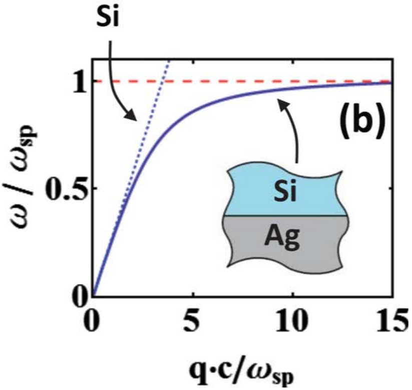
- Collective oscillation of electrons and electric field.
- Propagating along the interface.
- Momentum mismatch $k_p \gg \omega/c$ results in field enhancement ('compressed light').

Applications

- Nanophotonics: optics at subwavelength scale.
- Strong light-matter interaction: sensors.

Plasmons: photons + conduction electrons

Plasmon dispersion at a Si/Ag interface:



From [Jablan *et al.*, PRB 2009]

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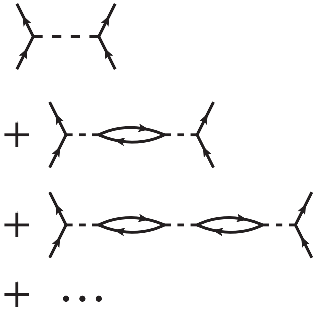
Plasmons in graphene

Screened Coulomb interaction in graphene:



[Wunsch, Stauber, FS, Guinea , NJP 2006]

[Hwang, Das Sarma, PRB 2007]

Screening: dielectric function $\epsilon(k, \omega)$

- Coulomb interaction v_k is screened by $\epsilon(k, \omega)$:

$$v^{\text{eff}} = v_k / \epsilon(k, \omega)$$

- Random-Phase-Approximation: sum up all bubble insertions.

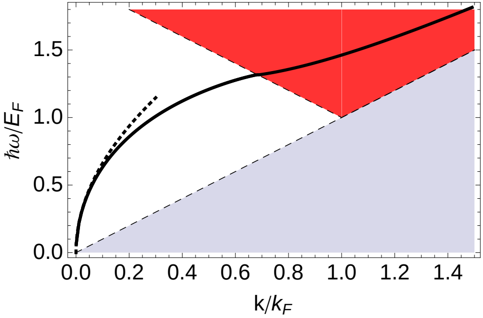
$$\epsilon_{\text{RPA}} = 1 - v_k \Pi^{(0)}(k, \omega)$$

- The zeros of ϵ_{RPA} yield the plasmon dispersion.

Plasmons in graphene

Plasmon dispersion in free-standing graphene ($\epsilon_{\text{eff}} = 1$):

[Wunsch *et al.*, 2006]
[Jablan *et al.*, 2009]



Graphene plasmons: long lifetimes, high field confinement and tuneability

For small k:

$$\omega(k) \approx \sqrt{k\, E_F/\epsilon_{\text{eff}}}$$

- Tuneable via E_F. (*In situ* via gate voltage.)
- Sensitive to environment via ϵ_{eff}.

Plasmons in graphene – applications

NANO LETTERS
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Graphene Plasmonics: A Platform for Strong Light−Matter Interactions

Frank H. L. Koppens,[*,†] Darrick E. Chang,[‡] and F. Javier García de Abajo[*,§,∥]

Photocurrent in graphene harnessed by tunable intrinsic plasmons

Marcus Freitag, Tony Low, Wenjuan Zhu, Hugen Yan, Fengnian Xia & Phaedon Avouris

Nature Communications **4**, Article number: 1951 doi:10.1038/ncomms2951

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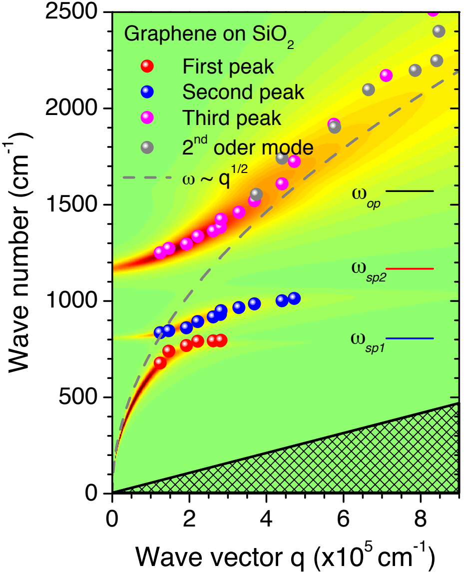
Single-photon nonlinear optics with graphene plasmons

M. Gullans,[1] D. E. Chang,[2] F. H. L. Koppens,[2] F. J. García de Abajo,[2,3] and M. D. Lukin[1]

[1] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2] *ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain*
[3] *ICREA - Instituci Catalana de Recerca i Estudis Avanats, Barcelona, Spain*

(Dated: September 12, 2013)

Polar substrates: hybridized phonon-plasmon states

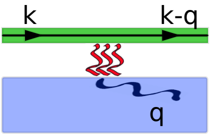


Plasmon dispersion in graphene on SiO_2.

There are three branches instead of one. (From [Yan *et al.*, Nat. Photon. 2013].)

Polar substrates: hybridized phonon-plasmon states

Coupling to substrate phonons:



Interaction with substrate phonons

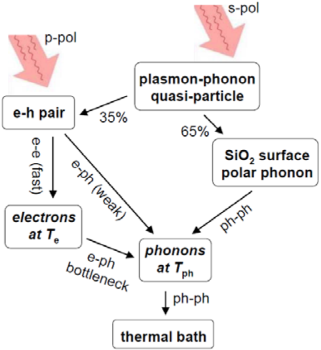
- Polar lattice vibrations in substrate create electric field.
- Graphene electrons couple to substrate phonons. [Schiefele, FS, Guinea, PRB 2012]

Phonon–plasmon modes

- Graphene plasmon hybridizes with substrate phonons.
- Dispersion splits into branches.
- Plasmon inherits long phonon lifetime.

Polar substrates: hybridized phonon-plasmon states

Electron/phonon content of hybridized modes:



[Freitag *et al.*, Nat. Commun. 2013]

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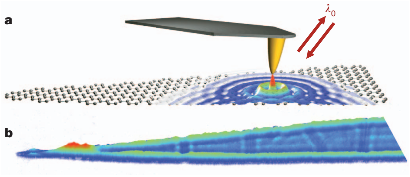
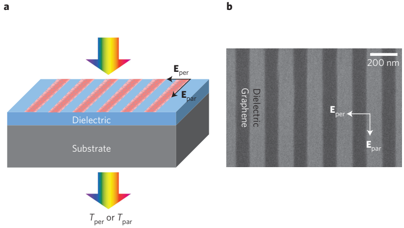


[Chen *et al.*, Nature 2012].



[Yan *et al.*, Nat. Photon. 2013]

Near field optics

- Scatter light at AFM tip.
- Narrow tip, large momentum uncertainity.

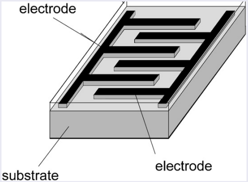
Sub-wavelength structures

- Patterned graphene ribbons.
- Ribbon width selects plasmon wavevector.

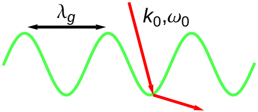
How to launch plasmons – our proposal

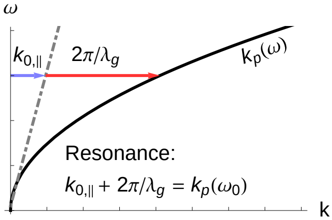
Excite a surface acoustic wave (SAW)

- An interdigital transducer (IDT) on a piezoelectric film excites a sinusoidal SAW. [Ruppert *et al.*, PRB 2010]



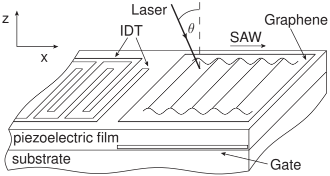
- SAW deforms graphene into a diffraction grating.
- Laser light scattered at the deformation excites plasmons.



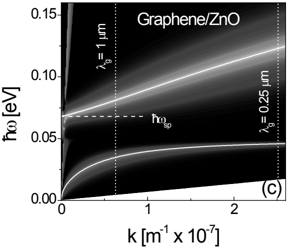


How to launch plasmons – our proposal

Sketch of the device:



Plasmon dispersion:



Features and advantages

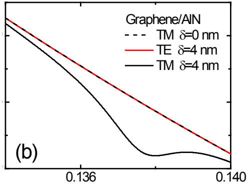
- Scalable approach – allows for integrated devices (no AFM).
- Excites propagating plasmons in extended graphene sheet (instead of patterned structures).
- No plasmon scattering at ribbon edges.
- Coupling between laser and plasmon electrically switchable (via IDT).

How to launch plasmons – our proposal

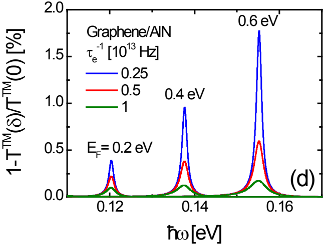
Efficiency

- plasmon excitation results in a dip in transmission spectrum T^{TM}.
- Calculated extinction values $1 - T(\delta)/T(0)$ comparable to those achieved with ribbon structures. [Yan *et al.*, Nat. Photon. 2013]
- Extinction depends on SAW amplitude δ and graphene quality (scattering time τ_e).
- Plasmon resonance can be tuned with E_F (backgate).

Transmittance vs. frequency with and without the SAW:



Extinction spectrum:



Summary

By electrically exciting a diffraction grating, we can couple laser light to graphene plasmons.

- The laser-plasmon coupling is switchable.
- Propagating plasmons in an extended graphene sheet are excited.
- No problems with unclean edges in patterned graphene.
- A versatile building block for future integrated plasmonic devices.

See arXiv:1309.0767.