Optical nano-imaging of gate-tunable graphene plasmons

Jianing Chen, Michela Badioli, Pablo Alonso-Gonza´lez, Sukosin Thongrattanasiri, Florian Huth, Johann Osmond, Marko Spasenovic, Alba Centeno, Amaia Pesquera, Philippe Godignon, Amaia Zurutuza Elorza, Nicolas Camara, F. Javier Garcı´a de Abajo, Rainer Hillenbrand & Frank H. L. Koppens

CIC nanoGUNE Consolider, Spain. Centro de Fisica de Materiales (CSIC-UPV/EHU) and Donostia International Physics Center (DIPC), ICFO-Institut de Cie´ncies Fotoniques, Barcelona, Spain. IQFR-CSIC, Madrid, Spain. IKERBASQUE, Basque Foundation for Science, Spain. Graphenea SA, Spain. CNM-IMB-CSIC–Campus UAB, Barcelona, Spain.
Neaspec GmbH,Munich, Germany.
GREMAN, Universite´ de Tours/CNRS, France.

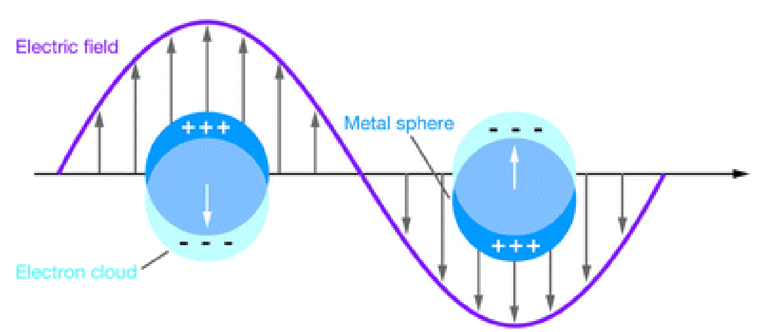
5 JULY 2012 | VOL 487 | NATURE | 77

Robin John
ph08d023

Plasmon

The plasmon is a quasiparticle resulting from the quantization of plasma oscillations just as photons and phonons are quantizations of electromagnetic and mechanical vibrations, respectively (although the photon is an elementary particle, not a quasiparticle). Maxwell equations of EM theory

Thus, plasmons are collective oscillations of the free electron gas density, for example, at optical frequencies plasmons can couple with a photon to create another quasiparticle called a plasma polariton.



Willets KA, Van Duyne RP. 2007.
Annu. Rev. Phys. Chem. 58:267–97

Optical properties of metals. Light of frequency below the plasma frequency is reflected, because the electrons in the metal screen the electric field of the light. Light of frequency above the plasma frequency is transmitted, because the electrons cannot respond fast enough to screen it. In most metals, the plasma frequency is in the ultraviolet, making them shiny (reflective) in the visible range.

Surface plasmon -polariton

nature

Background

- ability to manipulate light fields - central to modern communication technology

- as photons are chargeless – controlling them electrically was difficult

- a possible way to do it is to couple them with charge carriers ie through plasmon polariton

- graphene – amphipolar – carrier density can be tuned

- reports on optical plasmons in graphene through spectroscopy – so far no report on real space manipulation of plasmon

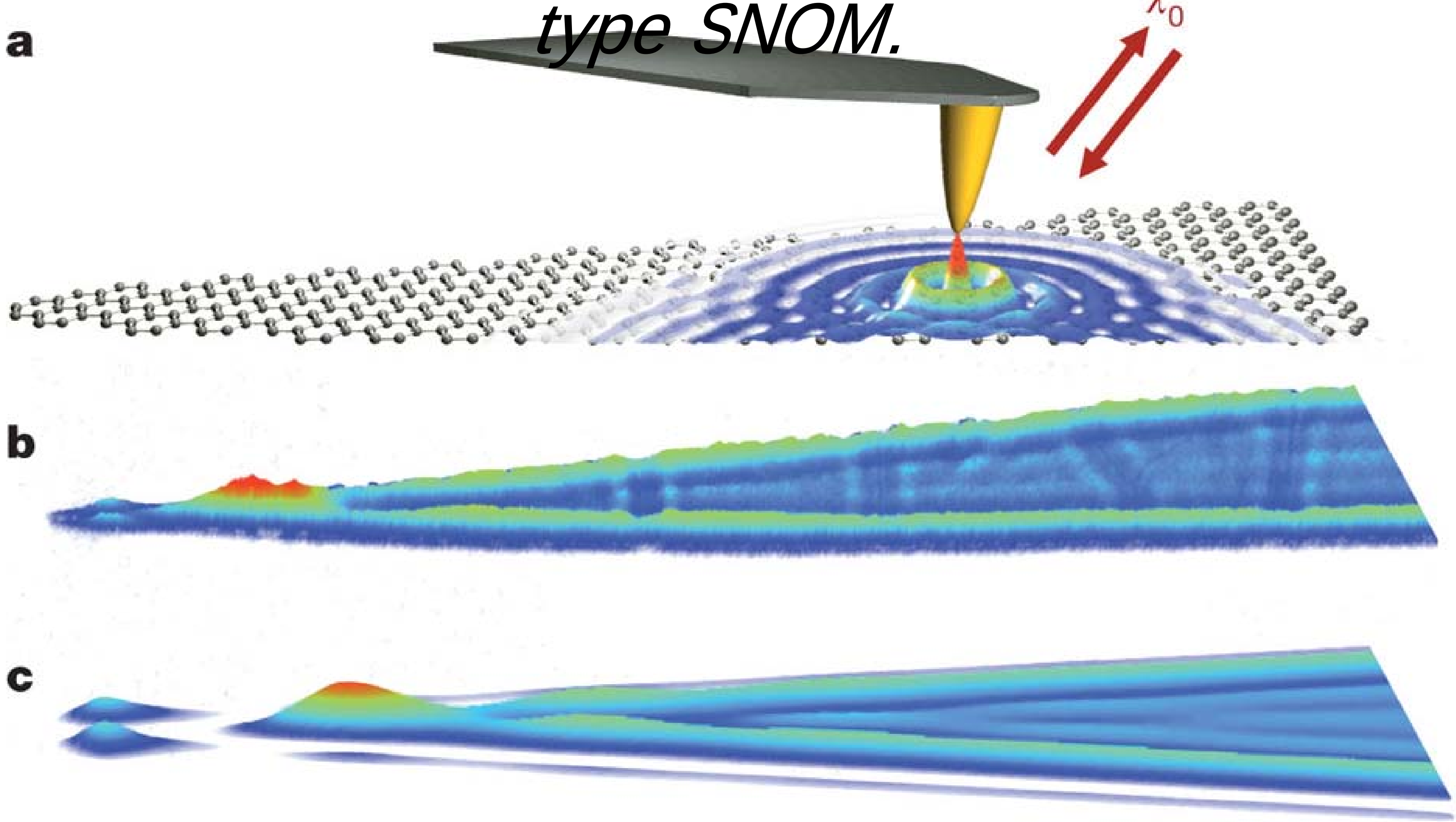
Present work

- launch and detect propagating optical plasmons in tapered graphene nanostructures using near-field scattering microscopy with infrared excitation light

- Controlling of plasmon using gate controll of carrier mobility

nature

Imaging propagating and localized graphene plasmons by scattering-type SNOM.



nature

tapered graphene ribbon on the carbon-terminated surface of 6H-SiC – 12x 1 micron

λ_0 = 9.7 µm

The distance between fringe maxima is approximately constant at ~130 nm inside the ribbon

By recording the local field scattered by the tip, we probe the interference of forward- and backward-propagating plasmons

λ_p = 260 nm 40 times smaller

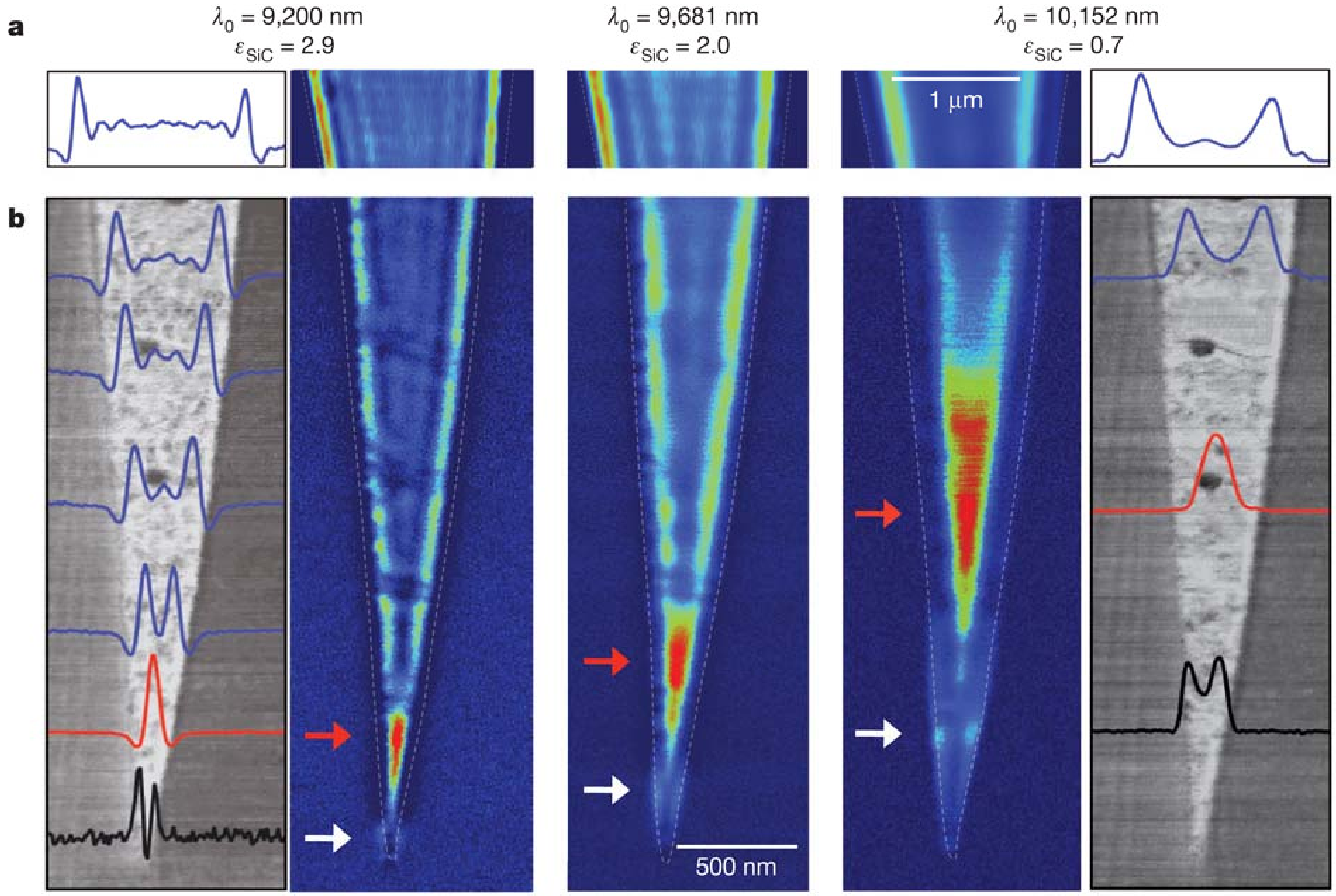
Calculated local density of optical states matches with the experiment
μ = 1,000 cm^2 V^{-1} s^{-1}

$$\lambda_p \approx \lambda_0 \alpha \frac{E_F}{E_P} \frac{4}{\varepsilon_r + 1}$$

305 nm

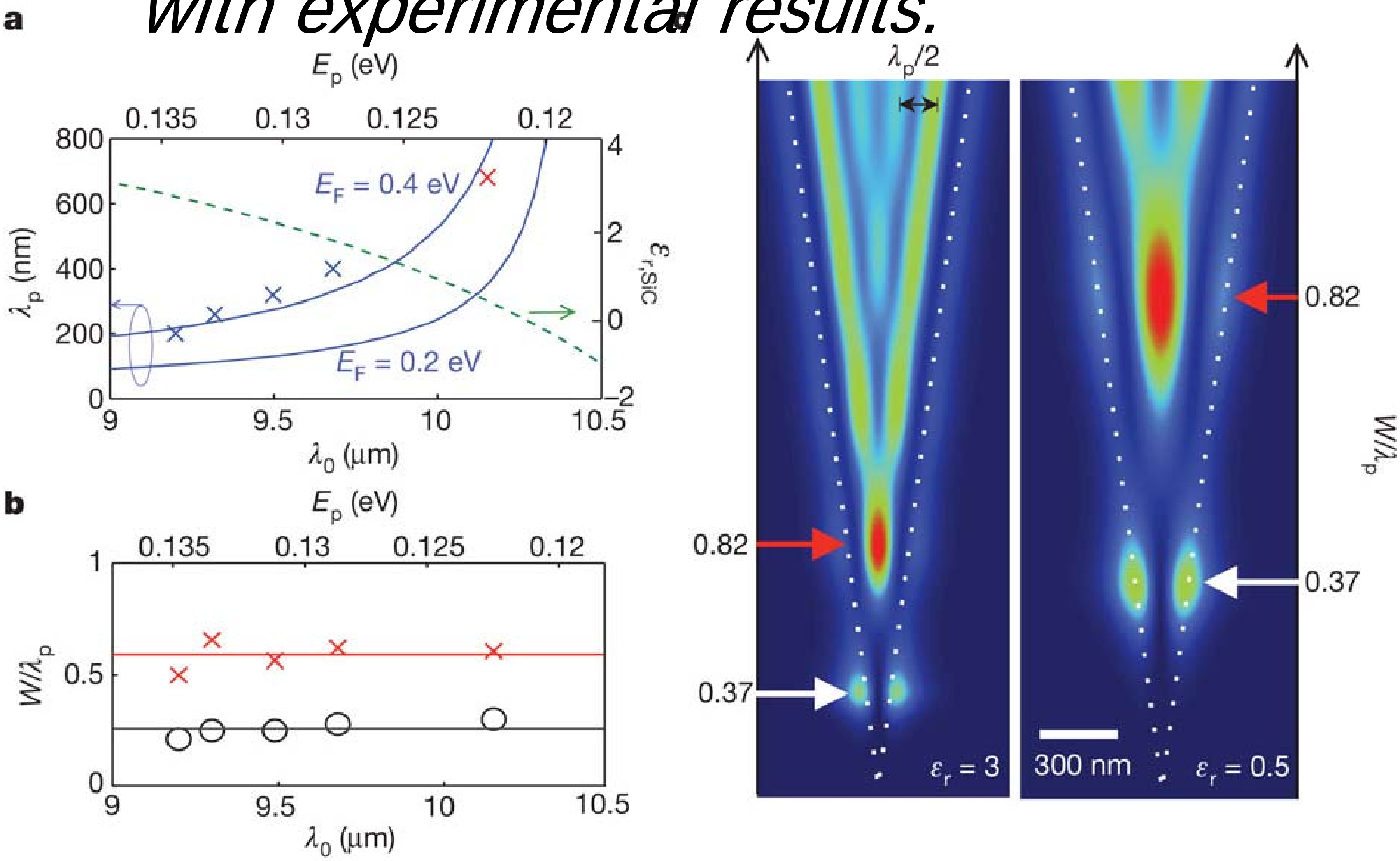
nature

Controlling the plasmon wavelength over a wide range.



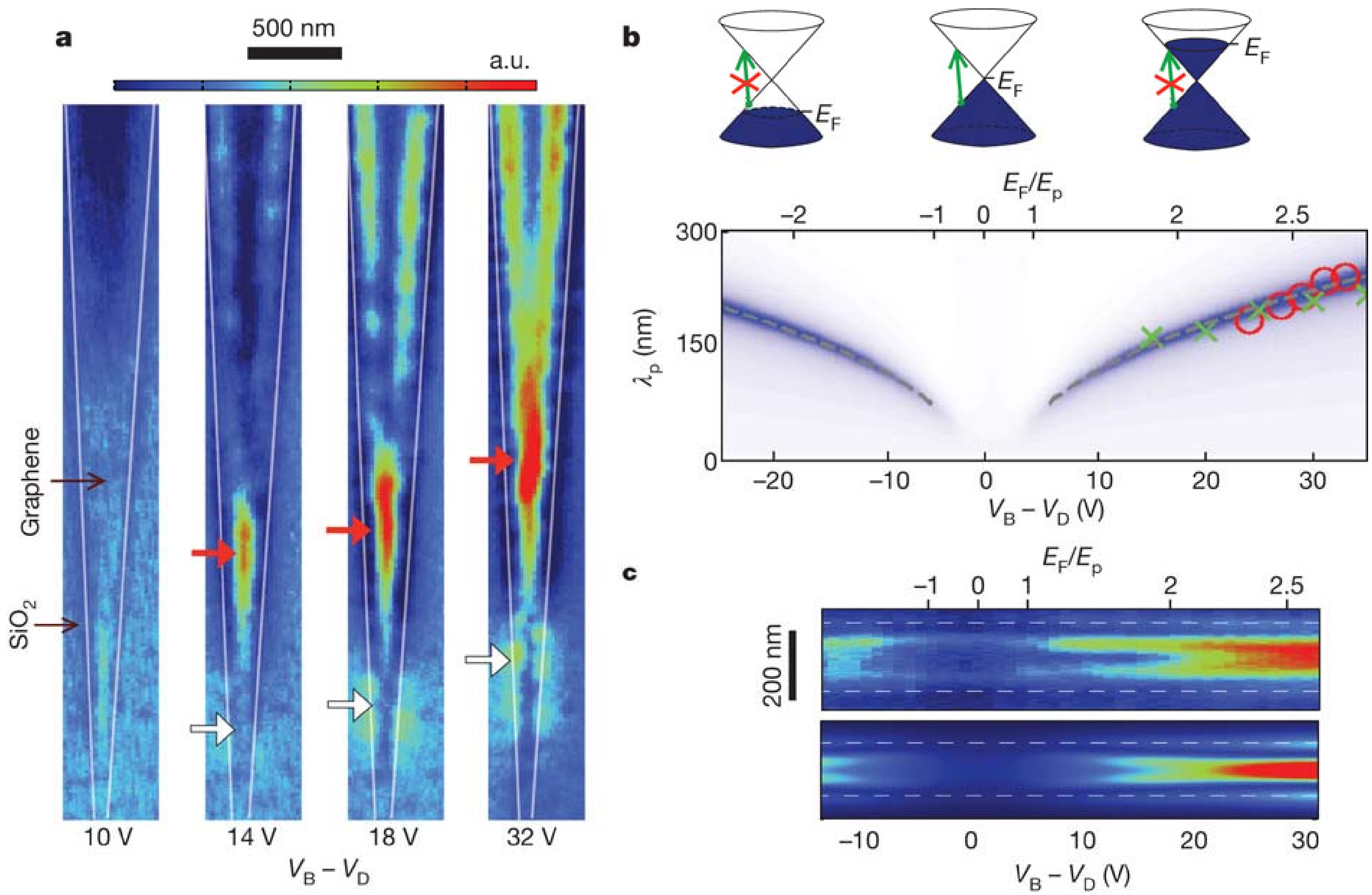
nature

Comparison of theoretical model with experimental results.



nature

Plasmonic switching and active control of the plasmon wavelength by electrical gating.



nature

Summary

• Launched and detect propagating optical plasmons in tapered graphene nanostructures using near-field scattering microscopy with infrared excitation light.

• Provided real-space images of plasmon fields, and find that the extracted plasmon wavelength is very short—more than 40 times smaller than the wavelength of illumination.

•We exploit this strong optical field confinement to turn a graphene nanostructure into a tunable resonant plasmonic cavity with extremely small mode volume.

• The cavity resonance is controlled *in situ* by gating the graphene, and in particular, complete switching on and off of the plasmon modes is demonstrated, thus paving the way towards graphene-based optical transistors.

• Successful alliance between nanoelectronics and nano-optics enables the development of active subwavelength-scale optics and a plethora of nano-optoelectronic devices and functionalities, such as tunable metamaterials, nanoscale optical processing, and strongly enhanced light–matter interactions for quantum devices and biosensing applications.

$$\mathrm{LDOS} = \mathrm{LDOS}_{\mathrm{vac}} + \frac{1}{2\pi^2 \omega |p|^2} \mathrm{Im}\left\{ \mathbf{E}^{\mathrm{ref}}(\mathbf{r}_0) \cdot \mathbf{p}^* \right\}$$

Thank you all