Mesoscopic Electrodynamics and Quantum Surface-response Functions of Metals Revealed by Acoustic Graphene Plasmons

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Graphene supports gate-tunable plasmons that are capable of confining electromagnetic fields into subwavelength volumes. Recently, it has been shown that when graphene is placed in the near vicinity of a metal substrate—with the graphene–metal separation controlled, with atomic precision, by the number of layers of hexagonal boron nitride—graphene plasmons are screened by the metal thereby giving rise to acoustic-like graphene plasmons [1]. These exhibit even higher field confinement, squeezing light down to nanometer dimensions [1]. For this reason, plasmons in such heterostructures make ideal candidates to probe the quantum nonlocal electrodynamic response of the nearby metal. We treat graphene at the level of the RPA and describe the nonclassical optical response of the metal using a framework of mesoscopic electrodynamics based on microscopic surface-response functions, known as Feibelman d-parameters, which include quantum corrections in the metal's response [2]. In the spectral range spanned by graphene plasmons—i.e., THz and mid-IR—the Feibelman $d_\perp$-parameter is well approximated by $d_\perp(\omega) = \zeta + i\xi\omega/\omega_p$, where ω_p is the plasma frequency of the metal, and ζ and ξ are constants (which only depend on the density parameter r_s) [3].
Here, we present a theory for calculating the spectrum of acoustic plasmons in graphene–dielectric–metal heterostructures (Fig. 1a). We show that the graphene plasmons' resonances exhibit a shift due to the quantum surface-response of the metal: toward the red for $Re\, d_\perp > 0$ (associated with electronic spill-out) and toward the blue for $Re\, d_\perp < 0$ (associated with "spill-in" of the induced charges); this is accompanied by a slight increase of plasmon damping (due to electron-hole pair excitations). Hence, using our approach, $d_\perp(\omega)$ can be constructed from the experimentally measured plasmon dispersion (Fig. 1b). Based on this work, we envision that by harnessing the record-high light confinement brought about by acoustic graphene plasmons one could shed light about the physics governing the complex electron dynamics of metals, superconductors, and strongly-correlated systems.

References

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[2] T. Christensen, Phys. *Rev. Lett.* **118**, 157402 (2017).
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Figures

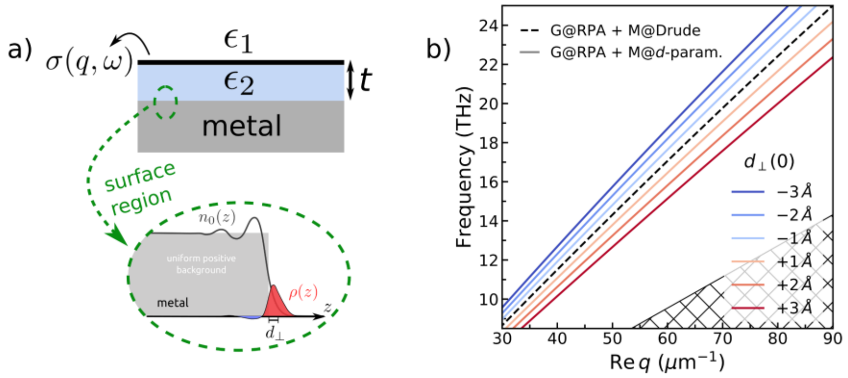

Figure 1: a) Illustration of a layered structure with graphene separated by a distance t from a metal substrate; the zoomed region shows the shift of the induced electron density $\rho(z)$ that is set up when the system is perturbed. $d_\perp$corresponds to the centroid of the induced charge. b) Shift of the acoustic graphene plasmon's dispersion for different values of $d_\perp(0) \equiv \zeta$.