



# Plasmonic modes in thin films: quo vadis?

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Herein, we discuss the status and the prospect of plasmonic modes in thin films. Plasmons are collective longitudinal modes of charge fluctuation in metal samples excited by an external electric field. Surface plasmons (SPs) are waves that propagate along the surface of a conductor with applications in magneto-optic data storage, optics, microscopy, and catalysis. In thin films, the electronic response is influenced by electron quantum confinement. Confined electrons modify the dynamical screening processes at the film/substrate interface by introducing novel properties with potential applications and, moreover, they affect both the dispersion relation of SP frequency and the damping processes of the SP. Recent calculations indicate the emergence of acoustic surface plasmons (ASPs) in Ag thin films exhibiting quantum well states and in graphene films. The slope of the dispersion of ASP decreases with film thickness. We also discuss open issues in research on plasmonic modes in graphene/metal interfaces.

**Keywords:** thin films, plasmons, plasmonics, silver, gold, graphene, magnetoplasmonics

Plasmons in low-dimensional systems never cease to amaze with new astonishing findings, although it has quite a long history, started with the discovery of surface plasmons (SPs) in thin films by Ritchie (1957).

Recently, novel modes, such as sheet (Langer et al., 2011; Politano et al., 2012a), Dirac (Fei et al., 2011; Stauber, 2014), and acoustic surface plasmons (ASPs) (Politano et al., 2011; Yuan et al., 2011) and, moreover, plasmarons (Krstajic and Peeters, 2013), have been observed in low-dimensional systems. Such excitations are supported by the two-dimensional electron gas (2DEG). The great interest toward plasmons arises from the exceptional range of the possible applications of plasmonics.

To date, plasmonic devices based on noble metals (Ag and Au) are widely diffused (Nyga et al., 2008; Pala et al., 2009). Nevertheless, current research is oriented toward the realization of graphene-based plasmonic devices. In fact, plasmons in graphene offer promising prospect of applications covering a wide frequency range, going from terahertz up to the visible (Vicarelli et al., 2012; García de Abajo, 2014).

Nanoscale thin films are an ideal playground for manipulating plasmon properties by peculiar phenomena occurring in thin films, such as quantum size effects (Hamawi et al., 1991; Wei and Chou, 2002) and quantum electron confinement (Ogando et al., 2005; Politano and Chiarello, 2010). Film morphology may originate plasmon confinement within disordered grains (Moresco et al., 1999) or periodic nanodomains (Politano et al., 2013a). Herein, the open challenges regarding plasmons modes in thin films will be presented to the reader, with a particular attention for the cases with higher prospect for plasmonic applications, i.e., noble metal (Ag and Au) and graphene films.

As a general rule, the electromagnetic fields of both sides forming an interface interact in such a way that the SP splits into two plasmonic excitations in which electron may oscillate in phase or not. For a Drude thin slab in vacuum of thickness  $a$  (Pitarke et al.,

2007), the dispersion relations of these modes can be obtained by applying appropriate boundary conditions and solving Maxwell's equations (Raether, 1980):

$$\omega = \frac{\omega_p}{\sqrt{2}} (1 \pm e^{-qa})^{1/2} \quad (1)$$

The high energy plasmon in the **Figure 1A** has anti-symmetric field distribution, whereas the low-energy one has symmetric field distribution.

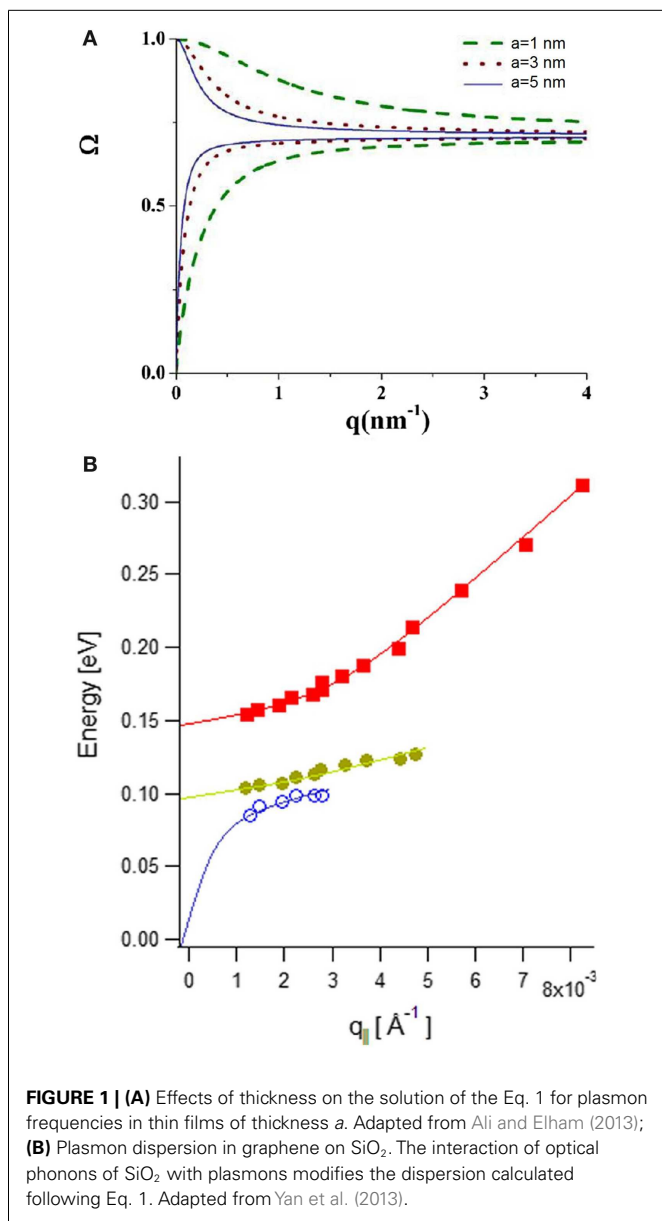
At short wavelengths ( $qa \gg 1$ ), the surface waves become decoupled and each surface sustains independent oscillations at the reduced frequency  $\omega_s = \omega_p/\sqrt{2}$  characteristic of a semi-infinite electron gas with a single plane boundary. At long wavelengths ( $qa \ll 1$ ), there are normal oscillations at  $\omega_p$  and tangential 2D oscillations at:

$$\omega_{2D} = (2\pi naq)^{1/2} \quad (2)$$

which were later discussed by Stern (1967) and observed in artificially structured semiconductors (Allen et al., 1977) and, more recently, in a metallic surface-state band on a silicon surface (Nagao et al., 2001a,b).

The plasmon dispersion in Eq. 1 is modified by the interaction with phonons. Plasmon–phonon coupling is a striking manifestation of the breakdown of the Born–Oppenheimer approximation (Jablan et al., 2011), with consequences on transport (Tediosi et al., 2007) properties. The plasmon–phonon coupling phenomenon implies the hybridization of the plasmon modes of the 2DEG with the optical phonon modes, giving rise to the coupled plasmon–phonon modes (shown in **Figure 1B** for the sample case of graphene/SiO<sub>2</sub>).

Concerning interfaces, different authors have invoked the existence of *interface plasmons* (Layet et al., 1986). Ahlqvist et al. (1982) have studied the electrostatics of the interface between two



semi-infinite electron gases, finding that the interface plasmon is characterized by

$$\omega_i^2 = (\omega_1^2 + \omega_2^2) / 2 \tag{3}$$

where  $\omega_i$ ,  $\omega_1$ , and  $\omega_2$  are the frequencies of the interface plasmon and of the two semi-infinite electron gases, respectively. Jewsbury and Summerside (1980) have suggested that an “interface plasmon” is not a pure mode but arises from the electronic band structure at the interface.

However, the traditional theoretical approach used to describe plasmons in thin films, based on Eqs 1 and 2 and on interface plasmons (Eq. 3) is inadequate to describe the extraordinary complexity of plasmon modes at interfaces. Thus, the overall

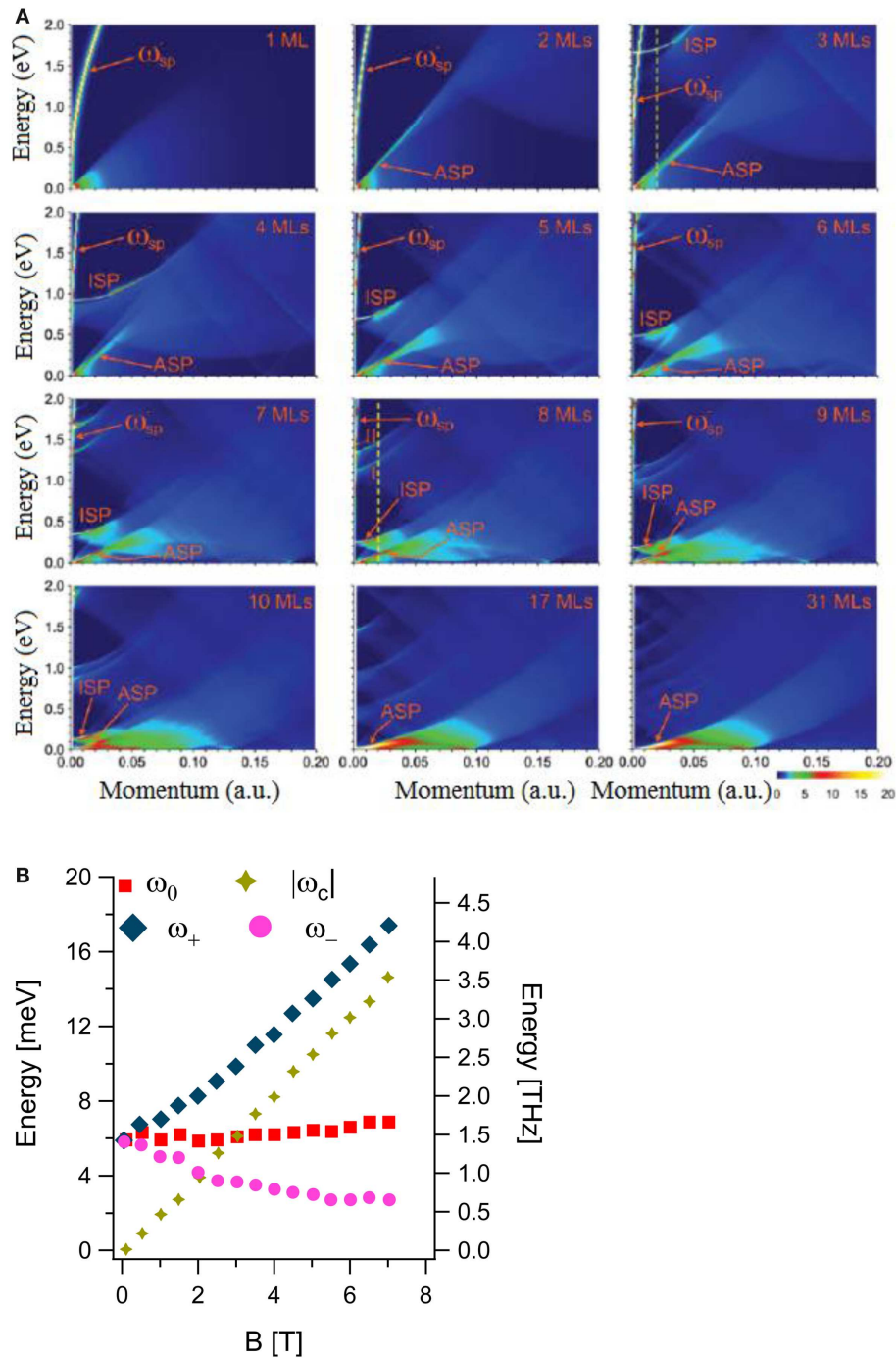
encouraging viewpoint for plasmonic applications is also accompanied by the possibility to carry out many other fascinating fundamental studies.

As an example, the strain resulting from the lattice mismatch between adlayer and substrate (Schell-Sorokin and Tromp, 1990; Sander et al., 1998) may further affect plasmonic excitations. Additional collective electronic modes may be induced by strain, as found by Pellegrino et al. (2010) for the case of graphene. However, experimental studies are still lacking due to the difficulties in following strain effects on plasmonic excitations.

Moreover, the influence of electron quantum confinement (presence of quantum well states, QWS) on the SP is still not clearly established. Theoreticians (Yuan and Gao, 2008) and experimentalists (Yu et al., 2005; Politano et al., 2009) have put in evidence the influence of QWS on the plasmon lifetime in films. Due to the opening of the decay channel of the SP into electron-hole pairs via interband transitions involving QWS, the line-width of the SP assumes an unusual dispersion relation as a function of the momentum transfer, as compared with the case of bulk samples. The effects of QWS on plasmon dispersion have been studied only for a few systems. In Politano et al. (2008) and Politano and Chiarello (2009), it has been shown that the screening properties are influenced by the presence of the modified electron distribution in the presence of QWS. However, rigorous and satisfactory theoretical description is still missing.

The presence of QWS and the subsequent enhanced SP density of states around the Fermi level in thin films may also increase the cross section for the excitation of intrinsically free-electron plasmons, such as the multipole surface plasmon (MP) (Liebsch, 1998). The nature of MP has been understood for alkali metals (Tsuei et al., 1990, 1991; Sprunger et al., 1992; Zielasek et al., 2006), alkaline-earth metals (Sprunger et al., 1992), and aluminum (Chiarello et al., 2000). Unfortunately, contradictory results are reported for the most popular plasmonic systems (Ag and Au). Calculations based on a s-d polarization model by Liebsch (1998) predicted the existence of the Ag and Au MP near  $\omega_m = 0.8 \cdot \omega_p = 7.2 \text{ eV}$  ( $\omega_p = 9.0 \text{ eV}$  is the s-electron bulk plasmon energy for both Ag and Au) as the density profile at the surface has predominantly s-electron character. Experiments on bulk Ag have not found this mode (Moresco et al., 1996; Barman et al., 2004a,b). In contrast, the Ag MP has been recently measured in Ag films on Ni(111). However, such excitation is revealed only in experimental conditions enhancing the surface sensitivity, i.e., at low impinging energies and grazing incidence (Politano et al., 2013b,d), in agreement with Liebsch’s prediction (Liebsch, 1998). Therefore, electron quantum confinement in Ag 5 sp-derived QWS (Miller et al., 1994) enhances the cross section for Ag MP excitation in thin films compared with semi-infinite media (bulk samples).

Another open issue is related to the possible existence of acoustic plasmon modes in thin films. Unfortunately, to date no experimental works exist on this topic, while from the theoretical side Silkin et al. (2011) have shown that ASP emerge in the electronic response of thin Ag films. The presence of Ag QWS in



**FIGURE 2 | (A)** Normalized surface loss function  $\text{Im}[g(q,\omega)]/q\omega$  for Ag(111) films with thickness ranging from 1 to 31 monolayers (ML) evaluated by using realistic effective masses in energy band dispersions. Note the strongly dispersing mode corresponding to a conventional  $\omega_{sp}$  mode of a thin film. Peaks denoted with “ISP” are

originated from the interband transition between the energy-split quantum states. Adapted from Silkin et al. (2011). **(B)** Dependence of the plasmon energy  $\omega_0$ , the cyclotron resonance energy  $\omega_c$  and the magnetoplasmon energies  $\omega_{\pm}$  on the magnetic field  $B$ . Adapted from Crassee et al. (2012).

ultrathin films induces the appearance of ASP, whose dispersion is determined by the QWS band. The slope of the dispersion relation decreases with film thickness.

The surface response function (**Figure 2A**) for film thickness higher than three layers shows an additional feature at about 2 eV, which correspond to interband transitions between energy-split

$SS^+$  and  $SS^-$  electronic states (interband SP, ISP). In contrast with ASP, the ISP energy has finite value at  $q=0$ . Moreover, the ISP energy decreases with increasing thickness and it merges with the ASP at higher thickness.

Acoustic surface plasmon owes its existence to the spatial coexistence of a 2DEG with a 3D electron gas. It has been also predicted to exist at the K/Be interface (Echeverry et al., 2010; Silkin et al., 2010a,b). The screening by the underlying metal substrate change the square-root-like dispersion of the 2D plasmon into linear.

Concerning graphene films, the most puzzling open issues are related to plasmonic modes in graphene/metal interfaces. Due to the difficulty in the theoretical description of the screening by the underlying metal substrate, accurate theoretical models for plasmons in graphene/metal interfaces are still missing. The out-of-plane charge transfer between graphene and the metal is determined by the difference between the work function of graphene and the metal surface and, in addition, by the metal-graphene chemical interaction that creates an interface dipole lowering the metal work function. The induced electrostatic potential decays weakly with the distance from the metal contact as  $V(x) \approx x^{-1/2}$  and  $\approx x^{-1}$  for undoped and doped graphene, respectively (Khomyakov et al., 2010). Instead, current models overestimate the screening by the metal substrate. Likely, the experimental study of plasmons in graphene deposited on jellium surfaces (Al) could help theoreticians to improve our understanding of screening processes at graphene/metals. Unfortunately, such experimental study is complicated by the difficult preparation of graphene on jellium surfaces.

Low-energy intraband plasmon in graphene is currently well understood (Shin et al., 2011; Stauber and Gómez-Santos, 2012b; Stauber, 2014). In contrast, theoretical models hitherto fail to describe the nature of a non-linear mode observed at  $\sim 0.5$  eV (Politano and Chiarello, 2014) and, moreover, the quadratic dispersion of interband plasmon (Generalov and Dedkov, 2012; Politano et al., 2012b) in graphene/metal interfaces. The dispersion of the interband plasmon is instead linear in both free-standing graphene (Kramberger et al., 2008) and Cs-decoupled graphene/Ni(111) (Cupolillo et al., 2013b; Ligato et al., 2013). The observation of the change of the interband plasmon from linear to quadratic as a function of the number of graphene layers on silicon carbide (Lu et al., 2009) may in principle afford important information for shedding light on the still confusing state-of-the-art of plasmon modes in epitaxial graphene. However, theoretical models describing the increasing wealth of experimental results on interband plasmons are yet missing.

Moreover, experimental studies on plasmons in bilayer graphene grown on metals would be essential to verify and improve current theoretical models for both plasmon dispersion (Wang and Chakraborty, 2007; Sensarma et al., 2010; Stauber and Gómez-Santos, 2012a; Roldán and Brey, 2013) and plasmaron formation (Van-Nham and Holger, 2012; Krstajic and Peeters, 2013).

Finally, another intriguing topic is magnetoplasmonics, which recently is attracting huge interest for its potential applications in technology (Belotelov et al., 2011; Bonanni et al., 2011). The 2D magnetoplasmons are collective excitations between Landau

levels (Lozovik and Sokolik, 2012). They can be observed through infrared optical absorption and inelastic light scattering (Kallin and Halperin, 1984; Oji and MacDonald, 1986; Cinà et al., 1999; Eriksson et al., 1999; Bychkov and Martinez, 2002; Li and Zhai, 2011). In layered and doped graphene structures, the instability and unusual dispersion of magnetoplasmon modes have been studied in recent years, within different approaches (Tahir and Sabeeh, 2007; Berman et al., 2008, 2009; Bychkov and Martinez, 2008a,b; Fischer et al., 2009, 2010; Roldán et al., 2009; Tahir et al., 2011; Wu et al., 2011; Bisti and Kirova, 2012; Ferreira et al., 2012; Lozovik and Sokolik, 2012; Wang et al., 2012; Yan et al., 2012; Chamanara et al., 2013a,b; Petkovic et al., 2013). Magnetoplasmons have been observed in graphene epitaxially grown on SiC (Crassee et al., 2012). The Drude absorption is transformed into a strong terahertz plasmonic peak due to nanoscale inhomogeneities, such as substrate terraces and wrinkles. Plasmonic excitations also modify the magneto-optical response and, in particular, the Faraday rotation (Crassee et al., 2012). This makes graphene a unique playground for plasmon-controlled magneto-optical phenomena thanks to a cyclotron mass, which is two orders of magnitude smaller than in conventional plasmonic materials, such as noble metals.

The field-induced splitting of the plasmon peak resembles strikingly the appearance of collective resonances previously observed in other systems (Allen et al., 1983; Glattli et al., 1985; Mast et al., 1985; Kukushkin et al., 2003). The upper and lower branches are attributed to the so-called bulk and edge magnetoplasmons, respectively, with the frequencies

$$\omega_{\pm} = \sqrt{\frac{\omega_c^2}{4} + \omega_0^2} \pm \frac{|\omega_c|}{2}$$

where  $\omega_0$  is the plasmon frequency at 0 field,  $\omega_c = \pm eB/mc$  is the cyclotron frequency, defined as positive for electrons and negative for holes,  $m$  is the cyclotron mass, and  $c$  the speed of light. At high fields ( $|\omega_c| \gg \omega_0$ ), the upper branch becomes essentially the usual cyclotron resonance with a linear dependence on magnetic field, while the lower branch represents a collective mode confined to the edges (Fetter, 1985) with the energy inversely proportional to the field (**Figure 2B**).

In conclusion, issues discussed herein provide the grounds for theoretical studies aimed at characterizing in more details how growth mode, quantum size effects, and the electron quantum confinement within the adlayer influence the dispersion and the lifetime of collective excitations in nanoscale thin films.

The comprehension of plasmonic excitations in thin films (Chiarello et al., 1997a,b), especially of noble metals (Politano and Chiarello, 2009; Politano, 2012a,b, 2013) and graphene (Politano et al., 2011, 2012a,b, 2013a,c; Cupolillo et al., 2012, 2013a,b; Politano and Chiarello, 2013a,b, 2014), could keep active researchers for a long time.

## REFERENCES

- Ahlqvist, P., Monreal, R., Flores, F., and Garcia-Moliner, F. (1982). Interface plasmons at the boundary of two semi-infinite electron gases. *Phys. Scripta* 26, 35. doi:10.1088/0031-8949/26/1/006

- Ali, B., and Elham, A. (2013). Effect of shell thickness on propagation of surface hybrid modes in metallic cylindrical nanoshells. *Phys. Scripta* 88, 035707. doi:10.1088/0031-8949/88/03/035707
- Allen, S. J., Störmer, H. L., and Hwang, J. C. M. (1983). Dimensional resonance of the two-dimensional electron gas in selectively doped GaAs/AlGaAs heterostructures. *Phys. Rev. B* 28, 4875–4877. doi:10.1103/PhysRevB.28.4875
- Allen, S. J., Tsui, D. C., and Logan, R. A. (1977). Observation of the two-dimensional plasmon in silicon inversion layers. *Phys. Rev. Lett.* 38, 980. doi:10.1103/PhysRevLett.38.980
- Barman, S. R., Biswas, C., and Horn, K. (2004a). Collective excitations on silver surfaces studied by photoyield. *Surf. Sci.* 566–568, 538–543. doi:10.1016/j.susc.2004.06.059
- Barman, S. R., Biswas, C., and Horn, K. (2004b). Electronic excitations on silver surfaces. *Phys. Rev. B* 69, 454131–454139. doi:10.1103/PhysRevB.69.045413
- Belotelov, V. I., Akimov, I. A., Pohlm, M., Kotov, V. A., Kastures, S., Vengurlekar, A. S., et al. (2011). Enhanced magneto-optical effects in magnetoplasmonic crystals. *Nat. Nanotechnol.* 6, 370–376. doi:10.1038/nnano.2011.54
- Berman, O. L., Gumbs, G., and Echenique, P. M. (2009). Quasiparticles for a quantum dot array in graphene and the associated magnetoplasmons. *Phys. Rev. B* 79, 075418. doi:10.1103/PhysRevB.79.075418
- Berman, O. L., Gumbs, G., and Lozovik, Y. E. (2008). Magnetoplasmons in layered graphene structures. *Phys. Rev. B* 78, 085401. doi:10.1103/PhysRevB.78.085401
- Bisti, V. E., and Kirova, N. N. (2012). Cyclotron excitations in pure bilayer graphene: electron-hole asymmetry and coulomb interaction. *Physica B Condens. Matter* 407, 1923–1926. doi:10.1016/j.physb.2012.01.065
- Bonanni, V., Bonetti, S., Pakizheh, T., Pirzadeh, Z., Chen, J., Nogués, J., et al. (2011). Designer magnetoplasmonics with nickel nanoferrromagnets. *Nano Lett.* 11, 5333–5338. doi:10.1021/nl2028443
- Bychkov, Y. A., and Martinez, G. (2002). Magnetoplasmons and band nonparabolicity in two-dimensional electron gas. *Phys. Rev. B* 66, 193312. doi:10.1103/PhysRevB.66.193312
- Bychkov, Y. A., and Martinez, G. (2008a). Magnetoplasmon excitations in graphene. *Physica E Low Dimens. Syst. Nanostruct.* 40, 1410–1411. doi:10.1016/j.physe.2007.09.026
- Bychkov, Y. A., and Martinez, G. (2008b). Magnetoplasmon excitations in graphene for filling factors  $\nu \leq 6$ . *Phys. Rev. B* 77, 125417. doi:10.1103/PhysRevB.77.125417
- Chamanara, N., Sounas, D., and Caloz, C. (2013a). Non-reciprocal magnetoplasmon graphene coupler. *Opt. Express* 21, 11248–11256. doi:10.1364/OE.21.011248
- Chamanara, N., Sounas, D., Szkopek, T., and Caloz, C. (2013b). Terahertz magnetoplasmon energy concentration and splitting in graphene PN junctions. *Opt. Express* 21, 25356–25363. doi:10.1364/OE.21.025356
- Chiarello, G., Cupolillo, A., Amoddeo, A., Caputi, L. S., Papagno, L., and Colavita, E. (1997a). Collective excitations of two layers of K on Ni(111). *Phys. Rev. B* 55, 1376–1379. doi:10.1103/PhysRevB.55.1376
- Chiarello, G., Cupolillo, A., Caputi, L. S., Papagno, L., and Colavita, E. (1997b). Collective and single-particle excitations in thin layers of K on Ni(111). *Surf. Sci.* 377, 365–370. doi:10.1016/S0039-6028(96)01419-7
- Chiarello, G., Formoso, V., Santaniello, A., Colavita, E., and Papagno, L. (2000). Surface-plasmon dispersion and multipole surface plasmons in Al(111). *Phys. Rev. B* 62, 12676–12679. doi:10.1103/PhysRevB.62.12676
- Cinà, S., Whittaker, D. M., Arnone, D. D., Burke, T., Hughes, H. P., Leadbeater, M., et al. (1999). Magnetoplasmons in a tunable periodically modulated magnetic field. *Phys. Rev. Lett.* 83, 4425–4428. doi:10.1103/PhysRevLett.83.4425
- Crassee, I., Orlita, M., Potemski, M., Walter, A. L., Ostler, M., Seyller, T., et al. (2012). Intrinsic terahertz plasmons and magnetoplasmons in large scale monolayer graphene. *Nano Lett.* 12, 2470–2474. doi:10.1021/nl300572y
- Cupolillo, A., Ligato, N., and Caputi, L. (2013a). Low energy two-dimensional plasmon in epitaxial graphene on Ni (111). *Surf. Sci.* 608, 88–91. doi:10.1016/j.susc.2012.09.018
- Cupolillo, A., Ligato, N., and Caputi, L. S. (2013b). Plasmon dispersion in quasi-free-standing graphene on Ni(111). *Appl. Phys. Lett.* 102, 111609. doi:10.1063/1.4798331
- Cupolillo, A., Ligato, N., and Caputi, L. S. (2012). Two-dimensional character of the interface- $\pi$  plasmon in epitaxial graphene on Ni(111). *Carbon N. Y.* 50, 2588–2591. doi:10.1016/j.carbon.2012.02.017
- Echeverry, J. P., Chulkov, E. V., and Silkin, V. M. (2010). Collective electronic excitations in a potassium-covered BE surface. *Phys. Status Solidi C* 7, 2640–2643. doi:10.1002/pssc.200983842
- Eriksson, M. A., Pinczuk, A., Dennis, B. S., Simon, S. H., Pfeiffer, L. N., and West, K. W. (1999). Collective excitations in the dilute 2D electron system. *Phys. Rev. Lett.* 82, 2163–2166. doi:10.1103/PhysRevLett.82.2163
- Fei, Z., Andreev, G. O., Bao, W., Zhang, L. M., Mcleod, S., Wang, C., et al. (2011). Infrared nanoscopy of dirac plasmons at the graphene-SiO<sub>2</sub> interface. *Nano Lett.* 11, 4701–4705. doi:10.1021/nl202362d
- Ferreira, A., Peres, N. M. R., and Castro Neto, A. H. (2012). Confined magneto-optical waves in graphene. *Phys. Rev. B* 85, 205426. doi:10.1103/PhysRevB.85.205426
- Fetter, A. L. (1985). Edge magnetoplasmons in a bounded two-dimensional electron fluid. *Phys. Rev. B* 32, 7676–7684. doi:10.1103/PhysRevB.32.7676
- Fischer, A. M., Dzyubenko, A. B., and Römer, R. A. (2009). Localized collective excitations in doped graphene in strong magnetic fields. *Phys. Rev. B* 80, 165410. doi:10.1103/PhysRevB.80.165410
- Fischer, A. M., Römer, R. A., and Dzyubenko, A. B. (2010). Symmetry content and spectral properties of charged collective excitations for graphene in strong magnetic fields. *Europhys. Lett.* 92, 37003. doi:10.1209/0295-5075/92/37003
- García de Abajo, F. J. (2014). Graphene plasmonics: challenges and opportunities. *ACS Photonics* 1, 135–152. doi:10.1021/ph400147y
- Generalov, A. V., and Dedkov, Y. S. (2012). EELS study of the epitaxial graphene/Ni(111) and graphene/Au/Ni(111) systems. *Carbon N. Y.* 50, 183–191. doi:10.1016/j.carbon.2011.08.018
- Glattli, D. C., Andrei, E. Y., Deville, G., Poitrenaud, J., and Williams, F. I. B. (1985). Dynamical hall effect in a two-dimensional classical plasma. *Phys. Rev. Lett.* 54, 1710–1713. doi:10.1103/PhysRevLett.54.1710
- Hamawi, A., Lindgren, S. A., and Walldén, L. (1991). Quantum size effects in thin metal overlayers. *Phys. Scripta* T39, 339–345. doi:10.1088/0031-8949/1991/T39/053
- Jablan, M., Soljagic, M., and Buljan, H. (2011). Unconventional plasmon-phonon coupling in graphene. *Phys. Rev. B* 83, 161409. doi:10.1103/PhysRevB.83.161409
- Jewsbury, P., and Summerside, P. (1980). The nature of interface plasmon modes at bimetallic junctions. *J. Phys. F Met. Phys.* 10, 645. doi:10.1088/0305-4608/10/4/015
- Kallin, C., and Halperin, B. I. (1984). Excitations from a filled Landau level in the two-dimensional electron gas. *Phys. Rev. B* 30, 5655–5668. doi:10.1103/PhysRevB.30.5655
- Khomyakov, P. A., Starikov, A. A., Brocks, G., and Kelly, P. J. (2010). Nonlinear screening of charges induced in graphene by metal contacts. *Phys. Rev. B* 82, 115437. doi:10.1103/PhysRevB.82.115437
- Kramberger, C., Hambach, R., Giorgetti, C., Rummeli, M. H., Knupfer, M., Fink, J., et al. (2008). Linear plasmon dispersion in single-wall carbon nanotubes and the collective excitation spectrum of graphene. *Phys. Rev. Lett.* 100, 196803. doi:10.1103/PhysRevLett.100.196803
- Krstajic, P. M., and Peeters, F. M. (2013). Energy-momentum dispersion relation of plasmarons in bilayer graphene. *Phys. Rev. B* 88, 165420. doi:10.1103/PhysRevB.88.165420
- Kukushkin, I. V., Smet, J. H., Mikhailov, S. A., Kulakovskii, D. V., Von Klitzing, K., and Wegscheider, W. (2003). Observation of retardation effects in the spectrum of two-dimensional plasmons. *Phys. Rev. Lett.* 90, 156801. doi:10.1103/PhysRevLett.90.156801
- Langer, T., Förster, D. F., Busse, C., Michely, T., Pfnür, H., and Tegenkamp, C. (2011). Sheet plasmons in modulated graphene on Ir(111). *New J. Phys.* 13, 053006. doi:10.1088/1367-2630/13/5/053006
- Layet, J. M., Contini, R., Derrien, J., and Lüth, H. (1986). Coupled interface plasmons of the Ag-Si(111) system as investigated with high-resolution electron energy-loss spectroscopy. *Surf. Sci.* 168, 142–148. doi:10.1016/0039-6028(86)90844-7
- Li, C., and Zhai, F. (2011). Anisotropic magnetoplasmon spectrum of two-dimensional electron gas systems with the Rashba and Dresselhaus spin-orbit interactions. *J. Appl. Phys.* 109, 093306. doi:10.1063/1.3583651
- Liebsch, A. (1998). Prediction of a Ag multipole surface plasmon. *Phys. Rev. B* 57, 3803–3806. doi:10.1103/PhysRevB.57.3803
- Ligato, N., Cupolillo, A., and Caputi, L. S. (2013). Study of the intercalation of graphene on Ni(111) with Cs atoms: towards the quasi-free graphene. *Thin Solid Films* 543, 59–62. doi:10.1016/j.tsf.2013.02.121
- Lozovik, Y. E., and Sokolik, A. A. (2012). Influence of Landau level mixing on the properties of elementary excitations in graphene in strong magnetic field. *Nanoscale Res. Lett.* 7, 1–19. doi:10.1186/1556-276X-7-134



- Lu, J., Loh, K. P., Huang, H., Chen, W., and Wee, A. T. S. (2009). Plasmon dispersion on epitaxial graphene studied using high-resolution electron energy-loss spectroscopy. *Phys. Rev. B* 80, 113410. doi:10.1088/0953-8984/23/1/012001
- Mast, D. B., Dahm, A. J., and Fetter, A. L. (1985). Observation of bulk and edge magnetoplasmons in a two-dimensional electron fluid. *Phys. Rev. Lett.* 54, 1706–1709. doi:10.1103/PhysRevLett.54.1706
- Miller, T., Samsavar, A., and Chiang, T. C. (1994). Photoexcitation of resonances in Ag films on Ni(111). *Phys. Rev. B* 50, 17686. doi:10.1103/PhysRevB.50.17686
- Moresco, F., Rocca, M., Hildebrandt, T., and Henzler, M. (1999). Plasmon confinement in ultrathin continuous Ag films. *Phys. Rev. Lett.* 83, 2238–2241. doi:10.1103/PhysRevLett.83.2238
- Moresco, F., Rocca, M., Zielasek, V., Hildebrandt, T., and Henzler, M. (1996). Evidence for the presence of the multipole plasmon mode on Ag surfaces. *Phys. Rev. B* 54, 14333–14336. doi:10.1103/PhysRevB.54.R14333
- Nagao, T., Hildebrandt, T., Henzler, M., and Hasegawa, S. (2001a). Dispersion and damping of a two-dimensional plasmon in a metallic surface-state band. *Phys. Rev. Lett.* 86, 5747–5750. doi:10.1103/PhysRevLett.86.5747
- Nagao, T., Hildebrandt, T., Henzler, M., and Hasegawa, S. (2001b). Two-dimensional plasmon in a surface-state band. *Surf. Sci.* 493, 680–686. doi:10.1016/S0039-6028(01)01282-1
- Nyga, P., Drachev, V. P., Thoreson, M. D., and Shalaev, V. M. (2008). Mid-IR plasmonics and photomodification with Ag films. *Appl. Phys. B* 93, 59–68. doi:10.1007/s00340-008-3145-9
- Ogando, E., Zabala, N., Chulkov, E. V., and Puska, M. J. (2005). Self-consistent study of electron confinement to metallic thin films on solid surfaces. *Phys. Rev. B* 71, 205401. doi:10.1103/PhysRevB.71.205401
- Oji, H. C. A., and MacDonald, A. H. (1986). Magnetoplasma modes of the two-dimensional electron gas at nonintegral filling factors. *Phys. Rev. B* 33, 3810–3818. doi:10.1103/PhysRevB.33.3810
- Pala, R. A., White, J., Barnard, E., Liu, J., and Brongersma, M. L. (2009). Design of plasmonic thin-film solar cells with broadband absorption enhancements. *Adv. Mater. Weinheim* 21, 3504–3509. doi:10.1002/adma.200900331
- Pellegrino, F. M. D., Angilella, G. G. N., and Pucci, R. (2010). Dynamical polarization of graphene under strain. *Phys. Rev. B* 82, 115434. doi:10.1103/PhysRevB.82.115434
- Petkovic, I., Williams, F. I. B., Bennaceur, K., Portier, F., Roche, P., and Glatli, D. C. (2013). Carrier drift velocity and edge magnetoplasmons in graphene. *Phys. Rev. Lett.* 110, 016801. doi:10.1103/PhysRevLett.110.016801
- Pitarke, J. M., Silkin, V. M., Chulkov, E. V., and Echenique, P. M. (2007). Theory of surface plasmons and surface-plasmon polaritons. *Rep. Prog. Phys.* 70, 1–87. doi:10.1088/0034-4885/70/1/R01
- Politano, A. (2012a). Influence of structural and electronic properties on the collective excitations of Ag/Cu(111). *Plasmonics* 7, 131–136. doi:10.1007/s11468-011-9285-5
- Politano, A. (2012b). Interplay of structural and temperature effects on plasmonic excitations at noble-metal interfaces. *Philos. Mag.* 92, 768–778. doi:10.1080/14786435.2011.634846
- Politano, A. (2013). Low-energy collective electronic mode at a noble metal interface. *Plasmonics* 8, 357–360. doi:10.1007/s11468-012-9397-6
- Politano, A., Agostino, R. G., Colavita, E., Formoso, V., and Chiarello, G. (2008). Purely quadratic dispersion of surface plasmon in Ag/Ni(111): the influence of electron confinement. *Phys. Status Solidi Rapid Res. Lett.* 2, 86–88. doi:10.1002/pssr.200701307
- Politano, A., Campi, D., Formoso, V., and Chiarello, G. (2013a). Evidence of confinement of the  $\pi$  plasmon in periodically rippled graphene on Ru(0001). *Phys. Chem. Chem. Phys.* 15, 11356–11361. doi:10.1039/c3cp51954f
- Politano, A., Formoso, V., and Chiarello, G. (2013b). Collective electronic excitations in thin Ag films on Ni(111). *Plasmonics* 8, 1683–1690. doi:10.1007/s11468-11013-19587-x
- Politano, A., Formoso, V., and Chiarello, G. (2013c). Evidence of composite plasmon-phonon modes in the electronic response of epitaxial graphene. *J. Phys. Condens. Matter* 25, 345303. doi:10.1088/0953-8984/25/34/345303
- Politano, A., Formoso, V., and Chiarello, G. (2013d). Interplay between single-particle and plasmonic excitations in the electronic response of thin Ag films. *J. Phys. Condens. Matter* 25, 305001. doi:10.1088/0953-8984/25/30/305001
- Politano, A., and Chiarello, G. (2009). Collective electronic excitations in systems exhibiting quantum well states. *Surf. Rev. Lett.* 16, 171–190. doi:10.1142/S0218625X09012482
- Politano, A., and Chiarello, G. (2010). Enhancement of hydrolysis in alkali ultrathin layers on metal substrates in the presence of electron confinement. *Chem. Phys. Lett.* 494, 84–87. doi:10.1016/j.cplett.2010.05.089
- Politano, A., and Chiarello, G. (2013a). Quenching of plasmons modes in air-exposed graphene-Ru contacts for plasmonic devices. *Appl. Phys. Lett.* 102, 201608. doi:10.1039/c3nr02027d
- Politano, A., and Chiarello, G. (2013b). Unravelling suitable graphene-metal contacts for graphene-based plasmonic devices. *Nanoscale* 5, 8215–8220. doi:10.1039/c3nr02027d
- Politano, A., and Chiarello, G. (2014). Emergence of a nonlinear plasmon in the electronic response of doped graphene. *Carbon N. Y.* 71, 176–180. doi:10.1016/j.carbon.2014.01.026
- Politano, A., Formoso, V., and Chiarello, G. (2009). Damping of the surface plasmon in clean and K-modified Ag thin films. *J. Electron Spectros. Relat. Phenomena* 173, 12–17. doi:10.1016/j.elspec.2009.03.003
- Politano, A., Marino, A. R., and Chiarello, G. (2012a). Effects of a humid environment on the sheet plasmon resonance in epitaxial graphene. *Phys. Rev. B* 86, 085420. doi:10.1103/PhysRevB.86.085420
- Politano, A., Marino, A. R., Formoso, V., Fariás, D., Miranda, R., and Chiarello, G. (2012b). Quadratic dispersion and damping processes of  $\pi$  plasmon in monolayer graphene on Pt(111). *Plasmonics* 7, 369–376. doi:10.1007/s11468-011-9317-1
- Politano, A., Marino, A. R., Formoso, V., Fariás, D., Miranda, R., and Chiarello, G. (2011). Evidence for acoustic-like plasmons on epitaxial graphene on Pt(111). *Phys. Rev. B* 84, 033401. doi:10.1103/PhysRevB.84.033401
- Raether, H. (1980). *Excitation of Plasmons and Interband Transitions by Electrons*. Berlin: Springer-Verlag.
- Ritchie, R. H. (1957). Plasma losses by fast electrons in thin films. *Phys. Rev. B* 106, 874–881. doi:10.1103/PhysRev.106.874
- Roldán, R., and Brey, L. (2013). Dielectric screening and plasmons in AA-stacked bilayer graphene. *Phys. Rev. B* 88, 115420. doi:10.1103/PhysRevB.88.115420
- Roldán, R., Fuchs, J. N., and Goerbig, M. O. (2009). Collective modes of doped graphene and a standard two-dimensional electron gas in a strong magnetic field: linear magnetoplasmons versus magnetoexcitons. *Phys. Rev. B* 80, 085408. doi:10.1103/PhysRevB.80.085408
- Sander, D., Schmidthal, C., Enders, A., and Kirschner, J. (1998). Stress and structure of Ni monolayers on W(110): the importance of lattice mismatch. *Phys. Rev. B* 57, 1406–1409. doi:10.1103/PhysRevB.57.1406
- Schell-Sorokin, A. J., and Tromp, R. M. (1990). Mechanical stresses in (sub)monolayer epitaxial films. *Phys. Rev. Lett.* 64, 1039–1042. doi:10.1103/PhysRevLett.64.1039
- Sensarma, R., Hwang, E. H., and Das Sarma, S. (2010). Dynamic screening and low-energy collective modes in bilayer graphene. *Phys. Rev. B* 82, 195428. doi:10.1088/0957-4484/23/50/505204
- Shin, S. Y., Hwang, C. G., Sung, S. J., Kim, N. D., Kim, H. S., and Chung, J. W. (2011). Observation of intrinsic intraband  $\pi$ -plasmon excitation of a single-layer graphene. *Phys. Rev. B* 83, 161403. doi:10.1103/PhysRevB.83.161403
- Silkin, V. M., Chulkov, E. V., Echeverry, J. P., and Echenique, P. M. (2010a). Modification of response properties of the Be(0001) surface upon adsorption of a potassium monolayer: an Ab initio calculation. *Phys. Status Solidi B* 247, 1849–1857. doi:10.1002/pssb.200983843
- Silkin, V. M., Helsing, B., Walldén, L., Echenique, P. M., and Chulkov, E. V. (2010b). Photoelectron driven acoustic surface plasmons in  $p(2 \times 2)K/Be(0001)$ : Ab initio calculations. *Phys. Rev. B* 81, 113406. doi:10.1103/PhysRevB.81.113406
- Silkin, V. M., Nagao, T., Despoja, V., Echeverry, J. P., Eremeev, S. V., Chulkov, E. V., et al. (2011). Low-energy plasmons in quantum-well and surface states of metallic thin films. *Phys. Rev. B* 84, 165416. doi:10.1103/PhysRevB.84.165416
- Sprunger, P. T., Watson, G. M., and Plummer, E. W. (1992). The normal modes at the surface of Li and Mg. *Surf. Sci.* 269–270, 551–555. doi:10.1016/0039-6028(92)91307-W
- Stauber, T. (2014). Plasmonics in Dirac systems: from graphene to topological insulators. *J. Phys. Condens. Matter* 26, 123201. doi:10.1088/0953-8984/26/12/123201
- Stauber, T., and Gómez-Santos, G. (2012a). Plasmons and near-field amplification in double-layer graphene. *Phys. Rev. B* 85, 075410. doi:10.1103/PhysRevB.85.075410

- Stauber, T., and Gómez-Santos, G. (2012b). Plasmons in layered structures including graphene. *New J. Phys.* 14, 105018. doi:10.1088/1367-2630/14/10/105018
- Stern, F. (1967). Polarizability of a two-dimensional electron gas. *Phys. Rev. Lett.* 18, 546–548. doi:10.1103/PhysRevLett.18.546
- Tahir, M., and Sabeeh, K. (2007). Theory of Weiss oscillations in the magneto-plasmon spectrum of Dirac electrons in graphene. *Phys. Rev. B* 76, 195416. doi:10.1103/PhysRevB.76.195416
- Tahir, M., Sabeeh, K., and Mackinnon, A. (2011). Temperature effects on the magneto-plasmon spectrum of a weakly modulated graphene monolayer. *J. Phys. Condens. Matter* 23, 425304. doi:10.1088/0953-8984/23/42/425304
- Tediosi, R., Armitage, N. P., Giannini, E., and Van Der Marel, D. (2007). Charge carrier interaction with a purely electronic collective mode: plasmarons and the infrared response of elemental bismuth. *Phys. Rev. Lett.* 99, 016406. doi:10.1103/PhysRevLett.99.016406
- Tsuei, K. D., Plummer, E. W., Liebsch, A., Kempa, K., and Bakshi, P. (1990). Multipole plasmon modes at a metal surface. *Phys. Rev. Lett.* 64, 44–47. doi:10.1103/PhysRevLett.64.44
- Tsuei, K. D., Plummer, E. W., Liebsch, A., Pehlke, E., Kempa, K., and Bakshi, P. (1991). The normal modes at the surface of simple metals. *Surf. Sci.* 247, 302–326. doi:10.1016/0039-6028(91)90142-F
- Van-Nham, P., and Holger, F. (2012). Coulomb interaction effects in graphene bilayers: electron-hole pairing and plasmaron formation. *New J. Phys.* 14, 075007. doi:10.1088/1367-2630/14/7/075007
- Vicarelli, L., Vitiello, M., Coquillat, D., Lombardo, A., Ferrari, A., Knap, W., et al. (2012). Graphene field-effect transistors as room-temperature terahertz detectors. *Nat. Mater.* 11, 865–871. doi:10.1038/nmat3417
- Wang, W., Apell, S. P., and Kinaret, J. M. (2012). Edge magnetoplasmons and the optical excitations in graphene disks. *Phys. Rev. B* 86, 125450. doi:10.1021/nl3016335
- Wang, X.-F., and Chakraborty, T. (2007). Coulomb screening and collective excitations in a graphene bilayer. *Phys. Rev. B* 75, 041404. doi:10.1103/PhysRevB.75.041404
- Wei, C. M., and Chou, M. Y. (2002). Theory of quantum size effects in thin Pb(111) films. *Phys. Rev. B* 66, 233408. doi:10.1103/PhysRevB.66.233408
- Wu, J. Y., Chen, S. C., Roslyak, O., Gumbs, G., and Lin, M. F. (2011). Plasma excitations in graphene: their spectral intensity and temperature dependence in magnetic field. *ACS Nano* 5, 1026–1032. doi:10.1021/nn1024847
- Yan, H., Li, Z., Li, X., Zhu, W., Avouris, P., and Xia, F. (2012). Infrared spectroscopy of tunable Dirac terahertz magneto-plasmons in graphene. *Nano Lett.* 12, 3766–3771. doi:10.1021/nl3016335
- Yan, H., Low, T., Zhu, W., Wu, Y., Freitag, M., Li, X., et al. (2013). Damping pathways of mid-infrared plasmons in graphene nanostructures. *Nat. Photonics* 7, 394–399. doi:10.1038/nphoton.2013.57
- Yu, Y. H., Jiang, Y., Tang, Z., Guo, Q. L., Jia, J. F., Xue, Q. K., et al. (2005). Thickness dependence of surface plasmon damping and dispersion in ultrathin Ag films. *Phys. Rev. B* 72, 205405. doi:10.1103/PhysRevB.72.205405
- Yuan, Z., and Gao, S. (2008). Landau damping and lifetime oscillation of surface plasmons in metallic thin films studied in a jellium slab model. *Surf. Sci.* 602, 460–464. doi:10.1016/j.susc.2007.10.040
- Yuan, Z., Jiang, Y., Gao, Y., Käll, M., and Gao, S. (2011). Symmetry-dependent screening of surface plasmons in ultrathin supported films: the case of Al/Si(111). *Phys. Rev. B* 83, 165452. doi:10.1103/PhysRevB.83.165452
- Zielasek, V., Ronitz, N., Henzler, M., and Pfmür, H. (2006). Crossover between monopole and multipole plasmon of Cs monolayers on Si(111) individually resolved in energy and momentum. *Phys. Rev. Lett.* 96, 196801. doi:10.1103/PhysRevLett.96.196801

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