Solid State Communications 213-214 (2015) 6–9

Contents lists available at ScienceDirect

Solid State Communications

journal homepage: www.elsevier.com/locate/ssc

Role of metallic substrate on the plasmon modes in double-layer graphene structures

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ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form
25 February 2015
Accepted 30 March 2015
Communicated by E.Y. Andrei
Available online 9 April 2015

Keywords:
A. Graphene
B. Two-dimensional electron gas
C. Double-layers graphene structures
D. Collective modes

ABSTRACT

Novel heterostructures combining different layered materials offer new opportunities for applications and fundamental studies of collective excitations driven by interlayer Coulomb interactions. In this work, we have investigated the influence of the metallic-like substrate on the plasmon spectrum of a double layer graphene system and a structure consisting of conventional two-dimensional electron gas (2DEG) immersed in a semiconductor quantum well and a graphene sheet with an interlayer separation of d. Long-range Coulomb interactions between substrate and graphene layered systems lead a new set of spectrum plasmons. At long wavelengths ($q \to 0$) the acoustic modes ($\omega \sim q$) depend, besides on the carrier density in each layer, on the distance between the first carrier layer and the substrate in both structures. Furthermore, in the relativistic/nonrelativistic layered structure an undamped acoustic mode emerges for a certain interlayer critical distance d_c. On the other hand, the optical plasmon modes emerging from the coupling of the double-layer systems and the substrate, both start at finite frequency at $q=0$ in contrast to the collective excitation spectrum $\omega \sim q^{1/2}$ reported in the literature for double-layer graphene structures.

1. Introduction

A revolution of material science is coming since graphene was exfoliated successfully from graphite by Novoselov and Geim [1]. The electrons in graphene behave like massless Dirac-Fermions, which results in a extraordinary properties of carriers (electrons and holes) with ultra-high-mobility and long mean free path, gate-tunable carrier densities, anomalous quantum Hall effects, fine structure constant defined optical transmission, and so on [2]. Owing to the two-dimensional nature of the collective excitations, plasmons excited in graphene are confined much more strongly than those in conventional noble metals. One of the most important advantages of graphene would be the tunability plasmons, as the carrier densities can be easily controlled by electrical gating and doping. Consequently, graphene can be applied as terahertz metamaterial and it can be tuned conveniently even for an encapsulated device. On the other hand, graphene can help to tune the surface plasmons in conventional metals, such as Au, which makes it promising plasmonic materials. Refs. [3–7] focus on the recent progress of graphene plasmonics and its technological applications. A plasmon is a collective mode of a charge–density oscillation in the fee-carrier system, which is present both in classical and quantum plasmas. Studying the collective plasmon excitation in the electron gas has been among the very first theoretical quantum mechanical many-body problems studied in solid-state physics. The collective plasmon modes of monolayer graphene have been extensively studied theoretically [8–10] and experimentally [11–13] and are obtained by the zeros of the corresponding frequency and wave vector dependent dynamical dielectric function. The long-wavelength plasma oscillations are essentially fixed by the particle number conservation, and can be calculated using the random-phase approximation. The plasma dispersion frequency shows a $\boldsymbol{q^{1/2}}$ behavior and it is nonclassical (it depends explicitly on $\hbar$), this explicit quantum nature of long-wavelength graphene plasmon is a direct manifestation of its linear Dirac-like energy-momentum dependence, which has no classical analogy.

Based on monolayer graphene, novel double-layer structures have been recently realized experimentally [14,15] where massless fermions of two separate layers are coupled only through many-body Coulomb interactions. It is known [16,17], that when two graphene layers are put in close proximity with an oxide or semiconductor between them to prevent interlayer tunneling, the two-dimensional plasmon are coupled by the interlayer Coulomb interaction leading to the formation of two branches of longitudinal collective excitation spectra called the optical plasmon $\omega(q) \sim q^{1/2}$

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http://dx.doi.org/10.1016/j.ssc.2015.03.021
0038-1098/

and the acoustic plasmon with $\omega(q)\sim q$ where the density fluctuation in each component oscillates in-phase (optical plasmon) and out-of-phase (acoustic plasmon), respectively, relative to each other. These collective modes of the double-layer structures, which have been directly compared with the conventional double-layer two-dimensional electron gas (2DEG) [18], play important roles in the many body properties such as screening and drag [18,21].

In addition to the collective modes of two parallel two-dimensional graphene layers, special attention has been addressed on the double-layer system considering their plasmon modes for doped (extrinsic) [22,23] or undoped (intrinsic) double layers [24] at finite temperature.

Recently, particular interest has been paid to investigated plasmons and Coulomb drag in hybrid double-layer systems composed by a doped graphene sheet deposited on the surface of the semiconductor in close proximity to the 2DEG, long range Coulomb interactions between massive electrons and massless Dirac fermions lead to a new set of optical and acoustic intra-subband plasmons [25]. In particular, plasmons excitations of a system of coupled relativistic and nonrelativistic two-dimensional electron gas was considered by Balram et al. [26]. They found that the strength of the interaction between different charge carriers (that is, tunneling between graphene and 2DEG), play a significant role in determining the number of plasmon modes as well as their dispersions under certain parameters regimes. Such coexistence Dirac/Schrodinger hybrid electron systems have been directly experimentally observed [27,28] and they open a new research opportunities for fundamental studies of electron–electron interactions effects in two spatial dimensions.

It has been shown that the surface plasmons in graphene can be significant influenced by many-particle effects involving interactions between electrons and plasmons (plasmarons). A deep understanding of the coupling between charge carriers and plasmons in graphene is highly desirable because of large potential of this material in the context of plasmonics [3]. Graphene on metals is of interest as a route to synthesizing high quality graphene and for electrical contacts to devices. Graphene–metal systems can be roughly classified into two different of film and substrate binding i.e., weak or strong hybridization between graphene π and metal d bands [29, 30]. The coupling between plasmons in graphene and electron gas in metal-like substrate were investigated both, numerically [31] and theoretically [32,33].

In this article, we investigate the role of metallic-like substrates on the collective excitations of double layer two-dimensional electron systems. We concentrate on coupled system of two-dimensional Dirac fermions and 2DEG confined in a quantum-well at $T=0$ K, tunneling between carrier in different layers has been neglected. Plasmon modes in the hybrid double-layer system are calculated within the self-consistent-field linear approximation taking into account the interaction with the substrate. The interaction between the double-layer two-dimensional electron system and the substrate is discussed by replacing the dielectric constant of the substrate by a frequency dependent dielectric function.

2. Theoretical model

Firstly, we study the coupling between the two-dimensional double layer graphene system and the substrate. The model system under consideration corresponding to two graphene electron layers separated a distance d is shown in Fig. 1. The graphene electron layers system occupy a half-space $z > -\Delta$, of background dielectric constant ε_s. The substrate with dielectric constant ε_0 occupies the space $z < -\Delta$.

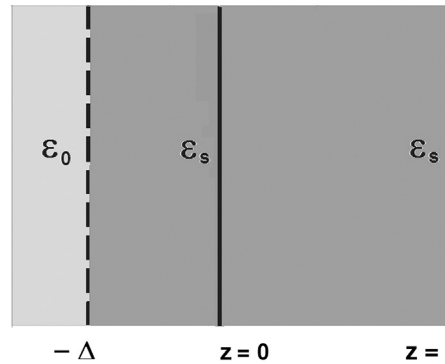

Fig. 1. A double-layer electronic system separated by a distance d, embedded in a dielectric environment with dielectric constant ε_s. A substrate with dielectric constant ε_0 occupies the space to the left from the first electron layer at $z=-\Delta$.

Within the self-consistent-field linear approximation theory (SCF) and assuming the relaxation time be infinite, each electron is assumed to move in the self-consistent field arising from the external field plus the induced field of all the electrons, then the electron density in the nth ($n=0,1$) graphene electron layer, $\rho_n(q,\omega)$ is given by

$$\rho_n(q,\omega)=\sum_m V_{n,m}(q)\Pi_m(q,\omega)\rho_m(q,\omega)+\Pi_n(q,\omega)\phi_n^{ext}(q,\omega) \tag{1}$$

where

$$V_{n,m}(q)=v_q\left[e^{-q|n-m|d}+\alpha e^{-(n+m)d}\right] \tag{2}$$

is the interlayer Coulomb interaction and the second term proportional to

$$\alpha=\frac{\varepsilon_s-\varepsilon_0}{\varepsilon_s+\varepsilon_0}e^{-2\Delta q} \tag{3}$$

gives the modified Coulomb interaction between the two Dirac electron layers due to the image charge and $\Pi_n(q,\omega)$ is the two-dimensional polarizability for layer n calculated in Refs. [8,9], $\phi_n^{ext}(q,\omega)$ is the external potential, and $v_q=2\pi e^2/\varepsilon_s q$ represents the two-dimensional Coulomb electron interaction.

In order to study the collective excitation spectrum, it is convenient to write Eq. (1) for zero external potential and considering that charge fluctuation $\rho_n(q,\omega)\neq 0$ in each layer, the plasmon dispersion of the coupled, spatially-separated two-dimensional graphene layers are obtained by the zeros of the dielectric constant

$$D(q,\omega)=[1-v_q(1+\alpha)\Pi_1(q,\omega)][1-v_q(1+\alpha e^{-2qd})\Pi_2(q,\omega)]-v_q^2(1+\alpha)^2e^{-2qd}\Pi_1(q,\omega)\Pi_2(q,\omega) \tag{4}$$

The collective modes occur between the intraband and interband single particle excitations where $\Pi_n(q,\omega)$ is real and positive and a decreasing function of frequency [8,9]. It has been demonstrated that the two-component plasma has two branches of longitudinal oscillation spectrum which are solutions of Eq. (4). In the higher frequency branch, the two carriers oscillate in phase with the long-wavelength limit at the square root, while in the lower branch the carriers oscillate out of phase, exhibiting at long-wavelength a linear dispersion.

In order to obtain the expression for the acoustic plasmon oscillations, we proceed as Santoro and Giuliani [34]. We first introduce for $q\sim 0$ the power expansion

$$\omega(q)=c_1q+c_2q^2+c_3q^3+\cdots \tag{5}$$

for the plasmon dispersion relation and define a function

$$F(q)=D(q,c_1q+c_2q+c_3q+\cdots) \tag{6}$$

where D is defined in Eq. (4). For $q\sim 0$, $F(q)$ can in turn be written