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Plasmon dispersion and damping in double-layer electron systems

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Abstract

We use dynamical local-field corrections to study the plasmon dispersion and damping in double-layer electron systems. The wave vector and frequency-dependent local-fields describing the exchange-correlation effects are obtained within the quantum version of self-consistent field approach. The calculated plasmon dispersions are modified by the dynamic local-fields at intermediate wave vectors (i.e. $q \sim k_F$). The plasmons are damped outside the single-particle excitation region. © 2000 Elsevier Science Ltd. All rights reserved.

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Models of electron gas in various low-dimensional structures are of major current interest; because of the advances in fabrication techniques electron systems confined in two-dimensional (2D) or quasi-one-dimensional (Q1D) geometries are readily achieved. In particular, Coulomb coupled electron systems in the form of double-layer structures provide a useful model to study the many-body effects in double quantum-wells when the barrier separating the wells is large enough to prevent tunneling. There is a wealth of interesting phenomena (see for instance, Ref. [1]) stemming from the interlayer Coulomb interactions, such as the appearance of new quantum Hall states when a strong perpendicular magnetic field is applied, the occurrence of Wigner crystallization at experimentally accessible electron densities, and frictional drag effect influencing the transport properties.

In this work we calculate the plasmon dispersion and damping in double-layer electron systems using a theoretical approach that includes dynamical correlations between interacting electrons. Our motivation comes from a number of recent experiments on double quantum-well structures [2–7]. In the Raman scattering experiments the dispersion and damping of the plasmon modes are directly observed. The Coulomb drag measurements [7] assess the role of plasmons indirectly through the temperature dependence of interlayer resistivity. In the analysis of these experimental results it is stated that the dynamic correlation effects must be included to explain the observed discrepancies between the existing theories. Our calculations should be useful as an attempt to understand the damping properties of the plasmon modes in these systems.

The importance of dynamic correlation effects in describing the many-body effects in an interacting system of electrons has been recognized in a number of other recent publications as well [8–10]. The theoretical efforts to incorporate the dynamic correlations have utilized diagrammatic perturbation theory at various levels of sophistication. The observed Raman scattering intensity spectrum of semiconducting structures has contributions from the collective excitations (plasmons), and from the single- and multi-pair excitations. We employ the self-consistent field method of Singwi et al. [11,12] to calculate the dynamic correlation effects. Our non-perturbative approach treats the dynamics of the Pauli hole around each electron; thus, the multi-pair excitations are ignored. As we show in our results the plasmon modes are significantly affected by the dynamic correlations at intermediate wave vectors.

In the following, we first describe the double-layer electron gas model and briefly explain our theoretical approach to calculate the plasmon dispersion and damping.

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We next present our results including the dynamic correlation effects in comparison to the static theories. We discuss our results in the light of experimental observations and conclude with a brief summary.

We consider two parallel layers of 2D electron gas interacting via the long-range Coulomb potential, in the presence of a rigid positive background for charge neutrality. Neglecting the finite widths of quantum wells, the contribution of the higher subbands, and tunneling effects between the layers, the Coulomb interactions (in Fourier space) between electrons within the same layer and between different layers are given by $V_{11}(q) = 2\pi e^2/\epsilon_0 q$ and $V_{12}(q) = (2\pi e^2/\epsilon_0 q)e^{-qd}$, respectively, where ϵ_0 is the background dielectric constant. We further assume that the density of electrons on both the layers is the same, in which case the system is characterized by the dimensionless density parameter $r_s = 1/\sqrt{\pi n a_B^{*}}$, where $a_B^{*} = \hbar^2\epsilon_0/e^2 m^{*}$ is the effective Bohr radius defined in terms of ϵ_0 and electron effective mass m^{*}. In the numerical calculations below we shall concentrate on the GaAs systems for which experiments are performed.

The dielectric properties of the electron system are typically determined by the random-phase approximation (RPA), which is valid at high densities (i.e. $r_s \ll 1$). As the density of the electrons in individual layers is decreased the many-body effects become non-negligible. A convenient way of taking the exchange-correlation effects beyond the RPA into account has been provided by the self-consistent scheme of Singwi et al. [11,12] (the so-called STLS approximation). Ground-state properties, various correlation functions, and spectrum of the collective excitations of a double-layer electron gas have been studied [13,14] within the static STLS. Here we use the quantum version of the STLS approach (qSTLS), generalizing the previously reported [15–19] formalism and applications to a two-component system. In the dynamical theory the intra- and interlayer local-field factors ($G_{11}(q,\omega)$ and $G_{12}(q,\omega)$, respectively) describe the Pauli and Coulomb holes around each electron within the system. The qSTLS theory considers the hierarchy of coupled equations satisfied by the Wigner distribution functions and truncates them with the assumption that the two-particle Wigner distribution function is written as a product of one-particle distribution functions and the pair correlation function. The details of the derivation of self-consistent equations within the qSTLS scheme have been given in several places [15–19]. We note that the specific assumptions underlying the qSTLS approach amount to taking the frequency-dependent correlation effects at the level of Pauli hole dynamics only.

We performed self-consistent calculations of the ground-state correlation functions and the wave vector and frequency-dependent local-field factors in a double-layer electron system for a range of values of the parameters r_s and d. In what follows, we make use of the dynamic local-field factors to calculate the dispersion and damping properties of the collective excitations. Previous calculations [13,14] mostly employed static local-field factors to account for the many-body correlations; thus we will be in a position to compare and assess the importance of dynamic correlations within the same theoretical framework. The calculated dynamic local-field factors generally have oscillatory dependence on ω in both the real and imaginary parts. The static local-field factors in contrast are purely real. Thus, we expect modifications in the damping properties of plasmons as well as their dispersions.

The dispersion of the collective excitations are obtained by solving for the zeros of the dielectric function

$$D(q,\omega) = [1 - \phi_{11}(q,\omega)\chi_0(q,\omega)]^2 - [\phi_{12}(q,\omega)\chi_0(q,\omega)]^2, \tag{1}$$

where the effective intra- and interlayer interactions are given by $\phi_{11} = V_{11}(q)[1 - G_{11}(q,\omega)]$ and $\phi_{12} = V_{12}(q)\times[1 - G_{12}(q,\omega)]$, respectively. Note that ϕ_{11} and ϕ_{12} are frequency dependent within the present approximation in contrast to the RPA and static STLS. $\chi_0(q,\omega)$ is the density–density response function of a non-interacting 2D electron gas. The solution of $D(q,\omega) = 0$ yields two plasmon modes. In the long-wavelength limit and within the RPA these plasmons behave as

$$\omega_{op}(q) \simeq \sqrt{q v_F k_{TF}}, \qquad \omega_{ap}(q) \simeq q v_F \frac{1 + dk_{TF}}{\sqrt{1 + 2 v_F k_{TF}}}, \tag{2}$$

where $k_{TF} = 2/a_B^{*}$ is the Thomas–Fermi wave vector and v_F is the Fermi velocity. The higher-energy mode with $\sim\sqrt{q}$ behavior is termed the optical plasmon, whereas the lower-energy mode with $\sim q$ behavior is called the acoustic plasmon.

In Fig. 1 we display the plasmon dispersions in a double-layer electron system at $r_s = 2$ and $d = 200$ Å. As would be expected, the results of the qSTLS calculation are rather different from those of the RPA. The exchange-correlation

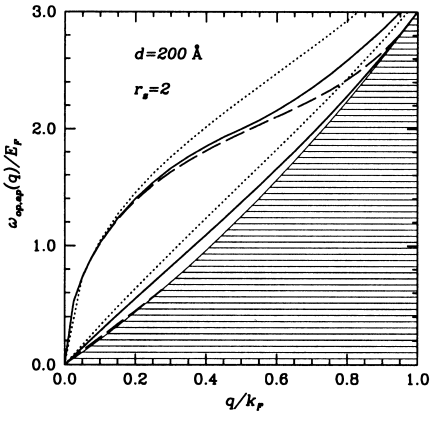

Fig. 1. The plasmon dispersions for a double-layer system of electrons at $r_s = 2$ and $d = 200$ Å. The acoustic (lower curves) and optical (upper curves) plasmons are depicted for the RPA (dotted lines), static STLS (dashed lines), and qSTLS (solid lines). The shaded area indicates the single-particle excitation region.

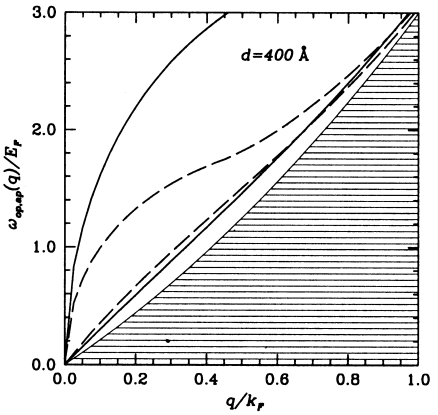

Fig. 2. The plasmon dispersions within the dynamic STLS for a double-layer electron system ($d = 200$ Å) at $r_s = 2$ (dashed lines) and $r_s = 5$ (solid lines). The upper and lower curves are for optical and acoustic plasmons, respectively, and the shaded area indicates the single-particle excitation region.

effects push the plasmons down to lower energies. The qSTLS plasmon dispersions also differ from the static STLS. Similar conclusions have also been reached in single-layer electron systems [18,19]. The most notable result here is that dynamic local-fields significantly modify the plasmon dispersions at intermediate wave vectors. For instance, within the static STLS the acoustic plasmon mode is very close to the edge of the single-particle excitation region and it ceases to exist for $q \gtrsim 0.25k_F$ at $r_s = 2$ (cf. Fig. 1). On the other hand, the dynamical correlations render the existence of acoustic plasmons in a larger range of q values. In the recent experiment of Bhatti et al. [4,5] and Kainth et al. [6] plasmon dispersions were determined out to $q \sim 0.15k_F$, but if access to higher wave vector values were possible, our predictions could be tested.

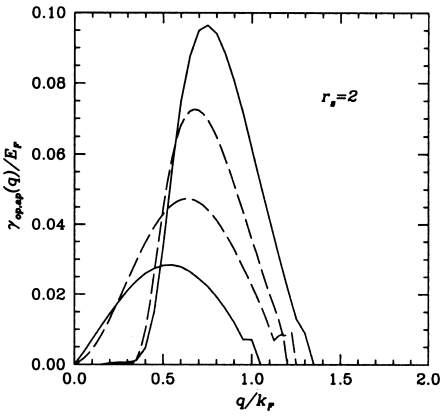

Fig. 3. The damping of acoustic (upper curves) and optical (lower curves) plasmons in a double-layer electron system at $r_s = 2$. The solid and dashed lines indicate layer-separation distances $d =$ 200 Å and $d = 400$ Å, respectively.

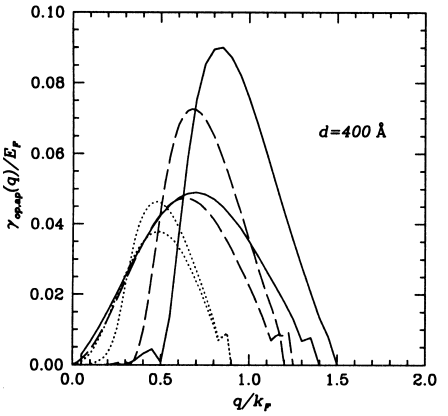

Fig. 4. The damping of optical (lower curves) and acoustic (upper curves) plasmons for a double-layer electron system with $d =$ 400 Å. The dotted, dashed, and solid lines indicate $r_s = 1$, $r_s = 2$, and $r_s = 3$, respectively.

To discuss the exchange-correlation effects further, we show in Fig. 2 the dispersion of optical and acoustic plasmons at $d = 400$ Å and at two different densities characterized by $r_s = 2$ and $r_s = 5$. It appears that the optical plasmons are affected very significantly, whereas the acoustic plasmons are largely unaffected by the dynamic correlations. It is interesting to note that the dynamical treatment of the correlation effects within the qSTLS theory causes the plasmon dispersion to lie between those in RPA and static STLS.

The damping of the collective modes are calculated from the expression

$$\gamma_{\mathrm{op,ap}}(q) = \frac{\mathrm{Im}\, D(q, \omega_{\mathrm{op,ap}}(q))}{[\partial \mathrm{Re}\, D(q,\omega)/\partial\omega]_{\omega_{\mathrm{op,ap}}(q)}}, \tag{3}$$

where $\omega_{\mathrm{op,ap}}(q)$ are the previously determined roots of $\mathrm{Re}\, D(q, \omega) = 0$. It is interesting to note that in the RPA and static STLS where $V_{ij}(q)$ and $V_{ij}(q)[1 - G_{ij}(q)]$ are used, respectively, $\mathrm{Im}\, D(q, \omega)$ is determined solely by $\mathrm{Im}\, \chi_0(q, \omega)$; thus the modes are Landau damped only within the single-particle excitation region. In the dynamic STLS, the frequency-dependent local-field factors $G_{ij}(q, \omega)$ are instrumental in modifying $\mathrm{Im}\, D(q, \omega)$, and we obtain finite damping even at zero temperature. Fig. 3 shows the damping of optical (lower curves) and acoustic (upper curves) plasmons for a double-layer system at $r_s = 2$ and two different layer-separation distances $d = 200$ Å (solid lines) and $d = 400$ Å (dashed lines). We observe that the acoustic plasmon damping is larger than the optical plasmon, the modes are damped outside the single-particle excitation region, and as the layer separation increases $\gamma(q)$ for both the modes approach each other. All these features are in qualitative agreement with the experimental findings.

In Fig. 4 we explore the dependence of $\gamma(q)$ for optical and acoustic plasmons at different densities. At fixed layer

separation ($d = 400$ Å), as we decrease the density of electrons in each layer, the damping of the modes increases in magnitude and in the range of q values. The recent experiments of Bhatti et al. [4,5] and Kainth et al. [6] on double quantum-well systems were performed at finite temperature and a systematic study of the damping of acoustic plasmons was presented. We cannot compare our results with these experiments since our calculations were carried out at $T = 0$. The temperature dependence of the dynamic local-field factors are largely unexplored in the literature. However, if we assume that $G_{ij}(q, \omega)$s depend weakly on T, our results of Figs. 3 and 4 will be qualitatively broadened by the temperature effects coming from the T-dependence of $\chi(q, \omega)$. Although further detailed work needs to be done in this direction, it is clear that an approach taking the dynamic correlations into account might be useful in understanding the experimental results.

In summary, we have calculated the plasmon dispersion and damping in double-layer electron systems within the quantum (dynamic) version of the STLS approximation scheme. We have found that the dispersion of plasmon excitations are noticeably affected by the dynamical correlations at intermediate wave vectors. The dynamical correlations also influence the damping properties of acoustic and optical plasmons for wave vectors outside the single-particle excitation region. Our calculations should provide a good starting point to understand the experimental results. It would be interesting to extend our calculations to include the effects of finite temperature to confront recent experimental results. The methodology and analysis given here can be applied also to double-layer electron–hole systems for which more interesting results are expected because of the different single-particle excitation regions for each species.

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