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Plasmon-phonon coupling in a two-dimensional electron gas

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The collective excitation spectrum of a two-dimensional electron gas interacting with the LO-phonon mode of the host lattice is calculated. The electronic polarization is treated within the random-phase approximation. Numerical results for the energy-loss function and the oscillator strength of the plasmon and phonon peaks are presented for different values of the electron density in a GaAs heterostructure.

I. INTRODUCTION

In this paper we present a calculation of the collective excitation spectrum and the electron energy-loss function of a two-dimensional electron gas (2DEG) embedded in a polar semiconductor. The frequency dependence of the dielectric function of the medium is explicitly taken into account. The electron gas is treated within the random-phase approximation (RPA).

The system in mind is the 2DEG in a heterostructure made of a polar semiconductor (e.g., GaAs-$Al_{1-x}Ga_xAs$ heterostructure). In those systems the electron density can be made sufficiently high such that plasmon-phonon resonant coupling becomes important. The aim of the present paper is to investigate the effect of this coupling on the plasmon and phonon branch. The simplifying assumption of an infinitely thin 2DEG layer will be made. It is expected that this assumption will not influence the qualitative findings of the present paper. We will limit ourselves to the situation with no magnetic field applied and at zero temperature.

Recently, many studies on the collective excitations in quasi-two-dimensional systems have appeared in the literature.[1-6] In those calculations essentially two different approaches were used: (i) a hydrodynamical model for the electron gas,[2,3] and (ii) a self-consistent-field (SCF)[4-6] approach. The latter approach will yield the same results as found in the present study if the RPA approximation is used for the dielectric function of the electron gas. However, in the calculations of Refs. 4–6, further simplifying approximations were made on the RPA dielectric function such that analytic expressions for the excitation frequencies could be obtained for small wave vectors. Such simplifications will not be made in the present work and we will consider the full RPA expression for the 2DEG dielectric function, which implies that our results will be valid for all wave vectors.

II. DIELECTRIC FUNCTION OF THE 2D POLARON GAS

Consider a 2DEG embedded in a polar semiconductor (this system may be called a 2D polaron gas). The effect of the background is incorporated in the present calculation by assuming the following simplified form for the frequency-dependent dielectric function

$$\epsilon_b(\omega)=\epsilon_\infty(\omega^2-\omega_{LO}^2)/(\omega^2-\omega_{TO}^2)\ , \tag{1}$$

where ϵ_∞ is the high-frequency dielectric constant of the background and ω_{LO} and ω_{TO} are the LO- and TO-phonon frequencies of the polar semiconductor. In Ref. 7 it was shown that within RPA the polarizabilities are additive. Consequently, the total dielectric function is obtained by adding the contribution of the electron gas:

$$\epsilon(k,\omega)=\epsilon_b(\omega)-V(k)\chi(k,\omega)\ , \tag{2}$$

where $V(k)=2\pi e^2/k$ is the Fourier transform of the unscreened 2D electron-electron interaction potential and $\chi(k,\omega)$ is the polarization of the electron gas.

The electronic contribution to the dielectric function is taken within RPA approximation, which gives[8]

$$\mathrm{Re}[-V(k)\chi(k,\omega)]=\frac{2\pi\alpha_D}{k^2/k_F^2}[k/k_F+\mathrm{sgn}(\nu_+)\theta(\nu_+^2-1)(\nu_+^2-1)^{1/2}+\mathrm{sgn}(\nu_-)\theta(\nu_-^2-1)(\nu_-^2-1)^{1/2}]\ , \tag{3a}$$

$$\mathrm{Im}[-V(k)\chi(k,\omega)]=\frac{2\pi\alpha_D}{k^2/k_F^2}[\theta(1-\nu_+^2)(1-\nu_+^2)^{1/2}-\theta(1-\nu_-^2)(1-\nu_-^2)^{1/2}]\ , \tag{3b}$$

where

$$\nu_\pm=\pm\frac{m_b}{\hbar k_F}\frac{\omega}{k}-\frac{k}{2k_F},\quad \alpha_D=\frac{r_s}{\sqrt{2\pi}},\quad r_s=\frac{m_b e^2/\epsilon_\infty}{\hbar^2\sqrt{\pi n_e}}\ ,$$

with k_F the Fermi wave vector, n_e the electron density and $\theta(x)=0,\ (x<0),\ 1,\ (x>0)$.

In the following units are used such that k is expressed in units of k_F and ω (also ω_{LO} and ω_{TO}) in units of $2E_F/\hbar$, where $E_F=\hbar^2k_F^2/2m_b$ is the Fermi energy.

The different collective excitation modes are determined from the zeros of the longitudinal dielectric function:

$$\mathrm{Re}\epsilon(k,\omega)=0 \ . \tag{4}$$

Undamped modes are found when $\mathrm{Im}\epsilon(k,\omega)=0$ for those frequencies which satisfy Eq. (4).

In the long-wavelength limit (i.e., $k \ll k_F$) Eq. (4) results in the following three modes:

$$\omega_+=\omega_{LO}+\frac{\omega_{LO}^2-\omega_{TO}^2}{\omega_{LO}^3}\sqrt{2}r_s\frac{k}{4} \ , \tag{5a}$$

$$\omega_-^{(1)}=\frac{\omega_{TO}}{\omega_{LO}}\left(\frac{r_sk}{2}\right)^{1/2} \ , \tag{5b}$$

$$\omega_-^{(2)}=k-\frac{k^2}{2} \ , \tag{5c}$$

where ω_+ and $\omega_-^{(1)}$ are undamped modes. ω_+ is a phonon-like mode, while $\omega_-^{(1)}$ is a plasmon mode which is softened by the medium. The acoustic mode $\omega_-^{(2)}$ is located in the electron-hole excitation region and is strongly damped. For large k (i.e., $k \gg k_F$), only one mode is found:

$$\omega_+=\omega_{LO}-\frac{\omega_{LO}^2-\omega_{TO}^2}{\omega_{LO}}\frac{\sqrt{2}r_s}{k^3} \ , \tag{6}$$

which is damped and which approaches the LO-phonon frequency asymptotically from below.

III. NUMERICAL RESULTS AND DISCUSSION

In Fig. 1 we show the numerical results for the zeros of the real part of the dielectric function for the electron densities $n_e=10^{11}$ cm^{-2} [Fig. 1(a)] and $n_e=10^{12}$ cm^{-2} [Fig. 1(b)]. The physical parameters $\omega_{TO}=5.14\times10^{13}$ Hz, $\omega_{LO}=5.58\times10^{13}$ Hz, $\epsilon_\infty=10.9$, and $m_b/m_e=0.0657$ correspond to the material GaAs. For $n_e=10^{11}$ cm^{-2} the Fermi wave vector is $k_F=7.9\times10^5$ cm^{-1} and the unit of frequency is $2E_F/\hbar=1.1\times10^{13}$ Hz, while for $n_e=10^{12}$ cm^{-2} we have $k_F=1.8\times10^6$ cm^{-1} and $2E_F/\hbar=1.1\times10^{14}$ Hz.

It is interesting to compare the present results with the collective excitations of a 3D polaron gas (see Ref. 7). In the 3D case, the frequency of the mode $\omega_-^{(1)}$ does not approach zero when $k\to0$, while in 2D $\omega_-^{(1)}$ does tend to zero in this limit. The reason is that the 3D unperturbed plasmon frequency is a constant, different from zero, for $k=0$, while the 2D unperturbed plasmon frequency behaves like $k^{1/2}$ for $k\to0$. The mode ω_+ is also different in 3D for $k\to0$. In 2D ω_+ always approaches the optical phonon frequency ω_{LO} for $k\to0$, while in 3D ω_+ approaches a value which is larger than ω_{LO}. In Figs. 1(a) and 1(b), it is apparent that the branch ω_- is always below the unperturbed plasmon frequency [heavy dashed curve in Figs. 1(a) and 1(b)]. The unperturbed plasmon branch ends at the point $(\omega,k)=(2.64,1.51)$ for $n_e=10^{11}$ cm^{-2} and (1.11, 0.80) for $n_e=10^{12}$ cm^{-2}. The branch ω_- enters the continuum at $(\omega,k)=(2.25,1.34)$ for $n_e=10^{11}$ cm^{-2} and (0.44, 0.38) for $n_e=10^{12}$ cm^{-2}. For the upper branch ω_+ one finds for penetration in the continuum the values $(\omega,k)=(5.28,2.4)$ for the density $n_e=10^{11}$ cm^{-2} and (1.13,0.81) for $n_e=10^{12}$ cm^{-2}.

In Refs. 2–5, only two excitation modes were found for zero magnetic field. This is different from the present investigation, where for small wave vectors three modes are present, while for large wave vectors only one excitation mode is found. The differences originate from the approximations made in Refs. 2–5 in the electronic contribution to the dielectric function; namely, the part with $\mathrm{Im}\epsilon(k,\omega)\neq0$ was neglected. As a consequence the branch of collective

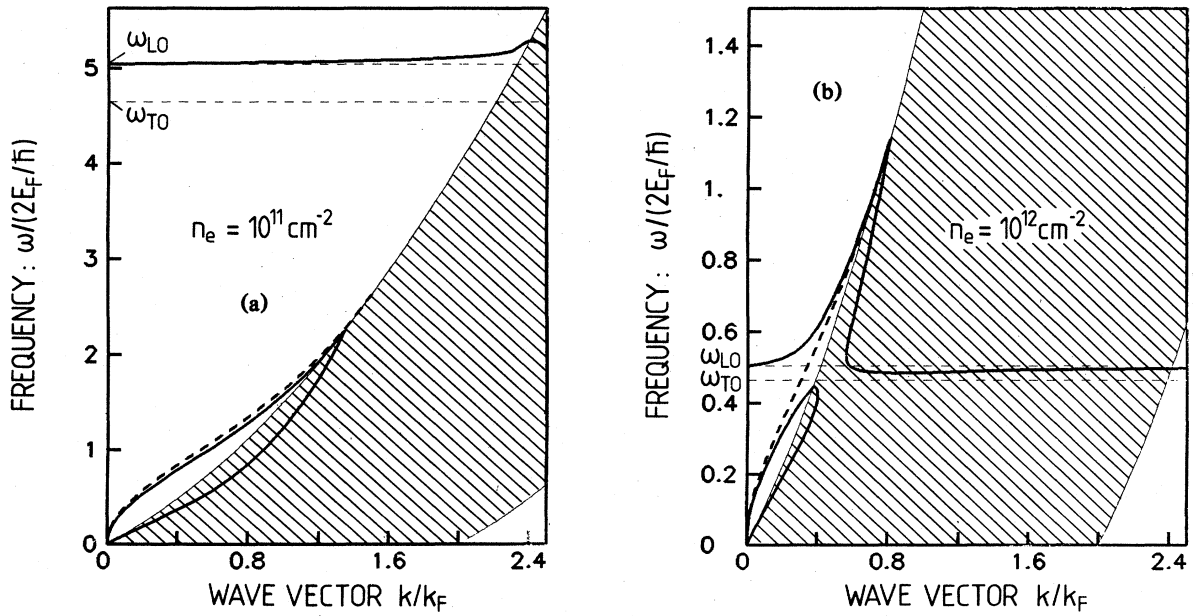

FIG. 1. The collective excitations of the 2DEG in GaAs heterostructure (heavy solid curves) are shown as a function of the wave vector k. The plasmon branch for the unperturbed 2DEG is given by the heavy dashed curve. The shaded area corresponds to the pair-excitation region ("Landau damping"). The electron density is (a) $n_e=10^{11}$ cm^{-2} and (b) $n_e=10^{12}$ cm^{-2}.

excitations in the electron-hole excitation region was not incorporated. Although this branch is damped, it still exhibits a peak structure in the energy-loss function as shown below.

The electron energy-loss function is defined as

$$\mathrm{Im}\frac{-1}{\epsilon(k,\omega)}=\frac{\mathrm{Im}\epsilon(k,\omega)}{[\mathrm{Re}\epsilon(k,\omega)^2+\mathrm{Im}\epsilon(k,\omega)]^2} \quad . \tag{7}$$

In Figs. 2(a) and 2(b), this energy-loss function is plotted as a function of the frequency for different values of the wave vector for the electron densities $n_e=10^{11}$ cm^{-2} and $n_e=10^{12}$ cm^{-2}, respectively. When both $\mathrm{Im}\epsilon(k,\omega)$ and $\mathrm{Re}\epsilon(k,\omega)$ vanish, the energy-loss function is a delta function with oscillator strength

$$\frac{\pi}{|(\partial/\partial\omega)\mathrm{Re}\epsilon(k,\omega)|_{\omega=\omega_l(k)}} \quad , \tag{8}$$

where $\omega_l(k)=\omega_+(k)$ or $\omega_l(k)=\omega_-(k)$. The oscillator strength of the delta peaks in Figs. 2(a) and 2(b) is indicated by the numbers above these peaks.

In Figs. 3(a) and 3(b) the oscillator strength of the different delta peaks [branch $\omega_-^{(1)}$ (dashed curve) and branch ω_+ (dashed-dotted curve)] and the continuum (solid curve) is plotted for the electron densities $n_e=10^{11}$ cm^{-2} and $n_e=10^{12}$ cm^{-2}, respectively. From Figs. 3(a) and 3(b) we observe that in the long-wavelength limit almost all oscillator strength is contained in the delta-function plasmonlike peak ω_- [dashed line in Figs. 3(a) and 3(b)]. The LO-phonon-type peak ω_+ [dashed-dotted line in Figs. 3(a) and 3(b)] has its maximum oscillator strength outside the continuum for intermediate values of k. The continuum [solid curve in Figs. 3(a) and 3(b)] gains importance with increasing wave vector. Discontinuities in the oscillator strength are found for those k values at which a delta peak disappears in the continuum.

In conclusion, we showed that especially for large electron densities ($n_e\sim10^{12}$ cm^{-2} in GaAs heterostructures) the plasmon-phonon coupling alters the 2D unperturbed plasmon excitation spectrum considerably. Two main effects are found: (i) a shift in the phonon and the plasmon frequency (for $\omega_p<\omega_{TO}$ the plasmon frequency is lowered, while for $\omega_p>\omega_{TO}$ the plasmon frequency is enhanced due to the plasmon-phonon coupling) and (ii) for sufficiently large electron densities ($n_e\sim10^{12}$ cm^{-2}) there is a splitting of the plasmon branch and the LO branch when ω_p reaches ω_{TO}.

Experimentally, the effect of the plasmon-phonon coupling can be detected in different ways. The $k\approx0$ mode (i.e., wave vectors small compared to the size of the first Brillouin zone) is detected in one-photon experiments like, e.g., reflectivity and transmission. In these experiments the behavior given by Eqs. (5a)–(5c) is expected. In other physical situations like transport, screening, inelastic scattering, etc., higher values of the wave vector are relevant, and in these cases the effects of the plasmon-phonon coupling is

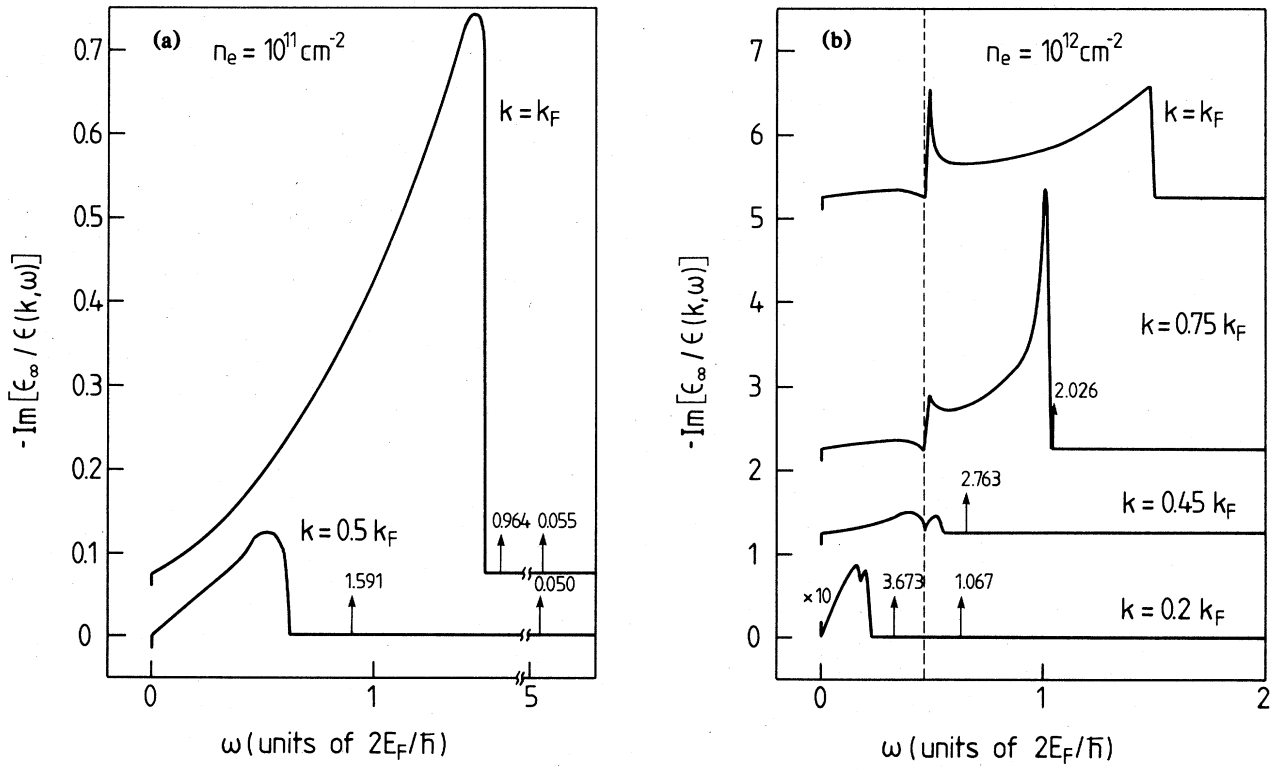

FIG. 2. The energy-loss function as a function of frequency for different values of the wave vector k. The arrows correspond to delta peaks with an oscillator strength indicated by the number above the arrows. The electron density is (a) $n_e=10^{11}$ cm^{-2} and (b) $n_e=10^{12}$ cm^{-2}. The dashed line in (b) indicates the position of the TO frequency.

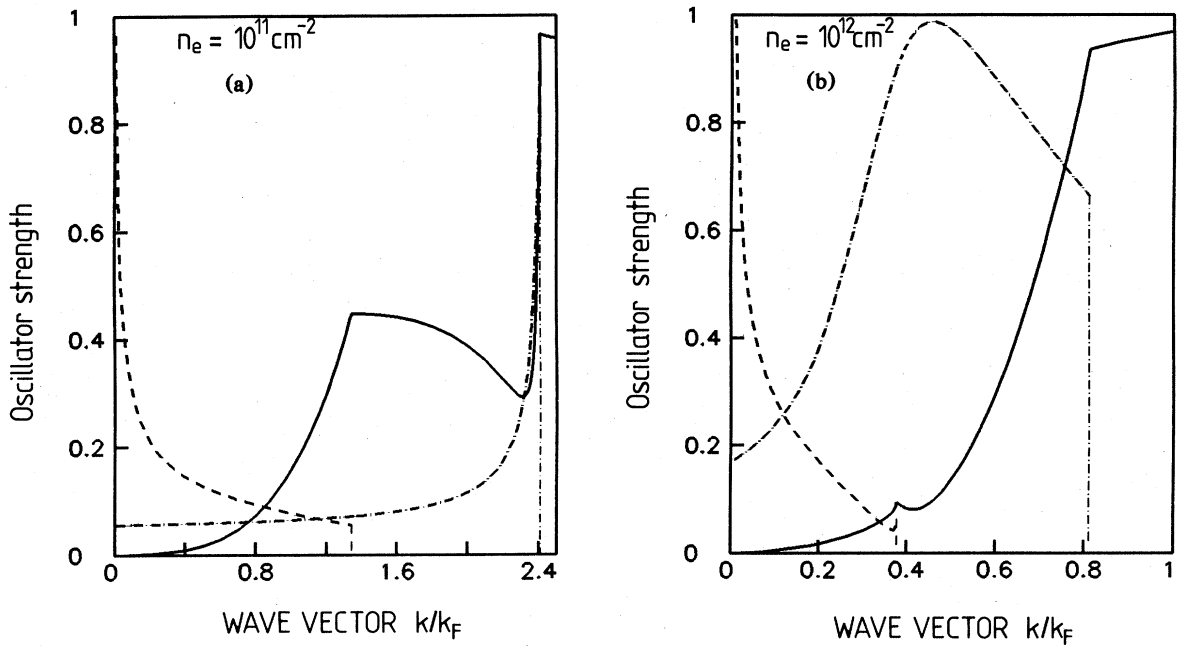

FIG. 3. The oscillator strength of the $\omega_{-}^{(1)}$ (dashed curve) and the ω_{+} (dashed-dotted curve) excitations. The portion of the oscillator strength contained in the continuum is given by the solid curve. The electron density is (a) $n_e = 10^{11}$ cm^{-2} and (b) $n_e = 10^{12}$ cm^{-2}.

more important and should be observed more clearly. The collective excitation spectrum of the coupled plasmon-LO-phonon system can be measured by inelastic light scattering (Raman scattering, as was done in Ref. 9 for the 3D plasmon-phonon system in GaAs) or inelastic scattering with low-energy electrons. For GaAs heterostructures the latter approach may not be useful, because of the small penetration depth (~ 30 Å) of the electrons.

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[1]T. N. Theis, Surf. Sci. **98**, 515 (1980).
[2]J. T.Gersten, Surf. Sci. **92**, 579 (1980); **97**, 206 (1980).
[3]A. Puri and W. L. Schaich, Phys. Rev. B **31**, 974 (1985).
[4]S. Das Sarma, Phys. Rev. B **29**, 2334 (1984).
[5]S. Das Sarma, and J. J. Quinn, Phys. Rev. B **25**, 7603 (1982).
[6]S. Das Sarma, Phys. Rev. B **28**, 2240 (1983).
[7]L. F. Lemmens and J. T. Devreese, Solid State Commun. **14**, 1339 (1974); L. F. Lemmens, F. Brosens, and J. T. Devreese, *ibid.* **17**, 337 (1975).
[8]F. Stern, Phys. Rev. Lett. **18**, 546 (1967).
[9]U. Nowak, W. Richter and G. Sachs, Phys. Status Solidi (b) **108**, 131 (1981).