Coupled plasmon–LO-phonon modes in $Ga_xIn_{1-x}As$ heterostructures

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The coupled plasmon–longitudinal-optical (LO)-phonon modes are calculated, within the random-phase approximation, for a two-dimensional electron gas imbedded in a polar semiconductor exhibiting two LO-phonon modes. Numerical results are given for the collective excitation spectrum and the energy-loss function and applied to $Ga_xIn_{1-x}As$ heterostructures.

I. INTRODUCTION

In a degenerate polar semiconductor the electric dipole moment associated with the longitudinal-optical phonons will couple with the electric field associated with the plasmons. In three-dimensional (3D) systems the effect of this coupling has been extensively studied with Raman scattering, infrared reflectivity measurements, electron-energy-loss spectroscopy (EELS), etc., on materials like GaAs (Refs. 1–7) and $Al_xGa_{1-x}As$.[8–11] More recently, with the advent of novel sample growth techniques it has become possible to make two-dimensional (2D) electron systems. Examples of such systems[12] are Si metal-oxide-semiconductor (MOS) transistors, $GaAs/Al_xGa_{1-x}As$ heterostructures and superlattices, and $Ga_xIn_{1-x}As$ heterostructures.

One of the fundamental differences between plasmons in 3D and 2D electron gases (EG) is that in a 3D electron gas the plasmon frequency attains a nonzero value in the long-wavelength limit: $\omega_p^2(3D)=n_e e^2/m\epsilon_\infty$ while in a 2D EG it approaches zero:[13] $\omega_p^2(2D)=(2\pi n_e e^2/m\epsilon_\infty)k$ as $k\to 0$ (n_e is the electron density, m the electron mass, and k the plasmon wave vector). In the long-wavelength limit the plasmon frequency can be taken as a constant in 3D (the plasmon spectrum has a gap), while in 2D systems one has a continuum of frequencies which extends to $\omega=0$. In a 3D system changing the electron density changes the plasmon frequency or the gap in the collective-excitation spectrum, while in 2D the change in frequency for $k\to 0$ alters the range of the spectrum of available plasmon frequencies.

Experimentally a large amount of information is available on spectroscopic intersubband excitations in quasi-two-dimensional semiconductor systems.[14] Less well studied are the intraband excitations[15,16] which probe the 2D EG in the plane in which the electrons are free. Plasmons in a single 2D EG have been studied using a grating-coupler technique.[14] In layered electron-gas structures (i.e., quantum wells) plasmon modes have been studied extensively both theoretically[17–19] and experimentally.[20,21] Different discrete plasmon modes are observed, which is a manifestation of the correlation of electronic motion in the different layers. In those experiments the low-energy part of the plasmon spectrum is investigated and plasmon-phonon coupling is of secondary importance.

In the present paper we are interested in another part of the spectrum where coupling to the optical phonons is important and changes the collective-excitation spectrum appreciably. For convenience we will limit ourselves to a single 2D layer. As far as we know, no direct experimental investigations have been performed in order to observe the plasmon-phonon coupling in a 2D EG. In contrast, in 3D systems several observations of this coupling have been made and they are well understood theoretically.[22–24]

There are some indirect experimental results which indicate plasmon-phonon coupling. Cyclotron-resonance experiments in $Ga_xIn_{1-x}As$ heterostructures reveals a *frequency-shifted polaron coupling*. Nicholas *et al.*[25] found that the coupling occurs at the TO-phonon frequencies, while theoretically one expects (at least in a one-electron picture) that only coupling with the LO-phonon modes should be possible.[26] Interaction with plasmon modes may result in a mixed plasmon-phonon mode with a frequency smaller than the LO-phonon frequency. Another possible mechanism has been put forward, namely the interaction of the surface optical-phonon modes; but these modes do not[25] seem to have the correct frequency. Plasmon-phonon coupling is also very important in electronic transport where this interaction modifies[27–29] the optical-phonon scattering rate (i.e., the probability for emitting an LO-phonon).

II. PLASMON-PHONON COUPLING

In what follows the longitudinal dielectric function $\epsilon(\mathbf{k},\omega)$ of the 2D many-electron gas imbedded in a polar semiconductor with two LO-phonon modes will be calculated within the random-phase approximation (RPA). In the region where $\mathrm{Im}\epsilon(\mathbf{k},\omega)=0$ the *collective excitation spectrum* is then given by the zeros of $\mathrm{Re}\epsilon(\mathbf{k},\omega)=0$. The latter condition gives the collective plasmon-phonon modes $\omega(k)$.

Within the RPA the polarizabilities are additive and consequently the total dielectric function is given by

$$\epsilon(\mathbf{k},\omega)=\epsilon_{\mathrm{ph}}(\omega)-V(k)\chi(\mathbf{k},\omega)\ , \tag{1}$$

with $\epsilon_{\mathrm{ph}}(\omega)$ the dielectric constant of the polar semiconductor, $V(k)=2\pi e^2/k$ is the Fourier transform of the

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unscreened 2D electron-electron interaction potential, and $\chi(\mathbf{k},\omega)$ is the polarizability of the electron gas which has been calculated within the RPA by Stern.[30] The nonzero width of the 2D EG layer is, in general, incorporated by averaging the Coulomb potential $V(k)$ over the electric subband wave function in the z direction which results in a renormalization $V(k)f(k,b)$, where $f(k,b)$ is a form factor[12] and b is a measure for the inverse width of the 2D layer, i.e., $f(k,b=\infty)=1$.

For the dielectric function of a polar semiconductor background with two LO-phonon modes we take the simplified form[31]

$$\epsilon_{\rm ph}(\omega)=\epsilon_\infty+(\epsilon'-\epsilon_\infty)\frac{\omega_{\rm TO}^2(\omega_{\rm TO}^2-\omega^2)}{(\omega_{\rm TO}^2-\omega^2)^2+\nu^2\omega^2}+(\epsilon_0-\epsilon')\frac{\omega_{\rm TO'}^2(\omega_{\rm TO'}^2-\omega^2)}{(\omega_{\rm TO'}^2-\omega^2)^2+\nu^2\omega^2}\ , \tag{2}$$

where ϵ' satisfies the generalized Lyddane-Sachs-Teller relation

$$\frac{\epsilon'}{\epsilon_\infty}=\frac{\omega_{\rm LO}^2}{\omega_{\rm TO}^2},\quad \frac{\epsilon_0}{\epsilon'}=\frac{\omega_{\rm LO'}^2}{\omega_{\rm TO'}^2}\ , \tag{3}$$

with $\omega_{\rm LO}$ ($\omega_{\rm TO}$)=233 (226) $\rm cm^{-1}$ the frequencies of the InAs-like LO-end TO-phonon modes and $\omega_{\rm LO'}$ ($\omega_{\rm TO'}$) =272(256) $\rm cm^{-1}$ the frequencies of the GaAs-like LO- and TO-phonon modes in the compound $Ga_xIn_{1-x}As$ where $x=0.47$ was taken. ν describes the phonon damping and is a phenomenological phonon-relaxation time. Inserting the static $\epsilon_0=13.77$ and the high-frequency $\epsilon_\infty=11.47$ dielectric constant into the Lyddane-Sachs-Teller relation gives $\epsilon'=12.95$. In writing Eq. (2) it was assumed that there is no influence of the interface, although there exists some evidence[31] that, under certain conditions, the interface may be important (for example, for thin quantum wells an appreciable influence from strongly polar interfaces may be observed). Applying relation (3) we obtain in the limit of no phonon damping (i.e., $\nu\to0$) the dielectric function

$$\frac{\epsilon_{\rm ph}(\omega)}{\epsilon_\infty}=1-\frac{\omega_{\rm TO}^2-\omega_{\rm LO}^2}{\omega_{\rm TO}^2-\omega^2}-\frac{\omega_{\rm LO}^2}{\omega_{\rm TO}^2}\frac{\omega_{\rm TO'}^2-\omega_{\rm LO'}^2}{\omega_{\rm TO'}^2-\omega^2}\ . \tag{4}$$

In the long-wavelength limit, which is most easily accessible experimentally, the behavior of the different collective excitations can be obtained analytically. In this limit the real part of the contribution of the 2D EG to the dielectric function is given by

$$\mathrm{Re}[V(k)\chi(k,\omega)]=\frac{2\pi e^2 n_e}{m}\left[\frac{k}{\omega^2}\right]+\cdots\ , \tag{5}$$

which, if inserted into Eq. (1), shows us that in the long-wavelength limit the plasmon frequency is altered to

$$\omega_p=\left[\frac{\omega_{\rm TO}}{\omega_{\rm LO}}\right]\left[\frac{\omega_{\rm TO'}}{\omega_{\rm LO'}}\right]\left[\frac{2\pi e^2 n_e}{\epsilon_\infty m}\right]^{1/2}k^{1/2} \tag{6}$$

For the $Ga_xIn_{1-x}As$ heterostructure this leads to a 10% reduction of the plasmon frequency (i.e., $\omega_{\rm TO}\omega_{\rm TO'}/\omega_{\rm LO}\omega_{\rm LO'}=0.91$).

III. NUMERICAL RESULTS AND DISCUSSION

For arbitrary values of the wave vector the zeros of $\mathrm{Re}\epsilon(\mathbf{k},\omega)=0$ have been obtained numerically for the case of the ideal 2D electron layer. In Fig. 1 we show the zeros of the real part of the dielectric function for a typical density of $n_e=4\times10^{11}$ $\rm cm^{-2}$. The electron mass is taken equal to[31–33] $m/m_e=0.047$. The GaAs and InAs TO- and LO-phonon modes are also indicated in Fig. 1 as straight dashed lines (for convenience the phonons are considered to be dispersionless). The unperturbed plasmon branch is given by the pointlike curve and the pair-excitation region where the excitations are *Landau damped* is indicated by the shaded area.

The general trend of the wave-vector dependence of the different collective excitations are qualitative similar to those found before[34] for the *one* LO-phonon mode problem, which was then applied to the GaAs/$Al_xGa_{1-x}As$ heterostructure. The difference with the previous one-phonon problem is that here there are two LO-phonon branches which complicates the picture.

For small k values there are three undamped collective excitation modes (see Fig. 1) which are the plasmon-like mode [with the $k\to0$ behavior as given by Eq. (6)] and two phononlike modes. The frequency of all these modes increases with increasing wave vector. In the small k region there is also another mode with the be-

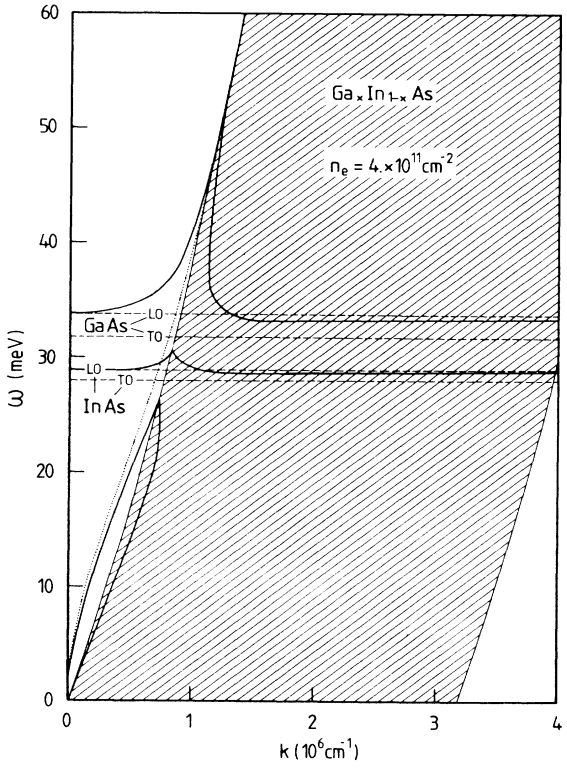

FIG. 1. The collective excitations (thick solid curves) of the 2D EG in a $Ga_xIn_{1-x}As$ heterostructure as obtained from the condition $\mathrm{Re}\epsilon(\mathbf{k},\omega)=0$. The other curves give the unperturbed result and the shaded area is the pair excitation region.

havior $\omega \sim k$ which is damped and carries only a very small amount of the oscillator strength.

With increasing wave vector the three undamped modes approach the pair-excitation region. At the boundary of this region they attain then higher frequencies. For still larger k values the modes penentrate the Landau damped region and the frequency decreases with increasing wave vector. They attain a minimum value below the respective LO-phonon frequencies, subsequently their frequency increases with k and approaches the LO-phonon frequency from below as $k \rightarrow \infty$. Note that no crossing occurs for any of the collective excitations with any of the TO-phonon frequencies.

From Fig. 1 we note that all the collective excitations have frequencies which are markedly different from any of the TO-phonon frequencies. Furthermore, referring to the experiment of Nicholas *et al.*[25] in the case of the polaron splitting of the cyclotron-resonance peak the important wave vectors are $k \leq k_{LO} \simeq 2 \times 10^6$ cm^{-1}. From the present analysis we may conclude that in the absence of a magnetic field there is no evidence that plasmon-phonon coupling will result in a polaron–TO-phonon coupling.

The relative importance of the different collective excitations becomes apparent if one plots the electron

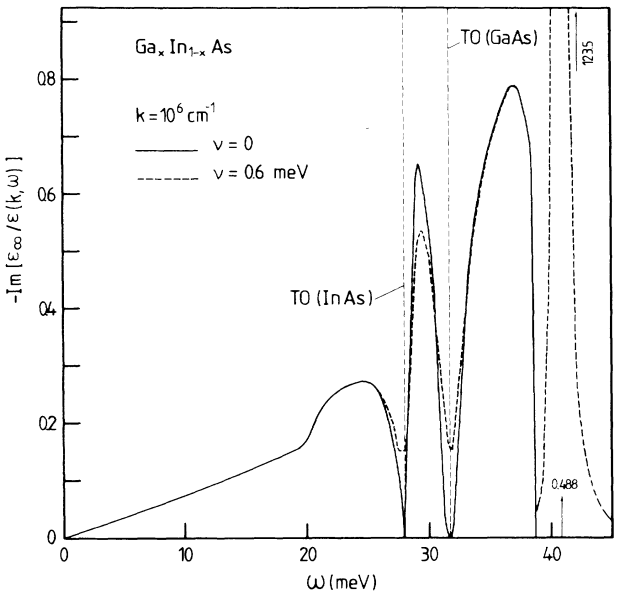

FIG. 3. Same as Fig. 2 but now only for $k = 10^6$ cm^{-1} in the case with phonon damping (i.e., $\nu = 0.6$ meV) and without phonon damping (thick solid curve).

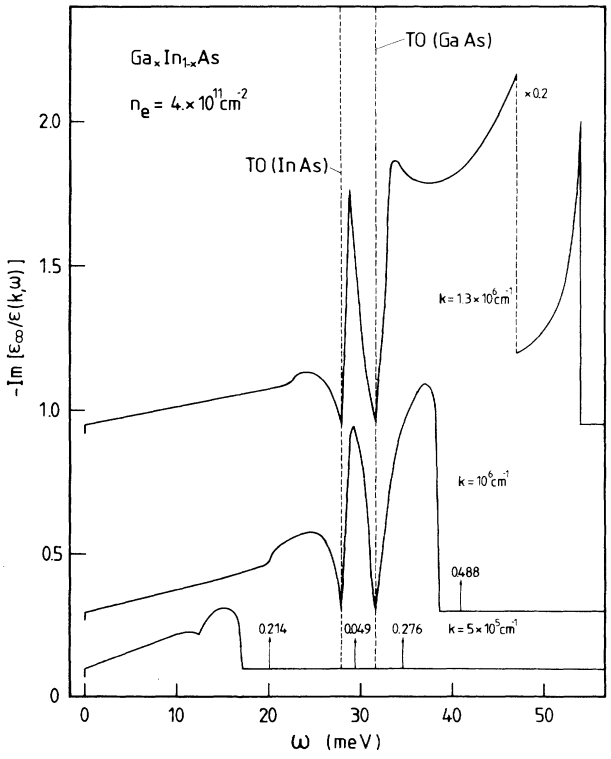

FIG. 2. The electron energy-loss function as a function of the frequency for different values of the wave vector k. The arrows indicate the undamped collective excitations which are δ functions with an oscillator strength given by the number above the arrow.

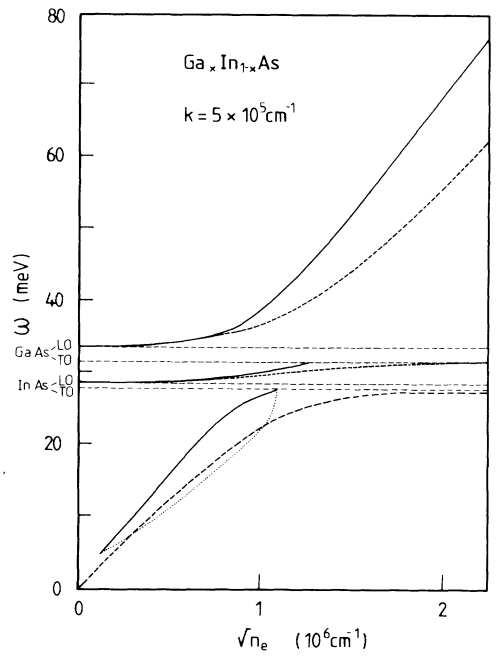

FIG. 4. The collective excitations as a function of the square root of the 2D electron density for a fixed value of the wave vector. The thick solid curve corresponds to the result with the full RPA expression for the 2D EG polarizability while the thick dashed curve was obtained from a small-k expansion of the electron polarizability function. The horizontal dashed lines are the LO- and TO-phonon modes of GaAs and InAs.

energy-loss function which is given by $-\mathrm{Im}(1/\epsilon(\mathbf{k},\omega))$. This function is plotted in Fig. 2 as function of the frequency for different values of the wave vector and for the same electron density as before. In the absence of phonon damping (i.e., $\nu=0$) the energy-loss function is zero at the TO-phonon frequencies. The undamped excitations results in δ peaks in the energy-loss spectrum which are indicated by vertical arrows and the oscillator strength of the δ function is given by the number on top of this arrow. For small-k values most of the oscillator strength is contained in the plasmon-like peak. With increasing k the oscillator strength is transferred to the phononlike peaks and to the pair-excitation continuum. The oscillator strength contained in the peak, located between the two TO-phonon frequencies, is relatively small for all values of k.

In Fig. 3 the influence of a finite relaxation time for the unperturbed phonon modes (i.e., broadening of the phonon peaks) on the electron energy-loss function is investigated. The solid curve corresponds to the result without broadening and the dashed curve is the energy-loss spectrum in the presence of phonon broadening with a typical value of[32] $\nu=0.6$ meV. The spectrum is not appreciably altered in the Landau damped region, but around the TO-phonon frequency the spectrum becomes more smooth. Furthermore, all collective excitations are damped (i.e., broadened) in this case.

In three-dimensional systems one often measures the frequency of the collective excitations as a function of the square root of the electron density for a fixed wave vector. This is shown in Fig. 4 for the present 2D system. The solid curve gives the present result while the thick dashed curve corresponds to the result as one would obtain from a small-k expansion of the 2D EG dielectric function. The horizontal lines correspond to the TO- and LO-phonon modes of GaAs and InAs. Note that there are some essential differences. First of all the plasmon peak does not occur for small electron densities if one incorporates the full RPA 2D EG polarizability expression. Second, for relatively large densities, i.e., $n_e \geq 10^{12}$ cm^{-2}, the plasmonlike peak approaches the InAs TO-phonon frequency and disappears for larger electron densities. This is different from the result as obtained from a small-k expansion of the 2D EG polarizability function which predicts a continuous low-frequency excitation as function of the electron density. The differences between the full RPA and the small-k expansion result for the phononlike collective excitations are very small when $n_e \ll 10^{12}$ cm^{-2} but become appreciable for $n_e \geq 10^{12}$ cm^{-2}.

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