Absence of Spin-Density Excitations in Quasi-Two-Dimensional Electron Systems

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Inelastic light scattering spectra reveal a new behavior of electron-electron interactions in two-dimensional double quantum well semiconductor structures. It manifests in intersubband excitations when both subbands are densely populated. In such high density limit, spin excitations, well defined when only one subband is populated, cannot be distinguished from single-particle transitions. A quantitative analysis shows a collapse of vertex corrections (exciton shift), which we attribute to the cancellation between contributions from electrons in the two subbands.

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The study of the electron gas in semiconductor nanostructures has revealed remarkable new phenomena associated with electron-electron interactions under reduced dimensions [1]. In collective excitation spectra the shifts from single-particle transition energies are a measure of the strength of Coulomb interactions [2]. The splitting between spin-density collective excitations (SDE) and single-particle transitions (SPE) is due to exchange-correlation vertex-corrections (or exciton shift), while the energy spacings between charge-density modes (CDE) and SDE follow from depolarization shifts due to direct terms [2,3]. The need to understand fundamental interactions stimulates theoretical and experimental research of the elementary excitation spectra. These studies seek the mode energies and character with the aim of understanding electron-electron interactions.

Resonant inelastic light scattering experiments give unique insights into Coulomb interactions in the intersubband excitations of the two-dimensional electron gas [3,4]. Spectra of sharp CDE and SDE, together with broader SPE, enable quantitative determinations of Coulomb interactions. SDE observed at energies well below the SPE demonstrate that exchange vertex corrections are significant [3]. Different theoretical approximations that explicitly take into account exchange interactions were used to describe such experimental results. The local-density approximation [2,5], variational techniques [6], and the solution of the Bethe-Salpeter equation [7] were used to calculate the irreducible polarizability of the 2D electron gas. These calculations show an excellent agreement with light scattering results. In infrared optical absorption (FIR) experiments light couples with electric dipole excitations, SDE are not measured and vertex corrections are inferred from energies of CDE modes [8]. Surprisingly, RPA calculations [9], where exchange is not considered, show agreement with FIR absorption experiments in quasi-one-dimensional systems with many occupied subbands [10].

Here we report on a new regime of intersubband excitations of the 2D electron gas, which reveals an unexpected behavior of electron-electron interactions in low-dimensional systems. At high densities, defined as the range showing substantial occupation of the two subbands, the energy spacing between SDE and SPE modes decreases with increasing density. These determinations reveal the existence of a "critical" density where SDE and SPE merge. A quantitative analysis indicates the abrupt collapse of vertex corrections when the critical density is approached. Our results show that the evolution from a purely 2D system towards a more classical one is not continuous at all.

The excitations studied here by inelastic light scattering are associated with transitions between the two lowest subbands of double quantum wells (DQW). Free electrons in DQW are characterized by the parameter $\eta = \Delta_{SAS}/E_F$, where Δ_{SAS} is the symmetric-antisymmetric splitting (see the inset of Fig. 1) and E_F is the Fermi energy. In these systems the critical density for the collapse of vertex corrections occurs at $\eta \simeq 0.12$. We attribute

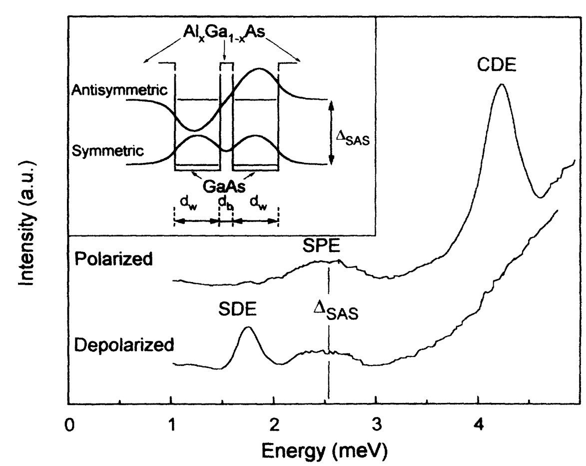

FIG. 1. Inelastic light scattering spectra of intersubband excitations of the DQW. The peaks of spin-density excitations (SDE), charge-density excitations (CDE), and single-particle excitations (SPE) are shown. The sample has only one subband occupied, $\eta = 1.04$. Inset: The symmetric and antisymmetric states of the DQW.

this effect to the cancellation between contributions to vertex corrections from particles in different subbands. The collapse is not described by any of the current approximations used to calculate the many-body electron-electron interactions, and we suggest second order Feynman diagrams that could explain our observations. While the critical density may vary for other systems, the collapse of vertex corrections could be a behavior common to electron gases with dense population of several subbands. A similar cancellation of vertex-corrections would explain the success of RPA in dense 1D electron systems.

The DQW were grown by molecular beam epitaxy. They consist of two nominally identical GaAs quantum wells of width $d_w = 139$ Å separated by an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ barrier. The electrons are provided by remote Si-δ-doped donor layers, set back from each side of the DQW by $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ spacer layers. The total density is in the $(0.75\text{–}6.35)\times 10^{11}$ cm^{-2} range and the low temperature mobility is in the range $(0.5\text{–}2.0)\times 10^{6}$. Δ_{SAS} is easily tuned by changing the thickness and Al content of the barrier [11]. We selected symmetric DQW because high densities, where $\eta < 1$, can be easily reached. η was determined from values of Δ_{SAS} and E_F obtained in spectra of inelastic light scattering and luminescence, respectively. Spectra were obtained at 1.7 K using a dye laser tuned to excitonic optical transitions. A conventional backscattering geometry allowed in-plane wave-vector transfer by rotating the sample relative to the incident light beam [3,12]. In this configuration the wave vector is $\mathbf{q} = \frac{4\pi}{\lambda}\sin\theta$, where λ is the wavelength of the incident light and θ is the angle between the incident beam and the normal to the sample.

Figure 1 shows spectra obtained in a sample where only the lowest symmetric subband is occupied and $\mathbf{q} \le 0.5 \times 10^4$ cm^{-1}. The sharp peaks with well defined polarization selection rules arise from SDE and CDE [3,4,12]. SDE are active in depolarized spectra, where incident and scattered light polarizations are perpendicular and CDE occur in polarized spectra measured with parallel polarizations. The collective modes have FWHM $\simeq 0.2$ meV, comparable to those in the best single quantum wells (SQW) [3]. The sharpness of the collective excitations is consistent with the high electron mobility.

The spectra of Fig. 1 also show a broader peak at energies in between those of SDE and CDE. As in previous work [3,4], this feature is assigned to SPE. For $q \ll K_F$, where K_F is the Fermi wave vector, the intersubband SPE occur within the continuum of energies bounded by $\Delta_{\mathrm{SAS}} \pm \hbar q v_F$ [13], where v_F is the Fermi velocity. Results for a sample with two densely populated subbands are shown in Fig. 2. We see that the SPE broaden with increasing $\mathbf{q}$, showing the expected width of about $2\hbar q v_F$, and, more importantly, two well-defined maxima emerge. This is the fingerprint of SPE in a 2D system with two occupied subbands [13]. In the high density limit under study the phase space for the transition is severely reduced by the Pauli exclusion principle, and the only particles that can be excited are those with $v \simeq v_F$. In comparison to $\mathbf{q} = 0$, the effect of phase-space reduction is negligible for particles with $\mathbf{k}$ either parallel or antiparallel to $\mathbf{q}$ (whose transition energies are $E \simeq \Delta_{\mathrm{SAS}} \pm \hbar q v_F$), but it is very important when the particles have $\mathbf{k}$ perpendicular to $\mathbf{q}$, giving rise to the observed characteristic minimum. Figure 2 shows that the imaginary part of the polarizability function of a noninteracting 2D electron gas with two occupied subbands, which represents the density of states for the SPE, gives a very good fit to the spectra [13].

Figure 3(a) shows depolarized spectra of samples with different η. We normalized the energy shift by the Δ_{SAS} of each sample. The figure shows that the SDE move

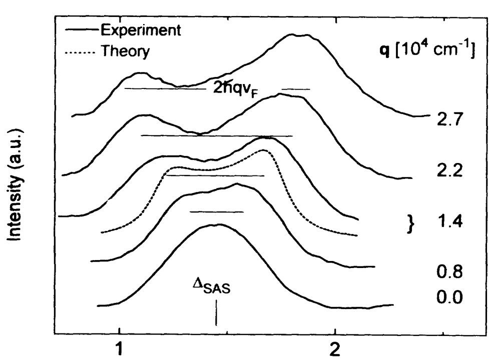

FIG. 2. Wave-vector dependence of the intersubband SPE of the sample with $\eta \simeq 0.12$. The dashed line is a fit to the experimental data using the polarizability function for the intersubband transition of the noninteracting gas. The fit incorporates a phenomenological broadening of 0.08 meV.

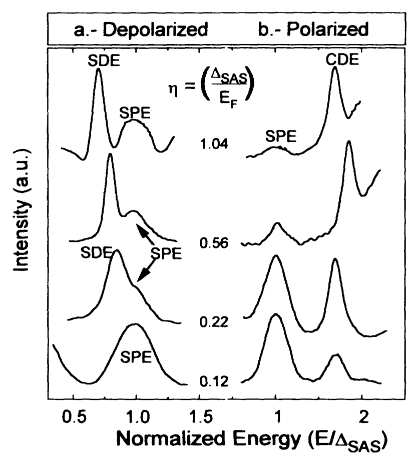

FIG. 3. (a) Depolarized spectra as a function of the normalized energy shift. For each spectrum the energy shift has been normalized by the Δ_{SAS} of the corresponding sample. The spectra are labeled with their values of $\eta = \Delta_{\mathrm{SAS}}/E_F$. (b) Same as (a), but for polarized spectra.

closer to the SPE with decreasing η and disappears at the critical density $\eta \simeq 0.12$. On the other hand, the CDE remains always well defined, as can be seen in Fig. 3(b). The disappearance of the intersubband SDE into the intersubband SPE at high densities is the main result of the present work. We show below that this behavior is due to a collapse of vertex corrections.

In order to obtain quantitative values for the depolarization shift α and exciton shift due to vertex corrections β we use the usual parametrization [2–4]

$$\alpha = \epsilon(\omega_{\rm CD}) \frac{\omega_{\rm CD}^2 - \omega_{\rm SD}^2}{2\Delta_{\rm SAS}(n_{\rm S} - n_{\rm AS})} \qquad (1)$$

and

$$\beta = \frac{\Delta_{\rm SAS}^2 - \omega_{\rm SD}^2}{2\Delta_{\rm SAS}(n_{\rm S} - n_{\rm AS})}, \qquad (2)$$

where $\omega_{\rm CD}$ ($\omega_{\rm SD}$) is the energy of the CDE (SDE), $n_{\rm S}$ ($n_{\rm AS}$) is the electron density of the symmetric (antisymmetric) band, and $\epsilon(\omega)$ is the dielectric function of the polar lattice [5]. The factor $(n_{\rm S} - n_{\rm AS})^{-1}$ takes into account the reduction of available phase space when two subbands are populated. From the measured values of $\omega_{\rm CD}$, $\omega_{\rm SD}$, $\Delta_{\rm SAS}$, $n_{\rm S}$, and $n_{\rm AS}$, and using Eqs. (1) and (2), we obtain the values of α and β displayed in Fig. 4. The figure shows that at $\eta \simeq 0.25$, β begins a relatively abrupt decrease which ends in a full collapse at $\eta \simeq 0.12$.

In Fig. 4 the strength of vertex corrections when $\eta \geq 1$ is the same as that obtained in 250 Å asymmetric SQW with similar electron densities. This is not unexpected since the matrix element for β is determined by the spread of the wave function, that is similar in the case of the SQW and in our DQW of total width $\simeq$ 300 Å. However, here α is substantially larger because the depolarization shift is proportional to the overlap integral between the wave functions [2], which is larger in the symmetric DQW. These considerations also explain the smaller ratio $\frac{\beta}{\alpha} \simeq 0.15$ obtained in symmetric DQW.

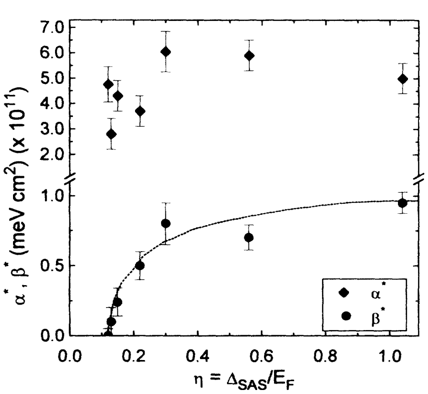

FIG. 4. Depolarization shift α and vertex corrections β as a function of η for the investigated samples. The line is a guide to the eye.

The collapse of β is not caused by screening of the exchange interaction. Screening is related to the total number of particles in the system and SQW with similar total electron densities do not show the collapse. Further, in the system under study, the samples with η = 0.12, 0.13, 0.15, 0.22, and 0.30 have a total density of 6.35, 2.82, 5.05, 2.68, and 1.28 $\times 10^{11}$ cm^{-2}, respectively. This shows that there is no correlation between β and the total carrier density.

The shift between SDE and SPE is dictated by the exchange interaction [2,6,7]. Given that the strength of exchange interactions in DQW and in 250 Å SQW are comparable, the collapse of vertex corrections should arise from a cancellation of terms when the two subbands are occupied. In this framework, the key point of our experiment is that it reveals the importance of exchange interactions with electrons in the antisymmetric subband, which must overwhelm the contribution of particles in the lowest symmetric subband.

However, from the theoretical point of view the answer is far from trivial. The simplest contribution to vertex corrections arises from the ladder diagrams, which are the *only* vertex corrections included in any of the existing response calculations using the generalized RPA. The ladder diagrams can be explicitly calculated in the case of two subband occupancy. The calculation of β, defined in Eq. (2), with the only contribution of ladder diagrams does not show the observed vertex corrections collapse. For this reason the usual ladder diagrams (diagrams 1.I and 2.I in Fig. 5, together with all higher order ones) cannot be the explanation for the observed behavior. The experimental effect is, therefore, beyond the TDLDA and ladder diagrams. The lowest order vertex corrections beyond the ladder diagrams are those shown as diagrams 2.II and 2.III in Fig. 5. The diagram 2.III does not participate in SDE vertex corrections because the Coulomb interaction is spin conserving [14]. A crude estimate of diagram 2.II shows that the vertex correction is indeed reduced by this higher-order diagram when both subbands are occupied. An explicit calculation is not possible to

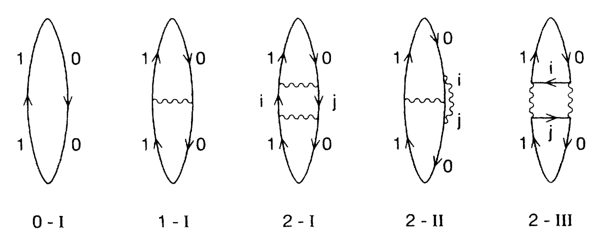

FIG. 5. Some topologically distinct irreducible polarizability diagrams in the first few orders of the many-body perturbation theory. Diagram 2.II (and its counterparts in all the higher orders) is responsible for the observed collapse of vertex corrections. The indices i, j have the values 1 or 2 when both subbands are occupied (1 corresponds to the symmetric and 2 to the antisymmetric subbands).

carry out because one must sum an infinite series of diagrams (of the type 2-II) to obtain β. At this stage, all we can say is that while we believe that these higher-order diagrams are responsible for the observed vertex correction collapse, considerable theoretical work will be required before the situation can be clarified quantitatively [15]. No cancellation is expected for the depolarization shift.

The observations of SPE in light scattering spectra are critical to our study. Figure 2 shows that the SPE have the wave vector defined by the scattering geometry. This demonstrates that their presence in spectra of high quality systems is intrinsic to resonant inelastic light scattering, and rules out the disorder-assisted processes proposed in previous work [3]. The results indicate that the resonant light scattering cross sections do not have a simple proportional dependence with the dynamical structure factor, which would predict only collective modes, as in the nonresonant cases. At this time we do not have a full explanation. We note, however, that resonant enhancements were previously invoked to explain the unexpected observation of SPE in polarized spectra of bulk n-GaAs [16].

In conclusion, we have uncovered a new aspect of electron-electron interactions in the 2D electron gas. It appears as a collapse of the exciton shift due to vertex corrections in dense systems. We attribute the collapse to a cancellation of contributions when the two subbands are densely populated. A similar collapse could also explain the success of quantitative interpretations of FIR spectra that ignore exchange interactions in dense 1D electron systems [9,10]. The theoretical interpretation is beyond the reach of commonly used approximations, a feature that is critically manifested when the occupancies of two subbands are similar.

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[15] Explicit time-dependent local-density-approximation calculations [P. I. Tamborenea and S. Das Sarma (unpublished)] for the structures used in these experiments give good agreement with the data only for $\eta \gtrsim 0.3$, but does not lead to the collapse of vertex corrections.

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