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Inelastic Light Scattering by Elementary Excitations of the 2D Electron Gas at High Densities

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We have investigated the dependence on carrier density of elementary excitations of the 2D electron gas formed in a modulation-doped single quantum well structure. The 2D electron density n, as obtained from lineshape fits to the photoluminescence spectra, is continuously increased by applying dc voltages ranging from 5 to 100 V between the electron gas and a back contact. A substantial population of the second electron subband is revealed at high voltages by the strong redshift of the corresponding emission line due to bandgap renormalization effects. In this high-density regime, we observe a large reduction of the exchange-correlation term of the Coulomb interaction.

Studies of the many-body behavior of high-mobility two-dimensional electron gases (2DEG) in semiconductor nanostructures have uncovered remarkable new phenomena associated with electronic correlations in reduced dimensions [1]. Coulomb interactions manifest themselves in the spectrum of elementary excitations of the electron gas, which can be measured by inelastic light scattering [2,3]. In strongly diluted electron gases obtained by applying high hydrostatic pressures, exchange–correlation effects dominate the many-body behavior of 2DEGs [4,5]. In contrast, a collapse of vertex corrections has been observed at high carrier densities, when there is a substantial occupation of the *two* lowest subbands of a symmetric double quantum well structure [6]. This behavior, however, was claimed to be characteristic of electronic 2D systems with many occupied subbands.

In this work we show that the high-density regime can be reached in modulation-doped single quantum wells by applying a large dc bias between the 2DEG and a back contact on the substrate side. The population of the second electron subband is revealed by a significant reduction of the energy of its photoluminescence emission. The Hartree and exchange–correlation terms of the Coulomb interaction are determined as a function of carrier density from the energies of collective as well as single-particle excitations measured in inelastic light scattering experiments. With increasing 2D density the exchange–correlation term arising from vertex corrections decreases in its magnitude by more than a factor of three.

The sample consists of a modulation-doped 245 Å-wide GaAs single quantum well (SQW) with $Al_{0.33}Ga_{0.67}As$ barriers grown by molecular-beam epitaxy. The growth se-

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quence is given elsewhere [4]. Without bias only the lowest subband is occupied with electrons with Fermi energy $E_F \approx 20$ meV. The energy separation to the second subband is $E_{01} \approx 27$ meV. Photoluminescence (PL) and inelastic light scattering spectra were excited with a tunable Ti:sapphire laser and recorded with optical multichannel detection. Light scattering measurements were performed in backscattering geometry with incident photon energies in resonance with excitonic transitions between higher excited states of the SQW.

The dependence of the 2D electron density n_{2D} on applied voltage has been determined from a quantitative analysis of PL lineshapes. Fig. 1 shows two PL spectra recorded at 5 K and for different bias. The low-energy emission line corresponds to recombination processes between the lowest electron and heavy-hole subbands (with subband index 0). The peak labeled as E_1 is associated with optical transitions between the first excited electron subband and the hole ground state, which become dipole allowed due to the lack of inversion symmetry of the triangular potential in doped QWs. The peak at 1.515 eV originates from the band-gap emission of the GaAs buffer layer. At high voltages a high-energy cutoff at the Fermi energy $E'_F = E_F(1 + m_e/m_h)$ is clearly apparent from the PL spectra. The factor containing the ratio of electron and hole effective masses accounts for the curvature of the valence band. The results for the carrier densities n_0 and n_1 of the first and second confined electron states, respectively, as obtained from the PL data are plotted as a function of the applied voltage in the inset to Fig. 1 together with the total density values.

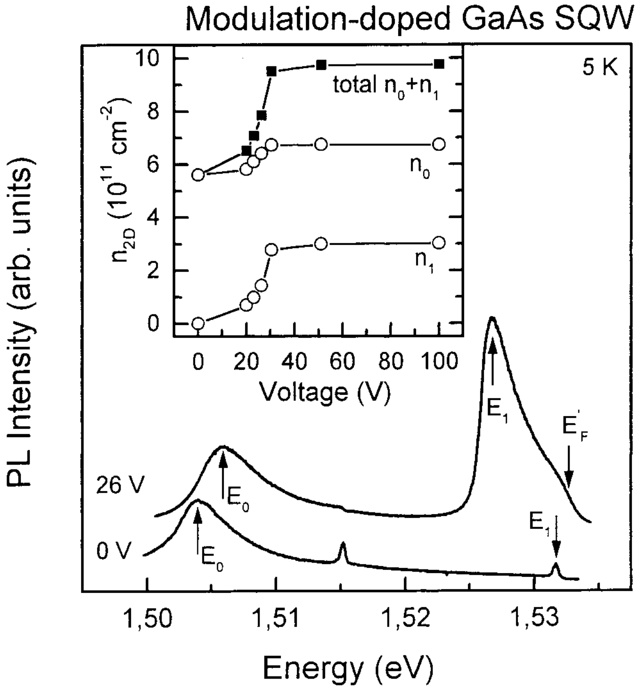

Fig. 1. Photoluminescence spectra of a modulation-doped single quantum well at 5 K and for two different voltages. Arrows indicate the position of bandgaps and Fermi energy. The peak at 1.515 eV arises from bulk GaAs luminescence. The inset shows the variation of the 2D densities of the first two electron subbands as a function of applied voltage

At voltages higher than 50 V the total electron density in the quantum well doubles its initial value, the larger contribution arising from the population of the second electron subband. Its occupation, however, proceeds abruptly between 20 and 30 V (see inset to Fig. 1). This results from the reduction of the E_1 gap energy as a consequence of renormalization effects due to exchange–correlation corrections in the presence of free carriers [7]. Bandgap renormalization acts as a feedback mechanism for subband filling leading to a sudden population of the second electron subband and, in addition, causing the pronounced decrease of the intersubband spacing energy E_{01}.

Fig. 2 shows inelastic light scattering spectra in the energy range of intersubband excitations measured at 5 K and at different voltages. The sharp peak observed in spectra with parallel linear polarization of incident and scattered beams corresponds to the collective charge-density excitation (CDE), whereas the spin-density excitation (SDE) is only active in crossed polarization. The broader peak labeled SPE, which appears in spectra with both polarizations, is assigned to single-particle electron–hole pair excitations and is centered at the intersubband spacing energy E_{01}. With increasing voltage, i.e. carrier density, the energies of the excitations decrease due to the reduction of E_{01}, while changing their separation to each other.

From the measured excitation energies we obtain the dependence on electron density of the direct or Hartree and exchange–correlation terms of the Coulomb interaction,

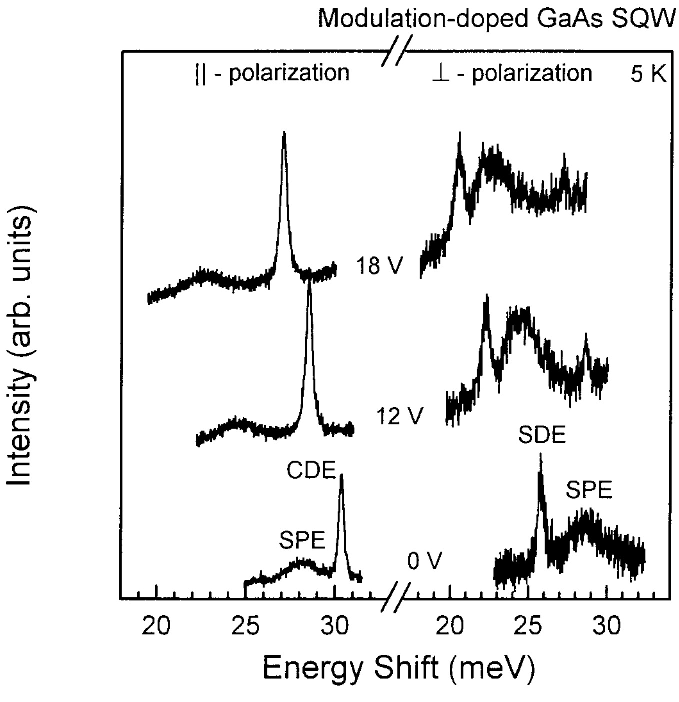

Fig. 2. Depolarized (⊥) and polarized (||) light scattering spectra of intersubband excitations at different voltages. The assignment of peaks to charge-density (CDE), spin-density (SDE), and single-particle excitations (SPE) is indicated

which are commonly represented by the parameters [2,8]

$$\alpha_{01} = \tilde{\epsilon}(\omega_{\mathrm{CDE}}) \frac{\omega_{\mathrm{CDE}}^2 - \omega_{\mathrm{SDE}}^2}{2E_{01}\,\Delta n_{2\mathrm{D}}}\,, \tag{1}$$

$$\beta_{01} = \frac{E_{01}^2 - \omega_{\mathrm{SDE}}^2}{2E_{01}\,\Delta n_{2\mathrm{D}}}\,, \tag{2}$$

respectively, where $\tilde{\epsilon}$ is the phonon contribution to the dielectric function of the polar lattice and $\Delta n_{2\mathrm{D}} = n_0 - n_1$ is the difference between the 2D densities of both occupied subbands. The parameters α_{01} and β_{01} are plotted in Fig. 3 as a function of $\Delta n_{2\mathrm{D}}$. We note that this difference decreases while the total 2D density increases at higher bias.

An important result concerns the strong reduction of the exchange–correlation term of the Coulomb interaction at high electron densities. The decrease of β_{01} by a factor in excess of three sets in as soon as the second subband becomes populated with electrons. Such behavior of vertex corrections has been previously demonstrated by the absence of SDE in double quantum wells when the Fermi energy overcomes the symmetric–antisymmetric splitting [6]. This effect might arise from the mutual cancelation of exchange–correlation contributions of electrons in the upper subband and holes left behind in the lower one by the creation of a collective intersubband excitation. In contrast, the Hartree term α_{01} increases at high carrier densities indicating a *hardening* of Coulomb force constants for fluctuations of the charge-density in spite of the reduction of available phase space when two subbands are populated.

In summary, we succeeded in increasing the electron density of a modulation-doped single quantum well beyond the point for which there is substantial occupation of the second electron subband by applying a dc bias to the 2DEG. Simultaneous with the population of the second subband we observe a significant renormalization of its en-

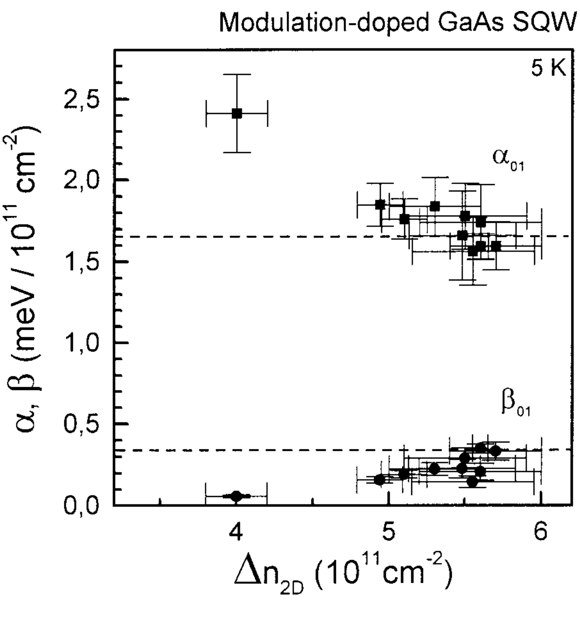

Fig. 3. Dependence on the difference in subband carrier densities of the parameters α_{01} and β_{01} which represent the Hartree and exchange Coulomb interactions, respectively. Note that $\Delta n_{2\mathrm{D}}$ decreases with higher voltage

ergy, which leads to the reduction of the intersubband spacing E_{01}. In this high-density regime, the exchange–correlation term of the Coulomb interaction β_{01} decreases in magnitude, as reported earlier for symmetric double quantum well structures.

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