Collective effects in optical spectra of high-density–high-mobility two-dimensional electron gases

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A special GaAs structure with a two-dimensional electron gas having simultaneously high density and high mobility has been fabricated. Its photoluminescence excitation spectrum displays strong and clear optical singularities at the Fermi edge for electron densities as high as 1.6×10^{12} cm^{-2}. The power-law exponent of the singularities is determined to be between 0.3 and 0.4 both for heavy- and light-hole transitions. Comparison of these results with GaAs quantum wells codoped with a low-density Be-δ layer shows that hole localization is needed for the observation of the Fermi-edge singularity in emission spectra. However, hole localization plays a minor role, if any, in the singularity observed in photoluminescence excitation. Spectra of similar quantum wells made of $In_xGa_{1-x}As$ show no singularities at all, probably as a consequence of the lower electron mobility. [S0163-1829(99)06423-1]

I. INTRODUCTION

The optical properties of high-mobility two-dimensional electron gases (2DEG's) have been studied for the last 15 years with the purpose of looking for potential optoelectronic applications and also to get insight into fundamental aspects, such as the collective Coulomb effects in low-dimensional systems. Among these effects, the appearance of a singularity at the Fermi level (Fermi-edge singularity or FES) in the optical absorption and emission spectra has been the object of intense experimental[1–10] as well as theoretical[11–15] research. The origin of the FES is the coherent response of the Fermi sea to the sudden creation or annihilation of the photocreated hole in the absorption or emission process, respectively, similar to the case of the x-ray absorption spectra of metals.[16–18] The spectral shape of the FES has the form of a power-law dependence on energy, which broadens and disappears very rapidly as the temperature is raised, compared to excitonic transitions in undoped systems. The corresponding power-law exponent in the 2DEG depends on electron density, and it is related to the number of electrons needed to screen the photocreated hole.[10,11,14,16] FES's have been observed in modulation-doped GaAs and $In_xGa_{1-x}As$ multiple (generally symmetric) quantum wells[1,5,6,10] (MQW's) or single (generally asymmetric) quantum wells (SQW's).[2,3,8–10] The first studies on GaAs QW's (Refs. 1–5) report FES only in photoluminescence excitation (PLE) spectra, as the lack of holes with the Fermi wave vector (k_F) at low temperatures prevents its observation in photoluminescence (PL) spectra. However, a weak FES has recently been observed[19] in the PL spectrum of a high-quality GaAs QW, whose intensity was consistent with a nonequilibrium population of holes at k_F. In $In_xGa_{1-x}As$/InP wells the mixing of heavy and light holes produces a strong nonparabolicity of the valence band with very high values of the hole mass.[20] This, together with hole localization produced by alloy disorder, results in the observation of FES in PL spectra.[6–8] FES can also be observed in PL by including an acceptor δ-doping layer in the QW to trap the photocreated holes.[9] Existing theoretical models require either hole localization,[13–15] and/or coupling of electrons at the Fermi level to empty conduction subbands[8,15] for the FES to be observed. Other authors[11,12] consider that FES can be observed in PLE spectra for mobile holes, but it would be smeared out by indirect transitions assisted by zero-energy excitations of the Fermi sea, as the electron density increases.[11] This appears to be the case of the PLE spectra of the GaAs MQW reported in Ref. 10, where the FES power law evolves into a steplike function for electron densities above 7×10^{11} cm^{-2}. When trying to analyze the influence of electron density on the FES intensity and shape one has to bear in mind that increasing the doping level usually results in a decrease of the electron mobility by remote impurity scattering. This can affect the screening properties of the electron gas and therefore the FES itself.

In this paper we present PL and PLE measurements on a 2DEG formed in GaAs single quantum wells with simultaneously high electron density of about 1.6×10^{12} cm^{-2} and electron mobility of 1.2×10^{6} cm^2/V s.[21] We observe strong and clear FES in the PLE spectra at low temperatures, both for the heavy- and light-hole transitions. The high-temperature spectra indicate an energy-independent joint density of states (DOS), reflecting parabolic energy bands, and a finite effective mass for the holes. This allows for the experimental determination of the power-law exponent and its comparison with previously reported values.[10] To study the role of the localization of photogenerated holes in the FES we used a similar QW with a low-density Be-δ-doped layer, placed at the center of the well, which exhibits FES in both PL and PLE spectra. Finally an $In_xGa_{1-x}As$ QW grown in the same way has been studied for comparison. Our results indicate that FES appears in the PLE spectra in high-density 2DEG with delocalized holes, provided that the electron mo-

0163-1829/99/60(7)/4897(5)/$15.00 PRB 60

TABLE I. Main characteristics of the samples: n_s is the electron density measured by Hall effect, ϵ_F^n is the Fermi energy determined by the density, ϵ_F^{PL} is the value obtained from the optical spectra, and μ is the low-temperature electron mobility derived from Shubnikov–de Haas measurements.

Sample no.	QW	n_s (10^{12} cm^{-2})	ϵ_F^n (meV)	ϵ_F^{PL} (meV)	μ (cm^2/V s)
1	GaAs	1.6	54.8	47.6	800 000
2	GaAs	1.2	41.1	36.4	1 200 000
3	GaAs-Be	1.5	51.4	53.4	160 000
4	$In_{0.2}Ga_{0.8}As$	2.8	96		30 000

bility is high. Instead, hole localization is crucial for the observation of FES in PL, as expected, because it allows for the indirect recombination of electrons at the Fermi level.

II. EXPERIMENT

Two samples with different electron densities (samples 1 and 2) each with a single GaAs QW and barriers made of AlAs-GaAs short period superlattices (SPSL) have been grown by solid-source molecular beam epitaxy. Modulation doping was provided on both sides of the QW in a GaAs sequence of the SPSL by a δ-Si layer located at 9 mm and 14 nm from the QW interface, respectively. With appropriate values of the layer thicknesses, and the position and density of the Si-δ-doping layers, the first states to be populated by electrons are the X conduction-band minima of the barriers in the AlAs sequence of the SPSL. These electrons are able to screen effectively the potential fluctuations and therefore to reduce the remote impurity scattering.[21] The resulting 2DEG confined in the QW exhibits simultaneously high electron densities and high electron mobility. In the QW of sample 3 an additional Be-δ-doping layer with Be density of about 1.2×10^{10} cm^{-2} was inserted into the center of the QW in order to localize the photocreated holes. Another QW (sample 4) is made of $In_{0.2}Ga_{0.8}As$ instead of GaAs. Due to alloy scattering processes its mobility is rather low. All the QW's are 10 nm thick. Relevant data of the QW's are listed in Table I. The electron densities and mobilities have been obtained from Shubnikov–de Haas and Hall measurements in parallel samples. The Fermi energies (ϵ_F^n) obtained from the electron densities are listed in Table I, together with the corresponding values resulting from the optical spectra (ϵ_F^{PL}). For samples 1 and 2 ϵ_F^{PL} has been taken as the energy difference between the inflection points at the low-energy side of the low-temperature PL and PLE spectra shown in the next section (corresponding to transitions at the Brillouin zone center and at k_F, respectively), corrected by the valence-band curvature factor $1+m_e/m_h$ (m_e and m_h are the conduction- and valence-band effective masses, respectively). The small disagreement (near 10%) between both sets of values can be due to uncertainties in the electron effective mass or the exact location of the emission threshold. For sample 3 the determination of ϵ_F^{PL} is more complicated due to the presence of the Be acceptors and will be explained in the next section. The valence-band nonparabolicity of InGaAs (sample 4) prevents the correct estimation of the Fermi energy from the optical spectra. In all cases the conduction intersubband energy spacing is significantly larger than the Fermi energy, so that only the lowest subband is occupied by electrons. PL and PLE measurements have been performed at temperatures between 1.7 and 100 K in a helium bath cryostat. The excitation source was a Ti-sapphire laser with a power density of 10 W/cm^2.

III. RESULTS AND DISCUSSION

The PL and PLE spectra of sample 1 are shown in Fig. 1 for different temperatures. The PL emission (left) is narrow at low temperature and broadens progressively to higher energies as the temperature increases, due to the increasing population of photogenerated holes away from the Brillouin zone center. This is a clear indication that in this sample the holes are not localized. The peak at 1.49 eV is the band-to-acceptor (carbon) transition of the GaAs substrate. The PLE spectrum (right) at the lowest temperature has an abrupt onset at the Fermi level (E_F) followed by two asymmetric peaks, which correspond to the heavy-hole (hh) and light-hole (lh) FES, respectively. This result shows that the FES can exist in a relatively dense electron gas with high electron mobility and mobile holes. The strong peak at 1.67 eV rep-

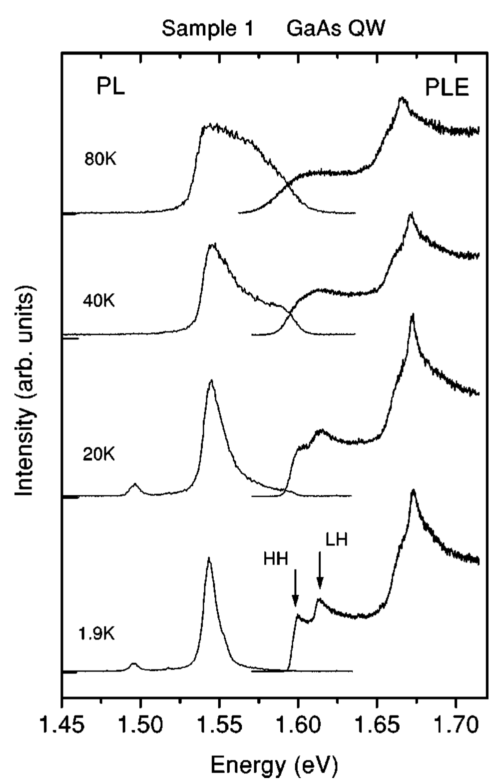

FIG. 1. PL (left) and PLE (right) spectra of sample 1 for different temperatures. The FES's corresponding to hh and lh holes are indicated.

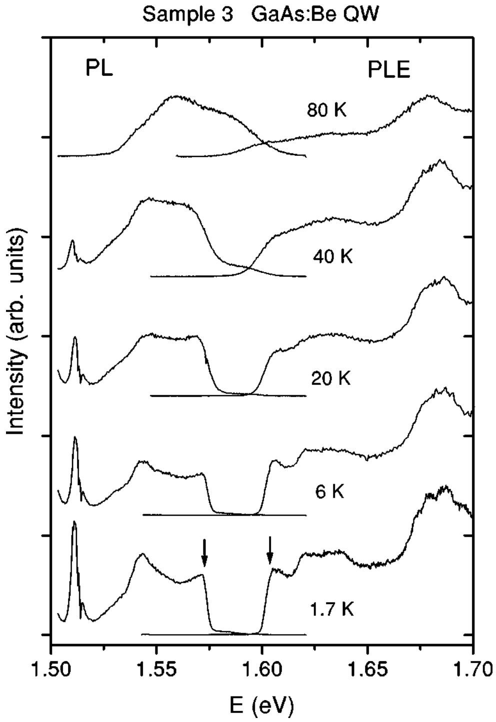

FIG. 2. PL and PLE spectra of the GaAs QW with additional Be-δ doping (sample 3) for different temperatures. FES energies are indicated by arrows in the 1.7-K spectra. The gap between the low-temperature PL and PLE spectra corresponds to the Be activation energy.

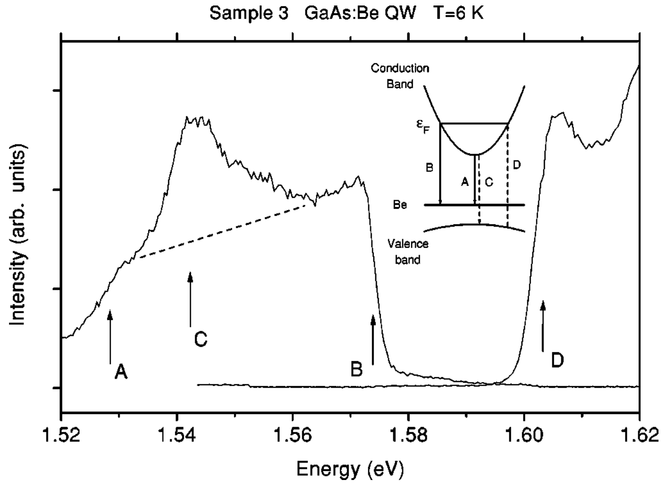

FIG. 3. Detail of the spectra of sample 3 at 6 K. The dashed line between *A* and *B* indicates schematically the separation between contributions from the band-to-band and the band-to-acceptor transitions to the PL spectrum. These transitions are indicated in the inset by solid and dashed vertical lines, respectively.

resents the excitonic transition to the second (empty) conduction subband. As the temperature is raised the FES rounds off at 20 K and disappears completely at 40 K, whereas the excitonic transition to the empty subband remains practically unchanged, as expected. Apart from this excitonic transition, the flatness of the PLE spectra at high temperatures indicates an energy-independent DOS corresponding to parabolic energy bands. Consequently, the spectral shape of the FES (the power law) can be obtained from the low-temperature PLE spectra by assuming a constant background. The spectra of sample 2 (not shown) are almost identical to those of sample 1 except for the lower value of ϵ_F. Sample 3 with the Be layer in the well (see Fig. 2) shows some important differences with respect to samples 1 and 2. First, the PL spectra, even at low temperature, have a much larger width, indicating that recombination of electrons away from the Brillouin zone center becomes allowed. This is possible because part of the photogenerated holes get localized at the acceptor states and therefore the wave vector conservation condition is lifted. In fact, the PL spectral shape results from the sum of two sets of transitions, which are indicated in Fig. 3. One set corresponds to band-to-band (wave vector conserving) transitions involving recombination of conduction electrons with free holes at the valence band, as in samples 1 and 2. They contribute to the total PL spectrum with a peak at 1.54 eV and the tail decreasing towards higher energies in analogy with the PL spectra shown in Fig. 1. The second set are band-to-acceptor (wave vector nonconserving) transitions involving recombinations of electrons with wave vector comprised between 0 and k_F with holes localized at the Be acceptors. Its corresponding spectral shape is schematically indicated by the dashed line in Fig. 3. As in the PL spectra found in InGaAs-doped QW's,[7] it reflects the rectangular shape of the joint DOS with the FES enhancement towards the Fermi level. The set of band-to-acceptor transitions is shifted 28 meV to lower energies with respect to the band-to-band ones, corresponding to the Be activation energy in bulk GaAs.[22] The intensity of the band-to-band spectrum is proportional to the excitation power, while the intensity of the band-to-acceptor one saturates when the excitation power is increased. The Fermi energy ϵ_F^{PL} of sample 3 can be estimated from both the band-to-band spectrum, as in samples 1 and 2, and from the width of the band-to-acceptor spectrum. The resulting values are 53.4 meV and 48 meV, respectively, the difference being probably due to the Stokes shift between PL and PLE spectra. The former value has been included in Table I for coherence with the values of samples 1 and 2. The peak at 1.51 eV is the bound exciton of the GaAs substrate. The PLE onset corresponds, as in Fig. 1, to transitions from the valence band to the Fermi level. It shows also a FES similar in strength and temperature dependence to that of Fig. 1. This similarity and the fact that FES appears simultaneously in PL and PLE spectra of sample 3 deserves some discussion. Hole localization is commonly accepted as a requirement for the FES to appear.[13–15] This is so because an infinitely extended hole would cause a uniform change of the electrostatic potential, thus not producing any response of the Fermi sea. In the case of PL, hole localization is also needed, as mentioned before, to lift the wave vector conservation condition in the recombination of electrons at k_F. However, our PLE spectra involve valence-band holes, which are assumed to be free. For them, ''localization'' can only be understood as the hole localization length (l_h) being larger than the Fermi wavelength ($\lambda_F = 20$ nm in sample 1), but smaller than the typical length of the spatial region occupied by electrons participating in the FES (let us call it l_c). A rough estimate of the minimum value of l_h compatible with hole dispersion is to take it ten times larger than λ_F, giving $l_h = 200$ nm for sample 1. The observation of a FES in the PLE spectra of Figs. 1–3 then would imply

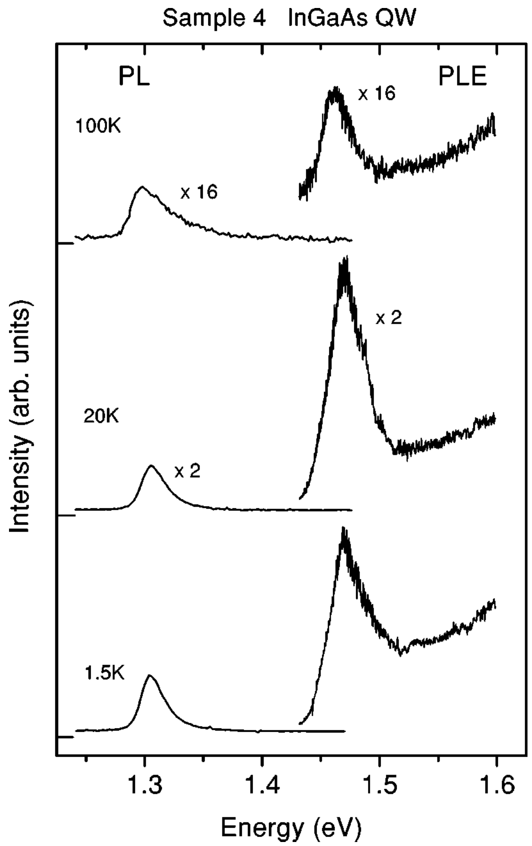

FIG. 4. PL and PLE spectra of the $In_xGa_{1-x}As$ QW (sample 4) for different temperatures.

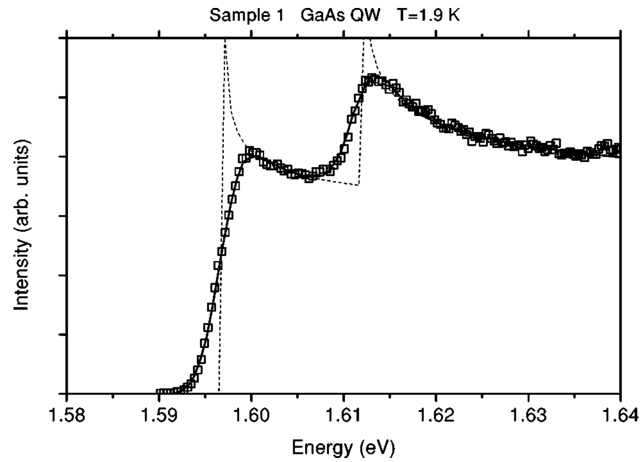

FIG. 5. Fit of the PLE-FES of sample 1, at 1.9 K, using Eq. (3.1) without convolution (dotted line) and convoluted with a Gaussian with a width of 1.9 meV (solid line). The symbols are the experimental data.

that l_c should be significantly larger than this value, and therefore much larger than the static screening length given by the effective Bohr radius (10 nm in our case).[24] This is a rather puzzling result, because to our knowledge, there is no theoretical support for a dynamic response of the electrons extending over mesoscopic lengths. Then there are two possibilities left: The first one is that the FES observed in the PLE spectra is not due to free holes, but to holes which are weakly localized, either at the interfaces due to microscopic roughness, or by any other weak localization mechanism. However, the total number of these weakly localized holes has to be very small in our case, as indicated by the very low PL intensity near the Fermi level in the spectra of Fig. 1 (at least two orders of magnitude weaker than the band-edge PL). Also, they should be practically degenerate in energy with the free valence-band holes at k_F, as the FES observed in PLE coincides with the onset of the band-to-band continuum. It is then difficult to attribute the strong FES observed in our PLE spectra to these hypothetical few weakly localized holes, while a similar one is not observed associated to the Be-bound holes. The second possibility is that the FES observed in our PLE spectra involves indeed free holes. Then our results would indicate that the understanding of the role played by the hole localization in the screening properties of a high-mobility 2DEG (and therefore in the FES) has to be reexamined.

Finally, the spectra of the InGaAs QW (sample 4) are shown in Fig. 4. Contrary to the GaAs case, these spectra are essentially independent of temperature. The large energy separation between the PL and PLE onsets is due to the high Fermi energy, related to the lower-energy gap of $In_xGa_{1-x}As$. The large peak at the PLE onset is not related to the FES, as it does not change with temperature (its change in intensity is due to the intensity decrease of the PL spectrum itself). It rather reflects the valence-band nonparabolicity typical of this material.[20] The lack of FES in this sample contrasts with previous results on the $In_xGa_{1-x}As/InP$ QW,[7,8,23] where it was clearly observed in PL spectra. This difference can be ascribed to the higher electron density and to a smaller degree of hole localization in our sample, expected from the lower In content. The fact that the FES is also absent in the PLE spectra of sample 4, which differs from the case of the GaAs QW (samples 1–3), strongly indicates again that the presence of FES in PLE is more related to the high electron mobility (see Table I) than to hole localization.

As mentioned above, the flat DOS shown by samples 1 and 2 allows the experimental determination of the power-law exponent of the FES. The hh and lh peaks in the PLE spectra have been fitted using the power-law function,[16]

$$I_{\mathrm{FES}}=A*(E-E_0)^{-\alpha}, \qquad (3.1)$$

where E_0 is the hh or lh transition energy and A is the FES amplitude. The total signal is assumed to consist of a constant background associated to the joint DOS I_0, and the FES intensity I_{FES} given by Eq. (1). The sum of the hh and lh contributions to the PLE spectrum has then been convoluted with a Gaussian, representing broadening effects, whose width is determined from the slope of the PLE onset. In Fig. 5 the fits without (dashed line) and with convolution (solid line) of the PLE spectra are presented for sample 1 together with the experimental data.

The fit of the hh peak is very sensitive to the choice of E_0, resulting in a large uncertainty for α. One obtains $\alpha=0.3 +/-0.1$ and $A/I_0=0.22$. For the lh FES the fit is more robust, resulting in $\alpha=0.38+/-0.02$ with the same value of A/I_0. The above values give equally good fits for both samples 1 and 2. The values for the Gaussian widths are $\sigma=1.9$ meV and 1.5 meV, respectively. Finite-temperature corrections given by the Fermi-Dirac distribution have not been included, as they affect only σ by 10–15 % at 2 K. Our α values are larger than the one (<0.1) reported in Ref. 10 for the same Fermi energy, probably due to differences in the sample characteristics in both cases. Instead, they are closer to the values calculated in Ref. 10 extrapolated to high electron density (see Fig. 4 of this reference). According to this calculation, α depends weakly on electron density for high values of ϵ_F, in agreement with the fact that we find the same value for samples 1 and 2.

IV. SUMMARY

In summary we present a study of the conditions required for the observation of optical FES in PL and PLE spectra. The use of a two-dimensional electron gas of simultaneously high density and high mobility allows us to study this many-body effect under such conditions. Direct comparison of spectra involving both localized and extended holes in a Be-doped sample indicates that hole localization is essential for the FES to be observed in PL spectra, because no mobile holes exist at the Fermi wave vector at low temperatures. Instead, localization of holes does not appear to be required in PLE, as FES is clearly observed for valence-band holes in high-mobility samples. To reconcile this result with the common assumption that hole localization is required for the FES to appear, it would be necessary to assume that the electrons participating in the FES in a high-mobility 2DEG extend over a much larger region than the static screening length. As to the best of our knowledge there is no theoretical support for such an assumption we have to conclude that the role played by hole localization in the appearance of FES, and more generally in the dynamic response of the electron gas, has to be reexamined.

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