Influence of screening in the magneto-optical properties of a two-dimensional electron gas: Photoluminiscence from $In_{0.53}Ga_{0.47}As/InP$ quantum wells

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Different modulation doped $In_{0.53}Ga_{0.47}As/InP$ quantum wells have been studied by photoluminescence and photoluminescence excitation at variable temperature and magnetic field. Clear manifestations of many-body effects as band-gap renormalization, optical Fermi-edge singularities, and shake-up sidebands are observed to depend on the electron concentration. A correlated evolution of the Fermi-edge singularity and the shake-up intensities with the filling factor is observed and explained in terms of the screening properties of the two-dimensional electron gas. The role of the hole mass on the optical spectra is also considered. These results provide a unified picture of the main effects of electron-electron interaction on the magneto-optical properties of the two-dimensional electron gas. [S0163-1829(97)52624-1]

I. INTRODUCTION

Modulation-doped semiconductor heterostructures and quantum wells (MDQW's) have been extensively studied by optical spectroscopy. The rich phenomenology associated with their absorption and emission processes provides valuable insight on the electron-electron interaction in the two-dimensional electron gas (2DEG),[1] which in turn determines important physical phenomena like the integer and fractional quantum Hall effects.[2,3] Among the manifestations of carrier correlation in the optical spectra, special attention has been paid to the enhancement of the optical emission and absorption at the Fermi level (optical Fermi-edge singularity or FES)[4–9] and to the appearance of low-energy sidebands in the luminescence spectrum due to phonon replicas (PR) or shake-up (SU) processes in the Fermi sea.[10–12] The details of the physical mechanisms underlying these effects are not yet fully understood in spite of the considerable theoretical effort invested.[1,5,13–16] This is due in part to the difficulty of controlling experimentally some crucial parameters that determine the appearance and strength of both FES and SU sidebands, like the details of the valence-band structure and the intersubband coupling, and localization by impurities or potential fluctuations.

The presence of an external magnetic field has a strong effect on the electronic properties, including intersubband coupling, the energy spectrum of electronic excitations, and the screening properties of the electron gas. As a result the optical spectra are drastically changed, offering new possibilities to study the above-mentioned many-body effects.

In this paper we present a systematic study of the photoluminescence (PL) and photoluminescence excitation (PLE) of symmetric modulation doped $In_{0.53}Ga_{0.47}As/InP$ quantum wells as a function of temperature, carrier density, and magnetic field. The optical FES and SU subbands are clearly observed to depend on these parameters. In some of the samples studied, SU sidebands are observed without mixing with PR, at difference with previous work,[10,11] thus enabling the observation of its intrinsic dependence on magnetic field. In addition, relevant information is obtained on the band-gap renormalization (BGR) and the FES dependence on electron concentration and temperature, showing that intersubband coupling is negligible in the present case. In the presence of a magnetic field the intensity and line shape of both FES and SU emissions change periodically with the filling factor, reflecting the variation of the screening properties of the 2DEG.

In the next section the sample characteristics are given as well as details of the experimental methods. Section III is devoted to PL and PLE measurements at zero magnetic field. PL results under magnetic field are presented and discussed in Sec. IV. Finally, the main conclusions are summarized in Sec. V.

II. EXPERIMENT

The samples studied are 8-nm-wide $In_{0.53}Ga_{0.47}As/InP$ MDQW's grown by low-pressure metal-organic vapor-phase epitaxy on InP substrates. Two 10-nm-thick layers containing 1.7×10^{18} cm^{-3} sulphur donor atoms are symmetrically located in the InP barriers. Different values of the width of the spacer layer separating the dopants from the well lead to different densities of the 2DEG. In our case the samples denoted A, B, and C have spacer layers of 30, 15, and 5 nm, respectively. Typical electron mobilities at low temperature are around 175 000 cm^2/V s. The main characteristics of the three samples studied in this work are presented in Table I. Electron densities have been measured by Shubnikov–de Haas oscillations and Fermi energies are obtained from the width of the photoluminescence spectra.

PL and PLE spectra at zero magnetic field for different temperatures were taken in a He-bath cryostat. The light source was a tungsten lamp attached to a 275-grating monochromator for selecting the wavelength. PL measurements under magnetic field were performed at fixed temperature (3 K) in a superconducting coil reaching 13 T. The samples

TABLE I. Main characteristics of the tree samples. The electron density is obtained from Shubnikov–de Haas oscillations, the Fermi energy from the PL spectra, and the effective masses from the fan plots.

Sample	Electron density n (cm^2)	Fermi energy (meV)	Effective mass (m_0)
A	5×10^{11}	27	0.052
B	8×10^{11}	42	0.051
C	1.2×10^{12}	72	0.052

were excited in Faraday configuration by the 457.9-nm line of an Ar laser with a 1 mW power focused on a 200-μm spot. In both cases the emitted light was analyzed in a double spectrometer of 0.85 m focal length and detected by a liquid-nitrogen-cooled germanium detector.

III. TEMPERATURE AND DENSITY DEPENDENCE

Even without considering many-body effects, the PL spectrum of a degenerate electron gas depends already on the degree of hole localization. In a 2D system with parabolic bands the joint density of states is energy independent and the shape of the spectrum is determined by the energy distribution of photocreated holes and the possible relaxation of the crystal momentum conservation condition. One can consider two extreme cases. For free holes with finite mass the PL maximum occurs for transitions to the edge of the valence band because of the rapid hole relaxation to its lowest-energy state. At higher energies the PL intensity decreases following the energy distribution of holes in the valence band, which for low excitation power, is Boltzman-like. On the other extreme, if the holes are completely localized by impurities or potential fluctuations, crystal momentum is no longer conserved and the spectrum becomes squarelike. One deals often with an intermediate situation, especially in a ternary compound, where compositional disorder allows indirect transitions.

Many-body interactions introduce several modifications to this single-particle picture.[1] First they produce the well-known renormalization of the band gap. It is a consequence of the corrections of the self-energy of electrons and holes by exchange and static correlation terms.[1,17] A general expression for the BGR is proposed in Ref. 17:

$$\Delta E_g/E_B = -3.1(na_B^2)^{1/3}, \tag{1}$$

where ΔE_g is the correction of the energy gap and E_B and a_B are the appropriate exciton binding energy and the effective Bohr radius, respectively.[18] According to Eq. (1) the fundamental gap of samples *B* and *C* should lie 5.3 and 10.5 meV below that of sample *A*. Measured values are 5.5 and 10 meV, in excellent agreement with theory. For this calculation an effective mass of $0.042m_0$ has been used[19] neglecting nonparabolicity of the bands.[20]

Another effect of the electron gas is the suppression of exciton lines due to phase space filling.[1] Yet a new spectral feature appears due to the collective response of the electrons at the Fermi level to the presence of the hole. This is the well-known optical singularity at the Fermi edge, which results from the broadening into a power law of the so-called

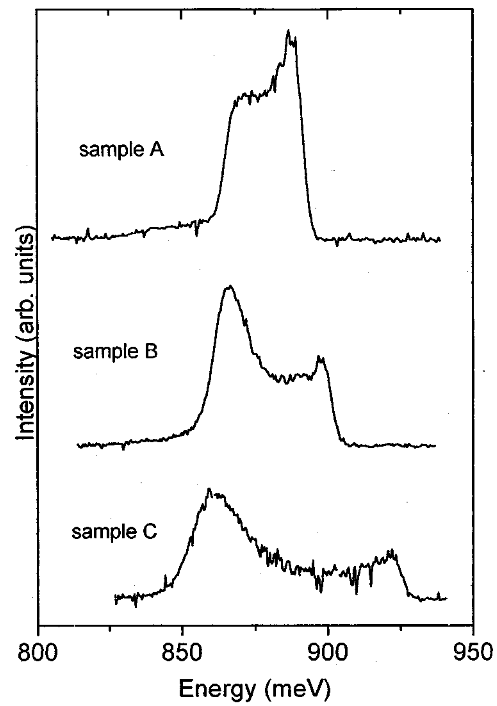

FIG. 1. Luminiscence of the tree samples at 3 K. Differences in electron density yield different values of BGR and FES intensity.

''Mahan exciton'' in the static Fermi-sea picture.[5] The intensity of the optical FES in two dimensions depends on several factors, among which the hole mass is of crucial importance.[13–16] The FES intensity increases with the hole mass as a result of the reduction of the hole recoil.[21] We observe experimentally (Fig. 1) a strong FES in the emission of sample *A*, and much weaker ones in samples *B* and *C*, which have higher electron densities. Another circumstance that favors the observation of the FES is the coupling to near unoccupied subbands.[7,16] In our case, however, this mechanism is not relevant as the nearest empty electron subband is around 100 meV above the Fermi level as can be seen in the PLE spectra of Fig. 2.

The spectral shape of the PL curves of Fig. 1 indicates that localized holes are dominant in sample *A* as shown by

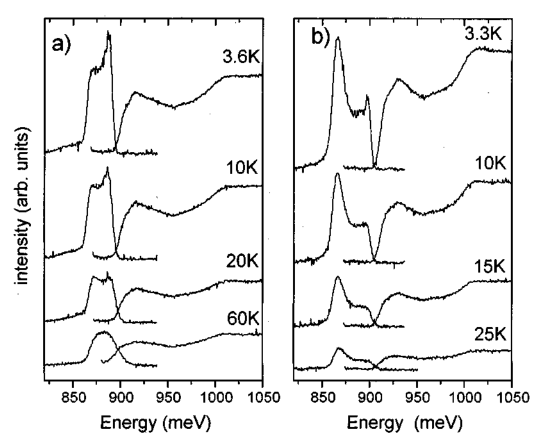

FIG. 2. Evolution of PL and PLE spectra with temperature for (a) sample *A* and (b) sample *B*.

the steplike onset of the PL spectrum, which reflects the 2D density of states of the (parabolic) conduction band. Emission of samples *B* and *C*, however, exhibit an essentially ''free-hole'' behavior, as indicated by the intensity decrease at energies higher than the band edge. Further evidence for the stronger hole localization in sample *A* is given by the unusually intense low-energy tail in its PL spectrum. As proved by the magneto-PL results presented in the next section, this tail contains contributions from both shake-up and phonon replica processes in sample *A*, while only the former are observed in samples *B* and *C*. At difference with shake-up mediated recombination,[13] phonon sidebands require hole localization in order to preserve momentum conservation.[12,22] The different regime of hole localization can be understood as a result of the better screening in high density samples of the potential fluctuations due to interface roughness and alloy composition. These are known to be the most important sources of disorder in these kinds of structures at low temperatures.

In Fig. 2 the PL and PLE spectra of samples *A* and *B* are presented for different temperatures. As expected, the optical FES in emission disappears very quickly as the temperature is raised due to the smearing of the Fermi distribution. The sharpness of the Fermi surface is a decisive factor in the strength of the FES because it determines the available states for the coherent scattering of the electrons by the photocreated hole. The analysis of the PLE spectra is more complicated because of the details of the valence-band structure and the competition between direct and indirect transitions to the Fermi level, the later being allowed by disorder. For both samples the PLE onset is less abrupt than the PL cutoff, and the PLE maximum is reached at a higher energy. A shoulder on the low-energy side of the PLE maximum is also clearly observed. The intensity decreases at higher energies as reported in previous measurements on other MDQW's.[8,9] The PLE spectral shape indicates that is starts with the indirect transitions from the top of the valence band to the conduction band at the Fermi wave vector k_F. These absorption processes are much weaker than the direct ones, but dominate the emission spectrum because of the hole relaxation. They correspond to the FES observed in PL, and that is the reason why it is more sensitive to temperature than PLE.[5] For increasing energy the PLE intensity grows as the transitions progress to the vertical (direct) one at k_F. Therefore the PLE shoulder is most probably due to transitions from the heavy-hole (HH) state and the maximum to light-hole (LH) transitions. The greater intensity related with the light hole is a consequence of the valence-band structure. The Fermi wave vector lies near the anticrossing between HH_1 and LH_1 subbands[23] in both samples Here the dispersion of the ''light'' hole subband has its maximum; consequently the density of states is higher and the hole recoil is smaller for it. The step around 1 eV in both samples corresponds to the second electron subband. This large energy separation excludes any intersubband coupling as the origin of the observed FES.

IV. MAGNETIC-FIELD DEPENDENCE

Upon application of a magnetic field to the 2DEG the density of states becomes a series of discrete Landau levels

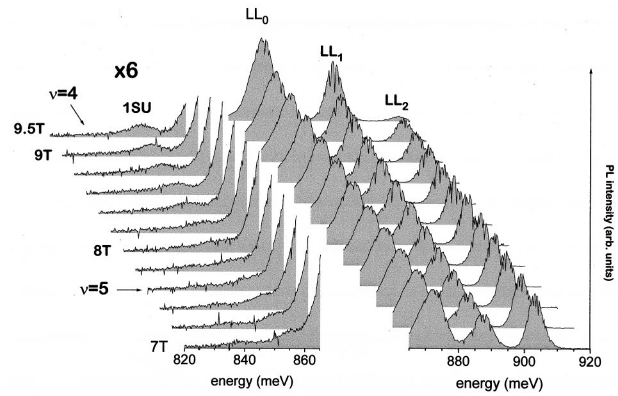

FIG. 3. PL spectra of sample *B* for different magnetic fields.

(LL's) of energy $E_N=(N+\frac{1}{2})\,\hbar\omega_c$, with the cyclotron frequency ω_c given by eB/m^*. In real samples these levels are broadened by lifetime effects and disorder. The latter introduces a difference between the states at the center of a LL, which are extended, while those whose energy lies in the tails of the LL have a localized character. The emission spectrum is then a collection of well-defined peaks, of certain linewidth, corresponding to recombination from all occupied LL's. This is shown in Fig. 3, where the PL spectra of sample *B* are displayed for different values of the magnetic field. As the field increases one observes the depletion of the third LL until it becomes empty at 9.5 T. From these data we can estimate the electron density under the present illumination conditions. It is found to by 8.7×10^{11} cm^{-2}. Magneto-PL taken with circularly polarized light displayed very small Zeeman splittings, indicating that the LL in our samples are essentially spin degenerate. As in the case of zero magnetic field other recombination processes take place where the energy of the transition is shared by an excitation of the system and the emitted photon. The former are usually phonons or SU excitations of the Fermi sea. Both types of excitation have been observed coupled to each other in previous work.[10,11] Also SU sidebands without significant coupling to LO phonons have been reported recently.[24] They are shown in the low-energy side of Fig. 3 and will be discussed below.

The energies of the PL peaks for samples *A* and *B* are represented in Fig. 4. The LL's follow the expected linear dependence on magnetic field, showing only small deviations towards lower energy (very clear in LL_0 of sample *A*) at fields corresponding to even values of the filling factor $\nu=hn/eB$. Such behavior, which has been observed in similar QW's,[10,11,25] reflects the changing properties of the 2DEG with the filling factor. When the Fermi level lies between two LL's, the creation of electron-hole pairs requires a finite energy $\hbar\omega_c$, the screening becomes poor, and the 2DEG is said to be incompressible. The situation is opposite for odd filling factors in the absence of Zeeman splitting.[26] In this case there are degenerate extended states at the Fermi level allowing for easy charge redistribution, and the 2DEG is then compressible. In our case no significant differences have been detected between the unpolarized and circularly polarized spectra, indicating that the Zeeman splitting is smaller than the inhomogeneous width of the PL peaks. This means that for odd filling factors, even if the Fermi level,

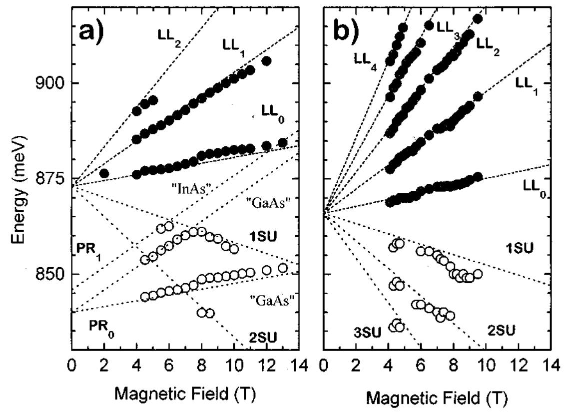

FIG. 4. (a) Fan plot for sample A showing the position of the LL, as well as SU and PR sidebands. The dashed lines are theoretical positions of the peaks with infinite hole mass and $m_e^* = 0.052 m_0$. Dotted lines indicate the theoretical position of the PR sidebands associated with the GaAs-like and InAs-like vibrations of the well. (b) Same for sample B with $m_e^* = 0.051 m_0$ and $m_h^* = 0.46 m_0$. In both cases the spin splitting of the hole is included following Ref. 28.

strictly speaking, is not located at extended states, the screening length will be strongly reduced with regard to the even filling factors. With these considerations in mind the picture described above remains essentially valid and one can consider the screening properties of the 2DEG periodically changing with the filling factor. The oscillations of the LL energies around E_N observed in Fig. 4 can be therefore understood as a partial recovering of excitonic interactions in the insulating state.[25]

The energy positions of PR and SU sidebands are also shown in Fig. 4. PR sidebands, which run parallel to their parent LL, are predominant in sample A. They correspond to InAs-like and GaAs-like vibrational modes of the QW. The first SU sideband of LL_0 (1SU) is also observed in sample A. It has negative slope in the fan plot and appears strongly coupled to the LO phonon replica.[10,11] The energy of the SU excitations, $E(LL_0)$-$E(1SU)$, is usually larger than $\hbar\omega_c$ due to magnetoroton effects.[11,27] However, this effect is not strong enough to account for the large difference in sample A. Indeed, if one tries to fit the LL energies to $\hbar\omega_c$, an anomalously large electron mass $(0.066 m_0)$ is obtained. The reason for that anomaly is the influence of Zeeman splitting of the valence-band states. For the localized holes of sample A the energy of the upper spin-split hole state increases with magnetic field, leading to a reduction of the LL slopes. The expected LL energies have been calculated using infinite hole mass for sample A and bulk mass[19] for sample B, together with the reported value of the hole g factor in the QW of this compound.[28] The results are the straight lines of Fig. 4. In this way a common and reasonable value of the electron effective mass $(0.052 m_0$ and $0.051 m_0)$ is obtained in both samples.

An important difference of sample B compared with sample A is the lack of PR lines in the field range studied. This can be understood remembering again that holes are essentially mobile in sample B. Consequently, creation of quasiparticles with nonzero wave vector (phonons or magnetorotons) in recombination process are restricted. Sample B

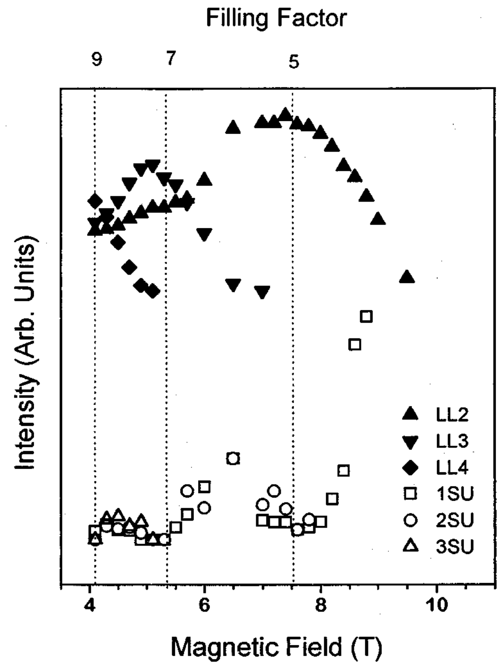

FIG. 5. Intensity of the FES (full symbols) and intensity to background ratio of the SU bands (open symbols). Filling factor is denoted in the top axis.

is therefore a good system to study the joint evolution of FES and SU sidebands in a magnetic field, even if some residual coupling to phonons is present, as suggested by the small bending of the 1SU line at 8 T.

The most remarkable effect of the filling factor on the PL spectrum is the variation of intensity and shape of the FES and SU bands.[24] These changes are illustrated in Figs. 3 and 5 for sample B. In the upper part of Fig. 5 (full symbols) the intensity of different LL's is plotted as a function of the magnetic field. For increasing field, the intensity of a given LL increases as it approaches the Fermi level, then reaches a maximum at the corresponding odd value of the filling factor, i.e., when the Fermi level is in the middle of the spin quasidegenerate LL, and decreases as the LL is further depopulated. The evolution of the SU bands with magnetic field is different. They change from well-defined peaks separated by energies close to $\hbar\omega_c$ for even values of the filling factor to an essentially structureless tail for odd filling factors. This is clearly seen in Fig. 3 for ν near 5. The peak to background ratio of the SU bands is plotted in the lower part of Fig. 5 (open symbols) and is a quantitative measure of this change in the spectral shape. These results can be understood on the basis of the already mentioned variable screening properties of the 2DEG. For odd filling factors the situation is more favorable to the appearance of the FES, as there is a continuum of extended final states at the Fermi level for the scattering by the hole. In other words, the charge can be redistributed at low energy cost. The fact that the intensity of the last occupied LL is larger when it is half filled than when it is full is the best indication of its edge singularity nature. The high density of electronic states around the Fermi level also explains the flattening of the SU emission at odd filling factors, because there is a continuum for the SU excitations across the Fermi level. Conversely, for even ν the lowest-energy excitation across the Fermi level is the (inter-Landau) defined peaks at energies close to $\hbar\omega_c$. They appear at higher energies, as shown in Fig. 4, because the highest transition rate corresponds to the magnetoroton minimum,[11] occurring at a wave vector of the order of the inverse magnetic length. The poor screening of the potential fluctuations at even filling factors helps these non-**q**-conserving transitions to take place.

V. CONCLUSIONS

We have studied the influence of the electron-electron interaction on the optical emission and absorption spectra of modulation-doped quantum wells. At zero magnetic field the band-gap renormalization has been found to follow the universal $n^{1/3}$ law with electron concentration. The particular shape of the PLE onset has been related to the valence band structure. Measurements in magnetic field show periodic dependence of three different experimental results on the filling factor: (1) The oscillations of the LL transitions energies around $(N+\frac{1}{2})\hbar\omega_c$, (2) the changes of the FES intensity, which is maximum at odd filling factors, and (3) the spectral line shape of the SU bands, which are sharper at even filling factors. These results are the consequence of the variable screening properties of a spin-degenerate 2DEG as a function of the magnetic field.

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