Magnetoluminescence study of many-body effects in homogeneous quasi-two-dimensional electron-hole plasma in undoped $In_xGa_{1-x}As/InP$ single quantum wells

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The photoluminescence of a highly homogeneous quasi-two-dimensional electron-hole plasma in undoped lattice-matched $In_{1-x}Ga_xAs/InP$ quantum wells has been investigated up to densities of 4×10^{12} cm^{-2} under magnetic fields $H\leq10$ T. The band-gap renormalization due to many-body interactions is found to be significantly larger for the $n_z=1$ than the $n_z=2$ subbands. We observe an energy-dependent renormalization of the reduced effective mass for carrier concentrations in the $(1\text{–}4)\times10^{12}$ cm^{-2} range. The renormalization is $\sim10\%$ near the band bottom for a kinetic energy ~50 meV while it reaches 25% in the intermediate range. This variation is attributed to the influence of the light-hole–heavy-hole subband-splitting renormalization.

I. INTRODUCTION

During the past few years, a number of studies have addressed the properties of electron-hole plasma (EHP) in three-dimensional (3D) and 2D semiconductor structures. The many body effects in dense quasi-2D electron-hole (*e-h*) systems were discussed in a number of studies.[1–7] Interparticle interactions in a dense *e-h* system in semiconductors lead to a renormalization both of the band gap and the electron and hole dispersion laws. In many-particle theory, these changes are described by a self-energy Σ, which depends on the energy ε and the quasimomentum k of the quasiparticles.[7–9]

In 3D systems, the quantity $\Sigma(k,\varepsilon)$ depends only weakly on k and ε and even on the particular species of charged particles because the screened interaction in the dense *e-h* system is of a short-range nature.[8] The electron and hole bands in highly excited semiconductors thus undergo a basically rigid shift.[8] The rigid-shift approximation has been used as well for a description of emission spectra of the quasi-2D EHP in quantum wells (QW's).[1]

The most reliable information on the density dependence both of the band-gap shrinkage and the carrier dispersion law may be obtained from magneto-optical measurements. A magnetic field perpendicular to the QW plane leads to a quantization of the movement of the quasi-2D carriers in the QW plane and, as a consequence, to a discrete energy spectrum of electrons and holes in the QW's. The effective mass renormalization is detected as a change in the energy gaps between Landau levels.

We have investigated the influence of the multiparticle interactions on the dispersion law of the quasi-2D carriers in a dense $[r_s=(\pi n_{eh}a_{ex}^2)^{-1/2}<1]$ EHP confined in QW's in undoped $In_{1-x}Ga_xAs/InP$ heterostructures. Here n_{eh} and a_{ex} are the EHP density and excitonic Bohr radius, respectively. To obtain reliable results, great care was taken to prepare a photoexcited nonequilibrium *e-h* system of high homogeneity. The experimental technique is described in Sec. II. After a discussion of the spectra of the plasma at zero magnetic field (Sec. III), photoluminescence spectra of a dense plasma in a wide region of plasma densities and magnetic fields are presented in Sec. IV. The spectra are discussed in the framework of a plasma approximation that is found to be satisfactory in the limit of a high-density EHP with a strong damping [exceeding the direct Coulomb (exciton) energy] and for electron temperatures comparable to the cyclotron energy (Secs. V A and V B). The damping of the one-particle states in the plasma (Sec. V A), the band-gap renormalization for the lowest and higher index subbands (Sec. V C), and the renormalization of the reduced dispersion laws for electrons and holes (Sec. V D) are determined.

II. EXPERIMENTAL

To investigate the properties of a dense quasi-2D EHP we have used lattice-matched undoped $In_{0.53}Ga_{0.47}As/InP$ single quantum-well (SQW) heterostructures (QW width $L_z=8$, 15, and 19 nm) grown by low-pressure metalorganic vapor-phase expitaxy. The maximum quasi-2D EHP density in a QW is determined by the QW width and depth (i.e., band offset). In our structures this maximum density is increasing from 4×10^{12} to 6×10^{12} cm^{-2} ($r_s\sim0.25$) as L_z is increased from 8 to 19 nm.

The photoluminescence measurements were carried out with the use of a cw Ar^+-ion laser at $\lambda=5145$ Å.

The emission was dispersed by a grating monochromator with a dispersion of 26 Å/mm and detected by a cooled Ge detector. The samples were located in superfluid He in a cryostat with a superconducting solenoid.

To realize high and homogeneous EHP densities by the cw Ar^{+}-ion laser excitation, we have defined mesa structures in the QW plane with dimensions as small as $30\times30\mu$m. The mesas were prepared by optical lithography and dry etching.[10] The lateral confinement in the small mesas makes it possible to reach very high densities of about 5×10^{12} cm^{-2} for laser powers of 1 W and to use a cw rather than a pulsed laser. The variation of the plasma density near the mesa edges in the $In_{1-x}Ga_xAs$ QW is not significant because of the small surface recombination rate in $In_{1-x}Ga_xAs$.[11]

III. EHP IN QW WITHOUT MAGNETIC FIELD

Figure 1 represents the emission spectra of a 15-nm $In_{0.53}Ga_{0.47}As$/InP QW recorded at 2 K for various excitation densities. For low excitation densities the emission of excitons prevails in the spectra. The line halfwidth is about 5 meV and depends only on the QW quality. The free exciton transition energies for the $n_z=1,2$ subbands determined by excitation spectroscopy are indicated by the arrows.

For excitation levels below 5 W/cm^2, the intensity of the emission line varies approximately linearly with the excitation power and the linewidth remains nearly constant. For higher excitation powers the peak intensity saturates and we observe a broadening on the high-energy side of the emission. The saturation of the maximum intensity corresponds to the complete filling of the conduction and valence $n_z=1$ subband edges and is a direct consequence of the Pauli principle. At the highest excitations a new well-pronounced step appears in the emission spectra due to filling of the $n_z=2$ subbands. This step corresponds to allowed transitions between the electron and heavy-hole subbands ($\Delta n_z=0$). Note that a saturation of the maximum emission intensity was never observed in samples without mesas even at excitation levels as high as 10^6 W/cm^2. This indicates a strong lateral expansion of EHP in large-area samples.

Besides the strong emission line broadening associated with the increase in the kinetic energy of electrons and holes in a dense EHP, the emission spectra show a well-pronounced redshift of the low-energy edge of the emission line with increasing excitation intensity (see Fig. 1). The second step in the emission spectra shows a similar shift, but with a markedly smaller rate.

The redshift of the low-energy edge of the steps gives us information about the band-gap renormalization, whereas the broadening of these steps is mainly due to the decay of one-particle states in a dense EHP. To determine the EHP parameters from the photoluminescence line-shape analysis, however, a few assumptions have to be used regarding the energy dependence of the effective masses of the carriers, the one-particle decay, and the transition probabilities in the EHP.[1,10] This may lead to errors in the determination of some EHP parameters (plasma density, band-gap renormalization, and one-particle decay) and provides no information on such an important parameter as the renormalization of the effective masses.

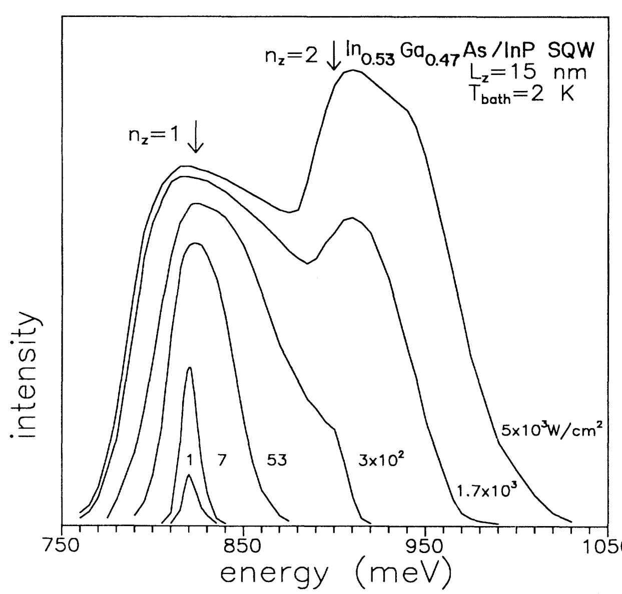

FIG. 1. Photoluminescence spectra of a 150-Å $In_{0.53}Ga_{0.47}As$/InP QW at $T_{bath}=2$ K for various excitation densities. The arrows indicate the $n_z=1$ and 2 band edges at $n_{eh}=0$ as determined by the photoexcitation spectroscopy measurements.

IV. MAGNETOLUMINESCENCE SPECTRA OF EHP

In the emission spectra of 2D EHP in a magnetic field perpendicular to the QW plane, the effective masses, transition probabilities, and magnitudes of the one-particle damping in the EHP are responsible for different spectrum parameters, namely, for the emission line spacings, the relative line intensities, and their half-widths, respectively. Figure 2 illustrates the change of the emission spectra of the EHP in a constant magnetic field $H=8.65$ T with increasing density. First of all the spectra show a pronounced Landau-level structure. Only allowed $j_e-j_h=0$ transitions between the electron (j_e) and hole (j_h) Landau levels are observed in the spectra of the undoped structures with an equal filling of Landau levels.

An increase in the EHP density gives rise to (i) the appearance of new lines corresponding to allowed transitions between higher Landau levels, due to a filling of these levels; (ii) a broadening of the emission lines, due to an increase of the one-particle damping; (iii) a shift of all lines to low energies, due to the band-gap renormalization; and (iv) a change in the spacings between the lines, due to the effective-mass renormalization.

The density dependences of the Landau-level transition energies are represented in Fig. 3 for the 15-nm QW at $H=8.65$ T. The EHP densities were determined directly from the emission spectra by calculating the number of

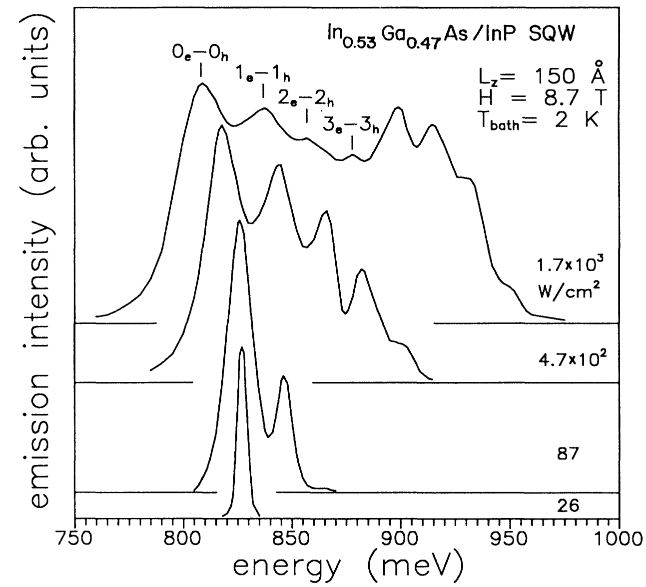

FIG. 2. Photoluminescence spectra of the 150-Å $In_{0.53}Ga_{0.47}As/InP$ QW at $H=8.65$ T and $T_{bath}=2$ K for various excitation densities.

filled Landau levels, because the number of states in the Landau levels is determined by the magnitude of the magnetic field and does not depend on the EHP density. It is seen from Fig. 2 that the intensity of emission lines connected with transitions between the filled Landau levels well below the Fermi energy is nearly independent of the level number. Therefore the density contribution of partially filled levels near the Fermi level was determined

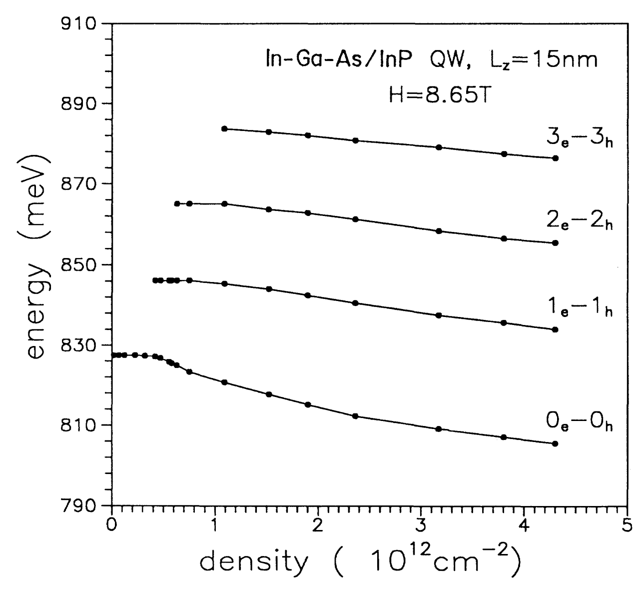

FIG. 3. Density dependence of the energies of allowed Landau transitions in the optically excited quasi-2D EHP in a 150-Å $In_{1-x}Ga_xAs$ QW at $H=8.65$ T, $T_{bath}=2$ K.

from the relative intensities of these transitions. This is possible because the Fermi-edge singularities are negligible at high electron temperature.[12,13]

Figure 3 shows that all filled Landau levels show a monotonic shift to the low-energy side with increasing plasma density. This is in qualitative agreement with the expected behavior of the self-energy in the dense EHP.

V. DISCUSSION

In many-particle theory, the contribution from many-body effects in the ε-k dispersion of the quasiparticles in the EHP in zero magnetic field is described by a self-energy,

$$\Sigma_{e,h}(k,\varepsilon)=\mathrm{Re}\Sigma_{e,h}(k,\varepsilon)+\mathrm{Im}\,\Sigma_{e,h}(k,\varepsilon)\ . \tag{1}$$

$\mathrm{Re}\Sigma$ describes the renormalizations of the noninteracting electrons and holes dispersion laws

$$\varepsilon_{e,h}(k)=\varepsilon^0_{e,h}(k)+\mathrm{Re}\Sigma_{e,h}(k,\varepsilon) \tag{2}$$

and $\mathrm{Im}\Sigma_{e,h}(k,\varepsilon)$ represents the damping of the one-particle states in the dense e-h system which is connected with Auger processes resulting from three-particle collisions.[14] The representation (1) is valid if the collision damping of the one-particle states described by the imaginary part of $\Sigma_{e,h}(k,\varepsilon)$ is relatively small. Usually $\mathrm{Im}\Sigma_{e,h}(k,\varepsilon)$ is small near the Fermi level but increases rapidly with energy in going from the Fermi surface to the band extremum.

This approximation remains valid in the case of vanishingly small magnetic fields when the cyclotron energy is negligible as compared with the Fermi energy and the plasma temperature. In this case one can take the wave vector corresponding to the electrons and holes at the νth Landau level to be equal to

$$\langle k^2\rangle = eH(2\nu+1)/\hbar c\ , \tag{3}$$

and determine the quasiparticle dispersion $\varepsilon(k)$ from the Landau-level energies. Here e, $\hbar$, and c denote the electron charge, the Planck constant divided by 2π, and the light velocity *in vacuo*, respectively. However, an increase of the magnetic field results in a discrete energy spectrum of both the electrons and holes. As a consequence, a strong enhancement of the exciton effects appears that gives rise to additional restrictions for the applicability of the plasma approximation. So, it was found in optical investigations of the low-temperature neutral magnetoplasma with integerly filled Landau levels[15] that the carriers in the Landau levels closest to the Fermi level form bound excitonlike states. Further excitonic effects are well displayed at low density in Fig. 3. Here we show that the transition energies do not depend on density for $n_{eh} < 10^{12}$ cm^{-2}. A study of excitonic effects in the emission spectra of low-temperature magnetoplasma has been published elsewhere.[16]

A detailed analysis of transition energies[15] has shown that the excitonic approximation fails for Landau levels below that closest to the Fermi level. This occurs even in the case of only two filled Landau levels. Thus, the choice of the model is of great importance in the studies of the magnetoluminescence spectra of the quasi-2D EHP. This problem is discussed in more detail in the next two sections devoted to consideration of the damping and the ε-k dispersion of quasiparticles in a QW plasma.

A. The damping of the one-particle states

The damping of the one-particle states in a dense e-h system is an important parameter in all many-particle theories. The damping increases for the one-particle states when going below the Fermi level because of an increase of the scattering probability.[14] For high-quality QW's with a small intrinsic Landau-level half-width, the half-width of the lines corresponding to transitions between discrete Landau levels directly reflects the damping of the states

$$\Gamma^2=\Gamma_e^2+\Gamma_h^2 \ . \qquad (4)$$

It is seen from the spectra in Fig. 2 that in the case of an EHP with a fixed density, the half-width of the lines and, hence, the one-particle damping, increases monotonically in going from the Fermi level to the low-energy edge of the emission. In addition, the comparison of the spectra corresponding to different EHP densities shows that the halfwidth and therefore the scattering rate of one-particle states at a fixed energy increases monotonically with the plasma density. This is in qualitative agreement with the theoretical predictions.[9,14,17]

The measured dependences of $\Gamma(n_{eh})$ near the band bottom ($\varepsilon=0$) and $\Gamma(\varepsilon)$ at n_{eh}=const are shown in Figs. 4(a) and 4(b), respectively. The damping $\Gamma(0)$ measured at fixed magnetic field is a very weak function of the density until the first Landau level is filled and strongly changes when the carriers appear in the second Landau level. As a result there is an essential difference in the magnitudes of damping of states near the band bottom found at two different fields if the number of occupied Landau levels is small. This difference is associated with the fact that the magnetic field strongly modifies the energy spectrum of carriers and, hence, their scattering. For this reason the decay of one-particle states in the magnetic field differs from that in zero field. The difference disappears for a dense plasma with $\varepsilon_F \gg \hbar\omega_c$ and $\Gamma \sim \hbar\omega_c$ where $\hbar\omega_c$ is the cyclotron energy. In the last case the magnitudes of Γ are nearly independent of the strength of a magnetic field (Fig. 4) and correspond to magnitudes of Γ which are necessary to describe the broadening of the low-energy edge of the EHP spectra without magnetic field.

Figure 4 shows as well that in the region of high densities ($n_{eh} > 10^{12}$ cm^{-2}, $\varepsilon_F > 40$ meV), the decay of the one-particle states near the band bottom in the EHP is an essentially sublinear function of the Fermi energy or plasma density. In addition, we observe for a fixed plasma density a rather weak energy dependence of $\Gamma(\varepsilon)$ far from the Fermi level. Both results are in agreement with expectations of the properties of a dense EHP in the random-phase approximation (RPA).[9,17]

B. ε-k dispersion in the EHP

As follows from Eqs. (1)–(3), in the region of densities where excitonic effects can be neglected, information about the dispersion of the one-particle states in the EHP can be obtained from the Landau transition energies. In the framework of the rigid band shift model, the gaps $\Delta_{i,i-1}$ between the adjacent Landau levels are independent of the plasma density. Figure 3 shows that this is

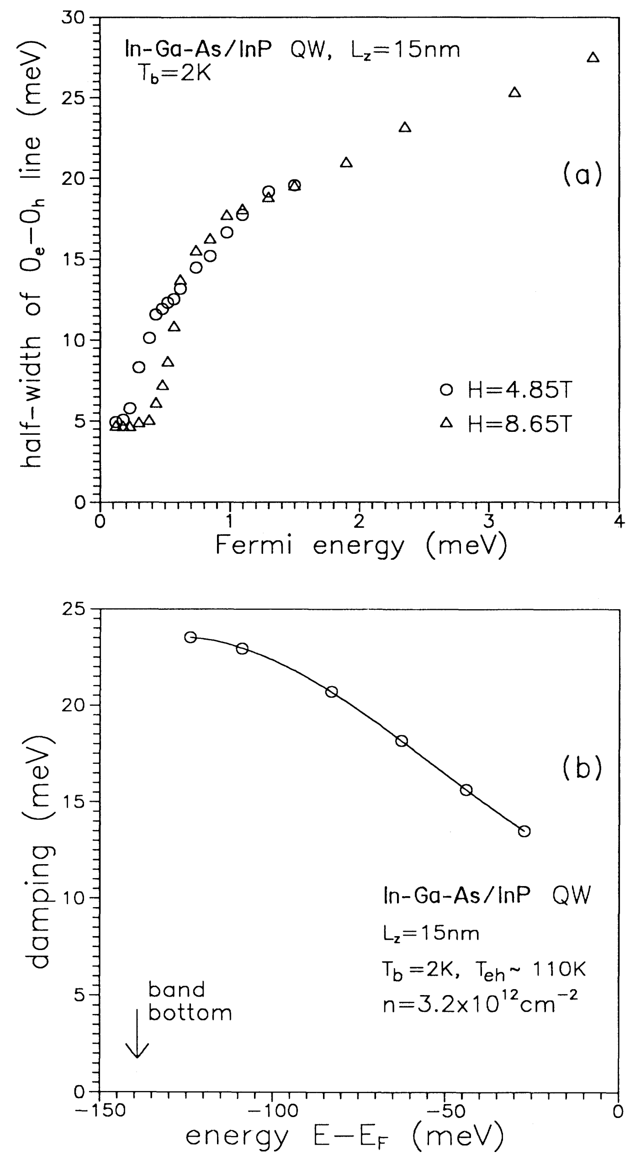

FIG. 4. (a) Dependences of the half width of the 0_e-0_h emission line on the carrier density in the EHP for two different magnetic fields $H=4.85$ and 8.65 T for an $In_{0.53}Ga_{0.47}As/InP$ 150-Å SQW, $T_{bath}=2$ K. (b) Energy dependences of the damping of one-particle states in a neutral EHP with $n_{eh}=3.2\times10^{12}$ cm^{-2} confined in a 150-Å $In_{1-x}Ga_xAs/InP$ SQW at $T_{bath}=2$ K. The estimated electron-hole temperature in the EHP is approximately 110 K.

not the case. This indicates that the approximation of the rigid band shift for the quasi-2D EHP is too crude.

Figure 5 shows the typical Landau fan for transition energies in the dense plasma with several filled Landau levels. It was obtained from the emission spectra of an EHP with $n_{eh}=1.8\times10^{12}$ cm^{-2} from the 190-Å thick QW. Though the sample is placed in liquid He, Fig. 2 shows that the electron temperature is comparable with $\hbar\omega_c$. In addition, it is seen from Fig. 2 that the j-j line width is everywhere larger than the excitonic energy ($\sim$10 meV) and comparable with $\hbar\omega_c$. These two factors indicate that the plasma approximation can be used for the evaluation of our data. This assumption is strongly supported by the fact that the envelope of the emission spectrum recorded in magnetic field with $\hbar\omega_c\sim\Gamma$ practically coincides with the spectrum recorded at $H=0$, cf. Figs. 1 and 2.

The observed Landau transitions within the two lowest subbands $n_z=1$ and 2 give rise to Landau fans which originate below 800 meV and at 850 meV, respectively. As displayed in Fig. 5, a linear extrapolation to zero field of the Landau transitions within the second subband converges with high accuracy at an energy of 850 meV. The Landau transitions associated with the $n_z=1$ subband behave remarkably different. The linear extrapolation to $H=0$ of the 2-2 and 3-3 transitions implies a band gap at zero field of 798 meV. The linear extrapolation of the 0-0 transition results in a subband gap of 788 meV. Furthermore the variation of the 1-1 transition energies with magnetic field is nonlinear. A linear extrapolation of the low-field transition energies ($H<6$ T) converges with the data of the 0-0 transition. The extrapolation of the energy dependence at $H>6$ T, in contrast, converges with the data obtained for the 2-2 and 3-3 transitions.

This indicates a change in the effective masses which occurs at energies $\varepsilon\sim30$ meV above the subband minimum. This energy is close to the magnitude of the light-hole–heavy-hole splitting in the QW. Therefore, the drastic change in the reduced effective mass can be naturally connected with a strong nonparabolicity of the light-hole subband in this energy range. At higher and smaller energies, the Landau-level splitting increases approximately linearly with magnetic field in a wide range of $H\leq9$ T.

Figure 6 shows the reduced ε-k dependence $\varepsilon=\varepsilon_e+\varepsilon_h$ for carriers in the 190-Å QW for EHP with $n_{eh}=9\times10^{11}$ cm^{-2}. It was determined from the Landau fan with the use of Eq. (3). Figure 6 shows that the scattering of the experimental data obtained at different magnetic fields between 3.5 and 8.7 T is relatively small. This can be considered as an additional support for using the plasma approximation. An analysis of experimental data has shown that the disagreement between the points taken from different magnetic fields increases with decreasing plasma density and with decreasing plasma temperature. When the number of occupied Landau levels is smaller than three the excitonic corrections become too large to be neglected.[16]

C. Band-gap renormalization

To determine the band-gap renormalization we have measured the shift of the lowest EHP emission line 0_e-0_h as a function of the plasma density. For both the $n_z=1$ and 2 subbands, the energy gap at zero density was determined from the spectral position of the excitonic lines in the photoexcitation spectra corrected by the appropriate excitonic Rydberg. We consider only EHP's with three

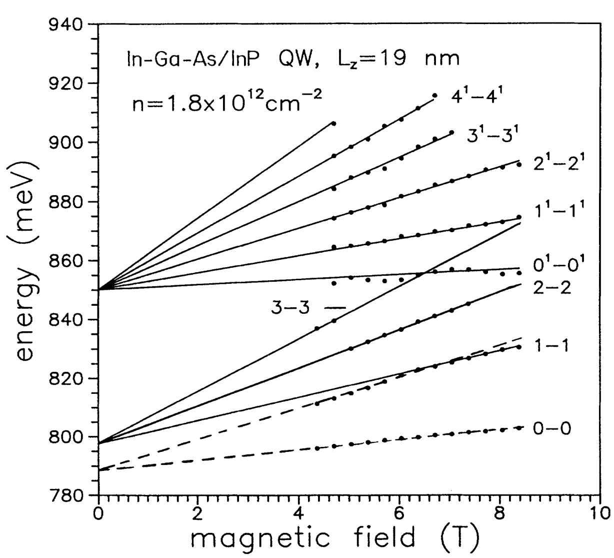

FIG. 5. The fan for allowed interband Landau transitions in a quasi-2D EHP with $n_{eh}=1.8\times10^{12}$ cm^{-2} confined in a 19-nm $In_{1-x}Ga_xAs/InP$ SQW. Experimental data are shown by dots; the solid and dashed lines represent approximations linear in magnetic field.

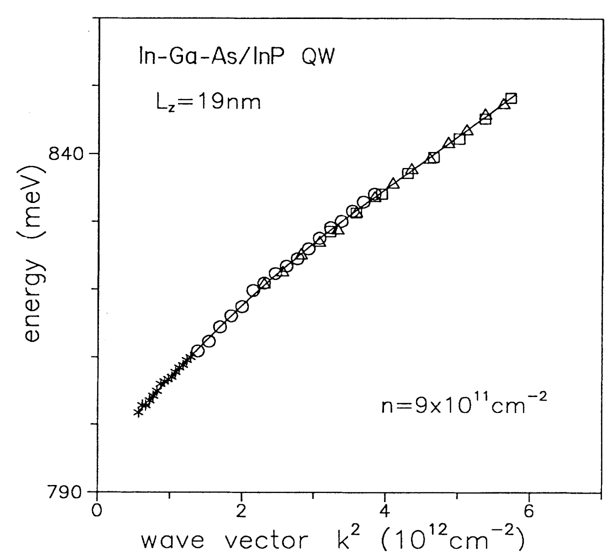

FIG. 6. Reduced carried dispersion ε-k in a 19-nm QW for $n_{eh}=9\times10^{11}$ cm^{-2}. The points taken from the different Landau-level transitions are shown by different labels: 0-0, stars; 1-1, circles; 2-2, triangles; and 3-3, squares.

or more occupied Landau levels to neglect the excitonic effects. Under these conditions the line 0_e-0_h moves monotonically with the EHP density to lower energies. A comparison of Figs. 1 and 2 demonstrates the advantage of the magnetic-field studies. A significantly higher accuracy in the determination of the band gap is obtained because the band-gap edge in the EHP emission spectra recorded without magnetic field is strongly broadened.

The experimentally determined density dependences of the band-gap renormalization for the $n_z = 1$ and 2 subbands are shown in Fig. 7 for undoped $In_{1-x}Ga_xAs/InP$ QW's with $L_z = 80$, 150, and 190 Å. These dependences are close to those found earlier[10] from the emission line of EHP without magnetic field.

The results of the available theoretical calculations[18] for the fundamental band-gap renormalization in the full RPA are shown in Fig. 7 by the solid lines. The measured fundamental band-gap shrinkage is in agreement with the theoretical calculations only for $n_{eh} < 2 \times 10^{12}$ cm^{-2} ($r_s > 0.6$). The disagreement for higher densities is striking because an RPA should provide a better accuracy in the high-density limit.

The difference in the theoretical and experimental renormalization value may be, in principle, due to several effects. First, in the calculation the intersubband scattering contribution to screening effects[18] and the effective-mass renormalization which occurs in the dense plasma (Sec. V D) are not considered. Second, taking into account that the electron temperature in the dense photoexcited EHP reaches 200–250 K, an additional band-gap shrinkage might occur if the lattice temperature increases markedly too. However, this effect is negligible in our measurements. If the lattice temperature would be increased at high pumping powers, a lattice-temperature-induced band-gap shrinkage should result in a spectral shift of all j-j emission lines corresponding to the transitions between the different Landau levels. However, Fig. 2 shows that the shift of the upper QW j-j transition lines is negligible. Such a small heating of the QW lattice is expected due to the fact that short-wavelength acoustic phonons generated in the QW have a high velocity ($\sim 10^5$ cm/s) and therefore leave the QW before decaying into long-wavelength ones. An increasing electron temperature at the fixed lattice temperature is as well not expected to lead to the additional band-gap shrinkage.[9] Thus, further studies are needed to understand the origin for the observed discrepancy between the experimental and calculated band-gap renormalizations at high plasma densities.

Figure 7(b) shows that the band-gap shrinkage for the $n_z = 2$ subband is significantly smaller than for the fundamental one. The difference in the band-gap renormalization of the $n_z = 1$ and 2 subbands was observed earlier[4] in exciton absorption measurements using nanosecond excitation of an EHP in multiple QW $Al_yGa_{1-y}As/GaAs$ structures. The authors[4] have considered only the region of relatively small EHP densities insufficient to fill the $n_z = 2$ subbands and to destroy $n_z = 2$ exciton states.

We consider in our measurements the opposite case of a high EHP density when (i) the $n_z = 2$ carriers are not bound into excitons and (ii) the splitting of the $n_z = 1$ and 2 subbands is significantly smaller than the Fermi energy. In this case one would expect from a simple analogy with a 3D EHP distributed over a few different bands[19] that the shifts of the $n_z = 1$ and 2 subbands are approximately identical. Theoretically and experimentally it is well established[19] that in the case of a 3D plasma the deficiency in the exchange energy contribution for a weakly occupied band is strongly compensated by an increase in the correlation energy, their sum being only the function of the total plasma density in all bands. However, Fig. 7(b) shows that the correlation energy contribution to the

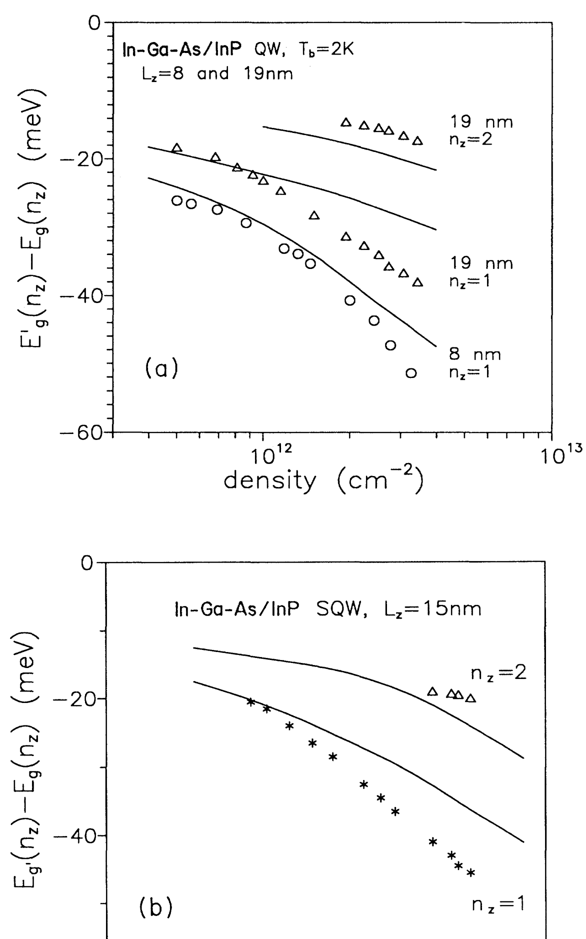

FIG. 7. Measured density dependences of the band-gap renormalization for the $n_z = 1$ and 2 subbands in the 80 and 190 Å (a) and 150 Å (b) $In_{0.53}Ga_{0.47}As$ SQW's determined from spectra recorded at $T_{bath} = 2$ K. The renormalization for each subband is plotted relatively to the corresponding subband edge at zero density. The solid and dashed lines represent the band-gap renormalizations for the $n_z = 1$ and 2 subbands, repectively, calculated for a quasi-2D EHP in the full RPA (Ref. 18).

self-energy of the quasi-2D EHP for the weakly occupied second subband is too small to compensate the deficiency in the exchange energy arising from its weak filling. Therefore, to explain the experimental result we have to take into account the specific features of wave functions of quasi-2D carriers in QW's.[18]

The results of the calculations of the band-gap renormalization for the $n_z=2$ subband for our QW's in the full RPA approximation are represented in Fig. 7(b) by the dashed line.[18] Both the finite QW width and offsets for conduction and valence band were taken into account. We see that the strong difference in the renormalizations of the fundamental and $n_z=2$ subbands finds a qualitative description in the framework of the full RPA calculations.

D. The renormalization of the dispersion

As discussed in Sec. V B, in the region of EHP densities where excitonic effects can be neglected, information about the dispersion of the one-particle states in the EHP can be obtained. Therefore we have investigated the magnetic-field dependence of the energy gaps Δ_{ij} between the emission lines i_e-i_h and j_e-j_h corresponding to allowed transitions between Landau levels to study many-body effects on the dispersion.

Some important details of the changes in the reduced carrier effective mass, $\mu=(m_e^{-1}+m_h^{-1})^{-1}$, for carriers in the EHP are seen from the density dependences of the gaps between a few low Landau levels (Fig. 8). At high densities of $n_{eh}>2\times10^{12}$ cm^{-2} all the gaps Δ_{ij} show a similar behavior. They slightly increase with the EHP density. Taking into account that $\mu(\varepsilon)$ is inversely proportional to Δ one can conclude that below the Fermi level μ decreases weakly and monotonically with increasing n_{eh}.

At smaller EHP densities the weak dependence of Δ_{ij} on n_{eh} is observed only for energies far from the band bottom (see, e.g., the weak change of Δ_{12} and Δ_{23} in Fig. 8). The density dependence of Δ_{01} shows, however, that the change of μ near the band bottom is strong. The decrease of n_{eh} from 2 down to 1×10^{12} cm^{-2} leads to a 25% decrease of Δ_{01} which indicates an increase of the effective mass by a similar amount.

Figure 9 shows the reduced carrier dispersion, $\varepsilon(k)=\varepsilon_e(k)+\varepsilon_h(k)$ determined from the energies of the allowed Landau transitions. The ε-k dispersions are similar for different n_{eh} and L_z. In the region of large k the ε-k dependence is approximately linear in k^2. At small k the band nonparabolicity strongly increases. An enhancement of the $\varepsilon(k^2)$ slope indicates the mass reduction near the band bottom.

The dependences of the reduced effective mass on k^2 are shown in Fig. 10 for different n_{eh} in a 15-nm-thick QW. The values of μ for different k were determined from the slope of $\varepsilon(k^2)$. It is seen that there is a $\sim35\%$ reduction of μ near the band bottom. Similar dependences for $\mu(k)$ are also observed for QW's with $L_z=8$ and 19 nm.

The strong dependence of μ on k seems to be mainly connected with the valence-band nonparabolicity in the $In_{1-x}Ga_xAs/InP$ QW's originating from an interaction between light- and heavy-hole subbands. The estimated in-plane hole mass, m_{hh}, at energies $E_h\ll\Delta E_v$ is comparable with the electron mass ($m_e\sim0.05m_0$, $m_{hh}\sim0.1m_0$), while at $E_h>\Delta E_v$ it increases 5–10 times. Here ΔE_v is the splitting between the light- and heavy-hole subbands. Such a nonparabolicity of m_{hh} explains qualitatively the k dependence of the reduced mass. At large k when $m_e\ll m_{hh}$ we found the reduced mass

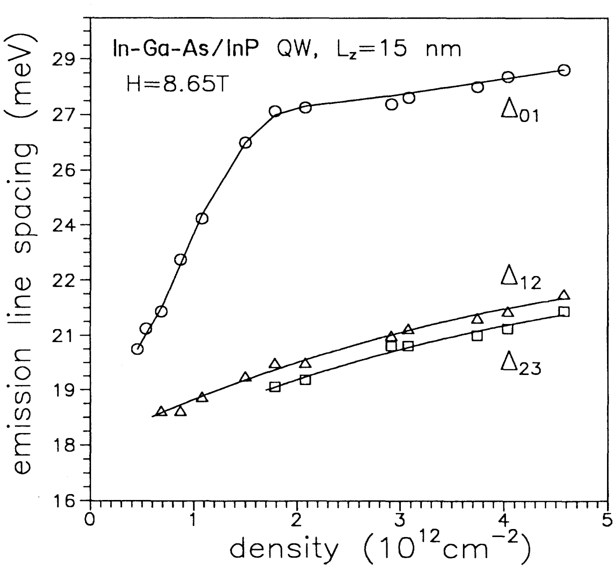

FIG. 8. Measured density dependences for the energy gaps between the four lowest Landau levels in the quasi-2D EHP in an $In_{0.53}Ga_{0.47}As$ QW ($H=8.65$ T).

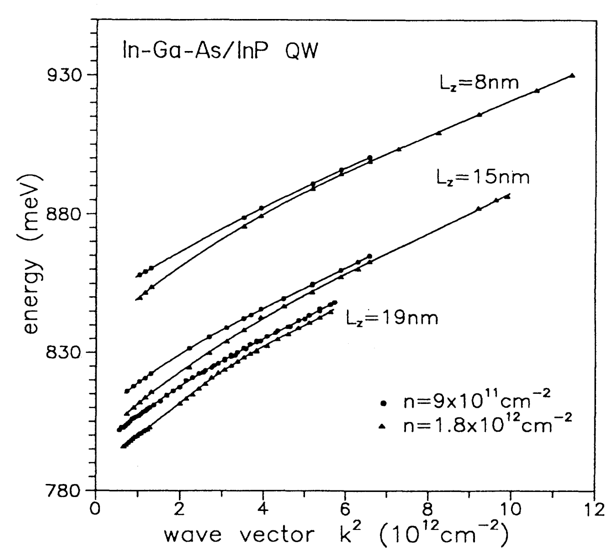

FIG. 9. Reduced ε-k dispersion in QW's with $L_z=8$, 15, and 19 nm for different plasma densities.

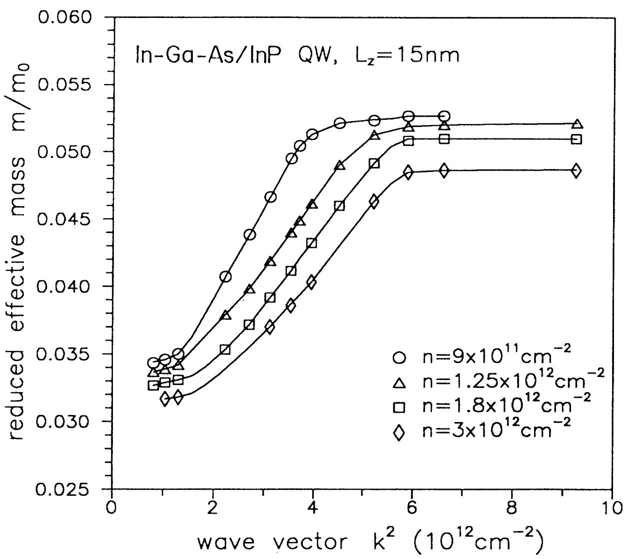

FIG. 10. Dependence of reduced carrier effective mass in a 15-nm QW on square-wave vector for different EHP densities.

$\mu \sim m_e$; at smaller k when m_{hh} decreases and becomes comparable with m_e, the reduced mass decreases 1.3–1.5 times.

Figure 11 displays the density dependence of the reduced effective mass as a function of the plasma density for different wave vectors. The monotonic reduction of μ at fixed k observed for increasing EHP density should be mainly connected with the effective-mass renormalization. The mean value of the mass reduction is close to the theoretically[17] predicted value of 10%. Figure 11 shows, however, that the mass reduction is strongly different for various values of k. The reduction of μ near

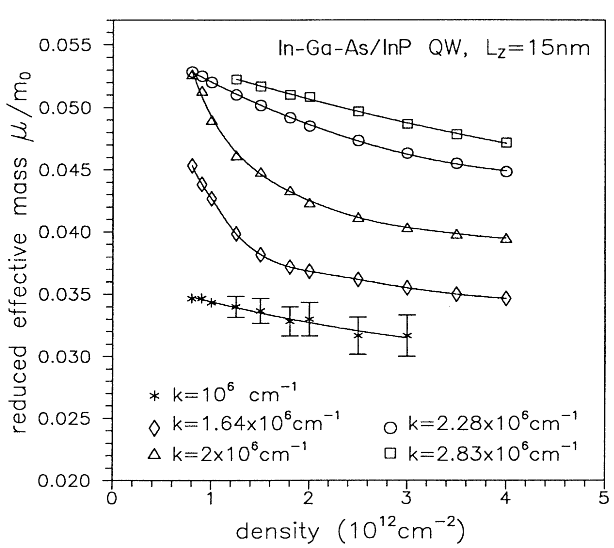

FIG. 11. Density dependence of the reduced carrier effective mass in a 15-nm QW for different wave vectors.

the band bottom is $\sim 10\%$. The change of μ at intermediate $k \sim 1.8 \times 10^6$ cm^{-1} is unexpectedly large (about 25%). At higher k it again decreases to $\sim 10\%$. The additional reduction of μ in the intermediate range seems to be connected with the following effect. Interparticle interactions in the EHP lead to a change of the light-hole–heavy-hole subband splitting because of the different filling of the bands. This should result in an additional reduction of m_{hh} at $E_h \sim \Delta E_v$ and, hence, of μ at the corresponding k.

Note as well that recent RPA calculations predict a strong decrease of the density of states in the 2D EHP near the band edge due to interparticle interactions[17] regardless of the valence-band structure. The direct applicability of the results of these calculations to the EHP in a magnetic field is questionable as the magnetic field strongly renormalizes both the electron-electron and electron-phonon interactions. Nevertheless the contribution of the interparticle interaction in the $\mu(k)$ dependence can be appreciable as well.

VI. CONCLUSION

The magneto-optical measurements reported here have allowed us to determine the major properties of the quasi-2D EHP in $In_{1-x}Ga_xAs/InP$ QW's with high accuracy. Great care was taken in the experiment to obtain a highly homogeneous carrier distribution in space and time. The plasma approximation satisfactorily describes the Landau-level splitting the dense EHP if the damping exceeds the direct Coulomb (exciton) energy and if the temperature is comparable with the cyclotron energy. The EHP properties determined here are found to be different from earlier discussed properties obtained from EHP's prepared without such precautions.[1,5,6] In particular, in the present study no saturation effects were found in the band-gap and effective-mass renormalizations. We observe significantly different band-gap renormalizations for subbands with different occupation. The reduced carrier effective mass reveals a sharp $\sim 30\%$ change in its magnitude in a small region of momenta near the band bottom. This occurs at any plasma density and QW thickness and is mainly due to the interaction of the heavy- and light-hole subbands.

Due to interparticle interactions, the reduced carrier effective mass is found to decrease with plasma density. The mass renormalization in the range $(1-4)\times 10^{12}$ cm^{-2} is $\sim 10\%$ for carriers near the band bottom and for those with a kinetic energy of ~ 50 meV while it reaches 25% in the intermediate range. In the latter case the additional mass renormalization is attributed to the renormalization of the heavy-hole–light-hole subband splitting.

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