Magnetoluminescence study of many-body effects in a dense electron-hole plasma of strained $In_xGa_{1-x}As/GaAs$ quantum wells

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High-excitation luminescence spectra from a highly homogeneous electron-hole system have been investigated in strained undoped $In_xGa_{1-x}As/GaAs$ quantum wells (QW's) with nearly parabolic conduction and valence bands in magnetic fields $H \leq 12$ T. The spectra show well pronounced Landau levels which are shifted to lower energy with respect to separately measured magnetoexciton photoexcitation maxima in the empty QW. The shift depends on the carrier density, subband, and Landau-level number. For the dense ($n_{e\text{-}h} > 10^{12}$ cm^{-2}) magnetoplasma with electron temperature of the order of the cyclotron energy, a simple plasma approximation has been found to describe the Landau-level splitting. The band-gap shrinkage and reduced effective-mass $\mu^{-1} = m_e^{-1} + m_e^{-1}$ renormalization have been carefully measured and compared with those in the unstrained $In_{0.53}Ga_{0.47}As/InP$ QW's. The difference has been revealed in the reduced effective-mass renormalization connected with renormalization of m_h due to the change of the light-hole–heavy-hole subband splitting.

I. INTRODUCTION

Recently many-particle effects in the quasi-two-dimensional (2D) electron-hole system of semiconductor quantum wells (QW's) have received much attention. For a low photoexcitation level, the electrons and holes in undoped QW's form excitons. With increased carrier density, the electron-hole system loses its excitonic properties because of the screening of the Coulomb interaction and a neutral electron-hole plasma (EHP) is formed.[1–3] The interparticle interaction gives rise to a strong renormalization of the energy gap as well as the energy-momentum (ε-k) dispersion of the carriers. Recently the renormalization of the band gap has been investigated both in undoped QW's (Refs. 1–6) where large densities of electrons and holes were created using high excitation, and in modulation doped structures[7–10] where a high density, usually electrons, was attained by doping. However, there are only a few studies of the effective-mass renormalization[4,6,9] which result in contradictory conclusions.

The first investigations of the neutral 2D EHP in a magnetic field were carried out by Maan and coworkers.[5] High-quality undoped $Al_xGa_{1-x}As/GaAs$ multiple QW structures were used and two striking results were claimed.[5,6,11] These were (i) the coexistence in the QW of both a dense EHP and excitons having the energy of free excitons in an empty QW, and (ii) the independence of the Landau-level transition energies on the carrier density in the dense plasma.[5,6] These results are in contradiction with conventional theoretical predictions.[12,13–15]

Previously we have studied photoluminescence spectra for selectively doped $In_xGa_{1-x}As/GaAs$ single-quantum-well (SQW) structures[8,9] and have found them to be very sensitive to the magnetoplasma homogeneity. The spectra were well structured and reproducible only when special precautions were taken to provide the uniformity of the excited carriers over the whole QW plane. Under this condition all the Landau transition energies appeared to decrease with carrier density, $n_{e\text{-}h}$, up to 5×10^{12} cm^{-2}. A similar behavior was also observed in a neutral homogeneous plasma in unstrained $In_{0.53}Ga_{0.47}As/InP$ SQW's.[3,4] Below the Fermi level, the reduced effective mass of electrons and holes, $\mu = (m_e^{-1} + m_h^{-1})^{-1}$, was found to increase when $n_{e\text{-}h}$ decreased from 5×10^{12} to 10^{12} cm^{-2}. The magnitude of the enhancement depended on the carrier energy and turned out to be unexpectedly strong, more than 30%, near the band bottom. This was suggested[4] to be connected with an additional contribution to the hole mass renormalization which arises in the unstrained QW's from the renormalization of the small heavy- and light-hole splitting, ΔE_v.

In the present paper we have studied many-body effects in a quasi-2D EHP confined in strained $In_xGa_{x-1}As/GaAs$ SQW's. They have a simple, nearly parabolic, hole band because the strain induces large splitting of the heavy- and light-hole states. Therefore all the renormalization effects are due to the direct influence of many-body effects. We consider only an electron-hole system which is dense enough ($n_{e\text{-}h} > 10^{12}$ cm^{-2}) to neglect any excitonic effects. The influence of the excitonic correlations on the emission spectra from the electron-hole system with lower density is discussed in Ref. 16.

The paper is organized as follows. The experimental details are described in Sec. II. In Sec. III the magnetoluminescence spectra of the EHP are presented in detail. These spectra are used in Sec. IV to determine the band gap E_g and the effective mass μ as a function of plasma density. The values of E_g and μ in the case of an empty (unexcited) QW without plasma were determined from the free magnetoexciton photoexcitation spectra. Section IV includes a discussion of the applicability of the simple plasma approximation for the EHP in a magnetic-field analysis of the band gap and effective-mass renormalization in a dense EHP in the framework of this approximation.

II. EXPERIMENT

The measurements were performed on undoped $In_xGa_{1-x}As/GaAs$ SQW's grown by solid source molecular-beam epitaxy (MBE) on a GaAs substrate. QW's with $x=0.18$ and thickness $L=10$ nm as well as with $x=0.28$ and $L=9$ and 7.5 nm were investigated. The sample was immersed in liquid helium in a cryostat having a superconducting coil. The plane of the SQW was oriented normally to the magnetic field whose strength H varied from 0 to 12 T. A 0.8-mm-quartz fiber was applied to transmit both the excitation and luminescence light. The latter, after passing a grating monochromator, was detected by a cooled photomultipler with an S-1 photocathode. The e-h pairs were excited by a Cu-vapor laser ($\lambda=510.5$ nm) with a pulse duration of 20 ns and repetition rate of 10 kHz. Photoluminescence excitation spectra were recorded using a tungsten glow lamp and a grating monochromator as the excitation source.

Special precautions were taken to obtain luminescence from a spatially as well as temporally homogeneous EHP, which is essential for correct interpretations of the results. Thus we abandoned the use of a multiple-quantum-well (MQW) structure where the excitation of various quantum wells would necessarily be different. In order to oppose the lateral inhomogeneity due to fast diffusion of photoexcited electrons and holes, a sample with a surface of 0.4×0.4 mm was cut and placed near the edge of the 0.8-mm fiber without additional focusing. Due to low surface recombination[13] of $In_xGa_{1-x}As$, this configuration facilitated a high spatial uniformity of the carrier density. By using a boxcar integrator with a gate width of 4 ns we were able to choose a time interval such that $n_{e\text{-}h}$ was nearly constant (near the signal maximum). The luminescence spectra of the highly excited electron-hole system obtained under such conditions had a steplike shape mirroring the density of states of 2D carriers. Any disturbance of the temporal or spatial uniformity of the electron-hole system resulted in additional emission in the excitonic region of the spectrum.

III. PHOTOLUMINESCENCE AND PHOTOEXCITATION SPECTRA

A. Excitons and electron-hole plasma in a zero magnetic field

Figure 1 displays the luminescence spectra from a homogeneous neutral electron-hole (e-h) system in an $In_{0.28}Ga_{0.72}As/GaAs$ SQW ($L=7.5$ nm) at 4.2 K for excitation intensities from 10 to 10^5 W/cm^2. The relative intensities of the spectra are maintained in the figure. A narrow exciton line was observed at low excitation intensity. Its intensity increased with excitation power whereas the linewidth remained nearly constant up to 30–60 W/cm^2.

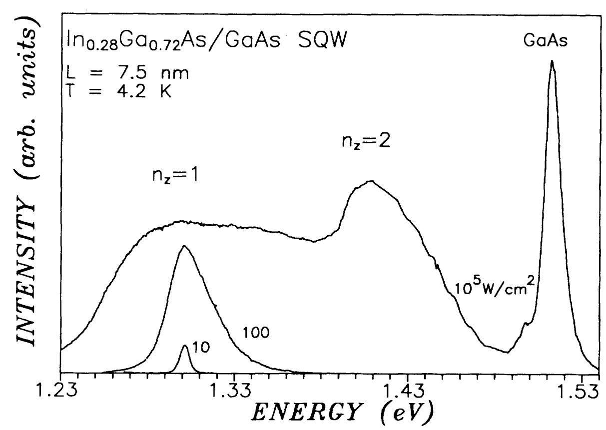

FIG. 1. Photoluminescence spectra from a 7.5-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ SQW at 4.2 K for various excitation intensities.

At higher densities the line transformed into a broad emission band from the e-h plasma. The line broadened mainly to the high-energy side due to filling of the conduction- and valence-band states in the QW, whereas the line intensity was saturated. The saturation indicated filling of the states near the $n_z=1$ subband edges, as expected for free electrons and holes because of the Pauli principle. Note that the high-energy edge of the line was not sharp despite the low lattice temperature. The estimated electron temperature in the dense electron-hole plasma P is 150–250 K. As a consequence, the Fermi-edge singularity[7] is very weak. The shape of the emission band corresponds to the steplike density of electron and hole states in the QW that broadens at the low-energy side due to damping of one-particle states.

B. Measurements in a magnetic field

Figure 2(a) shows emission spectra from an $In_{0.28}Ga_{0.72}As/GaAs$ SQW ($L=7.5$ nm) recorded at 4.2 K and 11.5 T for various excitation densities. Also in this case the relative intensities of the spectra were maintained. At $P<100$ W/cm^2, only the lowest Landau levels in the conduction and valence bands were occupied and the single line 0_e-0_h was observed. With increased $n_{e\text{-}h}$ additional peaks appeared, indicating occupation of upper Landau levels. The dominating lines correspond to the allowed $j_e=j_h$ transitions between the electron (j_e) and hole (j_h) Landau levels. The spectra are well structured, which is the main advantage of using a magnetic field. It enabled us to obtain the following important physical parameters:[4,6] (i) the band-gap renormalization from the redshift of the 0_e-0_h emission line, (ii) the cyclotron effective masses from the energy spacing between the adjacent spectral maxima, and (iii) the damping of the one-particle states from the linewidths.

Magnetophotoluminescence spectra give information only about the occupied conduction and valence bands. Therefore the Landau-level energies for empty bands have been determined from photoexcitation spectra of the basic 0_e-0_h magnetoexciton luminescence. An example of such a spectrum is shown in Fig. 2(b). The dominating lines are related to the dipole-allowed transitions into magnetoexciton states with $j_e = j_h$. As the valence band in a strained $In_xGa_{1-x}As/GaAs$ SQW is nondegenerate, the interpretation of the spectra is very simple. The spacing, $\Delta^*_{j,j-1}$, between adjacent peaks in Fig. 2(b) is the difference between the magnetoexciton energies rather than the unbound carrier energies at adjacent Landau levels,[6]

$$\Delta^*_{j,j-1} = \Delta_{j,j-1} + \mathrm{Ry}_{j-1} - \mathrm{Ry}_j \ , \tag{1}$$

where Ry_j is the magnetoexciton binding energy at the jth Landau level.

The dependence of the spectral position on the carrier density for several allowed transitions is presented in Fig. 3. The plasma density was found independently, from a number of luminescence peaks.[6,9] Figure 3 shows that the magnitude of $\Delta^*_{j,j-1}$ is significantly larger than the spacing $\Delta_{j,j-1}$ between the Landau levels in the e-h plasma with a low density. This is in agreement with earlier observations in spectra from unstrained $Al_xGa_{1-x}As/GaAs$ (Refs. 5 and 6) and $In_{0.53}Ga_{0.47}As/InP$ (Ref. 4) QW's, both having a complex valence band. Further, Fig. 3 shows that $\Delta_{j,j-1}$ increases with plasma density. This behavior is qualitatively different from that observed in $Al_xGa_{1-x}As/GaAs$ QW's (Refs. 5 and 6) where the magnitude of $\Delta_{j,j-1}$ was found to be independent of the density. In connection with this fact we can note that a strong distortion of the emission spectra was usually observed if there was any lateral inhomogeneity in the e-h plasma or any temporary change in its density. The emission lines became asymmetric with their maxima corresponding to a lower EHP density. This seems to be connected with the fact that the lines narrowed with decreased density.[16]

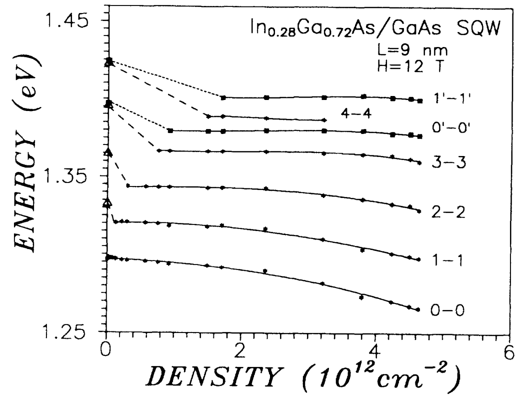

FIG. 3. The energy of allowed Landau transitions at 12 T and 4.2 K as a function of carrier density for a quasi-2D EHP in a 9-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ QW.

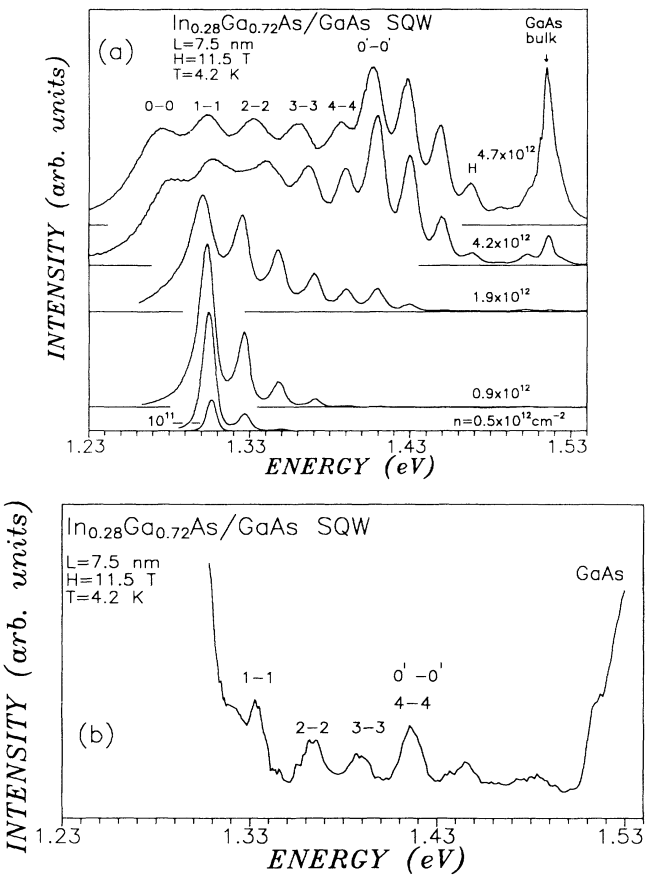

FIG. 2. (a) Magnetophotoluminescence spectra at 11.5 T from a 7.5-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ SQW for various excitation densities at 4.2 K. (b) Photoluminescence excitation spectra of the 0-0 magnetoexciton for a 7.5-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ QW at 11.5 T and 4.2 K.

IV. DISCUSSION

Analysis of the Landau transition energies for the empty and occupied QW enabled us to determine the band gap and reduced effective-mass renormalization, which is connected with interparticle interaction in the dense EHP. For this purpose a simple plasma approximation[1] was used. The validity of this approximation for a magnetoplasma is not obvious because the high magnetic field changes the energy spectrum of carriers from continuous to discrete states. Therefore, we start by considering the applicability of the plasma approximation.

A. Plasma approximation

In the many-particle theory, the contribution from many-body effects to the carrier ε-k dispersion is described by a self-energy $\Sigma_{e,h}(\mathbf{k},\varepsilon) = \mathrm{Re}\Sigma_{e,h}(\mathbf{k},\varepsilon) + \mathrm{Im}\Sigma_{e,h}(\mathbf{k},\varepsilon)$. Here the real part represents renormalization of the noninteracting electron and hole dispersion, $\varepsilon^0_{e,h}(\mathbf{k})$,

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

This representation is valid if the collision damping of the one-particle states described by the imaginary part of $\Sigma_{e,h}(\mathbf{k},\varepsilon)$ is relatively small. Usually $\mathrm{Im}\Sigma_{e,h}(\mathbf{k},\varepsilon)$ is small near the Fermi level but increases far from the Fermi surface.[17]

The plasma approximation remains to be valid for very small magnetic fields when the cyclotron energy is negligible as compared to the Fermi energy or plasma temperature.[18] In this case one can relate the wave vector corresponding to electrons and holes at the nth Landau level according to

$$\langle k^2 \rangle = eH(2n+1)/\hbar c \ , \qquad (3)$$

and thus determine the quasiparticle dispersion $\varepsilon(k)$. For larger magnetic fields a well-defined discrete energy spectrum of both electrons and holes is developed that can result in strong exciton effects.[12,18–20] These appear first at low temperatures. Electrons and holes in Landau levels closest to the conduction- and valence-band Fermi levels form excitonlike states.[19,20] These are well defined even in a dense magnetoplasma with several filled Landau levels. However, the excitonic approximation fails for Landau levels below the Fermi energy.[20] Thus, the choice of the model for the description of the quasi-2D magnetoplasma depends on its density, temperature, and strength of the magnetic field.

We assume that the plasma approximation describes a dense magnetoplasma at temperatures which are comparable with the cyclotron energy, $\hbar\omega_c$. It should also be applicable at moderate magnetic fields when the Landau-level broadening is larger than the excitonic binding energy but of the order of $\hbar\omega_c$. In our case the EHP satisfies these conditions when $n_{e\text{-}h} > 10^{12}$ cm^{-2}. First, as was mentioned in Sec. III, the effective electron temperature reaches above 200 K (i.e., comparable to $\hbar\omega_c$) despite the fact that the sample is placed in liquid He. Second, the Landau levels in the EHP are strongly broadened [cf. Fig. 2(a)]. Their half-width Γ is of the order of $\hbar\omega_c$ and markedly exceeds the excitonic energy (~ 10 meV).

The validity of the plasma approximation at these conditions is further strongly supported by the following two results. First, the envelope of the emission spectrum recorded at a magnetic field giving $\hbar\omega_c \sim \Gamma$ nearly coincides with the spectrum recorded at $H=0$, cf. Figs. 1 and 2. Second, the magnetic-field dependence of the transition energies in the dense plasma (with several filled Landau levels) is approximately linear in a wide range of $H < 12$ T. This is illustrated in Fig. 4. The linear dependence indicates that the carriers below the Fermi level can be described in the framework of a simple effective-mass approximation.

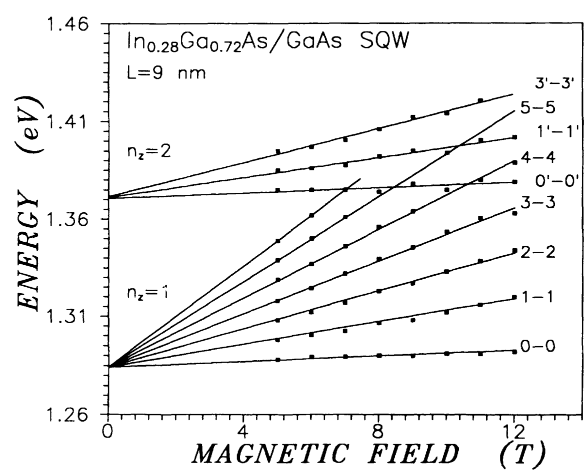

FIG. 4. The Landau fan for allowed interband transitions in a quasi-2D EHP, $n_{e\text{-}h} = 1.7\times10^{12}$ cm^{-2}, confined in a 9-nm-thick $In_{0.28}Ga_{0.72}As$/GaAs SQW. Experimental data are shown by dots.

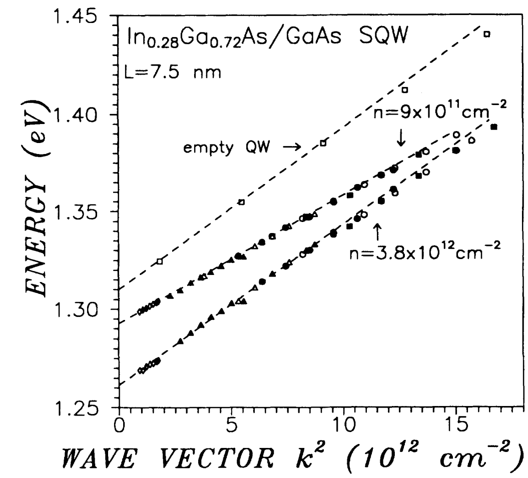

FIG. 5. Reduced carrier ε-k dispersion in a 7.5-nm-thick $In_{0.28}Ga_{0.72}As$/GaAs QW at the e-h densities 0, 0.9, and 3.8×10^{12} cm^{-2}. Data points taken from the different Landau-level transitions are shown by different labels.

Figure 5 displays the reduced ε-k dispersion ($\varepsilon = \varepsilon_e + \varepsilon_h$) for carriers in the QW filled to $n_{e\text{-}h} = 0.9$ and 3.8×10^{12} cm^{-2}. They were determined using Eq. (3) and the Landau transition energies in the range 5–12 T. For both densities the scattering in data extracted from different Landau levels is within the experimental error. The small scattering also indicates the weak influence from excitonic effects in the magnetoplasma with $n_{e\text{-}h} \geq 0.9\times10^{12}$ cm^{-2}. The excitonic effects were found to increase with reduced $n_{e\text{-}h}$ and T_e and increasing H. In particular, for the magnetoplasma with $n_{e\text{-}h} < 0.5\times10^{12}$ cm^{-2} and $T_e \sim 50$ K, the excitonic corrections became too large to be neglected already at $H \sim 8$ T. Therefore only the dense plasma, with $n_{e\text{-}h} \geq 0.9\times10^{12}$ cm^{-2}, will be further discussed.

B. Band-gap renormalization

The band-gap renormalization ΔE_g in a quasi-2D EHP has been widely discussed based on line-shape analysis of emission spectra at $H=0$ from unstrained GaAs/$Al_xGa_{1-x}As$ and $In_{0.53}Ga_{0.47}As$/InP QW's.[1–3,10] The value of ΔE_g weakly depends on the QW thickness. An increase in ΔE_g with $n_{e\text{-}h}$ was found to agree with calculations[15] using the random-phase approximation (RPA) for $n_{e\text{-}h} = 0.8-2\times10^{12}$ cm^{-2} but unexpectedly large for higher $n_{e\text{-}h}$. This is illustrated in Fig. 6. The dashed line represents the calculated dependence[15] while the measured values of ΔE_g for the $In_{0.53}Ga_{0.47}As$/InP QW are

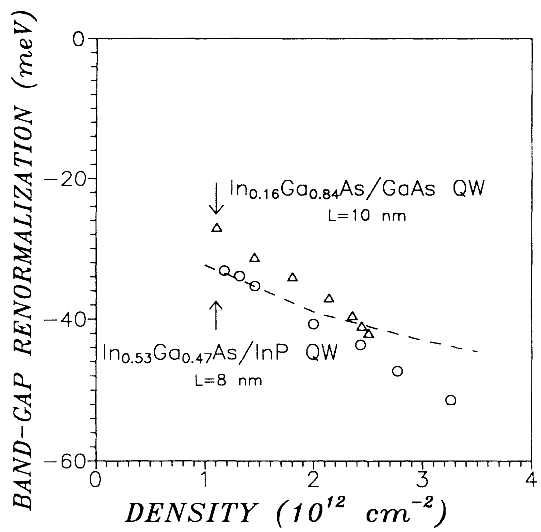

FIG. 6. The band-gap renormalization in a strained 10-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ SQW and an unstrained 8-nm-thick $In_{0.53}Ga_{0.47}As/InP$ SQW determined from spectra recorded at 2 K. The dashed line represents the band-gap renormalization for the 8-nm QW calculated in the full RPA approximation [from C. Ell and H. Haug, Phys. Status Solidi B **159**, 117 (1990)].

shown by circles.

In the present paper we have used magnetoluminescence spectra which provide a higher accuracy. The experimental dependence of ΔE_g on $n_{e\text{-}h}$ in the case of QW's with $x = 0.16$, $L = 10$ nm is shown in Fig. 6 by triangles. The energy gap (at $k = 0$) in the empty and occupied QW was extracted from the ε-k dispersion shown in Fig. 5. For the empty QW, the transition energies were taken from the 0-0 magnetoexciton photoluminescence excitation spectra and corrected by the magnetoexciton binding energy. Figure 6 shows that the dependence of ΔE_g for both the strained and unstrained QW's is very similar. At high plasma densities there is some deviation between theory and experiment. This could be due to a temperature-induced shrinkage of the energy gap under high laser intensity.[4,15]

With the use of magnetoluminescence measurements one can separate between the density- and temperature-induced shrinkage of the band gap. The temperature-induced Landau-level shift is nearly independent of the quantum number j until the energy of Landau level is small as compared with energy gap E_g. On the contrary, the density-induced renormalization of the occupied Landau-level energy strongly decreases with j. Indeed we found in our experiments that the transition-energy behavior changed qualitatively when the excitation density P was increased above 10^5 W/cm^2 (the average input power about 30 mW). When P exceeded 10^5 W/cm^2 ($n_{e\text{-}h} \sim 4.2\times10^{12}$ cm^{-2}) the highest energy QW emission line [labeled as H in Fig. 2(a)] moved markedly to low energies, and at $P > 2\times10^5$ W/cm^2 the magnitude of its shift became close to the shift of the 0-0 emission line. At $P > 3\times10^5$ W/cm^2 a redshift of the free exciton emission line from the GaAs cladding layers was also observed. These facts indicate that the lattice temperature increased markedly in this excitation range.

For $P < 10^5$ W/cm^2 lattice heating was found to be negligible. First, no change in the GaAs free exciton transition energy was observed in this excitation range. Hence, the lattice temperature of the GaAs cladding layers is not greater than 20 K. In addition, contrary to the high excitation range, the shift of the highest energy QW emission line was negligible at $P < 10^5$ W/cm^2. As the corresponding Landau-level energies ε_j are smaller than $0.1E_g$, their temperature-induced shift should coincide approximately with the temperature-induced band-gap shrinkage, similarly to what is observed at higher excitation level. Therefore the strong shift of the lowest electron and hole Landau levels should be due to many-body effects. The data presented in Fig. 6 were obtained at $P < 10^5$ W/cm^2 ($n_{e\text{-}h} \sim 4.2\times10^{12}$ cm^{-2}) when the temperature induced shift was negligible.

Systematic deviations between theory and experiment that occur at high plasma densities could be[15] due to neglected intersubband scattering contributions to the screening in band-gap renormalization calculations. They can also be due to a contribution to self-energy arisen from increased carrier temperature, T_e. For EHP with $n_{e\text{-}h} \sim 3\times10^{12}$ cm^{-2}, T_e reached 200–500 K, comparable with the hole Fermi level.

C. Renormalization of carrier effective masses

Strained $In_xGa_{1-x}As/GaAs$ QW's are very suitable for studies of many-body effects because the strain causes a strong splitting of the light- and heavy-hole subbands. The strain also gives rise to a nondegenerate and nearly parabolic valence band. This is clearly seen from the reduced ε-k dispersion of the empty QW displayed in Fig. 5. A change of the ε-k dispersion for increased plasma density is shown in Fig. 5. It is seen that the slope of the ε-k dispersion below the Fermi energy markedly varies with plasma density revealing a density dependence of the reduced effective mass, $\mu^{-1} = m_e^{-1} + m_h^{-1}$.

A decrease in the slope of the $\varepsilon(k^2)$ dependence when the QW is filled with $\sim 10^{12}$ cm^{-2} carriers indicates a strong increase of μ in the diluted EHP. A similar effect was found in recent magneto-optical studies of the EHP in $GaAs/Al_xGa_{1-x}As$ QW's.[5,6] As shown in Fig. 5(a), further increase of the carrier density gave rise to the opposite effect. For $n_{e\text{-}h} \sim 3.8\times10^{12}$ cm^{-2} the net influence of the many-body interactions on μ is negligible. This is connected with enhanced screening of the Coulomb potential and is in qualitative agreement with theoretical predictions.[21]

A more detailed description of the renormalization of μ due to the many-particle interaction is found in Figs. 7 and 8, showing the dependence of μ on the wave vector and plasma density both for strained $In_xGa_{1-x}As/GaAs$ and unstrained[4] $In_{0.53}Ga_{0.47}/InP$ QW's. The reduced mass strongly increased with the wave vector for the unstrained QW. It is rather difficult to extract the contribution from the many-body effects in this dependence because of the strong valence-band nonparabolicity. However, Fig. 7 shows that in strained (both empty and occu-

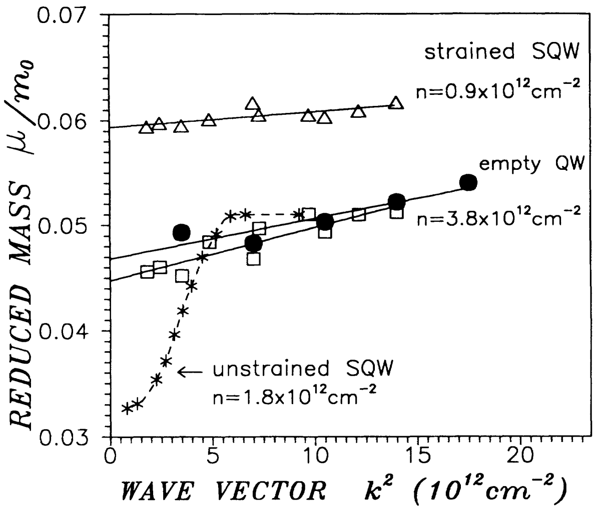

FIG. 7. The reduced carrier effective mass as a function of square-wave vector for different EHP densities. The dependence is shown for both a strained 7.5-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ and an unstrained 15-nm-thick $In_{0.53}Ga_{0.47}As/InP$ SQW's.

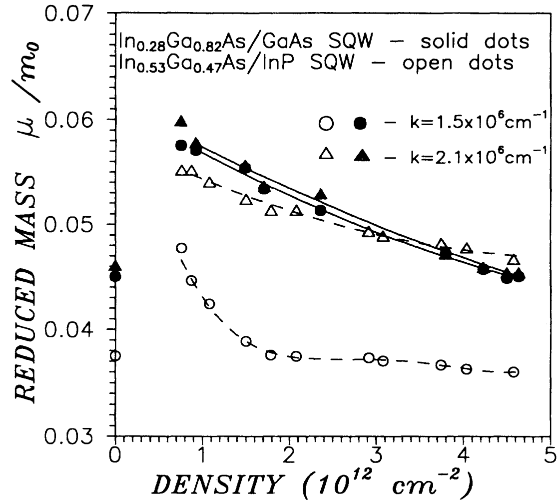

FIG. 8. Reduced carrier effective mass in two SQW's as a function of the carrier density with the wave vector as parameter. The SQW's are strained 7.5-nm-thick $In_{0.28}Ga_{0.72}As/GaAs$ and unstrained 15-nm-thick $In_{0.53}Ga_{0.47}As/InP$.

pied) QW's, μ only weakly increased with k. It means that the many-body interaction itself does not lead to any strong k dependence of μ. Therefore we conclude that the observed band nonparabolicity in the unstrained QW is originated from its valence-band complex structure.

For strained QW's, the dependence of $(n_{e\text{-}h},k)$ on the density is nearly independent of the k values below the Fermi momentum. This is illustrated in Fig. 8 for $k=1.5$ and 2.1×10^6 cm^{-1}. Figure 8 also shows a similar density dependence of μ for both the strained and unstrained QW's at $k=2.1\times10^6$ cm^{-1}. This result was expected. The unstrained QW has a small heavy-hole–light-hole subband splitting ΔE_v. For $k>2\times10^6$ cm^{-1} the hole mass in this QW is large as compared to m_e and, hence, the hole contribution in μ is negligible. Thus, a similar dependence of $(n_{e\text{-}h})$ originates from electron mass renormalization in these QW's. Further, Fig. 8 shows that for the unstrained QW's the dependence $(n_{e\text{-}h})$ qualitatively changes with decreasing k. This occurs at $k<1.7\times10^6$ cm^{-1}, when the hole mass strongly decreases and becomes comparable to m_e. Therefore, it is natural to relate the strong reduction in μ, observed in unstrained QW's, to the additional hole mass renormalization which comes from the small heavy-hole–light-hole subband splitting. In particular, this could be due to an indirect influence of electron-hole interactions on the hole mass through the renormalization of the splitting ΔE_v. Obviously, such an influence has to disappear in strained QW's with large ΔE_v, in agreement with the experimental data in Fig. 8.

Recent RPA calculations have predicted a strong decrease of the density of states near the band edge in a 2D EHP due to electron-electron and electron-phonon interactions.[21] This effect was not observed in our magneto-optical studies of the EHP in QW's with parabolic bands. However, this cannot be considered as the evidence of the absence of the predicted effect since the magnetic field renormalizes both the electron-electron and electron-phonon interactions.

V. CONCLUSION

The magneto-optical measurements enabled us to investigate the properties of a quasi-2D EHP in strained $In_xGa_{1-x}As/GaAs$ SQW's with high accuracy. Reliable data were obtained by realizing an EHP with a high homogeneity in space and time. The plasma approximation was found to satisfactorily describe the Landau-level splitting in a dense EHP with its electron temperature comparable to the cyclotron energy and its one-particle state damping above the direct Coulomb (exciton) energy.

The band-gap shrinkage and effective-mass renormalization in the strained QW's with a nondegenerate, weakly nonparabolic valence band were measured and compared with those in unstrained QW's with a complex valence band. The band-gap renormalization was found to be similar in both cases, whereas the mass renormalization was significantly different. We assigned this to the additional hole mass change appearing in the unstrained QW's due to renormalization of the small light-hole–heavy-hole subband splitting.

In strained SQW's, the effective-mass renormalization due to the many-particle interaction in the dense plasma is strong when $n_{e\text{-}h}\sim10^{12}$ cm^{-2} (the enhancement of μ reaches 20%) but decreases at higher densities. For $n_{e\text{-}h}\sim4\times10^{12}$ cm^{-2} the effective mass is close to that of the empty QW, which agrees with theoretical expectations.

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[1]G. Tränkle, E. Lach, A. Forchel, P. Scholz, C. Ell, H. Haug, G. Weimann, G. Griffiths, H. Kreemer, and S. Subbanna, Phys. Rev. B **36**, 6712 (1987); G. Tränkle, H. Leier, A. Forchel, H. Haug, C. Ell, and G. Weimann, Phys. Rev. Lett. **58**, 419 (1987).

[2]K.-H. Schlaad, C. Weber, J. Cunningham, C. V. Hoff, G. Borghs, G. Weimann, W. Schlapp, H. Nickel, and C. Klingshirn, Phys. Rev. B **43**, 4268 (1991).

[3]V. D. Kulakovskii, E. Lach, A. Forchel, and D. Grützmacher, Phys. Rev. B **40**, 8087 (1989).

[4]L. V. Butov, V. D. Kulakovskii, and A. Forchel, Zh. Eksp. Teor. Fiz. **96**, 2135 (1990) [Sov. Phys. JETP **71**, 1199 (1990)]; L. V. Butov, V. D. Kulakovskii, E. Lach, A. Forchel, and D. Grützmacher, Phys. Rev. B **44**, 10 680 (1992).

[5]M. Potemski, J. C. Maan, K. Ploog, and G. Weimann, in *Proceedings of the 19th International Conference on the Physics of Semiconductors, Warsaw,* edited by W. Zawadski (Institute of Physics, Warsaw, 1989), Vol. 1, p. 119.

[6]M. Potemski, J. C. Maan, K. Ploog, and G. Weimann, Surf. Sci. **229**, 380 (1990); J. C. Maan, M. Potemski, K. Ploog, and G. Weimann, Solid State Commun. **75**, 185 (1990).

[7]S. M. Skolnick, J. M. Rorison, K. J. Nash, D. J. Mowbray, P. R. Tapster, S. J. Bass, and A. D. Pitt, Phys. Rev. Lett. **58**, 2130 (1987).

[8]L. V. Butov, V. D. Kulakovskii, T. G. Anderson, and Z. G. Chen, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 280 (1988) [JETP Lett. **48**, 256 (1988)].

[9]L. V. Butov, V. D. Kulakovskii, and T. G. Andersson, Phys. Rev. B **44**, 1692 (1991).

[10]G. Bongiovanni, J. L. Staehli, A. Bossachi, and S. Franchi (unpublished).

[11]M. Potemski, J. C. Mann, K. Ploog, and G. Weimann, Solid State Commun. **75**, 185 (1990).

[12]G. E. W. Bauer, Phys. Rev. Lett. **64**, 60 (1990).

[13]S. Schmitt-Rink, C. Ell, and H. Haug, Phys. Rev. B **33**, 1183 (1985).

[14]R. Jalabert and S. Das Sarma (unpublished).

[15]C. Ell and H. Haug, Phys. Status Solidi B **159**, 117 (1990).

[16]L. V. Butov, V. D. Kulakovskii, G. E. W. Bauer, A. Forchel, and D. Grützmacher (unpublished); L. V. Butov and V. D. Kulakovskii, Phys. Status Solidi (to be published).

[17]Zimmermann, *Many-Particle Theory of Highly Excited Semiconductors,* Teuner-Texte zur Physik Vol. 18, edited by W. Ebeling (Teubner-Texte, Leipzig, 1988).

[18]G. E. W. Bauer, in *Proceedings of the 6th International Winterschool. Mauterndorf,* edited by G. Bauer and H. Heinrich (Springer-Verlag, Berlin, 1990).

[19]L. V. Butov, V. D. Kulakovskii, A. Forchel, and D. Grutzmacher, Superlatt. Microstruct. **10**, 489 (1991).

[20]L. V. Butov, V. D. Kulakovskii, and E. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **53**, 104 (1991) [JETP Lett. **53**, 109 (1991)].

[21]S. Das Sarma and R. Jalabert, Phys. Rev. B **40**, 9723 (1989).