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Band-gap renormalization and band-filling effects in a homogeneous electron-hole plasma in $In_{0.53}Ga_{0.47}As/InP$ single quantum wells

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By use of homogeneously excited small mesa structures a highly uniform electron-hole plasma (EHP) is created by cw excitation of $In_xGa_{1-x}As/InP$ single-quantum-well (SQW) structures. Because of the high homogeneity of the EHP in space and time we observe many-body effects and band filling under very clear experimental conditions. Our luminescence measurements demonstrate the subband dependence of the band-gap renormalization and a strong dependence of the band-gap reduction on the width of the $In_xGa_{1-x}As/InP$ SQW's.

During the past few years, a number of studies have addressed the properties of electron-hole plasmas (EHP's) in three-dimensional (3D) and 2D semiconductor structures. One of the results of many-body effects in high-density EHP's is a density-dependent renormalization of the fundamental band gap of the semiconductor. Experiments as well as many-body theories[1] show that the carrier-carrier induced exchange-correlation energy in 3D semiconductors is independent of the details of the band structure. It is a universal function of the electron-hole density when the energy is expressed in excitonic Rydbergs and the density in units of the excitonic Bohr radius.[2] This insensitivity is due to the short-range character of the screened interaction in a dense EHP. In going from 3D to 2D electron-hole systems, the screening of the Coulomb interaction strongly decreases. This leads to a change in the density dependence of the many-body effects in the electron-hole system.[3-6]

Previously, most experimental studies have been performed on large-area multiple-quantum-well samples.[4,5,7,8] Under these conditions the density profile is inhomogeneous in depth and in lateral dimensions. Moreover, usually pulsed excitation has to be used resulting in a transient variation of the plasma density. All plasma properties evaluated under these conditions represent averages in space and time which may deviate significantly from the results in a homogeneous plasma. Most experimental work has been carried out on $GaAs/Al_xGa_{1-x}As$ quantum wells (QW's) whereas comparably little is known of the properties of 2D EHP's in other systems.

We present the results of a luminescence investigation of EHP properties in $In_{0.53}Ga_{0.47}As$ single quantum wells (SQW's) for a very wide region of EHP densities $n = (0.2\text{–}6.5)\times 10^{12}$ cm^{-2}. This corresponds to interparticle distances of $(1.3\text{–}0.25)a_{2D}$, where a_{2D} is the strictly 2D excitonic Bohr radius. Great care was taken to obtain a homogeneous plasma in the SQW. Large and homogeneous EHP densities were obtained under stationary excitation conditions with the use of small 20–30-μm-diam mesas conserving photoexcited carriers in a limited excited volume. Our approach allows us to investigate the band-gap renormalization dependence on both the EHP density and the QW width for the fundamental and higher-index subbands.

To investigate the properties of a dense quasi-2D EHP we have used lattice-matched $In_{0.53}Ga_{0.47}As/InP$ SQW heterostructures with QW widths $L_z = 15$ and 8 nm corresponding to $1.6a_{2D}$ and $0.85a_{2D}$. The structures were grown by low-pressure metalorganic vapor-phase epitaxy technique. The EHP was excited using a cw Kr^+-ion laser ($\lambda = 647.1$ nm) with power densities P_{ex} up to 10^5 W/cm^2. The emitted light was dispersed with a double spectrometer and detected by a cooled Ge detector. All samples have been characterized in the low-density limit by excitation spectroscopy. The samples were mounted in a variable-temperature cryostat (2 K $< T <$ 300 K).

To avoid uncertainties in the interpretation of the experimental data associated with an EHP inhomogeneity, we have defined mesa structures in the quantum-well plane with dimensions down to 20×20 μm. The mesas were prepared by optical lithography and dry etching. The exciting cw laser spot and the mesa structure are of comparable size. The lateral confinement in the small mesas makes it possible to reach very high EHP densities of about 5×10^{12} cm^{-2} for relatively low laser powers of 1 W. This allowed us to excite a dense EHP using a cw rather than a pulsed laser and thus to obtain a stationary electron-hole system.

Figure 1 displays luminescence spectra for an $In_{0.53}Ga_{0.47}As/InP$ sample with a SQW with a width $L_z = 15$ nm recorded at a bath temperature $T_b = 77$ K under different excitation intensities between 0.012 and 56 kW/cm^2. The relative intensities of the spectra measured for different excitation densities are maintained in the figure. The excitonic transition energies for the $n_z = 1\text{–}3$ subbands determined by excitation spectroscopy are indicated by the arrows.

As shown in Fig. 1 for excitation levels below 20 W/cm^2, the intensity of the emission line increases approximately proportionally to the excitation power and the linewidth remains nearly constant. For excitation powers above 40 W/cm^2 the line broadens on the high-energy side due to the filling of the conduction and valence bands in

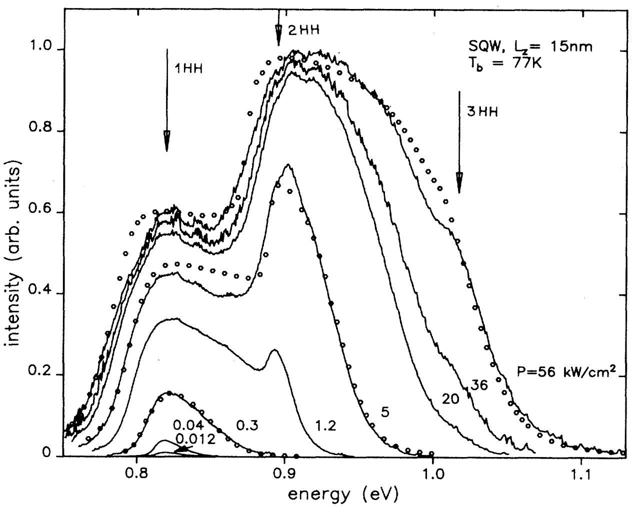

FIG. 1. Experimental luminescence (solid lines) spectra and line-shape fits (circles) for an $In_xGa_{1-x}As/InP$ sample with a 15-nm SQW as a function of the excitation intensity. The arrows indicate the energies of exciton transitions for n_z equal to 1HH, 2HH, and 3HH (where HH denotes heavy hole), as determined by excitation spectroscopy.

the QW. We observe that the EHP emission intensity at $h\nu < 0.87$ eV saturates for excitation powers above 3 kW/cm^2. Under these conditions a new well-pronounced step appears in the emission spectra due to filling of the $n_z = 2$ subbands. The intensity of this step saturates at $P_{ex} > 20$ kW/cm^2. The saturation of the emission intensity corresponds to the complete filling of the respective subband edges and is a direct consequence of the Pauli principle. 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. At the highest excitation intensities used in our experiments ($P_{ex} \geq 30$ kW/cm^2), one can see the appearance of the emission from the third subbands ($h\nu > 1.03$ eV). A further increase of the EHP density is not possible due to the transfer of electrons into the InP conduction band. This can be understood very easily because in the 15-nm QW the third electronic subband is located close to the InP conduction-band edge.

All observed steps correspond to allowed transition between the electron and heavy-hole subbands ($\Delta n_z = 0$). The spectra give no indication of parity allowed $\Delta n_z = 2$ forbidden transitions. These would lead to additional steps which are not observed.

Besides the strong emission line broadening associated with the increase in the kinetic energies of electrons and holes in a dense electron-hole system, the EHP emission spectra in Fig. 1 show a well-pronounced red shift of the low-energy edge of the emission line with increasing excitation intensity. The second step in the emission spectra reveals a similar shift, but with a markedly smaller rate.

To obtain the quantitative dependences of the band-gap renormalization on the EHP density for different subbands we have carried out an analysis of the EHP emission lines using calculated plasma spectra.[4] Such an analysis allows us to obtain the plasma density and temperature, and the renormalized band gaps for occupied subbands. Our line-shape model assumes parabolic electron and hole subbands, momentum conservation, electron-hole recombination with constant matrix elements for transitions between the different subbands, as well as an energy-dependent broadening $\Gamma(\epsilon)$[4] to account for various effects leading to the experimentally observed broadening of the EHP spectra. The main parameters n and E_g' were found to be nearly independent of the specific choice of $\Gamma(\epsilon)$.

The results of our line-shape fitting are represented for a few experimental spectra in Fig. 1 by dotted lines. From the analysis we obtain densities between 2×10^{11} cm^{-2} and 7×10^{12} cm^{-2} and temperatures between 80 and 140 K. As shown in Fig. 1, the experimental data and the calculated line shapes are in good agreement. The slight differences in the first-step intensities are most likely due to differences in the matrix elements for the recombination of the light and heavy holes. Furthermore, the mixing of heavy- and light-hole states gives rise to nonparabolicities in the hole dispersions.[9] We have used parabolic dispersions basing on the heavy- and light-hole masses of the 3D case in our calculations as no numerical dispersion calculations for $In_xGa_{1-x}As/InP$ are available yet. As was shown for the electron-hole plasma in GaAs quantum wells, the 3D hole masses approximate the nonparabolic valence-band dispersion in the limit of large band filling rather well.[10] Furthermore, we would like to point out that the band-gap renormalization and the plasma density determined from the line-shape fits are rather insensitive to the exact values of the hole masses. To a first approximation, the emission width is described by the electron Fermi energy only.

Figure 2 represents the subband edge renormalization of the $n_z = 1$, 2, and 3 subbands as a function of the total carrier density as obtained by the line-shape analysis for the 15-nm QW. For each subband, the energy gap at zero density was determined from the spectral positions of the excitonic lines in the photoexcitation spectra corrected by the excitonic Rydberg. For the lowest subband we observe a very large shift of about 55 meV at the EHP density of 6×10^{12} cm^{-2}. Figure 2 clearly shows that the band-gap reduction in $In_xGa_{1-x}As$ QW's is different for subbands with different n_z. For carrier densities of the order of 10^{12} cm^{-2} the difference of the band-gap renormalization amounts to about 17 meV. As shown by the inset in Fig. 2, the subband splitting increases to 26 meV if the density is raised to 7×10^{12} cm^{-2}. As depicted in Fig. 2, the renormalization of the third subband is again smaller, as is the renormalization of the second subband. This indicates that rather strong deviations from the model of a rigid band-gap shift[4] occur for dense EHP's in QW's. Our results are in qualitative agreement with the difference in the shifts of the $n_z = 1$ band-gap edge and the $n_z = 2$ exciton energy observed recently in absorption measurements on GaAs MQW structures.[5]

Qualitatively, we can understand the observed differences in the renormalization for the different subbands if

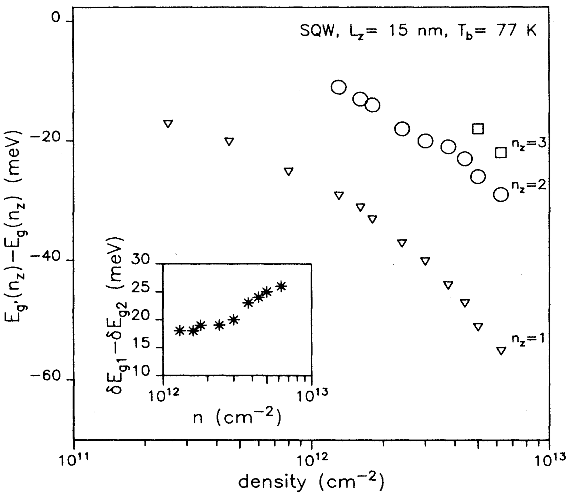

FIG. 2. Measured density dependences of the band-gap renormalization for the different subbands in the 15-nm $In_{0.53}Ga_{0.47}As/InP$ SQW at $T_b=77$ K. The renormalization for each subband is plotted relative to the corresponding subband edges at zero density. The inset demonstrates the density dependence for the difference in the band-gap renormalizations of the $n_z=1$ and 2 subbands.

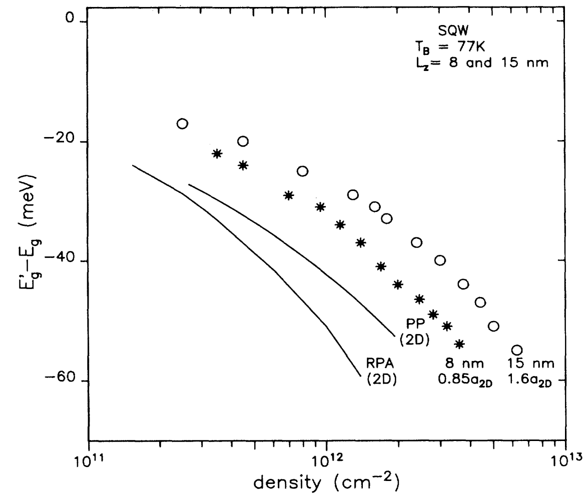

FIG. 3. Comparison of the fundamental band-gap renormalization measured for the 8- and 15-nm $In_{0.53}Ga_{0.47}As/InP$ SQW structures (points) with theoretical results calculated for a 2D EHP in the full random-phase approximation (RPA) (Ref. 6) and in the RPA with the use of a plasmon-pole (PP) approximation (Ref. 4) (solid lines RPA and PP, respectively).

we consider the variation of the shape of the wave function with the subband index. First, the electron-hole interaction will be particularly efficient for the strongly localized states of the fundamental subbands. Second, the many-body interactions are correlated with the overlap of the wave functions of the carriers in the different subbands. We expect, e.g., a comparatively weak renormalization for $n_z=2$ states due to interaction with $n_z=1$ states, because the wave functions of the $n_z=2$ states have a node at the center of the QW where the $n_z=1$ wave functions have a maximum. Furthermore, the exchange-energy contribution to the band-gap renormalization results only from the interaction of carriers within the same subband.[5]

In Fig. 3 we compare the density dependences of the renormalization of the fundamental band gap for $In_{0.53}Ga_{0.47}As/InP$ SQW's with thicknesses of $L_z=15$ and 8 nm ($L_z/a_{2D}=1.6$ and 0.85). Independent of the number of occupied subbands, the band-gap reduction decreases for all densities for increasing QW width. As indicated by the solid lines in Fig. 3, the experimentally observed band-gap reduction is essentially smaller than calculated for a strictly 2D EHP at zero temperature in various approximations.[4,6] The difference between experiment and theory and between the experimental results for different L_z are correlated with the changes in the excitonic Rydberg, due to an increase of the QW width.

In summary, the use of quasistationary excitation and mesa-structured $In_xGa_{1-x}As/InP$ SQW's has allowed us to study very dense and highly homogeneous quasi-2D EHP's by luminescence spectroscopy. We observed a complete filling of subband levels resulting in steplike emission spectra with saturating maximum intensity. A line-shape analysis of these spectra shows that the many-body effects in the quasi-2D EHP lead to different values of the band-gap renormalization for the different subbands. Furthermore, we observe a strong dependence of the band-gap reduction on the QW width. These effects are correlated with the specific structure of the electron and hole wave functions in QW's.

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