Renormalization of effective carrier masses in neutral quasi-2*D* electron-hole plasma in InGaAs/InP quantum wells

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Magnetoluminescence has been used to study how multiparticle interactions in a quasi-2D electron-hole plasma in quantum wells affect the carrier energy spectrum. A large change ($>30\%$) has been observed in the effective carrier mass near the band edge.

1. Quantum wells in semiconductor heterostructures open up extensive opportunities for realizing quasi-two-dimensional (2D) electron systems and for studying their properties. Multiparticle interactions in an electron-hole (*e–h*) system in a quantum well lead to a renormalization of both the width of the band gap E_g and the energy

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dispersion of the carriers, $\epsilon^0_{e,h}(K)$, as in a $3D$ plasma.[1-6] In many-body theory, these changes are described by the eigenenergy part of Σ, which depends on the quasimomentum K and the energy ϵ of the quasiparticles. If the decay of single-particle states ($\mathrm{Im}\Sigma$) is small in comparison with the Fermi energy ϵ_F we can write[7]

$$\epsilon_i(K) = \epsilon_i^0(K) + \mathrm{Re}\Sigma(K, \epsilon_i) .$$

In a bulk e–h plasma the dispersion $\mathrm{Re}\Sigma(K)$ is slight, and the carriers can be described at $\epsilon < \epsilon_F$ in the approximation of a rigid band shift: $\mathrm{Re}\Sigma = \mathrm{const}$. The primary reason for the slight dispersion $\mathrm{Re}\Sigma$ in a $3D$ plasma is the short-range nature of the interaction of the particles, which is a consequence of the strong screening of the Coulomb potential.[7] Because of the substantially different screening in the $2D$ case, we would expect a strengthening of the dispersion $\mathrm{Re}\Sigma(K)$.

2. For a study of the effect of interparticle interactions in a $2D$ plasma, we selected an InGaAs quantum well with a thickness $L = 8$ nm and with excitons with a first Bohr radius $a_B(3D) \sim 20$ nm. Undoped $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ heterostructures with isolated quantum wells were grown by metal-organic chemical vapor deposition.[8] The nonequilibrium carriers were excited by an Ar^+ laser (5145 Å). The emission from the sample was analyzed by a grating monochromator (600 lines/mm) and detected with a cooled Ge detector. The samples were immersed in superfluid helium in a cryostat with a superconducting solenoid ($H < 8.7$ T).

A well-defined peak in the exciton emission region in the emission spectra of a dense e–h plasma in a quantum well has been reported in several places (e.g., Ref. 4). This observation led to the question of whether a dense e–h plasma and excitons can coexist in a quantum well. We accordingly paid particular attention to the homogeneity of the e–h plasma. A plasma which is excited locally in a quantum well is highly inhomogeneous unless additional measures are taken to restrict its propagation in the plane of the quantum well. In contrast with the previous studies, we limited this propagation of the e–h plasma by means of mesas $30 \times 30\ \mu\mathrm{m}^2$ in size (the diameter of the exciting laser beam was $50\ \mu$m). It thus became possible to use a cw 1-W laser to excite high plasma densities, $n_{eh} \sim 3 \times 10^{12}\ \mathrm{cm}^{-2}$. In the same manner, we achieved a homogeneity of n_{eh} over time. The mesas were fabricated by optical lithography and dry etching.[8]

The emission spectra of the homogeneous e–h plasma (Fig. 1) turned out to be qualitatively different from the spectra reported in Ref. 4 for an e–h system. Their shape reflects the density of states of the $2D$ carriers, and (as expected) they have no additional structural features in the exciton part of the spectrum.

3. The most important information about the changes in the carrier dispersion comes from magnetooptic measurements. When a magnetic field is imposed in the direction perpendicular to the plane of the well, it localizes the motion of the electrons and holes and thus causes their spectrum to become discrete. Changes in the dispersion are detected from changes in the energy gaps between Landau levels. Unfortunately, the localization of the motion of the electrons and holes simultaneously causes a substantial intensification of exciton effects and limits the range of applicability of the plasma approximation.[5,6]

Figure 1 shows the changes which occur in the emission spectra of an e–h system in a quantum well ($L = 8$ nm) as the excitation density is raised. These particular results were recorded at 2 K in a field $H = 8.62$ T. The spectra are dominated by allowed ($j_e = j_h$) transitions between electron Landau levels (j_e) and hole Landau levels (j_h). As n_{eh} is raised, several changes occur. New lines, resulting from the filling of higher-lying Landau levels, appear in the spectrum. The emission lines broaden greatly because of the increase in the decay of single-particle states. A renormalization of E_g then leads to a shift of all lines toward lower energies. Finally, there are changes in the energy gaps Δ_{ij} between the i_e–i_h and j_e–j_h lines. The changes in Δ_{ij} characterize the change in the reduced effective mass $\mu^{-1} = m_e^{-1} + m_h^{-1}$ of the electrons (of mass m_e) and the holes (of mass m_h).

Figure 2 shows the spectral position of the i_e–i_h lines, i.e., $h\omega_i$, as a function of n_{eh}. The values of n_{eh} were found directly from the emission spectra, from the filling of the Landau levels (the number of states at the Landau level is determined by the value of H and does not depend on the plasma density). We see in Fig. 2 that there is no change in the energy of the transition between the partially filled upper Landau levels until they are almost completely filled. This behavior is a consequence of exciton

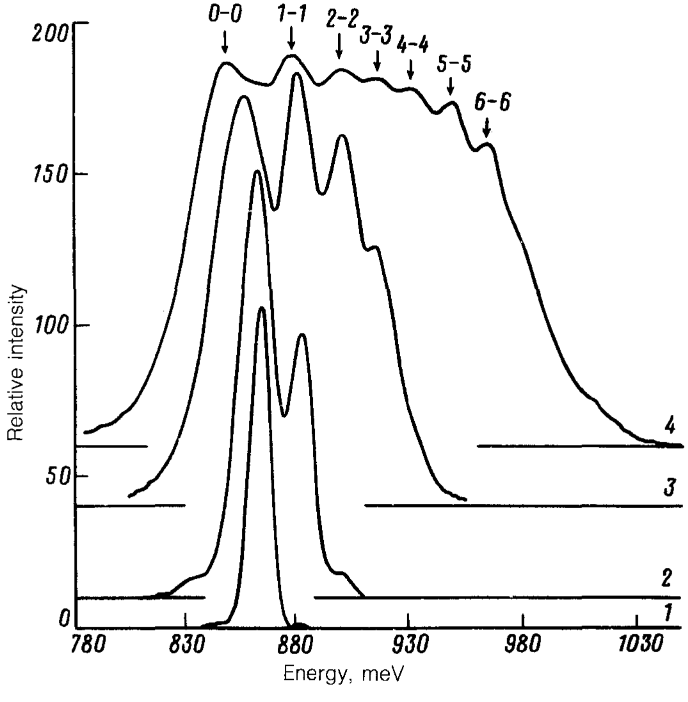

FIG. 1. Emission spectra of an $In_{0.53}Ga_{0.47}As/InP$ quantum well ($L = 8$ nm) recorded at $T = 2$ K, $H = 8.62$ T, and various excitation densities: *1*–$W = 0.08$; *2*–0.3; *3*–1; *4*–4 kW/cm^2.

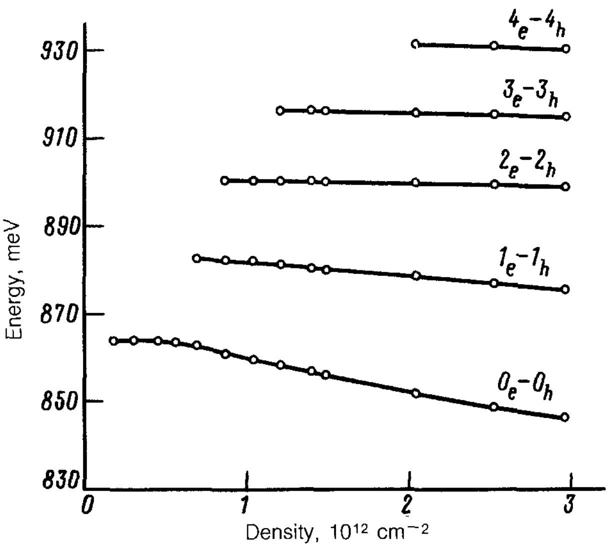

FIG. 2. Changes in the energies of Landau transitions for an $In_{0.53}Ga_{0.47}As/InP$ quantum well ($L = 8$ nm) at $H = 8.62$ T with increasing density of the e–h system.

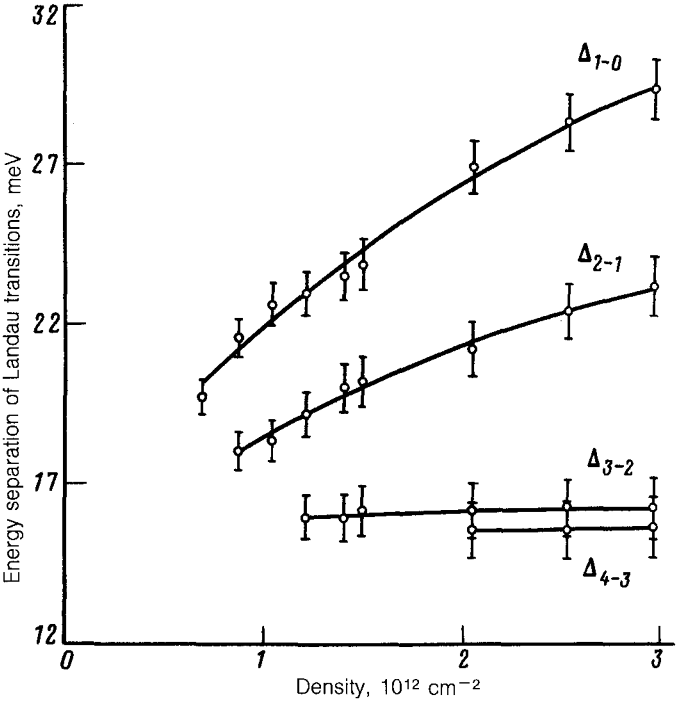

FIG. 3. Energy gaps between Landau transitions in an 8-nm quantum well versus the density of the e–h plasma ($H = 8.62$ T).

effects. These effects fade away rapidly with distance from the Fermi level,[6] so magnetic fields and plasma densities corresponding to the presence of at least three filled Landau levels should be used to determine the properties of the *e–h* plasma.

4. Figure 3 shows the energy gaps between Landau transitions versus the plasma density in a field of 8.62 T. The values of Δ_{ij} and thus the effective mass $\mu \sim \Delta^{-1}{}_{i,i-1}$ vary markedly with increasing n_{eh}. It follows in particular from Fig. 3 that μ decreases by 30% near the bottom of the band as n_{eh} is increased from 0 to 3×10^{-12} cm^{-2}. We recall that the model of a rigid band shift assumes that the effective mass does not depend on the carrier energy, so the value of $\Delta_{i,i-1}$ does not depend on the density of the *e–h* plasma. For this reason, the observed change in Δ_{ij} with increasing n_{eh} is evidence that the model of a rigid band shift is a quite crude one for a quasi-2*D* *e–h* plasma.

It can be seen from Fig. 3 that the n_{eh} dependence of Δ_{ij} weakens with increasing index of the Landau level. The meaning here is that the effect of interparticle interactions on the effective mass in the *e–h* plasma decreases with increasing carrier energy. Analyzing the spectra, we find that the energy region which the change in μ occurs becomes larger with increasing n_{eh}. At $n_{eh} \sim 3\times10^{-12}$ cm^{-2}, the change in μ is substantial over the energy region $\epsilon = E - E_g < 50$ meV. At larger values of ϵ, the change in μ does not exceed 5%. As a result of this effect of interparticle interactions, the value of μ near the bottom of the band in a dense *e–h* plasma depends very strongly on the carrier energy. The strong dependence of μ on ϵ is manifested in particular in the circumstance that at large values of n_{eh} the magnetic field dependence of the energies of Landau transitions is nonlinear for O_e–O_h and I_e–I_h transitions.

5. These results thus show that the reduced effective mass of the carriers in a neutral *e–h* plasma in an $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ quantum well undergoes sharp changes near the bottom of the band. This behavior stands in contrast with the behavior of $\mu(\epsilon)$ in an *e–h* plasma in stressed InGaAs/GaAs quantum wells with selective doping[2] ($n_e > 10^{12}$ cm^{-2}). In this case μ varies smoothly with the energy, and the change in μ is much smaller. The sharp change in $\mu(\epsilon)$ near the bottom of the band may be a specific feature of a neutral *e–h* plasma. It should be noted, however, that unstressed quantum wells in $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As/InP}$ structures differ from stressed quantum wells in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ structures in that the splitting Δ_h of the light- and heavy-hole subbands is small. Under these conditions, the renormalization (increase) of Δ_h in the dense *e–h* plasma can also cause a sharp change in $\mu(\epsilon)$. Note, however, that the increase in Δ_h would have to be anomalously large if we wish to explain the observed $\mu(\epsilon)$ dependence on the sole basis of a renormalization of the splitting of the light- and heavy-hole subbands. In order to determine how the renormalization of Δ_h affects the effective hole mass in an *e–h* plasma, we should study the behavior of $\mu(\epsilon)$ in undoped stressed $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ quantum wells with a large initial splitting of the light- and heavy-hole subbands.

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