# Effective carrier masses in a neutral quasi-two-dimensional electron–hole plasma in InGaAs/GaAs quantum wells with a nondegenerate valence band

L. V. Butov, V. D. Kulakovskii, V. D. Egorov,[1)] and T. G. Andersson[2)]
*Institute of Solid State Physics, Academy of Sciences of the USSR, 142432, Chernogolovka*

(Submitted 4 December 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 1, 37–42 (10 January 1991)

The luminescence and photoexcitation spectra of InGaAs/GaAs quantum wells with a nondegenerate valence band have been studied in a magnetic field. The interparticle interaction leads to an increase in the reduced carrier mass $\mu^{-1} = m_e^{-1} + m_h^{-1}$ in a neutral electron–hole ($e$–$h$) plasma. The magnitude of the renormalization falls off with increasing plasma density. The additional change in $\mu$ near the bottom of the band, which is observed in InGaAs/InP quantum wells with a complex valence-band structure, is shown to stem from a renormalization of the splitting of the light- and heavy-hole subbands.

**1.** Quantum wells in semiconductor heterojunctions provide wide opportunities for realizing quasi-two-dimensional (2D) electron systems and for studying their properties. Many-particle interactions in an electron–hole ($e$–$h$) system in a quantum well lead to a renormalization of the band gap and to a carrier energy dispersion $\epsilon_{e,h}(K) = \epsilon^0_{e,h}(K) + \mathrm{Re}\,\Sigma(K)$, where $K$ is the quasimomentum, $\epsilon^0_{e,h}(K)$ is the dispersion law of the noninteracting $e$ and $h$, and $\Sigma(K)$ is the eigenenergy part, which describes the contribution from interparticle interactions in many-body theory.[1-6] A renormalization of the reduced effective masses of the electrons ($m_e$) and of the holes ($m_h$), $\mu^{-1} = m_e^{-1} + m_h^{-1}$, can be detected reliably in magnetooptic measurements, from the change in the energy gaps between allowed transitions in the emission spectrum of the $e$–$h$ plasma.

Analysis[1] of the emission spectra of a neutral $e$–$h$ plasma in unstressed $\mathrm{In_{0.53}Ga_{0.47}As/InP}$ quantum wells in a magnetic field has shown that $\mu$ decreases monotonically with increasing plasma density $n_{eh}$ over the entire energy range below the Fermi energy $\epsilon_F$. Near the bottom of the band, a substantially more rapid change in $\mu$ is observed. Two reasons for this pronounced decrease in $\mu$ near the bottom of the band have been discussed. It was found in the calculations of Ref. 5, for example, that the direct effect of the electron–phonon and electron–plasmon interactions on the carrier dispersion law in an $e$–$h$ plasma could lead to such an effect. However, there is another possible cause[1] of the effect in $\mathrm{In_{0.53}Ga_{0.47}As/InP}$ quantum wells, with their complex valence-band structure: a renormalization of the splitting of the light- and heavy-hole subbands, $\Delta E_V$, by interparticle interactions and thus an additional change in $m_h$ and therefore in $\mu$ near the bottom of the band.

To decide between these two explanations of the effect, we have carried out a study of the renormalization of the effective mass in an $e$–$h$ plasma in highly stressed InGaAs/GaAs quantum wells. In such quantum wells, the splitting $\Delta E_v$ due to the compression of the InGaAs layer, as a result of the lattice mismatch of InGaAs and

GaAs, reaches 100 meV. It thus becomes possible to ignore the split-off subband and to measure the change in $\mu$ caused by the direct effect of the interparticle interaction on the $\Sigma(K)$ dependence.

**2.** For the measurements we used undoped $In_{0.28}Ga_{0.72}As/GaAs$ junctions with single quantum wells with a thickness $L = 9$ nm, grown by molecular beam epitaxy.[7] Nonequilibrium carriers were excited by a pulsed copper-vapor laser ($\lambda = 5105$ Å) with a pulse length ~20 ns. Samples were placed directly in helium in a cryostat with a superconducting solenoid ($H \leqslant 12$ T). An optical fiber 1 mm in diameter was used to excite the sample and to collect the emission from the sample, without additional focusing. The emitted light was sent to a 600-line/mm grating monochromator and then detected by a cooled photomultiplier with an S-1 cathode.

The basic experimental problem in a study of the emission spectra of an *e–h* plasma in quantum wells is to achieve a uniform density of the photoexcited *e–h* system in the quantum well. We paid particular attention to this point. In the first place, we used samples with a single quantum well. Second, we used quantum wells with a size no greater than the diameter of the exciting beam, in order to prevent a nonuniformity in the plane of the quantum wells. To maintain a constant plasma density over the time required to record the emission, we used a boxcar integrator with time gates of 4 ns. The emission spectra of the *e–h* plasma realized under these conditions have the stepped shape characteristic of a homogeneous plasma, reflecting the density of states of the 2D carriers.

**3.** Information on the variation of the carrier dispersion law was extracted from magnetooptic measurements. A magnetic field perpendicular to the plane of the quantum well causes a localization of the motion and thus gives the electrons and holes a discrete spectrum. The changes in the dispersion law are determined from the changes in the energy gaps between Landau levels. A localization of the motion of the electrons and holes simultaneously leads to a substantial amplification of exciton effects and a contraction of the range of applicability of the plasma approximation.[1,8] This range of applicability was discussed in detail in Ref. 1. The influence of exciton effects diminishes rapidly with distance from the Fermi level.[1,8] To determine the parameters of the *e–h* plasma, we accordingly used magnetic fields and plasma densities such that no fewer than three Landau levels were occupied.[1]

Figure 1 shows the changes in the emission spectra of the *e–h* system in a quantum well ($L = 9$ nm) with increasing excitation density at 4.2 K in a field $H = 12$ T. The spectra are dominated by allowed ($j_e = j_h$) transitions between electron ($j_e$) and hole ($j_h$) Landau levels. Several changes occur as $n_{eh}$ is increased. New lines appear in the spectrum as a consequence of the filling of progressively higher Landau levels. The emission lines broaden because of an increase in the decay of one-particle states. In addition, the renormalization of the width of the band gap causes the lines to shift down the energy scale. Finally, one observes a change in the energy gaps ($\Delta_{ij}$) between $i_e$–$i_h$ and $j_e$–$j_h$ lines. This change provides information about the change in the effective reduced mass of the electrons and holes, $\mu \sim \Delta_{i,i-1}^{-1}$.

Figure 2 shows the behavior of the energies of several allowed transitions as a function of the strength of the magnetic field for an *e–h* plasma with $n_{eh} = 1.7 \times 10^{12}$ cm$^{-2}$. The values of $n_{eh}$ were found directly from the emission spectra, from the filling

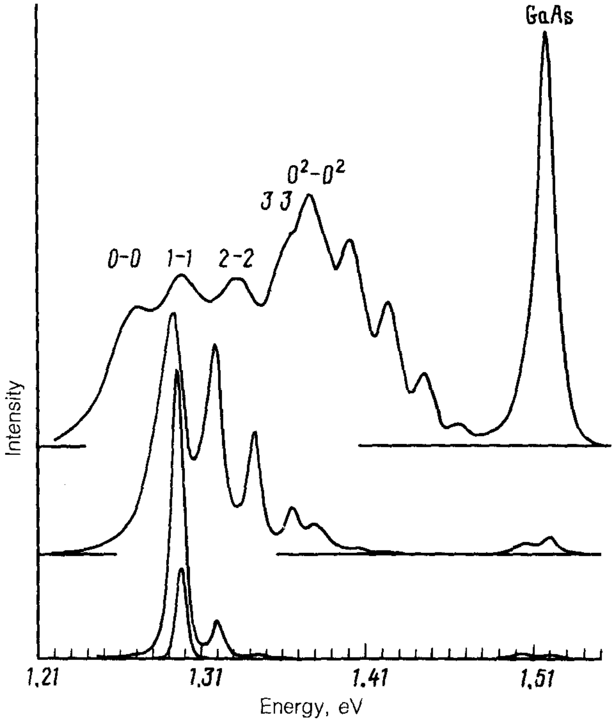

FIG. 1. Emission spectra of an $In_{0.28}Ga_{0.72}As/GaAs$ quantum well with a thickness of 9 nm in a magnetic field of 12 T at several excitation densities (from bottom to top): $W = 7\times10^2$, $3\times10^3$, $10^4$, and $10^5$ W/cm$^2$. $T_{\text{bath}} = 4.2$ K.

of Landau levels (the number of states in a Landau level was determined by the value of $H$ and was independent of the plasma density). Since the deviation from a parabolic shape is only slight in stressed InGaAs/GaAs quantum wells, for both the conduction band and the valence band, the curves of $\Delta_{i,i-1}(H)$ are essentially linear over the entire range $H \leqslant 12$ T.

**4.** The effect of an increase in the density of the *e–h* plasma on the effective mass in stressed $In_{0.28}Ga_{0.72}As/GaAs$ quantum wells with nondegenerate bands is shown by Fig. 3, as plots of $\Delta_{i,i-1}(n_{eh})$ for $i = 1$–3 in a field $H = 10$ T. Shown for comparison in the same figure are curves for $\Delta_{10}$, $\Delta_{21}$, and $\Delta_{32}$ for unstressed $In_{0.53}Ga_{0.47}As/InP$ quantum wells with a slight splitting of the light- and heavy-hole subbands in the valence band.[1] It can be seen from this figure that not only the increase in the quantities $\Delta_{i,i-1}$ (and thus $\mu$) with increasing $n_{eh}$ but also the qualitative behavior at $\Delta_{i,i-1}(n_{eh})$ at $i > 1$ is common to the quantum wells with valence bands differing in structure. On the other hand, we find an important distinction in the behavior of the quantity $\Delta_{10}$, which reflects the value of $\mu$ near the bottom of the band: The value of $\Delta_{10}$ varies in the manner of $\Delta_{21}$ and $\Delta_{32}$ the stressed quantum wells with a simple valence band. Consequently, the additional change in $\Delta_{10}$ in the unstressed quantum wells at densities $n_{eh} < 2.5\times10^{12}$ cm$^{-2}$ should be attributed to an indirect

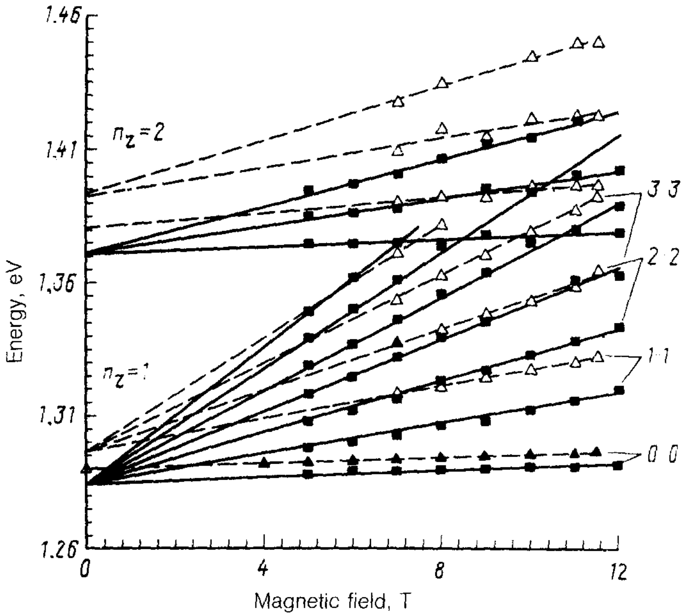

FIG. 2. Energies of allowed transitions versus the magnetic field in the photoexcitation spectra of the line of a 0–0 magnetoexciton during weak excitation (open triangles) and in the emission spectra at $n_{eh} = 1.7\times 10^{12}$ cm$^{-2}$ (squares). Filled triangles—Emission energy of the 0–0 magnetoexciton in the case of weak excitation. Here $n_z$ is the index of the quantum-size subband.

effect of the interparticle interaction on the effective hole masses through a renormalization of the splitting of the light- and heavy-hole subbands.

**5.** To find the absolute value of the renormalization of the effective mass due to the interparticle interaction, we should compare the effective reduced carrier mass in the *e–h* plasma with its value in an empty band, $\mu_0$. To determine $\mu_0$, we used the photoexcitation spectrum of the emission of a 0–0 magnetoexciton (which includes *e* and *h* with zero Landau levels) in a magnetic field. The photoexcitation spectra were recorded at 4.2 K with the help of an incandescent lamp and a monochromator. The spectrum is dominated by lines which correspond to dipole-allowed transitions to excited magnetoexciton states with $j_e = j_h$. Since neither the conduction band nor the valence band is degenerate in stressed quantum wells, it becomes an extremely simple matter to interpret these exciton–photoexcitation spectra in a magnetic field.

Figure 2 compares curves of the energies of allowed transitions in an *e–h* plasma and of exciton energies in an empty quantum well versus the magnetic field. It is obvious from this figure that all the Landau levels in the *e–h* plasma lie below the corresponding levels in the empty band. The magnitude of this shift increases markedly with increasing index of the Landau level, indicating a substantial increase in the effective mass in the *e–h* plasma.

The cyclotron energies $\Delta_{i,i-1}$ are related to the energy gaps in the photoexcitation spectrum, $\Delta^{ex}_{i,i-1}$, by $\Delta_{i,i-1} = \Delta^{ex}_{i,i-1} + \mathrm{Ry}_i - \mathrm{Ry}_{i-1}$, where $\mathrm{Ry}_i$ is the binding

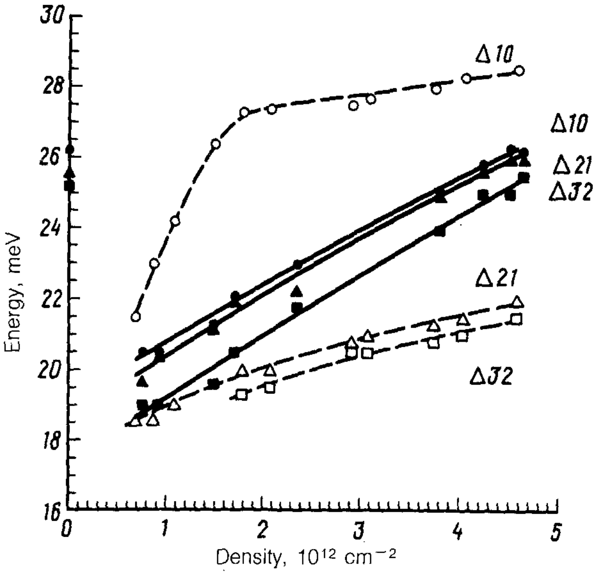

FIG. 3. Differences between transition energies in a neutral *e–h* plasma between different Landau levels, $\Delta_{i,i-1}$ for an $In_{0.28}Ga_{0.72}As/GaAs$ quantum well ($L = 9$ nm) with nondegenerate bands (filled points, $H = 10$ T) and for $In_{0.53}Ga_{0.47}As/InP$ quantum wells ($L = 15$ nm) with a complex valence band (open points, $H = 8.65$ T). The values of $\Delta_{i,i-1}$ for an empty quantum well ($n_{eh} = 0$) were found from the exciton–photoexcitation spectra corrected for the binding energy of the magnetoexcitons.

energy of a magnetoexciton in the state $i_e = i_h = i$. Values of $\mathrm{Ry}_i$ for $H \geqslant 10$ T were calculated in the approximation of a strong magnetic field.[9] The corrections $\mathrm{Ry}_i - \mathrm{Ry}_{i-1}$ are small: $\sim$4, 1.6, and 1 MeV for $i = 1,2,3$, respectively. Values found for $\Delta_{i,i-1}$ with $n_{eh} = 0$ are shown in Fig. 3. Comparison of the values of $\Delta_{i,i-1}$ in empty and filled quantum wells shows that the greatest renormalization of the effective mass in the *e–h* plasma occurs at $n_{eh} = 0.7 \times 10^{12}$ cm$^{-2}$, at which the increase in $\mu$ reaches 25%. The magnitude of the renormalization falls off monotonically with increasing $n_{eh}$; at $n_{eh} = 4.5 \times 10^{12}$ cm$^{-2}$, the value of $\mu$ agrees with the value in the empty band. This behavior of $\mu$ is in qualitatively good agreement with that expected on the basis of the theory of Refs. 5 and 6, according to which a decrease in density strengthens the effect of the interparticle and increases the effective mass.

**6.** In summary, the use of highly stressed InGaAs/GaAs quantum wells with nondegenerate electron and hole bands has made it possible, for the first time, to experimentally observe and evaluate the direct effect of the interparticle interaction on the effective carrier masses in a neutral *e–h* plasma. It has been shown that, in agreement with the theoretical predictions, the interparticle interaction causes an increase in the effective reduced mass of the carriers. The magnitude of the effect decreases with increasing plasma density. Comparison of the results for *e–h* plasmas in $In_{0.53}Ga_{0.47}As/InP$ and InGaAs/GaAs, with different valence-band structures, shows that there is an additional change in the effective mass in the unstressed $In_{0.53}Ga_{0.47}As/InP$ quantum wells, with a complex valence-band structure, as a result of a renormalization of the splitting of the light- and heavy-hole subbands.

We wish to thank I. V. Kukushkin and V. B. Timofeev for useful discussions, Z. G. Chen for the InGaAs/GaAs heterostructure, and A. O. Kolomiits for assistance in arranging the computer control of the experiments.

1) Permanent address is Central Institute of Electron Physics, D-1086, Berlin, FRG.

2) Chalmers Technical University, S-41296, Göteborg, Sweden.

---

[1] L. V. Butov, V. D. Kulakovskiĭ, A. Fotchel *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **52**, 759 (1990) [JETP Lett. **52**, 121 (1990)]; L. V. Butov, V. D. Kulakovskiĭ, and A. Forchel, Zh. Eksp. Teor. Fiz. **97**, 2135 (1990) [Sov. Phys. JETP (to be published)].

[2] L. V. Butov, V. D. Kulakovskiĭ, T. G. Andersson *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 256 (1988) [JETP Lett. **48**, 280 (1988)].

[3] G. Tränkle, E. Lach, A. Forchel *et al.*, Phys. Rev. B **36**, 6712 (1987).

[4] J. C. Maan, M. Potemski, and Y. Y. Wang, *High Magnetic Fields in Semiconductor Physics. II* (ed. G. Landwehr), Springer-Verlag, Berlin, Heidelberg (Springer Series in Solid-State Sciences, 1987, 87, 248).

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

[6] B. Vinter, Phys. Rev. B **13**, 4447 (1976).

[7] T. G. Anderson, Z. G. Chen, V. D. Kulakovskii *et al.*, Phys. Rev. B **37**, 4032 (1988).

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

[9] I. V. Lerner and Yu. E. Lozovik, Zh. Eksp. Teor. Fiz. **78**, 1167 (1980) [Sov. Phys. JETP **51**, 588 (1980)].

Translated by D. Parsons