# Renormalization of the carrier dispersion law in a dense electron-hole system in an InGaAs quantum well

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The emission from a quasi-2D electron-hole system in an InGaAs quantum well has been studied at low temperatures and high excitation densities. The renormalizations of the band gap and of the reduced electron and hole masses due to multiparticle effects are determined.

**1**. Interparticle interactions in a dense electron-hole (*e-h*) system in a semiconductor lead to a renormalization of the band gap and of the electron and hole dispersion law. In many-body theory, this change is described by the eigenenergy part of $\Sigma$, which depends on the quasimomentum $k$ and energy $\epsilon$ of the quasiparticles: $\epsilon_{e,h}(k) = \hbar^2 k^2/2m_{e,h} + \mathrm{Re}\Sigma_{e,h}(k,\epsilon)$. In 3D systems, the quantity $\Sigma(k,\epsilon)$ depends only weakly on $k$ and $\epsilon$ and even on the particular species of charged particles. The reason is that the screened interaction is of a short-range nature.[1] The electron and hole bands in highly excited semiconductors thus undergo a basically rigid shift.[1] The behavior of $\Sigma(k,\epsilon)$ in quasi-2D systems, in which the screening of the Coulomb potential is greatly reduced, has remained an open question.

In this letter we report a study of an *e-h* plasma in an InGaAs quantum well in the density interval $r_s = (\pi n a_0^2)^{-1/2} \sim 1$–$0.25$ ($n$ is the density of *e-h* pairs, and $a_0$ is the first Bohr radius of an exciton). We have found that the maximum change in the effective mass in this density interval is about 10%.

**2.** The $n$-AlGaAs–InGaAs–GaAs structure which we studied falls in the category of so-called stressed heterostructures, since the difference between the InGaAs and GaAs(AlGaAs) lattice constants (1.5%) results in a pronounced compression of the InGaAs layer. Such structures have the advantage that the valence band has a simple structure: The stress splits the quadruply degenerate valence band of InGaAs into two subbands, with spins $j = \pm 3/2$ (the main subband) and $j = \pm 1/2$ (the split-off subband). The split-off valence subband in structures consisting of unstressed GaAs and stressed InGaAs is below the valence band of GaAs at the $\Gamma$ point.[2]

Nonequilibrium $e$-$h$ pairs were excited in a quantum well either by the beam from a cw $\text{Ar}^+$ laser ($\lambda = 5145$ Å) or by a pulsed beam from a copper-vapor laser ($\lambda = 5105$ Å), with a pulse length ($\sim 10$ ns) sufficient to achieve quasisteady conditions. As the spectral instrument we used a double monochromator with a dispersion of 10 Å/mm; the emission was detected by a photomultiplier with an $S$–1 cathode. The pulsed measurements were carried out with the help of a boxcar integrator with a strobe width of 5 ns. The samples were placed in a cryostate with a superconducting solenoid, directly in superfluid helium. The size of the excitation spot was chosen equal to the size of the samples ($\leqslant 0.5$ mm). This choice resulted in a sufficient uniformity of the system in the quantum well over the entire area of the sample.

A modulated doping of the AlGaAs with silicon donors provided an initial density $n_{2D}^e = 1.2 \times 10^{12}$ cm$^{-2}$ of 2D electrons in the InGaAs quantum well. This density remained essentially constant at excitation densities $W < 10$ W/cm$^2$. The maximum density of the $e$-$h$ system in the quantum well, $n_{\max}$, was determined by the depth and width of the well. In the particular structure which we studied, this maximum density was $n_{\max} = 5.5 \times 10^{12}$ cm$^{-2}$ ($r_s \sim 0.25$).

**3.** Because of the relatively high initial density of electrons in the quantum well at all excitation densities $W > 10^{-2}$ W/cm$^2$, the spectrum is dominated by an emission resulting from interband recombination of electrons and holes. At small values of $W$ the emission linewidth is determined by the electron Fermi energy (Fig. 1).

As $W$ is increased from $10^{-2}$ to 10 W/cm$^2$, we observe a slight ($\sim$4-meV) shift of the line up the energy scale. A similar shift was observed in Ref. 3 and attributed to a decrease in $\Sigma(\kappa,\epsilon)$ due to a proposed decrease in the density of equilibrium 2D electrons, $n_{2D}^e$, in the quantum well as a result of recombination with nonequilibrium holes. Our measurements, however, show that the value of $n_{2D}^e$ remains constant over this $W$ interval. The reason for the shift of the lines is that at very low values $W < 10^{-1}$ W/cm$^2$ and $T \sim 1.8$ K most of the nonequilibrium holes are in state-density tails.

**4.** Interparticle interaction effects have important manifestations only at $W > 10^3$ W/cm$^2$ where the density of nonequilibrium pairs becomes comparable to $n_{2D}^e$ (Fig. 1). In this density region, an increase in $W$ is accompanied by a broadening of the emission line, due to increases in the electron and hole Fermi energies. The emission line shifts down the energy scale, because of a renormalization of the band gap. At high excitation densities the emission spectrum becomes stepped, as we would expect for an allowed mechanism of interband recombination of electrons and holes in the 2D system, characterized by state densities in the electron and hole bands which are independent of the energy. The distance between the steps corresponds to the energy gap between the quantum-size sublevels in the quantum well. It can be seen from Fig.

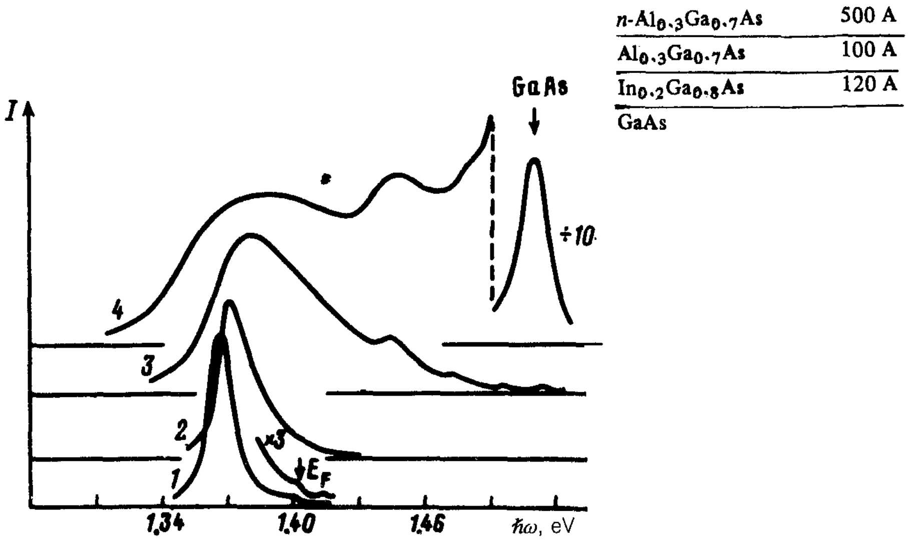

FIG. 1. Photoluminescence spectra of an $n$-AlGaAs–InGaAs–GaAs heterostructure at 2 K and at the following excitation densities $W$ (W/cm$^2$): 1—$10^{-2}$; 2—10; 3—$5\times10^3$; 4—$10^5$. The structure is shown schematically in the inset at the top.

1 that the blurring of the steps, caused primarily by the pronounced decay of the one-particle states far from the Fermi level, is quite substantial, and the error in the determination of $\Delta E_g$ is large. We accordingly resorted to measurements in a transverse magnetic field (Fig. 2).

At high excitation densities or at high temperatures, where the electrons and

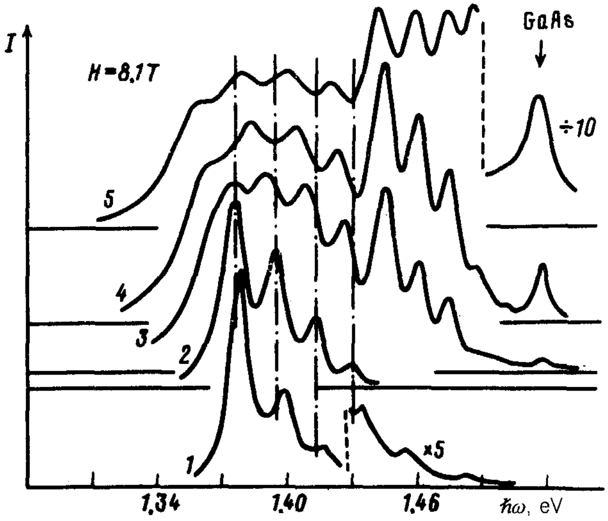

FIG. 2. Photoluminescence spectra of an $n$-AlGaAs–InGaAs–GaAs heterostructure in a transverse magnetic field $H = 8.1$ T. 2–5—Pulsed excitation at $2\times10^3$, $10^4$, $3\times10^4$, and $10^5$ W/cm$^2$, respectively, at a bath temperature of 2 K; 1—steady-state excitation (10 W/cm$^2$) at 120 K. Spectrum 1 is shifted up the energy scale by an amount equal to the temperature-induced decrease in the band gap.

holes are distributed over several Landau levels, the emission spectrum of a quantum well is dominated by the emission, due to allowed transition between electron and hole levels with identical indices, of both the size quantization and the quantization in the magnetic field. Figure 2 shows how an increase in the excitation density is accompanied by a filling of the electron and hole Landau levels, a broadening of these levels, and a shift of these levels down the energy scale because of an interparticle interaction of electrons and holes in the quantum well.

It follows from a comparison of the emission spectra in the case of low and high pumping levels that the broadening of the Landau levels at high densities of *e–h* pairs in the quantum well is a consequence not of imperfections of the well but of a decay of the one-particle states, $\Gamma_{e,h}$. The value of $\Gamma_{e,h}$ increases with distance from the Fermi level, and at $\epsilon_F = \epsilon_{F_e} + \epsilon_{F_h} = 150$ meV its value at the bottom of the band is $\sim 15$ meV or $\sim 0.1\epsilon_F$.

The change in Re $\Sigma$ ($\Sigma = \Sigma_e + \Sigma_h$) can be reconstructed from the shift (with increasing $n_{e-h}$) of the emission lines corresponding to transitions between different Landau levels. The magnitude of the renormalization of the band gap is found from the shift of the 0-0 line (a transition between zero Landau levels). It can be seen from Fig. 2 that $\Sigma(0)$ increases monotonically with increasing $n_{e-h}$; the change in $\Sigma(0)$ as the density of free carriers in the quantum well is increased from the equilibrium value $n_{2D}^e \sim 10^{12}$ cm$^{-2}$ to $5.5 \times 10^{12}$ cm$^{-2}$ is 20 meV.

It can be seen from Fig. 2 that as the excitation density is increased, the shifts of the lines corresponding to transitions between different Landau levels are different. On the other hand, at any fixed value of $W$ we observe a linear increase in the energy gaps between the Landau levels in fields $H \leqslant 8.3$ T (Fig. 3). The change in these gaps at a fixed $H$ as $n_{e-h}$ is increased indicates a change in the effective carrier masses because of interparticle interaction, i.e., a dependence of $\Sigma$ on $k$. The cyclotron frequencies vary

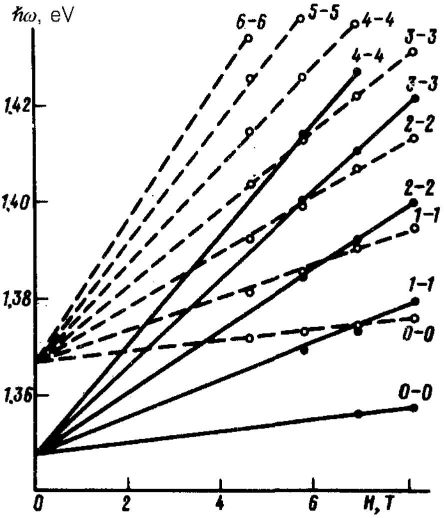

FIG. 3. Splitting of the photoluminescence line of the *e-h* system in an InGaAs quantum well in a magnetic field at various excitation densities. Filled circles—$10^5$ W/cm$^2$ ($n_{e\text{-}h} \sim 5.5 \times 10^{12}$ cm$^{-1}$); open circles—$2 \times 10^3$ W/cm$^2$ ($n_{e\text{-}h} \sim 5 \times 10^{11}$ cm$^{-2}$).

in a nonmonotonic way: At $W \leqslant 2 \times 10^3$ W/cm$^2$ we observe a decrease in these frequencies [i.e., an increase in the reduced effective mass of the electrons and holes, $\mu = (m_e^{-1} + m_h^{-1})^{-1}$, while at large values of $W$ the cyclotron frequencies increase ($\mu$ decreases). This behavior of $\mu$ agrees qualitatively with the expected behavior, since the increase in $\mu$ stems from interparticle-interaction effects, and at high densities ($r_s \ll 1$) the interparticle interaction would weaken markedly because of the screening of the Coulomb potential.

The values of $\mu$ for all $n_{e\text{-}h}$ turn out to be greater than the reduced effective mass for an empty quantum well, $\mu_0 = 0.040m_0$, calculated from the known parameter values of the bands in GaAs and InAs, with allowance for the deformation of the $In_{0.2}Ga_{0.8}As$ in the quantum well. The initial, maximum, and minimum values of $\mu$, which correspond to equilibrium electron densities $n_{2D}^e \sim 10^{12}$ cm$^{-2}$ and $n_{e\text{-}h} \ll n_{2D}^e$, $n_{e\text{-}h} \sim 5 \times 10^{11}$ cm$^{-2}$, and $5 \times 10^{12}$ cm$^{-2}$, are $0.047m_0$, $0.050m_0$, and $0.045m_0$, respectively, ($\pm 0.001m_0$). As expected, the value of $\mu$ for a dense *e-h* system in the quantum well is close to the value of $\mu_0$ in an empty well. The change in $\mu$ for the *e-h* system in the 120-Å quantum well studied, and also for 3D *e-h* systems in Ge (Refs. 1 and 4), is within 15%.

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