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Bandgap renormalization: GaAs/AlGaAs quantum wells

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ABSTRACT

Bandgap energy renormalization by many-body interactions has been studied in a series of n-type 8-nm-wide GaAs/AlGaAs single quantum wells using magnetoluminescence spectroscopy at 1.4K and for magnetic fields up to 30T. The 2D-carrier densities varied between 1 and 12×10^{11} cm^{-2}. At the maximum 2D-carrier density, the bandgap energy difference between the doped and undoped samples was about 34 meV.

Keywords: photoluminescence, quantum wells, bandgap renormalization, many body effects

1. INTRODUCTION

For last several years, there have been many experimental and theoretical treatments for bandgap energy renormalization effects resulting from many body interactions[1-11] in semiconductor quantum-well structures. For optoelectronic systems which rely on the electronic bandgap in heavily doped quantum wells, such as high-power injection lasers, these many body effects can result in bandgap renormalization energies approaching 20 to 40 meV, i.e., for GaAs/AlGaAs systems, the bandgap energy can vary as much as a 2% depending on laser intensity. Thus, for precise laser wavelength design or control, a knowledge of the dependence of the renormalized bandgap energy on carrier density is mandatory.

In this paper, we present a study for the bandgap renormalization as a function of the 2D-carrier density N_{2D} for a series of modulation doped n-type 8-nm-wide GaAs/AlGaAs single quantum wells. One method of determining of the bandgap reduction for a heavily-doped semiconductor quantum well is to model[12] the zero-field photoluminescence lineshape function to yield a value for the bandgap energy. Here, we use an unambiguous method for obtaining accurate bandgap energies in 2D-electron structures by studying the photoluminescence spectrum in the presence of a magnetic field. With the application of an external magnetic field the photoluminescence spectrum forms a series of peaks, Landau levels. The energy of each Landau level is proportional to the magnetic field. Thus by extrapolating the magnetoluminescence "Fan" diagram to zero magnetic field yields the true bandgap energy without complications of spectral shifts[13] to the zero-field photoluminescence lineshape caused by coulomb interactions between the 2D-carriers (electrons and holes) and the positive-charged modulation-doping layer. Recently, the magnetoluminescence technique was also employed to study[11] bandgap renormalization in compressively strained n-type GaInP/AlGaInP quantum well structures where bandgap renormalization energies of nearly 36 meV for $N_{2D} \sim 1 \times 10^{13}$ cm^{-2}. Because of the heavier conduction-band masses for InGaP, compared to GaAs, pulsed magnetic fields approaching 50T were required.

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2. EXPERIMENTAL

The modulation doped GaAs/AlGaAs SQW structures were prepared using metal organic vapor phase epitaxy. All samples were grown on semi-insulating (100) GaAs substrates. An undoped 1-μm-thick GaAs buffer layer was grown on top of the substrate and on top of this buffer layer, a single 8-nm-wide unintentionally doped GaAs quantum-well was placed between 100-nm-wide $Al_{0.30}Ga_{0.70}As$ barriers, followed by an undoped 5-nm-thick GaAs cap layer. The upper AlGaAs barrier layer was delta-doped with silicon 30 nm from the GaAs quantum well, with doping densities in the range between 0.5 and 2.5 × 10^{18} cm^{-3}. For absolute calibration of the bandgap energy reduction, an unintentionally doped structure was also prepared in the same manner. The growth temperature for all layers and structures was 750C.

The magnetoluminescence measurements were made using two different magnet systems: (1) A 14T superconducting magnet with a variable temperature insert allowing sample temperatures as low as 1.4K and (2) A 30T resistive magnet system with a fixed temperature (4.2 K) liquid helium dewar. The luminescence measurements were made with an Argon-ion laser operating at 514.5 nm and an IEEE488-based data acquisition system. The direction of the applied magnetic field was parallel to the growth direction, i.e., the resulting Landau orbits are in the plane of the GaAs quantum well. The laser excitation and photoluminescence signal from the sample were brought in and carried out along the same single optical fiber using a beam-splitter to separate the two light sources. The tip of the optical fiber was placed directly on the sample and the resulting maximum laser power density on the sample was about 1 W/cm^2.

The 2D-carrier densities were determined by two different methods, magnetoluminescence and low temperature transport measurements. The magnetoluminescence method notes when each Landau level and hence each interband transition disappears from the photoluminescence spectrum. The transport method relies on an analyses of Shubnikov-deHaas oscillations in the conductivity, but essentially provides the same information as magnetoluminescence method by recording the magnetic field and filling factor ν when the Fermi energy lies half-way between two adjacent Landau levels, one filled and one empty. These two different measurement techniques for the 2D-density give similar results for each sample.

3. RESULTS AND DISCUSSION

Because the results obtained using the 30 T magnet system are similar to the 14 T superconducting magnet data, only the only the latter will be presented here. The 1.4K zero-field photoluminescence spectrum for an n-type, $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}, sample (#EMC-2218) is shown in Fig. 1. Anticipating the analyses of the magnetoluminescence data presented below, we indicate where the *true* bandgap energy E_{gap} = 1557.6 meV is located. It is apparent from the figure that the energy of the peak intensity of the photoluminescence spectrum at 1563 meV is shifted above the *true* bandgap value E_{gap}, i.e., the spectral shift is about 6 meV. The photoluminescence line shape function and the resulting spectral shifts for degenerate quantum wells will not be discussed here, but the reader is referred to reference 13 where it has been treated in detail. The high energy shoulder near 1590 meV is due to band-to-band transitions near the Fermi energy E_f.[13] Also indicated in the figure is the energy E' = 1585.7 meV for the undoped structure where the effective Rydberg $E_{ex} \approx 9$ meV for an 8-nm-wide quantum well[14] has been added to observed zero-field exciton photoluminescence energy for the undoped structure. Thus, for the spectrum shown in Fig. 1, where $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}, the bandgap energy reduction is nearly 30 meV!

Magnetoluminescence is simply photoluminescence in the presence of a magnetic field. A free particle, with mass m and charge e, moving in a magnetic field B forms quantized states, Landau levels, with an energy $E(n) = (n + 1/2)(e\hbar B/mc)$ (cgs units) $\equiv (n + 1/2)\hbar\omega$ where n is the Landau level index, $\hbar$ is Planck's constant over 2π, c is the velocity of light, and $\hbar\omega$ is the quantized cyclotron resonance energy. The distribution function for a degenerate 2D-electron gas (conduction-band states for a n-type material) is based on Fermi-Dirac statistics. But, because of the very small 2D-density of photo-induced hole-states, the distribution function for the valence-band holes are governed by Maxwell-Boltzmann statistics. For temperatures where kT is much larger than valence-band cyclotron energy $\hbar\omega_v$, the $n_v = 0, 1, 2, \ldots$ valence-band Landau levels are populated according to the Maxwell-Boltzmann distribution function and all magnetoluminescence transitions between the n_c and n_v Landau levels obey the $\delta n_{cv} \equiv (n_c - n_v) = 0$ selection rule. Because of heavy-hole light-hole valence-band mixing for an 8-nm-wide GaAs quantum well, the ground state in-plane valance-band masses are "heavy" (and nonparabolic) and hence the condition that $kT > \hbar\omega_v$ is satisfied[15] even at 1.4K. As discussed in reference 15, the heavy-hole light-hole energy difference for a 4.5-nm-wide GaAs/AlGaAs quantum well is sufficiently large (~ 30meV) and at 1.4K, $kT < \hbar\omega_v$ and here, only the $n_v = 0$ valence-band Landau level is populated. Thus for these narrow quantum wells at 1.4K, only the $n_c = 0$ to $n_v = 0$ transition is allowed; however, a series of higher energy *zeroth-order forbidden* $n_c = 0, 1, 2, \ldots$ to $n_v = 0$ transitions are observed.[15-17] For either case,

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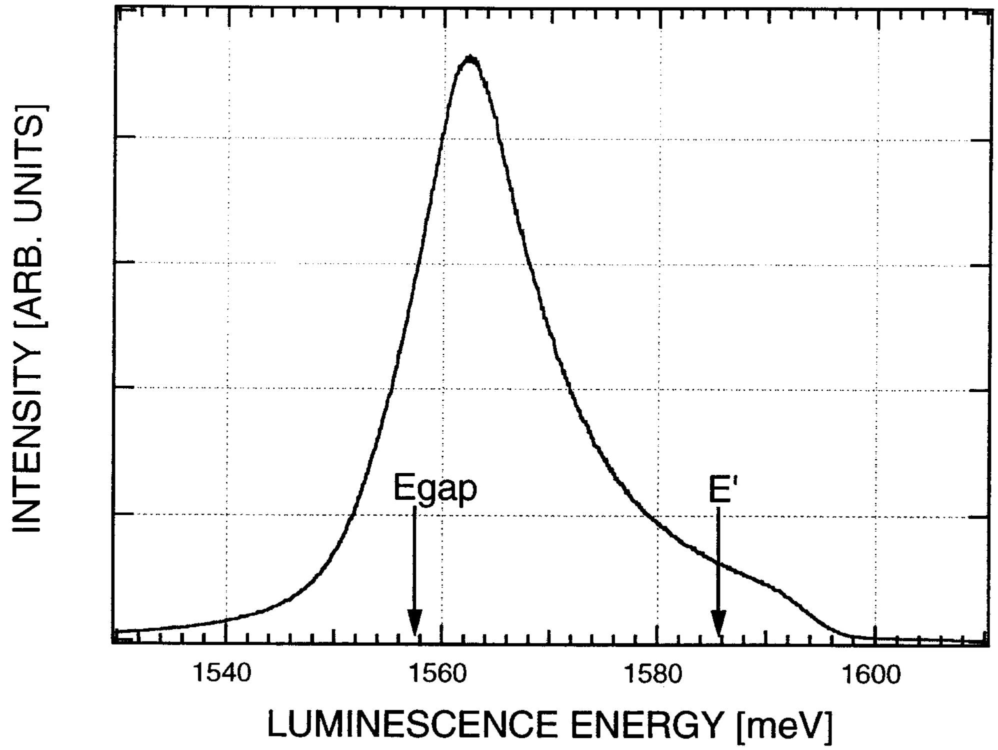

Figure 1. The zero-field 1.4-K photoluminescence spectrum for an 8-nm-wide n-type GaAs/AlGaAs single quantum well. The 2D-carrier density $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}. The energy of the photoluminescence peak intensity is nearly 1563 meV and the *true* bandgap energy $E_{gap} = 1557.6$ meV is the extrapolated bandgap energy from the magnetoluminescence "Fan" diagram shown in Fig. 3. The bandgap energy for an undoped quantum well is labeled E'.

allowed or zeroth-order forbidden transitions because the Landau-level energy shifts are proportional to the magnetic field, the zero-field extrapolated value is the bandgap energy. Thus, for all of the 8.5-nm-wide n-type GaAs/AlGaAS single quantum well samples discussed here, the interband Landau level transition energies E(n) are *allowed* and are given by the expression

$$E(n) = E_{gap} + \left(n + \frac{1}{2}\right)\frac{e\hbar B}{\mu c}, \qquad (1)$$

where E_{gap} is the bandgap energy, n = 0, 1, 2, ... is the Landau level index, μ is the reduced mass given by $\mu^{-1} = m_c^{-1} + m_v^{-1}$, where m_c and m_v are respectively the conduction or valence-band effective masses. The Landau level index $n \equiv (n_c = n_v)$ because, as mentioned above, the selection rule for *allowed* transitions is $\delta n_{cv} = 0$.

Figure 2 shows a magnetoluminescence spectrum at B = 8 tesla and T = 1.4K for the n-type sample whose zero-field photoluminescence spectrum is shown in Fig. 1. As can be seen, the zero-field spectrum breaks up into a series of peaks whose energies are given by Eq. (1). The Landau transition value $n_c \leftrightarrow n_v$ for each peak is indicated in the figure. At 1.4K, 8T and $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}, only the $n_c = 0, 1, 2$, and 3Landau levels are occupied and therefore the highest energy photoluminescence peak that can be observed is the $3 \leftrightarrow 3$ transition. Because of the nonparabolic[15] valence-band mass, it is difficult to determine the valence-band hole temperature from the ratio of the photoluminescence peak intensities using a Maxwell-Boltzmann distribution. However, for InGaAs/GaAs single-strained-quantum wells, where the heavy-hole light-hole valence bands are well separated ($\delta E \sim 60$ meV) and the resulting in-plane valence band masses are lighter and much more parabolic than found for the GaAs/AlGaAs structures discussed here, the Maxwell-Boltzmann determined ratio of the photoluminescence peak intensities do indicate that the valence-band holes are in good thermal equilibrium with the lattice.

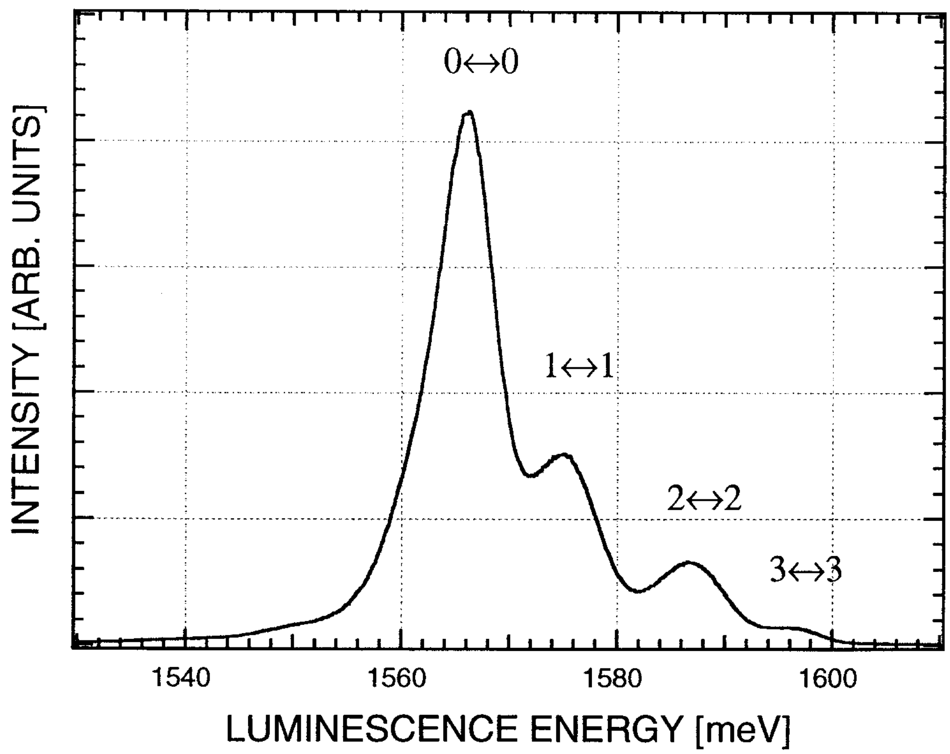

Figure 2. The photoluminescence spectrum at 8 tesla and 1.4-K for the n-type 8-nm-wide GaAs/AlGaAs single quantum well sample shown in Fig. 1. The Landau transition value $n_c \leftrightarrow n_v$ is indicated for each peak.

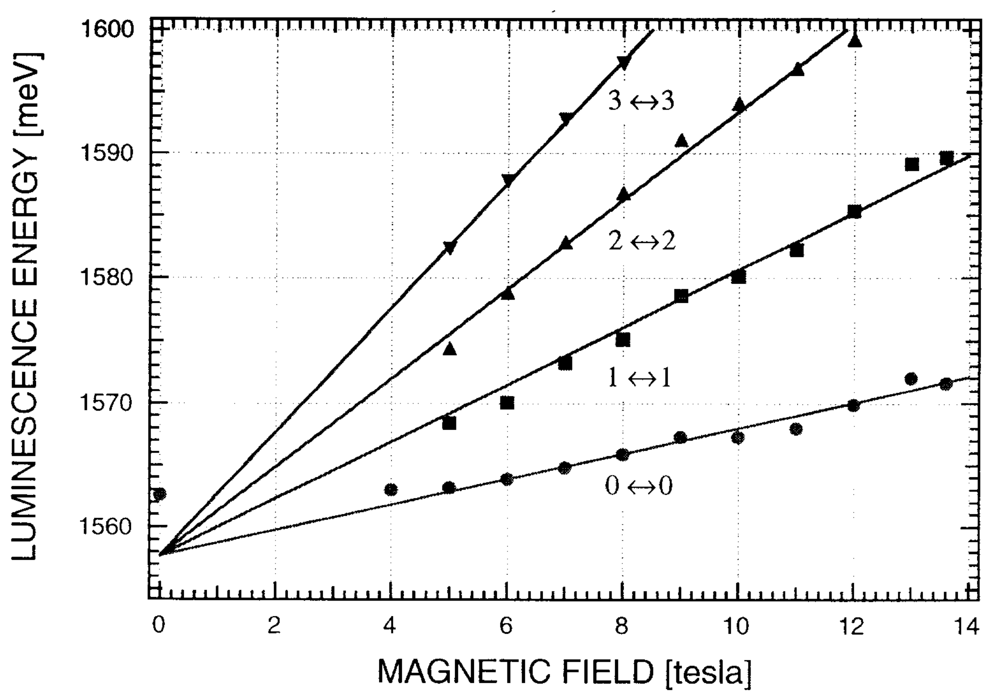

Figure 3. The magnetoluminescence "Fan" diagram for the 1.4-K data. The Landau transition values $n_c \leftrightarrow n_v$ are indicated. The lines are best fits of Eq. (1) to the data and the extrapolated zero-field bandgap energy is 1557.6 meV. The ratio of the straight line slopes is nearly 1:3:5:7 in agreement with Eq. (1).

A magnetoluminescence energy "Fan" diagram can be generated by plotting the energy of each Landau level transition energy (See Fig. 2) as a function of magnetic field and this result is shown in Fig. 3. The Landau transition values $n_c \leftrightarrow n_v$ are indicated and the lines drawn through the data are best fits of Eq. (1) to the data. The ratio of the slopes are nearly 1:3:5:7 as predicted by Eq. (1) again verifying the *allowed* nature of the transitions. The bandgap energy E_{gap} can be uniquely determined from a zero-field extrapolation of the straight lines shown in Fig. 2 with the result, E_{gap} = 1557.6 meV.

For all of the n-type GaAs/AlGaAs single quantum well structures, magnetoluminescence "Fan" diagrams similar to the one shown in Fig. 3 can be generated using the above described procedures. The bandgap energy reduction ΔE for each sample can then be calculated by subtracting the magnetoluminescence determined zero-field bandgap energy E_{gap} from the undoped structures' bandgap energy E' shown in Fig. 1.

An excellent review of the nonlinear properties of electron-hole plasmas in semiconductors has been presented by Schmidt-Rink et. al.[5] Among other subjects, these authors have discussed the bandgap energy reduction (BGR) due to many body effects in both bulk (3D) and 2D-systems. Also, problems of using random phase approximations (RPA) to solve the zero-temperature BGR have been discussed in detail. However, as mentioned in reference 5, a simple interpolation formula derived by Schmidt-Rink and Ell2 gives good agreement not only with RPA-type calculations and but also with experiment. From Schmidt-Rink et. al.[2,5], the size of the BGR can be calculated from the expression

$$\Delta E = -3.1\left(N_{2D}a_0^2\right)^{1/3} E_{ex}, \tag{2}$$

where $\Delta E \equiv (E_{gap} - E')$ is the difference in energy between the bandgap energy E_{gap} the 2D-electron gas and the bandgap energy E' of the undoped structure, N_{2D} is the 2D-carrier density, a_0 is the bohr radius, and E_{ex} is the exciton binding energy.

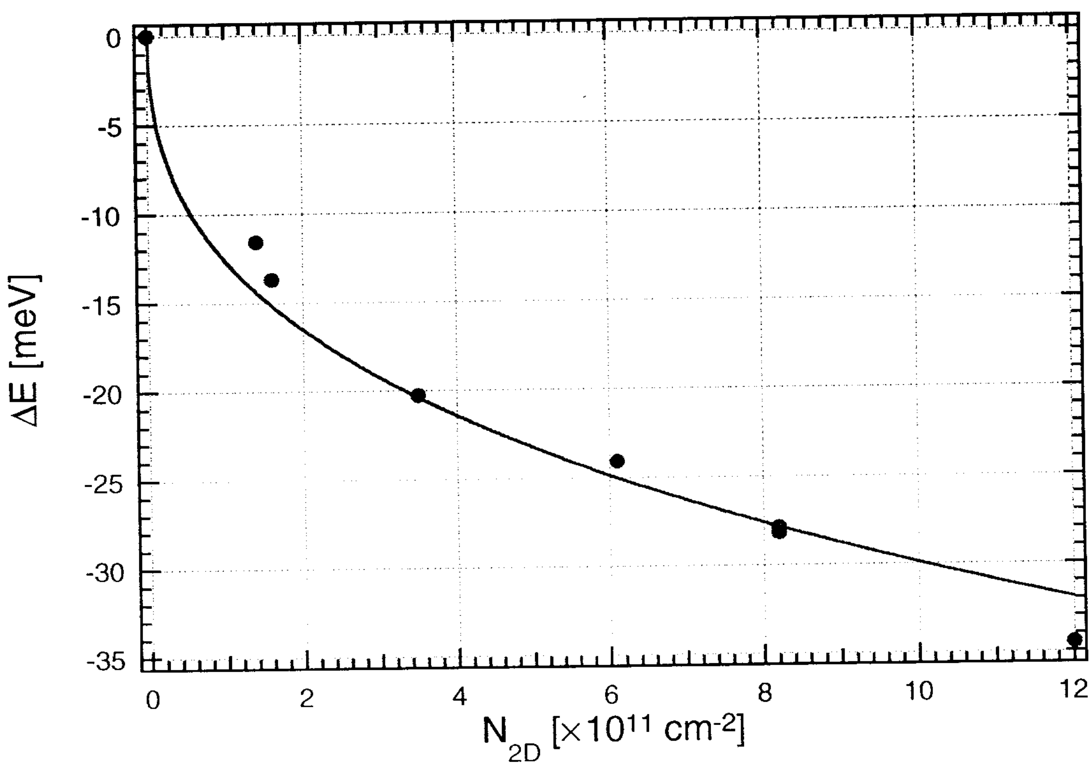

Figure 4. The energy difference ΔE between the undoped bandgap energy E' and the n-type GaAs/AlGaAs single quantum well energies E_{gap}. The curve through the data is given by $\Delta E = -3.22 \times 10^{-3} N_{2D}^{1/3}$ meV.

As mentioned previously, we estimate for an 8-nm-wide undoped GaAs/AlGaAs single quantum well that $E_{ex} \sim 9$ meV and also that $a_0 \sim 12.5$ nm. From Eq. (2), we thus expect that the 2D-density dependence for bandgap reduction energy will be given by

$$\Delta E \sim -3.2 \times 10^{-3} N_{2D}^{1/3} \ meV. \tag{3}$$

Figure 4 shows the result of plotting ΔE as a function of the 2D-carrier density N_{2D}. The energy difference ΔE for each structure $\Delta E = (E' - E_{gap})$. The solid curve drawn through the data is a result of a best fit of $\Delta E = AN^{1/3}$ to the data given by

$$\Delta E = -3.22 \times 10^{-3} N_{2D}^{1/3} \ meV. \tag{4}$$

The experimental curve shown in Fig. 4 (Eq. (4)), is in good agreement the estimated $\Delta E \sim -3.2 \times 10^{-3} N^{1/3}$, i.e., Eq. (3).

4. CONCLUSIONS

In conclusion, we have shown that the magnetoluminescence technique allows a direct determination of the bandgap energy for degenerate quantum well samples. Furthermore, the complications of spectral shifts to the photoluminescence peak line shape are avoided by this method. Finally, agreement between the data and the expectations based on the calculation by Schmidt-Rink et. al., is good. Currently, we are extending these types of bandgap energy reduction measurements to strained and lattice matched InGaAs/InAlAs n-type single quantum wells on InP.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. D. A. Kleinman and R. C. Miller, "Band-gap renormalization in semiconductor quantum wells containing carriers", *Phys. Rev.* **B32**, pp 2266-2272, 1985.
2. S. Schmitt-Rink and C. Ell, "Excitons and electron-hole plasma in quasi-two-dimensional system", *J. Lumin.* **30**, pp 585-596, 1985.
3. G. Tränkle, H. Leier, A. Forchel, H. Haug, C. Ell, and G. Weimann, "Dimensionality dependence of the band-gap renormalization in two- and three-dimensional electron-hole plasmas in GaAs", *Phys. Rev. Lett.* **58**, pp 419-422, 1987.
4. C. Delalande, G. Bastard, J. Orgonasi, J. A. Brum, H. W. Liu, M. Voos, G. Weimann, and W. Schlapp, "Many-body effects in a modulation-doped semiconductor quantum well", *Phys. Rev. Lett.* **59**, pp 2690-2692, 1987.
5. S. Schmitt-Rink, D. S. Chemla and D. A. B. Miller, "Linear and nonlinear optical properties of semiconductor quantum wells", *Adv. Phys.* **38**, pp 89-188, 1989.
6. M. Potemski, J. C. Maan, K. Ploog, and G. Weimann, "High intensity excitation luminescence of quantum wells in high magnetic fields", *Surf. Sci.* **229**, pp 380-383, 1990.
7. R. Jalabert and S. Das Sarma, "Many-body effects in GaAs-based two-dimensional electron systems", *Surf. Sci.* **229**, pp 405-409, 1990.
8. T. L. Reinecki, D. A. Broido, E. Lach, V. Kulakovskii, A. Forchel, and D. Gruetzmacher, "Bandgap renormalization at finite carrier densities in semiconductor quantum wells and mesa structures", *Superlattices and Microstructures* **7**, pp 437-440, 1990.

9. M. Potemski, J. C. Maan, K. Ploog, and G. Weimann, "Properties of a dense quasi-two-dimensional electron-hole gas at high magnetic fields", *Solid State Communications* **75**, pp 185-188, 1990.
10. R. Cingolani, G. C. La Rocca, H. Kalt, K. Ploog, M. Potemski, and J. C. Maan, "Magnetoluminescence of the two-dimensional electron-hole fluid", *Phys. Rev.* **B43**, pp 9662-9671, 1991.
11. A. N. Priest, R. J. Nicholas, S. P. Najda, G. Duggan, and A. H. Kean, "Bandgap and mass renormalization in GaInP/AlGaInP quantum wells", *Physica* (to be published 1998).
12. See, for example, References 3 and 5.
13. S. K. Lyo and E. D. Jones, "Photoluminescence line shape in degenerate semiconductor quantum-wells", *Phys. Rev.* **B38**, pp 4113-4119, 1988.
14. R. L. Green and K. K. Bajaj, "Binding energies of Wannier excitons in GaAs-$Ga_{1-x}Al_xAs$ quantum-well structures in a magnetic field", *Phys. Rev.* **B31**, pp 6498-6502, 1985.
15. E. D. Jones, S. K. Lyo, J. F. Klem, J. E. Schirber, and S. Y. Lin, "Ground-state in-plane light-holes in GaAs/AlGaAs structures", *Inst. Phys. Conf. Ser. No* **120**, pp 407-412, 1991.
16. S. K. Lyo, E. D. Jones, and J. F. Klem, "Breaking of the usual selection rule for magnetoluminescence in doped semiconductor quantum-wells", *Phys. Rev. Lett.* **61**, pp 2265-2267 1988.
17. E. D. Jones, "Band structure parameters for quantum wells: Magnetoluminescence determinations", *Twenty-Sixth State-of-the-Art Program on Compound Semiconductors (SOTAPOCS XXVI),* Edited by D. N. Buckley, S. N. G. Chu, H. Q. Hou, R. E. Sah, J. P. Vilcot, and M. J. Deen, pp 127 - 137 (Electrochemical Society, Pennington, NJ 1997).

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