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Bandgap Renormalization Studies of n-type GaAs/AlGaAs Single Quantum Wells

E. D. Jones, M. Blount, W. Chow, H. Hou, and J. A. Simmons
Sandia National Laboratories
Albuquerque, NM 87185, USA

Bandgap energy renormalization due to many body effects has been studied in a series of n-type 8-nm-wide GaAs/AlGaAs single quantum wells using magnetoluminescence spectroscopy at 1.4K. The 2D-carrier densities varied between 1 and 12×10^{11} cm^{-2}. At the maximum 2D-carrier density, the bandgap energy reduction compared to an undoped specimen was found to be about 34 meV.

1. Introduction

In the last several years, there has been much focus on bandgap energy renormalization resulting from many body effects [1-11]. For structures relying on the electronic bandgap in heavily doped quantum wells, e.g., high-power injection lasers, many body effects can lead to bandgap renormalization energies approaching 20 to 40 meV, i.e., for GaAs/AlGaAs systems, the bandgap energy can change as much as a 2%. For precise laser wavelength control, a knowledge of the bandgap energy versus carrier density is mandatory.

In this paper, we present a study of the bandgap renormalization as a function of the 2D-carrier density for a series of modulation doped n-type 8-nm-wide GaAs/AlGaAs single quantum wells. We use an unambiguous method for obtaining accurate bandgap energies by measuring the photoluminescence spectrum as a function of magnetic field. With the application of external magnetic fields, Landau energy levels are formed and the energy of the PL transition for each Landau level energy is shifted linearly. Extrapolating the magnetoluminescence "Fan" diagram to zero magnetic field yields the true bandgap energy without complications of spectral shifts in the zero-field PL line shape [12].

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 epilayer was grown on top of the substrate and on top of this GaAs-epilayer, a single 8-nm-wide GaAs quantum-well was placed between 100-nm-wide $Al_{0.30}Ga_{0.70}As$ barriers, followed by an unintentionally doped 5 nm thick GaAs cap layer. The top AlGaAs barrier layer was delta-doped 30 nm from the GaAs quantum well, with silicon 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 at 1.4K, and the magnetic field varied between 0 and 14 tesla. The luminescence measurements were made with an Argon-ion laser operating at 514.5 nm and an IEEE-488-based photon counting data acquisition system. The direction of the applied magnetic field is parallel to the growth direction, i.e., the resulting Landau orbits are in the plane of the GaAs quantum well. The laser excitation and sample PL signal were respectively brought in and carried out along the same 100-μm-diameter optical fiber. The fiber tip 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 PL spectrum. The transport method relies on an analyses of Shubnikov-deHaas oscillations in the conductivity, but essentially provides the same information as PL 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 gave similar results for the 2D-carrier density.

3. Results and Discussion

The 1.4-K zero-field PL spectrum for a $N_{2D} = 8.2 \times 10^{11}$ cm^{-2} sample (#EMC-2218) is shown in Fig. 1. The bandgap energy E_{gap} = 1557.6 meV is indicated in the figure and it is apparent that the energy of the peak intensity of the PL spectrum at 1563 meV is shifted above the bandgap value, i.e., the spectral shift is 6 meV. The PL line shape for degenerate quantum wells will not be discussed here, but the reader is referred to [12] where it has been treated in detail. The high energy shoulder near 1590 meV is due to transitions near the Fermi energy E_f. Also shown in the figure is the energy E' = 1585.7 meV for the undoped structure where the effective Rydberg for an 8-nm-wide quantum well [13] has been added to the observed PL energy. Thus, for this sample, where $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}, the bandgap energy reduction is nearly 20 meV.

A free particle, with mass m and charge e, moving in a magnetic field B forms quantized states, Landau levels, with an energy $E = (n + 1/2)(e\hbar B/mc) \equiv (n + 1/2)\hbar\omega$ (cgs units) 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

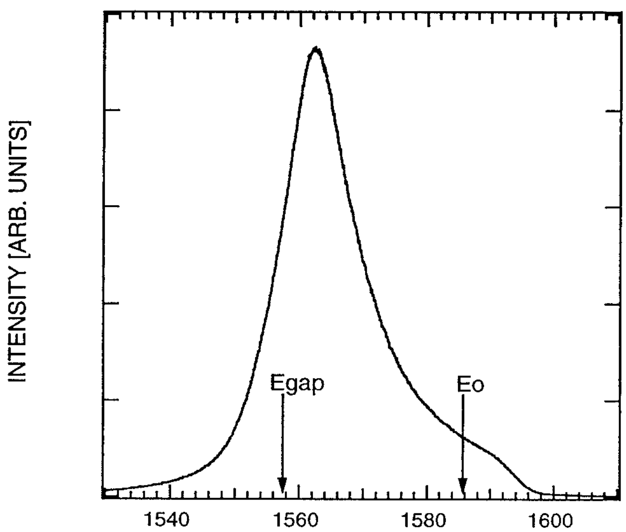

Figure 1. Zero-field 1.4K PL spectrum for an 8-nm-wide n-type GaAs/AlGaAs SQW. The 2D-carrier density is $N_{2D} = 8.2 \times 10^{11}$ cm^{-2}. The bandgap energy for the undoped quantum well is labeled E_0 and E_{gap} = 1557.6 meV is bandgap energy from the magnetoluminescence "Fan" diagram shown in Fig. 3.

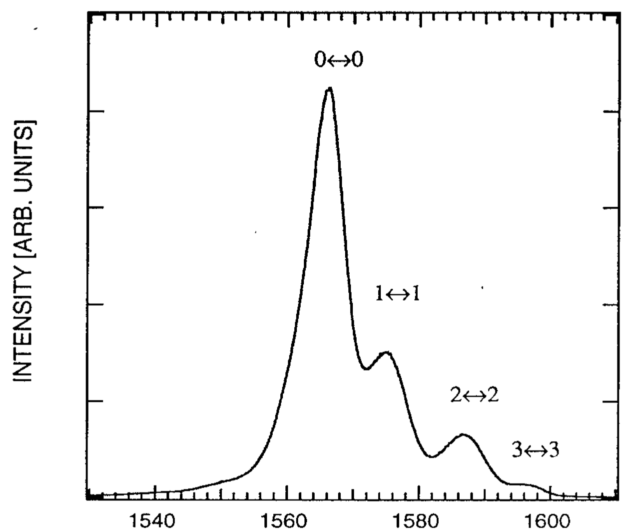

Figure 2. The magnetoluminescence spectrum at 8 tesla and 1.4K for the zero-field spectrum shown in Fig. 1. The Landau transition indices $n_c \leftrightarrow n_v$ for each transition are indicated above their respective peak energies.

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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 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 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 at 1.4K. The interband PL transition energy E is thus given by

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

where E_{gap} is the bandgap energy, μ is the reduced mass ($\mu^{-1} = m_c^{-1} + m_v^{-1}$) where m_c and m_v are respectively the conduction or valence-band effective masses.

Figure 2 shows a magnetoluminescence spectrum at 8 tesla and 1.4K for the sample whose zero-field 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 indices $n_c \leftrightarrow n_v$ for each peak are indicated in the figure. A "Fan" diagram can be generated by plotting the energy of each Landau transition energy (See Fig. 2) as a function of magnetic field and this result is shown in Fig. 3. The Landau transition indices $n_c \leftrightarrow n_v$ 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). The bandgap energy E_{gap} can be uniquely determined from a straight line zero-field extrapolation of the lines shown in Fig. 2 with the result, E_{gap} = 1557.6 meV.

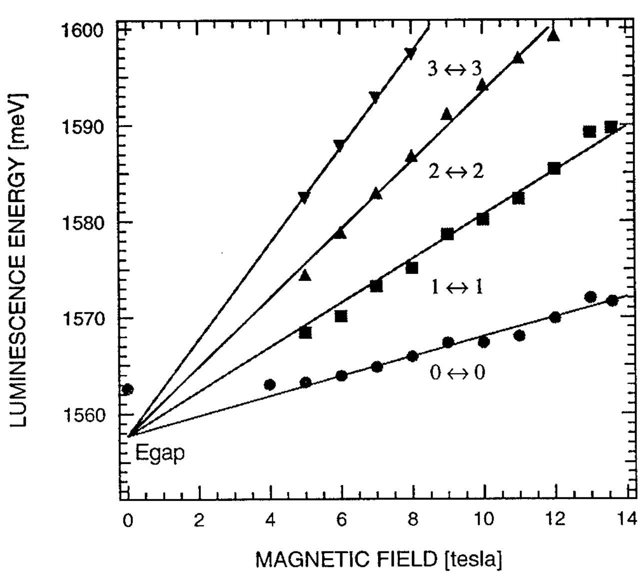

Figure 3. Magnetoluminescence "Fan" diagram for the 1.4K data.The Landau transition indices $n_c \leftrightarrow n_v$ for each transition are indicated. The lines are a best of Eq. (1) to the data and the bandgap energy is 1557.6 meV. The slope ratio of the lines is nearly 1:3:5:7.

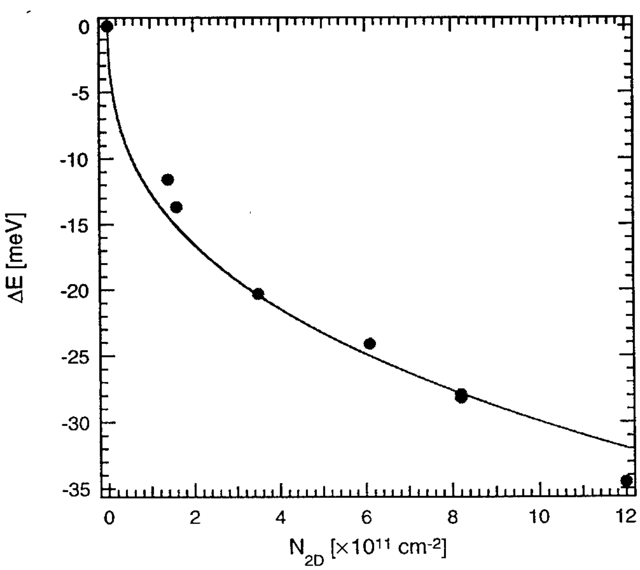

Figure 4. The energy difference ΔE between the undoped bandgap energy and the renormalized bandgap energy due to many body corrections. The curve through the data is given by Eq. (2).

For all of the n-type samples, magnetoluminescence "Fan" diagrams similar to the one shown in Fig. 3 can be made using the above described procedures. The bandgap energy reduction ΔE for each sample can then be calculated by subtracting the magnetoluminescence determined bandgap energy E_{gap} from the undoped bandgap energy E_0 shown in Fig. 1. Figure 4 shows the result of plotting ΔE as a function of the 2D-carrier density N_{2D}. The solid line drawn through the data is a result of a best fit curve of the form

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

The proportionality factor of Eq. (2) is in good agreement with the results for n-type 10-nm-wide GaAs/ AlGaAs quantum well [5].

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 PL-peak intensity are avoided by this method. Finally, agreement with previously reported measurements was found for the dependence of the bandgap energy reduction on the 2D-carrier density.

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References

[1] Kleinman D A and Miller R C 1985 *Phys. Rev. B*32 2266-2272
[2] Schmitt-Rink S and Ell C 1985 J. Lumin. 30 585-
[3] Tränkle G, Leier H, Forchel A, Haug H, Ell C and Weimann G 1987 *Phys. Rev. Lett.* 58 419-422
[4] Delalande C, Bastard G, Orgonasi J, Brum J A, Liu H W, Voos M, Weimann G and Schlapp W 1987 *Phys. Rev. Lett.* 59 2690-2692
[5] Schmitt-Rink S, Chemla D S and Miller D A B 1989 *Adv. Phys.* 38 89-
[6] Potemski M, Maan J C, Ploog K and Weimann G 1990 *Surf. Sci.* 229 380-383
[7] Jalabert R and Das Sarma S 1990 *Surf. Sci.* 229 405-409
[8] Reinecki T L, Broido D A, Lach E, Kulakovskii V, Forchel A and Gruetzmacher D 1990 *Superlattices and Microstructures* 7 437-440
[9] Potemski M, Maan J C, Ploog K and Weimann G 1990 *Solid State Communications* 75 185-188
[10] Cingolani, R, La Rocca G C, Kalt H and Ploog K, Potemski M and Maan J C 1991 *Phys. Rev. B*43 9662-9671
[11] Priest A N, Nicholas R J, Najda S P, Duggan G and Kean A H 1997 Physica (to be published)
[12] Lyo S K and Jones E D 1988 *Phys. Rev. B*38, 4113-
[13] Bajaj and Green

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