We report on low-temperature magnetoluminescence determinations of bandstructure parameters for an 8.5nm-wide n-type In_{0.20}Ga_{0.80}As/GaAs strained single-quantum well structure. We find that the conduction-band is almost parabolic, with its mass varying from 0.067m_0 at zone center to 0.069m_0 at a Fermi energy E_f = 50 meV, and that the valence-bands are highly non-parabolic with the valence band masses m_v varying from about 0.1m_0 at zone center to about 0.3m_0 for large k-vectors. A comparison with a k·p calculation for the valence-band mass and dispersion curve show good agreement. An accurate and unambiguous determination for the band-gap energy E_{gap} is made by extrapolating the magnetic field dependent Landau level transition energies to zero field.

**INTRODUCTION**

The semiconductor quantum-well laser is the principal component for optoelectronic applications. The need for custom laser wavelengths, higher laser powers, and better beam quality or control has led to many different laser diode designs and configurations. The most common combination for semiconductor laser materials for these devices have been GaAs and AlGaAs. The desirability for light-hole valence-band masses for optoelectronic devices, lasers, or high-speed electronic devices has been well documented \[1-3\]. Light-hole valence-band masses have been mainly achieved in layered semiconductor structures by the introduction of compressive biaxial strain in the active quantum layers. The biaxial strain is achieved by growing layered structures from materials with differing lattice constants, e.g., layers of In_xGa_{1-x}As and GaAs. However, because of anti-level crossing effects between the in-plane heavy and light-hole valence-band states, the resulting in-plane valence-band energy dispersion curves (and masses) near the crossing energy are nonparabolic. For lattice-matched quantum well devices, the same conditions hold because of the quantum confinement splitting of the heavy and light-hole valence bands. For these structures, the in-plane heavy-hole light-hole mixing and hence valence-band nonparabolicity occurs at small values of the wave vector. For the devices based upon GaAs and AlGaAs, quantum confinement can be an effective method to alter the energy difference \[\Delta E_{HL}\] between the heavy and light-hole valence bands. However, for wide (≈15 nm) GaAs/AlGaAs structures, \[\Delta E_{HL}\] is small (≈ 5meV) and thus the amount of heavy-hole light-hole mixing is large. For these wide quantum well structures, the in-plane valence-band ground state energy is also “heavy,” i.e., for Fermi energies E_f > 2 meV, the valence-band mass m_v ≈ 0.35m_0. By reducing the quantum-well width, the energy differ-
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ence $\Delta E_{HL}$ can be increased by quantum confinement. For GaAs/AlGaAs lattice-matched quantum wells, a maximum $\Delta E_{HL} = 30$ meV occurs near a quantum-well width of about 4.5 nm.

Valence-band nonparabolicity, for lattice-matched or strained-layer optoelectronic devices, means that with increasing carrier densities the valence-band mass also increases, thereby changing laser threshold currents, modulation frequency response, magneto-optic parameters, device transconductance, etc. Thus a device which performs satisfactory at low power levels, i.e., low-carrier densities, may not perform as expected, under high power or high-current operation. Furthermore, device modeling codes predicting the optical or carrier response function should account for effects which can be attributed to valence-band mixing. As digital communication speeds increase, a knowledge of the energy-band dispersion curves is mandatory if these design criteria are to be modeled or achieved.

Photoluminescence (PL) characterization of semiconductor materials has been a standard nondestructive diagnostic tool for a number of years. With the advent of quantum well structures, the photoluminescence technique has been used to study exciton and impurity states, interface roughness, impurity (dopant) diffusion, quantum-well energy levels, valence-band offset energies, etc. A recent review by Herman et. al. [4] presents an excellent summary for these kinds of studies. In particular, the use of two dimensional (2D) excitons to study interface roughness is discussed. However, magnetic field effects on the PL spectrum were not considered. With the current availability of high-field magnet systems and the advent of novel semiconductor systems based upon epitaxy growth techniques, magnetoluminescence has become a valuable diagnostic tool.

The PL line shape function in degenerate (doped) quantum wells has also received attention as a measure of the 2D-carrier concentration [5,6]. Recently, two distinct PL peaks were observed [7] in heavily doped n-type quantum wells and the energy difference between the two peaks was used as a measure of the difference between the quantum-well’s ground state and the first excited state energies. Because of spectral energy shifts, care must be taken in interpreting the meaning the PL-peak energy if this kind of information is vital to the analysis of the transport data as presented in [7]. The spectral shift contributions to the PL line shape could be large and the PL peak energy may be shifted from the actual bandgap energy by tens of milli-electron-volts [8,9].

Calculations for the PL spectral line shape function in doped quantum wells ignore the second-order contributions arising from carrier-impurity scattering. For modulation doped structures, the majority of ionized-impurities are restricted to the modulation layer, located some distance from the quantum well. A microscopic theory for the PL line shape for degenerate semiconductor quantum wells which includes the effects due to ionized-impurity scattering of the carriers is treated in detail [8]. This paper shows that the experimental PL line shape is nearly accounted for by ionized-impurity scattering of the carriers. Also discussed were PL line shape changes as a function of temperature and also distance between the modulation-doped region and the quantum well.
An important result of the line shape calculation [8,9] is the spectral shift of the line shape, i.e., the peak intensity of the PL spectrum is shifted by from the actual bandgap energy. A complete description of the origins of the spectral shift can be found in [8] where it is shown how ionized impurity scattering couples the large number of conduction-band carriers with energies greater than kT with those electrons within kT of the bottom of the band. The photo-generated holes have an energy of \( \sim kT \) which is much less than the conduction-band Fermi energy \( E_f \sim 35 \text{ meV} \). The spectral shift is found to be strongly dependent upon the distance between the dopant-layer in the barrier and the quantum well and also upon the carrier densities. Magnetoluminescence data will be presented that graphically demonstrate the importance of these spectral shifts and we will show that an unambiguous determination for the bandgap energy \( E_{\text{gap}} \) can be uniquely determined.

The first subject of this paper is a demonstration of the spectral shift to the energy of the peak of PL spectrum as well as an unambiguous measurement of the bandgap energy. The second part reports on electronic band structures of doped quantum-well structures. Specifically, data for a single-strained-quantum well (SSQW) structure based on InGaAs/GaAs will be presented. It is found that while the valence-bands are highly nonparabolic, the conduction-band energy dispersion curves are nearly parabolic.

EXPERIMENTAL

The InGaAs/As SSQW structure was prepared using molecular beam epitaxy. The SSQW structure (#BC042) consisted of a single 8-nm-wide \( \text{In}_{0.20}\text{Ga}_{0.80}\text{As} \) strained quantum-well and unstrained GaAs barriers. The quantum well barrier material was silicon-doped, with a spacing of about 8 nm between the \( \sim 3\)-nm-wide silicon-modulation layer and the quantum well. The energy difference \( \Delta E_{\text{HL}} \) between the heavy-hole and light-hole valence-bands, which includes contributions from both strain effects and quantum confinement, is about 60 meV. The 4-K 2D-carrier concentration \( N_{2d} \) and mobility \( \mu \) are respectively \( 5 \times 10^{11} \text{ cm}^{-2} \) and \( 1.2 \times 10^4 \text{ cm}^2\text{/Vsec} \). The magnetoluminescence measurements were made in the temperature range of 1.4 and 76 K, and the magnetic fields varied between 0 and 30 T. The luminescence measurements were made with an Argon-ion laser operating at 514.5 nm and an IEEE-488-based data acquisition system using an InGaAs enhanced photomultiplier tube for photon counting. 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 quantum well. With this geometry, all measurements concerning the conduction and valence-band dispersion curves and masses refer to their \textit{in-plane} values.

LANDAU LEVELS AND PHOTOLUMINESCENCE

A free particle, with mass \( m \) and charge \( e \), moving in a magnetic field \( B \) forms quantized states, Landau levels, with an energy \( E = (n + 1/2)(e\hbar B/mc) = (n + 1/2)\hbar \omega \) (cgs units) where \( n \) is the Landau level index, \( \hbar \) is Planck’s constant over \( 2\pi \), \( c \) is the velocity of light, and \( \hbar \omega \) is the quantized cyclotron 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.
high temperatures, where $kT$ is much larger than $\hbar \omega_{cv}$, the $n_v = 0, 1, 2, 3, \ldots$ valence-band Landau levels are populated and all magnetoluminescence transitions between the $n_c$ and $n_v$ Landau levels are allowed, obeying the $\delta n_{cv} = (n_c - n_v) = 0$ selection rule. For these high temperatures, the interband luminescence transition energy $E$ is given by

$$E(n) = E_{\text{gap}} + \left( n + \frac{1}{2} \right) \left( \frac{eB}{\mu c} \right),$$

where $E_{\text{gap}}$ is the bandgap energy, $\mu$ 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 expressed in terms of the free electron mass $m_0$. In this paper we assume that the sample temperature is always less than the Fermi temperature, $kT_f = E_F$ of the degenerate 2D-electron gas.

A schematic showing the allowed transitions for a n-type structure is shown in the right side of Fig. 1. The Fermi energy $E_F$, the bandgap energy $E_{\text{gap}}$, and the Landau level indices $n$ are also indicated in the figure. For large magnetic fields and low temperatures ($\hbar \omega_{cv} \gg kT$) only the $n_v = 0$ valence-band Landau level is populated. Here, the PL transition between the $n_c = 0$ and $n_v = 0$ Landau level is allowed while transitions between the higher energy conduction-band Landau levels $n_c = 1, 2, 3, \ldots$ and the $n_v = 0$ ground state valence-band Landau level are zeroth-order forbidden, but are observable due to higher-order ionized-impurity scattering processes [10,11]. The left side of Fig. 1 shows the energy level diagram for this case.

Two magnetoluminescence spectra ($B = 5.75$ T) at 4 and 76 K are shown in Fig. 2. The origins of the energy axes of the two spectra have been adjusted in order to allow a comparison of the spacing between the magnetoluminescence transitions. For 4 K, $E_{\text{gap}} =$

![Figure 1](image1.png)

**Figure 1.** Landau levels for a n-type quantum well. The spacing of energy level spacings $\delta E_c$ and $\delta E_v$ are in terms of the respective cyclotron energies $\hbar \omega_c$ and $\hbar \omega_v$. The left side is the low temperature case, $\delta E_v \gg kT$, and the right side is the high temperature condition $\delta E_v \ll kT$.

![Figure 2](image2.png)

**Figure 2.** Magnetoluminescence spectra for $B = 5.75$ T at 4 and 76 K, for an n-type InGaAs/GaAs SSQW showing the allowed, $\delta n_{cv} = 0$, and the $\delta n_{cv} \neq 0$ zeroth-order forbidden transitions. The energy axes of the two spectra have been shifted in order to compare them.
1330.1 meV while at 76 K, $E_{\text{gap}} = 1324.1$ meV. The indices $n_c \leftrightarrow n_v$ for each peak are labeled in the figure. As can be seen in Fig. 2, all observed transitions for the 76 K data are allowed, i.e., $\delta n_{cv} = (n_c - n_v) = 0$, while for the 4.2 K data, the only zero$^{\text{th}}$-order allowed transition is the $0 \leftrightarrow 0$ peak. Because of the low 2D-carrier density for the holes, the energy dependence of the 76-K magnetoluminescence peak-amplitudes are also governed by a Maxwell-Boltzmann distribution function. An analysis of the energy dependence of the peak-amplitudes for this spectrum yields a temperature of about 80 K, which is in good agreement with the expected temperature of liquid nitrogen. A theoretical treatment of the energy dependence of the amplitudes of the zero$^{\text{th}}$-order forbidden transitions has been performed by Lyo [11] and the amplitudes of the low temperature PL-data shown in Fig. 2 is in good agreement with his calculation.

**SPECTRAL SHIFTS AND BANDGAP ENERGIES**

For the SSQW structure discussed earlier, the spectral shift of the PL peak intensity is about 7 meV. However, because of the many contributions to the PL line shape, it is difficult to clearly demonstrate the importance, or size, of the spectral shift by merely presenting agreements between calculated and experimental zero-field line shapes.

Referring to the 76-K allowed PL spectrum shown in Fig. 2, the amplitude of the $0 \leftrightarrow 0$ peak is the larger than the other transitions. At very high magnetic fields, where the energy spacing between the peaks is large, the line shapes of the allowed transitions are almost gaussian [12] and the $0 \leftrightarrow 0$ transition is the dominant transition. At low magnetic fields, the amplitudes of the Landau level transitions is a convolution of the inherent gaussian line shape with the zero-field line shape function. Thus if there are large spectral shifts, there may be situations where after convolving the two line shapes (gaussian and zero-

![Figure 3. Magnetoluminescence spectra at 76 K for 0 and 3 tesla. The energy of the allowed $n_c \leftrightarrow n_v$ transitions are indicated. The amplitude of the $0 \leftrightarrow 0$ transition is smaller than the $1 \leftrightarrow 1$ transition. The zero-field (true) bandgap energy $E_{\text{gap}}$ is is also indicated.](image)

![Figure 4. Fan-diagram for the 77-K Landau-level allowed transitions. The straight lines through the data meet have a common origin yield $E_{\text{gap}} = 1324$ meV. The curvature in the data is indicative of the nonparabolic nature of the valence-band.](image)
field line shape), the peak intensity of the $1\leftrightarrow 1$ transition is larger than the $0\leftrightarrow 0$ transition. Figure 3 is a graphic demonstration for this situation. This data was part of the high temperature spectra used to obtain the valence-band dispersion curves for the SSQW structure. At slightly higher magnetic fields, the spectrum appears normal. The spectral shift is again estimated from Fig. 3 to be of the order of 7 meV.

The fan diagram for the interband magnetoluminescence transitions at liquid nitrogen temperatures is shown in Fig. 4. The lines are drawn through the data points in order to aid the eye. All transitions for the 77 K data are “allowed”, i.e. $\delta n_{cv} = (n_c = n_v) = 0$. The inset identifies the various transitions as A00, A11, A22, ..., where A00 is the $0\leftrightarrow 0$ transition data, A11 is the data for the $1\leftrightarrow 1$ transition, etc. The slopes of the straight lines drawn through the data, normalized to the slope of the line drawn through the A00 data, are in the expected ratios of 1, 3, 5, 7, ... as predicted by Eq. 1. The curvature, nonlinearity, in the data is an indication of the valence-band nonparabolicity. The bandgap energy $E_{\text{gap}}$ is derived from the zero-field intercept of the straight lines and is about 1324 meV, which is also indicated in Fig. 3 as the true 77-K bandgap energy for this sample. Thus if zero-field PL spectra are being used to measure bandgap energies in heavily doped semiconductor quantum wells, correct interpretation and understanding of the origins of the PL line shape must be made to obtain meaningful bandgap energies.

**DISPERSION CURVES AND MASSES**

As is obvious from the left-hand side of Fig. 1, where $\hbar \omega_c \gg kT$, the energy difference $\delta E$ between the $E(n_c)$ and $E(n_c-1)$ magnetoluminescence peaks depends only on the conduction-band cyclotron energy $\hbar \omega_c$. Setting $n_v = 0$ and using Eq. 1, the magnetoluminescence transition energy $E(n_c)$ is given by in terms of the respective conduction and valence-band cyclotron energies as

$$E(n_c) = E_{\text{gap}} + \frac{1}{2} \left( \frac{\hbar B}{m_c} \right) + \frac{1}{2} \left( \frac{\hbar B}{m_v} \right),$$

where $n_c = 0, 1, 2, 3, \ldots$. Thus, utilizing low temperatures and measuring the energy differences as a function of magnetic field, Eq. 2 provides a method for obtaining all the information about the conduction band energy dispersion curves.

Figure 5 shows the derived low-temperature-derived conduction-band dispersion curve for the InGaAs/GaAs SSQW. The method (and justification) used relating the magnetic field $B$ to the wavevector $k$ has been adequately discussed [13,14]. The maximum value of the wavevector $k$ of about 3% of the Brillouin zone is determined by the conduction-band Fermi energy $E_F$ of about 35 meV. The minimum wavevector determinations are limited by our ability to distinguish magnetoluminescence peaks at low magnetic fields. The conduction-band dispersion curve is found to have a small nonparabolic correction with the zone center conduction-band mass $m_c \sim 0.067m_0$ and at the Fermi energy $m_c \sim 0.069m_0$. Nonparabolic effects upon the cyclotron resonance measured conduction-band masses have been discussed in detail [15,16] and the magnetoluminescence results presented here are in agreement with that derived by conduction-band cyclotron resonance.
With a knowledge of the conduction-band dispersion curve, we can, using Eq. 1, derive the valence-band dispersion curve by performing 76-K magnetoluminescence measurements and analyzing the zeroth-order allowed transition peaks as a function of magnetic field. The valence-band data is shown in Fig. 6 and it is evident that the dispersion curve is nonparabolic. For the range of data shown in the figure, the valence-band effective mass \( m_v \) for the SSQW structure BC042 varies between a zone-center 0.11\( m_0 \) to about 0.3\( m_0 \) at \( E_v(k) \sim 20 \) meV. The solid line through the valence-band data is a best-fit nonparabolic curve to the data of the form

\[
E = \left( \frac{\hbar^2 k^2}{2m_v^0} \right) \left( 1 + \frac{K}{E_{\text{gap}}} \frac{\hbar^2 k^2}{2m_v^0} \right),
\]

where \( m_v^0 = 0.11m_0 \) is the zone center valence-band mass and \( K \approx 16 \) which is about an order of magnitude larger than measured for the conduction band [15]. A comparison with a \( k\cdot p \) calculation for the valence-band dispersion, which includes strain and valence-band mixing, is also shown in Fig. 6. The agreement between the \( k\cdot p \) calculation and the data is reasonable in view of the fact that the \( k\cdot p \) calculation did not include the contributions from the conduction band or split-off valence band. Magnetoluminescence determined valence-band dispersion curves for other samples with varying indium concentration and hence, with differing values for the heavy-hole light-hole valence band splitting \( \Delta E_{\text{HL}} \), confirm that as \( \Delta E_{\text{HL}} \) increases the valence-bands become more parabolic and that the ground state in-plane valence-band mass remains relatively constant [17].

**CONCLUSIONS**

We have shown that magnetoluminescence measurement techniques is a powerful tool for performing single-sample simultaneous measurements of both the conduction and
valence-band dispersion curves (and masses). We showed that for quantum-well devices the amount of heavy-hole light-hole splitting is the determining factor for valence-band nonparabolicities and that the larger the heavy-hole light-hole energy difference, the smaller the valence-band nonparabolicity. The experimental agreement with $k\cdot p$ calculations for the valence-band energies are good and with these dispersion curves, it is possible to model not only optoelectronic behavior, but also predict electronic phenomena which rely upon these dispersion curves. In particular, the amount of valence-band nonparabolicity can now be experimentally quantified and predictions for new material systems may be possible.

We also provided a graphical example of large spectral shifts by examining a high-temperature low-magnetic field spectrum of the SSQW data. Finally the magnetoluminescence technique offers an unambiguous and accurate determination for the bandgap energy.

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