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MAGNETO-OPTICAL STUDIES OF COMPOUND SEMICONDUCTORS

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Abstract - A simultaneous determination of both the conduction and valence-band dispersion curves (and masses) from a single compound semiconductor quantum-well structure using magnetoluminescence is discussed. Data from InGaAs/GaAs strained-single-quantum wells and GaAs/AlGaAs lattice matched quantum wells are presented. The conduction bands are found to be parabolic for densities approaching densities of $1 \times 10^{12} \text{ cm}^{-2}$. However, the valence bands are highly nonparabolic and strongly affected by heavy-hole light-hole interactions.

Keywords: A. semiconductor quantum wells, C. magnetoluminescence, D. electronic structure, D. photoluminescence.

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The semiconductor laser diode has become one of the principle optical components for magneto-optical devices. The need for custom laser wavelengths and higher laser powers has led to many different laser diode designs and configurations. Currently, the most common combination of semiconductor laser materials for these devices are GaAs and AlGaAs. As the read/write speed or laser power requirements increase, a knowledge of the energy-band dispersion curves is mandatory if these design criteria are to be achieved. The necessity for light-hole valence-band masses for these kinds of optoelectronic devices has been well documented [1, 2]. 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 realized by growing layered structures with materials with differing lattice constants, e.g., layers of $\text{In}_x\text{Ga}_{1-x}$ and GaAs. However, because of level crossing repulsion between the heavy and light-hole valence-band states, the resulting valence-band energy dispersion curves (and masses) are nonparabolic. For optoelectronic devices, valence-band nonparabolicity means that as the carrier densities, or biasing electric fields are increased, the valence-band mass also increases, thereby changing lasing thresholds, magneto-optic parameters, etc. Furthermore, device modeling codes predicting the optical response function should take into account any effects which can be attributed to nonparabolicity.

Recently, it was shown that both the conduction and valence-band energy dispersion curves of modulation doped strained single-quantum-well (SSQW) and lattice-matched single-quantum-well (LMSQW) structures can be simulta-

neously determined by magnetoluminescence measurements from a single sample [3-5]. These papers discuss the importance of the energy difference ΔE between the heavy and light-hole valence energy dispersion curves in determining the degree of mixing of the heavy and light-hole valence bands. Large values for ΔE not only give rise to small ground-state in-plane light-hole masses, but also reduce the valence-band nonparabolicity factor.

For the LMSQW devices such as GaAs/AlGaAs, quantum confinement can also be an effective method to change the energy difference ΔE between the heavy and light-hole valence bands. However, for wide (~ 15 nm) GaAs/AlGaAs LMSQW structures, ΔE is small ($\lesssim 5$ meV) 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 “heavy”, i.e., for Fermi energies $E_f > 2$ meV, the valence-band mass $m_v \approx 0.35m_0$. Upon reducing the quantum-well width, the energy difference ΔE can be increased by quantum confinement. For GaAs/AlGaAs lattice-matched quantum wells, a maximum $\Delta E \approx 30$ meV occurs near a quantum-well width of about 4.5 nm.

In this paper, we present results of magnetoluminescence measurements of band structure dispersion curves of n-type InGaAs/GaAs SSQW and GaAs/AlGaAs LMSQW structures. The samples were prepared using molecular beam epitaxy. The magnetoluminescence measurements were made in the temperature range of 4 and 76 K, and the magnetic fields varied between 0 and 7 T. 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 *in-plane* values. Magnetoluminescence data for two representative SSQW and LMSQW structures will be presented and discussed. 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. Here, the energy difference ΔE between the heavy and light-hole valence-bands, which includes contributions from both strain effects and quantum confinement, is about 60 meV. The two dimensional carrier concentration N_{2d} and mobility μ at $T = 4$ K are respectively $5 \times 10^{11} \text{ cm}^{-2}$ and $1.2 \times 10^4 \text{ cm}^2/\text{Vsec}$. The GaAs/AlGaAs LMSQW structure (#G0260) has a 4.5-nm-wide GaAs quantum well with $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ barriers, and as mentioned above, the heavy and light-hole valence-band energy difference $\Delta E \approx 30 \text{ meV}$. For G0260, $N_{2d} = 6.6 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 2.2 \times 10^4 \text{ cm}^2/\text{Vsec}$.

For n-type structures at high temperatures, e.g., 76 K, the $n_v = 0, 1, 2, 3, \dots$ valence-band Landau levels are populated according to Maxwell-Boltzmann statistics and hence all magnetoluminescence transitions between the n_c and n_v Landau levels are *allowed* and obey the $\delta n \equiv (n_c - n_v) = 0$ selection rule. For these temperatures, the interband luminescence transition energy E is given by (cgs units)

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

where E_{gap} is the bandgap energy, n is the Landau index $n = 0, 1, 2, 3, \dots$, B is the applied magnetic field, here 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 expressed in terms of the free electron mass m_0 , and

c is the velocity of light. A schematic showing these transitions for a n-type structure is shown in the right side of Fig. 1. The Fermi energy E_f and bandgap energy E_g are shown in the figure. The Landau levels resulting from the applied magnetic field B are also marked. In Fig. 1, the cyclotron energies $\hbar\omega_{c,v} \equiv e\hbar B/m_{c,v}c$ are given by (1). As can be seen, the number of conduction-band states are determined by the Fermi-Dirac statistics of the degenerate two dimensional electron gas, but the distribution for the valence-band holes are governed by Maxwell-Boltzmann statistics.

For the same n-type semiconductor structure at large magnetic fields, minimum laser power, and low temperatures, only the $n_v = 0$ valence-band Landau level is populated. Therefore, the transition between the $n_c = 0$ and $n_v = 0$ Landau level is allowed while transitions between the higher energy Landau levels $n_c = 1, 2, 3, \dots$ and the $n_v = 0$ ground state Landau level are zeroth-order forbidden, but are observable due to higher order processes [3, 6]. The left side of Fig. 1 shows the energy level diagram for this case. Here, all of the holes are in the $n_v = 0$ ground state because we have postulated that $\hbar\omega_v > kT$. Fixing $n_v = 0$ and using (1), the magnetoluminescence transition energy E is given by

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

where $n_c = 0, 1, 2, 3, \dots$. From (2), the energy difference δE between the $E(n_c)$ and $E(n_c-1)$ magnetoluminescence peaks depends only on the conduction-band energy. Hence, using the low temperature data and (2) provides all the information about the conduction band energy dispersion curves.

The magnetoluminescence spectra ($B = 5.75$ T) at 4.2 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 4.2 K, $E_{\text{gap}} = 1330.1$ meV while at 76 K, $E_{\text{gap}} = 1321.1$ meV. The indices $n_c \rightarrow n_v$ for each peak are identified in the figure. As can be seen in Fig. 2, all observed transitions for the 76 K data are “allowed”, i.e, $\delta n = 0$, while only the $0 \rightarrow 0$ transition is “allowed” for the 4.2 K data. The energy dependence of the 76 K magnetoluminescence peak amplitudes is governed by Maxwell-Boltzmann statistics and an analysis of this spectra 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 zeroth-order forbidden transitions has been performed by Lyo [7] and data shown in Fig. 2 is in good agreement with his calculation.

An analysis of magnetic field dependent shifts at 4.2 K show that the two conduction-band dispersion curves for the SSQW and LMSQW structures are nearly parabolic with respective conduction-band masses of $m_c \approx 0.067m_0$ and $m_c \approx 0.085m_0$. The increase to m_c for the LMSQW conduction-band mass between the bulk GaAs $m_c \approx 0.065m_0$ to $0.085m_0$ is attributed to effects caused by the increased quantum confined bandgap energy. These conclusions are in agreement with previous cyclotron resonance determinations of conduction-band masses in GaAs-based quantum-well structures [8,9]. The conduction-band masses for both the SSQW and LMSQW structures were measured on the same samples by far infrared cyclotron resonance tech-

niques with the result that their respective Fermi energies, $m_c \approx 0.069m_0$ for the SSQW sample and $m_c \approx 0.082m_0$ for the LMSQW structure in good agreement with the aforementioned magnetoluminescence data. With this knowledge of the conduction-band dispersion curves and masses, the magnetic field dependent valence-band energy can be inferred from the high temperature (76 K) data using (2). The resulting valence-band dispersion curves for both the SSQW and LMSQW samples are shown in Fig. 3. The method and justification used relating the magnetic field B to the wavevector k has been adequately discussed by Lyo and Jones [10]. The dispersion curves (solid lines) drawn through the two sets of data are based upon a plane wave $k \cdot p$ calculation also presented by Lyo and Jones [10]. For reference, a parabolic dispersion curve for the predicted zone-center valence-band mass for both samples is also indicated in the figure. The maximum values of the wavevector k of about 3% of the Brillouin zone is determined by the respective conduction-band Fermi energies. From Fig. 3, it is evident that valence bands are very nonparabolic. For the range of data shown in the figure, the valence-band mass m_v for the SSQW structure varies between $0.11m_0$ and $0.22m_0$. However for the LMSQW sample at small wavevectors, $m_v \approx 0.15m_0$ and for larger wavevectors, e.g., $E_v \approx 10$ meV, $m_v \approx 0.35m_0$. As previously mentioned, the heavy-hole light-hole energy separation ΔE is about 60 meV for the SSQW structure and about 30 meV for the LMSQW sample. It is obvious from Fig. 3, that the valence-band dispersion curve for the SSQW structure is more parabolic than that of the LMSQW sample and this result is due to the increased heavy-hole light-hole energy

separation in the SSQW sample. Magnetoluminescence determined valence-band dispersion curves for other samples (with differing values for ΔE) confirm that as ΔE increases the valence-bands become more parabolic and also that the valence-band masses become lighter.

In conclusion, 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). The agreement with $k \cdot p$ calculations are good and thus 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.

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Figure Captions

Figure 1. A schematic representation for the Landau levels in a n-type quantum well. The left side is the low temperature case ($\delta E > kT$) and the right side is the high temperature condition ($\delta E < kT$.) A large magnetic field is assumed.

Figure 2. Magnetoluminescence spectra at 4.2 and 76 K for an n-type InGaAs/GaAs SSQW ($B = 5.75$ T) showing the allowed ($\delta n = 0$) and the zeroth-order forbidden ($\delta n \neq 0$) transitions. The origins energy axes of the spectra have been adjusted in order to compare the energy difference between the magnetoluminescence transitions.

Figure 3. The valence-band dispersion curves measured by magnetoluminescence techniques. The solid lines through the data are a result of a $k \cdot p$ calculation. The zone center parabolic dispersion curve is also shown for reference.

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