CONDUCTION BAND MASS DETERMINATIONS FOR N-TYPE
InGaAs/InAlAs SINGLE QUANTUM WELLS

CONF-980729--

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JUN 02 1998

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ABSTRACT

We report the measurement of the conduction band mass in n-type single 27-ML-wide InGaAs/InAlAs quantum well lattice matched to InP using two methods: (1) Magnetoluminescence spectroscopy and (2) far-infrared cyclotron resonance. The magnetoluminescence method utilizes Landau level transitions between 0 and 14 T at 1.4 K. The far infrared cyclotron resonance measurements were made at 4.2 K and to fields as large up to 18 T. The 2D-carrier density $N_{2D} = 3 \times 10^{11} \text{ cm}^{-2}$ at low temperatures. The magnetoluminescence technique yielded an effective conduction-band mass of $m_c = 0.062m_0$ while the far-infrared cyclotron resonance measurements gave $m_c = 0.056m_0$. Both measurements show no evidence for any significant conduction-band nonparabolicity.

Keywords: conduction-band mass, cyclotron resonance, magnetoluminescence, quantum well

1. INTRODUCTION

Conduction-band masses for InGaAs/InAlAs multi-quantum well and superlattice structures on InP have been reported using variety of techniques including exciton absorption,¹⁻⁶ photoconductivity,^{7,8} magnetotransport,^{9,10} and cyclotron resonance.¹¹ Depending on the experimental technique, the reported values for the effective mass m_c varied from $0.041m_0$ to as high as $0.066m_0$, where m_0 is the free electron mass. Because information about conduction-band masses is important for the design and modeling of lasers, light emitting diodes, and other microelectronic devices, a fifty-percent uncertainty to m_c is unacceptable. Earlier, we have reported¹² measurements of InGaAs/InAlAs multiple quantum well (MQW) systems and also found heavy conduction-band masses. In this paper, we have extended these measurements to a n-type single quantum well (SQW) lattice matched InGaAs/InAlAs structure on InP and will report on both magnetoluminescence and cyclotron resonance determinations for the conduction-band mass. The principal concern with our previous studies on MWQ structures was possible valence-band corrections arising from strain effects. The results and conclusions presented in this paper are in agreement with our earlier work.¹²

2. EXPERIMENTAL

The modulation doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW structures were prepared using molecular beam epitaxy. The SQW sample was grown on a Fe-doped semi-insulating InP (100) substrate. The oxide was thermally removed from the InP substrate by heating to 530 °C under an arsenic overpressure. Since this procedure roughens the surface, a 600-nm-thick InAlAs buffer was grown to assure the existence of smooth quantum well interfaces. The thickness of the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ QW was 27 monolayers, i.e., 7.9 nm. In order to remove effects due to quantum-well-width fluctuations, the quantum well was grown with an integer number of lattice constants. The upper barrier was a modulation doped $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ layer 500-nm-wide. A setback of 10 nm was used with a 5-nm-wide layer doped n-type (Si) at $1.5 \times 10^{18} \text{ cm}^{-3}$. A 10-nm-wide $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ layer doped with silicon at $5 \times 10^{18} \text{ cm}^{-3}$ was grown for the cap layer. The growth temperature for all layers was 530 °C. X-ray

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rocking curve measurements were taken with a double crystal x-ray diffraction system. The x-ray peak from InAlAs layer was visible as a shoulder on the main InP substrate peak, indicating that the materials were lattice matched to InP to within 35 arc-seconds. A schematic diagram of the sample structure is shown in Fig. 1.

Figure 1. Sample schematic. The growth temperature was 530 °C

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 references 14 and 15 where it has been treated in detail. The 2D-carrier density can be estimated from the difference between the Fermi energy E_f and the bandgap energy with the result $N_{2D} = 3 \times 10^{11} \text{ cm}^{-2}$ for a conduction band mass of $0.06m_0$.

Magnetoluminescence is simply photoluminescence in the presence of a magnetic field.¹⁶ A free particle, with mass m and charge e , moving in a magnetic field B form quantized states, called 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 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. However, 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. At temperatures where kT is much larger than valence-band Landau energy, i.e., the cyclotron energy $\hbar\omega_v$, the $n_v = 0, 1, 2, \dots$ valence-band Landau levels are populated in accordance with the Maxwell-Boltzmann distribution function and thus, 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 a 27-ML-wide $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ quantum well, the ground state in-plane valence-band masses are believed to "heavy" and hence the condition that $kT > \hbar\omega_v$ is satisfied even at 1.4K. The experimental results presented below confirm that the assumption for "heavy-holes" appears to be justified. Another reason for in-plane

The magnetoluminescence measurements were made using a 14-T-maximum superconducting magnet with a variable temperature insert which allowed sample temperatures as low as 1.4 K. 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 2D-Landau orbits are in the plane of the InGaAs 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.¹³ 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 far infrared cyclotron resonance measurements were carried out with a Brüker-113v Fourier transform interferometric spectrometer. The transmission measurements utilized a metal light-pipe condensing-cone assembly. The sample was maintained at 4.2 K (liquid He) in a 17.5-T-maximum superconducting magnet system. The detector used for the cyclotron resonance measurements was a silicon bolometer operating at liquid helium temperatures.

3. RESULTS AND DISCUSSION

The zero-field photoluminescence spectrum for sample #EA0248, an n-type $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW, is shown in Fig. 2. The temperature was 1.4K and the high energy shoulder near 885 meV results¹⁴ from band-to-band transitions near Fermi energy E_f of the 2D-electron gas. The low energy shoulder is associated with bandgap energy edge states, i.e, impurity and or defect states. Anticipating the analyses of the magnetoluminescence data presented below, the *true* bandgap energy of this sample is $E_{\text{gap}} \approx 860 \text{ meV}$. It is apparent that the energy of the peak intensity of the photoluminescence spectrum at 863 meV is shifted above the bandgap value E_{gap} , i.e., the spectral shift resulting from the Si-doped modulation doping layer is about 3

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Figure 2. The zero-field 1.4-K photoluminescence spectrum for an 27-ML-wide n-type InGaAs/InAlAs SQW.

Figure 3. The 10T, 1.4-K photoluminescence spectrum for the 27-ML-wide n-type InGaAs/InAlAs SQW. The Landau transitions $n_c \leftrightarrow n_v$ are indicated

“heavy-holes” may be that the quantum well may in fact be under slight tension, making the in-plane mass heavy, even with quantum confinement. For either case, the interband Landau level transition energies $E(n)$ are given by the expression

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

where E_{gap} is the bandgap energy, $n = 0, 1, 2, \dots$ 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. For the case assumed here, $m_v \gg m_c$, the reduced mass in (1) $\mu \equiv m_c$ and hence the slope of the magnetic field dependent energy is inversely proportional to the conduction-band mass. The Landau level index $n \equiv (n_c = n_v)$ because, as mentioned above, the selection rule for *allowed* transitions is $\delta n_{cv} = 0$. Because the Landau-level energy shifts are proportional to the magnetic field, the zero-field extrapolated value is the bandgap energy E_{gap} .

Figure 3 shows a magnetoluminescence spectrum at $B = 10$ tesla and $T = 1.4$ K. The zero-field spectrum shown in Fig. 2, 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 1.4 K, 10 T, and $N_{2D} = 3 \times 10^{11} \text{ cm}^{-2}$, only the $n_c = 0$ and $n_c = 1$ Landau levels are occupied and therefore the highest energy photoluminescence peak that can be observed is the $1 \leftrightarrow 1$ transition. A magnetoluminescence energy “Fan” diagram can be generated by plotting the Landau level transition energies (See Fig. 3) as a function of magnetic field and this result is shown in Fig. 4. 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 as predicted by Eq. (1) again verifying the allowed nature of the transitions, i.e., that $kT \gg \hbar\omega_v$. 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, $E_{gap} = 859.9 \text{ meV}$ which is in good agreement with expectations of a 7.9-nm-wide $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW. Bandgap renormalization effects for $N_{2D} = 3 \times 10^{11} \text{ cm}^{-2}$ may reduce the quantum well confinement energy by as much as 20 meV.¹⁷ For comparison, the bandgap energy for undoped bulk $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ on InP is about 810 meV at 1.4 K.¹⁸

An alternative and informative method for plotting the shown in Fig. 4 is shown in Fig. 5, where each data point is plotted versus the effective magnetic field $(n + 1/2) \cdot B$ where the same symbols are used in both figures. The effect of spectral shifts are evident in Fig. 5 at low magnetic fields where the peak of the photoluminescence spectrum are clearly not to be associated with Landau level transitions.¹⁵ From the slope of the data shown in Fig. 5 or alternately, from the data shown in Fig. 4, the conduction-band mass m_c is calculated to be $m_c = 0.062m_0$. This value, of course, assumes a heavy hole mass. In order to verify this magnetoluminescence determination, low temperature (4.2 K) far infrared cyclotron resonance was performed on the same sample and this result is shown in Fig. 6. The slope of the data shown in Fig. 5 yields $m_c = 0.056m_0$ which is in satisfac-

Figure 4. The magnetoluminescence "Fan" diagram for the 1.4-K magnetoluminescence data. The Landau assignments for n_c are shown. The extrapolated zero-field band-gap energy is 859.9 meV and the ratio of the slopes is nearly 1:3:5 in agreement with Eq. (1).

Figure 5. Luminescence energy versus "effective" magnetic field $(n + 1/2) * B$. The extrapolated zero-field band-gap energy again is 859.9 meV. The data symbols are the same as shown in Fig. 4.

tory agreement with the magnetoluminescence determined value. Also to noted from Figs. 5 and 6 is the linearity of the data for energies approaching 30 meV above the bandgap energy. This linearity is further evidence of negligible nonparabolicity over the range of energy shifts for which the data was taken.

Figure 6. Far infrared transmission cyclotron resonance energies for the 27-ML-wide n-type InGaAs/InAlAs sample. The slope yields $m_c = 0.056m_0$. Also, note the straight line behavior indicating no strong nonparabolicity.

4. CONCLUSIONS

We have presented both magnetoluminescence and cyclotron resonance determinations for the conduction-band mass for an n-type InGaAs/InAlAs 27-ML-wide single quantum well lattice matched on InP. The conduction band mass was measured at liquid helium temperatures and found to be respectively $0.062m_0$ and $0.056m_0$ by the two different techniques. Both measurements show no evidence for strong nonparabolicity in the range of magnetic fields used for these experiments. These results are in good agreement with our earlier study¹² of an n-type multiple quantum well InGaAs/InAlAs structure. Future experiments will be conducted on compressively strained samples of InGaAs/InAlAs in order to remove any valence-band ambiguities where we do not have knowledge of the ground state of the valence-band. However, for strong compressively strained quantum wells, the in-plane valence-band masses are "light" which will permit the use of zeroth-order forbidden transitions as an alternate method for measuring the conduction-band mass.¹⁶

5. ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company. Part of this work is supported by the Division of Material Science, Office of Basic Energy Science, for the United States Department of Energy under Contract DE-AC04-94AL85000. Also a portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-9527035 and by the State of Florida.

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M98005453

Report Number (14) SAND--98-0111C
CONF-980729--

Publ. Date (11) 199805
Sponsor Code (18) DOE/DP, XF
UC Category (19) UC-700, DOE/ER

19980706 046

DOE