High conduction-band offset of AlInAsSb/InGaAs multiple quantum wells grown by metalorganic vapor phase epitaxy

J. R. Chang, Y. K. Su, a) C. L. Lin, and K. M. Wu
Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan, Republic of China

Y. T. Lu
Department of Physics, National Cheng Kung University, Tainan 701, Taiwan, Republic of China

D. H. Jaw
Department of Electronic Engineering, Wu-Feng Institute of Technology and Commerce, Chiyi 621, Taiwan, Republic of China

H. P. Shiao and W. Lin
Photonic Technology Research, Telecommunication Laboratory, Minister of Transportation and Communication, Taoyuan 326, Taiwan, Republic of China

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Unstrained Al0.66In0.34As0.85Sb0.15/In0.53Ga0.47As multiple-quantum-well (MQW) structures have been grown by metalorganic vapor phase epitaxy. Low-temperature photoluminescence was performed for these MQW structures. We compared the experimental data with the theoretical calculations. The conduction-band offset ratio of AlInAsSb/InGaAs heterojunction was set as an adjustable parameter in the theoretical model. We estimated the conduction-band offset ratio to be 0.90 ± 0.05 for the Al0.66In0.34As0.85Sb0.15/In0.53Ga0.47As heterojunction. © 1999 American Institute of Physics. [S0003-6951(99)04823-8]

InP-based multiple-quantum-well (MQW) structures are very suitable and attractive for applications in optical communications and high-speed devices. Recently, large conduction-band offset heterojunction has attracted lots of attention for its possibility of intersubband absorption for infrared detector operating at 2–4 μm, which is one of the key devices in the ultralow-loss fiber communications systems.1,2 The AlInAsSb/InGaAs MQW with lattice matched to InP is one of the most promising material systems for this purpose. This heterojunction has a large conduction-band offset, which allows a broader band tailoring engineering. Furthermore, AlInAsSb has a high Schottky barrier and high band gap, which make this material system a potential candidate for high-breakdown characteristics heterostructure field-effect transistors (HFETs).3 For the accurate modeling of these band-gap-engineering devices, the key parameter is the band offset.

In this letter, we report the low-temperature photoluminescence (PL) measurements on unstrained AlInAsSb/InGaAs MQW structures. The conduction-band offset ratio (Qc) of the AlInAsSb/InGaAs heterojunction was estimated by the dependence of transition energy on the well width. The dependence between the transition energy and the well width was compared with the calculated results obtained from an envelope function approximation.4 Qc is estimated by adjusting its value to reach a best fit between the experimental data and the theoretical results.

The studied AlInAsSb/InGaAs MQW samples were all grown by metalorganic vapor phase epitaxy (MOVPE) system on (100)-oriented Fe-doped InP substrates. The samples consisted of a 0.5-μm-thick undoped InP buffer layer, 10 periods of undoped Al0.66In0.34As0.85Sb0.15/In0.53Ga0.47As MQW and finally a 0.2-μm-thick undoped InP capped layer. The quantum-well width varied between 6 and 18 nm, whereas the barrier-layer thickness was 30 nm in all cases. The growth temperature and pressure were 650 °C and 100 Torr, respectively. Trimethylgallium (TMG), trimethylindium (TMI), trimethylaluminum (TMA), trimethylantimony (TMSb), arsine (AsH3), and phosphine (PH3) were used as the Ga, In, Al, Sb, As, and P sources, respectively. The solid composition of AlInAsSb was determined by JEO (XMA-8800M) electron-probe microanalysis (EPMA). The uncertainty of the measured composition was within ±0.01 compared to the standards of calibration. The lattice mismatch, with respect to the InP substrate, was estimated from double crystal x-ray diffraction measurement (DCXRD). The lattice mismatches of the InGaAs and AlInAsSb bulk layers were within ±0.0003. The layer widths were estimated by the growth rate. They were confirmed further by DCXRD. Figure 1 shows the (400) rocking curve of a 10-period Al0.66In0.34As0.85Sb0.15/In0.53Ga0.47As (18 nm) MQW structure. In the measured curve, satellite peaks could be clearly seen, and the peak spacing yields an average quantum well period thickness 48 ± 0.5 nm, which is in good agreement with the designed value of 48 nm.

For the PL study, the samples were mounted in a cryostat at a temperature of 8 K. Luminescence was excited by 1 W/cm² of focused light from an Ar-ion (514.5 nm) laser. The PL spectra were analyzed by a Spex focal length = 3/4-m spectrometer and detected with a liquid-nitrogen cooled Ge detector. A conventional lock-in amplifier was used for synchronous measurements.

Figure 2 shows the 8 K PL spectra of 0.5-μm-thick...
In$_{0.35}$Ga$_{0.47}$As bulk layer and four unstrained AlInAsSb/InGaAs MQW samples, with well widths of 6, 8, 10, and 18 nm, respectively. All samples were illuminated by the same intensity of laser excitation with the power density of 1 W/cm$^2$. A single peak is observed over all MQW samples within our scanning range. It is identified as the exciton transition from the first electron subband to the first heavy hole subband (C1–H1). The full width at half-maximum (FWHM) of the bulk layer is as small as 7 meV, indicating good crystalline quality of the material. AlInAsSb/InGaAs MQW samples show broader luminescence spectra. The 10 nm MQW has a FWHM of 18 meV, which is comparable to the results for the AlInAs/InGaAs quantum wells grown by MBE.$^5$ The peak energy of the InGaAs bulk luminescence is located at 810 meV, which is very close to the value of 812 meV obtained by Goetz et al.$^6$ We adopt this energy as the reference energy, the band gap of the bulk material. For other samples, the peak energy increases with decreasing well width, which is the well-known quantum confinement effect.

To calculate the transition energy, we need the band gap of the barrier layer in addition to that of the well. It is known that the band gaps of the most quaternary materials do not vary linearly with composition. To take the bowing effect into consideration, we evaluate the band gap of the Al$_{0.66}$In$_{0.34}$As$_{0.85}$Sb$_{0.15}$ by the method given in Ref. 7. Besides the band gap, effective mass in the quaternary layer is also needed for calculation. As mentioned in Ref. 8, the carrier masses are related inversely to the matrix elements of the crystal potential. We extend their formulation for the effective mass of a quaternary alloy $A_xB_{1-x}C_yD_{1-y}$:

$$
\frac{1}{m_{ABCD}} = \frac{1}{m_{AC}} + x(1-y) \frac{1}{m_{AD}} + (1-x)y \frac{1}{m_{BC}} + (1-x)(1-y) \frac{1}{m_{BD}}.
$$

All of the binary parameters used were listed in Table I. The confine energies of conduction and valence bands were then calculated with an envelope function approximation. In order to compare calculated transition energy with the PL peak position, we evaluate the exciton binding energy $E_b$ using the method given in Ref. 9. The $E_b$ varies between 9 and 5 meV as the well width increases from 6 to 18 nm.

Figure 3 plots the C1–H1 transition energy of AlInAsSb/InGaAs MQWs at 8 K against the inverse of the well width square. The experimental measured peak energies are shown as dark squares. The solid line represents the calculated transition energy between the first electron subband and the first heavy hole subband. The calculations are evaluated with $Q_c$ as a fitting parameter. The transition energies are more sensitive to the smaller well width. Observing the curve in the region of smaller well width, we obtain the value of $Q_c$ to be 0.90±0.05. The error percentage is estimated by assuming one-monolayer fluctuation at the interface and 1% in composition variation.

In conclusion, we have reported 8 K PL measurements for unstrained AlInAsSb/InGaAs MQW structures grown by MOVPE system. We estimated the $Q_c$ from the dependence of transition energy on the well width. Fitting the experimental data, we find that $Q_c$ is 0.95 for the well width between 6 and 18 nm.

### Table I. Parameters used for theoretical calculation. All values are taken from Refs. 10–13, except for a, b, c, and d.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_x$ (eV)</th>
<th>$a_0$ (Å)</th>
<th>$m_e^*/m_0$</th>
<th>$m_h^*/m_0$</th>
<th>$m_{hh}^*/m_0$</th>
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<tr>
<td>InAs</td>
<td>0.42</td>
<td>6.0584</td>
<td>0.203</td>
<td>0.410</td>
<td>0.028</td>
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<td>AlAs</td>
<td>3.13</td>
<td>5.6611</td>
<td>0.150</td>
<td>0.760</td>
<td>0.150</td>
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<tr>
<td>AlSb</td>
<td>2.32</td>
<td>6.1355</td>
<td>0.110</td>
<td>0.390</td>
<td>0.110</td>
</tr>
<tr>
<td>InSb</td>
<td>0.23</td>
<td>6.4794</td>
<td>0.016</td>
<td>0.180</td>
<td>0.016</td>
</tr>
<tr>
<td>AlInAsSb</td>
<td>1.92</td>
<td>5.8688$^a$</td>
<td>0.049$^b$</td>
<td>0.505$^b$</td>
<td>0.055$^b$</td>
</tr>
<tr>
<td>InGaAs</td>
<td>0.81$^c$</td>
<td>5.8688$^d$</td>
<td>0.041</td>
<td>0.465</td>
<td>0.050</td>
</tr>
</tbody>
</table>

$^a$This value was calculated by the method given in Ref. 7.
$^b$These values were given using Eq. (1).
$^c$This value was determined from PL measurement.
$^d$These values were determined from DCXRD measurement.
tal data to the calculated values, we obtained a large $Q_c$ of $0.90 \pm 0.05$ for the $\text{Al}_{0.66}\text{In}_{0.34}\text{As}_{0.85}\text{Sb}_{0.15}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ heterojunction.

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