Measurement of AlInAsSb/GaInAsSb heterojunction band offset by photoluminescence spectroscopy

J. R. Chang, Y. K. Su,[a] C. L. Lin, K. M. Wu, and W. C. Huang
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

W. L. Li and S. M. Chen
Department of Electrical Engineering, Far East Institute of Technology, Tainan 701, Taiwan, Republic of China

(Received 28 April 1999; accepted for publication 18 May 1999)

We have grown unstrained $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ multiple-quantum-well (MQW) structures on InP substrates by metalorganic vapor phase epitaxy. Low-temperature photoluminescence was performed for these MQW structures. By comparing the luminescence peak energies with the theoretical calculations, we estimated the conduction-band offset ratio to be 0.75 ± 0.10 for the $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ heterostructure. © *1999 American Institute of Physics.* [S0003-6951(99)02528-0]

Sb-based compounds and heterostructures lattice matched to InP substrate have received much attention for their potential applications in optoelectronic devices[1–3] and high-speed devices,[4–6] because of the special features of these materials such as large refractive-index difference, large conduction-band offset, and high Schottky barrier. In spite of the applications, they are the least investigated III–V compounds. This is due to the difficulty of growing these materials. This difficulty corresponds to the fact that the Sb-based alloy has a wide miscibility gap limiting the range of the composition. However, good quality Sb-based materials have been grown by molecular beam epitaxy[7,8] and metalorganic vapor phase epitaxy (MOVPE).[9,10] Among these materials, we proposed that the AlInAsSb/GaInAsSb quaternary heterojunction is also very suitable for the above-mentioned applications.

In this article, we have grown unstrained AlInAsSb/GaInAsSb multiple-quantum-well (MQW) structures on InP substrates by MOVPE. Double crystal x-ray diffraction (DCXRD) and low-temperature photoluminescence (PL) were performed. We employed an envelope function approximation[11] to calculate the transition energies of the MQW structures. The conduction-band offset ratio (Q_c) of the AlInAsSb/GaInAsSb heterojunction was then estimated by the dependence of transition energy on well width.

The AlInAsSb/GaInAsSb MQW structures were grown on (100)-oriented Fe-doped InP substrates by MOVPE. The growth temperature and pressure were 650 °C and 100 Torr, respectively. Trimethylgallium (TMG), trimethylindium (TMI), trimethylaluminum (TMA), trimethylantimony (TMSb), arsine (AsH_3), and phosphine (PH_3) were used as the Ga, In, Al, Sb, As, and P sources, respectively. The MQW samples consisted of a 0.5-μm-thick undoped InP buffer layer, 10 periods of undoped $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ MQW and finally a 0.2-μm-thick undoped InP capped layer. Four samples with different GaInAsSb layer widths of 5, 6, 8.5, and 13.5 nm were investigated. The AlInAsSb layer width was held constant at 30 nm in all cases. The layer widths were estimated by the growth rate. They were confirmed further by DCXRD measurement.

The solid compositions of the quaternary alloys were determined by JEOL (JXA-8800M) electron-probe microanalysis (EPMA). The uncertainty of the measured composition was within ±0.01 compared to the standards of calibration. Their lattice mismatches to InP substrate were determined by DCXRD. We estimated the mismatches less than 0.0003. For the PL experiment, the MQW samples were mounted in a cryostat at a temperature of 8 K. The 514.5 nm line of argon ion laser was used as a pump source. PL signals

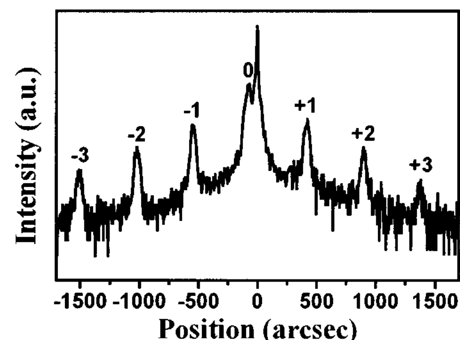

FIG. 1. The (400) rocking curve for a 10-period $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}$(30 nm)/$Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$(8.5 nm) MQW structure.

[a]Electronic mail: yksu@mail.ncku.edu.tw

 © 1999 American Institute of Physics
Downloaded 26 Apr 2010 to 140.116.208.53. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp

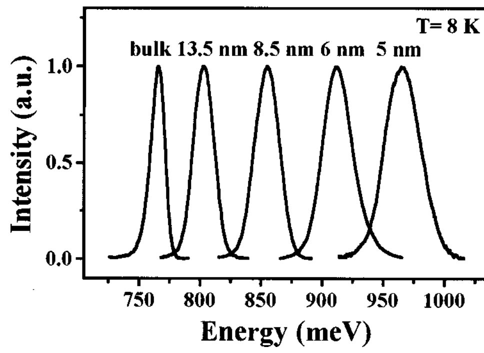

FIG. 2. Low-temperature (8 K) PL spectra of a 0.5-μm-thick $Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ bulk layer and four 10-period $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ MQW structures, with well widths of 5, 6, 8.5, and 13.5 nm, respectively.

were dispersed in a 0.75 m monochromator and detected with a liquid-nitrogen cooled Ge detector. A standard synchronous technique was used with a lock-in amplifier.

Figure 1 shows the (400) rocking curve of a 10-period $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}$(30 nm)/$Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$(8.5 nm) MQW structure. In the measured curve, three orders of satellites could be clearly seen, indicating the high quality of MQW. From the satellite peak spacing, we estimate the period of the MQW to be 38.5 ± 0.5 nm, which is in good agreement with the designed value of 38.5 nm.

Figure 2 shows the PL spectra of a 0.5-μm-thick $Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ bulk layer and four AlInAsSb/GaInAsSb MQW structures. PL spectra of four MQW structures exhibit a single peak corresponding to the excitonic transition between the first electron subband to the first heavy-hole subband. The presence of the quantum size effect is evidenced by the increase of the PL peak energy with the decreasing well width. The peak energy of the GaInAsSb bulk luminescence is located at 765.4 meV. This energy will serve as the band gap of this quaternary material in the following theoretical calculation.

Since the AlInAsSb is an indirect-gap material, we evaluate its band gap by the method given in Ref. 12, which takes into account the bowing effect. The effective masses in quaternary layers are also needed for the theoretical calculation. As mentioned in Ref. 13, the carrier masses are inversely related to the matrix elements of the crystal potential.

TABLE I. Parameters used for theoretical calculation.

	E_g (eV)	a_0 (Å)	m_e^*/m_0	m_{hh}^*/m_0	m_{lh}^*/m_0
GaAs	1.42	5.6533	0.067	0.450	0.074
AlAs	3.13	5.6611	0.150	0.760	0.150
InAs	0.42	6.0584	0.023	0.410	0.028
GaSb	0.72	6.0959	0.046	0.390	0.046
AlSb	2.32	6.1355	0.110	0.390	0.110
InSb	0.23	6.4794	0.016	0.180	0.016
AlInAsSb	1.92[b]	5.8688[e]	0.049[c]	0.505[c]	0.055[c]
GaInAsSb	0.7654[d]	5.8688[e]	0.037[c]	0.397[c]	0.042[c]

[a]All values are taken from Refs. 15–18, except for b, c, d, and e.
[b]This value was calculated by the method given in the Ref. 7.
[c]These values were given using Eq. (1).
[d]This value was determined from PL measurement.
[e]This value were determined from DCXRD measurement.

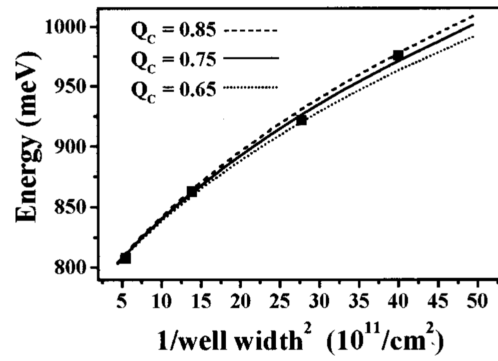

FIG. 3. The C1–H1 transition energy vs inverse of the well width square.

We extend their formulation for the effective mass of a quaternary alloy $A_xB_{1-x}C_yD_{1-y}$:

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

where m_{ABCD} is the effective mass of the quaternary alloy, and m_{AC}, m_{AD}, m_{BC}, and m_{BD} are the effective masses of the binary alloys. All of the parameters used in the theoretical calculation were summarized in Table I. The transition energies between conduction and valence bands were then calculated with an envelope function approximation.[11] In order to compare calculated transition energy with the PL peak position, we also evaluate the exciton binding energy E_b using the method given in Ref. 14. The E_b varies between 10 and 5.2 meV as the well width increases from 5 to 13.5 nm.

Figure 3 plots the C1–H1 transition energy of AlInAsSb/GaInAsSb MQW as a function of the inverse of the well width square. The experimental peak energies are shown as dark squares. Three lines represent the calculated transition energies with different values of Q_c. The dark squares are scattered over the fitting range of 0.85–0.65. Therefore, we conclude the value of Q_c to be 0.75 ± 0.10.

In conclusion, we have reported a photoluminescence study of unstrained AlInAsSb/GaInAsSb MQW structures grown by MOVPE. We estimated the conduction-band offset ratio (Q_c) from the dependence of transition energy on well width. By fitting the experimental data to the calculated values, we obtained a Q_c of 0.75 ± 0.10 for the $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/Ga_{0.64}In_{0.36}As_{0.84}Sb_{0.16}$ heterostructure.

This work was supported by the National Science Council of the Republic of China under Contract No. NSC-88-2215-E-006-005.

[1]O. Blum, I. J. Fritz, L. R. Dawson, A. J. Howard, T. J. Headley, J. F. Klem, and T. J. Drummond, Appl. Phys. Lett. **66**, 329 (1995).
[2]B. Lambert, Y. Toudic, Y. Rouillard, M. Gauneau, M. Baudet, F. Alard, I. Valiente, and J. C. Simon, Appl. Phys. Lett. **66**, 442 (1995).
[3]K. Tai, R. J. Fischer, A. Y. Cho, and K. F. Huang, Electron. Lett. **25**, 1160 (1989).
[4]T. Inata, S. Muto, Y. Nakata, and T. Fujii, Jpn. J. Appl. Phys., Part 2 **29**, L1382 (1990).
[5]W. K. Chen, R. H. Cheng, and J. Ou, Appl. Phys. Lett. **71**, 1373 (1997).

Downloaded 26 Apr 2010 to 140.116.208.53. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp

[6] J. S. Su, W. C. Hsu, W. Lin, and S. Y. Jain, IEEE Electron Device Lett. **EDL-19**, 195 (1998).
[7] W. T. Tsang, T. H. Chiu, S. N. G. Chu, and J. A. Ditzenberger, Appl. Phys. Lett. **46**, 659 (1985).
[8] P. W. Yu, C. E. Stutz, M. O. Manasreh, R. Kaspi, and M. A. Capano, J. Appl. Phys. **76**, 504 (1994).
[9] M. J. Cherng and G. B. Stringfellow, Appl. Phys. Lett. **48**, 419 (1986).
[10] B. T. McDermott, E. R. Gertner, S. Pittman, C. W. Seabury, and M. F. Chang, Appl. Phys. Lett. **68**, 1386 (1996).
[11] G. Bastard, Phys. Rev. B **25**, 7584 (1982).
[12] T. H. Glisson, J. R. Hauser, M. A. Littlejohn, and C. K. Williams, J. Electron. Mater. **7**, 1 (1978).
[13] P. W. Yu, D. C. Reynolds, B. Jogai, J. Loehr, and C. E. Stutz, Appl. Phys. Lett. **61**, 2317 (1992).
[14] L. Hrivnák, J. Appl. Phys. **72**, 3218 (1992).
[15] Landolt–Bornstein, in *Numerical Data and Functional Relationships in Science and Technology*, edited by O. Madelung, M. Schulz, and H. Weiss (Springer, New York, 1982), Vols. 17a and 17b.
[16] S. Adachi, J. Appl. Phys. **61**, 4869 (1987).
[17] R. People and S. A. Jackson, in *Semiconductors and Semimetals*, edited by T. P. Pearsall (Academic, San Diego, 1990), Vol. 32, p. 154.
[18] J. I. Pankove, *Optical Process in Semiconductors* (Prentice-Hall, Englewood Cliffs, NJ, 1971), p. 412.

Downloaded 26 Apr 2010 to 140.116.208.53. Redistribution subject to AIP license or copyright; see http://apl.aip.org/apl/copyright.jsp