Structural and optical properties of strain-compensated GaAsSb/GaAs quantum wells with high Sb composition

X. H. Zheng, D. S. Jiang, S. Johnson, and Y. H. Zhang

Citation: Applied Physics Letters **83**, 4149 (2003); doi: 10.1063/1.1628395
View online: http://dx.doi.org/10.1063/1.1628395
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/83/20?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 20 17 NOVEMBER 2003

Structural and optical properties of strain-compensated GaAsSb/GaAs quantum wells with high Sb composition

X. H. Zheng[a)]
Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100080, People's Republic of China

D. S. Jiang
State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, People's Republic of China

S. Johnson and Y. H. Zhang
Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona 85287-6206

(Received 28 July 2003; accepted 23 September 2003)

The structural and optical properties of GaAsSb/GaAs quantum wells (QWs) and strain-compensated GaAsP/GaAs/GaAsSb/GaAs/GaAsP QWs grown on a GaAs substrate by molecular beam epitaxy are investigated using high-resolution x-ray diffraction and photoluminescence (PL) measurements. We demonstrated that the insertion of tensile GaAsP layers into the active region of GaAsSb/GaAs QWs effectively improves the structural and optical quality. Even the Sb composition is as high as 0.39. The PL spectra at 11 K and room temperature indicate that the PL peak of strain-compensated QWs has a narrower linewidth and higher intensity in comparison to the sample without strain compensation. The results of PL peak blueshift with increasing excitation show the strain-compensated GaAsSb/GaAs interface characteristic of type-I band alignment. [DOI: 10.1063/1.1628395]

The prospect of realizing 1.3 μm laser device structures on a GaAs substrate has attracted considerable interest because of the important applications in fiber-optics communications, photodiodes, data links, and optical interconnection.[1–4] For vertical cavity surface-emitting lasers, the active region structures, which can be epitaxially grown on a GaAs substrate, are of special technical interest. For this purpose, one promising candidate is the GaAsSb quantum well (QW) structure. However, the critical layer thickness of GaAsSb is limited[5,6] due to its large lattice mismatch with GaAs substrates and the higher composition of Sb in GaAsSb/GaAs QW is normally hard to be available for high-quality device structures. Moreover, a poor electron confinement due to a type-II interface and a small band offset becomes an obvious drawback and will result in a low characteristic T_0 temperature.[7] In order to compensate for the compressive strain in GaAsSb/GaAs QWs and improve the confinement effects of electrons, additional tensile GaAsP barrier layers had been proposed to incorporate in the active region to form a strain-compensated coupled QW structure.[7–9] However, the detailed structural and optical properties as introducing the GaAsP tensile-compensation layers are still not reported. In this letter, we performed high-resolution x-ray diffraction (HRXRD) and low-temperature photoluminescence (PL) measurements for both strain-compensated and uncompensated GaAsSb/GaAs QWs structure, indicating that the insertion of strain-compensated GaAsP layers effectively improves the structural quality at a very high Sb composition in $GaAs_{1-x}Sb_x$ layer up to 0.39. In addition, the PL peak of related strain-compensated QW structures shows narrower linewidth and higher intensity, as well as a remarkable redshift of the peak position.

The GaAsSb/GaAs QW and strain-compensated GaAsSb/GaAs/GaAsP QW structures were grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate. The growth details have been described elsewhere.[8] The samples studied here are three period GaAsSb/GaAs QWs (B325) and five period strain-compensated GaAsSb/GaAs/GaAsP QWs (B344), respectively. Their growth structures of one period QW are schematically shown in Fig. 1. It is noted that a higher number of QW periods were grown for the B344 in order to check the effect of strain-compensation on the structural and optical properties of multiple QWs. HRXRD and reciprocal space mapping (RSM) experiments were performed using a Bede D1 triple-axis diffractometer with a parabolic graded multiplayer Gutman mirror collimator, followed by a four-bounce channel-cut Si (220) mono-

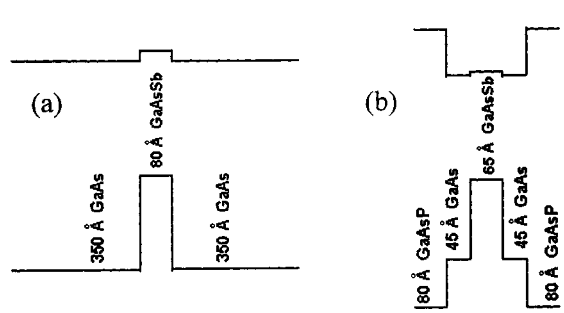

FIG. 1. Schematic energy band diagram of one growth period for (a) the normal GaAsSb/GaAs QWs and (b) the strain-compensated GaAsP/GaAs/GaAsSb/GaAs/GaAsP QWs with nominal thickness.

[a)]Electronic mail: elfiecn@yahoo.com.cn

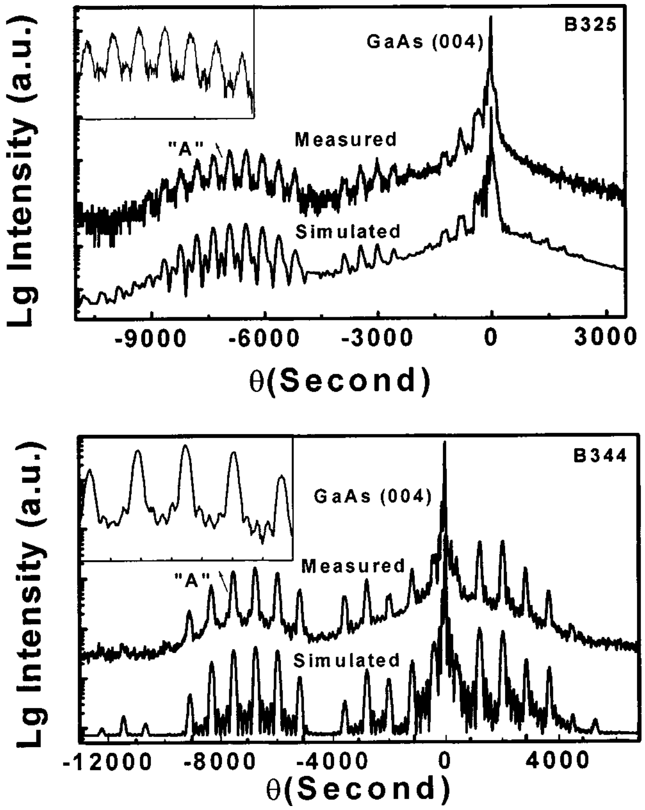

FIG. 2. The ω–2θ scan profiles of (004) reflection for B325 (up side) and B344 (down side) showing the measurement and simulation, respectively. "*A*" marks the envelope modulation induced by GaAsSb layer. Note that the Pendellösung fringes among satellite peaks in the top left inset for B344 can be clearly seen.

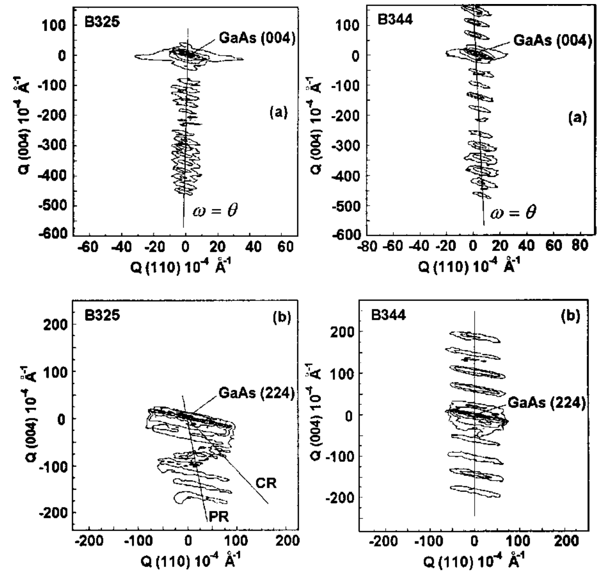

FIG. 3. (a) The symmetric (004) and (b) asymmetric (224) RSMs of the normal GaAsSb/GaAs QWs and strain-compensated GaAsP/GaAs/GaAsSb/GaAs/GaAsP QWs, respectively.

chromator, delivering a Cu $K\alpha_1$ line of wavelength $\lambda = 0.154\,056$ nm. The asymmetric two-bounce Si (220) analyzer crystal was placed in front of the detector. PL spectra measurements were carried out by the He-Ne laser line ($\lambda = 632.8$ nm) excitation with a power intensity.

Figure 2 shows the experimental (004) x-ray diffraction patterns of samples B325 and B344. The measured ω–2θ diffraction patterns were simulated using a computer program based on dynamical theory.[10,11] The strongest peaks are due to the GaAs substrates. A series of sharp satellite peaks appear, modulated by several slow-varying envelopes. Distinct higher orders of satellite peaks can be observed, indicating that the two multiple QW samples have good periodicity and high quality. The QW period was determined from the distance of the satellite peaks. Their periods are 432 and 238 Å, respectively. According to the best fit to the experimental curves, we obtained sublayer thickness as well as Sb and P composition. For B344, the Sb composition is up to 0.39. These results show that the composition and thickness were successfully controlled, as was expected. However, it should be noted that Pendellösung fringes can be clearly seen in the insets of Fig. 2 for sample B344, i.e., the strain-compensated GaAsSb/GaAs QW where tensile GaAsP barrier layers are added. Three fringes between every two neighboring satellite peaks correspond well to the five periods of QW structures in the active region. It means that the added GaAsP layers effectively compensate the compressive strain in GaAsSb/GaAs QWs and improve the interface quality, since any interface imperfection or compositional inhomogeneity would decrease the phase coherence and eliminate the Pendellösung fringes.[12] In addition, as can be seen in Fig. 2, the distances between the zero-order satellite peak and GaAs substrate peak for sample B344 are closer than that of B325. This result provides convincing evidence that tensile GaAsP layers help to reduce the overall strain in multiple QW structures.

To further investigate the structural properties of the QWs, HR-RSM measurements around the symmetric (004) and asymmetric (224) were performed, displayed in Fig. 3. In the (004) RSM, the intensity maximum of the GaAs substrate and SL peaks of the QW system are aligned along the line $\omega = \theta$, confirming that the QWs have grown on axis to the GaAs substrate. However, it is worth noting that the asymmetric (224) RSM for B325 and B344 is different. For B344, the diffraction peak of GaAs substrates and satellite peaks are aligned in a vertical line (dashed line) parallel to the $Q(004)$ or Q_z axis, indicating that the strain-compensated GaAsSb QWs are grown coherently on GaAs. Therefore, the QWs system is fully strained, showing that the assumption of totally strained GaAsSb layers used in the simulation procedure to estimate Sb composition is justified. For B325, a clear in-plane shift (marked PR) of the QW system with respect to the GaAs is observed, which corresponds to a partial relaxation of about 30%. The inclined line (marked CR) shows a completely relaxed QW structure. The partial relaxation considered also complies with our assumption of simulation program. The results are in agreement with those of ω–2θ scans.

To check the optical properties of QWs, PL measurements were performed. Figure 4 shows PL spectra of samples B325 and B344 at 11 K and RT, respectively. The 11 K PL results show that the linewidth is reduced by over a factor of 2 for sample B344, from 54 to 25 meV, where tensile-strained GaAsP barrier layers are added. The linewidth of B344 also decreases compared to that of B325 at RT. A reduced inhomogeneous broadening of the PL linewidth, due to lateral composition and thickness modulation,

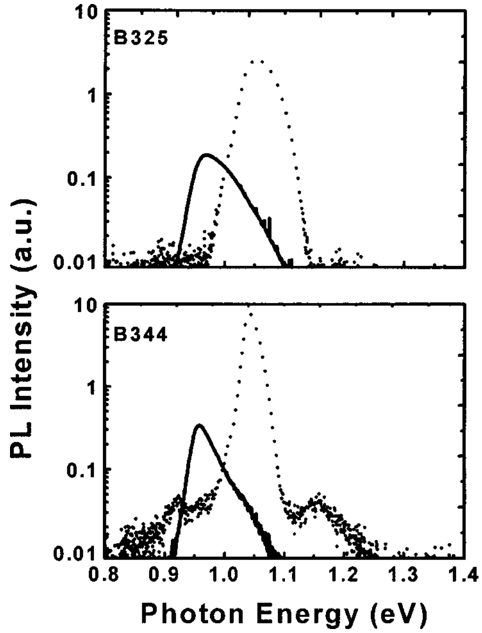

FIG. 4. PL spectra of normal GaAsSb/GaAs QWs (B325) and strain-compensated GaAsP/GaAs/GaAsSb/GaAs/GaAsP QWs (B344) at 11 K (dot lines) and room temperature (solid lines).

may be ascribed to the decrease in the strain accumulation and higher structure quality of strain-compensated QWs.[7] That is, the contribution of strain compensation to the overall structure is that it does not allow a significant amount of overall strain to accumulate as the layer is grown. Meanwhile, improvement in the PL emission strength is observed for the insertion of GaAsP layer. Higher peak intensity from B344 than from B325 at 11 K indicates that additional electron confinement enhances the oscillator strength of the QW transition. The lower RT emission intensity was also observed for B325, indicating that the dislocations that act as nonradiative recombination centers have possibly been introduced into B325 due to the partial relaxation. A very meaningful fact is that the PL peak energy shifts to 1.041 eV for B344 from 1.051 eV for B325, possibly owing to the Sb content increase from 0.36 to 0.39.

Actually, the PL peak position of B325 exhibits a much stronger blueshift as compared to that of B344 when the excitation intensity increases, as shown in Fig. 5. A larger blueshift is typical for the type-II QWs as the spatially separated photogenerated electrons and holes may accumulate on two sides of the GaAsSb/GaAs interface. They will attract each other due to the Coulombic interaction. The carrier filling effect and band bending induced by charge transfer will cause a blueshift of the luminescence peak when the excitation power density is enhanced.[2,3] However, in strain-compensated structure B344, the wave functions for electrons in the coupled double QW and holes in the deep step QW have a larger spatial overlap in the GaAsSb layer region.[7] Therefore, the half width of the PL peaks at both RT and low temperature is narrower for B344 than for B325 under the same excitation conditions as mentioned earlier, and the blueshift of PL peak induced by the increasing excitation intensity is much less than B325, demonstrating the fact that in the strain-compensated QW structure the optical transitions display a behavior similar to type-I QWs.

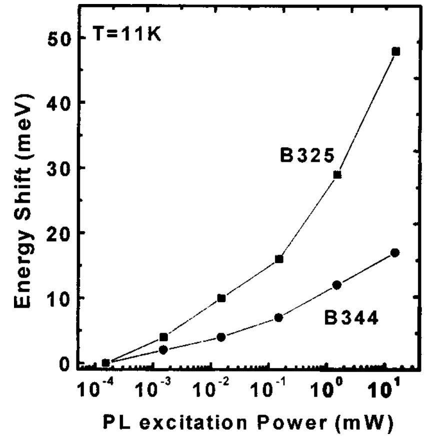

FIG. 5. PL peak shift as a function of the excitation power at $T=11$ K for B325 (solid squares) and B344 (solid circles). The much larger blueshift for B325 is characteristic of type-II QWs. The line is a guide for the eyes.

In conclusion, we investigated the structural and optical properties of the normal GaAsSb/GaAs QWs and strain-compensated GaAsP/GaAs/GaAsSb/GaAs/GaAsP QWs using HRXRD and PL. The interface quality becomes higher and the clearer Pendellösung fringes are observed for strain-compensated GaAsSb QWs. The asymmetrical (224) RSM measurements give us evidence that the GaAsSb base layers remain fully elastic despite the high composition of Sb, up to 0.39 when the tensile layers GaAsP are added to the QW structure, while the normal GaAsSb/GaAs QWs appears to have partial relaxation of about 30%. The narrower linewidth and higher intensity of the PL peak at 11 K and RT are in support of the improvement of the structural properties. The observations of PL peak blueshift with increasing excitation show us that the strain-compensated GaAsSb/GaAs QWs possess many characteristics of type-I QWs.

This work was partially supported by the National Natural Science Foundation of China through Grant No. 60276003 and by the National Science Foundation of the USA (No. 0070125). The authors are grateful for Professor Junming Zhou's help with the XRD experiment.

[1] T. Anan, K. Nishi, S. Sugou, M. Yamada, K. Tokutome, and A. Gomyo, Electron. Lett. **34**, 2127 (1998).
[2] R. Teissier, D. Sicault, J. L. Harmand, G. Ungaro, G. LeRoux, and L. Largeau, J. Appl. Phys. **89**, 5473 (2001).
[3] W. W. Chow and H. C. Schneider, Appl. Phys. Lett. **78**, 4100 (2001).
[4] T. T. Chen, C. H. Chen, W. Z. Cheng, W. S. Su, M. H. Ya, and Y. F. Chen, J. Appl. Phys. **93**, 9655 (2003).
[5] J. Y. Tsao, *Materials Fundamentals of Molecular Beam Epitaxy* (Academic, London, 1993), p. 167.
[6] J. E. Cunniingham, M. Dinu, J. Shah, F. Quochi, D. Kilper, and W. Y. Jan, J. Vac. Sci. Technol. B **19**, 1948 (2001).
[7] S. R. Johnson, S. Chaparro, J. Wang, N. Samal, Y. Cao, Z. B. Chen, C. Navarro, J. Xu, and S. Q. Yu, J. Vac. Sci. Technol. B **19**, 1501 (2001).
[8] W. Braun, P. Dowd, C. Z. Guo, S. L. Chen, C. M. Ryu, U. Koelle, S. R. Johnson, Y. H. Zhang, J. W. Tomm, T. Elsässer, and D. J. Smith, J. Appl. Phys. **88**, 3004 (2000).
[9] J. R. Meyer, C. A. Hoffman, F. J. Bartoli, and L. R. Ram-Mohan, Appl. Phys. Lett. **67**, 757 (1996).
[10] R. W. James, *The Optical Principles of the Diffraction of X-Ray* (Ox Bow, CT, 1982).
[11] V. S. Speriosu and T. Vreeland, Jr., J. Appl. Phys. **56**, 1591 (1984).
[12] L. Tapfer, W. Stolz, and K. Ploog, J. Appl. Phys. **66**, 3217 (1989).