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[1 1 1]B-oriented GaAsSb grown by gas source molecular beam epitaxy

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Abstract

We report the GaAsSb bulk layers and GaAsSb/GaAs quantum wells (QWs) grown on (1 1 1)B GaAs substrates by gas source molecular beam epitaxy. We found that Sb composition in the GaAsSb epilayers is very sensitive to the substrate temperature. The composition drops from 0.35 to 0.16 as the substrate temperature increases from 450 to 550 °C. The [1 1 1]B-oriented GaAsSb epilayers show phase separation when the substrate temperature is lower than 525 °C. For a GaAsSb/GaAs multiple quantum wells (MQWs) structure composed of five periods of 5 nm $GaAs_{0.73}Sb_{0.27}$ QW and 30 nm GaAs barrier, the room temperature photoluminescence emission is located at 1255, 80 nm longer than the [1 0 0]-oriented sample with the same Sb composition. The peak wavelength shows significant blue shift as the excitation level increases, which evidences the type-II band alignment in this heterostructure.

Keywords: Molecular beam epitaxy; GaAsSb; Phase separation; Type II

1. Introduction

Strained zincblende heterostructures grown along ⟨1 1 1⟩ direction have drawn considerable interest because of the large internal fields generated by the piezoelectric effect in such structures. It has been shown that the large piezoelectric field can substantially change the properties of the heterostructures and lead to nonlinear optic and electro-optical effects which have found applications in a number of nonlinear optical and electronic devices such as self-electro-optic effect devices [1,2]. In addition, the acousto-optical and electro-acoustic couplings in quantum well (QW)structures with piezoelectric field have been shown recently [3–5]. Ultrasonic waves propagation along the [1 1 1] direction can be induced by the piezoelectric field induced by a short light pulse, which would play an important role for future piezoelectric device application. Previous studies on strain-induced piezoelectric field were mostly on InGaAs/GaAs heterostructures. In this work, we report our studies on the growth of [1 1 1]B-oriented GaAsSb and GaAsSb/GaAs strained QW. The larger piezoelectric constant of GaSb [6], as compared with that of InAs, and the spatial charge field due to the type-II band alignment of GaAsSb/GaAs system [7] are expected to result in stronger piezoelectric field and more pronounced coupling effects.

2. Experiment

In this study, the samples were grown on semi-insulating (1 1 1)B GaAs substrates with 2° off-cut toward [1 0 0] direction and exact (1 0 0) GaAs substrate by using VG V80 gas–source molecular beam epitaxy (GSMBE). For comparison, besides the (1 1 1)B GaAs substrate, (1 0 0) GaAs substrate was also bonded on the same moly-block for deposition. Arsenic soruce was from thermally cracked arsine (AsH_3) and the antimony (Sb) source was provided by a Veeco (EPI) Sb cracked K-cell. The cracking temperature for Sb beam was 1050 °C, and the species were Sb_1 and Sb_2 [8]. Standard effusion cell was used to supply Ga beam.

The substrates were desorbed at 620 °C, and coated with a 300-nm-thick GaAs buffer layer at 600 °C. The 1-μm-thick GaAsSb bulk layers were then deposited on the buffer layer at their prearranged substrate temperature ranging from 450 to 550 °C. The AsH_3 pressure was fixed to 900 torr. Beam equivalent pressures (BEP) of Ga and Sb beams are 6.0×10^{-7} and 8.7×10^{-7} mbar, respectively. The growth rate, determined by the flux rate of Ga, was

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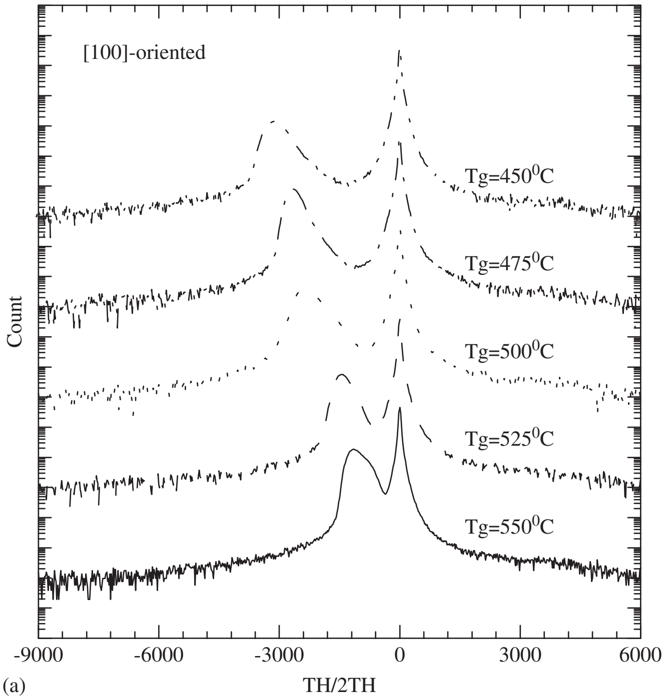
1 μm/h. GaAsSb/GaAs multiple quantum wells (MQWs) were grown under the same growth condition. The substrate temperature was 490 °C. The structure of the MQW is composed of five periods of 5 nm GaAsSb QW separated by a 30 nm GaAs barrier and a 100 nm GaAs cap layer overgrown on top of the QWs.

Characterizations of the grown samples include high-resolution X-ray diffraction (HRXRD), absorption measurement and photoluminescence (PL) measurement. For the absorption measurement, the light source from a tungsten–halogen lamp (PTI A1010H) was dispersed by a SPEX-500M spectrometer. The transmitted light was collected by an InGaAs photodetector. For the PL measurement, a diode-pumped 532 nm laser was used as the excitation source. The luminescence was dispersed by a the SPEX-500M spectrometer and collected by the InGaAs photodetector.

3. Results and discussions

Fig. 1(a) and (b) show the HRXRD rocking curves of the GaAsSb bulk layer grown on (1 0 0) and (1 1 1)B GaAs substrates, respectively. As can be seen, the [1 1 1]B-oriented GaAsSb epilayers suffer from phase separation when the substrate temperature is lower than 525 °C. For the single phase (1 0 0) GaAsSb samples, we measured their asymmetric (1 1 5) and $(\bar{1}\bar{1}5)$ DXRD rocking curves (not shown) to determine their lattice constant along the growth plane. The four (1 0 0) GaAsSb samples grown below 550 °C were close to fully relaxed, while the (1 0 0) GaAsSb sample grown at 550 °C is partially relaxed. For the single phase (1 1 1)B GaAsSb, we also characterized its (1 1 5) rocking curve. The result shows that this sample is also partially relaxed. Detailed results are summarized in Table 1. As can be seen, the Sb composition is very sensitive to the substrate temperature. It drops from 0.35 to 0.16 as the substrate temperature increases from 450 to 550 °C. This behavior could be due to the sublimation energy difference between Sb and As [9]. The higher sublimation energy for Sb makes its evaporation dominate the composition when temperature increases.

There have been several reports concerning the phase diagram of GaAsSb ternary compound in literatures [10,11]. From these calculations, the spinodal Sb compositions for 450 and 550 °C are 0.20 and 0.24, respectively, which means that most of our samples are within the unstable region of the phase diagram. One should note that these calculations are based the assumption of thermodynamic equilibrium. In MBE growth, which is commonly thought to be far from thermodynamic equilibrium, the growth kinetics may play an important role in determining the material structure. Our finding suggests that the Sb adatom on (1 1 1)B plane may have much better surface mobility than on (1 0 0) plane. The worse surface migration ability on (1 0 0) plane may limit the extent of phase separation in these (1 0 0) samples. The spare of phase separation in the (1 1 1)B GaAsSb sample grown at 550 °C may have two reasons. First, the Sb composition of this sample is less and outside the unstable region of the phase diagram. Second, this sample is partially strained according to our XRD analysis. The effect of strain may decrease the critical temperature of spinodal point [12] and drives the



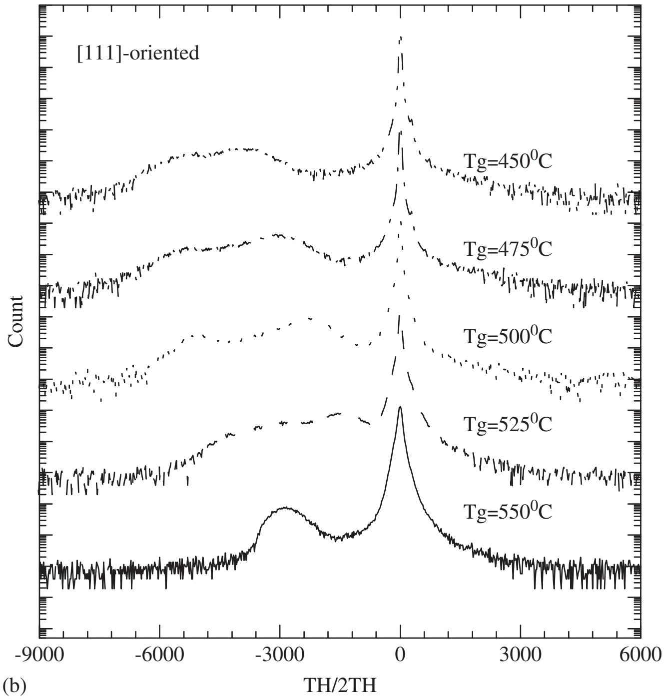


Fig. 1. (a) HRXRD (0 0 4) rocking curves of GaAsSb epilayers grown on [1 0 0]-oriented GaAs substrates (b) HRXRD (3 3 3) rocking curves of GaAsSb epilayers grown on [1 1 1]B-oriented GaAs substrates. The substrate temperature ranges from 450 to 550 °C.

Table 1
Sb composition, energy gap determined from absorption measure and energy gap calculated from Ref. [14] of $GaAs_{1-x}Sb_x$ epilayers

Sample	Substrate orientation	Sb content (x) from XRD	Growth temp. (°C)	E_g measured (eV)	E_g calculated (eV)	Relaxation
C1786	(0 0 1)	0.10	550	1.225	1.252	54%
C1787	(0 0 1)	0.14	525	1.155	1.188	Fully relax
C1788	(0 0 1)	0.23	500	1.012	1.056	Fully relax
C1789	(0 0 1)	0.26	475	0.987	1.017	Fully relax
C1790	(0 0 1)	0.31	450	0.936	0.956	Fully relax
C1786B	(1 1 1)B $2^0 \rightarrow (1\,0\,0)$	0.16	550	1.165	1.154	93%

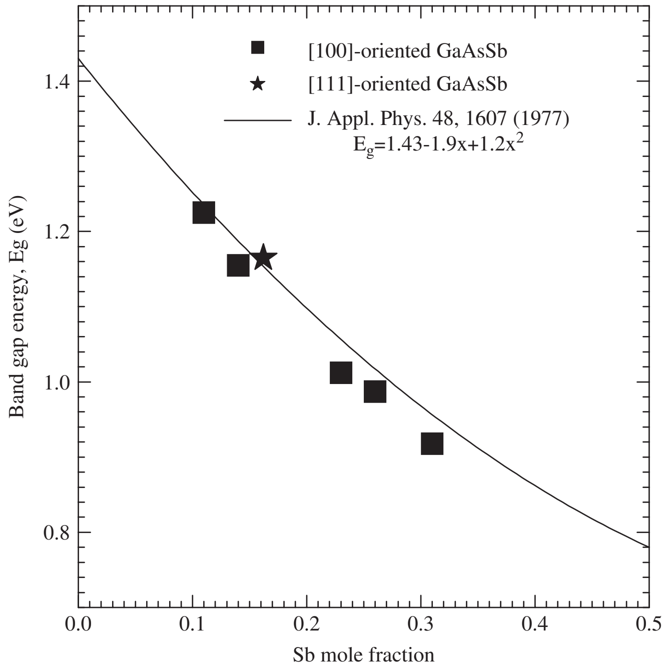


Fig. 2. GaAsSb room temperature band gap energy as a function of Sb composition. The band gap energy was determined by absorption measurement.

sample into the stable region. One thing worth to note for the samples grown at 550 °C is that the Sb composition of (1 1 1)B GaAsSb is higher than that of (1 0 0) GaAsSb. Similar effect has also been observed in GaAsSb lattice-matched to InP [13]. The higher Sb incorporation efficiency could be due to the longer surface lifetime of Sb adatom on (1 1 1)B plane.

The room temperature band gap energies of the GaAsSb samples were determined by the absorption measurement. Fig. 2 shows the band gap energy versus Sb composition plot of GaAsSb epilayers. For comparison, the energy gap versus composition function, $E_g = 1.43 - 1.9x + 1.2x^2$, given by Nahory et al. [14] is also depicted in the figure. Nahory et al.'s data was from random GaAsSb alloys grown by liquid phase epitaxy. As can be seen in the figure, the energy gap of our (1 0 0) GaAsSb samples are slightly lower than the curve of random GaAsSb. It suggests that these samples are slightly ordered. Though the (1 1 1) GaAsSb sample fits the curve, one should note that this sample is not fully relaxed. The residual compressive strain slightly increases the band gap energy by 11 meV. It indicates that As and Sb atoms in this sample is slightly ordered in their sublattice. In contrast, the (1 1 1)B GaAsSb lattice-matched to InP substrate in Ref. [15] is fully disordered.

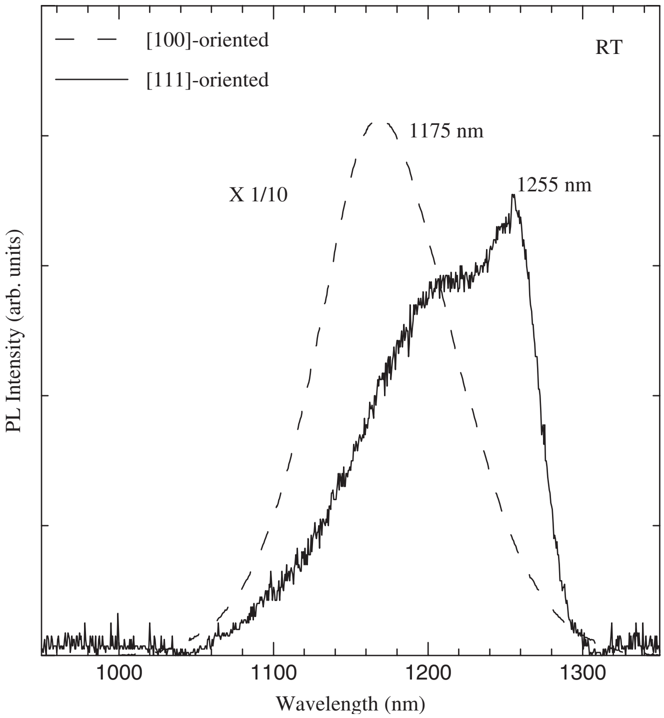


Fig. 3. Room temperature PL spectra of (1 0 0) and (1 1 1)B GaAsSb/GaAs MQW samples. The peak energies are located at 1255 and 1175 nm for (1 0 0) and (1 1 1)B samples, respectively. The peak shift between the two samples is 80 nm (67 meV), which is mainly due to the piezoelectric field in (1 1 1)B sample.

Fig. 3 shows the room temperature PL spectra of (1 0 0) and (1 1 1)B GaAsSb/GaAs MQW samples. The MQW structures were grown at 490 °C and consist of five periods of 5 nm $GaAs_{0.73}Sb_{0.27}$ QW and 30 nm GaAs barrier. The well thickness and composition were measured by HR XRD. As shown in the figure, the (1 0 0) GaAsSb/GaAs exhibits a single peak with its peak wavelength at 1175 nm. On the other hand, the (1 1 1)B sample has two peaks, located at 1200 and 1255 nm respectively. The peak shift between the two samples is ~80 nm (67 meV). Basically, the piezoelectric polarization induced by the strain in the GaAsSb wells of (1 1 1)B sample results in electric field change both in the barrier and well. The field change in the GaAsSb well causes a change in the potential drop across the well which lowers the transition energy. However, the field change in barrier and well both enhance the quantum shifts of the carriers. A rough estimation on the piezoelectric field based on the approximate formula for energy levels in triangular quantum well [16] gives 1.5×10^5 V/cm. This value is about 3 times lower than the expected value calculated by using the linear interpolated piezoelectric constant between GaAs and GaSb. However, the experimental result may be slightly underestimated. The extra field induced by strain may decrease the optical matrix element and the reduction of the recombination rate may increase the carrier densities in the (1 1 1)B samples and result in a blue shift in the luminescence.

4. Conclusion

In conclusion, we have studied the growth of (1 1 1)B GaAsSb epilayers and (1 1 1)B GaAsSb/GaAs MQWs. The Sb composition in the GaAsSb epilayers drops from 0.35 to 0.16 as the substrate temperature increases from 450 to 550 °C. Moreover, the [1 1 1]B-oriented GaAsSb epilayers show phase separation when the substrate temperature is lower than 525 °C. In contrast, [1 0 0]-oriented GaAsSb samples grown under the conditions show only single phase. It implies that the Sb adatoms on (1 1 1)B plane may have better surface mobility which drives the growth close to thermodynamic equilibrium.

Acknowledgements

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