The molecular beam epitaxy growth of InGaAsSb/AlGaAsSb quantum well on GaAs substrate with emission wavelength of ~2μm

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Abstract: InGaAsSb layers and InGaAsSb/AlGaAsSb quantum wells nearly lattice-matched to GaSb were grown by solid-source molecular beam epitaxy on GaAs substrates. As$_2$ and Sb$_2$ sources produce by valved crackers were used for the growth of quaternary InGaAsSb layer and InGaAsSb/AlGaAsSb quantum well structure, which greatly facilitated the lattice-matched to GaSb, as characterized by X-ray diffraction. In order to adjust the composition of indium in InGaAsSb, the indium flux was changed by different indium source temperature under the condition of fixed growth temperature and gallium flux, and InGaAsSb with emission wavelength of 2018 nm at room temperature was grown. By using this growth parameter, the InGaAsSb/AlGaAsSb quantum well structure with 20 nm well layer and emission wavelength of 1966 nm at room temperature was then grown. X-ray diffraction and photoluminescence results indicate that ~2 μm InGaAsSb/AlGaAsSb quantum well structure on GaAs with better crystal and optical properties had been prepared successfully.

1. Introduction

Antimony-based III–V semiconductors have received increasing attention because of their potential applications for optoelectronic devices in the infrared range such as lasers[1-3], photodetectors[4,5] and thermo–photovoltaic cells[6]. In particular, InGaAsSb alloy system lattice-matched to GaSb is interesting for optoelectronic applications as its broad band-gap energy variation in the range from 1.7 to 4.3 μm[7], and is among the most promising materials for use in infrared lasers. Significant efforts have been devoted to the development of InGaAsSb/AlGaAsSb quantum wells (QW) laser diodes, due to the wide applications of mid-infrared lasers beyond 2 μm wavelength[8-10]. However, problems also exist for effective laser diodes operating in mid-infrared range. For example, it is difficult to precisely control the composition of QW structures during high-temperature epitaxial growth, high cost of GaSb substrate.

Generally, high quality materials lead to the high properties of the laser devices and low cost and high performance of the laser devices the wider application it acquires. The photoluminescence (PL) properties of InGaAsSb/AlGaAsSb QW have been studied elsewhere[11-14]. All these results indicate the study of PL properties of the epitaxial wafer is important before the fabrication of laser devices.
However, the antimonide based InGaAsSb/AlGaAsSb QW grown on GaAs substrate and the detailed composition adjusting process of quaternary alloy in the molecular beam epitaxy experiment is rarely reported.

In this paper, we present the process of indium composition adjusting to quaternary alloy of InGaAsSb and the results of InGaAsSb/AlGaAsSb QW structure emission of ~2 μm. Double crystal X-ray diffraction (DCXRD) technique and photoluminescence (PL) spectroscopy were carried out to evaluate the crystal and optical properties of InGaAsSb layer and InGaAsSb/AlGaAsSb QW structure, and the temperature-dependent PL spectra were also carried out for the optical characterization of InGaAsSb/AlGaAsSb QW structure.

2. Experiment

A DCA P600 solid-source molecular beam epitaxy (MBE) system with conventional effusion cells for elemental Al, Ga, In, As and Sb sources was used for the growth of the quaternary InGaAsSb thin film and InGaAsSb/AlGaAsSb quantum well structure on semi-insulating (100) GaAs substrate. The As and Sb sources in this system were equipped with crack cells, which can make the tetramer As₄ and Sb₄ thermally decomposed into As₂ and Sb₂ dimers with high temperature cracking furnaces. The substrate was heated to 200 °C for 30 minutes in the loading chamber to desorb water vapor. Then, the substrate was transferred to buffer chamber and was heated to 400 °C for 2 hours for desorption of organic residues before being transferred to the growth chamber. Finally, at growth chamber prior to growth, the native surface oxide layer on GaAs substrate was typically desorbed at about ~680 °C with As flux, and the reflection high-energy electron diffraction (RHEED) system was used to monitor the crystallographic surface features. After the oxide layer desorbed, the temperature of substrate decreased to 530 °C and a 500 nm GaSb buffer layer grew on GaAs substrate by interfacial misfit dislocations (IMF) growth mode[15-17].

The composition of indium was adjusted by adjusting the indium source temperature to control the flux of indium under the condition of fixed growth temperature and gallium flux. The bulk InGaAsSb thin film, with indium flux of 5.36×10⁻⁸, 5.68×10⁻⁸, 7.30×10⁻⁸ Torr, was grown under 530 °C and then photoluminescence (PL) spectra was measured at room temperature to make sure the indium flux parameter for 2 μm InGaAsSb/AlGaAsSb quantum well structure. After obtaining the epitaxial growth parameters for bulk InGaAsSb thin film lattice-matched to GaSb, the InGaAsSb/AlGaAsSb quantum well structures with the growth parameter of ~2 μm InGaAsSb and different thickness of well layers were grown on GaSb buffer layer. Three InGaAsSb/AlGaAsSb quantum well samples were composed of 10nm, 15nm, 20 nm InGaAsSb wells separated by 30 nm AlGaAsSb barriers. The growth temperature of InGaAsSb is 530 °C, and the growth temperature of AlGaAsSb is 680 °C. The structural quality of the sample was evaluated by high-resolution X-ray diffraction with Cu-Kα radiation (HRXRD, Bruker D8 DAVINCI). The photoluminescence properties of the samples were evaluated by an HORIBA iHR550 monochromator, which equipped with an electric-cooled InGaAs detector and a standard lock-in amplifier technique was employed to enhance the signal-to-the noise ratio. A 655 nm continuous wavelength semiconductor laser as excitation source and a closedcycle helium cryostat with a lowest temperature of 10 K was equipped in this PL system.

3. Results & Discussion

3.1. The crystal quality and photoluminescence properties of InGaAsSb quaternary alloy

In order to confirm the crystalline quality of InGaAsSb quaternary alloy grown on GaAs substrate with different indium flux, double crystal X-ray diffraction (DCXRD) measurements were carried out by Bruker D8 system (as shown in Figure 1). The three InGaAsSb quaternary alloy samples were marked as L1, L2, and L3. Three obvious diffraction peaks can be found in XRD results from each sample, and they are diffraction peak of GaSb buffer layer, InGaAsSb epilayer, and GaAs substrate, respectively. This XRD results showed that InGaAsSb quaternary alloy had been grown on GaAs
substrate successfully. The diffraction peaks of GaSb and InGaAsSb are nearly, which indicated that the InGaAsSb epilayers were nearly lattice-matched to GaSb. The angles of the diffraction peaks correspond to InGaAsSb are 30.72°, 30.68° and 30.65° for sample L1, L2, and L3, and this indicated that the composition of indium was adjusted by the different indium flux.

Figure 1. The experimental XRD results for InGaAsSb quaternary alloy with different indium flux.

Figure 2 shows the results of room temperature PL spectra of InGaAsSb quaternary alloy samples marked as L1, L2, and L3. For each sample, a dominant radiative recombination peak can be found. By adjusting the indium flux of $5.36 \times 10^{-8}$ Torr, $5.68 \times 10^{-8}$ Torr, and $7.30 \times 10^{-8}$ Torr, the photoluminescence wavelength of the grown InGaAsSb quaternary alloy are 1978 nm, 1985 nm, and 2018 nm. The result shows that the higher indium flux the longer wavelength of the grown InGaAsSb quaternary alloy, and corresponding to higher composition of indium in the quaternary alloy of InGaAsSb. The suitable growth rate ratio of indium for L3 was identified as 0.128. The wavelength of sample L3 is 2018 nm with better photoluminescence properties, and considering the quantum confinement effect, the PL wavelength of ~2 μm InGaAsSb/AlGaAsSb quantum well structure need the wavelength of InGaAsSb longer than ~2 μm. The growth parameters of sample L3 will be used to grow the quantum well structure of ~2 μm InGaAsSb/AlGaAsSb.

Figure 2. The PL spectra of the InGaAsSb quaternary alloy with different indium flux at room temperature.

3.2. The crystal quality and photoluminescence properties of InGaAsSb/AlGaAsSb QW structure

By using the growth parameters of sample L3, three InGaAsSb/AlGaAsSb QW sample with different thickness of InGaAsSb well layer were prepared. Double crystal X-ray diffraction measurements were carried out by Bruker D8 system to confirm the crystalline quality of InGaAsSb/AlGaAsSb QW structure, the XRD results are shown in Figure 3. The three InGaAsSb/AlGaAsSb QW samples were marked as Q1, Q2, and Q3. For InGaAsSb/AlGaAsSb QW sample of Q1, Q2, and Q3, the thickness of AlGaAsSb barrier layer all is 30 nm, the thickness of InGaAsSb well layer for Q1 is 10 nm, for Q2 is
15 nm, and for Q3 is 20 nm. The inset figure shows the XRD result of InGaAsSb/AlGaAsSb QW sample of Q2, the diffraction peak of QW structure and GaAs substrate can be found obviously. The result of inset figure indicates that the InGaAsSb/AlGaAsSb QW structure had been grown on GaAs substrate successfully. In the XRD spectrum of both the InGaAsSb/AlGaAsSb QW sample of Q2 and Q3 multiple satellite peaks are observed, which indicates a better interface quality of InGaAsSb/AlGaAsSb QW structure. As the full-width at half-maximum (FWHM) of sample Q3 is narrower and the satellite peaks are more clearly than the other two, so this result indicated good crystalline and interface quality of quaternary InGaAsSb/AlGaAsSb QW structure for sample Q3.

Figure 3. The experimental XRD results of InGaAsSb/AlGaAsSb QW structure with different thickness well layer.

Figure 4 shows the results of the PL spectra of InGaAsSb/AlGaAsSb QW structure with different thickness well layer. For each sample, an apparent emission peak corresponding to the transition between the first heavy hole level (HH1) and the first electron level (E1) was shown in the PL spectra. Compared with the emission peak position of InGaAsSb sample of L3, the emission peak positions of InGaAsSb/AlGaAsSb QW both have a blue shift. The wavelength of sample Q1, Q2, and Q3 are 1835 nm, 1883 nm, and 1966 nm, respectively. Due to the quantum confinement effect, the narrower the InGaAsSb well thickness the bluer shift compared with the wavelength of InGaAsSb thin film. The inset in figure 4 shows the blue-shift compared to L3. Room temperature PL results show that the goal of growing wavelength of ~2 μm InGaAsSb/AlGaAsSb QW structure had been achieved, and the QW sample of Q3 with better crystal quality and photoluminescence properties than QW sample of Q1 and Q2.

Figure 4. The PL spectra of InGaAsSb/AlGaAsSb QW structure with different thickness well layer at room temperature.

For a further study of sample Q3, temperature-dependent PL spectra were carried out. Figure 5 shows temperature-dependent PL spectra of sample Q3 in the range of 20 K -300 K by using a 655 nm cw semiconductor laser with excitation power of 300 mW. The temperature dependence of PL shows that at temperature of 20 K the peak located at 1766 nm dominated the spectra with narrower FWHM.
As temperature increases from 20 K to 300 K, temperature-dependent energy shrinkage causes redshift of the PL peak, and the trend of peak position according to Varshni’s equation:

\[ E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T} \]

Where \( E_g(0) \) is the band gap of InGaAsSb/AlGaAsSb QWs at \( T=0 \) K; \( \alpha \) is the slope when \( \frac{dE_g(T)}{dT} \) at limit \( T \to \infty \) and \( \beta \) is the Debye temperature. The temperature-dependent energy shrinkage causes redshift of this PL peak indicates that this emission might originate from free exciton emission[13]. The wavelength of InGaAsSb/AlGaAsSb QW at temperature of 300 K is 1966 nm. Combined with the result of temperature-dependent PL spectra, ~2 μm InGaAsSb/AlGaAsSb QW structure with better photoluminescence properties had been grown on GaAs substrate successfully.

4. Conclusion
In summary, InGaAsSb quaternary alloy with different indium composition lattice-matched to GaSb and InGaAsSb/AlGaAsSb QW with different well thickness grown by solid source molecular beam epitaxy have been demonstrated. High-resolution XRD and photoluminescence spectra indicated the growth of InGaAsSb layer and InGaAsSb/AlGaAsSb QW structure prepared successfully with better material quality. By fixing the growth temperature and Gallium flux to adjust the indium flux and then achieved InGaAsSb quaternary alloy with PL wavelength of 2018 nm. By using this growth parameter, InGaAsSb/AlGaAsSb QW structure with 1966 nm PL wavelength at 300 K was achieved. The result of XRD shows that the QW with well thickness of 20 nm has better crystal and interface quality. Further study of the optical properties by temperature-dependent PL for this QW shows a better optical properties. XRD and PL results indicate that ~2 μm InGaAsSb/AlGaAsSb QW structure on GaAs substrate had been successfully grown by molecular beam epitaxy technology.

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