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Properties of InAsSbN quantum well laser diodes operating at 2 μm wavelength region grown on InP substrates

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Abstract

Effects of rapid thermal annealing (RTA) on emission properties of InAsSbN quantum well laser diodes grown on InP substrates were studied. It was found that a marked enhancement of electroluminescence (EL) intensity about one order of magnitude and a blue-shift of the EL peak energy was observed at low temperature upon RTA. On the other hand, no blue-shift of the EL peak energy was observed near at room temperature. The observed EL peak blue-shift at low temperature can be explained by decrease in localized levels formed by nitrogen introduction in the InAsSbN quantum wells. Laser operation was obtained for both diodes with and without RTA. It was found that threshold current density J_{th} of the InAsSbN laser diode with RTA reduces compared to that without RTA. The lasing wavelength of the diode before RTA is 2.31 μm at 190 K, while that of the diode after RTA is 2.28 μm at 210 K. The T_0 values are 60 K for both diodes.

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1. Introduction

Semiconductor lasers operating at a 2-μm-wavelength region are highly desirable for many applications, such as pollution monitoring, chemical gas analysis and medical diagnostics. Thus far, most of these lasers have been developed for GaSb-based material systems, such as InGaAsSb/AlGaAsSb quantum well lasers [1,2]. It is very convenient to obtain 2-μm-wavelength lasers using InP-based material systems, since the technology for InP-based lasers has been well developed during the research on 1.3–1.5 μm lasers for optical communication systems. Room temperature operation up to 2.2 μm wavelength was reported for InAs strained quantum well lasers grown on InP substrates [3]. In order to get longer wavelength operation, laser diodes using dilute nitride III–V compound semiconductors, such as InAsN, InGaAsN and InGaAsSbN quntum well lasers grown on InP substrates were also reported [4–6]. Recently, we reported fabrication of InAsSbN quantum well laser diodes grown on InP substrates by molecular beam epitaxy (MBE), where 2.51 μm electroluminescence (EL) at room temperature and 2.31 μm laser operation at 190 K were obtained without annealing [7]. In this paper, effects of rapid thermal annealing (RTA) on emission properties of InAsSbN quantum well laser diodes were studied. It was found that a marked enhancement of EL intensity about one order of magnitude and a blue-shift of the EL peak energy was observed at low temperature upon RTA. However, at room temperature, no blue-shift of the EL peak energy was observed and the EL intensity is almost unchanged. Laser operation was obtained for both diodes with and without RTA. It was found that J_{th} of the diode with RTA decreases compared to that without RTA. Laser operation up to 210 K was obtained for the diode upon

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RTA with the lasing wavelength of 2.28 μm and the threshold current density of $4.2\,kA/cm^2$.

2. Experimental procedure

The InAsSbN quantum well laser diodes were grown on Sn-doped n-type (1 0 0) InP substrates by plasma-assisted MBE. The schematic layer structure is shown in Fig. 1. It was composed of a Si-doped n-type lower $In_{0.52}Al_{0.48}As$ cladding layer (thickness: 1 μm, carrier density: $1\times10^{18}\,cm^{-3}$), a Si-doped n-type lower $In_{0.53}Ga_{0.47}As$(2.5 nm)/$In_{0.52}Al_{0.48}As$(2.5 nm) superlattice (SL) optical confinement layer (thickness: 150 nm, carrier density: $5\times10^{17}\,cm^{-3}$, effective band-gap: 1.05 eV), an undoped lower $In_{0.53}Ga_{0.47}As$ optical confinement layer (thickness: 100 nm), undoped 3 nm $InAs_{0.846}Sb_{0.14}N_{0.014}$ double quantum well active layers separated by a 10 nm $In_{0.53}Ga_{0.47}As_{0.986}N_{0.014}$ barrier layer, an undoped upper $In_{0.53}Ga_{0.47}As$ optical confinement layer (thickness: 100 nm), a Be-doped p-type upper $In_{0.53}Ga_{0.47}As$(2.5 nm)/$In_{0.52}Al_{0.48}As$(2.5 nm) SL optical confinement layer (thickness: 150 nm, carrier density: $5\times10^{17}\,cm^{-3}$), a Be-doped p-type upper $In_{0.52}Al_{0.48}As$ cladding layer (thickness: 2 μm, carrier density: $1\times10^{18}\,cm^{-3}$), and a Be-doped p-type $In_{0.53}Ga_{0.47}As$ cap layer (thickness: 300 nm, carrier density: $2\times10^{18}\,cm^{-3}$). All the layers, except the strained InAsSbN/InGaAsN double quantum well active layer (the effective compressive strain is 1.32%), were lattice matched to the InP substrates. The growth temperature was 505 °C, which was monitored using a calibrated infrared pyrometer. In, Ga, and Al metals were used as group III beam sources, while tetramers As_4 and Sb_4 were used as group IV beam sources. Nitrogen was supplied using an electron cyclotron resonance (ECR) plasma source. The nitrogen gas flow rate was 0.7 sccm with an ECR power of 40 W. The background pressure during growth was about 9×10^{-3} Pa. The InAsSbN quantum well laser diodes had a broad-stripe structure of 100 μm width. The cavity length was about 500 μm. AuGeNi and AuZnNi were used as n-electrodes and p-electrodes, respectively. We compared two kinds of the InAsSbN quantum well laser diodes with and without RTA, which was carried out at 600 °C for 30 s in a nitrogen cover-gas environment.

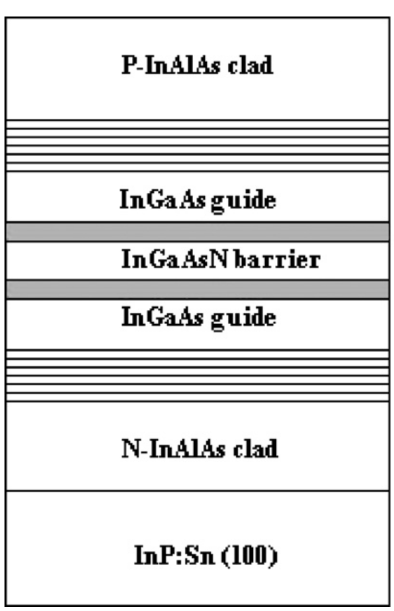

Fig. 1. Schematic layer structure of the InAsSbN quantum well laser diodes.

3. Results and discussion

Fig. 2 shows the EL spectra of the InAsSbN quantum well laser diodes at 10 K before and after RTA. The injection current is 50 mA. EL measurements were carried out using a standard lock-in amplifier technique. EL was detected by a cooled InSb photo-detector. It is known from this figure that upon RTA, a marked enhancement of EL intensity about one order of magnitude is obtained at 10 K. This EL intensity enhancement is probably due to decrease in non-radiative recombination centers related to nitrogen doping in to the InAsSbN active layers. In addition, the EL peak energy shows a blue-shift (~15 meV) upon RTA. It was reported that in the case of InGaAsN layers, a rearrangement of the N nearest-neighbor environments from Ga-rich to In-rich causes a band gap blue-shift [8]. However, in the InAsSbN layers studied here, N is always bounded with In atoms. Therefore, the observed peak blue shift is considered to be induced another mechanisms. Another possibility is improvement of uniformity of nitrogen atom distribution. In fact, the narrowing of the

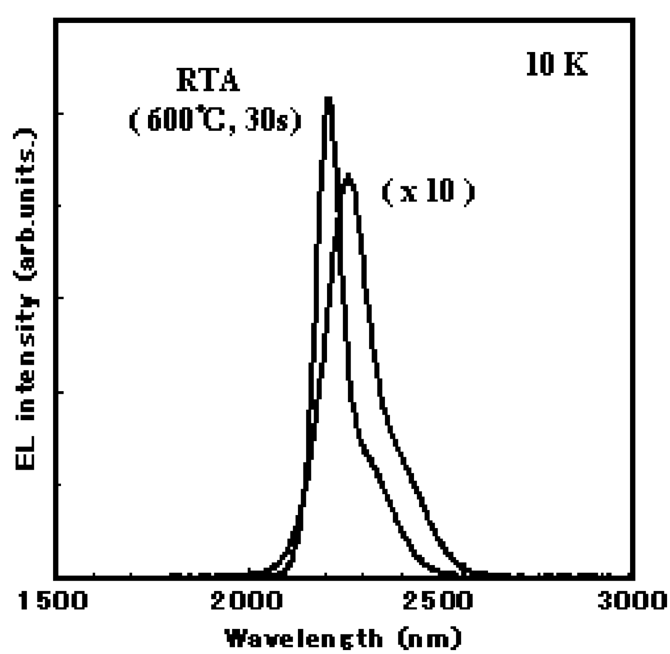

Fig. 2. EL spectra of the InAsSbN quantum well laser diodes with and without RTA at 10 K.

spectral half-width can be explained by this effect. However, no change of the EL spectrum at room temperature can not be explained by the improvement of uniformity of the nitrogen atom distribution.

On the other hand, it was reported that defect-related relatively deep localized levels were formed in the InGaAsN layer on GaAs in the concomitant presence of both In and N [9]. Probably, defect-related localized levels are formed in the InAsSbN quantum well layers, and RTA at 600 °C reduces these localized levels. The decrease in the localized levels causes the observed blue-shift of the EL peak energy at low temperature. In addition, it is noted that there is a shoulder structure at lower energy side of the EL spectra even after RTA. The origin of this shoulder structure is not clear at present. Probably, this shoulder structure is related to phase separation between Sb-rich region and As-rich region in the InAsSbN layer, although further studies are still necessary.

In order to clarify the mechanism of the effect of RTA on the EL spectrum, the temperature dependence of EL peak energy was measured in the range from 10 to 300 K, which is shown in Fig. 3. It is clearly seen that the peak energy difference between the diode with RTA and without RTA is about 15 meV at 10 K. However, with increasing temperature, the peak energy difference becomes small, and almost the same value at room temperature for both diodes. If the peak blue-shift at low temperature is caused by a band gap change, the peak blue-shift should be observed even at room temperature. Therefore, the result shown in Fig. 3 indicates that the peak energy shift at low temperature is not caused by a band-gap change, but is caused by a decrease of localized levels upon RTA, as is already explained.

Fig. 4 shows the temperature dependence of the EL peak intensity of the InAsSbN diodes before and after RTA. It was known from the figure that the EL intensity of the diode with RTA is about one order of magnitude larger than that without RTA at low temperature. However, near room temperature, the EL intensity becomes comparable for both diodes. This result also suggests that the EL enhancement of the diode with RTA at low temperature is related to the decrease of localized centers formed by nitrogen incorporation. Upon RTA, these localized centers diminished, which is consistent with the result shown in Fig. 3.

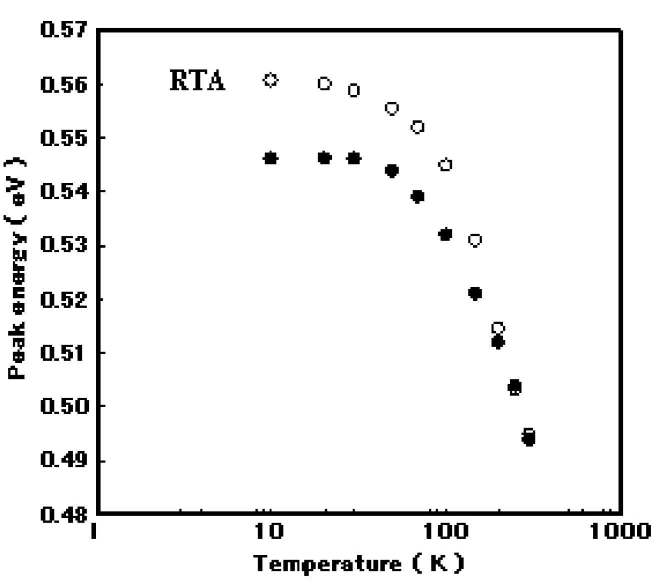

Fig. 3. Temperature dependence of the EL peak energy of the InAsSbN quantum well laser diodes with and without RTA.

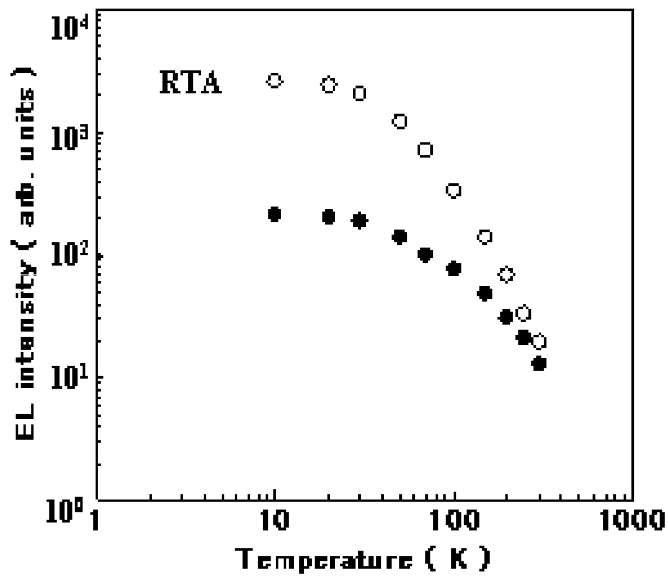

Fig. 4. Temperature dependence of the EL peak intensity of the InAsSbN quantum well laser diodes with and without RTA.

Laser operation was achieved for both diodes with and without RTA. Figs. 5(a) and (b) show the lasing spectrum of the laser diode before and after RTA under a pulsed condition. The lasing wavelength of the diode before RTA is 2.31 μm at 190 K with the threshold current density J_{th} of 4.2 kA/cm^2, while that of the diode after RTA is 2.28 μm at 210 K with the J_{th} of 4.4 kA/cm^2 (2.26 μm at 190 K with the J_{th} of 3.2 kA/cm^2). The slight blue-shift of the lasing wavelength upon RTA is considered to correspond to the blue shift of the EL peak energy at low temperature upon RTA. Lasing experiments at higher temperature region could not be carried out, because the maximum supplied current is limited to 2 A for the pulse generator used here. If a narrower stripe electrode structure is used (for example, a SiO_2 stripe structure), higher temperature operation will be possible in these lasers.

Fig. 6 shows the temperature dependence of the threshold current density in the temperature range from 10 to 210 K. The T_0 value estimated in the temperature range from 50 to 210 K is 60 K for both diodes. The reduction in threshold current density for InAsSbN diode with RTA is probably due to the decrease in the non-radiative recombination centers upon RTA. Room temperature operation will be possible by the improvements of the laser structure as well as optimization of RTA conditions.

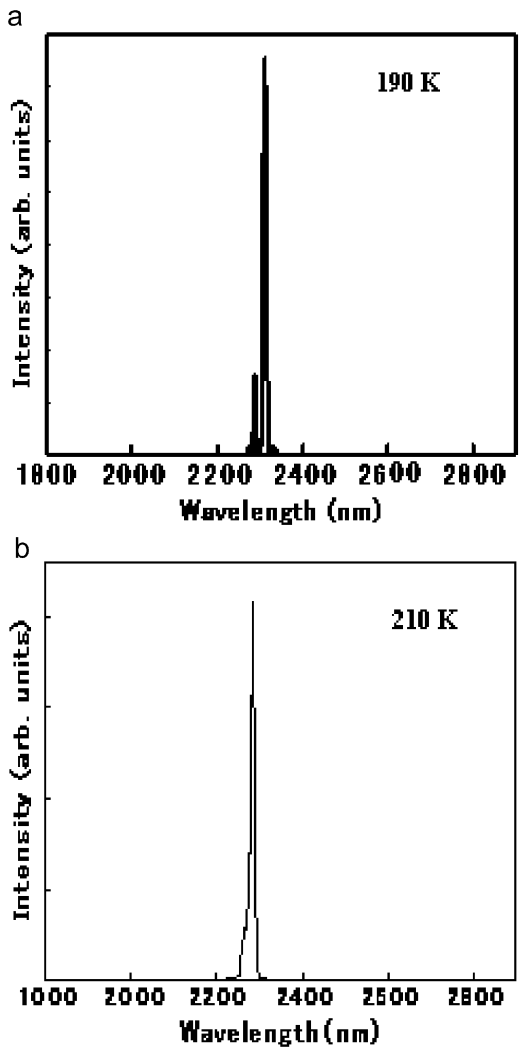

Fig. 5. (a) Lasing spectrum of the InAsSbN quantum well laser diode without RTA at 190 K. (b) Lasing spectrum of the InAsSbN quantum well laser diode without RTA at 210 K.

4. Conclusion

In conclusion, InAsSbN quantum well laser diodes operating at 2 μm wavelength region grown on InP substrates were fabricated by MBE and its emission properties were studied based on RTA effects. It was found that a marked enhancement of EL intensity about one order of magnitude and a blue-shift of the EL peak energy was observed at low temperature upon RTA at 600 °C for 30 s. However, no blue-shift of the EL peak

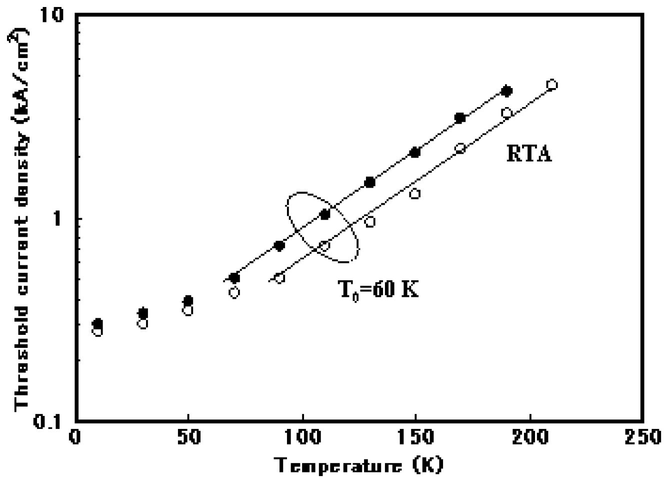

Fig. 6. Temperature dependence of the threshold current density in the temperature range from 10 to 210 K.

energy was observed and the EL intensity is almost unchanged at room temperature. These results suggest that the observed peak blue-shift is not caused by a band gap change, but caused by a reduction of localized levels formed by nitrogen doping upon RTA. Laser operation was obtained for both diodes with and without RTA. It was found that threshold current density J_{th} of the InAsSbN laser diode with RTA reduces compared to that without RTA. The lasing wavelength of the diode before RTA is 2.31 μm at 190 K, while that of the diode after RTA is 2.28 μm at 210 K. The To values are 60 K for both diodes.

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