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High nitrogen content InGaAsN/GaAs single quantum well for 1.55 μm applications grown by molecular beam epitaxy

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Abstract

The growth of high nitrogen content InGaAsN/GaAs single quantum well (SQW) for 1.55 μm applications on GaAs substrates using solid source molecular beam epitaxy and radio frequency plasma nitrogen source is reported. The nitrogen composition was determined using an X-ray diffractometer combined with dynamic simulation. The crystal and optical qualities of highly strained InGaAs/GaAs SQW grown at low temperature can be significantly improved by nitrogen incorporation due to reducing the lattice mismatch. Without the formation of additional nonradiative recombination in InGaAsN SQW with nitrogen composition up to 4.1% which corresponds to wavelength of 1.46 μm was achieved. The longest room-temperature PL peak wavelength obtained in this study is 1.59 μm by increasing the nitrogen composition up to 5.3%. And, the photoluminescence intensity of high nitrogen content InGaAsN SQW can be improved significantly by decreasing the growth temperature due to suppression of the phase separation of InGaAsN alloy. Our results show the potential for the fabrication of 1.55 μm InGaAsN QW lasers on GaAs substrates.

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1. Introduction

Long wavelength (1.3 or 1.55 μm) lasers are essential for optical fiber communication. However, the lasers made with the conventional InGaAsP–InP system exhibit relatively low characteristic temperatures due to its poor electron confinement. Kondow et al. [1] proposed the InGaAsN–GaAs material system as an alternative for 1.3 μm emission. It offers the advantage of better electron confinement due to a higher conduction band offset between InGaAsN wells

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and GaAs barriers, resulting in improved characteristic temperature. In addition, combining InGaAsN active regions with AlGaAs-based distributed Bragg reflectors, monolithic long wavelength vertical cavity surface emitting lasers (VCSELs) based on GaAs substrates can be made. Both molecular beam epitaxy (MBE) [2–5] and metalorganic chemical vapor deposition [6–8] have been employed successfully for 1.31 μm edge emitting lasers and VCSELs. However, there remain difficulties in obtaining high-quality material emitting at wavelength longer than 1.3 μm due to the large miscibility gap of InGaAsN materials. Yang et al. [9] have demonstrated a 1.53 μm room-temperature photoluminescence by introducing Sb during growth of InGaAsN/GaAs QWs. Fischer et al. [10] reported InGaAsN/GaAs laser diodes operating at 1.52 μm with high-threshold current density, 34 KA/cm^2, by increasing the nitrogen composition to as high as 5%. In this letter, we report the epitaxy growth of high nitrogen content InGaAsN/GaAs single quantum wells (SQWs), and investigate the effect of increasing nitrogen content. Photoluminescence emission at 1.59 μm was achieved at room temperature, which shows the potential for the fabrication of 1.55 μm InGaAsN QW lasers on GaAs substrates.

2. Experiment

The structures in this study were grown on n$^+$ type (1 0 0) GaAs substrates by a Riber Epineat solid source MBE (SSMBE). An EPI-Unibulb radio frequency (RF) plasma source was used to supply active nitrogen species from ultrapure N_2 gas. The plasma power and N_2 flow rate were varied from 200 to 600 W and 0.2 to 0.6 sccm, respectively. The intensity of plasma can be controlled by the RF power and the flow rate of N_2. A photodetector was employed to measure the plasma light intensity by the photodetector voltage, V_{OPT}. The indium and gallium were supplied from conventional Knudsen effusion cells, and As in the form of As_2 was supplied from a cracker source. The growth temperature in InGaAsN SQWs was from 375°C to 420°C while the growth temperature of the GaAs buffer and cap layers were 600°C. The V/III ratio was around 3 during the GaAs buffer layers, and the As flux was kept the same during the whole growth. A series of samples have been grown with varying N content while keeping In and Ga cell temperature constant to give a 34% In and 66% Ga composition. The detailed growth conditions are summarized in Table 1. The structure includes a 1-μm-thick GaAs buffer layer, a 6.5-nm-thick InGaAsN QW, and a 50-nm-thick GaAs cap layer. To remove the defects caused by low-temperature growth, in situ 700°C 10 min annealing was used after GaAs cap layer was grown. A mechanical gate valve which located between the growth chamber and plasma cell was used to control the irradiation of nitrogen beam during the growth of InGaAsN QW layers. The surface morphology during InGaAsN QWs was in situ monitored by the pattern of reflection high-energy electron diffraction (RHEED). X-ray diffraction was carried out with a Bede four crystal high-resolution X-ray diffractometer. And, the indium and nitrogen compositions of InGaAsN

Table 1
Growth parameters and nitrogen compositions of InGaAs(N) SQWs

Sample number	N_2 flow rate (sccm)	Plasma power (W)	Plasma light intensity (mV)	Growth temperature (°C)	RHEED	Nitrogen composition (%)
A	0	0	0	420	Dash-streaky	0
B	0.2	294	15.5	420	Dash-streaky	2.2
C	0.4	445	30.0	400	Dash-streaky	4.1
D	0.6	581	42.0	375	Dash-streaky	5.3
E	0.6	581	42.0	385	Spotty	5.3[a]

[a] Assume the same with sample D

SQWs were determined by fitting the XRD spectra using a commercial dynamic simulation software (RADS). Photoluminescence data was obtained using an argon ion laser and a cooled Ge photodetector.

3. Results and discussions

During the growth of QW layer a spotty-like reconstruction pattern of RHEED was observed in sample E, while the dash-streaky-like patterns were observed in all other samples. This result indicates too high a nitrogen composition causes the three-dimensional growth mode to appear presumably due to the phase separation phenomenon as relatively higher growth temperature was used. However, this kind of phase separation can be suppressed by decreasing the growth temperature, as in sample D. The XRD spectra of all samples are shown in Fig. 1, the solid curves are experimental results, while the dot curves are the results of best curve fitting using dynamic simulation software (RADS). The fitted indium composition was obtained from reference sample A, then the fitted nitrogen compositions were obtained by assuming the indium compositions were the same in all samples. All of the fitted results are summarized in Table 1.

As can be seen in Fig. 1, increasing the plasma light intensity shifts the peak of SQW toward the substrate peak, which indicates the reduction of lattice mismatch due to the incorporation of nitrogen. Note that the fringe features from GaAs caps in samples B and C are clearer and have better fitting results than those of sample A showing that flatter hetero-interfaces are achieved in InGaAsN/GaAs SQW samples due to their smaller lattice mismatch. However, sample D shows the worse interface fringe features due to crystal quality degradation caused by high nitrogen incorporation. On the other hand, it was found in sample E that the features of SQW almost disappeared in spite of the decreasing lattice mismatch as the plasma light intensity increase with higher growth temperature. These results are consistent with the results of RHEED. The degradation of the crystal quality might be due to the phase separation phenomenon of high nitrogen content InGaAsN materials as relatively high growth temperature was used.

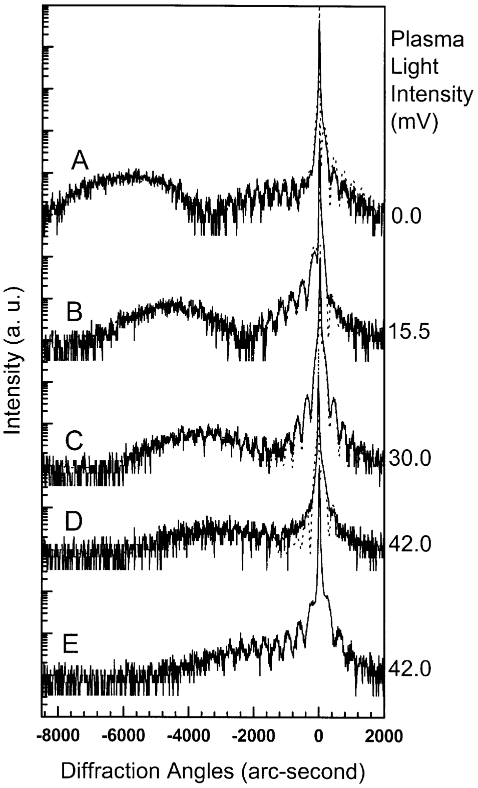

Fig. 1. X-ray diffraction spectra of InGaAs(N)/GaAs SQWs grown at different plasma light intensity as measured by a photodetector voltage, V_{OPT}. The solid curves are experimental results, while the dot curves are the results of best curve fitting using dynamic simulation software (RADS).

Fig. 2 shows the dependence of nitrogen composition in InGaAsN SQW on plasma light intensity as measured by the photodetector voltage, V_{OPT}. As can be seen, the result is not linearly proportional for the higher plasma light intensity. In general, the active species fraction of RF plasma nitrogen source is decreasing with increasing nitrogen flow rate, and saturated in high plasma power region [11]. Moreover, the photodetector also might receive some additional radiation due to the heating of plasma cell when higher power was applied. In our case, to increase the active nitrogen species we increased not only the flow rate of nitrogen gas but also the power of plasma, as shown in Table 1.

Fig. 3 shows the room-temperature PL spectra of all samples. The parameters of PL spectra are summarized in Table 2. As can be seen, the PL peak wavelength increases with increasing nitrogen composition. This result indeed confirms the bandgap bowing effect due to incorporation of nitrogen. However, the integrated PL intensity is improved with small amount of nitrogen incorporation which may be due to the reduction of defects by reducing the lattice mismatch. And, as the nitrogen composition becomes too high the PL intensity degrades again due to the phase separation of InGaAsN alloy. Note that without the formation of additional nonradiative recombination in InGaAsN, QW with nitrogen composition up to 4.1% corresponding to wavelength of 1.46 μm was achieved with a growth temperature of 400°C. However, the full-width at half-maximum (FWHM) increases with nitrogen composition which may be due to the composition fluctuation of InGaAsN alloy.

On the other hand, sample E with the same nitrogen composition in sample D, 5.3%, but grown at 385°C shows a poor integrated PL intensity with poor FWHM and PL peak wavelength as long as 1.59 μm. This result is consistent with the result of three-dimesional growth mode due to the phase separation. However, for sample D with the same 5.3% nitrogen but grown at as low as 375°C, an emission wavelength of 1.56 μm with improved PL intensity and FWHM compared with sample E was obtained. This indicates the optical quality of InGaAsN QW with high

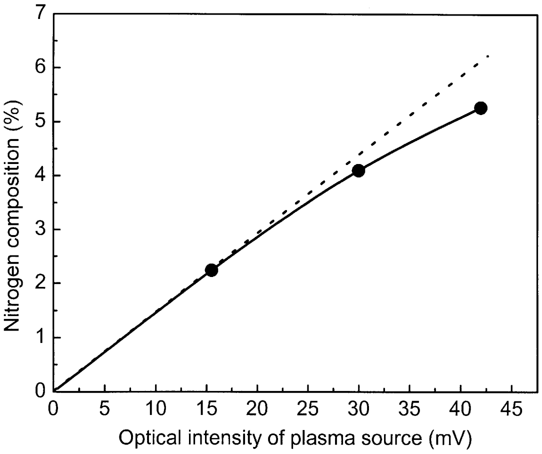

Fig. 2. Nitrogen composition in InGaAs(N) SQWs determined from XRD spectra as a function of plasma light intensity as measured by a photodetector voltage, V_{OPT}. A dashed line of linear proportion is also shown for comparison.

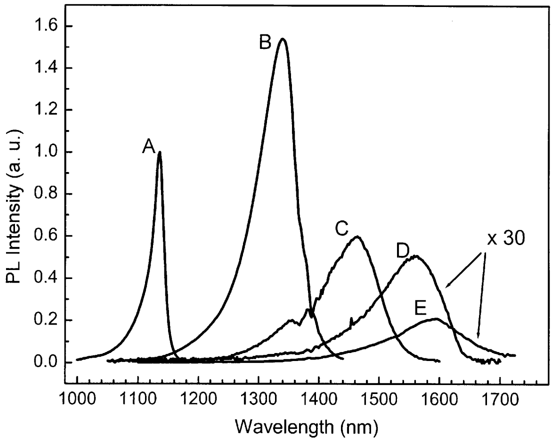

Fig. 3. Room-temperature PL spectra of InGaAs(N) SQWs.

Table 2
Summary of the parameters of PL spectra of InGaAs(N) SQWs

Sample number	Nitrogen composition	Peak energy (eV)	Peak wavelength (nm)	Peak intensity[a]	FWHM (meV)	Integrated intensity[a]
A	0	1.092	1136	1	23	1
B	0.022	0.927	1337	1.54	52	3.48
C	0.041	0.847	1464	0.60	65	1.70
D	0.053	0.795	1560	0.017	65	0.05
E	0.053	0.779	1592	0.007	71	0.02

[a] Normalized by sample A.

indium and nitrogen content can be improved significantly by using low-temperature growth to suppress the phase separation.

4. Conclusion

In summary, we have grown InGaAsN/GaAs SQWs on GaAs substrates by SSMBE with a nitrogen source. The nitrogen composition was determined using an X-ray diffractometer combined with dynamic simulation. The crystal and optical qualities of highly strained InGaAs/GaAs SQW grown at low temperature can be significantly improved by nitrogen incorporation due to the reduction of the lattice mismatch. The phase separation of InGaAsN materials can be suppressed by using low-temperature growth, therefore it improved the optical quality. The highest nitrogen composition obtained in this study is 5.3%, and its room-temperature PL peak wavelength is as long as 1.59 μm. This result shows the potential for the fabrication of 1.55 μm InGaAsN QW lasers on GaAs substrates.

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