In As/GaAs quantum dot lasers with dots in an asymmetric
In$_x$Ga$_{1-x}$As quantum well structure

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Abstract

We report the advantages of using InAs/GaAs quantum dots (QDs) having In$_x$Ga$_{1-x}$As asymmetric strain-released layers (ASRL) over the conventional InAs/GaAs QDs in long wavelength operation. Atomic layer molecular beam epitaxy was used to enhance the uniformity of InAs QDs in an In$_x$Ga$_{1-x}$As quantum well structure. The red shift as large as $\sim$50 nm could be achieved by varying the thickness and indium composition of the In$_x$Ga$_{1-x}$As ASRL. We observed the longest wavelength of 1288 nm produced by the InAs/GaAs QD with ASRL by photoluminescence (PL). However, the stimulated emission gave the longest wavelength of 1206 nm, blue-shifted as large as $\sim$82 nm from the PL peak at room temperature, which is attributed to the optical transitions via higher sub-band levels of the InAs/GaAs QDs.

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PACS: 78.67

Keywords: Strain relaxation; Quantum dot; Dots-in-a-well; Laser diodes

1. Introduction

Recent advances in semiconductor epitaxial growth methods such as molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD) has allowed successful formation of nearly defect-free semiconductor nanostructures such as InAs/GaAs and InGaAs/InP quantum dots (QDs) [1,2]. In particular, InAs/GaAs QDs have received much attention because of their low-cost and well-established fabrication processes based on GaAs substrates and because of their possible applications to laser diodes (LDs) operating at 1.3–1.55 $\mu$m wavelength bands in optical communications [3–5]. However, the performance of InAs/GaAs QD–LDs is still lower than expected because of technical difficulties in controlling the size, homogeneity and distributions of QDs. Increasing the emission wavelength up to 1.3 or 1.55 $\mu$m based on GaAs substrates is also one of the critical goals in this research area.

Dots-in-a-well (DWELL) structures applied to the QD–LDs has been effective in improving the performance of LDs in the long-wavelength regime since it helps not only to increase the optical gain and probability of carrier capture, but also to decrease the thermal escape rate of the carriers from QDs at high temperatures [5,6]. Despite these advantages, however, it is difficult to apply in the design of long-wavelength InAs/GaAs QD systems and in the control of defect formation caused by the coalescence of QDs on the high-density and multiple-stacked dot planes. In addition to the DWELL structure, strain-released layers (SRLs) on the top or bottom of the QDs might be helpful to increase the emission wavelength. S.K. Park et al. reported that red shifts in the emission wavelength could be enhanced by using relatively higher indium compositions for In$_x$Ga$_{1-x}$As SRL because of fewer lattice mismatch between InAs QDs and In$_x$Ga$_{1-x}$As SRLs [7]. For example, using the In$_{0.3}$Ga$_{0.7}$As SRLs would be more advantageous rather than using In$_{0.1}$Ga$_{0.9}$As SRLs in
enhancing the red shift. On the other hand, M. Gutierrez et al. reported that defect density in the QD region could be effectively reduced by growing the barrier layers at higher temperatures [8].

In this work, we investigated the effect of In$_x$Ga$_{1-x}$As asymmetric strain-released layers (ASRLs) on the emission wavelength of InAs/GaAs QDs according to the thickness and composition of the ASRL surrounding the QDs. The corresponding InAs/GaAs QD–LDs were grown by atomic layer molecular beam epitaxy (ALMBE), which is effective for growing multiple-stacked InAs/GaAs QDs with low defect densities. The photoluminescence (PL) measurement showed that red shift could be enhanced as much as ~50 nm by optimizing the thickness and indium compositions of the In$_x$Ga$_{1-x}$As ASRL. The experimental emission wavelengths and the simulated emission wavelengths of the InAs/GaAs QD–LDs with ASRLs were 1288 and 1206 nm by PL at room temperature (RT), respectively. The blue shift as much as ~82 nm from the PL peak might be due to the optical transitions via higher subband levels of the InAs/GaAs QDs.

2. Experimental details

InAs/GaAs QD–LDs with In$_x$Ga$_{1-x}$As ASRLs were grown on (0 0 1)-oriented n$^+$-GaAs substrates in a V80 ALMBE system equipped with an ion pump and a tetramer arsenic source. Fig. 1(a) shows schematic drawings of the InAs/GaAs QD–LD with In$_{0.2}$Ga$_{0.8}$As ASRLs. The laser structure consisted of a 200-nm-thick n-GaAs buffer layer ($n = 3 \times 10^{18}$ cm$^{-3}$), a 1.5-μm-thick n-Al$_{0.35}$Ga$_{0.65}$As lower cladding layer ($n = 1 \times 10^{18}$ cm$^{-3}$), 20 pairs of short period lower superlattice of a 2-nm-thick Al$_x$Ga$_{1-x}$As and a 2-nm-thick GaAs layer, a 380-nm-thick undoped GaAs guiding layer surrounding the active region, 18 pairs of short period upper superlattice of a 2-nm-thick Al$_x$Ga$_{1-x}$As and a 2-nm-thick GaAs layer, a p$^+$ Al$_{0.35}$Ga$_{0.65}$As upper cladding layer ($p = 1 \times 10^{18}$ cm$^{-3}$), and a 200-nm-thick GaAs p$^+$ contact layer ($p = 1 \times 10^{19}$ cm$^{-3}$) grown from the bottom at a temperature of 570°C. In the center of the guiding layer, the active region had dots in an asymmetric quantum well (QW) structure, which consisted of four alternately stacked 1.2-nm-thick In$_{0.2}$Ga$_{0.8}$As layer, a 3 mono-layer (ML)-thick InAs QD layer, and a 7.5-nm-thick In$_{0.2}$Ga$_{0.8}$As layer, with each stack separated by a 20-nm-thick GaAs strain barrier layer, respectively. Each InAs QD layer was formed by repeated deposition of 3 periods of indium, which is equivalent to 1 ML-thick InAs, and 2s-exposal of arsenic at a growth temperature of 480°C. The growth rate of InAs QDs was equivalent to 0.07 ML/s. The 50 μm wide broad-area InAs/GaAs QD–LDs with a 2 mm cavity length were fabricated. The Ti/Pt/Au p-type contacts were e-beam deposited, and AuGe/Ni/Au n-type contacts were thermally deposited after the substrate had been lapped down to a thickness of ~100 μm.

The density, height and width of the InAs/GaAs QDs were examined by atomic force microscopy (AFM) of XE-100 model from PSIA Co. The PL measurements were carried out by using a 75-cm monochromator, equipped with a liquid nitrogen-cooled InGaAs detector. The excitation source was the 514.5-nm line of an Ar+ laser with a power intensity of a 50 mW/cm$^2$, and the sample temperature was controlled between 18 and 300 K by using a He displex system. InAs/GaAs QD LDs had uncoated facets and were tested under RT pulsed operation with a 0.3 μs pulse and a 0.5% duty cycle.

3. Results and discussion

Fig. 1(b) shows the atomic force microscopic image of the InAs QDs observed within a 1 μm × 1 μm area. The dot density, height and width of InAs QDs measured by AFM were 5.4 × 10$^{10}$ cm$^{-2}$, 7.5 and 40 nm, respectively. Average and standard deviations of the height and width of the InAs QDs were 7.72 ± 2.15 and 40.08 ± 5.52 nm, respectively.

To design the emission wavelength of the InAs/GaAs QD–LD to 1.3 μm, first, the degree of shift in the PL wavelengths of the InAs/GaAs QD–LDs was investigated according to the thickness of the In$_x$Ga$_{1-x}$As SRL above the InAs QD layer and the indium composition of the In$_x$Ga$_{1-x}$As SRL. Fig. 2(a) shows the dependency of the PL peak wavelength of InAs QDs grown directly on the GaAs layer on the thickness of the In$_x$Ga$_{1-x}$As SRL for the composition $x = 0.1$ and 0.2, respectively. A schematic drawing for the sample structure is shown on the left hand side of Fig. 2(a) for reference. In Fig. 2(a), the maximum red shifts occur at PL wavelengths for increasing thickness of In$_x$Ga$_{1-x}$As SRL, specifically at 5 nm for the In$_{0.1}$Ga$_{0.9}$As SRL and 7.5 nm for In$_{0.2}$Ga$_{0.8}$As SRL. These red shifts are thought to be due to strain relaxation when In$_x$Ga$_{1-x}$As SRL is thinner than the critical thickness. Conversely, blue shifts occur probably due to strain effects as the thickness of the In$_x$Ga$_{1-x}$As SRL increases above...
the critical thickness. On the other hand, in the relationship between indium composition of the In\(_x\)Ga\(_{1-x}\)As layer and PL wavelengths from InAs QDs, the higher indium composition is preferred not only to enhance the red shifts but also to decrease the intermixing effects. However, the use of higher indium composition decreases the critical thickness of the In\(_x\)Ga\(_{1-x}\)As SRL and eventually limits the number of QD layers that can be stacked in the vertical direction.

Second, to optimize the thickness of the In\(_x\)Ga\(_{1-x}\)As layer below the InAs QD layer the same experiment was carried out by varying the thickness of the In\(_{0.2}\)Ga\(_{0.8}\)As layer below the InAs QD layer in the range of 0, 1.2 and 2.5 nm. The thickness of In\(_{0.2}\)Ga\(_{0.8}\)As SRL above the InAs QD layer was fixed at 7.5 nm. Fig. 2(b) shows the dependencies of the wavelength and intensity of PL spectra from the In\(_{0.2}\)Ga\(_{0.8}\)As layer below the InAs QD layer. A schematic drawing of the sample structure is shown on the left-hand side of Fig. 2(b).

Fig. 2. Schematic drawings of dots in asymmetric In\(_x\)Ga\(_{1-x}\)As QW structures (left) and the wavelength dependence of PL spectra (right) on the thickness of the In\(_x\)Ga\(_{1-x}\)As layer: (a) above the InAs QD layer for different indium compositions of \(x = 0.1\) and 0.2 and (b) below the InAs QD layer for the indium composition of \(x = 0.2\). In Fig. 2(b), the thickness of the In\(_{0.2}\)Ga\(_{0.8}\)As layer above the QD layer was fixed to 7.5 nm.

In the PL spectrum for a 2.5-nm-thick In\(_{0.2}\)Ga\(_{0.8}\)As layer, the occurrence of blue shift and degradation in optical quality of PL spectrum are probably due to the intermixing between the InAs QD and In\(_{0.2}\)Ga\(_{0.8}\)As layer. On the other hand, the PL spectra for a 1.2-nm-thick In\(_{0.2}\)Ga\(_{0.8}\)As layer show a red shift to 1306 nm. This red shift is thought to be due to reduced barrier height since the intermixing effects becomes negligible. Based on these findings, we designed a DWELL structure for our InAs/GaAs QL–LDs with a 7.5-nm-thick In\(_{0.2}\)Ga\(_{0.8}\)As layer above the InAs QD layer and a 1.2-nm-thick In\(_{0.2}\)Ga\(_{0.8}\)As layer below the InAs QD layer, to satisfy both the performance and long wavelength operation of InAs/GaAs QD–LDs.

Fig. 3 shows the PL spectrum taken at RT for the corresponding InAs/GaAs QD–LD sample, in which the p-AlGaAs cladding layer was etched out to facilitate the PL measurement. One dominant PL peak and two shoulders are observed at 1288, 1252, and 1201 nm, respectively, which correspond to optical transitions from the ground states, the first excited states, and the second excited states of the InAs/GaAs QDs, respectively. The full-width at half-maximum (FWHM) of PL spectrum from the ground state transition is less than 52 meV at RT.

Fig. 4 shows the light-output power versus current (L–I) characteristics measured from one facet of the corresponding InAs/GaAs QD–LD with a 2 mm cavity length in the pulsed mode. The stimulated emission was successfully observed at RT from the corresponding InAs/GaAs QD–LDs, while rarely observed from the InAs/GaAs QD–LDs with In\(_{0.2}\)Ga\(_{0.8}\)As symmetric SRLs. This is thought to be mainly due to the reduction in the defect density, which, in general, originates from the coalescence of highly dense QDs by insertion of the In\(_x\)Ga\(_{1-x}\)As ASRLs between the InAs/GaAs QD layers [8]. The threshold current of 2.5 A and its corresponding threshold current density of 25 K A/cm\(^2\) of the present InAs/GaAs QD–LDs were recorded at this moment. The threshold values observed were still higher than the best record in the relevant area; however, the optimization of the In\(_x\)Ga\(_{1-x}\)As ASRL in a DWELL structure is quite effective not only for improving the performance but also for the long wavelength operation of InAs/GaAs QD–LDs. On the other hand, the lasing wavelength of the corresponding laser is measured to be 1205.8 nm, approximately 82 nm blue-shifted from the PL peak wavelength, as shown in the inset of Fig. 4. This blue shift is thought to arise from the optical transition from the second excitation states of the InAs/GaAs QDs. It seems that high current density needed to reach the threshold condition makes it difficult
to make lasing from the ground states of the InAs/GaAs QDs. That is, when the threshold gain exceeds the maximum gain available on the ground state, the gain on the next excited energy states contributes to stimulated emission, and this contribution leads to lasing at the higher subband levels. At present, much research is focused on achieving the emission wavelength of 1.3 μm via lasing from the ground states of the InAs/GaAs QD by optimizing the laser structure.

4. Conclusions

We investigated the influence of the thickness and indium composition of the In_xGa_{1-x}As ASRL on the shifts in the emission wavelength of the InAs/GaAs QDs grown by ALMBE. As compared to the InAs/GaAs QD–LDs with In_xGa_{1-x}As symmetric SRLs, red shift as much as ~50 nm was achieved in the PL wavelengths. The released strain and reduced defect density in the InAs/GaAs QD region by optimization of the In_xGa_{1-x}As ASRLs are thought to be responsible for the red shifts. The longest PL wavelength from the corresponding InAs/GaAs QD–LD was measured to be 1288 nm, which corresponds to ~50 nm red shift from the PL peak of InAs/GaAs QD–LD having a symmetric SRL. This longest PL wavelength was obtained by optimizing the In_xGa_{1-x}As ASRL. However, the lasing action occurred at a wavelength as short as 1206 nm under RT pulsed operation, corresponding to the second excited states transition. Large threshold current density of the corresponding laser is attributed to the failure of the long wavelength operation via ground state lasing. Nevertheless, this report offers a very important finding: In_xGa_{1-x}As ASRLs in the DWELL structure is very useful in not only reducing the defect density but also in increasing the emission wavelength from the InAs/GaAs QD–LDs.

Acknowledgements

This work was supported by KOSEF through q-Psi at Hanyang University, Korea.

References