# Self-Assembled InAs Quantum Dots on InP(001) for Long-Wavelength Laser Applications

Jin Soo Kim, Jin Hong Lee, Sung Ui Hong, Ho-Sang Kwack, Chul Wook Lee, and Dae Kon Oh

**Self-assembled InAs quantum dots (QDs) embedded in an InAlGaAs matrix were grown on an InP (001) using a solid-source molecular beam epitaxy and investigated using transmission electron microscopy (TEM) and photoluminescence (PL) spectroscopy. TEM images indicated that the QD formation was strongly dependent on the growth behaviors of group III elements during the deposition of InAlGaAs barriers. We achieved a lasing operation of around 1.5 μm at room temperature from uncoated QD lasers based on the InAlGaAs-InAlAs material system on the InP (001). The lasing wavelengths of the ridge-waveguide QD lasers were also dependent upon the cavity lengths due mainly to the gain required for the lasing operation.**

**Keywords: InAs quantum dots, growth behavior, InP (001), laser.**

Manuscript received Mar. 21, 2004; revised June 2, 2004.

This work was supported by Ministry of Information and Communication (Grant No. 04MB2910), Korea.

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## I. Introduction

Recent progress in the application of a zero-dimensional structure, a quantum dot (QD), in optical devices such as laser diodes and light emitting diodes has stimulated further research for the use of fiber optic communications [1]. A QD laser is believed to have a lower threshold current density, a higher gain, and a higher thermal stability compared to other quantum structures due mainly to the atomic-like joint density of states for a QD system [2], [3]. A lasing operation from InAs QD lasers fabricated on GaAs substrates was reported at room temperature, but an operating wavelength of up to only around 1.3 μm was reached [4], [5]. Therefore, InAs QDs on an InP substrate have been studied for potential light-emitting devices in the range of 1.30 to 1.55 μm [6], [7]. However, the growth of high quality InAs QDs on InP was difficult compared to that of InAs QDs on GaAs, due mainly to the complexity of the QD formation associated with the relatively low strain of 3.2 % and a possible chemical reaction at the surface [6]-[10]. For example, an As/P exchange reaction and phase separations should be significantly considered during the growth of In(Ga)As QDs on In(Ga, As)P and InAl(Ga)As surfaces, respectively.

InP-based long-wavelength lasers using InAs quantum structures as an active medium were recently reported. A room temperature lasing operation of around 1.6 μm was demonstrated by growing InAs QDs on InP (311)B substrates [11], [12]. By using more conventional InP (100) substrates, gain-guided broad-area InAs QD lasers with quaternary InGaAsP barriers were fabricated, and a lasing operation of up to 190 K was observed [13]. R. H. Wang and co-workers, and R. Schwertberger and co-workers reported on the room-temperature operation of laser diodes having InAs quantum structures based on an InAlGaAs-InAlAs material system on InP (001) substrates [8]-[10]; however, the active layer was composed of InAs quantum dashes rather than QDs. The shape-dependent polarization effects should be significantly considered when quantum dashes are used as an active medium for a laser diode. Since to the best of our knowledge there has been no report on a room-temperature laser operation from InAs QD lasers based on the InAlGaAs-InAlAs-InP (001) material system, the lasing characteristics of QD lasers with an emission wavelength of 1.5 μm have not been systematically investigated.

In the present work, self-assembled InAs QDs in an InAlGaAs matrix were grown on InP (001) substrates by using a molecular beam epitaxy (MBE) with solid sources and were investigated by using cross-sectional transmission electron microscopy (TEM) and photoluminescence (PL) spectroscopy. We fabricated ridge waveguide QD lasers using seven stacks of InAs QDs based on an InAlGaAs-InAlAs material system on InP (001). We successfully achieved a room-temperature operation of uncoated InAs QD lasers, and studied the cavity-length dependence and temperature dependence of the lasing wavelength.

## II. Experimental Details

We grew the samples used in the present work using a V80H MBE system on n-type InP (001) substrates. The QD samples, in which InAs QDs were embedded in InAlGaAs barriers, were grown by varying the number of the QD layers in order to investigate the effects of the barrier materials on the formation of QDs. Before depositing the InAs QD layer, the substrate temperature was set to 510°C for the growth of an InAlGaAs buffer layer. Then, the substrate temperature was lowered to 480°C for the InAs QD layer. To observe the surface morphologies using an atomic force microscope (AFM), the samples were quickly cooled down to 250°C while arsenic was continuously provided to reduce surface reorganization. Confirmation on the formation of InAs QDs was already demonstrated in our previous report [14]. For a PL measurement, an undoped 100 nm InAlGaAs cap layer was grown after the deposition of InAs QDs followed by a 30 second growth-interruption time under arsenic-rich conditions.

TEM specimens were prepared by using standard ion milling and dimpling, and were investigated in a Philips EM 20 operating at 200 keV. For a PL measurement, an argon ion laser with a wavelength of 514.5 nm was used as an excitation source to generate electron-hole pairs. The luminescence light from the sample was focused using collection lenses dispersed by a 1.2 m SPEX single grating monochromator and detected by a liquid nitrogen cooled Ge detector.

The laser design is based on a spin index separate confinement heterostructure with 1500 nm thick InAlAs bottom and top cladding layers. The active region consists of seven-stacked InAs QD layers separated by 28 nm thick InAlGaAs barriers situated in the middle of a 260 nm InAlGaAs waveguide.

## III. Results and Discussions

Figure 1 shows the cross-sectional TEM image of seven-stacked InAs QD layers separated by 28 nm thick InAlGaAs barriers, which clearly indicates the formation of QDs. From the statistical processing using the TEM image, the InAs QDs have an average width of 26.5±1.0 nm and an average height of 3.0±0.5 nm. The average size of the QDs from this TEM image is smaller than that from an AFM image [14], which can be explained by interdiffusion at the interface between the InAs QD layer and the InAlGaAs barrier. The TEM images indicated that a specific spatial ordering with a certain angle instead of the usual on-top vertical alignment exists for the QD layers. This may be attributed to the different growth behaviors of group III elements during the deposition of the InAlGaAs barriers [15]. That is, considerable local deviations from the statistical distribution of In, Al, and Ga atoms due to the bottom QD layer may be provided resulting in a different growth front for the upper QD layer.

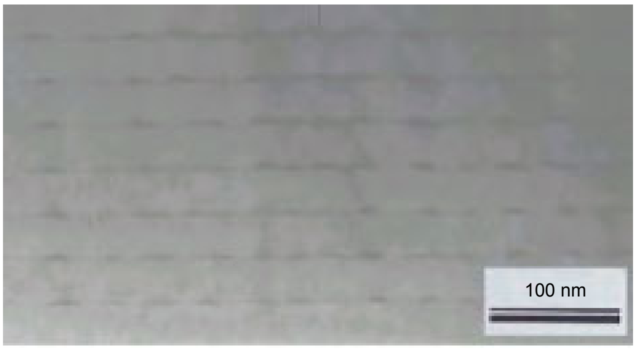


Fig. 1. Cross-sectional TEM image of seven-stacked InAs QD layers.

Figure 2 shows the room-temperature PL spectra from the QD samples with different numbers of InAs QD layers. The PL signals are very strong even at a low excitation intensity indicating the efficient capture of carriers into the QDs, even though no intended confining layers of the carriers were introduced. The dip at around 1.4 μm in the PL spectra is due to water absorption. The peak at 1.156 μm corresponds to emission from the InAlGaAs, which was confirmed by a PL measurement on an InAlGaAs layer without QDs. With an increase in the number of QD layers, the emission peak position was red-shifted from that of the single QD layer. The red-shift in PL peak position can be explained by the increase in the QD size, as the number of QD layers was added upon. This is directly confirmed by the cross-sectional TEM image for the seven-stacked InAs QD layers shown in Fig. 1. The intensity was also significantly enhanced for up to seven-stacked QD layers mainly due to the increase in the number of QDs. However, the intensity for the ten-stacked QD layers decreased, which may be due to the generation of defects during the deposition of the additional QD layers and barriers.

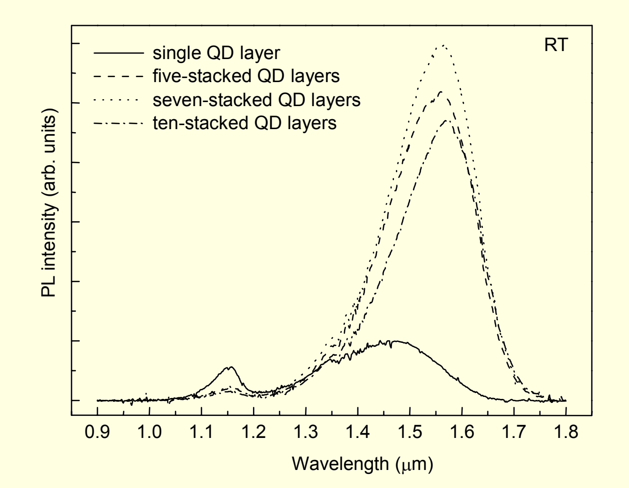


Fig. 2. Room-temperature PL spectra from the QD samples with different numbers of stacked QD layers.

Figure 3 shows the normalized PL spectra of the seven-stacked InAs QD layers measured at three different temperatures. The emission peak position at room temperature was 1.562 μm, which is red-shifted from those of a low-temperature PL. The red-shift in PL peak position when increasing temperature can be explained by the effects of the dilation of lattice and the electron-lattice interaction. The linewidth broadening for the room-temperature PL was 75 meV, which is narrower than those of other studies [6], [15]. The shape of the PL spectrum measured at 77 K is similar to those of the higher temperature PL spectra except for a relatively large linewidth broadening. That is, a Gaussian shape was still observed due mainly to the size distribution of the QDs. The PL spectra at low temperatures in the previous reports were not Gaussian shapes mainly due to the different QD branches with the features of the wetting layer [6], [16]. Therefore, InAs QDs with relatively high quality were formed under our experimental conditions. The features from the different QD branches and wetting layer can significantly affect the carrier dynamics for QD lasers.

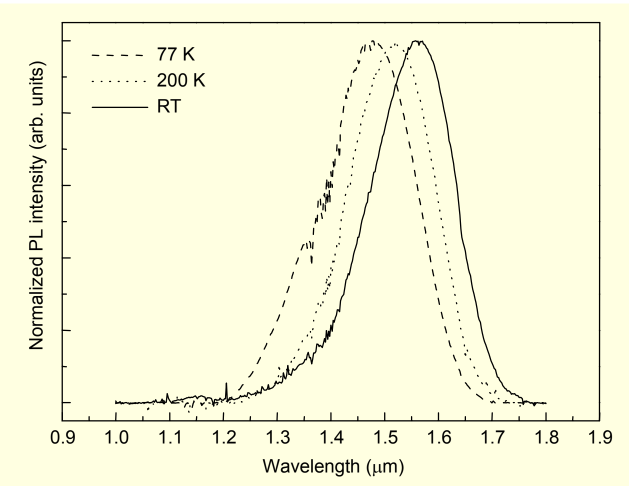


Fig. 3. PL spectra measured at 77 K, 200 K, and room temperature.

Room-temperature electroluminescence (EL) spectra from

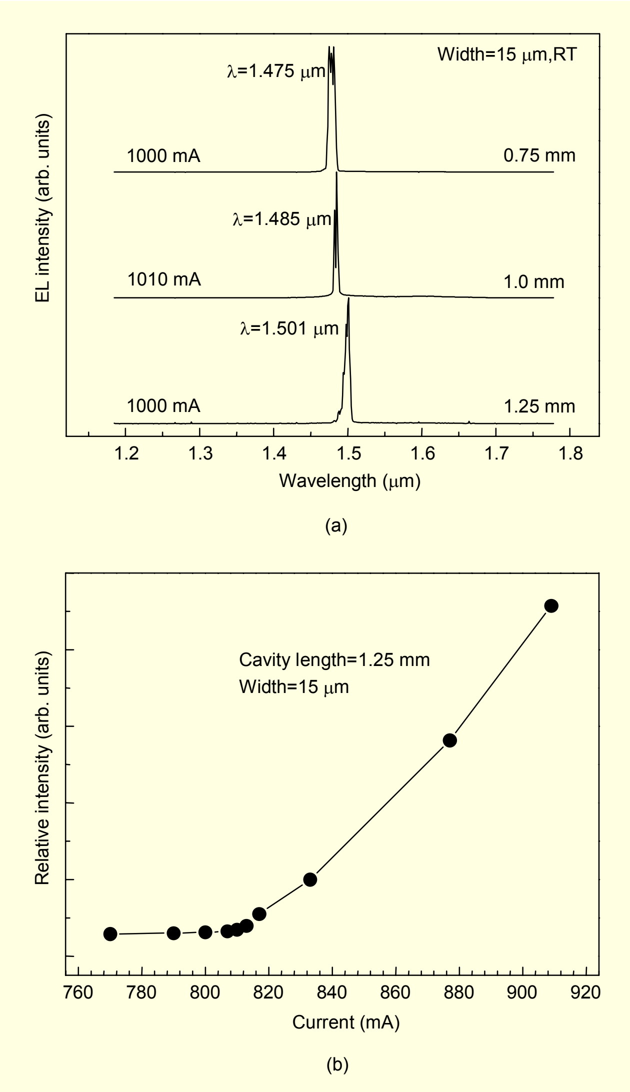


Fig. 4. (a) Room-temperature EL spectra from uncoated QD lasers with three different cavity lengths and (b) relative EL intensity under various injection current levels for a QD laser with a cavity length of 1.25 mm.

uncoated QD lasers with three different cavity lengths are shown in Fig. 4(a). All the EL spectra from the InAs QD lasers were obtained under pulsed excitation with a pulse width of 1.8 μs and a duty cycle of 0.1%. A lasing wavelength was located at 1.475 μm for an uncoated QD laser with a cavity length of 0.75 mm. With an increase in the cavity length, the lasing emission was red-shifted due mainly to the gain required for the lasing operation. Fig. 4(b) shows the relative EL intensity under various injection current levels for a QD laser with a cavity length of 1.25 mm. The EL intensity increased with an increase in the injection current. The lasing emission was then achieved because the gain became sufficient enough to compensate for photon absorption and mirror losses.

Figure 5(a) shows the EL spectra of an uncoated QD laser with a cavity length of 1.25 mm in a temperature range from

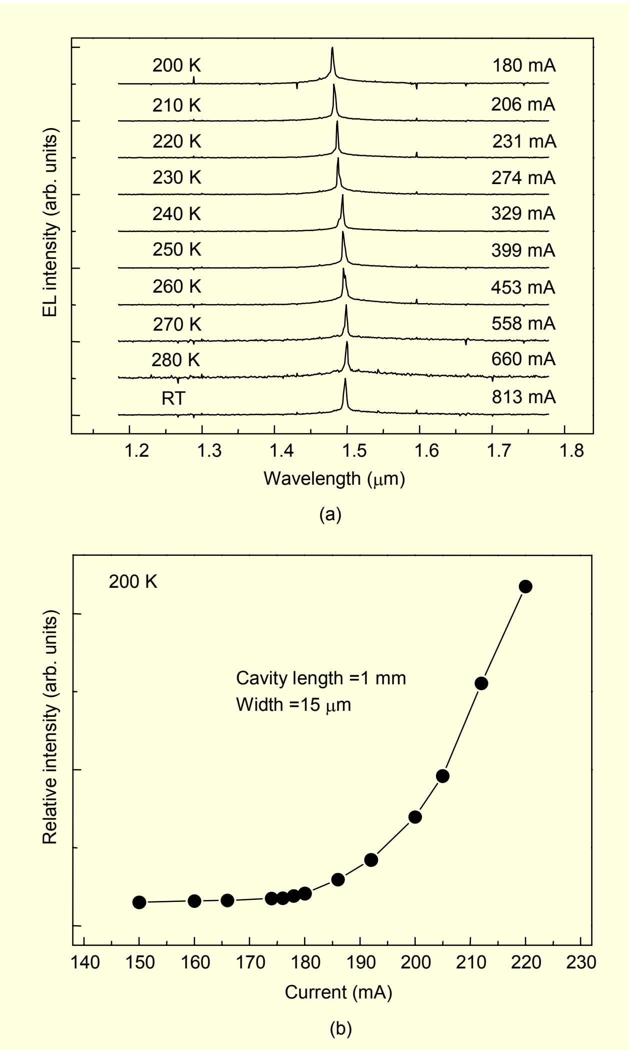


Fig. 5. (a) EL spectra of an uncoated QD laser with a cavity length of 1.25 mm in the temperature range from 200 K to room temperature and (b) relative EL intensity under various injection current levels at 200 K.

200 K to room temperature. The lasing wavelengths are different from the center wavelength of the PL spectra of the InAs QDs shown in Fig. 3. This may be attributed to the thermal behavior of the carriers and thus the variation in gain for the lasing operation. The lasing wavelength with an increase in temperature is linearly increased with a slope of 0.22 nm/K, which is more stable than quantum well lasers. The reduced temperature dependence of the emission wavelength for the QD lasers compared to quantum well lasers can be largely attributed to the gain saturation effects [17]. Figure 5(b) shows a relative EL intensity measured at 200 K under various injection current levels where the threshold current density of the QD laser is 0.95 kA/cm$^2$. We are currently unsure of the exact energy level involved in the lasing operation due to the uncertainty of the energy level caused by the large PL linewidth from the QDs. However, to our knowledge, this is the first study on the cavity length dependence and temperature dependence of the lasing wavelength for InAs QD lasers based on the InAlGaAs-InAlAs-InP (001) material system.

## IV. Conclusions

Specific spatial ordering with a certain angle instead of the usual on-top vertical alignment was observed for multiple stacked QD layers, which can be explained by the growth behavior of group III elements during the deposition of the InAlGaAs barriers. We fabricated InAs QD lasers based on the InAlGaAs-InAlAs material system on InP (001) substrates and successfully achieved a lasing operation of around 1.5 μm at room temperature. The gain-dependent lasing operation was presented by using QD lasers with three different cavity lengths. The temperature dependence of the lasing wavelength indicated that the QD laser has a high thermal stability.

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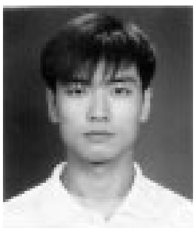

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