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Tuning InAs quantum dots for high areal density and wideband emission

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The authors report the effect of growth temperature and monolayer coverage on areal density and photoluminescence spectral width of InAs quantum dot (QD). Areal density and spectral width were found to be strongly dependent on growth temperature and monolayer coverage, respectively. Upon proper tuning, both high areal density and large photoluminescence spectral width were obtained. Areal density of $1.5 \times 10^{11}$ cm$^{-2}$ is four times higher than those previously reported, while spectral width of 136 nm is the broadest spectral width obtained without any forms of band gap engineering. These results will contribute to an improvement in the performance of QD superluminescent diode. © 2007 American Institute of Physics. [DOI: 10.1063/1.2713148]
monolayer coverage. Again, note that regardless of growth temperature, the spectral width of the PL spectra at 2.0 ML coverage is still larger (>100 nm) than that grown at higher $T_g$. As reported by Joyce et al., as reported by Joyce et al., 2.0 ML coverage provides insufficient material for the InAs QDs to reach its mature size. Hence, the large PL spectral width is due to the low InAs monolayer coverage, leading to a large number of QDs in various stages of development and consequently resulting in large QD size variation, as reflected by the wide PL spectral width.

The inset in Fig. 1 presents the integrated PL intensity as a function of growth conditions, while Fig. 2 shows the RT-PL spectra and AFM images (as insets) of the InAs QD samples grown at (a) 3.0 ML, 450 °C and (b) 2.0 ML, 510 °C. Hence, while high dot areal density can be obtained at low $T_g$ regardless of monolayer coverage, integrated PL intensity decreases and the number of large islands with width of ~100 nm increases following the increase in $T_g$ [as shown in inset of Fig. 2(a)]. As reported, transmission electron microscopy studies have shown the presence of dislocations within the large islands. Hence, these islands are nonradiative and act as a sink for photogenerated carriers, thus degrading the PL efficiency. On the other hand, while large spectral width (implying large size nonuniformity) can be obtained from low InAs coverage, the areal density decreases significantly following the increase in $T_g$. This is due to the exponential increase in In desorption rate at high growth temperature, hence giving rise to the sharp decrease in the areal density, as observed in Fig. 1 and the AFM image in inset of Fig. 2(b). The corresponding decrease in the integrated PL intensity is expected since, as mentioned above, low areal density ($\sim0.7 \times 10^{10}$ cm$^{-2}$) is detrimental to the output power of QD-SLDs. While extraction of the actual dot height from AFM is relatively straightforward, this is not so for the dot width (lateral size) due to convolution effects between the AFM tip and the dot. In this work, all AFM image widths have been corrected to obtain the actual widths (lateral size). The size nonuniformities for the insets of Figs. 2(a) and 2(b) are calculated to be 12.3% and 19.4%, respectively. It should be noted that the large islands in the inset of Fig. 2(a) are excluded from the nonuniformity calculations since they are nonradiative. The increase in size nonuniformity following the decrease in monolayer coverage is expected and can be inferred from the spectral widths of the PL spectra in Fig. 2.

As seen from Fig. 1, InAs QD areal density is strongly dependent on the growth temperature, while the size nonuniformity (thus spectral width of the PL spectrum) is strongly dependent on the monolayer coverage. This implies the ability to tune the dot areal density and size nonuniformity separately by changing the InAs QD growth conditions. Hence, using suitable monolayers coverage and growth temperature, one can obtain high dot areal density and large spectral width. As depicted in Fig. 1, this is realized for InAs QD sample grown at 2.0 ML and 450 °C, and Fig. 3 shows the AFM image and RT-PL spectra of the sample under various fractions of excitation power. The QD areal density obtained from the AFM image was $1.5 \times 10^{11}$ cm$^{-2}$ and the size nonuniformity was calculated to be 19.0%. This areal density is approximately four times higher than those previously reported and is expected to contribute to the higher output power of QD-SLDs. Comparison of the PL spectrum at 1.0$P_0$ with that at 0.25$P_0$ suggests that the broadband emission is contributed by a convolution of various ground and excited state emissions. This explains the presence of the shorter wavelength peaks at higher excitation levels.
density and size nonuniformity of InAs QDs. Under conditions of InAs QD growth temperatures at 450, 480, and 510 °C and monolayer coverages at 2.0, 2.5, and 3.0 ML, the InAs QD areal density was found to be strongly dependent on the growth temperature while the size nonuniformity was found to be strongly dependent on the monolayer coverage. With proper tuning of growth temperature and monolayer coverage, we have achieved both high areal density (1.5 × 10¹¹ cm⁻²) and large RT-PL spectral width (136 nm). These results will contribute to an improvement in the performance of the current QD-SLDs.

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FIG. 3. (Color online) (a) AFM image and (b) RT-PL spectra of InAs QD sample grown at 2.0 ML, 450 °C under various fractions of excitation power. The initial excitation power is P₀. The corresponding spectral widths are indicated. (Inset) Integrated PL intensity as function of excitation power.

20Using \( w_p = \sqrt{\frac{8 \pi}{r h}} \), where \( w_p \), \( r \), and \( h \) are the actual dot width, AFM image width, radius of curvature of the tip, and dot height, respectively. Derivation of the formula is included in the Appendix of J. Appl. Phys. (unpublished).
21Nonuniformity is defined as the ratio of the standard deviation of the sample size to the average of the sample size.