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Recent Progress in Quantum Dot Laser

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Abstract

We present recent progress on quantum dot (QD) lasers mainly focusing on 1.3 µm wavelength range. Historical progress of QD lasers has been promoted by epitaxial improvement to increase QD sheet density to enhance modal gain. Our new approach is to increase spatial QD density by thinning barrier layer in between QD layers by introducing strain engineering and the molecular beam epitaxy (MBE) growth improvement. Small signal modulation analysis of QD lasers exhibited that the modulation bandwidth of the conventional QD laser was limited by long carrier transport time due to the thick active layer, on the other hand, thinner active layer developed in our recent study showed larger and record-high modulation bandwidth up to 13 GHz as 1.3 µm-range QD lasers owing to the reduced carrier transport time.

1. Introduction

Quantum dot (QD) lasers have been attractive light source since its proposal at 1982 [1] not only for telecom/datacom [2] but also for Si-photonics [3] and for extremely-high temperature applications up to 200°C [4] owing to their temperature insensitive characteristics [1][4]. Recently QD lasers have been commercialized [5] using InAs/GaAs QD on GaAs substrate grown by multiple-wafer MBE [6] and fabricated by low cost fab based on DVD lasers. On the other hand, relatively insufficient gain of current QD active media tends to be a limiting factor to extend the variety of devices such as uncooled high-speed DFB lasers. To increase the gain, many researchers have been focusing on increasing "sheet" QD density by modifying epitaxial growth condition of QD layer. On the other hand, we have been focusing on increasing "spatial" QD density by reducing barrier thickness in the multiple stack of QDs, in which barrier thickness had been limited by the large lattice mismatch between InAs and GaAs. We have taken two approaches to reduce barrier layer thickness, one is to reduce average strain by using strain compensation (SC) technology, and the other is the local strain reduction (LSR) at just above buried dot by considering strain coupling through the barrier as a function of buried dot density. Both approaches effectively enabled to reduce the barrier thickness without losing quality of QD active layer, resulting in obtaining higher small signal bandwidth of QD laser owing to the reduction of carrier transport time in QD active layer.

2. Strain Compensation

We have focused on denser stacking of QD layers, which is thought to be a key to increase modal gain without losing the design flexibility, by applying strain-compensation (SC) technique to avoid the accumulation of the average strain. Room-temperature lasing operation of MOCVD-grown SC-QD LD using GaP thin-layer was reported [7], on the other hand, MBE-grown SC-QD LD is limited to all-arsenide materials on InP-substrate [4] probably due to the difficulty in the phosphorous growth in MBE. In this study, we have introduced GaP-SC layers into multiple-stacking of InAs/GaAs quantum dot structure by MBE for the first time. We found that the thickness management is a key to grow flat, tensile-strained GaP layers on GaAs substrate. As shown in Fig. 1, the 0th order peak of the satellite peak in XRD spectra showing the average strain, indicated by arrows in Fig. 1, shifted towards larger diffraction angle by increasing the number of inserted GaP layers on each dot layers. Thus we have confirmed the controllability of the average strain from non-compensation to over-compensation. We obtained first lasing operation for the MBE grown SC-QD LDs on GaAs substrate.

3. Local Strain reduction (LSR) by dot density control

Vertical alignment (VA) between upper and lower dots due to the local strain coupling is known to be a root-cause to compel the barriers to be thick [10], because migrated In-adatoms favor to accumulate into higher strain area during InAs-QD layer growth. Furthermore, VA induces the dot density reduction and dot size inflation (can be seen in Fig. 2), resulting in the peak gain reduction. We have found that higher QD density enables to reduce barrier thickness without increase of VA due to the minimization of local strain just above dot because of strain overlapping from neighboring dots by theoretical and experimental discussions [9], and obtained growth mode map for non-VA and VA as shown in Fig. 2. In this study, we employed 8 QD layer in QD laser structure considering the LSR with increased QD density and reduced barrier thickness respectively as 6.6×10^{10} cm^{-2} and 30 nm, which are recognized to be in the edge of no-VA mode, resulting in the total active layer thickness (L_a) of 310 nm by simply adjusting the growth temperature of QD layer. The broad-area laser with LSR showed ground-state lasing operation under pulsed injection up to 130°C, which was limited by measurement setup.

4. High Speed Modulation of QD Lasers

QD laser tend to have relatively thick active layer thickness due to the requirement of multiple stack to increase gain and the strain as discussed above. Typical active layer thickness is around 400 nm and thought to increase carrier transport time. We have evaluated the small signal modulation bandwidth for reference QD laser sample with sheet dot density D = 5.9×10^{10} cm^2, thinner active layer (310 nm) sample by using GaP-SC with D = 5.9×10^{10} cm^2, and also thinner active layer sample obtained by LSR employing with slightly higher QD density of D = 6.6×10^{10} cm^2. All samples were grown by MBE and fabricated into standard ridge laser structure with 375 μm × 1.8 μm in size. Rear facet was HR-coated and front facet was as-cleaved.

Fig. 3 shows the small signal responses at 25°C. Record high maximum 3 dB bandwidths max-f_{3dB} of 13.1 GHz as 1.3 μm-range QD lasers was obtained for LSR sample. GaP-SC sample exhibited max-f_{3dB} = 11.0 GHz, which was higher than the reference sample of max. f_{3dB} = 9.5 GHz but lower than LSR sample in spite of same active layer thickness. To clarify the reason, we analyzed the small signal modulation responses including carrier transport limitation [12][13]. As shown in Fig. 4, f_{3dB} for the reference sample was strongly limited by carrier transport limitation $f_{3dB\text{-}trans}$ down to the same level as the relaxation oscillation frequency f_r. On the other hand, GaP-SC sample showed almost the same f_r as reference but f_{3dB} extended due to the extension of the transport limitation. Furthermore, LSR sample showed significant f_r extension which might be due

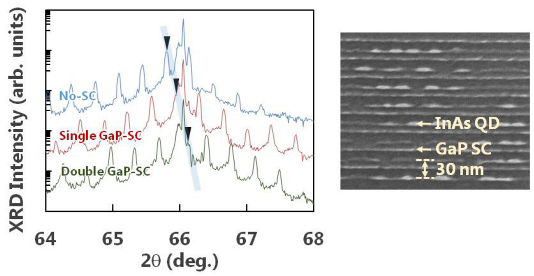

Fig. 1 X-ray diffraction (ω-2θ) spectra of InAs/GaAs 8QD with barrier thickness of 30 nm (left figure) without SC (blue), with single- (red) and double (green) 3ML GaP-SC in between QD layer. Arrows indicate 0th order peak. Right figure shows SEM cross-sectional image of InAs/GaAs 8QD with single GaP-SC.

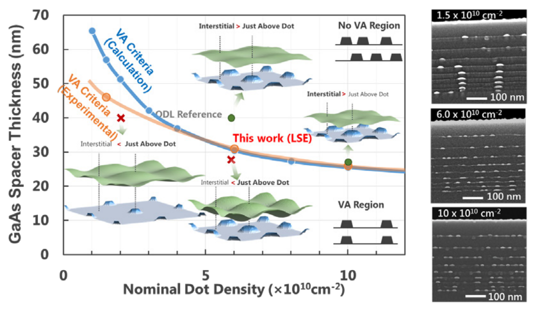

Fig. 2 Growth mode mapping of the QD multilayer obtained by LSR for VA and no-VA modes [9]. Inset 3D-maps show calculated strain of the GaAs surfaces above 3×3 InAs arrays, and their indicated growth modes. Right images show cross-sectional SEM of QDs for three different nominal QD densities with changing barrier thickness.

to the increased QD density, resulting in significant extension of f_{3dB}. These results indicate that not only QD density increase but also the barrier layer reduction is important factor to increase modulation bandwidth. These result indicate that increase in spatial and sheet QD density is the key to boost further the QD laser's performance.

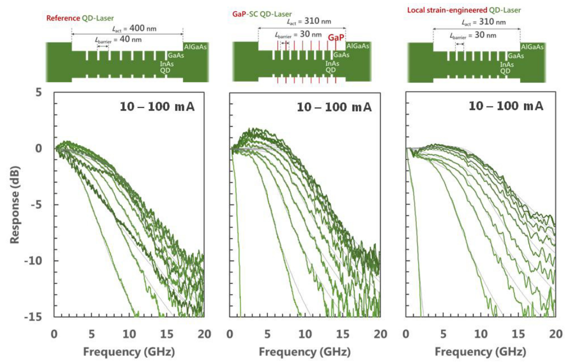

Fig. 3 Small signal modulation responses of conventional QD laser with active layer thickness L_{act} = 400 nm (left), GaP-SC QD laser with L_{act} = 310 nm (middle) and LSR QD laser with L_{act} = 310 nm (right). Fitting curves are overlaid.

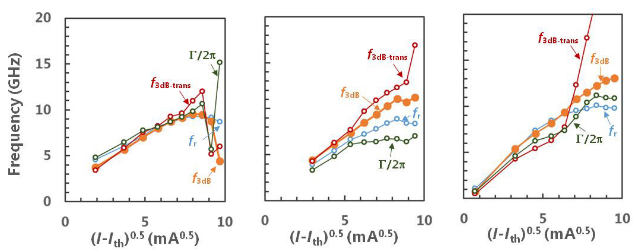

Fig. 4 Bias current dependence on extracted parameters (3dB bandwidth of small signal response f_{3dB}, transport-limited 3dB bandwidth $f_{3dB\text{-}trans}$, relaxation oscillation frequency f_r, and damping factor $\Gamma/2\pi$) derived from the small signal responses of conventional QD laser with active layer thickness L_{act} = 400 nm (left), GaP-SC QD laser with L_{act} = 310 nm (middle) and local strain engineered QD laser with L_{act} = 310 nm (right).

Acknowledgements

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