Single-layer InAs/InP (100) quantum-dots on well laser and mid-infrared emission

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Abstract— **We report a single layer InAs/InP (100) quantum dot (QD) laser operating in continuous wave mode at room temperature on the QD ground state transition grown by metal organic vapor phase epitaxy. The necessary high QD density is achieved by growing the QDs on a thin InAs quantum well (QW). This QDs on QW laser exhibits a high slope efficiency and a lasing wavelength of 1.74 µm. An extremely long-wavelength emission centered at 2.46 µm at 6 K is also observed from such QDs on QW structure.**

Keywords- III-V semiconductors; semiconductor quantum dots; semiconductor lasers; mid-infrared emission

I. Introduction

InAs/InP (100) quantum dot (QD) lasers operating in continuous wave (CW) mode at room temperature (RT) on the QD ground state (GS) transition require multiple stacked QD layers for sufficient gain [1-2]. A single layer InAs QD laser was reported on InP (311)B where the QD density is higher than on InP (100) [3]. Here we report a single layer InAs/InP (100) QD laser operating in CW mode at RT on the QD GS transition and an extremely long-wavelength emission centered at 2.46 µm at 6 K.

II. Device Fabrication

The QD lasers were grown by low-pressure metalorganic vapor-phase epitaxy (MOVPE) on n-type InP (100) substrates using trimethyl-indium (TMI), trimethyl-gallium (TMG), tertiarybutyl-arsine (TBA), and tertiarybutyl-phosphine (TBP) as gas sources. The InAs QDs on QW structures and conventional InAs QDs for reference were placed in the center of a 500 nm thick lattice-matched InGaAsP waveguide core with a RT band gap at λ_Q= 1.25 µm (Q1.25). For the InAs QDs on QW structure, a 1.6 nm-thick InAs QW was formed under metal stable conditions [4]. 1 ML InAs was deposited for QD formation which is already sufficient due to a large amount of surface segregated In on the InAs QW. The conventional InAs QDs (single and multiple stacked layers separated by 40 nm Q1.25) were formed by 3 ML InAs on a 1.5 ML GaAs interlayer. The GaAs interlayer allows the formation of pure InAs QDs on Q layers [5]. The InAs growth rate and growth temperature were 0.70 ML/s and 515 ^{o}C, and the TBA flow rate was 30 sccm which shifts also the lasing wavelength of the conventional QD lasers to around 1.75 µm. Bottom and top claddings of the laser structures were 500 nm n-InP and 1.5 µm p-InP completed by a compositionally graded 75 nm p-InGaAsP contact layer.

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III. Results

A. *Single-layer InAs/InP(100) QD laser*

Fig. 1 (a) and (b) show schematic drawing of the InAs QDs on QW structure and the InAs QDs grown with GaAs interlayer. Fig. 1 (c) and (d) are the atomic force microscopy (AFM) images of the QDs corresponding to the structures in Fig. 1 (a) and (b). The QD density is increased 5 ~ 6 times in the presence of the InAs QW from 6 x 10^9 cm^{-2} for the QDs grown on Q1.25 to 3.4 x 10^{10} cm^{-2}. This increase of the QD density on the InAs QW is attributed to the large amount of strain and surface segregated In [6].

Fig. 2 (a) - (c) show the electroluminescence and lasing spectra of the single layer InAs QDs on QW laser and the five-fold and three-fold stacked InAs QD lasers taken in CW mode at RT. Fig. 2 (d) shows the electroluminescence of the single layer InAs QD laser. QD GS lasing is obtained for the single layer InAs QDs on QW laser with lasing wavelength of 1.74 µm and for the five-fold stacked InAs QD laser. Excited state (ES) lasing of the single layer InAs QDs on QW laser sets in with increasing injection current, confirming GS lasing at

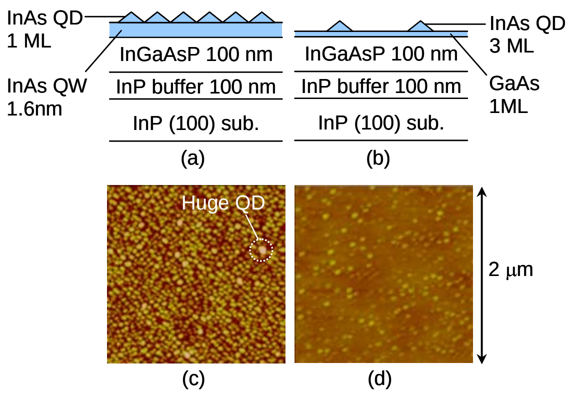

Fig. 1 Sample structure of the InAs QDs grown on (a) InAs QW and (b) GaAs interlayer on Q1.25. [(c) and (d)] AFM images of the corresponding QDs. The height contrast is 40 nm.

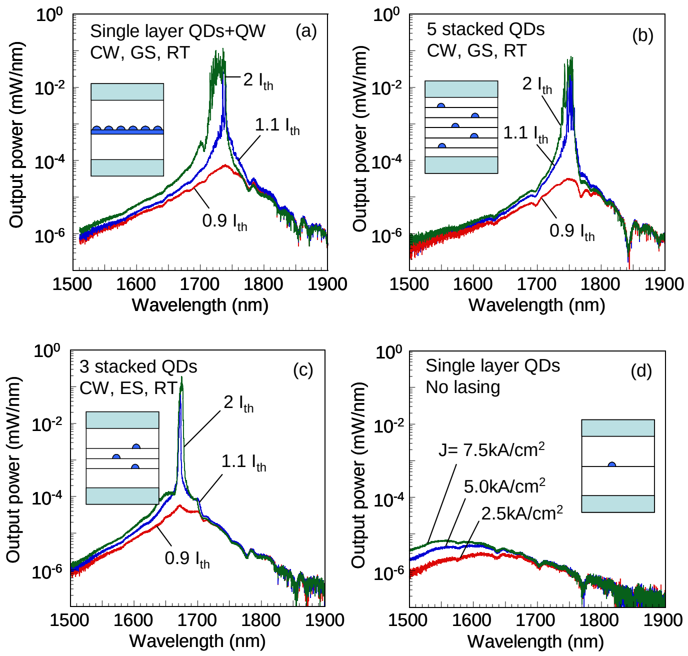

Fig. 2. Electroluminescence and lasing spectra of the four different laser structures. (a) single-layer InAs QDs on QW laser, (b) and (c) five-fold and three-fold stacked InAs QD laser, and (d) single-layer InAs QD laser.

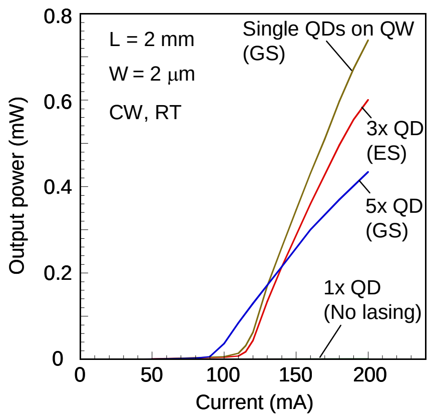

Fig. 3. Light output versus injection current curves of the four InAs QD lasers.

threshold, shown in Fig. 2 (a) at twice the threshold current (I_{th}). For the three-fold stacked InAs QD laser only lasing from ES is observed. For the single layer of InAs QDs lasing is not achieved.

Fig. 3 shows the single facet (as-cleaved) light output versus injection current curves of the four QD lasers. I_{th} of the single layer InAs QDs on QW laser and the five-fold stacked InAs QD laser are comparable. For the three-fold stacked InAs QD laser I_{th} density per QD layer is increased significantly to 0.97 kA/cm^2 from 0.46 kA/cm^2 for the five-fold stacked InAs QD laser due to the three-fold degeneracy of the ES. The slope efficiency of the single layer InAs QDs on QW laser is larger than that of the five-fold stacked InAs QD laser. This is attained by the high density QDs on QW, the related larger confinement factor for the single layer QDs on QW due to their location in the center of the waveguide (see insets in Fig. 2), and a better carrier injection into this single layer.

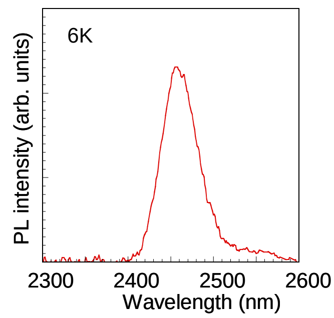

Fig. 4. PL spectrum at 6 K of the InAs QDs on QW structure in the wavelength range of 2.3 – 2.6 μm.

B. Mid-infrared emission from InAs QDs on QW structure

Fig. 4 shows the PL spectrum taken at 6 K in the wavelength range 2.3 – 2.6 μm of the InAs QDs on QW structure, revealing an extremely long-wavelength emission centered at 2.46 μm. This emission is found only for the QDs on QW samples. We believe this emission originates from the huge InAs QDs seen in the AFM image in Fig. 1 (c). They are nearly 20 nm high and over 100 nm wide and only found on the InAs QW, probably triggered by the large amount of surface segregated In after QW growth.

IV. Conclusion

We have successfully achieved lasing in CW mode at RT on the QD GS transition of a single layer InAs QDs on QW structure grown by MOVPE on InP (100) substrates. This is enabled by the 5 ~ 6 times increased QD density on the InAs QW compared to that of conventional QDs. The single layer QDs on QW laser exhibits a higher slope efficiency compared to that of multiple stacked InAs QD lasers. The lasing wavelength is 1.74 μm. Moreover, an extremely long-wavelength PL centered at 2.46 μm is observed at 6 K from the QDs on QW structure.

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