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Gain Measurement of Highly Stacked InGaAs Quantum Dot Laser with Hakki-Paoli Method

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1. Introduction

Quantum dot (QD) laser diode is attractive device to implement superior performance such as low threshold current [1] and higher speed modulation [2] because of three-dimensional carrier confinement.

However, it is difficult to fabricate large stacking of high density QD layers by conventional growth technique owing to the accumulation of strain [3, 4], which limits modal gain of QD laser. Recently the authors adopt ultra-high-rate molecular beam epitaxial (MBE) growth technique which enables higher stacking and thinner spacer thickness [5-7], and demonstrated up to 19 stacked InGaAs QD laser diode with extremely short cavity length of 99-μm [8].

In this work, we study net modal gain of these devices using Hakki-Paoli method [9, 10] and observed high maximum modal gain of 68 cm^{-1}.

2. Experimental

Using ultrahigh-rate MBE technique we fabricated 19 stacked $In_{0.4}Ga_{0.6}As$ QD layer separated 20-nm-thick GaAs spacer layer on GaAs (001) substrate. This active region was sandwiched between the 1500-nm n-type $Al_{0.3}Ga_{0.7}As$ lower-cladding layer and the 1500-nm p-type $Al_{0.3}Ga_{0.7}As$ upper-cladding layer capped with 200 nm GaAs contact layer. After 50-μm-wide electrode was defined by photolithography technique. This wafer was craved into stripe laser device of 150-μm long cavity.

The device was subjected to a 1-μs wide electric current pulse at a duty cycle of 1% at room temperature. The output power characteristic was measured by using an LD tester (Yuasa Electronic AT-143), and emission spectra were recorded by optical spectrum analyzer system (Yokogawa Electric AQ6370) with wavelength resolution of 0.05 nm.

3. Experimental result and discussion

Figure 1 shows the output power characteristic. The threshold current was 111 mA, corresponding to threshold current density of 1.5 kA/cm^2. High threshold current was owing to large mirror loss.

Figure 2 shows amplified spontaneous emission (ASE) spectrum observed at 68.6 mA, and ASE was observed at 1000 nm wavelength band (T-band) [11, 12]. The Fabry-Perot mode spacing ($\delta\lambda$) of 0.87 nm was evaluated, from which effective refractive index (n) of 4 was obtained $\delta\lambda$.

The inset of Figure 3 shows gain spectra calculated by Hakki-Paoli method [9, 10] for two injection currents below threshold. The gain spectra g_{net} are given by

$$g_{net} = \frac{1}{L}\ln\frac{\gamma^{1/2}-1}{\gamma^{1/2}+1} + \frac{1}{L}\ln\frac{1}{R} \qquad (1)$$

where L is cavity length of 150-μm, R is reflection coefficient calculated using the obtained value of n, and γ is the peak-to-valley ratio [10] of the Fabry–Perot oscillations.

Figure 3 plots maximum gain for various injection currents. The maximum modal gain was 68 cm^{-1} at 167.2 mA, which is larger than ~40 cm^{-1}, the maximum gain reported for laser device with 10 stacked InAs QDs separated 35-nm-thick GaAs spacer on GaAs substrate [13]. The surface QD density of our laser and that of ref. 13 was approximately the same value of 5×10^{10} cm^{-2} [6, 13]. These results indicates that highly stacking by using ultrahigh-rate MBE growth technique is more effective in getting large modal gain.

As the injection current increased, the wavelength blueshifts at a constant rate $\Delta\lambda/\Delta I \approx 0.27$ nm/ mA for currents below 100 mA in the range of 1022–1028 nm. The cause of the blueshift can be assumed to be band filling.

4. Conclusions

We measured gain spectra of 19-stacked InGaAs QD on GaAs substrate fabricated by ultrahigh-rate MBE growth technique using Hakki-Paoli method. High maximum modal gain of 68 cm^{-1} was evaluated, and a blueshift of 0.27 nm/ mA for currents below 100 mA was observed, which can be attributed to band filling.

Acknowledgements

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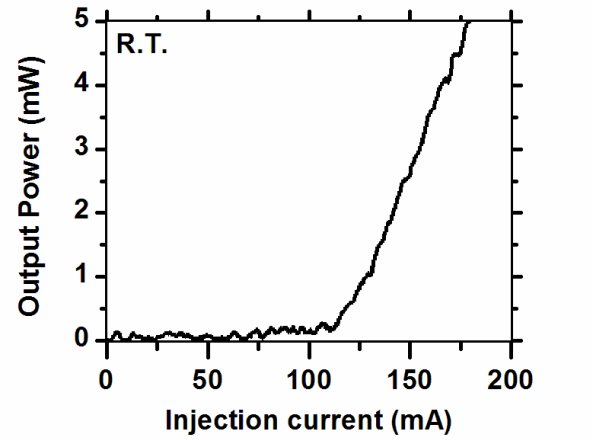

Fig. 1 Output power vs injection current of the device.

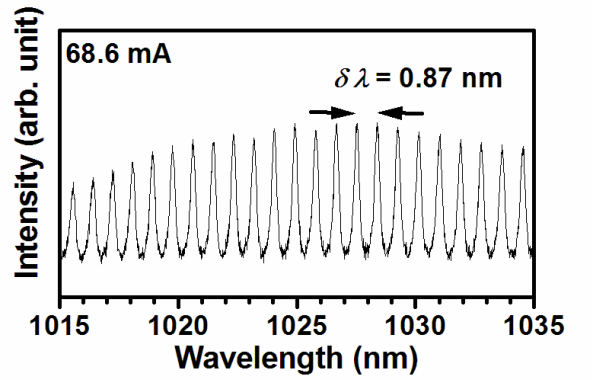

Fig. 2 Amplified spontaneous emission (ASE) spectra obtained at injection current of 68.6mA.

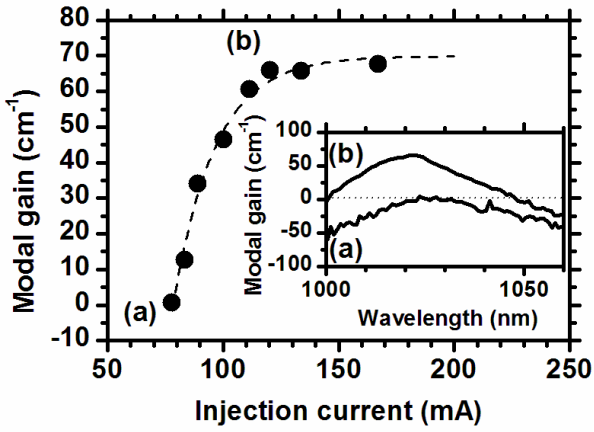

Fig. 3 Maximum modal gain vs injection current. Inset: gain spectra operated at (a) 68.6 mA and (b) 107.2 mA.

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