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Relaxation oscillations and damping factors of 1.3 μm In(Ga)As/GaAs quantum-dot lasers

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Abstract. In(Ga)As/GaAs quantum-dot (QD) lasers with emission wavelength at 1295 nm at room temperature are fabricated. The laser active region contains a threefold stack of QD layers with surface dot density of 4.56×10^{10} cm^{-2}. The laser structure is aluminum-free with InGaP as cladding layers. Threshold current density of a narrow stripe laser of 8 μm wide and 3.5 mm long is 152.5 A/cm^2. The highest relaxation oscillation frequency measured at room temperature is 1.8 GHz, corresponding to a modulation bandwidth of 2.8 GHz due to the small damping factor. From the above measurement, the differential gain and gain compression factor were extracted to be 4.3×10^{-16} cm^2 and 3.4×10^{-17} cm^3, respectively. Using these parameters, the maximum modulation bandwidth $f_{3\,\mathrm{dB\ max}}$ is estimated as 7.9 GHz.

Key words: damping factor, gain compression factor, quantum dot, quantum-dot laser, relaxation oscillation

1. Introduction

Because of the unique electronic structures and δ-function-like discrete density of states, quantum-dot (QD) lasers with zero-dimensional semiconductor structures as active media have attracted much attention due to their superior properties compared with quantum-well lasers (Arakawa and Sakaki 1982; Bimberg *et al.* 1999). QD lasers are expected to have many interesting and useful properties such as very low threshold current density, high differential gain, wide modulation bandwidth, and chirp-free operation under direct current modulation. Recently, there was much research interest in 1.3 μm In (Ga)As/GaAs QD lasers (Huffaker *et al.* 1998; Zhukov *et al.* 1999; Liu *et al.* 1999), because they serve as a GaAs-based candidate for light sources in fiber communication systems. Concerning the dynamic properties of QD lasers, there were several studies in the literature (Kamath *et al.* 1997; Mao *et al.* 1997; Kuntz *et al.* 2002; Pradhan *et al.* 2002; Kim and Harris 2003). Modulation bandwidth up to 22 GHz at room temperature at 1060 nm were reported using tunnel injection of carriers into the dots (Pradhan *et al.* 2002), thus demonstrating the potential of QD lasers for directly modulated 10 Gbit/s communication systems. For 1.3 μm In(Ga)As/GaAs QD lasers, the modulation bandwidth is much more limited to 10 GHz (Kim and Harris 2003). A modulation bandwidth of 2.3 GHz with emission wavelength at 1263 nm was also reported in the literature (Kuntz *et al.* 2002). Although the relaxation oscillation (RO) frequency reaches 1.7 GHz at room temperature, the modulation bandwidth is limited to be 2.3 GHz due to large damping factors.

In this work, In(Ga)As/GaAs QD lasers with emission wavelength at 1295 nm are fabricated and their dynamic properties will be investigated through the measurement of RO. Damping factors and gain compression factor will be also determined and compared with those in the literature.

2. Device fabrication

The sample designed for 1.3 μm QD lasers is grown using gas-source molecular beam epitaxy (GSMBE) on Si-doped n^+ (100) GaAs substrate. In the center of the waveguide, there is a threefold stack of QD layers. For each QD layer, 2.3 monolayer (ML) InAs was firstly deposited and followed by a 9.0 ML $In_{0.33}Ga_{0.67}As$ capping layer. This threefold stack of QD layers is then embedded in a 200-nm-thick waveguide layer with $In_{0.49}Ga_{0.51}P$ serving as upper and lower cladding. A heavily p^+-doped ($1.5 \times 10^{19} cm^{-3}$) 200-nm-thick GaAs layer is grown as contact layer. The QD density of each layer is determined by SEM to be 4.56×10^{10} cm^{-2} (Chang *et al.* 2004). After the epitaxial growth, the wafers were processed into 8-μm-wide ridge waveguide lasers with different cavity lengths by using standard photolithography, wet etching, and metallization techniques.

3. Experiments and discussions

The fabricated lasers were tested under pulsed mode with a pulse width 500 ns, and a repetition rate of 5 kHz for measurement of static properties, such as L–I curve and spectra. In Fig. 1, ground-state lasing at 1295 nm at room temperature with nominal threshold current density of 152.5 A/cm^2 is demonstrated from a laser structure of 3.5 mm long and 8 μm wide. With low threshold current 42.7 mA of this laser, it is possible to carry out the RO measurement.

With decreased cavity length down to 2 mm, the threshold current density is increased to 602.3 A/cm^2. Due to the shorter cavity and therefore larger mirror loss, carriers fill the excited states and the emission wavelength shifts to the excited states around 1207 nm when the modal gain from ground states cannot balance total loss, as shown in Fig. 2.

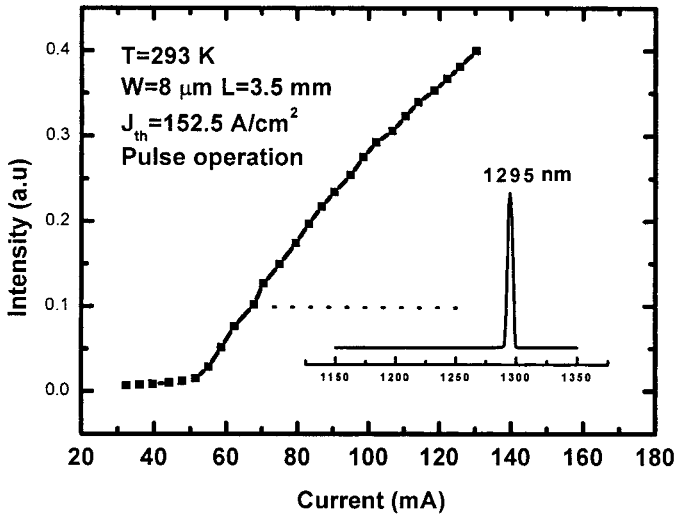

Fig. 1. L–I curve of a QD laser with wavelength at 1295 nm.

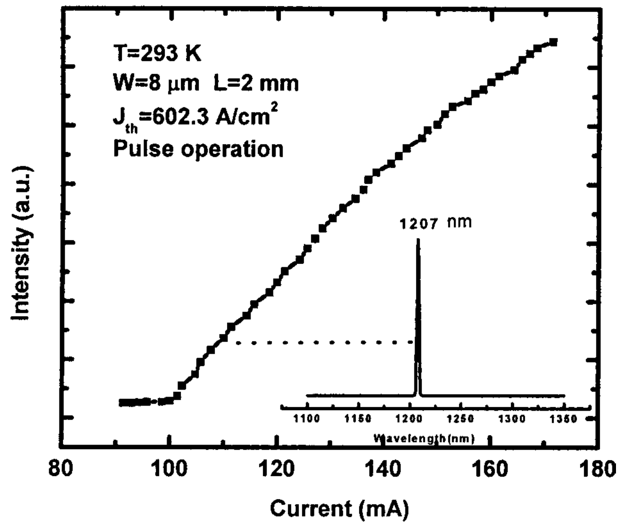

Fig. 2. L–I curve of a QD laser with wavelength at 1207 nm.

For the dynamic measurement, we use an ultra-high speed pulse generator with rise time less than 150 ps and pulse width 10 ns, an InGaAs photodetector with rise time 30 ps, a pre-amplifier, and a 50 GHz oscilloscope to observe the RO. As shown in Fig. 3, when we increase the injection current, the turn-on delay time decreases while RO frequency increases.

Fig. 4 shows a linear dependence of RO frequencies on the square root of normalized current, just as predicted theoretically (Lau and Yariv 1985). From our measurements, the highest RO frequency is 1.8 GHz. From the

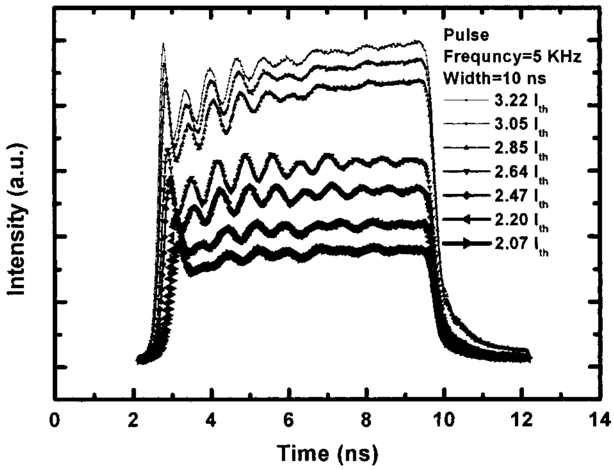

Fig. 3. QD laser dynamics under electrical square pulse excitation. Cavity length is 3.5 mm and the current increase from 2.07 I_{th} to 3.22 I_{th}.

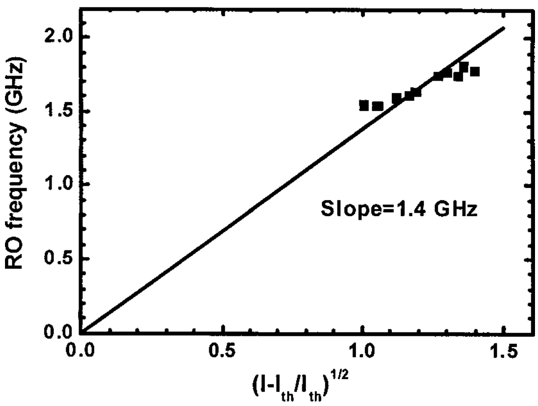

Fig. 4. Relaxation oscillation frequency versus square root of normalized current. The highest RO frequency is about 1.8 GHz.

slope of the linear fitting line, we can use the following equation to extract the differential gain (Coldren and Corzine 1995),

$$f_{\text{R}}^2 = \frac{1}{4\pi^2} \frac{v_{\text{g}} \times a}{q \times V_{\text{p}}} \eta_{\text{i}} (I - I_{\text{th}}), \tag{1}$$

where f_{R}, represents RO frequency; v_{g}, group velocity; a, differential gain; q, electron charge; V_{p}, cavity volume occupied by photons; η_{i}, internal quantum efficiency, respectively.

To extract the differential gain, the internal quantum efficiency η_{i} and internal loss were determined to be 68% and 2.9 cm^{-1} (Chang *et al.* 2004). From the slope in Fig. 4 and Equation (1), we evaluate that the differential gain is 4.3×10^{-16} cm^2 which is 2.5 times lower than that in the literature with differential gain 1×10^{-15} cm^2 for 1263 nm QD laser at 300 K (Kuntz *et al.* 2002). This is probably due to the threefold stack QD active region of our sample in comparison with the sixfold stack sample reported in the literature (Kuntz *et al.* 2002). However, compared with QD lasers with emission wavelength around 1 μm with high differential gain such as 8.8×10^{-14} cm^2 (Pradhan *et al.* 2002), long-wavelength 1.3 μm QD lasers show more than one order of magnitude smaller differential gain. This feature needs be improved in order to increase their modulation bandwidth.

Among high-speed properties of QD lasers, K factor and damping factor γ are two of the most important parameters. We can describe the damping properties under high-speed current modulation by the following equations (Coldren and Corzine 1995):

$$\frac{S(f)}{I(f)} \propto \frac{1}{4\pi^2 f_R^2 - 4\pi^2 f^2 + j2\pi f\gamma}, \tag{2}$$

$$\gamma = K f_R^2 + \gamma_0, \tag{3}$$

$$K = 4\pi^2 \left[\tau_p + \frac{\varepsilon}{v_g \cdot a} \right]. \tag{4}$$

$S(f), I(f), \tau_p$, ε, and a represent small signal photon density, modulation current, photon lifetime, gain compression factor, and differential gain, respectively. K factor and damping factor γ determine the system damping properties. The modulation bandwidth is defined as the frequency when the ratio of small signal photon density S to modulation I falls to −3 dB of its DC value. When the damping is small ($\gamma/2\pi f \ll 1$), the modulation bandwidth is equal to $1.55 f_R$ (Bowers *et al.* 1986). From the RO frequency 1.8 GHz measured above, we obtain a modulation bandwidth of 2.8 GHz since the damping is small, as shown in Fig. 5. However, the highest RO frequency 1.8 GHz is limited by the maximum current provided by the pulse generator, not by the QD laser itself. Therefore, we expect a modulation bandwidth higher than 2.8 GHz if the excitation current can be further increased.

K factor determines the damping of the modulation response with increasing RO frequency. It is an important parameter in high-speed characteristics of lasers. The damping factor offset γ_0 is only important in low laser power when the relaxation resonance frequency is small. From the Equations (2)–(4) above, it is clear that not only the differential gain but also gain compression influences the high-speed behavior of the laser.

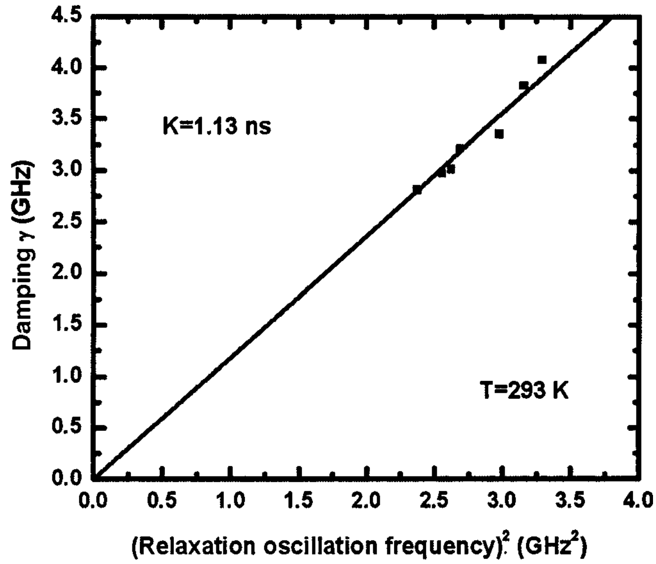

Fig. 5. QD laser damping factor versus (RO frequency)^2.

The damping factor γ can be obtained by fitting the laser transient behavior. Plotting γ versus f_R^2 diagram in Fig. 5, we can determine the value of K factor to be 1.13 ns from Equation (3), as shown in Fig. 5. In comparison with the K factor 4 ns in the literature (Kuntz *et al.* 2002), our results show a very small damping for 1.3 μm QD lasers.

From Equation (4), we can also determine the gain compression factor to be 3.4×10^{-17} cm^3. Compared with those reported in the literature (Kamath *et al.* 1997; Kuntz *et al.* 2002), such as 7.2×10^{-16} and 1×10^{-15} cm^3, our value is very small, but similar to the value 4.5×10^{-17} cm^3 for QD lasers with tunneling injection structures for suppression of carrier re-emission (Bhattacharya and Ghosh 2002). However, the emission wavelength of the tunneling injection QD lasers is around 1 μm. Therefore, a small gain compression factor 3.4×10^{-17} cm^3 of 1.3 μm QD lasers is demonstrated for the first time in this study.

The extraction of K factor also provides an estimation of maximum modulation bandwidth. The equation below relates the maximum modulation bandwidth $f_{3\ \mathrm{dB\ max}}$ with K factor (Coldren and Corzine 1995),

$$f_{3\,\mathrm{dB,max}} = \sqrt{2}\frac{2\pi}{K}. \quad (5)$$

In our case with K factor of 1.13 ns, the maximum modulation bandwidth $f_{3\ \mathrm{dB\ max}}$ is estimated to be 7.9 GHz. This demonstrates the potential of high-speed operation of QD lasers for fiber communication.

4. Conclusion

We have successfully fabricated long-wavelength In(Ga)As/GaAs QD lasers with emission wavelength at 1295 nm at room temperature. The highest RO frequency measured at room temperature is 1.8 GHz, corresponding to a modulation bandwidth of 2.8 GHz due to the small damping factor. However, the highest RO frequency 1.8 GHz is limited by the maximum current provided by the pulse generator, not by the QD laser itself. From the above measurement, the differential gain and gain compression factor were extracted to be 4.3×10^{-16} cm^2 and 3.4×10^{-17} cm^3, respectively, which is a small gain compression factor demonstrated for 1.3 μm QD lasers for the first time. Using these parameters, the maximum modulation bandwidth $f_{3\ \mathrm{dB\ max}}$ is estimated as 7.9 GHz that shows the potential of high-speed operation of QD lasers for fiber communication.

Acknowledgments

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