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Lasing Characteristics and Carrier Dynamics of 1.3- μm InGaAs/GaAs Quantum Dot LasersYuji Nakagawa¹, Mitsuru Sugawara^{1,2}, Kohki Mukai², Yoshiaki Nakata² and Hiroshi Ishikawa^{1,2}¹Tokyo Institute of Technology

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1. Introduction

Lasing characteristics of self-assembled quantum-dot lasers are closely related to the carrier dynamics and the inhomogeneous broadening of the optical gain due to the size distribution of dots. Though many works have been done to study the carrier dynamics including capture, relaxation and recombination processes of various quantum-dot structures both experimentally and theoretically¹⁻⁶, their effects on lasing characteristics has not yet been well understood. In this paper, we measured current-output power and the electroluminescence of our 1.3- μm quantum-dot laser and found the change of lasing levels depending on temperature and injection currents. We made a model on carrier dynamics in the laser active region to simulate lasing characteristics, and could completely reproduce the experimental results. We found that carrier relaxation time is about 0.7-1.5ps, and that there is a temperature dependence in carrier reexcitation rate.

2. Experiments on lasing characteristics

We used the quantum dot laser which shows the 1.3- μm room-temperature continuous-wave lasing at room temperature. The active region has four dot layers. The cavity is 300- μm long, and has a high-reflectivity coating (95%) on both facets. Fig. 1 shows the current-output power properties observed between 15 to 45 $^{\circ}\text{C}$. Note that the slope efficiency started to increase at 14 mA at 15 $^{\circ}\text{C}$ and at 17 mA at 25 $^{\circ}\text{C}$, and that lasing occurred with a higher slope efficiency at 35 and 45 $^{\circ}\text{C}$ than at 25 $^{\circ}\text{C}$. The electroluminescence at 25 $^{\circ}\text{C}$ shows that lasing started from the ground state at the threshold current, and that the additional lasing from the second state started with the increase of injection currents. At 35 $^{\circ}\text{C}$, lasing started from both the ground and the second state simultaneously. At 45 $^{\circ}\text{C}$, lasing started from the second state, and then the ground-state lasing occurred. We see that the change in the slope efficiency depending on currents and temperature is caused by the change in the lasing

level. These experimental findings look quite unique to quantum-dot lasers.

3. Carrier dynamics model and theoretical calculations

To explain this change in lasing levels, we introduce a carrier dynamics model taking into account carrier reexcitation between sublevels and direct carrier relaxation into sublevels from the wetting layer as shown in Fig. 2. Note that the direct carrier relaxation to the ground state is indispensable in explaining the results at 45 $^{\circ}\text{C}$. In this model, τ_{d1} is the carrier relaxation time, τ_{e1} is the carrier reexcitation time from ground to second state, τ_{e2} is the carrier reexcitation time from second state to wetting layer, τ_p is the photon lifetime, τ_r and τ_{nr} is the radiative and nonradiative recombination lifetime at sublevels respectively, τ_{qr} is the recombination lifetime at wetting layer, a is efficiency of current injection into wetting layer, N_q , N_1 , and N_2 is the carrier number in the wetting layer, the ground state, and the second state respectively, and S_1 and S_2 is the photon number of the ground and the second state respectively. Here, we assumed the

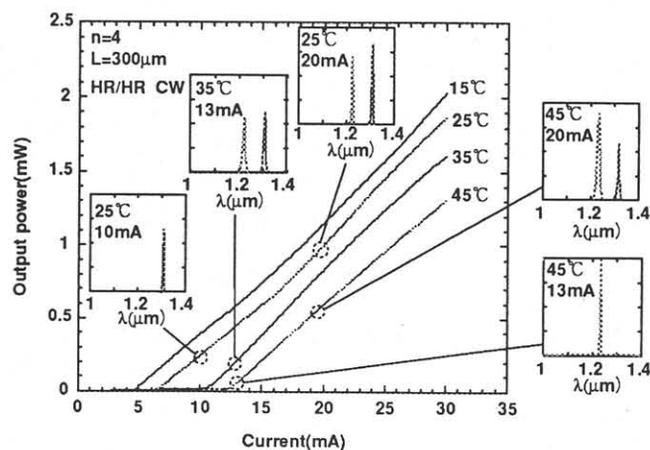


Fig. 1 Lasing characteristics of current-output power and electroluminescence between 15 to 45 $^{\circ}\text{C}$. Lasing level change occurs due to the increase of temperature and injection current.

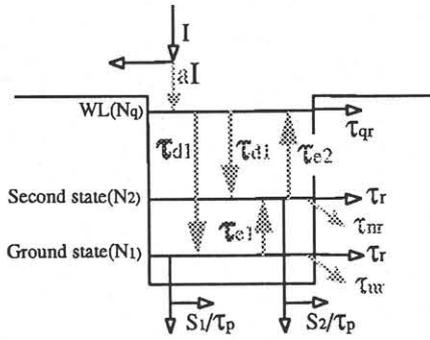


Fig.2 Carrier dynamics model of self-assembled QD. Direct carrier relaxation from wetting layer to sublevels and reexcitation to the upper energy state are introduced in this model.

same carrier relaxation time to the ground state and to the second state. We solved carrier - photon rate equations based on the model of Fig.2 by 4th-order Runge-Kutta method, and obtained the calculated lasing characteristics in Fig. 3. We could completely reproduce the change of lasing levels due to the increase of temperature and injection currents.

Through the simulation, we found the carrier relaxation time by the following procedure. The carrier relaxation time under lasing is given as

$$\frac{\Delta N_q}{\tau_{d1}} \equiv \frac{\Delta S}{\tau_p} \quad (1)$$

where ΔS is the increase in the photon number, and ΔN_q is the increase in the wetting layer carrier number. Here, we get the number of carriers in the wetting layer and its increase by comparing the measured spontaneous emission intensity between the wetting layer and the quantum-dot ground state. We get the photon number and its increase from the experimental output power. The inset of Fig.4 shows the injection current dependence of spontaneous emission intensity of the wetting layer at 25°C. We calculated the carrier number in the wetting layer

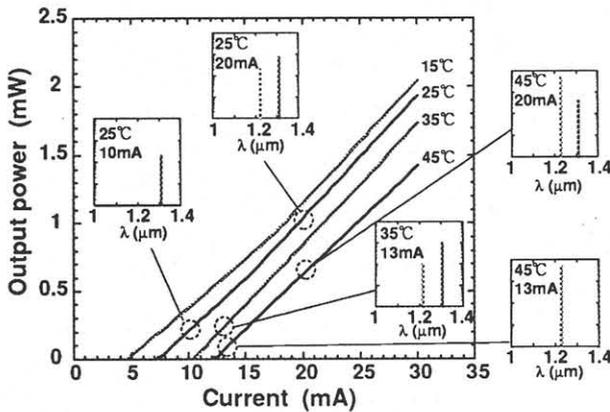


Fig.3 Calculated result of current-output power characteristics and lasing spectra. The change of slope efficiency at 15 and 25°C due to the increase of injection current and that of lasing levels due to the increase of temperature is completely reproduced.

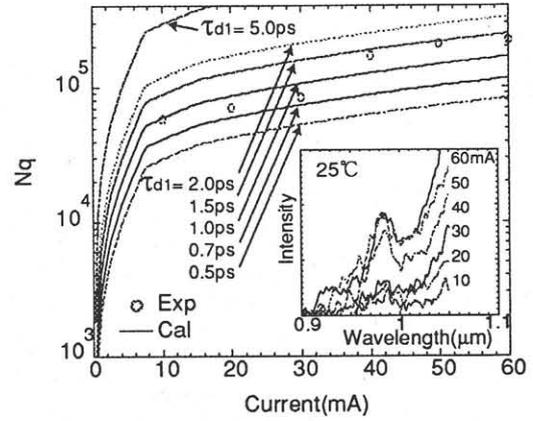


Fig.4 Carrier number in wetting layer. Open circles represent those from the experimental results and solid lines represent the calculations at different carrier relaxation time. Inset shows the injection current dependence of spontaneous emission intensity of the wetting layer at 25°C.

from this result. Detail of calculation procedure will be discussed in the talk. Fig.4 shows the carrier number in the wetting layer, where open circles represent those from the experimental results and solid lines represent the calculations at different carrier relaxation time. The results tell us that the carrier relaxation time is about 0.7-1.5ps.

4. Conclusions

We found the change of lasing levels of self-assembled quantum-dot lasers due to the increase of temperature and injection current. We considered a carrier dynamics model, which include reexcitation between sublevels and direct relaxation from wetting layer to sublevels, and could completely reproduce the change of lasing levels by the theoretical calculation. We found that the carrier relaxation time is about 0.7-1.5ps, which represents that 1.3μm quantum-dot lasers have potential for high-speed direct modulation.

Reference

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