行政院國家科學委員會專題研究計畫成果報告

三五族半導體量子點之成長與元件應用

Growth of III-V Semiconductor Quantum Dots and Device Application

計畫編號：NSC 90－2215－E－002－038－
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計畫參與人員：蔡俊儀、謝文瀚、吳戴仰、林士凱

中文摘要

本計畫的研究目標在於：In(Ga)As/GaAs 量子點的成長、其發光特性的分析、及其發光元件的研究。

InGaAs/GaAs 量子點結構，突破了在 GaAs 基板上成長 InGaAs/GaAs 量子井的限制，將發光波長延伸至 1.3 μm，因此可望在光纖通訊上有重要應用。我們將用 MBE 成長 InAs/GaAs 量子點，繼而延伸至發光波長在 1.3 μm 的 InGaAs/GaAs 系統。此外，也將製作 Fabry-Perot 量子點雷射二極體，並探討其高速調制應用方面的潛力。

關鍵詞：半導體量子點、半導體雷射、變率方程式

Abstract

The research topics of this project are: growth of In(Ga)As/GaAs quantum dots, analysis of their optical properties, and application as light-emitting devices.

InGaAs/GaAs quantum-dot structures have extended the emission wavelength to 1.3 μm, breaking the limit of InGaAs/GaAs quantum wells on the GaAs substrate. Therefore, they will find important applications in fiber communication. We use MBE to growth InAs/GaAs quantum dots, and extend to the InGaAs/GaAs system with emission wavelength at 1.3 μm. Furthermore, Fabry-Perot QD laser diodes are fabricated, and their potentials in high-speed modulation are investigated.

Keywords: Semiconductor quantum dots, Semiconductor lasers, Rate equations

Motivation and Goals

Semiconductor quantum dots have attracted much attention recently. Semiconductor lasers with quantum dots as active medium not only have been predicted theoretically, but also have been confirmed experimentally to have many outstanding properties, such as, ultra-low threshold current density (26 A/cm^2 [1]), ultra-high temperature stability (T_0=385K [2]), very small chirp (0.007 Å/mA [3]), and large modulation bandwidth (8.2GHz [4]). These properties are very important for the light sources used in optical communication systems. Therefore, quantum-dot lasers have large potentials for application in such systems. 1.3 μm is the wavelength with very low dispersion in optical fibers. Traditionally, InGaAsP/InP is the material for semiconductor lasers operating at this wavelength. InGaAs/GaAs quantum-dot structures have extended the emission wavelength to 1.3 μm, breaking the limit of InGaAs/GaAs quantum wells on the GaAs substrate. Therefore, they will find important applications in fiber communication.

We use MBE to grow InGaAs/GaAs quantum dots with emission wavelength at 1.3 μm. Furthermore, Fabry-Perot quantum-dot laser diodes are fabricated and their dynamic properties under high-speed modulation will be investigated. Simulation based on a rate-equation model will demonstrate the influences of material properties, such as homogeneous broadening, inhomogeneous broadening, and carrier capture time, on the dynamic properties of quantum-dot lasers. The research results will give guidelines for optimization of quantum-dot lasers and provide suitable models for their dynamic behaviors.

Results and Discussion

(1) Long-wavelength quantum-dot lasers

We have fabricated quantum-dot lasers with threshold current density 478A/cm^2 at room temperature. However, the emission wavelength is from excited states at 1189nm (Fig. 1). The quantum dot surface density is about 2.3*10^{10} cm^{-2}.

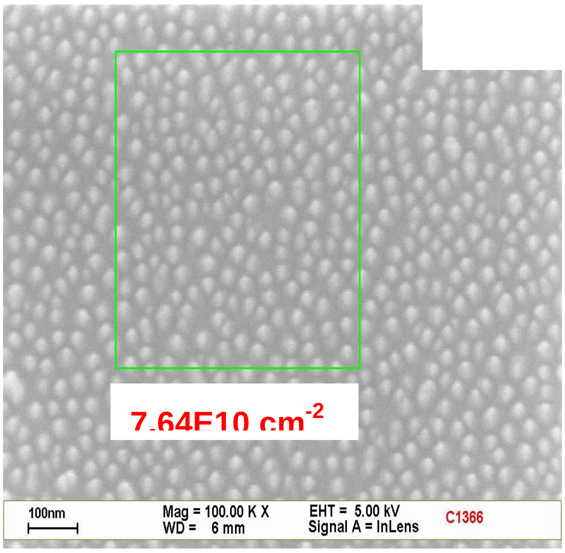


Fig. 2 SEM picture of quantum dots with surface density 7.64*10^{10} cm^{-2}.

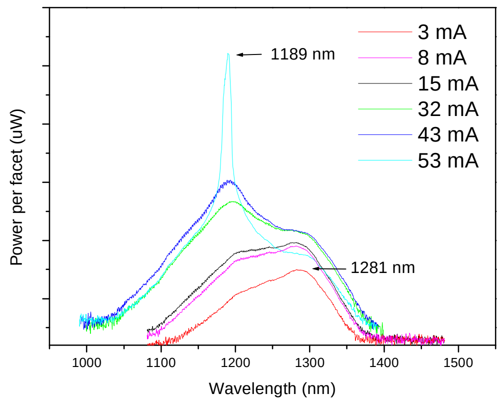


Fig. 1 A quantum-dot laser with emission wavelength at 1189 nm at room temperature.

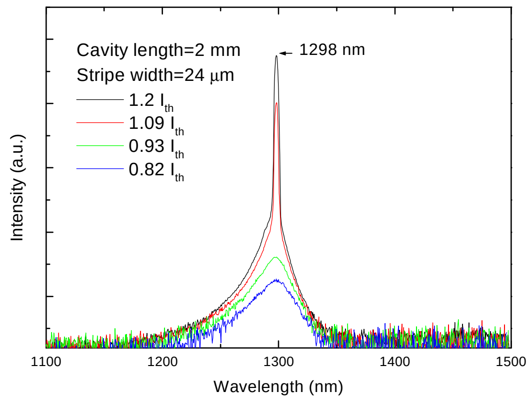


Fig. 3 A quantum-dot laser with emission wavelength at 1298 nm at room temperature.

The quantum dot surface density is then increased to 7.64*10^{10} cm^{-2} (Fig. 2). Laser diodes with such high quantum-dot density show ground-state lasing with emission wavelength at 1298 nm (Fig. 3) and threshold current density 1433A/cm^2 at room temperature. Therefore, the target wavelength 1.3 μm has been achieved.

(2) Modulation bandwidth

We have measured the relaxation oscillation frequencies of quantum-dot lasers in order to determine their modulation bandwidth. The highest we measured is about 5.1 GHz (Fig. 4), corresponding to a modulation bandwidth 8 GHz that is similar to the best value with the same device structure [4]. After optimization of quantum-dot lasers, we believe this bandwidth can be further increased.

bandwidth.

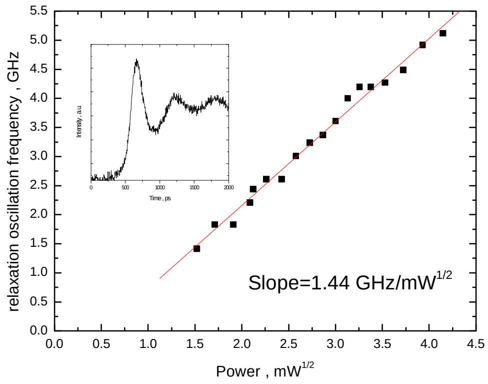


Fig. 4 Relaxation oscillation frequencies of a quantum-dot laser

(3) Rate-equation modeling

We use a rate equation model proposed in [5,6] to simulate the static and dynamic characteristics of quantum-dot lasers. The influences of the material and structural parameters, such as homogeneous and inhomogeneous broadening, and various time constants, on the static and dynamic characteristics of quantum-dot lasers are analyzed.

The rate equations proposed in [5] are re-written below with some modifications to include the gain compression factor £. V_A is the active region volume.

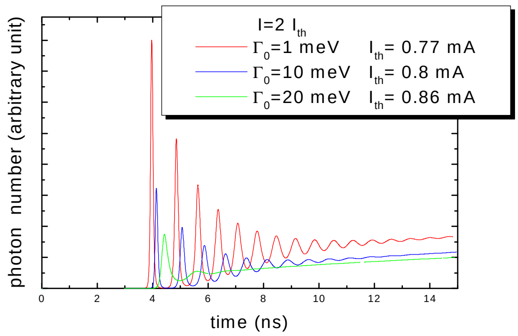
$$\frac{dN_s}{dt} = \frac{I}{q} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_{sr}} + \frac{N_q}{\tau_{qe}}$$

$$\frac{dN_q}{dt} = \frac{N_s}{\tau_s} + \sum_n \frac{N_n}{\tau_e} - \frac{N_q}{\tau_{qr}} - \frac{N_q}{\tau_{qe}} - \frac{N_q}{\tau_d}$$

$$\frac{dN_n}{dt} = \frac{N_q G_n}{\tau_{dn}} - \frac{N_n}{\tau_m} - \frac{N_n}{\tau_e} - \frac{c\Gamma}{n_r}\frac{\sum_m g_{mn} S_m}{1+\frac{\varepsilon\Gamma}{V_A}\sum_m S_m}$$

$$\frac{dS_m}{dt} = BN_m^2 + \frac{c\Gamma}{n_r}\frac{\sum_n g_{mn} S_m}{1+\frac{\varepsilon\Gamma}{V_A}\sum_m S_m} - \frac{S_m}{\tau_p}$$

In Fig. 5, the relaxation oscillation frequency of quantum-dot lasers decreases with increasing Γ_0. Therefore, the inhomogeneous broadening due to the size fluctuation of quantum dots needs to be reduced in order to have faster relaxation oscillations and therefore higher modulation bandwidth.



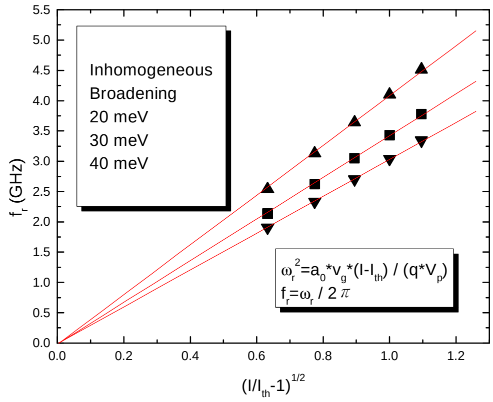


Fig. 5 Relaxation oscillation frequencies with increasing inhomogeneous broadening [7].

Conclusions

In this project, we have fabricated long-wavelength quantum-dot lasers with emission wavelength at 1298 nm successfully. Dynamic properties of quantum-dot lasers are measured. Modulation bandwidth of 8 GHz is experimentally demonstrated. Therefore, quantum-dot lasers have shown important applications in high-speed opto-electronic systems. Using a rate-equation model, we simulate the dynamic behavior of quantum-dot lasers. The influence of inhomogeneous broadening on modulation bandwidth is investigated. In order to achieve higher modulation speed, the size uniformity of quantum dots needs to be further improved.

We would like to thank F.-Y. Chang, Prof. H.-H. Lin, Dr. F. Heinrichsdorff, and Prof. D. Bimberg for providing samples.

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共同主持人：
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