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Effect of Cavity-Layer Thicknesses on Two-Color Lasing in a Coupled Multilayer Cavity with InAs Quantum Dots

Chiho Harayama[1], Sho Katoh[1], Yoshinori Nakagawa[1,2], Lu Xiangmeng[1], Naoto Kumagai[1], Takahiro Kitada[1] and Toshiro Isu[1]

[1] Center for Frontier Research of Engineering, Institute of Technology and Science, Univ. of Tokushima
2-1, Minami-Josanjima-Cho, Tokushima 770-8506, Japan
Phone: +81-88-656-7671 E-mail: harayama@frc.tokushima-u.ac.jp
[2] NICHIA Corp.
Anan, Tokushima 774-8601, Japan

Abstract

Two-color lasing in a GaAs/AlAs coupled multilayer cavity has been studied for novel type of terahertz emitting devices. In the structure, two cavity layers based on GaAs were connected by the intermediate GaAs/AlAs distributed Bragg reflector multilayer. Self-assembled InAs quantum dots were inserted only in the top side cavity layer as optical gain materials. The bottom side cavity layer was grown with lateral thickness variation in a wafer to investigate the effects of cavity-layer thickness on two mode emissions. Equivalent emission intensities of the two mode emissions at an optical frequency difference of 2.1 THz were realized when the optical thickness of two cavity layers were same as each other.

1. Introduction

Terahertz light sources based on semiconductor materials have been investigated because of the wide range of possible applications such as wireless communications, spectroscopy, and imaging. We have proposed novel terahertz (THz) emission devices based on a GaAs/AslAs coupled multilayer cavity structure in which two cavity layers are coupled by an intermediate distributed Bragg reflector (DBR) multilayer [1]. In the proposed device, optical gain materials in one of the cavity layers cause light emission of two cavity modes with an optical frequency difference in the THz region and then THz-waves are emitted by the difference frequency generation (DFG) through the second-order nonlinear process in the other side cavity. In our recent study, two-color lasing has been successfully demonstrated by optical pumping of the GaAs/AlAs coupled multilayer cavity structure which has self-assembled InAs quantum dots (QDs) only in the top side cavity [2]. However, emission properties were not desirable for the optical frequency difference. While the larger value of 3.2 THz was observed in the measured emission spectrum, the optical frequency difference of the designed structure is 2.3 THz. Moreover, emission intensity of long wavelength mode was more than one order of magnitude larger than that of short wavelength mode. It might result from a slight thickness difference between two cavity layers.

In this work, the effects of thickness difference between two cavity layers have been quantitatively investigated by introducing lateral thickness variation in one of the cavity layers grown on a 2-inch (001) undoped GaAs substrate. We found that equivalent emission intensities of two-color lasing were realized when the optical thickness of two cavity layers were exactly the same as each other.

2. MBE Growth

The coupled cavity structure shown in Fig. 1 was grown on an un-(001) GaAs substrate by solid-source MBE. Two double-wavelength-thick (2λ) cavities were coupled by an 11.5-period GaAs/AlAs (93 nm/110 nm) DBR multilayer. The top side 2λ cavity consists of three layers of InAs QDs. Each QD layer was placed in the position where the maximum light electric field is realized for both cavity modes. On the other hand, the bottom side 2λ cavity has a lateral thickness variation. The 24- and 28-period GaAs/AlAs DBR multilayers were formed at the top and bottom sides of the coupled structure, respectively. The top side cavity including QDs was grown at a substrate temperature (Ts) of 550 °C, while the bottom side cavity and DBR multilayers were grown at Ts = 630 °C under an As_4 pressure of 1×10^{-5} Torr. Growth rates of GaAs, AlAs, and InAs were 1.04, 1.04, and 0.176 μm/h, respectively. The substrate was rotated at 30 rpm during MBE except for the growth of GaAs layer composing the bottom side 2λ cavity.

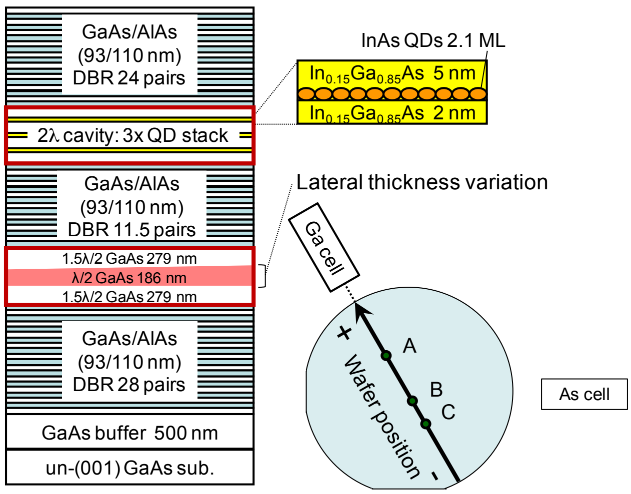

Fig. 1 Structure of the coupled cavity.

2. Optical Properties

Two-color lasing in the coupled cavity was examined by optical pumping at room temperature. The excitation source was a multimode semiconductor laser with a nominal wavelength of 920 nm at an excitation power of ~640 mW, which was operated in a cw mode. The laser beam was focused on the sample surface with a diameter of 250 μm and the emitting light from the sample surface was detected. In order to investigate the effects of thickness difference between two cavity layers, emission spectra were measured at several different positions in a wafer. Figure 2 shows the emission spectra at three different points. The emission spectrum was strongly dependent on the measurement position because the lateral thickness variation was introduced in the bottom side cavity. The measured frequency difference of two modes varied each measurement position. The minimum value of 2.1 THz was obtained at the position B where optical thicknesses of two cavity layers were exactly the same as each other. The minimum value was almost the same as the designed value of 2.3 THz. The emission intensities of the two modes were the same as each other at position B. The peak intensity ratio I_{Long} / I_{Short} was also strongly dependent on the measurement position. I_{Long} / I_{Short} is smaller or larger than unity when the bottom side cavity is thicker or thinner than the top side cavity, respectively. Figure 3 shows peak intensity ratio of the experimental two mode emissions versus the optical frequency difference. We simulated electric field intensities of the cavity modes for various cavity thicknesses. Ratio of the electric field intensity at the QD layer versus the optical frequency difference is also shown in the figure. The denominators of the ratios of the experiment and simulation are those of short wavelength modes. Relation between peak intensity ratio of the two mode emissions and the optical frequency difference was corresponded to that between simulated electric field intensity ratio and the optical frequency difference. The emission intensity ratio is well explained by the electric fields at the top side cavity region containing QDs. This means that the emission intensity ratio was dominantly determined by the thicknesses of the both cavity layers.

3. Conclusions

We fabricated a GaAs/AlAs coupled multilayer cavity with self-assembled InAs QDs grown by MBE. Top side cavity layer included three InAs QD layers as optical gain materials. Lateral thickness variation in a wafer was introduced in the bottom cavity layer. We investigated the effects of thickness difference between two cavity layers quantitatively. Equivalent emission intensities of two peaks with frequency difference of 2.1 THz were obtained from cavities of the same thickness. Non-equivalent emission intensities of two peaks were obtained from different thickness cavities. Ratio of the two peak intensities is well explained by the ratio of the electric fields at the top cavity region containing QDs. The frequency difference and the ratio of intensities of two peaks were dominantly determined by the thicknesses of the two cavity layers.

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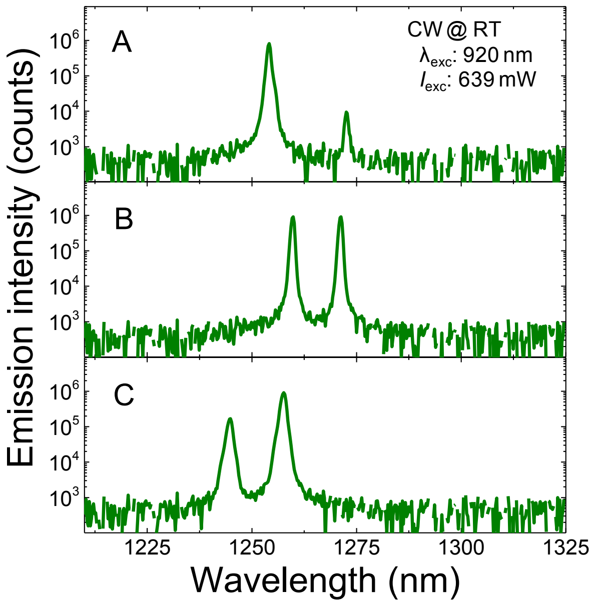

Fig. 2 Surface emission spectra at different positions.

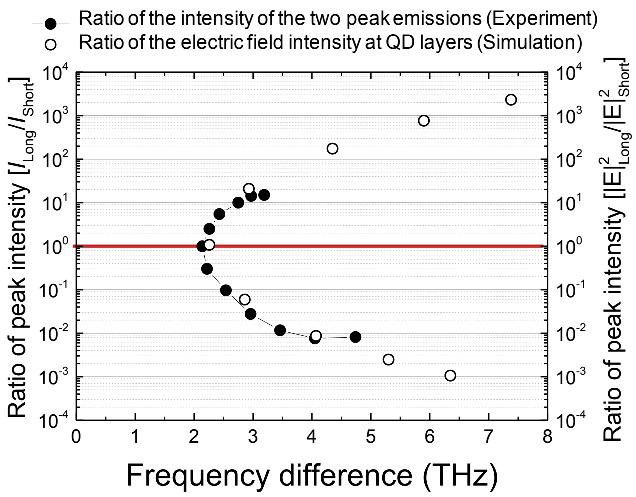

Fig. 3 Relation between peak intensity ratio of the two mode emissions (Experiment) and ratio of the electric field intensity at QD layer (Simulation).