Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp634-635

Fabrication of Two-Color Surface Emitting Device of a Coupled Cavity Structure with InAs QDs Formed by Wafer-Bonding

Hiroto Ota, Chiho Harayama, Tomohisa Maekawa, Xiangmeng Lu, Naoto Kumagai, Takahiro Kitada and Toshiro Isu

* Center for Frontier of Engineering, Institute of Technology and Science, Tokushima Univ.
2-1, Minami-Josanjima-Cho, Tokushima 770-8506, Japan
Phone: +81-88-656-7671 E-mail: c501538015@tokushima-u.ac.jp

Abstract

Two-color lasing in a GaAs/AlGaAs coupled multilayer cavity has been studied for a novel type of terahertz emitting devices. In the structure, two cavity layers based on GaAs were connected by the intermediate GaAs/AlGaAs distributed Bragg reflector multilayer. InAs quantum dots (QDs) were inserted only in the topside cavity layer as optical gain materials. Two epitaxial wafers with different substrate orientation were bonded in order to control the second order nonlinear optical responses. In this study, the bonding position was optimized for equivalent two-color emission by current injection. We succeeded in two-color emitting with nearly equivalent intensities by current injection at room temperature.

1. Introduction

Terahertz light sources based on semiconductor materials have been investigated because of the wide range of possible applications such as imaging, spectroscopy, and wireless communications. We have proposed a novel terahertz (THz) emission device based on a GaAs/AlAs 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 topside cavity [2]. An epitaxial wafer was grown on a high index wafer to emit THz-waves from two-color lasing. We have bonded the two epitaxial wafers in order to control the second order nonlinear optical responses in the coupled cavity structure.

In this work, we fabricated a two-color emitting device formed by wafer-bonding. We investigated interface position dependence of the coupled cavity structure on the position of wafer-bonding. We fabricated the GaAs/AlGaAs coupled multilayer cavity structure for two-color emission by current injection.

2. Fabrication Processes

Figure 1 shows a structure of two-color surface emitting device. Top side cavity structure and bottom side one were separately grown by molecular beam epitaxy (MBE) on a (001) GaAs wafer and (113)B GaAs wafer, respectively. The 2 λ cavity includes InAs QDs on the (001) GaAs wafer. These two epitaxial wafer were bonded at middle n-type DBR. Figure 3 shows the outline of fabrication processes and schematic structures. Two epitaxial wafers were bonded by the surface activated bonding method at room temperature. The (001) GaAs substrate was removed by polishing and chemical etching. Metal (Ti/Au) electrode was deposited on the surface of the p-type DBR. Chemical wet etching formed mesa shape on the substrate and stopped to etch at the first GaAs layer of the middle DBR layer. A current confinement AlAs layer just on the topside cavity layer was oxidized from the sidewall of the mesa structure by water vapor. An n-type metal (AuGe/Ni/Au) electrode was formed on the surface of the n-type DBR and a passivation layer was coated.

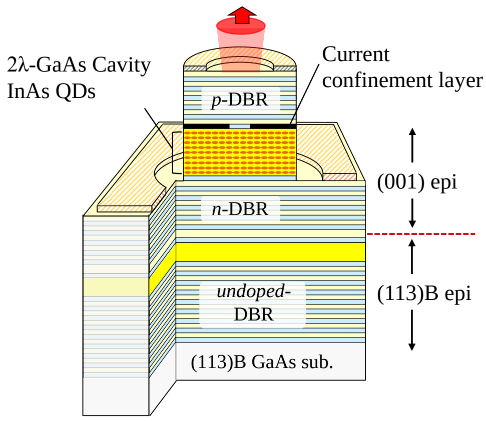

Figure 1. Structure of the two-color surface emitting device.

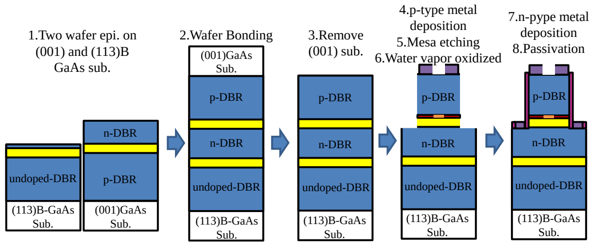

Figure 2. Outline of fabrication processes and schematic structures.

3. Coupled Cavity Structure Formed by Wafer-Bonding

We have shown equivalent two-color emission intensities when the optical thicknesses of two cavity layers were exactly same as each other for the coupled cavity structure grown on a 2-inch (001) undoped GaAs substrate [3]. A current injection device was fabricated on the similar structure that two epitaxial wafers were bonded at the center of middle DBR (Prototype wafer-bonding). Two-color emission was observed by current injection. However, the two-color emission intensities were not equivalent in the structure formed by wafer-bonding, although the thicknesses of two cavity layers were exactly same.

Figure 3 shows distribution of the optical intensity for two colors and refractive indices of wafer-bonding area. Figure 3 (a) shows the case when two epitaxial wafers were bonded at center of middle DBR (Prototype). A short wavelength's electric field had maximum at bonding interface, while a long wavelength's electric field had almost minimum at the bonding interface. Assuming optical loss at the bonding interface, the short mode may have loss. Figure 3 (b) shows the case when Two epitaxial wafers were bonded at near the 2λ cavity on (113)B substrate (New design). Both electric fields had minimums at bonding interface. In this condition, the optical loss is considered almost zero. Therefore, we bonded two epitaxial wafers at the position of Figure 3 (b) and fabricate the current injection devices.

4. Optical Properties

Figure 4 (a) shows the emission spectrum by current injection at 1 mA. The emission wavelengths were $\lambda_1 = 1274.3$ nm and $\lambda_2 = 1289.3$ nm, and the frequency difference was $\Delta\nu = 2.7$ THz. Figure 4 (b) shows the emission spectra by optical pumping. The solid line shows the emission spectrum at the same position as the current injection device. The emission wavelengths and the frequency difference were nearly same as those by current injection. The dashed line shows the emission spectrum at the position of equivalent cavity thickness where frequency difference was minimum value, $\Delta\nu = 2.1$ THz, and intensities of the two mode were equivalent. This means that both mode have no optical loss at the bonding interface. The inequivalent intensities of two modes for current injection were considered to be thickness difference between two cavity layers. Therefore, equivalent two-color emission by current injection will be realized by optimization of the device where two cavity layer thicknesses exactly are equalized.

5. Conclusion

We fabricated a GaAs/AlGaAs coupled multilayer cavity with InAs QDs formed by wafer-bonding. Topside cavity layer included nine InAs QDs layers as optical gain materials. We bonded two epitaxial wafers and fabricated a two-color emitting device. We investigated interface position dependence of the coupled cavity structure formed by wafer-bonding. We observed the two-color emission by current injection and obtained nearly equivalent intensities.

Acknowledgement

This work was partly supported by SCOPE (Strategic Information and Communications R&D Promotion Programme) from the Ministry of Internal Affairs and Communications, Japan.

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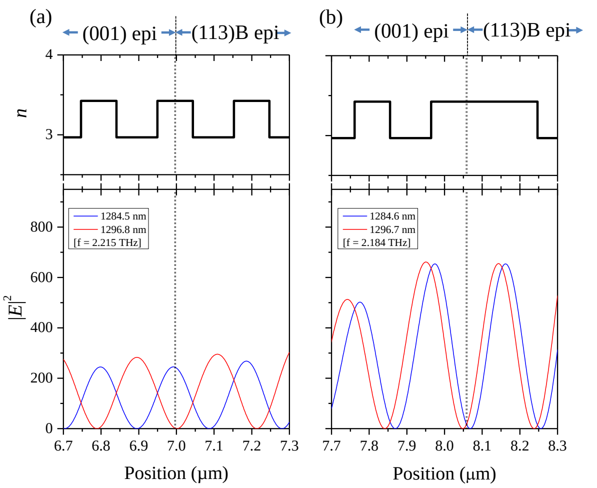

Figure 3. Distribution of the optical intensities for two colors and refractive indices at (a) the center of middle DBR and (b) the position near the 2λ cavity on (113)B substrate.

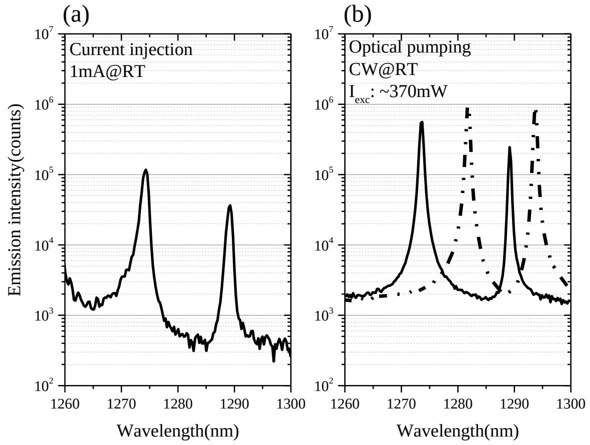

Figure 4. Surface emission spectrum by (a) current injection and (b) optical pumping.