3-5 Research on Sb-based Quantum Dot Laser

AKAHANE Kouichi, YAMAMOTO Naokatsu, and OHTANI Naoki

We have developed Sb-based quantum dot lasers operating at 1.3 μm fabricated on GaAs substrates. We introduce here two different methods; one is to use GaAsSb layers for reducing the stress effect on InAs quantum dots, the other is to make InGaSb quantum dots in the laser's active region. The fabricated laser diodes are successfully operating for a wavelength of 1.3 μm at room temperature.

Keywords
Quantum dot, Semiconductor laser, Antimony

1 Introduction

It is anticipated that the semiconductor quantum dot laser will replace conventional quantum well lasers, due to its low threshold current and superior temperature dependency. This new laser is also expected to play an important role as a key device in communications networks in the coming era of the ubiquitous society[1]. The semiconductor quantum dot laser features the lowest threshold current density of any laser developed to date. However, problems remain in the techniques of quantum dot fabrication, limiting the performance of this laser below the theoretically predicted values; as a result, quantum well lasers continue to dominate the commercial market. Typical problems include a lack of uniformity in quantum dot size and very low quantum dot densities insufficient to provide significant operational benefits. Further, although a laser operating in the optical communications waveband (1.3 to 1.55 μm) can now be fabricated on an InP substrate, less expensive substrates such as GaAs or Si will be required if the quantum dot laser is to see wide application in the ubiquitous networks of the near future.

Given these circumstances, our Optoelectronics Group has been studying the quantum dot laser[2][3] with the intention of fabricating a laser on a GaAs substrate for use in the optical communications waveband. In particular, we have applied the novel approach of using Sb in quantum dot growth. Our two main goals in the overall endeavor were (1) to use GaAsSb layers to reduce the strain on the InAs quantum dots, and (2) to fabricate quantum dots with InGaSb. We have recently accomplished both of these goals in our development of lasers capable of operating at approximately 1.3 μm at room temperature. Here we will report on the details of these experiments.

2 InAs quantum dot long-wavelength laser using GaAsSb strain-reducing layer[2]

InAs is often used to form quantum dots, and it is not difficult to form 1.5-μm InAs quantum dots on an InP substrate. However, on a GaAs substrate, the InAs quantum dot lattice is subject to compressive strain, which modifies the InAs band structure. Thus, the use of GaAs in the cap layer blueshifts the emission wavelength to 1 μm. A number of attempts have been made to use nitride materials such as GaNAs to reduce the InAs quantum dot lattice strain and to redshift the operating wavelength[4][5]. However, these attempts have not yet resulted in successful laser oscillation. In this study, we used GaAsSb for the cap layer in an attempt to reduce this lattice strain.

2.1 Structure of the device

Molecular beam epitaxy (MBE) equipment was used for crystal growth. After thermal cleaning of the GaAs(001) substrate at 610°C, the 300 nm GaAs buffer layer was deposited at 580°C at a growth rate of 1 ML/s. (1 ML corresponds to the thickness of 1 molecular layer.) A 1.7-ML InAs layer was then deposited at 500°C to construct the InAs quantum dots (growth rate of 0.1 ML/s). Here, the quantum dots are self-organized, as crystal growth tends to propagate in such a manner as to reduce the energy contributing to growth (including the strain energy attributable to the difference in the crystal lattices). As this method allows for the fabrication of structures in a vacuum chamber, it is possible to form high-quality quantum dots with little contamination.

Next, a GaAsSb layer was deposited on the quantum dots, which was in turn covered with a GaAs cap layer. The quantum dots were observed using an atomic force microscope (AFM), with growth halted prior to the embedding of the dots. Figure 1 shows the AFM image of the quantum dots. In this sample, quantum dots were formed with an average diameter of 36 nm, an average height of 4 nm, and a density of 3.5×10^{10}/cm^2.

We first examined the effect of the amount of Sb in the GaAsSb strain-reducing layer on the emission wavelength. Photoluminescence (PL) was measured for three samples with different values for the Sb ratio (y) in the GaAs$_{1-y}$Sb$_y$ strain-reducing layer: 0.140, 0.433, and 0.601. Here, the thickness of the strain-reducing layer was 8 nm and the thickness of the GaAs cap layer was 12 nm. The InAs quantum dot growth conditions were the same for the three samples. Each sample was cooled to 12 K for measurement; Fig.2 shows the results. The figure clearly shows that the emission wavelength shifted to the long-wavelength region with an increase in the Sb ratio (y). When GaAsSb is used in place of GaAs to embed the quantum dots, the lattice constant of GaAsSb approaches the value for the InAs quantum dots as the Sb ratio increased, reducing the compressive strain on the quantum dots. This releases the InAs quantum dots from the influence of compressive strain, and the emission wavelength shifts to the long-

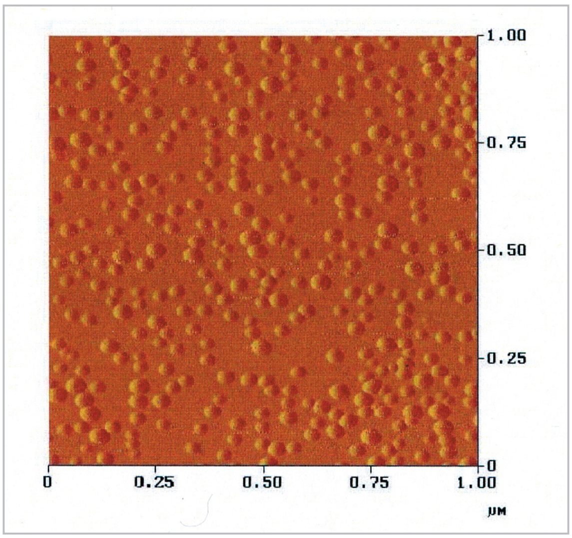

Fig.1 InAs quantum dots observed with the AFM

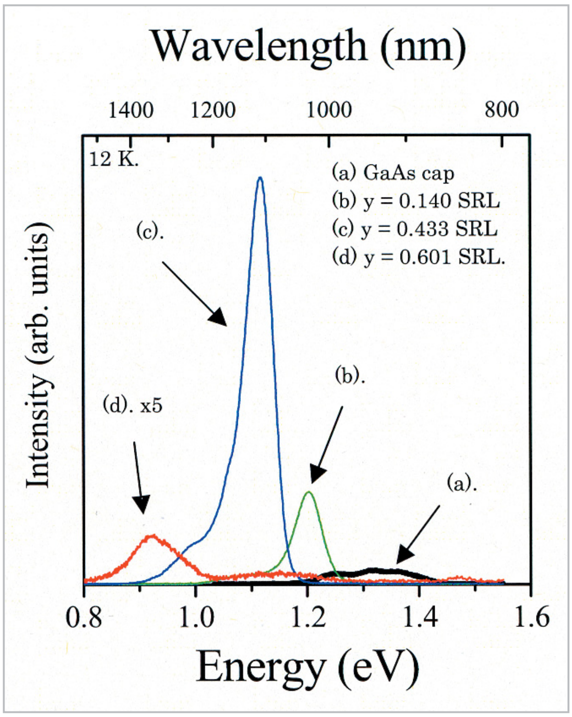

Fig.2 Photoluminescence results

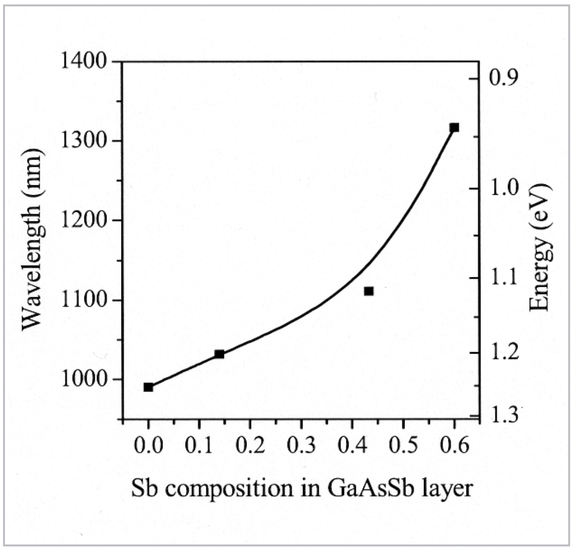

Fig.3 Relationship between the PL peak wavelength shift and the Sb ratio

wavelength region. Figure 3 shows the relationship between the PL peak wavelength shift and the Sb ratio.

2.2 Fabrication and evaluation of the laser diode

Next, a laser diode with simple stripe electrodes was fabricated and tested in operation. The device consisted of 3 layers of 2-ML InAs quantum dots with GaAs$_{0.567}$Sb$_{0.433}$ in the strain-reducing layer. The p-type and n-type Al$_{0.5}$Ga$_{0.5}$As-cladding layers were placed above and below the three-layer structure to confine light within the structure. After crystal growth, the sample was sent through a plasma CVD process for SiO$_2$ formation, etching, and photolithography to shape the electrode lines. The 5-μm wide electrodes were formed by vacuum evaporation of a metal. The 800 μm cavity was formed by cleaving. Figure 4 shows a schematic diagram of the laser structure.

Figure 5 shows the emission spectra obtained when a pulse voltage was applied to the laser diode. The temperature of the device was 15°C. When the input current reached 480 mA, a sharp peak was observed, confirming laser oscillation. The threshold current density was approximately 11.3 kA/cm^2.

When the GaAsSb strain-reducing layer was used, the PL emission efficiency was significantly larger than when the InGaAs layer was used. It had been reported that the confinement efficiency of thermally excited carriers is significantly elevated in the heterojunction of InAs and GaAsSb[6]; we concluded that this phenomenon led to the room-temperature laser oscillation observed in this study.

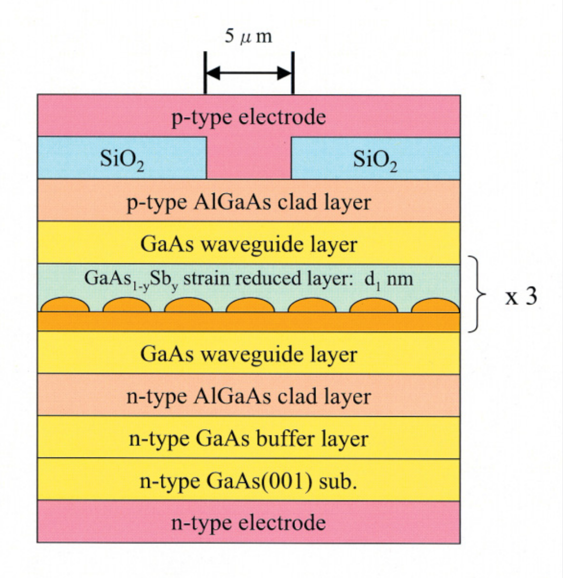

Fig.4 Schematic diagram of the laser structure

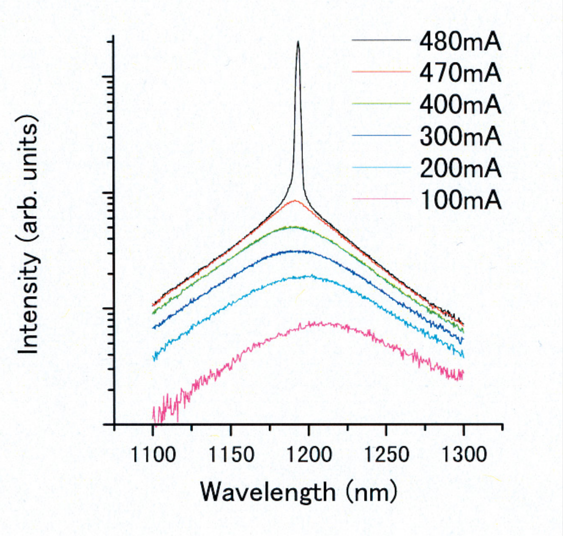

Fig.5 Emission spectrum on application of pulse voltage

3 Long-wavelength laser using InGaSb quantum dots[3]

In addition to the InAs quantum dot laser with a GaAsSb strain-reducing layer, we conducted research on the fabrication of InGaSb quantum dots and the application of this laser process to crystal growth in Sb compound semiconductors.

3.1 Densification of InGaSb quantum dots with the anti-surfactant effect

To apply quantum dot technology to lasers and optical amplifiers, it is first necessary to increase the operational volume of the device, which in this case corresponds to the density of quantum dots. Sb-based quantum dots are known to have low density and have been viewed as difficult to use in device applications. However, we have discovered that the irradiation of Si atoms can induce an anti-surfactant effect, leading to significantly increased density of InGaSb quantum dots[7].

Figure 6 shows the AFM images of the InGaSb quantum dots grown on the GaAs substrate. 2 ML of the InGaSb quantum dots were deposited at a growth rate of 0.1 ML/s in both of the examples shown in the figure, although the substrate in Fig. 6 (b) was irradiated with Si atoms before quantum dot growth. The density of the irradiated Si atoms was approximately 10^{11} /cm^2, which is an extremely low value. The difference in quantum dot density between the cases with and without Si-atom irradiation is obvious. The InGaSb quantum dot density with Si atom irradiation, as shown in Fig. 6 (b), was approximately 100 times greater than the density without irradiation, as seen in Fig. 6 (a). The surface density of quantum dots with Si atom irradiation was approximately 4.4×10^9 /cm^2. It was thus confirmed that the anti-surfactant effect of Si-atom irradiation is effective in increasing the density of InGaSb quantum dots.

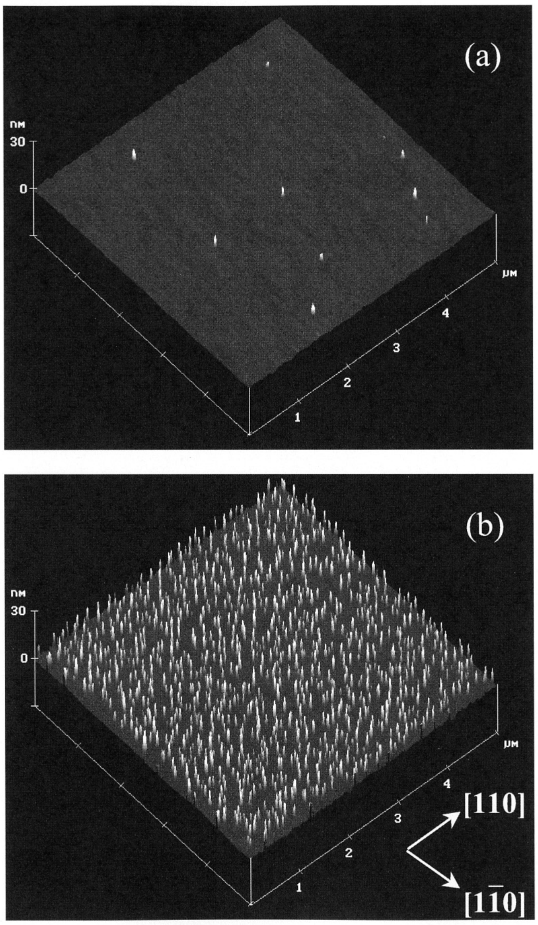

Fig.6 AFM images of the InGaSb quantum dots: (a) without Si atom irradiation and (b) with Si atom irradiation

3.2 Fabrication and evaluation of the laser diode

Figure 7 shows a cross-sectional diagram of the fabricated laser diode. An n-type Si-doped GaAs buffer layer and an n-type AlGaAs-cladding layer were deposited at 540°C on a thermally cleaned n-type GaAs (001) substrate. To grow the quantum dot layer, the temperature of the substrate was lowered to 400°C. The GaAs surface was irradiated with Si atoms with an Sb flux; 2 ML of $In_{0.5}Ga_{0.5}Sb$ quantum dots were then deposited, and the quantum dots were covered with a 20-nm GaAs layer (growth rate of 0.43 ML/s). To form the active region of the quantum dot laser, 8 quantum dot layers were stacked with an InGaSb quantum dot structure embedded in GaAs. GaAs-guiding layers were added above and below the quantum dot multi-layers. After the active region was grown, the temperature of the substrate was raised back to 540°C for deposition of the p-type Be-doped AlGaAs-cladding layer and the GaAs cap layer. An Si-dioxide layer was then deposited, with the plasma CVD serving as the insulation layer. Part of the Si-dioxide layer was etched to form a AuZn electrode 5 μm wide, with a cavity length of 900 μm. Figure 8 shows a scanning electron microscope(SEM) image of the fabricated laser diode electrode. The figure shows that a striped electrode structure is formed, and that a slab waveguide structure is formed in the substrate with AlGaAs as the cladding layer.

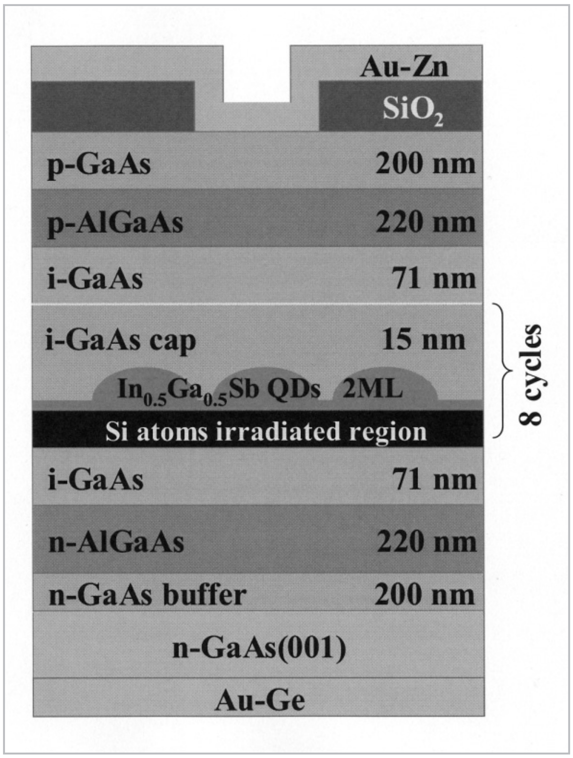

Fig.7 *Cross-sectional diagram of the laser structure*

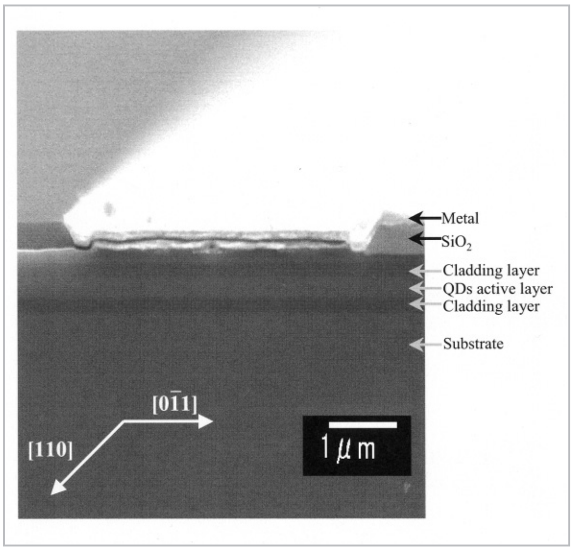

Fig.8 *SEM image of the laser diode*

Figure 9 shows the emission spectrum obtained when a current was introduced. The temperature of the device was 10°C with the application of a DC voltage. In the figure, a sharp peak may be observed with a current of 970 mA, indicating laser oscillation. The oscillation wavelength was 1.37 μm—extremely long for a quantum dot laser. These results show that high-density InGaSb quantum dots created by the anti-surfactant effect may be used effectively in laser applications.

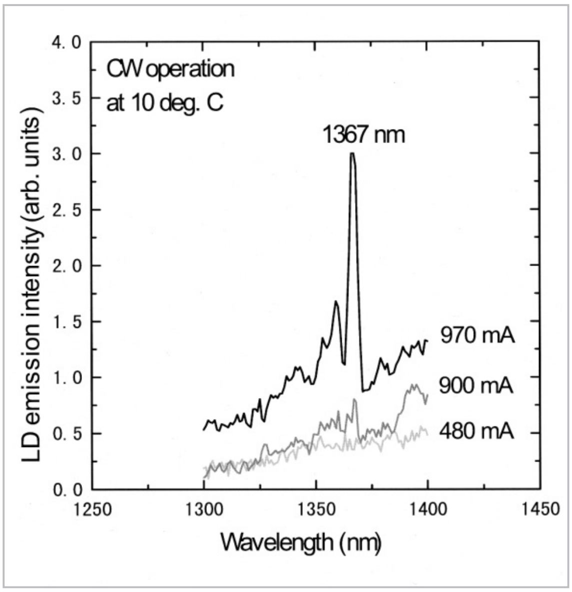

Fig.9 *Oscillation spectrum of the InGaSb quantum dot laser*

4 Summary

To develop a quantum dot laser on a GaAs substrate operating in the optical communications wavelengths, we proposed two types of laser structures involving the novel use of Sb. One structure involves the use of the Sb compound GaAsSb in the InAs quantum dot strain-reducing layer, while the other structure involves the use of the Sb compound InGaSb for the quantum dots. Both structures produced successful laser oscillation near the wavelength of 1.3 μm at room temperature. As the laser diodes fabricated in this study feature simple striped electrode structures, we conclude that the room temperature oscillation reflects the high quality of the crystal structure and high efficiency in emission. We would like now to focus on optimizing laser structures—that of waveguide lasers, for example—in order to improve the oscillation characteristics of the 1.3-μm band laser. Our next goal is the improvement of quantum dots to enable the realization of a 1.55-μm band laser on a GaAs substrate. A recent report has suggested that quantum dots may be suitable for semiconductor optical amplifiers[8]; we would also like to investigate this new application.

Other research topics of our Optoelectronics Group include studies to improve the density of quantum dots. We have successfully deposited more than 100 layers of InAs quantum dots on an InP substrate[9], with an emission wavelength of approximately 1.5 μm. We intend to demonstrate the superiority of super high-density quantum dots in terms of gain and emission efficiency in laser and optical-amplifier applications.

In terms of industrial applications, given that this new use of Sb materials promises production of better lasers, III-V compound semiconductors are now more commercially attractive than ever. Many problems remain regarding the growth of nanostructures and in the process technology involved, but we believe that the research results presented above point to the imminent emergence of new fields of application in these areas.

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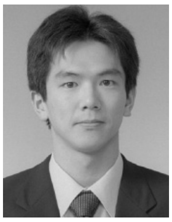

AKAHANE Kouichi, *Ph. D.*

Researcher, Optoelectronics Group, Basic and Advanced Research Department

Semiconductor Photonic Device, Crystal Growth of Semiconductor

YAMAMOTO Naokatsu, *Dr. Eng.*

Expert Researcher, Optoelectronics Group, Basic and Advanced Research Department

Semiconductor Photonic Device, Optoelectronics Materials

OHTANI Naoki, *Ph. D.*

Leader, Optoelectronics Group, Basic and Advanced Research Department

Semiconductor Photonic Device, Condensed Matter Photophysics