Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.94-95

E-1-2

1.55-µm-waveband lasing operation of Sb-based quantum-dot vertical-cavity surface-emitting lasers (Sb-based QD-VCSELs) fabricated on GaAs substrate

Naokatsu Yamamoto[1], Kouichi Akahane[1], Shin-ichirou Gozu[1], Akio Ueta[1] and Naoki Ohtani[2]

[1]National Institute of Information and Communications Technology, Basic and Advanced Research Department
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
Phone: +81-42-327-7453, e-mail: naokatsu@nict.go.jp
[2]Doshisha University
1-3, Tatara-Miyakodani, Kyotanabe-shi, Kyoto 610-0321, Japan

1. Introduction

QD-laser devices operating at long wavelengths around the 1.3- and 1.55-µm wavebands have excellent potentials for the development of novel optical communications network systems [1]. If long-wavelength QD lasers will be fabricated on GaAs substrates, low-cost, low-consumption, and high performance semiconductor lasers can be produced for the optical communications networks. However, it is difficult to achieve long-wavelength emissions by InAs QDs embedded in a GaAs matrix. Therefore, we attempted to develop InGaSb QDs as an Sb-based QD material, which has capable of achieving high-intensity, long-wavelength emissions on the GaAs substrate [2].

In this letter, we propose a silicon-atom irradiation technique to create high-density Sb-based QDs on GaAs substrates, and discuss the optical-communication wavelengths emissions around 1.3- and 1.55-µm from these InGaSb QDs embedded in GaAs [3]. We also discuss our successful demonstration of a long-wavelength laser emission at 1.55-µm from an InGaSb QD-VCSEL on a GaAs substrate under optically pumping.

2. Experiments and Results

The Sb-based QDs were grown on (001)-oriented n-GaAs substrates through solid-source molecular beam epitaxy (MBE). First, a GaAs buffer layer was grown to form an atomically-flat surface; then, the substrate temperature was decreased to 400ºC to grow the InGaSb

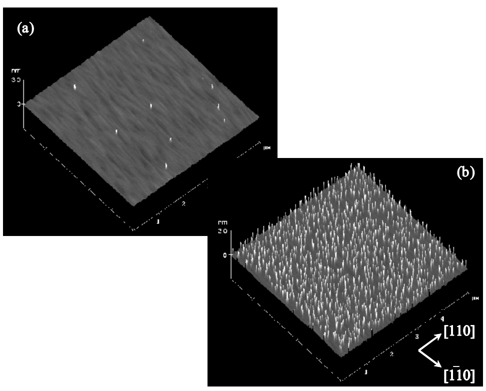

Fig. 1 AFM images of Sb-based QDs grown on GaAs surface (a) without and (b) with Si atom irradiation technique.

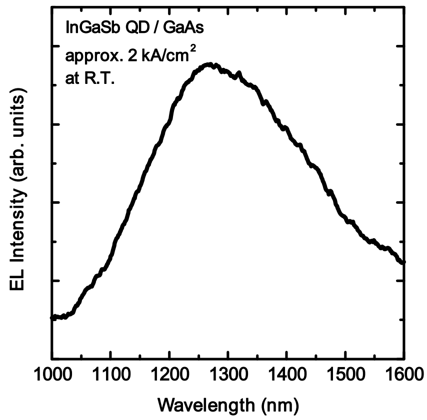

Fig. 2 Electroluminescence spectrum of InGaSb QD light emitting diode at room temperature.

QDs. After that, an Sb-flux (3.8×10^{-7} Torr) was irradiated onto the substrate surface with irradiating Si atoms as the anti-surfactant. The deposition ratio of Si atoms was fixed to 1.4×10^{10} /cm^2/s. The Si atom density on the substrate surface was controlled by changing the irradiation time. Finally, 2 MLs of $In_{0.5}Ga_{0.5}Sb$ QDs (growth rate: 0.1 ML/s) were grown on the GaAs surface irradiated by Si atoms. Figure 1 shows atomic force microscopy (AFM) images of the InGaSb QDs structures formed with and without the Si atom irradiation. We can observe a small number of InGaSb QDs in Fig. 1(a) without Si atom irradiation. When the Si atom irradiation time is 30 sec., high-density can be achieved in InGaSb QDs at around 4.4 x 10^9 /cm^2. This density corresponds to a density about 100 times more than that formed without Si atom irradiation. It is clear that the density of the InGaSb QDs is considerably enhanced by using the Si atom irradiation technique. From the AFM image in Fig. 1(b), the average height of InGaSb QDs is 6.6 nm, and the size in the [110] and [1-10] directions are respectively estimated as 32.2 and 47.5 nm.

A light emitting diode (LED) structure containing the high-density InGaSb QDs was fabricated on the (001)-oriented GaAs substrate. Figure 2 shows the electroluminescence (EL) spectrum from the InGaSb QD-LED at room temperature. We also observed a photoluminescence (PL) spectrum from the InGaSb QD embedded in a GaAs matrix using SHG:YAG laser (532

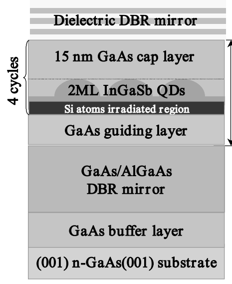

Fig. 3 Schematic structure of Sb-QD VCSEL

nm) excitation and a PbS photo detector. The EL spectrum was found to be similar to the PL spectrum. A peak of emission was observed in the 1.3-μm wavelength, and the EL spectrum had a wide wavelength over the 1.3- and 1.55-μm optical communication wavebands. Therefore, we found that the InGaSb QDs were useful materials for achieving novel optical communications devices on the GaAs substrate.

Very recently, optically pumped VCSELs have been expected to attain all-optical signal processing [4] and semiconductor optical amplifications (SOAs). We have been studied a long-wavelength VCSEL for optical communications by using the Sb-based QDs. We previously demonstrated over 1.3-μm lasing operation with an Sb-based QD-VCSEL fabricated on the GaAs substrate [5]. Here, we propose an optically pumped 1.55-μm Sb-based QD VCSEL fabricated on the GaAs substrate. Figure 3 outlines the structure of the Sb-based QD-VCSEL. In the optically-pumped VCSEL, the 35-pairs GaAs/AlAs distributed Bragg reflector (DBR) mirrors were grown on the (001)-oriented GaAs substrate. In the active region, the four stacked InGaSb QDs embedded in a GaAs matrix were also formed on the DBR. Naturally, Si atom irradiation (4 x $10^{11}/cm^2$) was applied to form the high density InGaSb QDs structure. A top dielectric DBR mirror composed of SiO_2 and Ta_2O_5 multi-stacked structure was deposited on the sample surface. Reflections of the top and bottom DBRs were respectively 99.90% and 99.97% at around 1.55 μm. The cavity-length was fixed to λ/2.

Emissions from the Sb-based QD-VCSEL were observed with a photo-multiplier tube with Ti:Sapp. laser (800 nm) continuous wave excitation. The inset in Fig. 4 plots an output emission intensity from the Sb-based QD-VCSEL on the excitation power density. The emission intensity increased non-linearly with increasing pumping power. A threshold pumping power density, P_{th}, of 2.88 kW/cm^2 can be observed at room temperature. The emission intensity is drastically increased with increasing pumping power that is over P_{th}. Figure 4 also plots the emission spectrum of an Sb-based QD-VCSEL under a pumping power of 22.9 kW/cm^2 (approx. 8 P_{th}). A sharp peak at 1546 nm can be observed at room temperature. From the results in Fig. 4, 1.55-μm CW lasing operation can be achieved at room temperature by using Sb-based QDs as active media. Linear polarization of the lasing peak at 1546 nm was also observed along the [1-10] direction on the (001)-oriented GaAs substrate. The direction of polarization may depend on the horizontal size of the InGaSb QD structure, i.e., the [1-10] of the polarization direction may be similar to the major axis of the elliptical QD structure. By using P_{th}, an equivalent threshold current density can be estimated as 295 A/cm^2 per QD layer, if the reflectance of the top dielectric DBR mirror and the absorption in the active region of the GaAs matrix are assumed to be 5% and 70% at a wavelength of 800 nm, respectively.

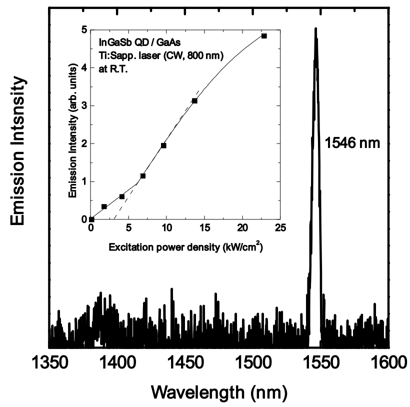

Fig. 4 1.55-μm lasing spectrum and PL emission intensity vs. optical-pumping-power density (inset) of Sb-QD VCSEL at room temperature.

3. Conclusion

We successfully demonstrated CW lasing operations at room temperature at around 1.55-μm wavelengths from Sb-based QD-VCSELs fabricated on GaAs substrates. This indicates that the Sb-based QD as new material has excellent potential for the development of long-wavelength VCSELs and novel optical communications devices on GaAs substrates.

Acknowledgements

We would like to thank Messrs. S. Miyashita, O. Ohguchi, and Y. Suzuki for their technical assistance, and Drs. F. Tomita, T. Itabe, M. Izutsu, and M. Tsuchiya at NICT for their encouragement throughout this work.

References

[1] K. Otsubo, N. Hatori, M. Ishida, S. Okumura, T. Akiyama, Y. Nakata, H. Ebe, M. Sugawara, and Y. Arakawa, Jpn. J. Appl. Phys. 43, L1124 (2004).

[2] N. Yamamoto, K. Akahane, S. Gozu, and N. Ohtani, Physica E **21** (2004) 322.

[3] N. Yamamoto, K. Akahane, S. Gozu, and N. Ohtani, Appl. Phys. Lett. **86** (2005) in press.

[4] Y. Onishi, N. Nishiyama, C. Caneau, F. Koyama, and Z. Chung-en, IEEE Photon. Technol. Lett. **16** (2004) 1236

[5] N. Yamamoto, K. Akahane, S. Gozu, N. Ohtani, Electron. Lett. **40**, 18 (2004) 1120.