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Fabrication of Sb-based QDs for long-wavelength VCSELs

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Abstract: Long-wavelength VCSELs are key-devices for the evolution of ubiquitous-communications society. We present that such a novel-material as Sb-based QDs have substantial potentials for realizing the VCSEL operating in fiber-optic communications wavebands.

1. Introduction

Long-wavelength vertical-cavity surface-emitting laser (VCSEL) fabricated on GaAs substrates for 1.3- and 1.5-µm operations are considered excellent candidates as low-cost, low-power consumption, high-performance light sources for fiber-optic communications and ubiquitous networks [1, 2]. Self-assembled quantum dot (QD) structures are one of the candidates for fabrication of a long-wavelength active media, since high-quality QD structure can be grown on various substrates without the restrictions of lattice constants. Additionally, the possibility of fabricating lasers with low threshold power and low temperature dependence by using QDs in an active media has been intensively investigated [3, 4]. Long-wavelength emissions on a GaAs substrate are expected when QDs are used with narrow-band gap materials. Generally, the emission wavelength of InAs QDs is restricted to around 1 µm because the compressive strain from GaAs substrates changes the energy band-gap of the InAs material. Therefore, we focused on developing Sb-based QDs to fabricate a high-quality active media capable of high-intensity and longer wavelength emissions on a GaAs substrate.

In this paper, we discuss the essential part in the successful demonstration of optical-communications wavebands emission from a VCSEL structure containing the Sb-based QDs on a GaAs substrate with a current injection [5, 6]. We also summarize our fabrication technique for creating a high-quality Sb-based QDs structure on GaAs.

2. Experiments

2-1. Fabrication and Optimization of Sb-based QDs

The Sb-based QDs were grown on (001)-oriented n-GaAs substrates through solid-source molecular beam epitaxy (MBE). Previously, we reported that the density of the Sb-based QDs can be increased by using a silicon-atom irradiation technique. We found that the QD density with this technique is about 100 times greater than without the Si atoms. Therefore, Si atom irradiation (with a deposition rate of 1.4×10^{10} /cm^2/s) was also carried out for 30 s in this experiment. A GaAs buffer layer was grown to form an atomically flat surface, then the substrate temperature was decreased to 400ºC to grow $In_{0.5}Ga_{0.5}Sb$ QDs such as those in the Sb-based QD structure. The growth rate of the InGaSb QD is fixed at 0.1 mono-layer/s (ML/s). Here, we optimized growth conditions, such as growth thickness and Sb-flux, during the QD formation in order to fabricate a high quality Sb-based QD structure.

Figure 1(a) shows dependence of QD density and height on growth thickness. A smooth surface was observed at 1 ML of growth using an Atomic Force Microscope (AFM), and a transition from 2-dimensional (2D) to 3D structure was also found by observing a refractive high-energy electron diffraction (RHEED) pattern. Therefore, the growth mode of the InGaSb on a GaAs (001) is considered to be an S-K growth mode. The QD density increased up to a growth thickness of 2.2 MLs after which it decreased as thickness increased. At a thickness of 2.5 MLs, we found that some coreless dots had been grown. Therefore, the optimal growth thickness for achieving high-quality Sb-based QDs was found to be 2.2 MLs.

We also varied Sb-flux between 9.0×10^{-8} and 9.0×10^{-7} Torr during QD growth. QD density also increased as Sb-flux increased up to 5.0×10^{-7} Torr and then reached saturation. A slight decrease in QD density was even observed over 5.0×10^{-7} Torr. Therefore, an Sb-flux higher than 5×10^{-7} Torr is selected to create a high-density QD structure. Figure 1(b) is an AFM image of high-quality Sb-based QDs, fabricated under optimized growth

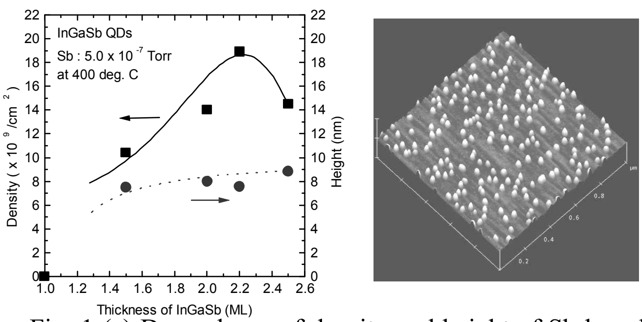

Fig. 1 (a) Dependence of density and height of Sb-based QD structure on growth thickness. (b) AFM image of a high-quality Sb-based QD structure on a GaAs (001) surface. (1µm × 1µm) conditions (Growth thickness: 2.2 MLs, and Sb-flux: 5.0×10^{-7} Torr). Average height and dimensions were 7.5 nm, 34 nm along [1-10] and 24 nm along [110], respectively. The density of this QD was as high as $2.0\times10^{10}/cm^2$, which may approach the density of InAs QDs on GaAs. The InGaSb QD was embedded in a 15 nm GaAs matrix, and then the 5-stacked InGaSb QD/GaAs layers were formed on a GaAs (001) at 400ºC. We found that the QD structure on top of the multi-stacked QD layers was very similar to the first QD layer. Figure 2 shows the photoluminescence spectrum of the multi-stacked InGaSb QD/GaAs structure at room temperature. Samples were excited using an SHG-YVO laser (532 nm), and then the monochromated emissions were detected using a photo-multiplier tube. A PL spectrum from the 25 MLs AlGaSb quantum well (QW) is also shown in Fig. 2. It seems that the emission intensity from Sb-based QD bears comparison with that from the Sb-based QW, however, the QW growth conditions are still not optimized. Therefore, it is thought that multi-stacked Sb-based QDs on GaAs may be a useful structure for optical communications and near-infrared light emitting devices.

2-2. Fabrication of Sb-based QD-VCSEL structures

Figure 3(a) shows a schematic InGaSb QD-VCSEL device structure for a current injection. The VCSEL structure was grown on an n-GaAs (001) substrate [7]. A bottom DBR mirror consisting of 38-period Si-doped AlAs/GaAs multi-layers was grown at 560ºC. An active layer containing 8-stacked 2.2 MLs $In_{0.5}Ga_{0.5}Sb$ QDs was also fabricated on an n-GaAs guiding layer under optimum growth conditions. A Si atom irradiation technique was carried out. The InGaSb QDs layers were covered with 15-nm-thick GaAs layers. A top DBR mirror consisting of 26-period Be-doped AlAs/GaAs multi-layers was also fabricated at 540ºC. After that, electrodes were fabricated using photolithography processes. Finally, the mesa-VCSEL structure was formed using a reactive dry etching (RIE) method. A 40-μm squired window for an optical-output was also formed on top of the VCSEL structures. These QD-VCSELs were electrically cooled down to 18ºC. Figure 3 shows the current versus light

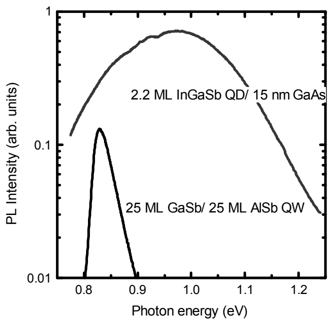

Fig. 2 Optical-communications waveband (0.8–0.95 eV) emissions from InGaSb QDs embedded in GaAs matrix at room temperature.

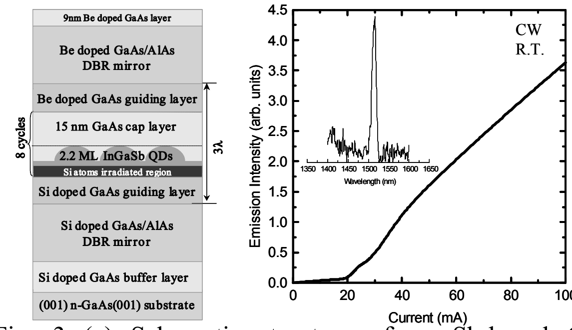

Fig. 3 (a) Schematic structure of an Sb-based QD VCSEL. (b) EL emission intensity vs. current and 1.52-μm cw-emission spectrum from Sb-QD VCSEL structure at room temperature.

output characteristic of the InGaSb QD-VCSEL. A dc voltage was then applied to the devices. The threshold current was found to be about 24.7 mA in cw operation. When the applied current is larger than the threshold value, an emission peak is observed at around 1516 nm, as shown in the inset of Fig. 3. We considered that the characteristics of these optimized Sb-based QD-VCSELs and Sb-based QD materials will need to be studied in more detail to clearly indicate the lasing operation characteristics and enable the development of attractive VCSEL devices on GaAs wafers.

3. Conclusion

We discussed optimizing growth conditions for creating high-quality Sb-based QD structure. We also demonstrated 1.5-μm emissions from an Sb-based QD-VCSEL structure with a current injection at RT. This indicates that Sb-based QDs on GaAs substrates have excellent potential for development of long-wavelength VCSELs and novel infrared light-emitting devices.

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