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Broadband Gain Superluminescent Diode based on Self-assembled InAs Quantum Dots with Segmented Contacts

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Abstract

We developed a broadband gain superluminescent diode (SLD) based on self-assembled InAs quantum dots (QDs) for optical coherence tomography (OCT). Four layers of InAs QDs with controlled emission wavelengths via strain reducing layers were embedded in a conventional GaAs and AlGaAs p/n-junction. A straight ridge waveguide with segmented contacts was formed on the grown wafer, and an as-cleaved 4-mm-length chip was prepared. Electroluminescence (EL) measurements under various injection currents indicated blue-shift of spectrum due to contributions of emissions from first and second excited states of the QDs. In addition, gain spectra were deduced from EL intensities with different lengths under identical injection currents obtained by using the segmented contacts. The gain spectra show a broadband gain beyond 160 nm. These results demonstrate the potential of the QD-based SLD as the light source for high-resolution OCT.

1. Introduction

Non-invasive cross-sectional imaging system, optical coherence tomography (OCT) [1], has been intensively developed and widely used in various medical fields. The OCT operates based on the low-coherence interferometry, and a broadband light source is required for achieving high-resolution OCT imaging [2]. In addition, a center wavelength of the light source should belong to the near-infrared (NIR) range, which can further penetrate in biological samples, to obtain a large imaging depth.

Self-assembled InAs quantum dots (QDs) grown on a GaAs substrate emit a broadband spectrum at NIR resulting from size and compositional distributions in the ensemble. Thus, the InAs QDs have been recognized as an ideal material for OCT light source [3]. We have so far fabricated a superluminescent diode (SLD) light source based on the InAs QDs with controlled emission wavelengths [4] and demonstrated OCT imaging by using the QD-based SLD [5]. However, the electro-luminescence (EL) emissions arose from recombination between only the ground states (GS) and the 1st excited states (ES1) of the QDs by a limitation of current density through a single contact electrode.

In this work, we developed a QD-based SLD with segmented contacts to increase the injection current density and induce emissions from higher (2nd) excited states (ES2) in QDs. The fabricated QD-based SLD was evaluated as a light source for OCT through EL measurements and deduced gain spectra.

2. Experiment

As shown in Fig. 1(a), a wafer including four InAs QD layers with multiple emission wavelengths was grown by molecular beam epitaxy (MBE) on an n+-GaAs (001) substrate. The emission wavelength of each QD layer was controlled by varying the thickness of the strain reduced layer (0-4 nm) deposited on the QD. A 240-nm-thick GaAs waveguide layer including QD layers is optically and electronically confined within 1.5-µm-thick p-/n-$Al_{0.35}Ga_{0.65}As$ cladding layers.

A straight ridge-type waveguide (RWG) was fabricated on the grown wafer. The width and height of the RWG are approximately 5 and 1.44 µm, respectively. Then, segmented contacts with 1 mm long, which are electrically isolated, were formed on the RWG, as shown in Fig. 1(b).

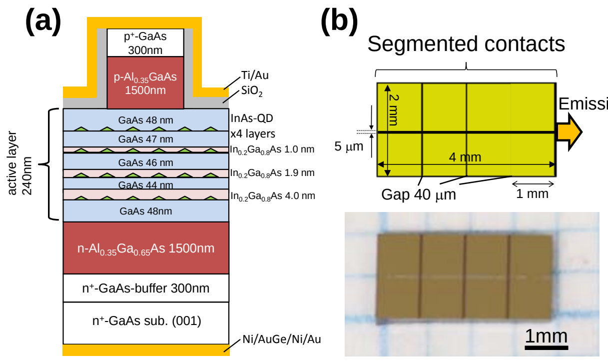

Fig. 1 (a) Profile and (b) Plan-view schematic images and a photograph of a fabricated chip.

The EL emission from the RWG was measured and the optical gain was deduced from EL spectra of driven RWG lengths of L and $2L$ (one and two segments) under identical injection current density, J, expressed as the following equation [6]:

$$G = \frac{1}{L}\ln\left(\frac{P(J,2L)}{P(J,L)} - 1\right). \qquad (1)$$

3. Results and Discussion

Figure 2(a) shows EL spectra obtained from the fabricated chip under various injection currents through the contact nearest to the edge. The peak wavelength was blue-shifted from approximately up to 1120 nm with the increase in the injection current. This can be attributed to the state-filling effect, which occurs in order of GS, ES1, and ES2 of QDs. The dominant emission sequentially arose from the GS centered at approximately 1220 nm, ES1 at 1150 nm, and ES2 at 1100 nm with increasing the injection current. Variations of EL intensity of each wavelength in the spectra clearly show the state-filling effects, as shown in Fig. 2(b).

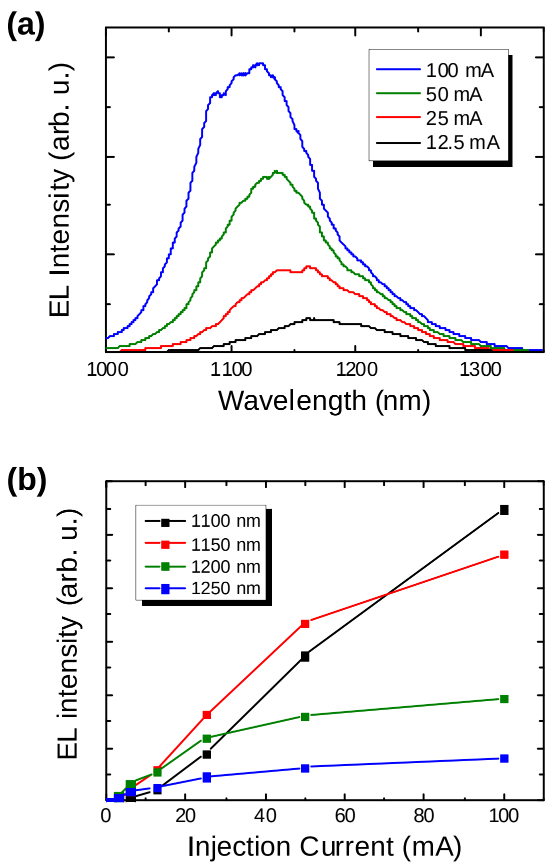

Fig. 2 (a) EL spectra obtained from the fabricated chip under various injection currents through the contact nearest to the edge. (b) EL intensity plotted for each wavelength as a function of injection current.

Figure 3 shows deduced net modal gain spectra under various injection currents. The positive and negative net modal gain spectrum means that the QDs work as gain and absorption media at the wavelength. The positive net modal gain extends to shorter wavelength with increase in injection current, and the bandwidth of the gain increased up to approximately 160 nm at an injection current of 100 mA. The extension of the positive gain can be attributed to the sequential state-filling effect from GS to ES2, corresponding to the EL spectrum. Although it is difficult to distinguish them, the gain value increased from GS to ES2. This can be resulted from increase in the number of states from GS to ES of QDs. These results indicate the effectiveness of the segmented contacts for inducing higher ES emissions and broadband gain from the QDs.

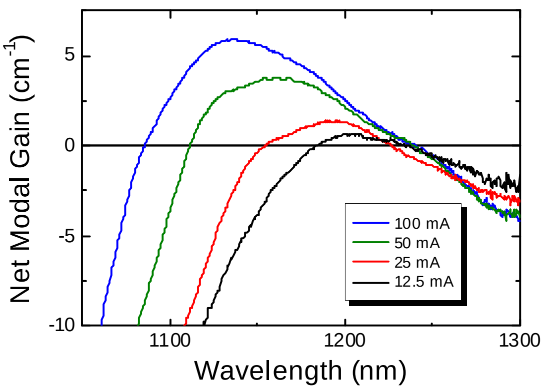

Fig. 3 Net modal gain spectra of the QD-SLD under various injection currents.

4. Conclusions

A self-assembled InAs QD-based SLD with segmented contacts was developed and demonstrated to exhibit a broadband gain spectrum. The gain spectrum indicate the QD-SLD as a broadband gain media (beyond 160 nm) and its potential as the light source for high-resolution OCT.

Acknowledgements

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