Near-field scanning optical microscopy of quantum dot broad area laser diodes

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Abstract Near-field scanning optical microscopy (NSOM) studies of self-assembled InAs quantum dot broad area laser diodes (QD-BALDs) with different active layer were performed. The high resolution (<100 nm) of NSOM provides a detailed mapping of the laser output from the active region. Representative near-field electroluminescence (EL) spectra taken the cross section of the QD-BALD structures below and above the lasing threshold are plotted. Moreover, spatially resolved near-field scanning images of the waveguide are obtained by collecting the EL as the tip is scanned across the surface. Such near-field measurements show a relationship between laser emission and different active layer structure.

1 Introduction

In the past several years, quasizero dimensional system, especially self-assembled semiconductor quantum dot (QD) has been investigated from a fundamental physics point of view and for the potential applications to a device such as a laser diode. The previous investigations have predicted that the quantum dot laser diode should have higher gain, lower threshold current density, and higher thermal stability compared with other quantum structure, which are due to the atomic-like density of state in QD system. Nevertheless, the behavior of a resonant cavity depends on both carrier and optical confinement, both of which are poorly understood. Although far-field optical spectroscopy measurements have proved to be powerful tools, spatially sensitive optical analysis at the onset of lasing will allow a better understanding of the optoelectric behavior in our near-field scanning optical microscopy (NSOM) system [1–4].

NSOM is a technique where a small optical probe is placed within a fraction of a wavelength of a sample and scanned over the surface. Typically a gold coated, tapered, single-mode optical fiber is used as the tiny aperture through which the light is coupled and yields a spatial resolution of the order of the tip size. The application of near-field imaging and spectroscopy to optoelectronic devices and laser diodes provides subwavelength information on device structure, performance, and output properties [5–8].

In this paper, we will present results of a direct comparison quantum dot broad area laser diodes (QD-BALDs) based on the same epitaxial layer structure except for the active region. Especially, we explain the near-field emission properties of the QD-BALDs by NSOM method. The high resolution of NSOM provides a detailed mapping of the laser output. In particular, observation of near-field
electroluminescence (EL) spectra and spatially resolved near-field scanning images by collecting the EL as the tip is scanned near the active region reveals compositional fluctuations as well as optical absorption and reemission effects of the lasing mode.

2 Experimental details

The QD-BALD samples used in the present work were grown by a molecular beam epitaxy on (100) Si-doped GaAs substrates. The QD is self-assembled during alternate supply of precursors by using the atomic layer epitaxy (ALE) technique. InAs ALE QD is grown by several repetitions of a 3 monolayer (ML) In/3 ML As cycle. This growth technique has the advantage that the QD size can be controlled by the repetition number of a cycle. Figure 1 shows a schematic diagram of our QD-BALD structures. The only difference between the lasers is their active layer. For QD1 sample, 3 InAs QD layers and 3 InGaAs/InAs QD layers are used. The active layer of QD2 sample consists of 3 InGaAs/InAs QD layers. The active QD layers were sandwiched by 18 periods of Al_{0.3}Ga_{0.7}As (2 nm)/GaAs (2 nm) for the separate confinement layer (SCL). The cladding layers outside the n- and p-SCL were n- and p-Al_{0.35}Ga_{0.65}As (1.52 μm, 3 × 10^{18}/cm^3). Finally, p^+-GaAs (400 nm, 2 × 10^{19}/cm^3) was grown as cap layer for the ohmic contact. The QD-BALDs were fabricated in the form of a 7° tilted triangular p-electrode. The active region was clearly defined by a triangular SiO_2 window. The taper angle was 3° with the center axis tilted by 7°. The length and aperture of the fabricated QDLDs were 1 mm and 25 μm, respectively [9, 10].

Collection mode NSOM system is used to study the near-field EL spectrum and the near-field scanning image as a function of bias current for the QD-BALDs with different active layer. Probe tip is mounted on an x-y-z piezo, which is scanned relative to the sample. Simultaneous shear-force measurements provide an independent measure of the surface topography to maintain a fixed proximity (~10 nm) between tip and sample. The laser emission was collected through a ~80 nm diameter aperture, resulting in <100 nm spatial resolution. EL light analyzed using a 1 m single grating monochromator and detected by a InGaAs detector. All the near-field measurements were performed at room temperature.

3 Results and discussion

Figure 2 shows clearly that the dependence of laser optical output power on excitation current for QD-BALD samples operated in continued mode is displayed. The threshold current was found to be dependent on the laser mounting technique [11]. When comparing QD2 sample with QD1 sample the threshold current could be reduced by 8.3% from 182 mA to 167 mA. It is note that there are significant variations of threshold current depending on different active layer design.

Fig. 1 Schematics of the QD-BALD structures with different active layer

(a) QD1 Sample
(b) QD2 Sample
Representative near-field EL spectra taken the cross section of QD-BALD structures below and above the lasing threshold are plotted in Fig. 3. As clearly shown in Fig. 3(a), the below threshold near-field EL spectrum of the QD1 sample has two well-separated, centered at 1.209 and 1.287 μm, caused by two active layers (InAs QD layer and InGaAs/InAs QD layer). However, further increasing injection current above threshold, we find a striking difference in EL intensity between the two peaks. That is, the

Fig. 2 Laser optical output power versus injection current characteristics

Fig. 3 Representative near-field EL spectra of the QD-BALD samples below and above the lasing threshold

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Fig. 4 A set of $30 \times 7 \, \mu m$ near-field scanning images by collecting the EL as the tip is scanned centered around the active region of the QD-BALD samples as a function of bias current
EL efficiency of at 1.209 μm peak at above threshold is quite high. This means that electrically injected carriers are not efficiently captured into the 1.287 μm QD layer and recombined above threshold. This is in strong contrast to the cases of QD laser where significant enhancement of the EL efficiency is observed due to the reduced non-radiative recombination processes and the enhanced radiative recombination rates.

On the other hand, the below threshold near-field EL spectrum of the QD2 sample shows single Gaussian line-shape with a full width half maximum (FWHM) of 27 nm (Fig. 3b). The large spectral width suggests that many carriers do not contribute to the lasing mode. But the 27 nm wide linewidth of the spontaneous emission before lasing is relatively broad, probably due to the In composition fluctuation, the rough interface of InGaAs layers, or the strain between dot and barrier layers [12]. Above the threshold current, strong stimulated emissions were observed. Two sharp stimulated emissions at 1.276 and 1.283 μm became dominant at a current of 167 mA.

Near-field scanning image of the waveguide is obtained by collecting the EL as the tip is scanned across the surface. In Fig. 4, a set of 30 × 7 μm images centered around the active region of the QD1 and QD2 samples are shown as a function of bias current. White regions represent areas emitting the most light, while darker regions represent areas emitting less light. A single-mode near-field scanning images from the QD1 sample are shown at \( I < I_{\text{TH}} \), \( I = I_{\text{TH}} \), and \( I > I_{\text{TH}} \) in Fig. 4(a). At the below threshold current, a broad emission distribution is observed. It is note that many carriers do not contribute to the lasing mode. However, the vertical- and lateral-mode narrows when the laser is driven above threshold, and that no filamenting is observed. On the other hand, multi-mode near-field scanning image from the QD2 sample is shown above threshold in Fig. 4(b). This suggests that different active layer from the...
QD-BALD structure not only affects the spectral emission (Fig. 3), but the waveguide as well.

Transverse-mode behavior can be extracted from cross sections of these spatial maps. For example, the transverse cross sections of the multi-mode emission of the QD2 sample (Fig. 4b) are plotted to scale with their laser structure in Figs. 5. Note in all plots, a large amount of EL is not guided within the active region and extends well into the AlGaAs layer. However, at threshold (Fig. 5b), we observe the mode narrowing, and well above threshold (Fig. 5c), we see a significant separation of the mode. We suppose that the result is related to the In compositional fluctuations as well as optical absorption and reemission effects near the active region [13–16].

4 Conclusions

We investigated near-field emission properties of self-assembled InAs QD-BALDs with different active layer by NSOM method. The high resolution (<100 nm) of NSOM provides a direct way of characterizing the near-field emission properties of the QD-BALDs. Especially, NSOM has demonstrated that different active layer from the QD-BALD structure not only affects the spectral emission (Fig. 3), but the waveguide as well (Fig. 4). Moreover, cross sections of the spatial maps (Fig. 5) show significant light guided near the active region. We expect that this capability will provide a useful tool for laser diode design and optimization.

References