InAs/GaAs submonolayer quantum dot superluminescent diode emitting around 970 nm*

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(Received 19 September 2011; revised manuscript received 19 October 2011)

According to the InAs/GaAs submonolayer quantum dot active region, we demonstrate a bent-waveguide superluminescent diode emitting at a wavelength of around 970 nm. At a pulsed injection current of 0.5 A, the device exhibits an output power of 24 mW and an emission spectrum centred at 971 nm with a full width at half maximum of 16 nm.

Keywords: quantum dot, submonolayer, self-assembled, superluminescent diode

PACS: 81.07.Ta, 81.16.Dn, 85.35.Be, 85.60.Jb **DOI:** 10.1088/1674-1056/21/2/028102

1. Introduction

Superluminescent diodes (SLDs) have been widely used in many areas such as optical coherence tomography (OCT),[1−4] optical fiber based sensors,[5] external cavity tunable lasers.[6−8] Recently, self-assembled quantum dots (QDs) have attracted a lot of attention for the fabrication of broadband and high-power SLDs, owing to the broad gain spectrum resulting from the intrinsic size inhomogeneity of self-assembled QDs grown by Stranski–Krastanow (SK) mode.[9−15] SLDs that operate at a short wavelength in a range of 850 nm–1 μm are very attractive due to the need of miniaturized and low cost systems. The short-wavelength SLD device also has a high resolution for ophthalmology OCT imaging.[16] A way to obtain QD materials emitting less than 1 μm is to incorporate aluminum component into In(Ga)As self-assembled QDs grown by SK mode.[17,18] Submonolayer (SML) QDs formed by cycled deposition of InAs insertions of less than one monolayer (ML) thickness in GaAs matrix is another way to achieve the emission below 1 μm. By comparison with SK QD, SML-QD has a narrow gain spectrum but much higher modal gain, which is close to QW material as demonstrated by Kovsh *et al.*[19] By varying the InAs deposition amount, the emission wavelength of the SML-QD can be adjusted in a large range. Recently, SML-QDs have been successfully utilized in the fabrication of high-power lasers. Zhukov *et al.*[20] reported on 3.9-W CW power from an InAs/GaAs SML-QD laser emitting at 947 nm. Xu *et al.*[21] fabricated an SML-QD laser emitting at 964 nm based on ten InAs (0.5 ML)/GaAs (2.5 ML) SML-QD multi-layers. Hopfer *et al.*[22] exhibited an SML-QD vertical-cavity surface-emitting laser (VCSEL) emitting near 980 nm with an output power of more than 1 mW. However, to the best of our knowledge, there is a lack of study on the SLDs based on SML-QDs.

In this paper, five InAs/GaAs SML-QD samples with 0.25 ML–0.45 ML InAs deposition amount per growth cycle were studied first. Dependences of the photoluminescence (PL) wavelength and full width at half maximum (FWHM) on InAs deposition amount are presented and then the chirped InAs/GaAs SML-QD active region, including five kinds of SML-QDs (totalled 12 layers) with different InAs deposition amounts, is adopted for fabricating SLD devices. For a bent-waveguide SLD device with 2-mm-length cavity and 5-μm-wide ridge, we demonstrate an emission spectrum centred at 971 nm with an FWHM of 16 nm and an output power of 24 mW under an injection current of 0.5 A at room temperature (RT).

2. Experiment

The epitaxial structures were grown by a Riber 32P solid-source molecular beam epitaxy (MBE) ma-

*Project supported by the National Basic Research Program of China (Grant No. 2006CB604904) and the National Natural Science Foundation of China (Grant Nos. 60876086, 60976057, and 60776037).

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chine on n-GaAs (001) substrates. Each SML-QD layer was formed by ten-cycled deposition of SML InAs and 2.25-ML GaAs as shown in Fig. 1(a). In order to study the dependence of the emission wavelength on InAs deposition amount, five InAs/GaAs SML-QD reference samples with different InAs deposition amounts were fabricated. The deposition amounts of the InAs submonolayer were varied from 0.25 ML to 0.45 ML by an interval of 0.05 ML (samples D1–D5). For the device epitaxial wafer (D0), the active layers all had a chirped SML-QD structure that consists of 12 InAs/GaAs SML-QD layers. Figure 1(b) shows the schematic band diagram of the chirped SML-QD structure D0. Each SML-QD layer was formed by cycled deposition of ten periods of InAs and GaAs. The GaAs deposition amount per cycle was 2.25 ML for each SML-QD layer. The InAs deposition amounts per cycle were 0.45 ML, 0.45 ML, 0.45 ML, 0.40 ML, 0.40 ML, 0.40 ML, 0.35 ML, 0.35 ML, 0.30 ML, 0.30 ML, 0.25 ML, and 0.25 ML, respectively. The whole active region was sandwiched between 1.5-μm n- and p-type $Al_{0.5}Ga_{0.5}As$ cladding layers. Finally, a p^+-doped GaAs contact layer completed the epitaxial structure.

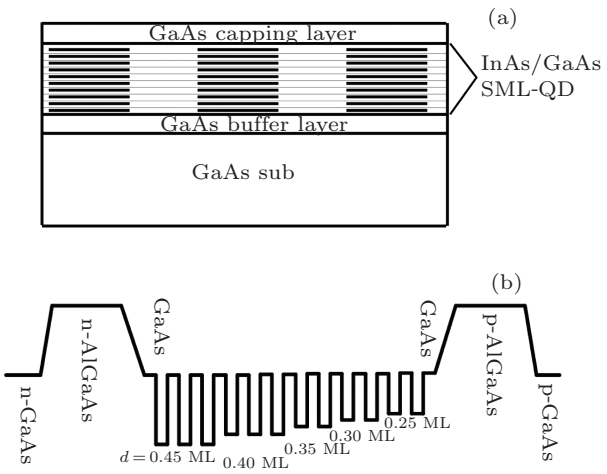


Fig. 1. Schematic diagrams of (a) the InAs/GaAs SML-QD samples D1–D5 and (b) the chirped InAs/GaAs SML-QD SLD device structure D0.

Bent-waveguide SLD devices[23] were fabricated, each of which was composed of a 1-mm-length straight waveguide and a 1-mm-bent waveguide as shown in the inset of Fig. 3. The ridge waveguide was 5-μm wide and determined by the wet chemical etching. The bent region had a curvature radius of 8.2 mm and titled from the normal direction of the cleaved facet by 7° to suppress lasing. The devices were mounted p-side down on a copper sink using indium solder. Both facets of the SLD device remained as-cleaved. The device was characterized by light power-injection current (P–I) and electroluminescence (EL) measurements at room temperature in pulsing injection mode with 1-kHz repetition rate and 3% duty cycle. The power value is presented as the peak power, which is deduced from the average one measured with a pyroelectric probe divided by the 3% duty cycle.

3. Results and discussion

Figure 2 (a) shows RT photoluminescence (PL) spectra of InAs/GaAs SML-QD samples (D1–D5) excited by an He–Ne laser. Dependences of the peak

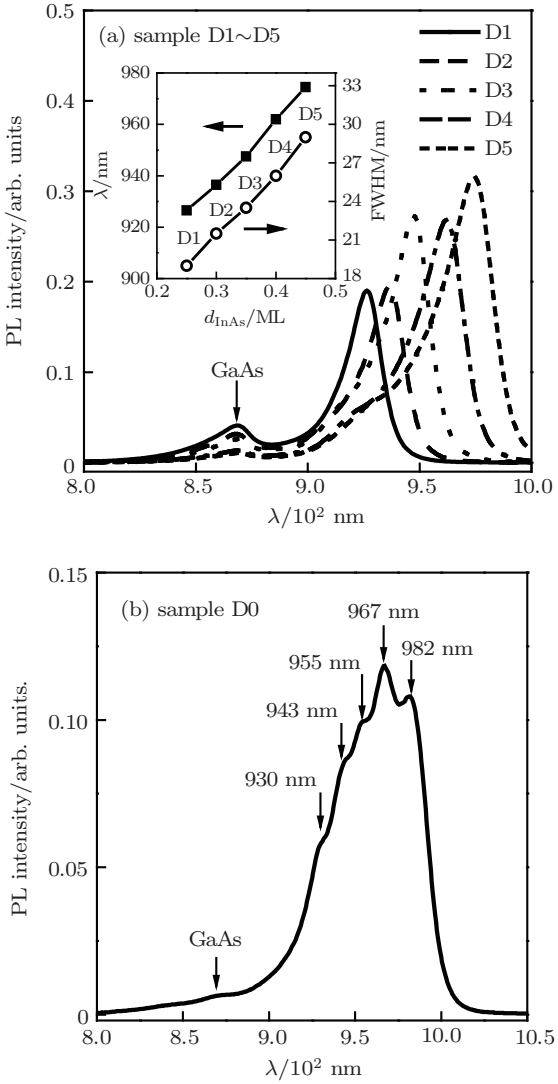


Fig. 2. RT PL spectra of (a) InAs/GaAs SML-QD samples (D1–D5) with different InAs deposition amounts and (b) the chirped InAs/GaAs SML-QD device structure (D0). The inset in panel (a) shows PL peak wavelength and FWHM each as a function of the InAs deposition amount.

wavelength and the spectral FWHM on the InAs deposition amount per cycle in the QDs are also shown.

Near 50-nm linear red-shift (from 926 nm to 975 nm) of the PL peak is observed with increasing the InAs deposition amount per InAs cycle from 0.25 ML to 0.45 ML. It could be attributed to increases of indium composition and size of the SML-QDs by more InAs deposition. The FWHM varies from 19 nm to 29 nm linearly with the InAs deposition amount. As compared to self-assembled InAs/GaAs QDs, whose PL FWHM always larger than 50 nm, SML-QDs usually exhibit a typical spectral width in the range of 20 nm–30 nm.[24−26] This is a shortcoming for fabricating broadband emitting SLD devices. In order to broadening the emission spectrum of the SML-QD SLD, a chirped InAs/GaAs SML-QD active region, which consists of five kinds of SML-QDs (refer to Fig. 1, totalled 12 QD layers), was used to construct the device wafer. Heretofore, chirped structure has already been used in SLDs' fabrications with self-assembled SK QD[27,28] and QW[29] active regions respectively. Figure 2(b) shows an RT PL spectrum of the chirped InAs/GaAs SML-QD device structure. A FWHM of 61 nm is achieved, which is much larger than the typical spectral width of ~ 25 nm for a single SML-QD layer. Such broadening of spectral width results from the overlap of PL emissions from SML-QD layers with different InAs deposition amounts. As shown in Fig. 2(b), the PL spectrum exhibits five emission peaks which correspond to the five kinds SML-QD layers with different InAs deposition amounts.

Utilizing the chirped InAs/GaAs SML-QD wafer, J-shaped waveguide SLD devices were fabricated.

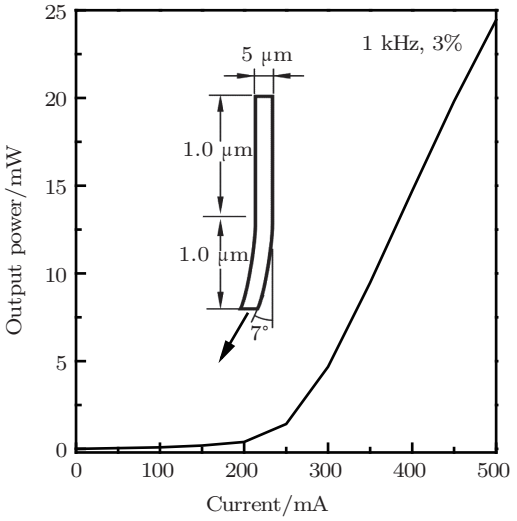


Fig. 3. *P–I* curve of an InAs/GaAs SML-QD SLD device, measured from the bent waveguide facet. The inset shows the schematic diagram of the device structure.

The *P–I* characteristic from the bent waveguide facet of an as-cleaved SLD device with a length of 2 mm is shown in Fig. 3. The inset shows the schematic diagram of the device dimensions. As shown in the figure, a clearly superluminescent behavior is exhibited by the super-linear increase in optical power with increasing current. With 0.2-A injection current, the output power increases rapidly and reaches up to 24 mW at an injection current of 0.5 A.

Figure 4 shows the EL spectra of the SML-QD SLD device at different injection currents, measured from the bent waveguide facet. At a low injection current of 50 mA, an emission spectrum with a spectral FWHM of 58 nm was observed. It is similar in shape to the PL spectrum in Fig. 2(b) to a great degree. Spontaneous radiation is dominated at the low injection level. Overlap of emissions from different kinds of SML-QD layers with different amounts of InAs deposition amounts forms the spectrum. With injection current increasing, spectral bandwidth becomes narrow gradually. It could be attributed to the increase of stimulated radiation at the high injection levels. Exponential optical amplification resulting from stimulated radiation reduces the spectral bandwidth. An emission spectrum centred at 974 nm with an FWHM of 18 nm was achieved at an injection current of 0.4 A. For a given current of 0.5 A, the SLD device gives 24-mW output power and exhibits a spectrum centred at 971 nm with 16-nm bandwidth. A high spectral modulation is observed in the emission spectrum. It is expected that higher output power and larger bandwidth could be obtained by more optimal device structure and antireflection coating on the output facet.

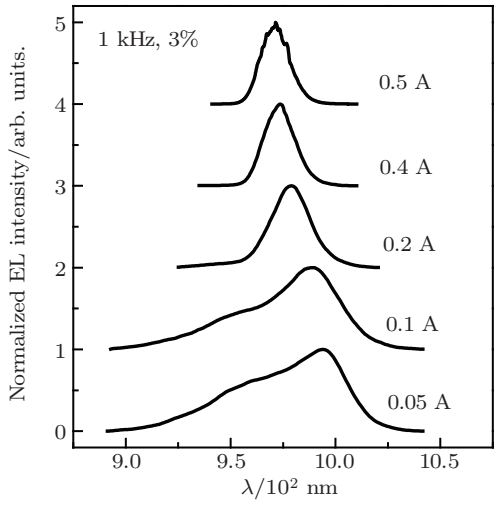


Fig. 4. Normalized EL spectra of an InAs/GaAs SML-QD SLD device under different injection currents, measured from the bent waveguide facet. Some spectra are shifted vertically for clarity.

4. Conclusion

A J-shaped bent-waveguide SLD device emitting at a short-wavelength around 970 nm based on the chirped InAs/GaAs SML-QD active region is demonstrated in this paper. For the QD SLD device with 2 mm in length and 5 μm in ridge width, a high output power of 24 mW with the emission spectrum centred at 971 nm and an FWHM of 16 nm is obtained under an pulsed injection current of 0.5 A.

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