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InGaAs submonolayer quantum-dot photonic-crystal LEDs for fiber-optic communications

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ABSTRACT

An InGaAs submonolayer (SML) quantum-dot photonic-crystal light-emitting diode (QD PhC-LED) with for fiber-optic applications is reported. The active region of the device contains three InGaAs SML QD layers. Each of the InGaAs SML QD layers is formed by alternate depositions of InAs (<1 ML) and GaAs. A maximum CW output power of 0.34 mW at 20 mA has been obtained in the 980 nm range.

1. Introduction

High brightness (HB) light-emitting diodes (LEDs) have drawn a lot of attentions because of their applications in mobile electronics, flat panel displays, automobiles, traffic signals, large outdoor displays, and general lighting [1]. More recently, photonic-crystal light-emitting diodes (PhC-LEDs) have achieved higher external quantum efficiency [2,3], as compared to conventional LEDs. For fiber-optic applications, LEDs made with smaller light-emitting apertures are needed because of their smaller divergence angles and better optical fiber coupling efficiency. For LEDs made with small oxide-confined structure, the device may have reliability problem, similar to that of vertical-cavity surface-emitting lasers (VCSELs) [4]. For LEDs made with integrated lenses, the deep wet chemical etch to form lenses is difficult to control uniformity in lens curvature and diameter. Small-aperture LEDs are designed for small light beam emission at lower currents for better optical fiber coupling. The current spreading can be improved for devices with smaller aperture, as compared to the large-aperture LEDs ($\geqslant$300 μm in diameter). Higher coupling efficiency can be achieved with the emitted light beam size smaller than core diameter of the optical fiber. Moreover, epitaxially grown distributed Bragg reflectors (DBRs) can be used to form microcavity for enhanced light emission [5,6]. The absorption of the spontaneous emission by the substrate can be minimized. Also, microhole array LEDs have demonstrated enhanced light output recently [7]. For shorter-wavelength emission, InGaAs/GaAs submonolayer (SML) QD embedded in a GaAs matrix shows luminescence peaks and high-power lasing performance in the 0.92–1 μm range [8,9]. The advantages of InGaAs SML QDs include better growth uniformity, narrower gain spectrum, higher differential gain, and lower threshold current density [8,9]. In this paper, we report our results on the InGaAs SML QD PhC-LEDs with in the 980 nm range. The photonic-crystal (PhC) structure in this work is the arrangement of etched holes as a triangular photonic-crystal structure with larger lattice constant (5 μm) and etched hole diameters (2–2.5 μm) [2,3]. Two-dimensional (2-D) photonic-crystal etched holes were formed within the p-type ohmic contact ring for light extraction and collimation. The collimation of the output light beam can be further improved by using the sidewalls within the etched holes for light deflection. A maximum continuous-wave (CW) output power of over 0.34 mW has been obtained. High-resolution imaging studies show that the device emits light beams which mainly through the etched holes.

2. Experiments

The epitaxial layers of the InGaAs SML QD LED wafers were grown on 3-in. n^+-GaAs(0 0 1) substrates by molecular beam epitaxy (MBE) in a Riber 49 chamber. The bottom distributed Bragg reflector (DBR) consists of a 33-pair n-type (Si-doped) quarter-wave stack ($\lambda/4$) of $Al_{0.9}Ga_{0.1}As/GaAs$. The top DBR consists of a 20-pair p-type (carbon-doped) $Al_{0.9}Ga_{0.1}As/GaAs$ quarter-wave stack. Above the top DBR, is a heavily doped p-type GaAs contact layer. The undoped 1λ cavity contains three 8 nm InGaAs SML QD layers, separated by 10 nm GaAs barrier layers. Each of the InGaAs SML QD layers is formed by alternate depositions of InAs (<1 ML) and GaAs. The current confinement of the device was carried out using a selectively oxidized AlO_x tapered aperture. Firstly, mesas with diameters varying from 68 to 78 μm were defined by reactive ion etching (RIE). The mesa dimension of the device is designed to be close to the core diameter (typically 50–100 μm) of the multi-mode optical fiber for better coupling efficiency. The p-ohmic

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contact ring with an inner diameter of 46–56 μm larger than the oxide aperture was formed on top of the p-contact layer. The AlAs layer within the $Al_{0.9}Ga_{0.1}As$ confinement layers was selectively oxidized to AlO_x. The oxidation depth was about 15–16 μm toward the center from the mesa edge so that the resulting oxide aperture varied from 36 to 48 μm in diameter. The oxide aperture was introduced in a minimum of optical field in order to reduce the lateral optical loss and the leakage current. The *n*-ohmic contact was formed at the bottom of the n^+-GaAs substrate. After that, triangular lattice patterns of PhC structure (Fig. 1a) with a single-point defect in the center were defined within the p-contact ring using deep ultraviolet (UV) photolithography and etched through the p-type DBR using RIE. The hole diameter (α) is 2–2.5 μm and the lattice constant (Λ) is 5 μm in the PhC structure (Fig. 1a). The PhC structure in this work was made with larger hole diameters and lattice constant, as compared with the previously reported PhC-LEDs [2,3]. The etching depth of the holes is about 16-pair thick into the 20-pair top DBR layer. The distance between etched holes is approximately 2.5–3 μm for conduction current to flow through and therefore better current spreading. The device structure is shown in Fig. 1b. We use the oxide aperture for current confinement and the photonic-crystal structure within the p-ohmic contact ring for light extraction.

3. Results and discussion

Fig. 2 shows the CW light–current (*L–I*) output of the InGaAs SML QD PhC-LEDs. The lattice constant (Λ) is 5 μm and the hole diameter (α) is 2.5 μm for both the 68- and 78-μm-mesa devices. The PhC-LEDs show maximum output powers of 0.19 and 0.34 mW for the 68- and 78-μm-mesa devices, respectively. The device emits a higher output power with larger oxide aperture and more etched holes. The lower output power of the devices is due to smaller oxide apertures for light emission (approximately 36 and 48 μm in diameter), as compared to other larger area LEDs.

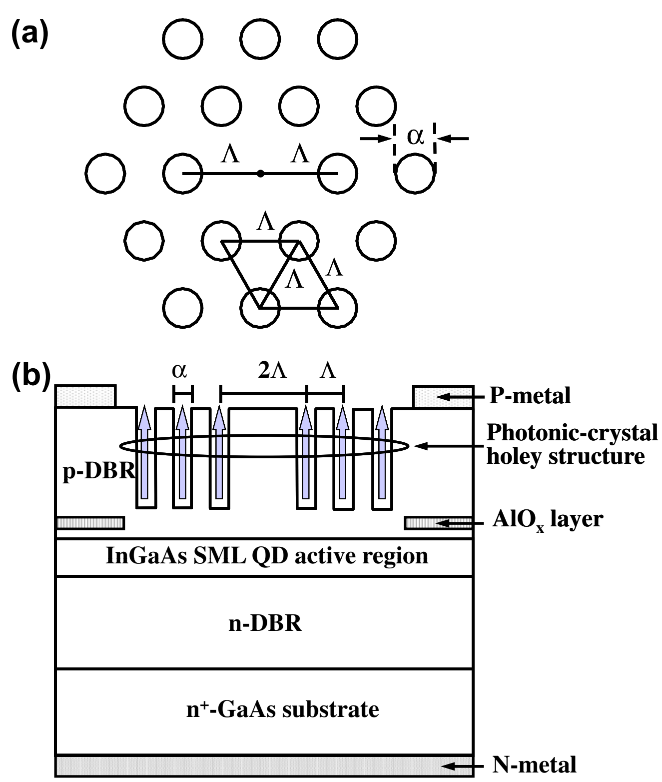

Fig. 1. (a) Plane-view of the photonic-crystal (PhC) structure, and (b) schematic of the InGaAs SML QD PhC-LED.

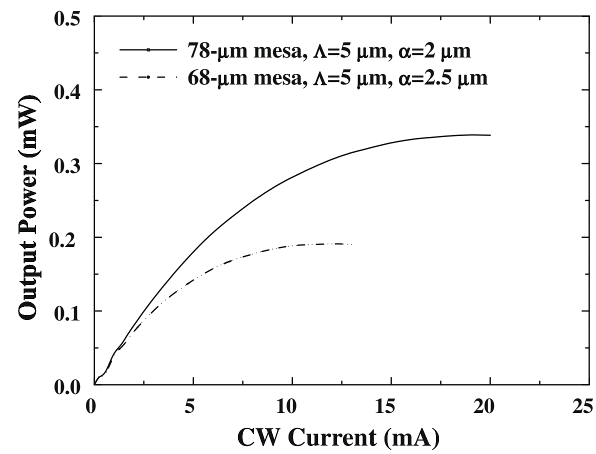

Fig. 2. CW *L–I* characteristics of the InGaAs SML QD PhC-LEDs. The lattice constant (Λ) of the photonic-crystal structure is 5 μm and the hole diameter (α) is 2.5 μm.

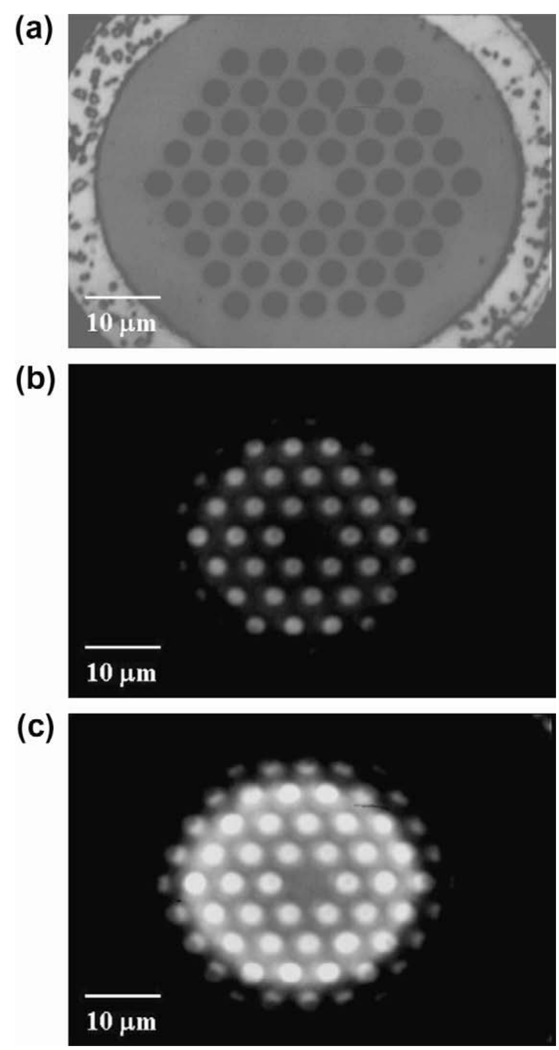

Fig. 3. Micrographs of the InGaAs SML QD PhC-LED at (a) 0, (b) 5, and (c) 15 mA. The lattice constant (Λ) of the photonic-crystal structure is 5 μm and the hole diameter (α) is 2.5 μm.

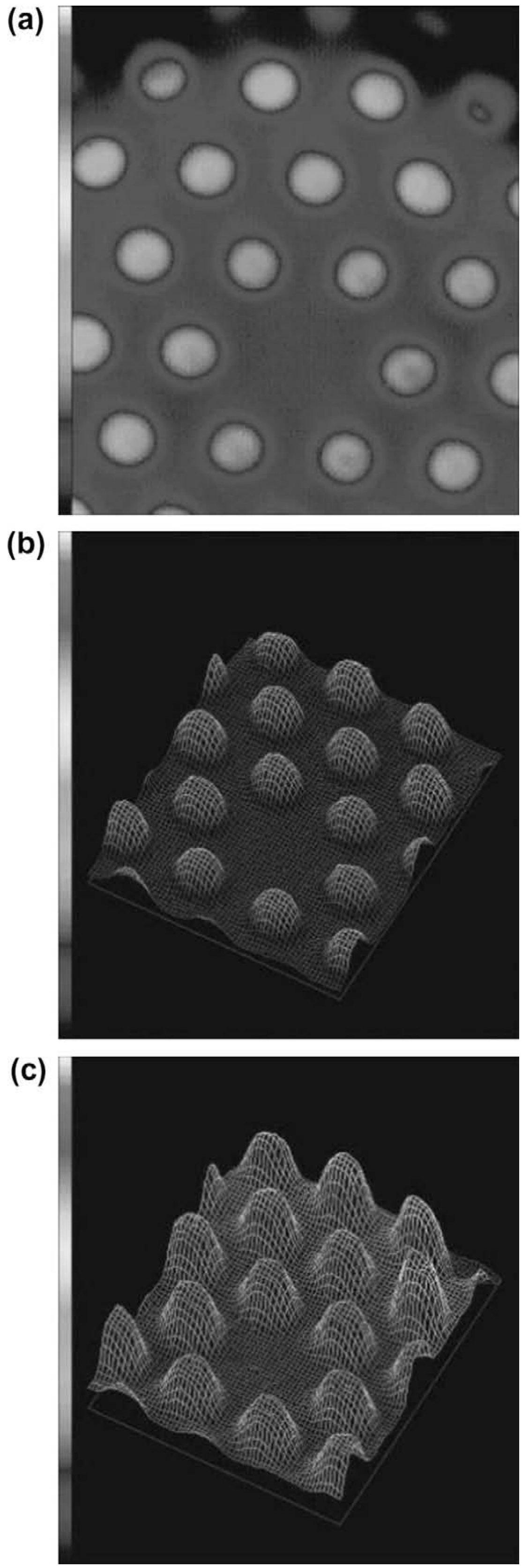

Fig. 4. (a) 2-D intensity profile at 5 mA, (b) 3-D intensity profile at 5 mA, and (c) 3-D intensity profile at 15 mA of the InGaAs SML QD PhC-LED. Neutral density (ND) filters were added to attenuate the beam, in order to avoid saturation of the charge-coupled device (CCD) imaging system. The lattice constant (Λ) of the PhC structure is 5 µm and the hole diameter (α) is 2.5 µm.

Fig. 3 shows the micrographs of the InGaAs SML QD PhC-LED at 0, 5, and 15 mA. The lattice constant Λ is 5 µm and the hole diameter α is 2.5 µm for the PhC structure. The micrographs were taken by a high-resolution charge-coupled device (CCD) imaging system. Fig. 3a was taken with additional light illumination on the device to clearly show the PhC structure of the device. As shown in Fig. 3b and c, the spontaneous emission mainly emits out of the PhC etched holes of the device. The intensity of the light emission increases with increasing current. The reflectance within the PhC etched holes is reduced by RIE (16 pairs of the top DBR being etched off), so that the internally reflected spontaneous emission (by the top and bottom DBRs) can be transmitted out of the PhC holes. The two-dimensional (2-D) intensity profile of the same device is shown in Fig. 4a. The three-dimensional (3-D) intensity profiles of the device are shown in Fig. 4b and c. Neutral density (ND) filters were added to attenuate the output beam, in order to avoid saturation of the high-resolution CCD system at higher currents. The output of the CCD system was connected to another image board of a computer, with a beam analyzing software to analyze the light output of the device. The results in Fig. 4 clearly show the spontaneous emission mainly emits out of the PhC etched holes of the device. The height of the 3-D intensity profile represents the intensity of the light output. As shown in Fig. 4b and c, the light emits out of the PhC etched holes and the light intensity increases with increasing current. The reflectance within the etched holes are reduced by RIE (16 pairs of the top DBR being etched off), so that the internally reflected spontaneous emission (by the DBRs) and light emission under the etched hole region can be transmitted out of the PhC etched holes (Fig. 1b).

The spectra of the InGaAs SML QD PhC-LED at 5 and 10 mA are shown in Fig. 5. The peak emission wavelengths are 971.6 and 972.2 nm at 5 and 10 mA, respectively. The line-width ($\Delta\lambda$) of the light emission, which is the full-width at half-maximum (FWHM) of the peak intensity value are 8.4 and 8.5 nm at 5 and 10 mA, respectively. The narrower line-width of the emission spectra is mainly due to the highly uniform grown QDs size and narrower gain spectrum of the QDs. The narrower line-width also related to the resonant cavity properties of the PhC-LED. The internally reflected light within the resonant cavity can transmit out of the PhC etched holes because of the lowered reflectance within the etched holes. The emission wavelength of the PhC-LED is similar to those of the $In_{0.2}Ga_{0.8}As/GaAs$ quantum-well (QW) LEDs. The InG-

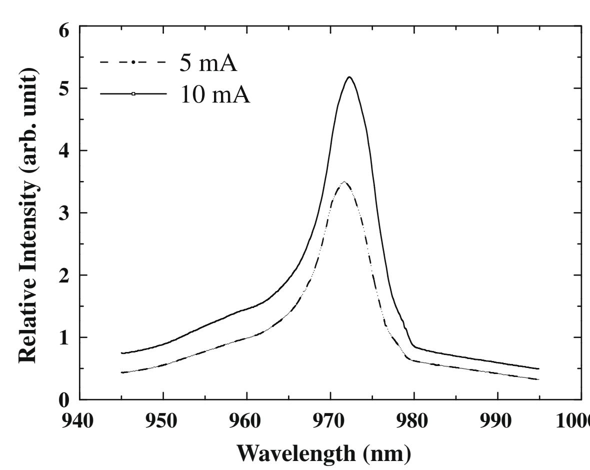

Fig. 5. Spectra of the broad-area InGaAs SML QD PhC-LED at 5 and 10 mA. The lattice constant (Λ) of the photonic-crystal structure is 5 µm and the hole diameter (α) is 2.5 µm.

aAs SML QD PhC-LEDs in this work emit with much narrower line-widths.

Compared to the previous studies of PhC-LEDs [2], our PhC-LEDs (oxide aperture = 48 μm in diameter) emit with higher output power of 0.34 mW. This output power value is lower than other PhC-LEDs [10] made with much larger device sizes (500 μm × 500 μm with output power larger than 44 mW). The average out power per unit area of our PhC-LED is 18.8 W/cm^2, which is comparable to other PhC-LEDs at similar current levels (17.6 W/cm^2 at 60 mA). The sidewall of cylindrical PhC air holes in this work also deflect the output light so as to make the light beam more collimated. The collimated light beam can therefore be more easily coupled into the core of the optical fiber so that the coupling efficiency is higher. The two 1/4-λ DBRs that form the reflectors of the resonant cavity of the LED can also make the output light emit with narrower line-width.

4. Conclusions

In conclusion, we report InGaAs SML QD PhC-LEDs for fiber-optic communications. A maximum CW output power of 0.34 mW has been obtained. The present results indicate that a PhC-LED using an oxide layer for current confinement and a photonic-crystal structure for light extraction is an alternative approach to achieve small light beam output for optical fiber coupling.

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