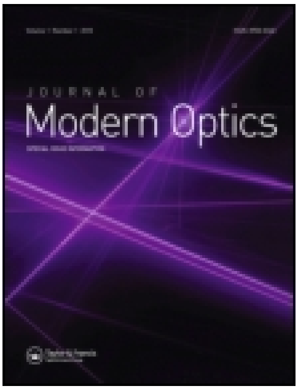

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Oxide-confined photonic-crystal (PhC) light-emitting diodes (LEDs) on p-type GaAs substrate in the 830 nm range are reported. The device consists of a bottom distributed Bragg reflector (DBR), quantum wells (QWs), and a top DBR, with a photonic-crystal structure formed within the n-type ohmic contact ring for light extraction. The etching depth of the PhC holes is 17-pair out of the 22-pair top DBR being etched off. The internally reflected spontaneous light emission can be extracted out of PhC holes because of lower reflectance within those areas. High-resolution micrographic imaging studies indicate that the device emits light mainly through the photonic-crystal holes and it is suitable for optical communications.

Keywords: light-emitting diodes; p-substrate; photonic-crystal

1. Introduction

High brightness (HB) light-emitting diodes (LEDs) have drawn a lot of attention 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 the conventional LEDs. The epitaxially grown distributed Bragg reflectors (DBRs) can be used for increasing the luminescence intensity of the LEDs, because the light absorption by the substrates can be avoided [4]. Moreover, microcavity LEDs (MCLEDs) are important because of their enhanced intensity and narrower line-width [5,6]. The active region of the MCLED is placed within the top and bottom DBRs which are the reflecting mirrors of the Fabry–Pérot cavity. For fiber-optic applications, LEDs made with smaller light-emitting apertures are needed because of their smaller optical beams and therefore their better optical fiber coupling efficiency. The increase in series resistance of the device is mainly attributed to the photonic-crystal (PhC) hole etching

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which partly blocks the current conduction. The implementation of p-substrate is preferred because the PhC pattern can be formed on the top n-type layer with smaller series resistance. In this paper, we report our results on p-substrate oxide-confined photonic-crystal LEDs in the 830 nm range. A photonic-crystal structure was formed within the n-type ohmic contact ring for light extraction. High-resolution imaging studies show that the device emits a light beam which is mainly through the PhC holes.

2. Experiments

The schematic of the device structure is shown in Figure 1. The PhC structure is formed by using a deep anisotropic etch of the n-DBR. The etching depth of PhC structure is 17-pairs out of the 22-pair top DBR being etched off. By using internal reflection of the spontaneous emission between top and bottom DBRs, the light emission can be extracted through the PhC holes. The epitaxial layers of the PhC-LED wafers were grown on p^+-GaAs substrates by metal-organic chemical vapor deposition (MOCVD). The bottom DBR consists of a 30.5-pair p-type (carbon-doped) quarter-wave stack ($\lambda/4$) of $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$. The top DBR consists of a 22-pair n-type (silicon-doped) $Al_{0.9}Ga_{0.1}As/Al_{0.12}Ga_{0.88}As$ quarter-wave stack. A heavily doped n-type contact layer was grown on top of the n-type DBR to facilitate ohmic contact. The graded index separate confinement (GRINSCH) active region contains three undoped GaAs/AlGaAs quantum-well (QW) layers, separated by GaAs barrier layers. The current confinement of the device was done by the selectively oxidized AlO_x layer. Mesas with diameters varying from 50 to 78 µm were defined by reactive ion etch (RIE). The dimension of the mesa was chosen to be close to the core diameter of a typical multi-mode optical fiber for better coupling efficiency. The $Al_{0.98}Ga_{0.02}As$ layer within the $Al_{0.9}Ga_{0.1}As$ confinement layers was selectively oxidized to AlO_x. The oxidation depth was about 12 µm

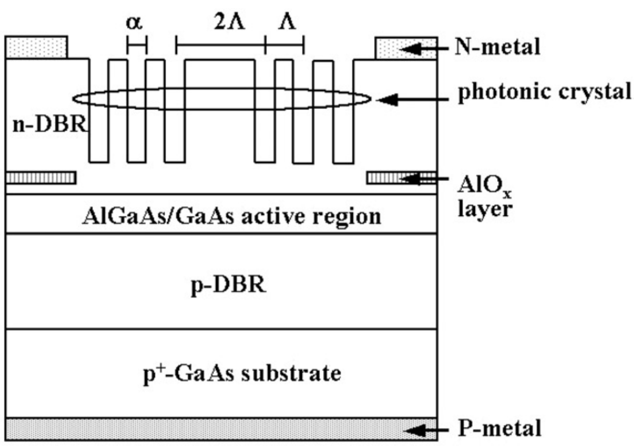

Figure 1. Schematic of the PhC-LED. The etching depth of photonic-crystal (PhC) structure is 17-pairs out of the 22-pair top DBR being etched off.

toward the center from the mesa edge so that the oxide aperture varied from 26 to 54 μm in diameter. The p-ohmic contact was evaporated on the bottom surface of the p^+-GaAs substrate. The n-ohmic contact ring was then formed on the top surface of the n-type contact layer. After that, the triangular lattice pattern of photonic crystal with a one-point or seven-point defect at the center was defined within the n-ohmic contact ring using photo-lithography and etched through the n-type DBR using RIE. The triangular lattice constant Λ is 5 μm and the PhC hole diameter α is 2 to 2.5 μm for the PhC-LED. The lattice constant and hole diameter of the device are larger than the previously reported PhC-LEDs [2,3], which can also provide a similar intensity enhancement effect for the device. The unetched areas of the PhC structure can be used for current spreading so that the overall light emission can be improved. We use the oxide aperture for current confinement and the PhC structure within the n-ohmic contact ring for light extraction.

3. Results and discussion

Figure 2 shows current–voltage (*I–V*) curves of the PhC-LEDs. The *I–V* measurements were done with biasing conditions opposite to the conventional n-substrate LEDs. The differential series resistances of the PhC-LEDs are approximately 100 to 150 Ω at 8 mA for the 60 μm mesa (in diameter) devices. The three different *I–V* curves correspond to three PhC-LEDs with slightly different series resistances. This is mainly due to the PhC hole etching process non-uniformity across the wafer by RIE. Figure 3 shows micrographs of the 60 μm mesa PhC-LED at 0, 10, and 20 mA. The lattice constant Λ is 5 μm and the PhC hole diameter α is 2.5 μm for the PhC-LED. The PhC was made with a one-point defect structure. The micrographs are taken by a high-resolution imaging system with additional light illumination on the device to clearly show the PhC structure of the device. The spontaneous emission mainly emits out of the PhC holes of the device.

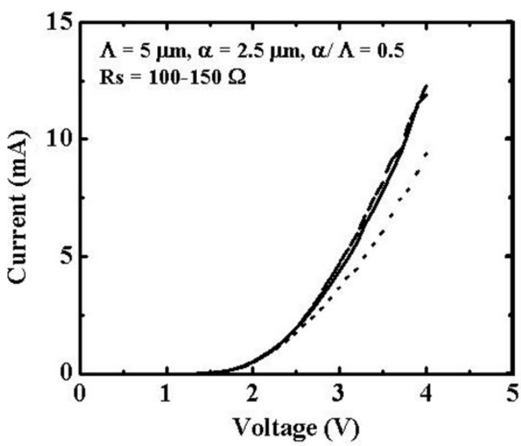

Figure 2. *I–V* characteristics of the 60 μm mesa PhC-LEDs. The lattice constant Λ is 5 μm and the PhC hole diameter α is 2.5 μm. The PhC is a one-point defect structure.

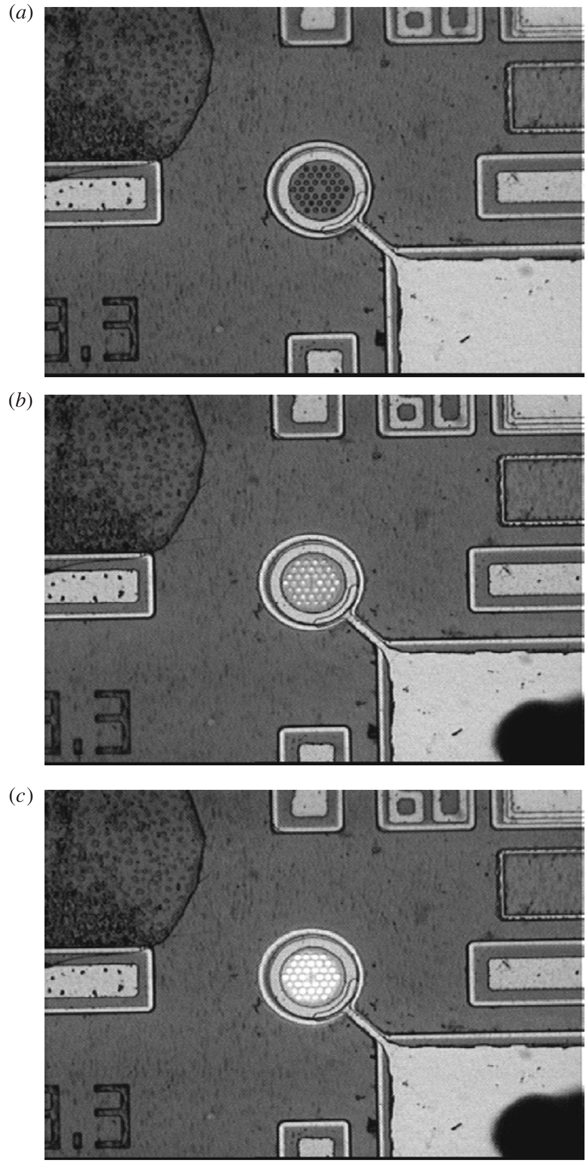

Figure 3. Micrograph of the PhC-LED at (*a*) 0 mA, (*b*) 10 mA, and (*c*) 20 mA. The mesa of the device is 60 µm in diameter. The lattice constant Λ is 5 µm and the PhC hole diameter α is 2.5 µm. The PhC is a 7-point defect structure.

The intensity of the spontaneous light emission increases with increasing current before thermal rollover. The reflectance within the PhC holes is reduced by RIE (17 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 PhC holes can

(a)

(b)

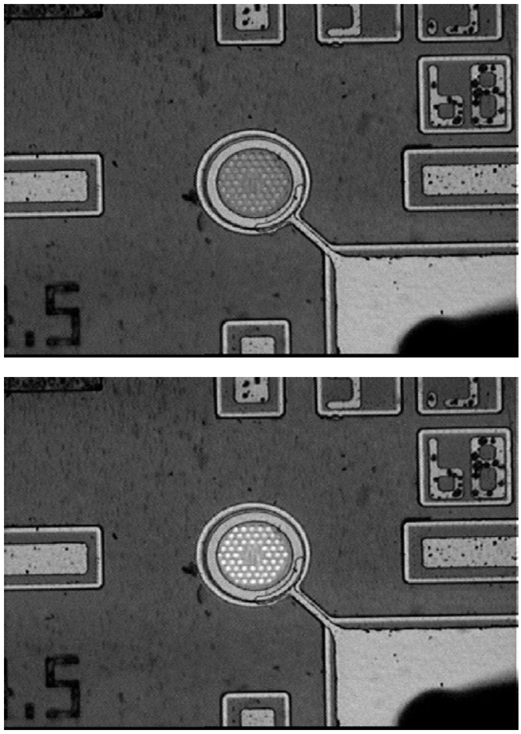

Figure 4. Micrograph of the PhC-LED at (a) 10 mA and (b) 20 mA. The mesa of the device is 68 μm in diameter. The lattice constant Λ is 5 μm and the PhC hole diameter α is 2.5 μm.

also be used for collimation of the transmitted light so that the output beam can be narrower [7]. Although the PhC hole diameter ($\alpha = 2$ to 2.5 μm) is only approximately 2.4 to 3 times the emission wavelength ($\lambda_o \approx 830$ nm), the diffraction of the output light by the PhC holes is smaller than the devices made with nano-scale PhC holes (with diameter $\alpha < 0.5$ μm). Most of the spontaneous emission was blocked by the top DBR and reflected internally within the LED cavity. Figure 4 shows micrographs of the 68 μm mesa PhC-LED at 10 and 20 mA. The PhC structure was made with the seven-point defect at the center so that the total series resistance of the device can be smaller. Figure 5 shows the light–current (*L–I*) characteristics of the 60 μm mesa (one-point defect) and 68 μm mesa (7-point defect) PhC-LEDs. The PhC structure of the 60 μm mesa is the same as Figure 3, while the PhC structure of the 68 μm mesa is the same as Figure 4. The maximum output power for the 60 and 68 μm mesa devices are 0.28 and 0.36 mW, respectively. The higher output power of the 68 μm mesa device is mainly because of the larger light emission area and more PhC holes for light transmission. The three-dimensional (3-D) beam intensity profiles of the 60 μm mesa PhC-LED at 3 and 10 mA are shown in Figure 6. The PhC structure is the same as Figure 3. The 3-D beam

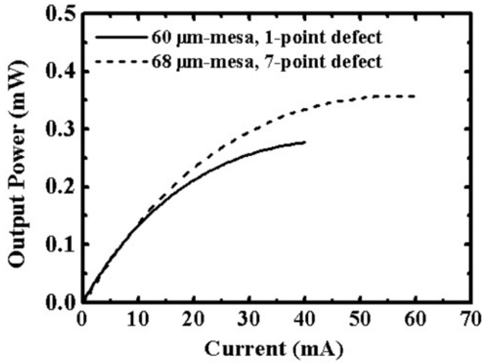

Figure 5. *L–I* characteristics of the 60 μm mesa (1-point defect) and 68 μm mesa (7-point defect) PhC-LEDs. The PhC structure of the 60 μm mesa is the same as Figure 3. The PhC structure of the 68 μm mesa is the same as Figure 4.

intensity profile shows the light intensity distribution profile of the device area. The intensity distribution was extracted out of the high-resolution imaging system. The beam profile shows higher intensity out of the PhC holes. The intensity of the light emission increase with increasing current was also observed by using this 3-D beam analysis system. The micrograph of the 60 μm mesa PhC-LED at 20 mA with illumination turned off is shown in Figure 7(*a*). The LED light clearly emits out of the PhC hole with higher intensity, while the rest of the aperture within the n-ohmic contact ring emits with lower intensity. For comparison, the micrograph of a LED without photonic-crystal structure at 20 mA is shown in Figure 7(*b*). The mesa of this unpatterned LED is also 60 μm in diameter. The intensity of the emitting light is slightly higher near the n-type contact ring of the device. The current spreading of the device is insufficient despite the thickness of the n-DBR being nearly 2.9 μm. A part of the light emission out of the top surface is blocked by the n-DBR (with very high reflectance of 99%). The spectrum of the PhC-LED is shown in Figure 8. The peak wavelength is approximately 827 nm. The line-width ($\Delta\lambda$) of the light emission, which is the full-width at half-maximum (FWHM) of the peak intensity value, is 23.5 nm. The spectrum of the unpatterned LED without PhC (not shown) is similar to that of Figure 8. Narrower resonant-cavity spectral characteristics were not observed for both PhC patterned and unpatterned devices, which may be due to phase mismatching of the grown epitaxial layers.

4. Conclusion

In conclusion, we report p-doped GaAs substrate PhC-LEDs for optical communication applications. 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 a small light beam for optical fiber coupling.

(a)

(b)

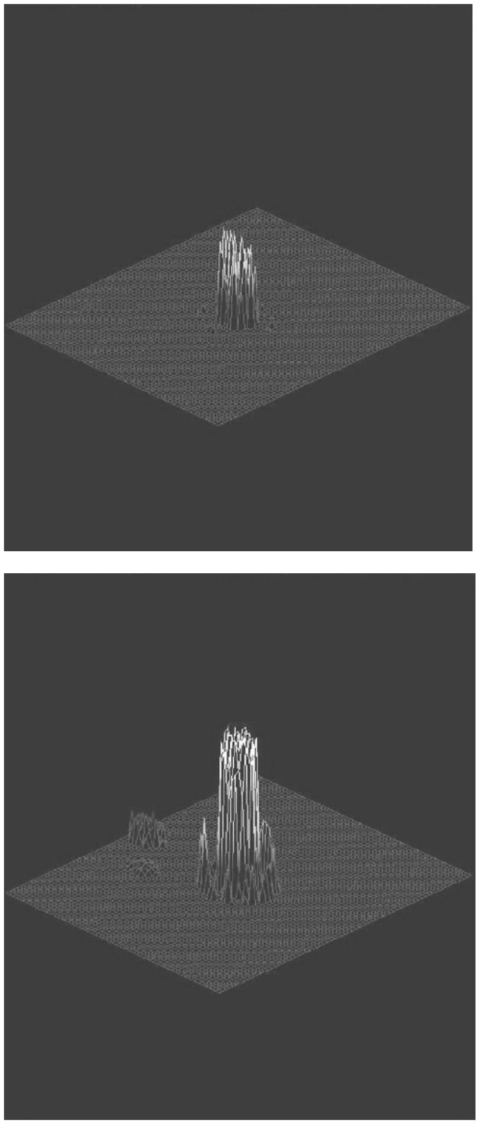

Figure 6. Three-dimensional (3-D) intensity profiles of the PhC-LED at (*a*) 3 mA and (*b*) 10 mA. The mesa of the device is 60 μm in diameter. The PhC structure is the same as Figure 3.

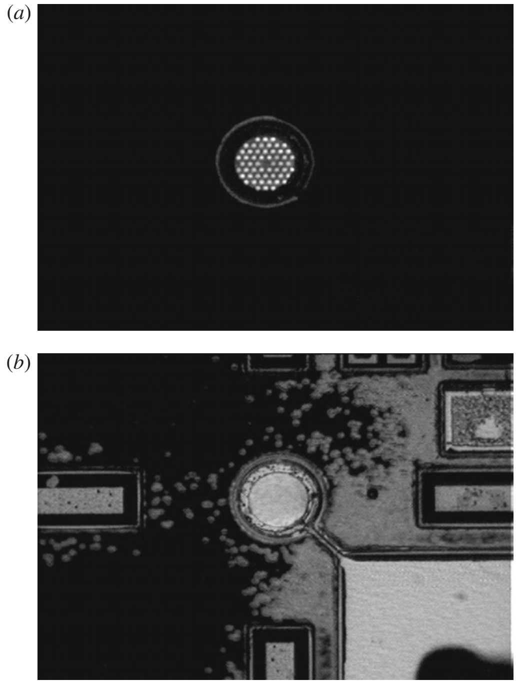

Figure 7. Micrographs of the (*a*) PhC-LED and (*b*) LED without PhC at 20 mA. The mesas of the devices are both 60 μm in diameter. The lattice constant Λ of the PhC structure is 5 μm and the PhC hole diameter α is 2.5 μm. The PhC structure is the same as Figure 3.

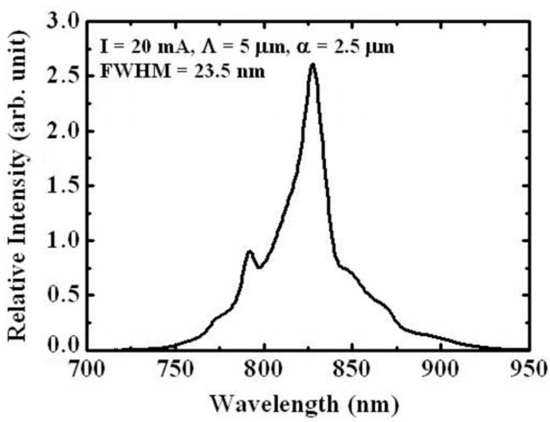

Figure 8. Spectrum of the PhC-LED at 20 mA. The PhC structure is the same as Figure 3.

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