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Characteristics of Multileaf Holey Light-Emitting Diodes for Fiber-Optic Communications

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An oxide-confined multileaf holey light-emitting diode (LED) in the 780 nm range is reported. The device is consisted of bottom distributed Bragg reflector (DBR), quantum wells (QWs), and top DBR, with a multileaf holey structure within the p-ohmic contact ring for light extraction. The spontaneous emission from under the etched holes and internally reflected lights can be extracted and collimated out of the smaller etched leaf holes. High-resolution imaging studies indicate that the device emits with smaller beams mainly through the multileaf etched holes made it suitable for fiber-optic communications.
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KEYWORDS: light-emitting diode (LED), multileaf, holey

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 LEDs (PC-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)] Also, the large resistance inherited from the small aperture limits the modulation bandwidth. 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 ($\geq 300\,\mu$m 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. More recently, a holey LED with a central etched hole for light extraction is reported.[7)] For the 780-nm LEDs, the light output of the devices is compatible with the Si or GaAs receivers in the 650- and 850-nm range for LED-based data communications. In this letter, we report our results on the oxide-confined holey LEDs in the 780 nm range. A multileaf holey structure mainly consisted of smaller etched holes was 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 sidewall within the etched holes for light deflection. High-resolution imaging studies show that the device emits smaller beams with higher intensity through the etched holes near the center. These results indicate that the LEDs emit with collimated beams are suitable for fiber-optic communications.

The schematic of the device structure is shown in Fig. 1. The radius (R) of the central un-etched area is 3 to 4 µm. The typical dimensions for the eight-leaf holey LED are the following. The inner and outer widths (W_1 and W_2) of the trapezoid leaf hole are 1.5 and 4 µm, respectively. The length (L_1) of the trapezoid leaf hole is 5.5 µm. The width of the un-etched area between trapezoid leaf holes is 1.6 to 3.6 µm. The etching depth of holey structure is 27-pair out of the 33-pair top DBR being etched off. Some of the spontaneous emission is reflected internally within the optical cavity formed between the top and bottom DBRs. The light emission from active region under the etched holes and internally reflected light (by the top and bottom DBRs) can be extracted through the etched leaf holes. The light emission can be deflected by the sidewall of the etched hole so that output beam can be more collimated. The epitaxial layers of the holey LED wafers were grown on n^+-GaAs substrates by metal–organic chemical vapor deposition (MOCVD). The bottom DBR consists of a 40.5-pair p-type (silicon-doped) quarter-wave stack ($\lambda/4$) of $Al_{0.9}Ga_{0.1}As/Al_{0.3}Ga_{0.7}As$. The top DBR consists of 33-pair p-type (carbon-doped) $Al_{0.9}Ga_{0.1}As/Al_{0.3}Ga_{0.7}As$ quarter-wave stack. A heavily doped p^+-GaAs contact layer was grown on top of the p-type DBR to facilitate ohmic contact. The 1λ-thick cavity, mainly consists of graded index separate confinement (GRINSCH) active region, contains three undoped $Al_{0.12}Ga_{0.88}As/Al_{0.3}Ga_{0.7}As$ quantum-wells (QWs). The current confinement of the device was done by the selectively oxidized AlO_x layer. Mesas with diameters varied from 42 to 52 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 to 100 µm) of the 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

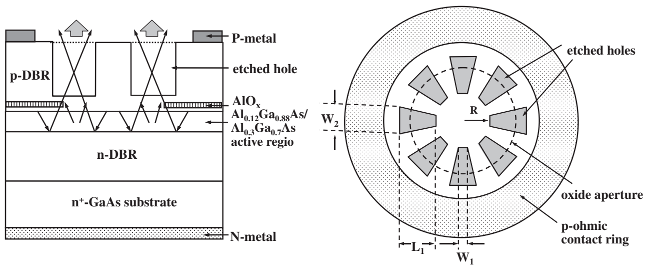


Fig. 1. Schematic diagrams of the multileaf holey LED, (a) cross-sectional view and (b) top view. The etching depth of holey structure is 27-pair out of the 33-pair top DBR being etched off.

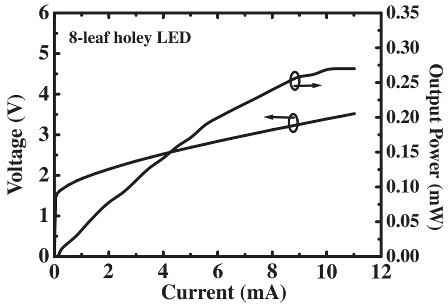
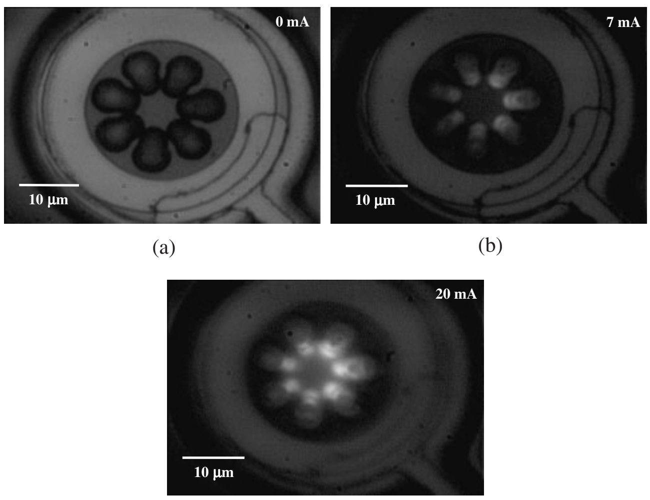


Fig. 2. *L–I–V* characteristics of the 52 μm mesa eight-leaf holey LEDs.

layers was selectively oxidized to AlO_x. The oxidation depth was about 16 μm toward the center from the mesa edge so that the oxide aperture varied from 10 to 20 μm in diameter. The p-ohmic contact ring was then formed on the top surface of the p^+-GaAs contact layer. The n-ohmic contact was evaporated on the bottom surface of the n^+-GaAs substrate. The multileaf holey structure was defined within the p-ohmic contact ring using deep UV photolithography and etched through the p-type DBR using RIE. The etching depth of etched hole is 27-pair out of the 33-pair top DBR being etched off. We use the oxide aperture for current confinement and the multileaf holey structure within the p-ohmic contact ring for light extraction. The current spreading is partly blocked by the multileaf holey structure.

Figure 2 shows CW light–current–voltage (*L–I–V*) output of the holey LEDs. The 52-μm mesa device emits a maximum output power of 0.27 mW at 25 mA (with a maximum output power of 0.3 mW). The output power of the device is smaller, as compared to other LEDs, which is mainly because of a smaller oxide aperture. The differential series resistance of the holey LEDs is 160 Ω at 6 mA. Figure 3 shows the micrographs of the seven-leaf holey LED at 0, 7, and 20 mA. The mesa of the device is 46 μm in diameter. The micrographs were taken by a high-resolution charged-coupled device (CCD) imaging system. The micrograph in Fig. 3(a) was taken with additional light illumination to clearly show the holey structure of the device. The



(a) (b) (c)

Fig. 3. Micrographs of the seven-leaf holey LED at (a) 0, (b) 7, and (c) 20 mA. The mesa of the device is 46 μm in diameter.

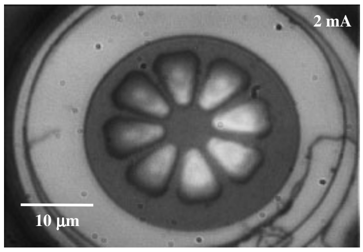


Fig. 4. Micrograph of the eight-leaf holey LED at 2 mA. The mesa of the device is 52 μm in diameter.

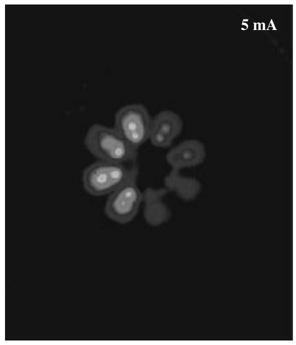


Fig. 5. 2-D beam intensity profile of the eight-leaf holey LED at 5 mA. The mesa of the device is 52 μm in diameter.

actual dimension of the leaf holes was slightly larger than the designed layout, which is mainly due to a deeper RIE etch. The spontaneous emission emits mainly out of the etched leaf holes. The intensity of the light emission increases with increasing current. Figure 4 shows the micrograph of the eight-leaf holey LED at 2 mA. The mesa of the device is 52 μm in diameter (oxide aperture ~ 20 μm in diameter). The light emission out of the leaf holes is clearly observed. As shown in Figs. 3 and 4, the intensity of the light emission is the highest out of the etched leaf holes, with a lower intensity emission near the central un-etched area. The intensity of this area is lower because the light emission is partly blocked by the top DBR. The reflectance within the etched leaf holes is reduced by RIE (27 pairs of the top DBR being etched off), so that the internally reflected spontaneous emission (by the DBRs) and the light emission from active region under the etched holes can be transmitted out of the etched leaf holes (Fig. 1). The two-dimensional (2-D) beam intensity profile of the 52-μm mesa eight-leaf holey LED is shown in Fig. 5. The beam intensity profile was taken using another high-resolution CCD system in combined with a beam analysis software. The intensity distribution is not quite uniform, which is due to slight misalignment of the holey structure with the oxide aperture. The three-dimensional (3-D) beam intensity profiles of the 52-μm mesa eight-leaf holey LED at 1, 3, and 5 mA are shown in Fig. 6. The beam profile shows higher intensity out of the etched leaf hole region. Neutral density (ND) filters were added to attenuate the output beam to avoid saturation of the high-resolution CCD imaging system. The beam intensity increases with increasing current, which indicates that the etched holey structure is well designed for light extraction with small beam sizes. The internally reflected spontaneous emission within the optical cavity and light

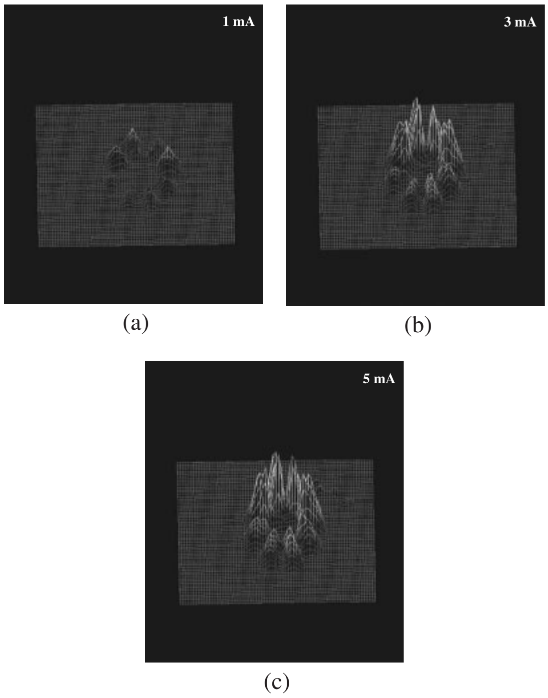


Fig. 6. 3-D beam intensity profiles of the eight-leaf holey LED at (a) 1, (b) 3, and (c) 5 mA. The mesa of the device is 52 µm in diameter. Neutral density (ND) filters were added to attenuate the beam to avoid saturation of the CCD imaging system.

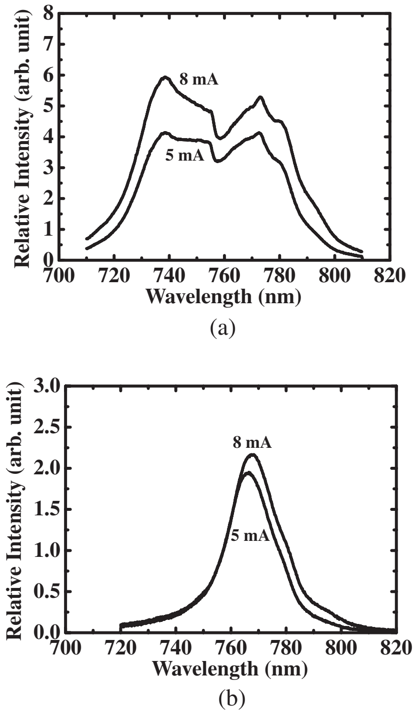


Fig. 7. Spectra of the eight-leaf holey LEDs, (a) device A and (b) device B. The mesas of both devices are 52 µm in diameter.

emission under etched hole region is clearly extracted out of the etched hole of the device, as shown in Figs. 5 and 6. Figure 7 shows two different measured spectra of two eight-leaf holey LEDs at 5 and 8 mA. In Fig. 7(a), the device (device A) shows a broader light emission range from 720 to 790 nm. The spectral linewidths ($\Delta\lambda$s) of the light emission, which are the full-width at half-maximum (FWHM) of the peak intensity value, are 57.5 and 59.3 nm at 5 and 8 mA, respectively. Linewidth narrowing of the emission spectra, similar to that of the resonant-cavity LEDs (RCLEDs),[8,9] was not observed in device A. This suggests that light emission out of the etched leaf holes (Figs. 3–6) may be dominant by nonresonant emission.[8] The reflectance within the etched hole region of the top DBR layers are greatly reduced, which may not able to achieve cavity resonance. The optical confinement of the active region is insufficient, which results in additional short-wavelength emission from 720 to 760 nm. The light emission is mainly contributed from the graded AlGaAs layers in the active region. There is another possible reason, the deep etching of the top DBR layers (approximately six-pair remaining) within the leaf hole region may result in detuning of the cavity resonance and quantum well emission. The emitted light also contains internally reflected spontaneous emission (Fig. 1). In Fig. 7(b), device B shows a narrower light emission range from 755 to 780 nm. The line-widths of the light emission are 21.0 and 22.9 nm at 5 and 8 mA, respectively. The measured linewidths of device B are close to those values obtained by the previous studies (~4–17 nm).[8–10] The spectra of device B are more likely the resonance emission (near 780 nm). The difference in the emission spectra of devices A and B is mainly due to non-uniformities in the epitaxial growth and leaf hole etching. For fiber-optic communications, the wavelength dispersion in Fig. 7(a) may introduce dispersion of the optical fiber,[11] which limit the maximum transmission range. With better leaf hole etching process (RIE) control and monitoring, devices with narrower spectral linewidths can be made.

In conclusion, we report a multileaf holey LED for fiber-optic communications. The present results indicate that a multileaf holey LED using an oxide layer for current confinement and a holey structure for light extraction is an alternative approach to achieve small light beam for optical fiber coupling.

1) D. A. Steigerwald, J. C. Bhat, D. Collins, R. M. Fletcher, M. O. Holcomb, M. J. Ludowise, P. S. Martin, and S. L. Rudaz: IEEE J. Sel. Top. Quantum Electron. **8** (2002) 310.
2) T. Kim, A. J. Danner, and K. D. Choquette: Electron. Lett. **41** (2005) 1138.
3) H. Ishikawa and T. Baba: Appl. Phys. Lett. **84** (2004) 457.
4) B. M. Hawkins, R. A. Hawthorne III, J. K. Guenter, J. A. Tatum, and J. R. Biard: Conf. Proc. 52nd Electronic Components and Technology, 2002, p. 540.
5) S. J. Chang, C. S. Chang, Y. K. Su, P. T. Chang, Y. R. Wu, K. H. Huang, and T. P. Chen: IEEE Photonics Technol. Lett. **9** (1997) 182.
6) P. Modak, M. D'Hondt, D. Delbeke, I. Moerman, P. Van Daele, R. Baets, P. Demeester, and P. Mijlemans: IEEE Photonics Technol. Lett. **12** (2000) 957.
7) H. P. D. Yang, J. N. Liu, F. I. Lai, H. C. Kuo, and J. Y. Chi: Jpn. J. Appl. Phys. **46** (2007) 2941.
8) R. Wirth, C. Karnutsch, S. Kugler, and K. Streubel: IEEE Photonics Technol. Lett. **13** (2001) 421.
9) M. Jalonen, M. Toivonen, J. Kongas, P. Savolainen, A. Salokatve, and M. Pessa: Conf. Proc. Lasers and Electro-Optics Society (LEOS) 10th Annu. Meet., 1997, p. 239.
10) E. F. Schubert, N. E. J. Hunt, R. J. Malik, M. Micovic, and D. L. Miller: J. Lightwave Technol. **14** (1996) 1721.
11) J. P. Powers: *An Introduction to Fiber Optic Systems* (Aksen Associates, Homewood, IL, 1993) Chap. 7.