AIP Applied Physics Letters

High Q microcavity light emitting diodes with buried AlN current apertures

Bo-Siao Cheng, Yun-Lin Wu, Tien-Chang Lu, Ching-Hsueh Chiu, Cheng-Hung Chen, Po-Min Tu, Hao-Chung Kuo, Shing-Chung Wang, and Chun-Yen Chang

Citation: Applied Physics Letters **99**, 041101 (2011); doi: 10.1063/1.3617418
View online: http://dx.doi.org/10.1063/1.3617418
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/99/4?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

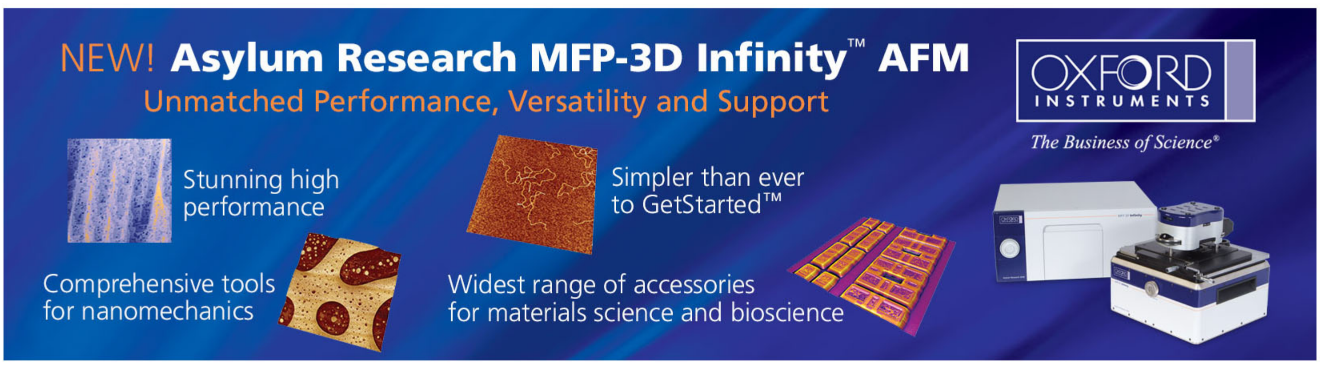
High current-induced degradation of AlGaN ultraviolet light emitting diodes
J. Appl. Phys. **109**, 103108 (2011); 10.1063/1.3590149

Gallium-nitride-based microcavity light-emitting diodes with air-gap distributed Bragg reflectors
Appl. Phys. Lett. **91**, 211108 (2007); 10.1063/1.2805028

Room temperature polariton luminescence from a Ga N Al Ga N quantum well microcavity
Appl. Phys. Lett. **89**, 071107 (2006); 10.1063/1.2335404

Progress in AlInN–GaN Bragg reflectors: Application to a microcavity light emitting diode
J. Appl. Phys. **97**, 084505 (2005); 10.1063/1.1872197

Crack-free fully epitaxial nitride microcavity using highly reflective AlInNGaN Bragg mirrors
Appl. Phys. Lett. **86**, 031107 (2005); 10.1063/1.1849851



This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 140.113.38.11 On: Wed, 30 Apr 2014 09:00:33

High Q microcavity light emitting diodes with buried AlN current apertures

Bo-Siao Cheng, Yun-Lin Wu, Tien-Chang Lu,[a)] Ching-Hsueh Chiu, Cheng-Hung Chen, Po-Min Tu, Hao-Chung Kuo,[b)] Shing-Chung Wang, and Chun-Yen Chang
Department of Photonics, National Chiao-Tung University, 1001 Ta Hsueh Rd., Hsinchu 300, Taiwan

(Received 13 May 2011; accepted 1 July 2011; published online 25 July 2011)

We demonstrate a GaN-based high-Q microcavity light emitting diode (MCLED) with a buried AlN current aperture. A thin AlN layer is inserted on the InGaN/GaN multiple quantum wells as a current blocking layer and an optical confinement layer. The GaN-based MCLED is composed of a 29-pair GaN/AlN distributed Bragg reflector (DBR), an eight-pair of SiO_2/Ta_2O_5 dielectric DBR, and a three-λ optical thickness InGaN/GaN active region. The current can be injected more effectively in the MCLED with a buried AlN current aperture. The output emission has a dominant emission peak wavelength at 440 nm with a very narrow linewidth of 0.52 nm, corresponding to a cavity Q-value of 846 at a driving current of 5 mA. © *2011 American Institute of Physics*. [doi:10.1063/1.3617418]

GaN-based materials have attracted a great attention since the early 1990s due to the wide direct band gap and the promising potential for the optoelectronic devices such as light emitting diodes and laser diodes.[1,2] So far, GaN-based edge emitting lasers have been demonstrated[3] and applied in commercial products for high density optical storage applications. However, the vertical cavity surface emitting lasers (VCSELs), with superior optical characteristics such as the single longitudinal mode emission, low divergence angle, and two-dimensional array capability, are still under development and currently gaining much attention due to the potential in realization of microcavity polariton lasers operated at room temperature.[4] Optically pumped GaN-based VCSELs have been reported by using different kinds of optical cavity structures, such as dielectric distributed Bragg reflectors (DBRs), VCSELs with cavities consisting of top and bottom dielectric DBRs,[5] and hybrid DBR VCSELs with cavities consisting of epitaxially grown bottom nitride-based DBRs and top dielectric DBRs.[6] We have recently demonstrated the continuous wave (cw) current injection of GaN-based VCSEL with hybrid mirrors at 77 K in 2008 (Ref. 7) and 300 K in 2010.[8] Meanwhile, the room temperature operation of GaN-based VCSEL devices was reported using optical cavities sandwiched by double dielectric DBRs.[9,10] The major improvements of these devices to achieve room temperature operation are by using a thinner transparent conducting layer of about 50 nm to improve the current spreading and by using the GaN substrate to ensure the good crystal quality of active layers. However, to form VCSELs with double dielectric DBRs required complex fabrication process, such as laser lift-off or elaborated polishing and bonding process.[11]

Despite of demonstration of room temperature current injected GaN-based VCSELs, the lateral optical confinement was still a lack in these VCSEL structures, resulting in higher optical loss and difficulty in controlling the quality of output beams.[12] In order to improve the optical confinement of these devices, we investigated a microcavity light emitting diode (MCLED) with a buried AlN current aperture, which can also be used as a lateral optical confinement layer. Since a pre-defined current aperture with a small diameter is introduced in the MCLED structure, the transparent current spreading layer can be omitted. The current still can be injected effectively in the current aperture and the optical loss introduced by the transparent current spreading layer could be neglected. The output emission of our device shows a very narrow linewidth of 0.52 nm, corresponding to a cavity Q-value of 846 at a driving current of 5 mA and a dominant emission peak wavelength at 440 nm. In addition, the emission peak wavelength as a function of the current is almost invariant with increasing injection current, demonstrating potential temperature-sensitive applications. This microcavity structure with a buried AlN current aperture is suggested to be a better configuration of GaN-based VCSELs for further threshold current reduction.

The schematics of GaN-based MCLEDs without and with a buried AlN current aperture structure are shown in Fig. 1. The microcavity and bottom DBR structure were grown in a vertical-type metal organic chemical vapor deposition (MOCVD) system (EMCORE D75), which could hold one 2-in. sapphire wafer. The nitride-based DBR with high reflectivity (~97%) used in the experiment was the stacks of 29-pair AlN/GaN layers with insertion of the AlN/GaN super-lattice. The super-lattice was inserted for releasing strain during the growth of AlN/GaN DBR to further improve the interface sharpness and to raise the reflectivity. Then, a microcavity formed by a GaN-based p-n junction was grown following the growth of the DBR structure. The microcavity composed of a 900 nm-thick n-type GaN layer, a ten-pair of $In_{0.2}Ga_{0.8}N$/GaN (2.5 nm/10.5 nm) multiple quantum wells, a 24 nm-thick AlGaN electron blocking layer, a 20 nm-thick p-GaN layer, a 30 nm-thick AlN current blocking layer, and a 155 nm-thick p-GaN layer. The MCLED with an AlN current aperture was fabricated by the following steps. First, the MCLED epi-structure was grown on a c-plane sapphire substrate and the growth stopped at the 20 nm-thick p-GaN layer just right above the AlGaN electron blocking layer. Then, the SiO_2 hard mask used to define the current aperture was grown on that MCLED epi structure

a)Electronic mail: timtclu@mail.nctu.edu.tw.
b)Electronic mail: hckuo@faculty.nctu.edu.tw.

 © 2011 American Institute of Physics

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 140.113.38.11 On: Wed, 30 Apr 2014 09:00:33

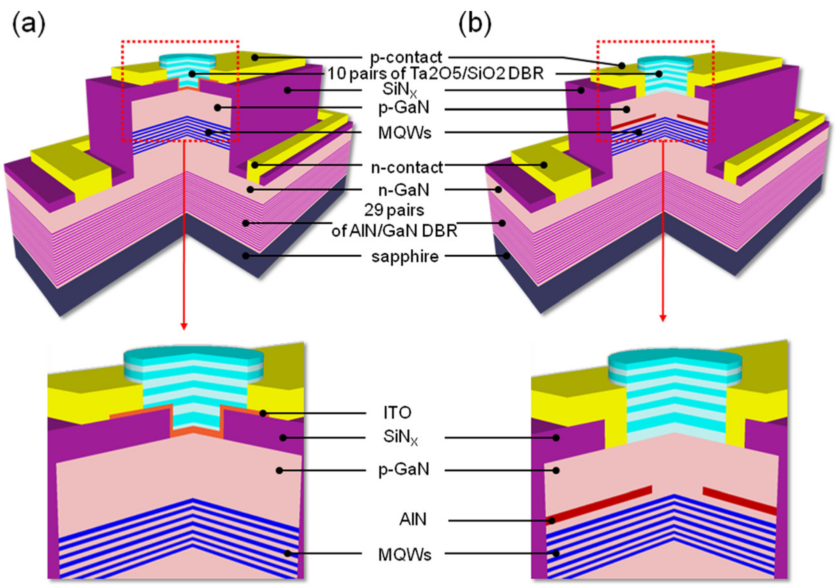


FIG. 1. (Color online) The schematics of MCLEDs (a) without and (b) with a buried AlN current aperture. To assist the current injection, an ITO layer was inserted in (a).

by plasma-enhanced chemical vapor deposition (PECVD) with the effective current apertures varying from 5 μm to 10 μm. The 30 nm-thick AlN layer was re-grown on the patterned sample surface by MOCVD system with the epitaxial environment at 1020°C and 100 torr. Then, the SiO_2 mask was lifted off by using buffered oxide etch (BOE) wet etching. The 130 nm p-type GaN and 2 nm InGaN layer were regrown on the sample. The 2 nm InGaN layer is used for reduction of the Schottky barrier height and improving the current spreading in p-type GaN. The buried AlN forms a current aperture in the MCLED shown as Fig. 1(b). For comparison, the conventional MCLED without an AlN current aperture fabricated with emission apertures formed by SiN_x patterns varying from 5 μm to 10 μm, shown as Fig. 1(a). In order to improve the current injection efficiency in the emission aperture, a 30 nm-thick indium tin oxide (ITO) layer was deposited on the top of the microcavity. The Ti/Al/Ni/Au and Ni/Au contacts were deposited to serve as n-type and p-type electrodes, respectively. Finally, a ten-pair Ta_2O_5/SiO_2 DBR (a measured reflectivity of over 99% at $\lambda = 440$ nm) was evaporated in an ion-assisted e-gun system as the top mirror to complete the MCLED devices. The 5 μm-diameter aperture MCLEDs with and without AlN were driven by a Keithley 238 current source in the cw operation mode. The emission light was then collected by a 25 μm-diameter multimode fiber using a microscope with a 40× objective and fed into the spectrometer/charge-coupled device (CCD) (Jobin-Yvon Triax 320 Spectrometer) with a spectral resolution of ~0.15 nm for spectral output measurement.

The voltage and the light output power of the MCLED with and without AlN as a function of injection current at 300 K is shown in Fig. 2. The turn on voltage and serial resistance of the 5 μm-diameter aperture MCLED without AlN are about 7.14 V and 385 Ω, respectively. The MCLED with AlN shows the slightly higher voltage and serial resistance of 7.35 V and 389 Ω compared with the conventional device, respectively. This is because the current path from the p-contact to active regions in MCLED with a buried AlN current aperture would be longer than the one without AlN. In addition, the effective area of aperture in MCLED with AlN for current passing through is smaller than the one without AlN. The light output power-current (L-I) shows that the MCLED with AlN has higher light output than the MCLED without AlN at the same injection current of 15 mA. The better light output performance in the MCLED with AlN could be attributed to the smaller optical loss due to lack of the ITO layer in the light path of microcavity.

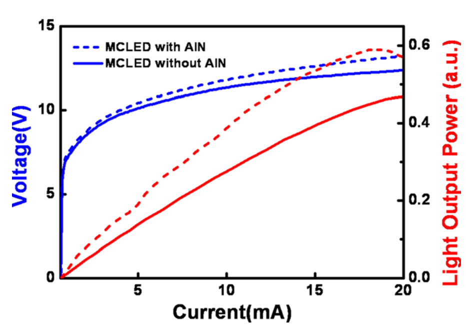


FIG. 2. (Color online) The voltage and the light output characteristics of the MCLEDs with and without a buried AlN current aperture as a function of injection current at 300 K.

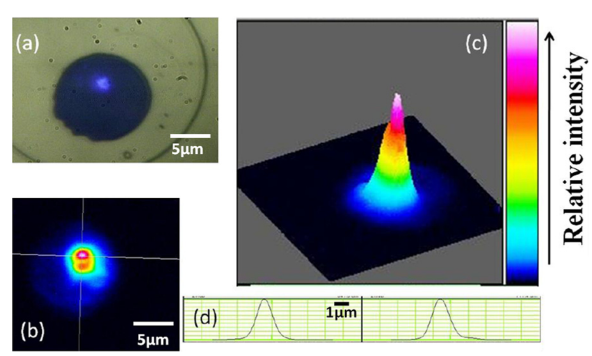


FIG. 3. (Color online) (a) The emission image of the MCLED with a buried AlN current aperture under high magnification CCD image (b)–(d) Beam-view of the emission profile on the AlN current aperture.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 140.113.38.11 On: Wed, 30 Apr 2014 09:00:33

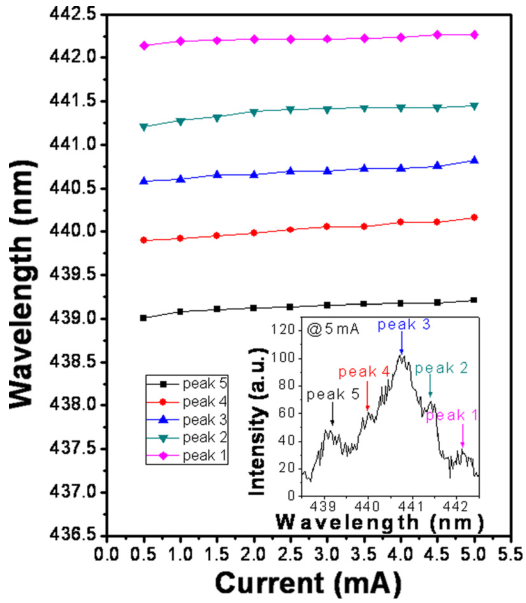


FIG. 4. (Color online) The cavity mode wavelength of GaN-based MCLED with a buried AlN current aperture as a function of current variation from 0.5 to 5 mA. The inset shows the spectrum of MCLED with a buried AlN current aperture at 5 mA.

We could clearly observe the light emission of the MCLED with a buried AlN current aperture locates pretty well in the aperture as shown in Fig. 3(a). In order to observe more details of the light emission in the current aperture, we also observed the optical intensity distribution by means of the CCD and beam-view program. The color in Figs. 3(b) and 3(c) represents the relative optical intensity emitted from observed device, and this figure shows the current is uniformly injected into the aperture. The light beam was observed a Gauss distribution shown in Fig. 3(d). Compared to the previous reports,[7,13] the carrier is tightly confined in the small aperture and no spotty light emission can be observed, indicating that this structure can lessen the spatial inhomogeneous broadening in the active region and is beneficial to laser operation.

Figure 4 shows the cavity mode wavelength of GaN-based MCLED with a buried AlN current aperture as a function of current variation from 0.5 to 5 mA. The inset of Fig. 4 is the spectrum of MCLED with a buried AlN current aperture at 5 mA current injection. From the emission peak wavelength at $\lambda = 440$ nm and the emission linewidth at $\Delta\lambda = 0.52$ nm, the cavity Q is estimated by $\lambda/\Delta\lambda$ to be 846. The emission wavelength of the MCLED is mainly determined by the average refractive index throughout the microcavity. The increase of the refractive index in the GaN cavity layer as the temperature increases will result in the red-shift of the emission wavelength. As a result, the wavelength shows a red-shift of about 0.2 nm as the current rose from 0.5 to 5 mA. The emission peak wavelength as a function of the current is almost invariant with an increasing injection current, demonstrating potential in temperature-sensitive applications. For an almost planar resonator, such as a MCLED with top and bottom DBRs, the mode spacing can be given by,[14] $\Delta v = \frac{C\lambda_0}{2\pi^2 n^2 w_0{}^2}$ where n is the effective refractive index and w_0 is the minimum spot size. The measured spot size is 1 μm and the estimated mode spacing is 0.7 nm for $n = 2.5$ and $\lambda_0 = 440$ nm. The measured mode spacing is approximately 0.7 nm as shown in Fig. 4, which is consistent with the estimated value.

In summary, we have investigated a MCLED with a buried AlN current aperture. In the electrical characteristics, the light output of the MCLED with a buried AlN layer was higher than the one without the AlN at the same injection current. The emission from the MCLED with a buried AlN layer shows a very narrow linewidth of 0.52 nm, corresponding to a cavity Q-value of 846, and a dominant emission peak wavelength at 440 nm. The measured cavity mode spacing is approximately 0.7 nm, which is consistent with the estimated value, demonstrating the effect of lateral optical confinement provided by the AlN layer. In addition, the emission peak wavelength as a function of the current is almost invariant with an increasing injection current indicating potential temperature-sensitive applications. Further optimization of bottom DBR growth and crystal quality in this structure would promise to realize low threshold GaN-based VCSELs or GaN-based polariton lasers.

This work was supported by the Ministry of Economic Affairs of the Republic of China (MOEA) and in part by the National Science Council of Taiwan under Contract Nos. NSC 99-2120-M-009-007 and 98-2923-E-009-001-MY3.

[1]S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, Appl. Phys. Lett. **70**, 868 (1997).
[2]S. Nakamura, Science **281**, 956 (1998).
[3]S. Nakamura, M. Senoh, S.-I. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, Appl. Phys. Lett. **69**, 4056 (1996).
[4]G. Christmann, R. Butté, E. Feltin, J. F. Carlin, and N. Grandjean, App. Phys. Lett. **93**, 051102 (2008).
[5]Y.-K. Song, H. Zhou, M. Diagne, I. Ozden, A. Vertikov, A. V. Nurmikko, C. Carter-Coman, R. S. Kern, F. A. Kish, and M. R. Krames, Appl. Phys. Lett. **74**, 3441 (1999).
[6]T. Someya, K. Tachibana, J. Lee, T. Kamiya, and Y. Arakawa, Jpn. J. Appl. Phys., Part 2 **37**, L1424 (1998).
[7]T. C. Lu, C. C. Kao, H. C. Kuo, G. S. Huang, and S. C. Wang, Appl. Phys. Lett. **92**, 141102 (2008).
[8]T. C. Lu, S. W. Chen, T. T. Wu, P. M. Tu, C. K. Chen, C. H. Chen, Z. Y. Li, H. C. Kuo, and S. C. Wang, Appl. Phys. Lett. **97**, 071114 (2010).
[9]Y. Higuchi, K. Omae, H. Matsumura, and T. Mukai, Appl. Phys. Express **1**, 121102 (2008).
[10]K. Omae, Y. Higuchi, K. Nakagawa, H. Matsumura, and T. Mukai, Appl. Phys. Express **2**, 052101 (2009).
[11]S. C. Wang, T. C. Lu, C. C. Kao, J. T. Chu, G. S. Huang, H. C. Kuo, S. W. Chen, T. T. Kao, J. R. Chen, and L. F. Lin, Jpn. J. Appl. Phys., Part 1 **46**, 5397 (2007).
[12]A. Castiglia, D. Simeonov, H. J. Buehlmann, J.-F. Carlin, E. Feltin, J. Dorsaz, R. Butté, and N. Grandjean, Appl. Phys. Lett. **90**, 033514 (2007).
[13]J. T. Chu, T. C. Lu, H. H. Yao, C. C. Kao, W. D. Liang, J. Y. Tsai, H. C. Kuo, and S. C. Wang, Jpn. J. Appl. Phys. **45**, 2556 (2006).
[14]A. Sharma, J. M. Yarrison-Rice, H. E. Jackson, and K. D. Choquette, J. Appl. Phys. **92**, 6837 (2002).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 140.113.38.11 On: Wed, 30 Apr 2014 09:00:33