AIP | Applied Physics Letters

Low-threshold stimulated emission at 249nm and 256nm from AlGaN-based multiple-quantum-well lasers grown on sapphire substrates

Xiao-Hang Li, Theeradetch Detchprohm, Tsung-Ting Kao, Md. Mahbub Satter, Shyh-Chiang Shen, P. Douglas Yoder, Russell D. Dupuis, Shuo Wang, Yong O. Wei, Hongen Xie, Alec M. Fischer, Fernando A. Ponce, Tim Wernicke, Christoph Reich, Martin Martens, and Michael Kneissl

Citation: Applied Physics Letters **105**, 141106 (2014); doi: 10.1063/1.4897527
View online: http://dx.doi.org/10.1063/1.4897527
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/105/14?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Deep ultraviolet photopumped stimulated emission from partially relaxed AlGaN multiple quantum well heterostructures grown on sapphire substrates
J. Vac. Sci. Technol. B **32**, 061204 (2014); 10.1116/1.4898694

Deep-ultraviolet lasing at 243nm from photo-pumped AlGaN/AlN heterostructure on AlN substrate
Appl. Phys. Lett. **102**, 101110 (2013); 10.1063/1.4795719

Stimulated emission at 340 nm from AlGaN multiple quantum well grown using high temperature AlN buffer technologies on sapphire
Appl. Phys. Lett. **95**, 161904 (2009); 10.1063/1.3253416

Room-temperature deep-ultraviolet lasing at 241.5 nm of AlGaN multiple-quantum-well laser
Appl. Phys. Lett. **84**, 3567 (2004); 10.1063/1.1737061

2.5–3.5 μm optically pumped GaInSb/AlGaInSb multiple quantum well lasers grown on AlInSb metamorphic buffer layers
J. Appl. Phys. **93**, 3177 (2003); 10.1063/1.1544425

Confidently measure down to 0.01 fA and up to 10 PΩ
Keysight B2980A Series Picoammeters/Electrometers
View video demo›
KEYSIGHT TECHNOLOGIES

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: 129.219.247.33 On: Mon, 22 Dec 2014 04:47:22

APPLIED PHYSICS LETTERS **105**, 141106 (2014)

Low-threshold stimulated emission at 249 nm and 256 nm from AlGaN-based multiple-quantum-well lasers grown on sapphire substrates

Xiao-Hang Li,[1] Theeradetch Detchprohm,[1] Tsung-Ting Kao,[1] Md. Mahbub Satter,[1]
Shyh-Chiang Shen,[1] P. Douglas Yoder,[1] Russell D. Dupuis,[1,a),b)] Shuo Wang,[2]
Yong O. Wei,[2] Hongen Xie,[2] Alec M. Fischer,[2] Fernando A. Ponce,[2] Tim Wernicke,[3]
Christoph Reich,[3] Martin Martens,[3] and Michael Kneissl[3]
[1]*Center for Compound Semiconductors and School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0250, USA*
[2]*Department of Physics, Arizona State University, Tempe, Arizona 85287-1504, USA*
[3]*Technical University of Berlin, Institute for Solid State Physics, Berlin D-10623, Germany*

(Received 16 May 2014; accepted 20 September 2014; published online 8 October 2014)

Optically pumped deep-ultraviolet (DUV) lasing with low threshold was demonstrated from AlGaN-based multiple-quantum-well (MQW) heterostructures grown on sapphire substrates. The epitaxial layers were grown pseudomorphically by metalorganic chemical vapor deposition on (0001) sapphire substrates. Stimulated emission was observed at wavelengths of 256 nm and 249 nm with thresholds of 61 kW/cm^2 and 95 kW/cm^2 at room temperature, respectively. The thresholds are comparable to the reported state-of-the-art AlGaN-based MQW DUV lasers grown on bulk AlN substrates emitting at 266 nm. These low thresholds are attributed to the optimization of active region and waveguide layer as well as the use of high-quality AlN/sapphire templates. The stimulated emission above threshold was dominated by transverse-electric polarization. This work demonstrates the potential candidacy of sapphire substrates for DUV diode lasers. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4897527]

Deep-ultraviolet (DUV) emitters with wavelengths shorter than 280 nm have numerous applications such as high-density optical storage, disinfection, and biochemical identification. However, most of the commercially available DUV emitters including mercury lamps, quadrupled Nd:YAG lasers, and excimer lasers have limitations in many applications due to their large footprint, poor reliability, or toxicity. Recently, the III-N semiconductor-based UV light emitters have drawn great attention, as the AlInGaN direct bandgap covers the entire DUV range (200–280 nm), which can lead to efficient, compact, and reliable DUV emitters.

The material quality of III-N semiconductors, especially for $Al_xGa_{1-x}N$ ($x > 0.50$) materials with bandgap energies from 4.4 to 6.0 eV, is the key to the development of high-performance DUV emitters. However, it has been shown that generally there is a degradation of the structural quality of heteroepitaxial $Al_xGa_{1-x}N$ ($x > 0.50$) materials with increasing Al molar fraction.[1] This has a negative impact on the performance of DUV emitters since the quantum efficiency is more sensitive to the dislocation-related non-radiative recombination centers than for InGaN-based visible emitters.[2,3] Although AlGaN-based electrically driven DUV light-emitting diodes (LEDs) have been realized on foreign substrates such as sapphire,[4] the high-dislocation density within the heteroepitaxial $Al_xGa_{1-x}N$ layers grown on foreign substrates makes the low-threshold DUV lasing below 280 nm by optical pumping or electrical pumping difficult to achieve[5–9] as the defects are more detrimental to performance of lasers.

Recently, low-threshold optically pumped DUV lasers containing AlGaN-based multiple-quantum wells (MQWs) have been demonstrated by homoepitaxial growth on c-plane bulk AlN substrates.[10–15] Bulk AlN substrates were used in these studies due to their low-dislocation density and the reduction of the lattice mismatch and thermal expansion difference between the AlN substrate and Al-rich AlGaN epitaxial layers, thus leading to high-quality active regions with relatively low-dislocation density. However, because of limited availability, smaller area, impurity absorption, and high cost of the bulk AlN substrates today, it is much more desirable to grow DUV lasers on the vastly more available and lower-cost sapphire substrates.

In this paper, we report optically pumped AlGaN-based MQW DUV lasers grown on (0001) sapphire substrates by metalorganic chemical vapor deposition (MOCVD). Lasing at 249 nm ("the 249-nm laser") and 256 nm ("the 256-nm laser") with low pumping-power thresholds were demonstrated in an edge-emission configuration at room temperature (RT). Atomic-force microscopy (AFM), X-ray diffraction (XRD), and power-dependent photoluminescence (PL) measurements were carried out to investigate crystalline quality of the lasers and stimulated emission characteristics.

The entire epitaxial AlGaN MQW laser structure was grown on 2-in. diameter *c*-plane sapphire substrates in a $3 \times 2''$ AIXTRON low-pressure MOCVD reactor with a close-coupled showerhead configuration. As shown in the cross-sectional schematic diagram in Figure 1, the structure first comprises an AlN template layer deposited directly on the sapphire substrate with a thickness of 3.5 μm estimated

---

[a)] Author to whom correspondence should be addressed; Electronic mail: dupuis@gatech.edu

[b)] Also at School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0250, USA.

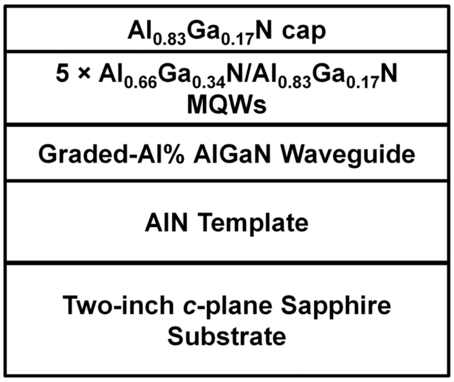

FIG. 1. Cross-sectional schematic diagram of the DUV AlGaN MQW laser structure grown on a (0001) sapphire substrate.

by *in-situ* reflectance monitoring. To achieve lasing from the MQW active region grown on sapphire substrates, the use of an AlN/sapphire template with relatively low threading dislocation density (TDD) was necessary to reduce the dislocation density in the active region and thus improve gain therein. In this work, the TDD of the template layer was $2.5 \times 10^9/cm^2$ as determined by cross-sectional transmission-electron microscopy (TEM). This level of TDD was shown to lead to an estimated internal quantum efficiency (IQE) of ∼40%–60% for the AlGaN MQWs emitting at ∼250 nm by Ban *et al.*, and thus can enable lasing.[3] The root-mean-square (RMS) surface roughness of the AlN template is less than 0.10 nm and 0.12 nm, respectively, as determined by $1 \times 1\,\mu m^2$ and $5 \times 5\,\mu m^2$ AFM measurements, which are comparable to bulk AlN substrates.[16] Thus, the AlN template layer used herein provided a smooth surface for subsequent growth of AlGaN-based laser structures.

Subsequently, a 90-nm $Al_xGa_{1-x}N$ grading waveguide layer, five periods of 2.0-nm-$Al_{0.66}Ga_{0.34}N$/4.8-nm-$Al_{0.83}Ga_{0.17}N$ MQWs designed for laser emission at around 250–255 nm and a thin $Al_{0.83}Ga_{0.17}N$ cap layer for surface passivation and carrier confinement were grown on the AlN template layer sequentially. The composition and thickness of these AlGaN-based layers were optimized experimentally to improve gain and enhance optical confinement in the active region and thus reduce threshold. In the future, detailed waveguide modeling will be carried out to further optimize the structure. As shown in the asymmetric (105) reciprocal space mapping (RSM) by XRD in Figure 2(a), all the epitaxial layers were pseudomorphically grown and thus fully strained, which retained the quality of the AlN template layer. The $5 \times 5\,\mu m^2$ AFM image of Figure 2(b) shows the surface of a MQW laser wafer, where terraced step flows were observed indicating two-dimensional epitaxial growth. The RMS roughness is 0.49 nm.

Subsequent to the growth, the wafer was cleaved into Fabry-Perot laser bars assisted by laser[17] or hand scribing from the back side of the 430 μm-thick sapphire substrates. The laser scribing was shown to lead to a smoother and more uniform facet than the hand scribing observed by scanning electron microscopy (SEM) in this study. No high-reflection (HR) coating was applied to facets of the bars as was done in one of our previous studies.[18] The laser bars were optically pumped at RT by an ArF excimer laser ($\lambda = 193$ nm) with a pulse width of 20 ns and frequency of 10 Hz. The excitation stripe was perpendicular to the cleaved facets of the laser bars. Details of optical pumping experiment can be found elsewhere.[12]

The RT PL spectra of the 249-nm laser and 256-nm laser with pumping power densities below and above the lasing threshold are shown in Figures 3(a) and 4(a), respectively. The 249-nm laser and 256-nm laser were scribed by laser and hand, respectively. The difference of the emission wavelengths of 7 nm between the two lasers is due to normal shift of sample condition between 2-in. wafers grown in this MOCVD reactor. The cavity lengths of the 249-nm laser and 256-nm laser are 1.20 mm and 1.17 mm, respectively. In Figures 3(b) and 4(b), the spectral integrated intensities as a function of the pumping power density of the 249-nm laser and the 256-nm laser demonstrate threshold pumping power densities of 95 kW/cm^2 and 61 kW/cm^2, respectively. As also shown in Figures 3(b) and 4(b), spectral linewidth of the 249-nm laser and the 256-nm laser gradually reduces with increasing pumping power density and reaches 0.8 and 1.6 nm at the maximum measured pumping-power density, indicating stimulated emission. The higher slope efficiency and smaller linewidth of the 249-nm laser than those of the 256-nm laser probably result from a smoother and more uniform facet because of the laser scribing. The thresholds are more than an-order-of-magnitude lower than the previously reported optically pumped AlGaN MQW DUV laser grown on foreign 4H-SiC substrates.[8] In addition, the thresholds are comparable with the reported state-of-the-art optically pumped AlGaN MQW DUV lasers grown on bulk AlN substrates lasing at 266 nm with a threshold of 41 kW/cm^2.[19]

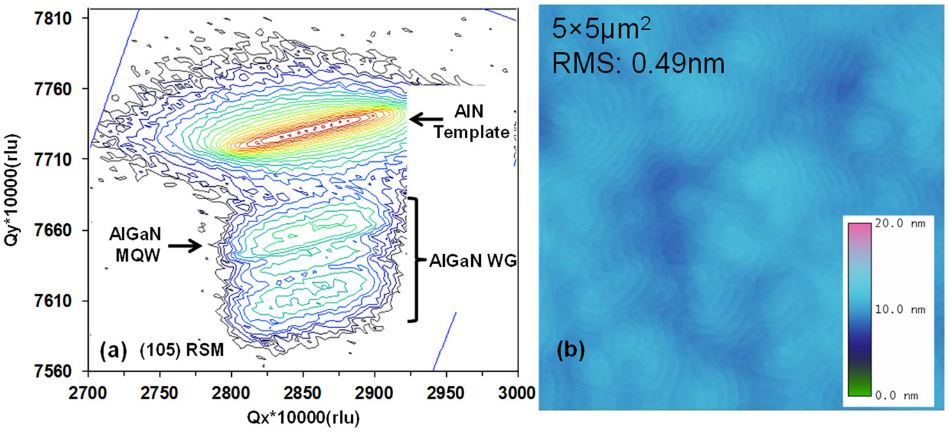

FIG. 2. (a) XRD (105) RSM of the laser structure on a (0001) sapphire substrate demonstrating pseudomorphic growth and (b) $5 \times 5\,\mu m^2$ AFM image of surface of the laser structure.

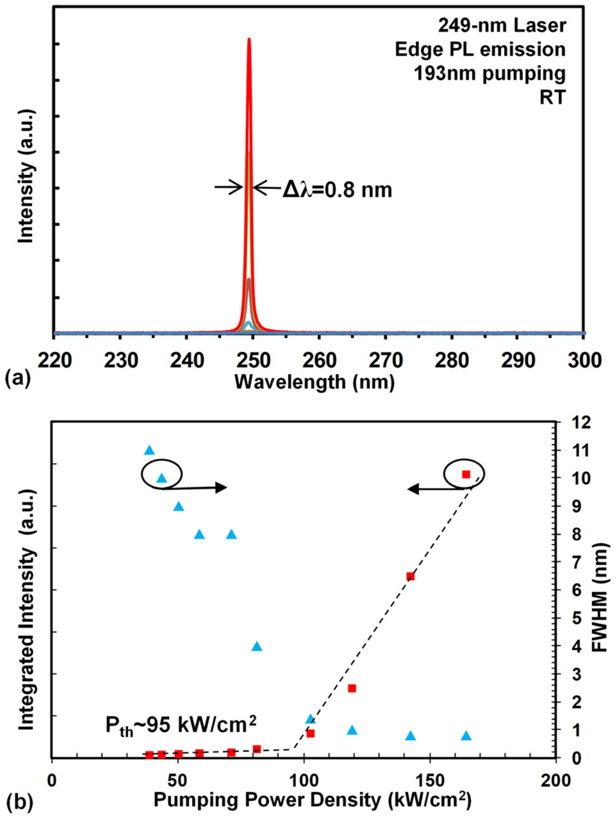

FIG. 3. (a) Laser emission spectra and (b) spectral integrated intensity and spectral linewidth versus pumping power densities of the 249-nm laser.

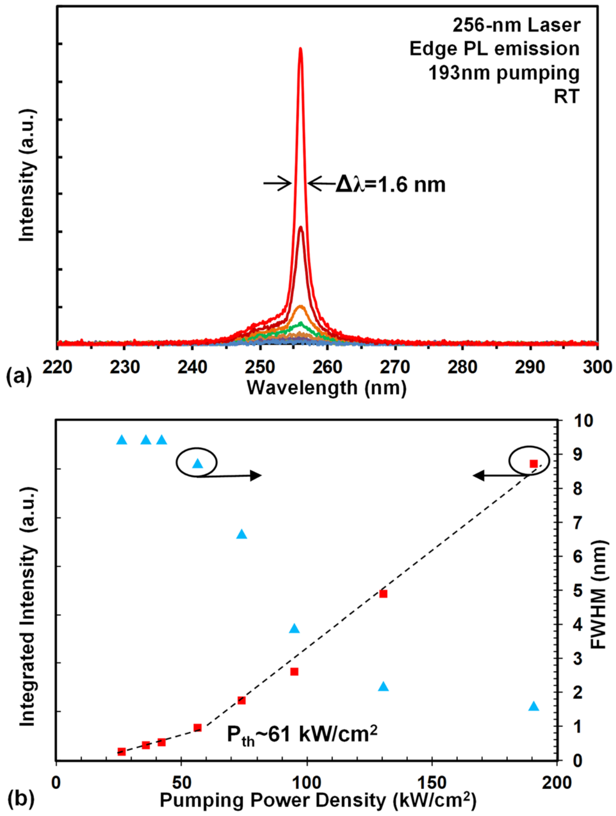

FIG. 4. (a) Laser emission spectra and (b) spectral integrated intensity and spectral linewidth versus pumping power densities of the 256-nm laser.

It is difficult to explain this comparability without knowing details such as structure, growth conditions, and pumping conditions of Ref. 19. The AlN substrate possesses much lower TDD than the AlN/sapphire templates used in this study and thus could potentially lead to a high IQE and an even lower threshold. However, the following studies may shed some light on explaining the comparability of thresholds. Preliminary results from temperature-dependent PL studies of AlGaN MQWs with different structures grown on the AlN/sapphire templates used in this study show IQE values are in the range of 30%–56% at 300 K at a power density of 134 kW/cm^2.[20] A recent study by Martens *et al.* have shown that the same AlGaN DUV MQW structure grown on an AlN/sapphire template (TDD $\sim 5 \times 10^8$/cm^2) had a higher IQE (20%–30%) than the IQE (10%–20%) of that grown on a bulk AlN substrate (TDD $\sim 10^4$/cm^2), which was attributed to lateral inhomogeneities and filamenting for AlGaN DUV MQW structure grown on bulk AlN substrates.[21] In addition, Bryan *et al.* have shown that an unoptimized growth condition of the AlGaN DUV MQW on the AlN substrate can lower the IQE significantly.[22] Moreover, Collazo *et al.* have shown that bulk AlN substrate can have a high absorption coefficient of $\alpha > 350\,\mathrm{cm}^{-1}$ in the DUV range because of carbon impurities[23] and Xie *et al.* show that there was considerable light leakage towards the substrate for the low-threshold photo-pumped DUV MQW laser grown on the AlN substrate because of imperfect optical confinement.[14] Thus, the severe absorption could limit the performance of AlGaN DUV MQW laser grown on currently available AlN substrates. These studies indicate that the AlGaN MQW DUV lasers on bulk AlN substrates may exhibit much lower thresholds than the current reported values with further optimized growth condition and reduced absorption in the DUV spectrum.

Polarization of the stimulated emission was measured at RT by the experimental setup reported elsewhere.[12] Figures 5(a) and 5(b) show the transverse electric (TE) and transverse magnetic (TM) emission spectra of the 249-nm laser and 256-nm laser operating at pumping power densities about three times of the respective thresholds. For the 249-nm laser and 256-nm laser, the stimulated emission is strongly TE-polarized with the degree of polarization (*P*),

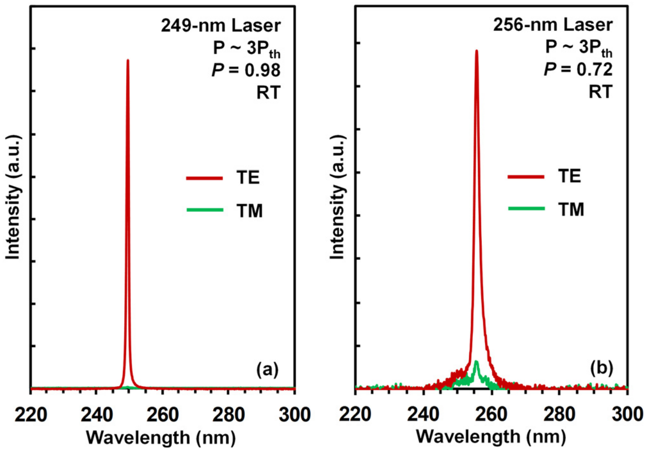

FIG. 5. Laser emission spectra of the TE mode and TM mode of the (a) 249-nm laser and (b) 256-nm laser operating above threshold at RT.

defined as $P = (I_{TE} - I_{TM})/(I_{TE} + I_{TM})$, equal to 0.98 and 0.72, respectively. This result indicates the dominant band transition was between the conduction band and heavy hole band for the AlGaN MQW DUV lasers grown on the sapphire substrate emitting at 249 nm and 256 nm, thanks to the pseudomorphic growth and thus strong compressive strain in the MQWs.[24] The result is similar to the stimulated emission polarization measured from the AlGaN MQW DUV lasers grown on AlN substrates at similar emission wavelengths.[17]

In summary, we have achieved room-temperature stimulated emission and laser operation from AlGaN-based MQW DUV heterostructures grown on (0001) sapphire substrates at 249 nm with a threshold of 61 kW/cm^2 and at 256 nm with a threshold of 95 kW/cm^2. The use of relatively low-dislocation-density AlN template layers and the optimization of the growth conditions for the waveguide layer and active region are the keys to enabling low-threshold laser action. The laser emission is dominated by TE-polarized emission, which is comparable to the lasers grown on bulk AlN substrates at similar wavelengths. The results demonstrate excellent candidacy of sapphire substrates for the development of high-performance III-N DUV laser diodes.

This work was partially supported by the Defense Advanced Research Projects Agency under Contract No. FA2386-10-1-4152 and the U.S. Department of Energy under DE-FC26-08NT01580. R.D.D. acknowledges additional support of the Steve W. Chaddick Endowed Chair in Electro-Optics and the Georgia Research Alliance.

[1] M. A. Khan, M. Shatalov, H. P. Maruska, H. M. Wang, and E. Kuokstis, Jpn. J. Appl. Phys., Part 1 **44**, 7191 (2005).

[2] D. Lester, F. A. Ponce, M. G. Craford, and D. A. Steigerwald, Appl. Phys. Lett. **66**, 1249 (1995).

[3] K. Ban, J.-I. Yamamoto, K. Takeda, K. Ide, M. Iwaya, T. Takeuchi, S. Kamiyama, I. Akasaki, and H. Amano, Appl. Phys. Express **4**, 052101 (2011).

[4] H. Hirayama, T. Yatabe, N. Noguchi, T. Ohashi, and N. Kamata, Appl. Phys. Lett. **91**, 071901 (2007).

[5] V. N. Jmerik, A. M. Mizerov, A. A. Sitnikova, P. S. Kop'ev, S. V. Ivanov, E. V. Lutsenko, N. P. Tarasuk, N. V. Rzheutskii, and G. P. Yablonskii, Appl. Phys. Lett. **96**, 141112 (2010).

[6] J. Mickevicius, J. Jurkevicius, K. Kazlauskas, A. Zukauskas, G. Tamulaitis, M. S. Shur, M. Shatalov, J. Yang, and R. Gaska, Appl. Phys. Lett. **100**, 081902 (2012).

[7] H. Yoshida, Y. Yamashita, M. Kuwabara, and H. Kan, Appl. Phys. Lett. **93**, 241106 (2008).

[8] T. Takano, Y. Narita, A. Horiuchi, and H. Kawanishi, Appl. Phys. Lett. **84**, 3567 (2004).

[9] H. Sun, J. Woodward, J. Yin, A. Moldawer, E. F. Pecora, A. Y. Nikiforov, L. D. Negro, R. Paiella, K. Ludwig, D. J. Smith, and T. D. Moustakas, J. Vac. Sci. Technol., B **31**, 03C117 (2013).

[10] T. Wunderer, C. Chua, Z. Yang, J. Northrup, N. Johnson, G. Garrett, H. Shen, and M. Wraback, Appl. Phys. Express **4**, 092101 (2011).

[11] Z. Lochner, X. H. Li, T. T. Kao, Md. M. Satter, H. J. Kim, S. C. Shen, P.-D. Yoder, J. H. Ryou, R. D. Dupuis, K. Sun, Y. Wei, T. Li, A. Fischer, and F. A. Ponce, Phys. Status Solidi A **210**, 9 (2013).

[12] Z. Lochner, T. T. Kao, Y. S. Liu, X. H. Li, Md. M. Satter, S. C. Shen, P. D. Yoder, J. H. Ryou, R. D. Dupuis, Y. Wei, H. Xie, A. Fischer, and F. A. Ponce, Appl. Phys. Lett. **102**, 101110 (2013).

[13] Y. S. Liu, Z. Lochner, T. T. Kao, Md. M. Satter, X. H. Li, J. H. Ryou, S. C. Shen, P. D. Yoder, R. D. Dupuis, Y. Wei, H. Xie, A. Fischer, and F. A. Ponce, Phys. Status Solidi C **11**, 2 (2014).

[14] J. Xie, S. Mita, Z. Bryan, W. Guo, L. Hussey, B. Moody, R. Schlesser, R. Kirste, M. Gerhold, R. Collazo, and Z. Sitar, Appl. Phys. Lett. **102**, 171102 (2013).

[15] W. Guo, Z. Bryan, J. Xie, R. Kirste, S. Mita, I. Bryan, L. Hussey, M. Bobea, B. Haidet, M. Gerhold, R. Collazo, and Z. Sitar, J. Appl. Phys. **115**, 10 (2014).

[16] A. Rice, R. Collazo, J. Tweedie, R. Dalmau, S. Mita, J. Xie, and Z. Sitar, J. Appl. Phys. **108**, 043510 (2010).

[17] J. R. van Look, S. Einfeldt, O. Kruger, V. Hoffmann, A. Knauer, M. Weyers, P. Vogt, and M. Kneissl, IEEE Photonics Technol. Lett. **22**(6), 416 (2010).

[18] T. T. Kao, Y. S. Liu, Md. M. Satter, X. H. Li, Z. Lochner, J. H. Ryou, P. D. Yoder, T. Detchprohm, Y. Wei, H. Xie, A. Fischer, F. A. Ponce, R. D. Dupuis, and S. C. Shen, Appl. Phys. Lett. **103**, 211103 (2013).

[19] N. M. Johnson, B. Cheng, S. Choi, C. L. Chua, C. Knollenberg, J. E. Northrup, M. R. Teepe, T. Wunderer, and Z. Yang, paper presented at the 9th International Symposium on Semiconductor Light Emitting Devices, Berlin, Germany, 23 July 2012.

[20] X. H. Li, T. Detchprohm, T. T. Kao, M. M. Satter, S. C. Shen, P. D. Yoder, R. D. Dupuis, T. Wernicke, C. Reich, M. Martens, and M. Kneissl, "Low-threshold deep-UV lasers grown on sapphire substrates," paper presented at the 17th International Conference on Metalorganic Vapor Phase Epitaxy (ICMOVPE-17), Lausanne, Switzerland, 17 July 2014.

[21] M. Martens, F. Mehnke, C. Kuhn, C. Reich, V. Kueller, A. Knauer, C. Netzel, C. Hartmann, J. Wollweber, J. Rass, T. Wernicke, M. Bickermann, M. Weyers, and M. Kneissl, IEEE Photonics Technol. Lett. **26**(4), 342 (2014).

[22] Z. Bryan, I. Bryan, J. Xie, S. Mita, W. Guo, L. Hussey, R. Kirste, M. Gerhold, Z. Sitar, and R. Collazo, in Proceedings of the 56th Electronic Material Conference, Santa Barbara, CA, USA, June 2014.

[23] R. Collazo, J. Xie, B. Gaddy, Z. Bryan, R. Kirste, M. Hoffmann, R. Dalmau, B. Moody, Y. Kumagai, T. Nagashima, Y. Kubota, T. Kinoshita, A. Koukitu, D. L. Irving, and Z. Sitar, Appl. Phys. Lett. **100**, 191914 (2012).

[24] J. E. Northrup, C. L. Chua, Z. Yang, T. Wunderer, M. Kneissl, N. M. Johnson, and T. Kolbe, Appl. Phys. Lett. **100**, 021101 (2012).