Recent progress of tunnel junction-based ultra-violet light emitting diodes

Yuwei Zhang1†, Zane Jamal-Eddine1 ‡, and Siddharth Rajan1,2 †

1Department of Electrical and Computer Engineering, The Ohio State University, Columbus, Ohio, 43210, United States of America
2Department of Materials Science and Engineering, The Ohio State University, Columbus, Ohio, 43210, United States of America

E-mail: yuweizhang@ucsb.edu; rajan@ece.osu.edu
Y. Zhang is currently with the University of California, Santa Barbara.

Received February 8, 2019; accepted March 11, 2019; published online May 29, 2019

1. Introduction

Significant research interest on III-nitride UV LEDs and laser diodes (LDs) has developed over the past decade because of promising applications for water purification, air disinfection, and medical sensing.1–3 Compared to the incumbent UV sources such as mercury lamps, solid-state UV light emitters are environmentally friendly, and they could provide significantly higher power density and lower heat generation. Therefore, UV LEDs and LDs are expected to enable various applications that have benefits for clean water, clear air and public health. Over the past decade there has been encouraging progress towards achieving highly efficient UV light emitters, including the substantial improvement in substrate quality which boosted the internal quantum efficiency above 80% in a wide wavelength range.4–7 However, both the carrier conversion efficiency [i.e. external quantum efficiency (EQE)] and power conversion efficiency [i.e. wall-plug efficiency (WPE)] of UV LEDs has remained significantly lower than their InGaN-based blue LED counterparts (whose EQE and WPE are as high as 80%).8,9 While UV LEDs products are now commercially available, the low efficiency and high cost have prevented the widespread adoption of UV LEDs in the aforementioned applications. The development of UV LDs is facing even more severe challenges. Even though lasing in a wide wavelength range from 360 nm to 220 nm was realized through optical pumping, electrically pumped planar UV LDs with an emission wavelength below 320 nm has not been demonstrated.

Several factors contributed to the low device efficiency for UV light emitters. As a result of the high acceptor activation energy (0.14 eV for GaN and 0.63 eV for AlN), low hole mobility and high p-type work function, p-AlGaN films typically suffer from poor conductivity and high contact resistance, which makes it challenging to achieve efficient hole injection and has been a critical issue for conventional UV light emitters.4,9 In an attempt to address the high acceptor activation energy in the AlxGa1-xN alloys used in UV LEDs, a heavily-doped p-GaN contact layer has been widely adopted in conventional UV LED structures to ensure effective hole injection, as shown in Fig. 1(a). While efficient hole injection is feasible in the conventional UV LED structures, the absorption loss in the p-GaN layer leads to severe penalties in the light extraction efficiency.10 Recently, by removing the absorbing p-GaN contact layer and using reflective metal contact directly on p-AlGaN, Takano et al. demonstrated a significant improvement of the light extraction efficiency, and a record EQE of 20%.11–13 However, the electrical efficiency of the devices was significantly compromised by the resistive p-type contact. As a result, the wall-plug efficiency was limited to a maximum of 6% for UV LEDs. For LDs, the strong internal optical loss and highly-unbalanced electron/hole injection are detrimental for optical mode confinement and the realization of lasing. Therefore, the efficiency ceiling in UV LEDs and LDs is substantially constrained by the conventional structures depicted in Fig. 1(a). Further improvement of the device efficiency necessitates innovation of the UV LED structures. A tunnel injected UV LED structure, shown in Fig. 1(b), was recently proposed to be a promising architecture to address the challenges faced by the conventional UV LED stacks. The novel structure implements a low resistance tunnel junction layer which is integrated on top of the p-AlGaN layer, allowing for tunneling hole injection into the active region, as shown schematically in Fig. 1(c).14 The proposed tunnel injected UV LED structure simultaneously addresses both fundamental light extraction efficiency and electrical injection efficiency limitations. Introducing the tunnel junction allows for efficient non-equilibrium hole injection into the active region while also allowing for the removal of the absorbing p-GaN contact layer. This could be especially beneficial for UV LDs emitting in the deep UV wavelength range. Furthermore, the combination of the transparent n-AlGaN top contact layer and reflective n-type contacts opens up a design space for novel light extraction techniques which could allow for similar light extraction efficiency to what has been realized in blue LEDs. In this paper, we review the recent progress on the development of III-nitride tunnel junctions, their applications in UV LEDs, and discuss future challenges and opportunities for tunnel junction-based UV LEDs.
explored the use of InGaN ternary alloy based tunnel junctions. High EQE of 90% were demonstrated by Grundmann et al. in 2006, followed by Simon et al. in 2009, a substantial improvement in the tunneling probability. The successful realization of Mg-activated InGaN layers was found to be critical for the tunneling process.

2. III-nitride tunnel junctions

Multiple research groups in the III-nitride optoelectronics community have investigated the applications of GaN tunnel junctions in visible LEDs. Attempts on GaN tunnel junctions were first reported in 2001. However, the demonstrated tunnel junction blue LEDs showed high on-resistance and large turn-on voltage due to poor tunneling efficiency. Following that, a new generation of III-Nitride tunnel junctions taking advantage of the strong polarization dipole which arises at the heterointerfaces of GaN and AlN was explored as a means to improving tunneling probabilities in GaN-based tunnel junctions. By introducing an ultra-thin AlN layer in the GaN PN tunnel junction structure, as demonstrated by Grundmann et al. in 2006, followed by Simon et al. in 2009, a substantial improvement in the tunneling efficiency was observed. While interband tunneling was feasible due to the reduced depletion width, the tunneling probability was limited by the large bandgap of AlN. More recently, Krishnamoorthy et al. demonstrated a further reduction of the tunnel junction resistance by replacing the AlN barrier with an ultra-thin InGaN layer. This design maintained the advantage of the polarization dipole narrowed depletion widths within the tunnel junction while utilizing lower InGaN bandgap for further improvement in the tunneling probability. The successful realization of Mg-activation in a buried p-GaN layer through etched sidewalls led to the demonstration of similar tunnel junction structures grown by metal-organic chemical vapor deposition (MOCVD). These lower resistance tunnel junctions led to successful demonstrations of blue LEDs with single active region, and cascaded blue LEDs with multiple active regions inter-connected by tunnel junctions. High EQE of 90% and white light emission by cascading RGB active regions have been demonstrated as well. References 27, 28 explored the use of InGaN ternary alloy based tunnel junctions in combination with graded layers as a means for further improvement of tunnel junction performance. They have also used these improved tunnel junctions to enable multijunction solar cells.

Recently, homojunction GaN tunnel junctions were also realized by pushing the doping concentrations to their solubility limits. The low tunnel junction resistance was demonstrated to be beneficial for various device applications, including blue LEDs, edge emitting LDs, and vertical-cavity surface-emitting LDs. As a specific feature of interband tunneling, repeatable negative differential resistance was observed at room temperature as well.

Compared to GaN tunnel junctions, AlGaN tunnel junctions have remained under-explored. Achieving efficient interband p–n tunnel junctions for ultra-wide bandgap AlGaN materials becomes especially challenging due to the wide depletion barriers and doping limitations. As such, the utilization of heterostructures and polarization engineering has been paramount in designing efficient AlGaN tunnel junctions. As shown in Fig. 2(a), AlGaN p–n tunnel junctions typically result in a wide depletion barrier and low tunneling probabilities. Through the insertion of an ultra-thin InGaN layer between the p+ and n+ AlGaN layers, strong polarization dipole arises at the InGaN/AlGaN interfaces. This creates a high electric field in the thin InGaN layer, enabling sharp band alignment across an ultra-thin distance. As a result, there is a significant reduction of the interband tunneling barrier as highlighted in the energy band diagrams in Fig. 2(b).

While the interband tunnel barrier can be substantially reduced by the thin InGaN layer, wide depletion barriers in the AlGaN layers arose from the high band offsets, which can be detrimental for the tunneling process. Further enhancement of the interband tunneling probability was proposed through the incorporation of graded AlGaN layers to take advantage of the bulk polarization charges [Fig. 2(c)]. Such bulk polarization charges can be obtained by a simple linear compositional grading of the AlGaN layers adjacent to the InGaN layer. The polarization induced negative bond charge could be especially helpful in reducing the extended depletion barrier on the p-AlGaN side, as shown in Fig. 2(c). Based on the design, tunnel junctions with low tunneling resistances and low voltage penalties are feasible.

We simulated the tunneling resistance and the voltage penalty at 1 kA cm−2 of the p+–AlGaN/InGaN/n+–AlGaN tunnel junction structures using a two-dimensional device simulator as shown in Fig. 3. The InGaN layer was fixed to be 4 nm in the simulations, while the alloy compositions, including Al and In compositions in the structures were varied. Graded AlGaN layers with a linear variation of 10% Al content over 3 nm were introduced on both the n- and p-AlGaN sides, as shown in Fig. 2(c) for the simulation of the graded tunnel junction structures. The compositional grading in the AlGaN layers was found to be critical to ensure low tunneling resistance and voltage drop, especially for the tunnel junctions with high Al compositions. As the In content in the InGaN layer increases, the tunnel junction resistance and voltages decrease monotonically because of the reduced barrier height for interband tunneling. Nevertheless, efficient tunnel junctions with low resistances below 1 mΩ cm² were
predicted to be feasible even for p-AlGaN/GaN/n-AlGaN tunnel junction structures. These simulations depict the great potential for integrating the graded tunnel junction designs into efficient UV LED structures for the purpose of tunneling hole injection.

3. Tunnel junction UV LEDs

UV LEDs with interband tunnel junctions were demonstrated experimentally. The structure is typically comprised of a UV LED active region, a p+-AlGaN/InGaN/n+-AlGaN TJ
layer and a transparent n-AlGaN top contact layer, as shown in Fig. 4. Since sharp doping profiles and interfaces are critical for the realization of efficient tunnel junctions, the tunnel-injected UV LED structure was realized using MBE growth. The scanning transmission electron microscope image of the structure showed sharp interfaces for the quantum wells, electron blocking layer and the tunnel junction layer, as can be seen in Fig. 4(a). The energy band diagram, Fig. 4(c), indicates a narrow depletion width in the tunnel junction region, allowing for efficient hole injection through interband tunneling.

The tunnel junction UV LEDs are expected to show PN junction performance, with the turn-on voltage determined by the bandgap of the quantum wells. The current–voltage (IV) characteristics of a tunnel-injected UV-A LED emitting at 327 nm are shown in Fig. 5. The device showed low resistance and high current operation, with a series resistance of less than $5.6 \times 10^{-4}$ Ω cm$^2$. Benefitting from the transparent n-AlGaN top contact layer, the light emission from the quantum wells can be extracted from the top surface of the devices, and an output power of 0.58 mW was measured at 20 mA. In addition, the high conductivity of the n-AlGaN top contact layer allowed for uniform light emission from the entire device mesa even though only small part of the device was covered by the top metal contact [Fig. 5(b)]. This suggests that high density hole injection can be realized through the designed n-AlGaInGaN top contact layer allowed for uniform light emission from the entire device mesa even though only small part of the device was covered by the top metal contact [Fig. 5(b)]. This suggests that high density hole injection can be realized through the designed n-AlGaInGaN top contact layer allowed for uniform light emission from the entire device mesa even though only small part of the device was covered by the top metal contact [Fig. 5(b)].

Further development of AlGaN tunnel junctions has led to the demonstration of light emissions over a wide spectral range from 365 nm to 257 nm (Fig. 8). This confirmed the feasibility of hole injection into ultra-wide bandgap AlGaN with Al content up to 75% through interband tunneling. The measured EQE of 3.4% (325 nm) and 2.8% (287 nm) and WPE of 1.6% (325 nm) and 1.1% (287 nm) for the tunnel junction UV LEDs are comparable to state-of-the-art results.14,38) Recently, similar tunnel junction UV LED structures were demonstrated in nanowire UV LEDs by Refs. 39, 40) High emission powers of 0.37 mW at 242 nm and more than 8 mW at 275 nm were achieved.31,42) Those values are already comparable to what was achieved for conventional UV LEDs, which further indicates the great potential of the tunnel junction UV LED structures for high power UV emitter applications. The development of the tunnel junction UV LEDs is still in its early stage and the majority of studies have been focusing on the realization of
Fig. 5. (Color online) $I$-$V$ characteristics (a) and output power (b) of a tunnel-injected UV-A LED emitting at 327 nm. The inset to (b) shows a microscope image of a top emitting UV LED device (300 $\times$ 300 $\mu$m$^2$). Reproduced from Ref. 14, with the permission of AIP Publishing.

Fig. 6. (Color online) (a) Epitaxial stack of the tunnel junction UV LED structure with a graded p-AlGaN layer. (b) The charge distribution and equilibrium energy profiles of the UV LEDs with different net acceptor concentrations in the p-AlGaN layer. Reproduced from Ref. 36, with the permission of AIP Publishing.

Fig. 7. (Color online) Output power (a), EQE (b) and WPE (c) of the tunnel junction UV LEDs (Fig. 6) with different doping concentration and thickness of the p-AlGaN layers. Reproduced from Ref. 36, with the permission of AIP Publishing.
There is still much room for improvement of the tunnel junction design itself, and further optimization of the active region and incorporation of proper device packaging and surface roughening are expected to substantially improve the device performance.

Although successful hole injection has been demonstrated, ultra-wide bandgap AlGaN tunnel junctions are still far from their optimal performance. Figure 9 summarizes the IV characteristics, the extracted tunnel junction resistances and the excess voltages of the tunnel-injected UV LEDs with different Al content in the tunnel junction layers. Even though low series resistances were realized for high Al content AlGaN, the tunnel junctions showed a significant increase in the threshold voltage to start effective interband tunneling. This is attributed to increased barrier height, reduced intentional doping efficiency and possible lattice relaxation in the tunnel junction layer. Therefore, further improvement of the tunnel junction UV LEDs necessitates concerted optimizations of the tunnel junction structure.

4. Future perspective of tunnel junction-based UV LEDs

The successful demonstrations of AlGaN tunnel junctions set the stage for the development of tunnel junction-based UV LEDs and the systematic optimizations for improved tunneling efficiencies. As discussed above, reducing the voltage penalties for AlGaN tunnel junctions is critical in reaching their expectations. One approach to increasing the tunneling probability would be to reduce the bandgap energy or thickness of the InGaN interlayer. However, one must consider the large lattice mismatch between InGaN and high composition AlGaN which could lead to lattice relaxation and reduced piezoelectric polarization charge density at the interface. If relaxation were to occur, the lowered polarization charge density at the interface would result in a lower electric field in the thin InGaN layer, as well as a larger depletion barrier for tunneling. Maintaining reliable tunnel junction operation necessitates stable strain status in the tunnel junction layer, which could set a limit on the In content that is allowed in the tunnel junction structure.

Replacing the InGaN layer with GaN or AlInGaN could potentially alleviate the lattice relaxation issue, and at the same time, further reduce the internal light absorption loss in the tunnel junction layer. Additionally, utilizing the three-dimensional polarization charge through Al compositional grading was proposed to be helpful for reducing the depletion barriers. This requires precise control of the grading schemes during the epitaxial growth.

A significant improvement of the interband tunneling process can be realized through the introduction of defects in the midgap of the semiconductors and extended band tail states near the band edge. Intentional insertion of GdN islands between p+ and n+ GaN layers was demonstrated to be effective in improving the tunneling probability, which

![Fig. 8. (Color online) (a) EL spectra achieved from tunnel-injected UV LEDs. (b) Comparison of the achieved tunnel junction UV LED efficiencies with state-of-the-art UV LEDs. The navy blue squares and yellow circles represent the EQE and WPE, respectively, reported for other state-of-the-art UV LEDs.](image)

![Fig. 9. (Color online) Summary of the electrical characteristics (a) and the extracted tunnel junction resistance/excess voltage drop (b) for tunnel junction UV LEDs with different Al content in the tunnel junction layers. Reproduced from Ref. 38, with the permission of AIP Publishing.](image)
was attributed to defect-assisted tunneling through GdN nano-islands. More recently, the high density unintentional dopants from the air were utilized for the realization of low-resistance GaN tunnel junctions by exposing the p⁺ GaN surface to air before the regrowth of n⁻ GaN. Intentional doping to above 10²⁰ cm⁻³ for both n-type and p-type dopants were also demonstrated to be feasible for the realization of low resistance GaN tunnel junctions. As such methods have not been investigated for AlGaN tunnel junctions, a large design space offering potential reduction of the series resistance and threshold voltage of such ultrawide bandgap AlGaN-based tunnel junctions remains largely unexplored.

Better tunnel junction performance could be realized based on innovations in the tunnel junction structure. One promising structure is shown in Fig. 10, where the n-AlGaN/InGaN/p-AlGaN tunnel junction structure is modified to a metal/InGaN/p-AlGaN structure. The metal/InGaN/p-AlGaN structure maintains a high density polarization charge at the InGaN/p-AlGaN interface. This produces a similar tunneling barrier to the n-AlGaN/InGaN/p-AlGaN structure as shown in Fig. 10. Proper design of the InGaN layer thickness could ensure minimal depletion in the p-AlGaN layer, and therefore, electrons could tunnel through the InGaN barrier with low resistance. The barrier height varies with the choice of the metal layer. While lower work function metal can create higher barrier for tunneling, the tunnel barrier height when Al is used is comparable to the barrier height in a n-AlGaN/InGaN/p-AlGaN semiconductor tunnel junction structure. This makes the metal/semiconductor tunnel junction promising for UV LED applications especially considering that Al is the only metal that has high reflectivity above 90% for UV light in a wide wavelength range.

The IV characteristics of the devices (Fig. 11) showed that higher turn-on voltage was required for the devices with lower work function metal contacts, which is as expected from the energy band diagrams shown in Fig. 10. Nevertheless, the devices with Al contacts showed higher output power and device efficiency compared to the devices with Ni contacts because of the higher reflectivity of Al to the emitted UV light, as shown in Fig. 11(b). Better device performance is expected through the combination of an ultra-thin Ni layer and thick Al layer as metal contact to take advantage of the low tunnel barrier and high UV reflectivity simultaneously. Additionally, the devices with Al/InGaN/p-AlGaN contacts showed lower turn-on voltage compared to the devices with n-AlGaN/InGaN/p-AlGaN tunnel junctions. This suggested improved tunneling efficiency possibly assisted by high density surface states at the metal-semiconductor interface. Furthermore, realization of the semiconductor tunnel junctions requires AlGaN growth on top of the ultra-thin InGaN layer, which could be challenging for MOCVD growth due to the large temperature difference for the layers and potential decomposition of the thin InGaN layer. Therefore, the n-AlGaN/InGaN/p-AlGaN tunnel junctions have been demonstrated only through MBE growths because of a lower temperature difference for the growths. In comparison, the metal/semiconductor tunnel junctions bring less challenges for epitaxial growths, making it feasible for mass production in MOCVD systems.

The tunnel-injected UV LED structure allows for novel designs for efficient light extraction because of the absence of absorbing p-type contacts. The packaging materials used by conventional UV LEDs, such as epoxy and silicone, suffer from poor UV transparency, especially for deep UV LEDs. The lifetime and stability of the encapsulants are also limited by the high photon energy emitted from the UV LED active
region. The incorporation of UV reflective contacts in tunnel-injected UV LED structures makes it possible to substitute the widely used organic-based encapsulants with semiconductor-based encapsulants, which could provide improved UV transparency and long operation lifetime.

5. Conclusion
The recent progress of tunnel junction-based UV LEDs was reviewed in this paper. Interband tunnel junctions have been realized for ultra-wide bandgap AlGaN-based on polarization engineering, with low tunnel junction resistances below \(2 \times 10^{-3} \, \Omega \, \text{cm}^2\) for Al compositions up to 75%. The non-equilibrium hole injection has led to the demonstrations of UV light emission in a wide spectrum range from 365 nm to 257 nm. High external quantum efficiency of 3.4% and 2.8% have been demonstrated for the tunnel junction UV LEDs emitting at 325 nm and 287 nm, respectively, which are comparable to the best device performance obtained for conventional UV LEDs. The challenges and future perspectives for tunnel injected UV LEDs were discussed. Further optimization of the AlGaN tunnel junctions to reduce the threshold voltage, and the development of novel light extraction techniques are expected to enable high power high efficiency UV emitters.

Acknowledgments
We acknowledge funding from the National Science Foundation (ECCS-1408416 and PFI AIR-TT 1640700), and the OSU TCO Accelerator Award.

ORCID iDs
Yuweizi Zhang [https://orcid.org/0000-0002-4192-1442]
Zane Jamal-Eddine [https://orcid.org/0000-0003-1052-8450]
Siddharth Rajan [https://orcid.org/0000-0003-4241-3391]

1) M. Kneissl and J. Rass, *III-Nitride Ultraviolet Emitters*. (Springer, Cham, 2016).
2) H. Hirayama, N. Maeda, S. Fujikawa, S. Toyoda, and N. Kamata, *Appl. J. Jpn. Appl. Phys.* 53, 100209 (2014).
3) J. R. Grandusky, S. R. Gibb, M. C. Mendrick, C. Moe, M. Wraback, and L. J. Schowalter, *Appl. Phys. Express* 4, 082101 (2011).
4) Y. Taniyasu, M. Kasa, and T. Makimoto, *Nature* 441, 325 (2006).
5) J. R. Grandusky, J. Chen, S. R. Gibb, M. C. Mendrick, C. G. Moe, L. Rodak, G. A. Garrett, M. Wraback, and L. J. Schowalter, *Appl. Phys. Express* 6, 032101 (2013).
6) S. Islam, K. Lee, J. Verma, V. Protasenko, S. Rouvimov, S. Bharadwaj, H. Xing, and D. Jena, *Appl. Phys. Lett.* 110, 041108 (2017).
7) Z. Bryan, I. Bryan, J. Xie, S. Mita, Z. Sitar, and R. Collazo, *Appl. Phys. Lett.* 106, 142107 (2015).
8) A. Khan, K. Balakrishnan, and T. Katona, *Nat. Photonics* 2, 77 (2008).
9) N. Maeda and H. Hirayama, *Phys. Status Solidi. C* 10, 1521 (2013).
10) H.-Y. Ryu, I.-G. Choi, H.-S. Choi, and J.-I. Shim, *Appl. Phys. Express* 6, 062101 (2013).
11) M. Jo, N. Maeda, and H. Hirayama, *Appl. Phys. Express* 9, 012102 (2015).
12) H. Hirayama, S. Fujikawa, N. Noguchi, I. Norimoto, T. Takano, K. Tsukabi, and N. Kamata, *Phys. Status Solidi. (a)* 206, 1176 (2009).
13) T. Takano, T. Mino, J. Sakai, N. Noguchi, K. Tsukabi, and H. Hirayama, *Appl. Phys. Express* 10, 031002 (2017).
14) Y. Zhang, S. Krishnamoorthy, J. M. Johnson, F. Akyol, A. Allerman, M. W. Moseley, A. Armstrong, J. Hwang, and S. Rajan, *Appl. Phys. Lett.* 106, 141103 (2015).
15) T. Takeuchi, G. Hasnain, S. Corzine, M. Hueschen, R. P. Schneider Jr., C. Kokot, and L. W. Cook, *Jpn. J. Appl. Phys.* 40, L681 (2001).
16) I. Ozden, E. Makarova, A. V. Nurmiikko, T. Takeuchi, and M. Krames, *Appl. Phys. Lett.* 79, 2532 (2001).
17) S. R. Jeon, H. H. Song, H. J. Jang, G. M. Yang, S. W. Hwang, and S. J. Son, *Appl. Phys. Lett.* 78, 3265 (2001).
18) M. J. Grundmann, PhD. Dissertation University of California, Santa Barbara (2007).
19) M. J. Grundmann and U. K. Mishra, *Phys. Status Solidi. (c)* 4, 2830 (2007).
20) J. Simon, Z. Zhang, K. Goodman, H. Xing, T. Kosei, P. Faye, and D. Jena, *Phys. Rev. Lett.* 103, 026801 (2009).
21) S. Krishnamoorthy, D. N. Nath, F. Akyol, P. S. Park, M. Esposto, and S. Rajan, *Appl. Phys. Lett.* 97, 203502 (2010).
22) Y. Kuwano, M. Kaga, T. Morita, Y. Kuwano, K. Yamashita, K. Yagi, M. Iwaya, T. Takeuchi, S. Kamiyama, and I. Akasaki, *Jpn. J. Appl. Phys.* 52, 08JK12 (2013).
23) F. Akyol, S. Krishnamoorthy, Y. Zhang, and S. Rajan, *Appl. Phys. Express* 8, 082103 (2015).
24) M. Malinverni, D. Martin, and N. Grandjean, *Appl. Phys. Lett.* 107, 051107 (2015).
25) S.-J. Chang, W.-H. Lin, and C.-T. Yu, *IEEE Electron Device Lett.* 36, 366 (2015).
26) S.-J. Chang, W.-H. Lin, and W.-S. Chen, IEEE J. Quantum Electron. 51, 1 (2015).
27) M. Kaga, T. Morita, Y. Kuwano, K. Yamashita, K. Yagi, M. Iwaya, T. Takeuchi, S. Kamiyama, and I. Akasaki, *Jpn. J. Appl. Phys.* 52, 08JE06 (2013).
28) D. Takasuka, Y. Akatsuka, M. Ino, N. Koide, T. Takeuchi, M. Iwaya, S. Kamiyama, and I. Akasaki, *Appl. Phys. Express* 8, 081005 (2016).
29) H. Kurokawa, M. Kaga, T. Goda, M. Iwaya, T. Takeuchi, S. Kamiyama, I. Akasaki, and H. Amano, *Appl. Phys. Express* 7, 034104 (2014).
30) B. Yonkee, E. Young, S. DenBaars, S. Nakamura, and J. Speck, Appl. Phys. Lett. 109, 191104 (2016).
31) B. P. Yonkee, E. C. Young, C. Lee, J. T. Leonard, S. P. DenBaars, J. S. Speck, and S. Nakamura, Opt. Express 24, 7816 (2016).
32) J. Leonard, E. Young, B. Yonkee, D. Cohen, T. Margalith, S. DenBaars, J. Speck, and S. Nakamura, Appl. Phys. Lett. 107, 091105 (2015).
33) F. Akyol, S. Krishnamoorthy, Y. Zhang, J. Johnson, J. Hwang, and S. Rajan, Appl. Phys. Lett. 108, 131103 (2016).
34) Y. Zhang, S. Krishnamoorthy, F. Akyol, A. A. Allerman, M. W. Moseley, A. M. Armstrong, and S. Rajan, Appl. Phys. Lett. 109, 121102 (2016).
35) J. Simon, V. Protasenko, C. Lian, H. Xing, and D. Jena, Science 327, 60 (2010).
36) Y. Zhang, S. Krishnamoorthy, F. Akyol, A. A. Allerman, M. W. Moseley, A. M. Armstrong, and S. Rajan, Appl. Phys. Lett. 109, 191105 (2016).
37) Y. Zhang, S. Krishnamoorthy, F. Akyol, S. Bajaj, A. A. Allerman, M. W. Moseley, A. M. Armstrong, and S. Rajan, Appl. Phys. Lett. 110, 201102 (2017).
38) Y. Zhang, Z. Jamal-Eddine, F. Akyol, S. Bajaj, J. M. Johnson, G. Calderon, A. A. Allerman, M. W. Moseley, A. M. Armstrong, and J. Hwang, Appl. Phys. Lett. 112, 071107 (2018).
39) S. M. Sadaf, Y.-H. Ra, H. P. T. Nguyen, M. Djavid, and Z. Mi, Nano Lett. 15, 6696 (2015).
40) S. Sadaf, Y. Ra, T. Szkopek, and Z. Mi, Nano Lett. 16, 1076 (2016).
41) S. M. Sadaf, S. Zhao, Y. Wu, Y.-H. Ra, X. Liu, S. Vanka, and Z. Mi, Nano Lett. 17, 1212 (2017).
42) S. Zhao, S. M. Sadaf, S. Vanka, Y. Wang, R. Rashid, and Z. Mi, Appl. Phys. Lett. 109 (2016).
43) S. Krishnamoorthy, T. F. Kent, J. Yang, P. S. Park, R. Myers, and S. Rajan, Nano Lett. 13, 2570 (2013).
44) E. C. Young, B. P. Yonkee, F. Wu, S. H. Oh, S. P. DenBaars, S. Nakamura, and J. S. Speck, Appl. Phys. Express 9, 022102 (2016).
45) Y. Zhang, S. Krishnamoorthy, F. Akyol, J. Johnson, A. A. Allerman, M. W. Moseley, A. M. Armstrong, J. Hwang, and S. Rajan, Appl. Phys. Lett. 111, 051104 (2017).