Light Emission Enhancement of GaN-Based Photonic Crystal With Ultraviolet AlN/AlGaN Distributed Bragg Reflector

Cheng-Chang Chen, Jun-Rong Chen, Yi-Chun Yang, M.-H. Shih, and Hao-Chung Kuo, *Senior Member, IEEE*

***Abstract*—In this study, we demonstrated two-dimensional (2-D) photonic crystal band-edge coupling operation in the ultraviolet wavelength range. The light extraction enhancement was obtained from the photonic crystal structure with an ultraviolet AlN/AlGaN distributed Bragg reflector (UVDBR). The DBR provides a high reflectivity of 85% with 15-nm stopband width. A fivefold enhancement in photoluminescence emission was also achieved compared with the emission from the unpatterned area on the same sample at 374 nm wavelength. We also study the photonic crystal band-edge coupling with finite-difference time-domain and plane-wave expansion methods.**

***Index Terms*—Band-edge coupling, photonic crystal, ultraviolet distributed Bragg reflector (UVDBR).**

I. Introduction

DIRECT wide-bandgap gallium nitride (GaN) and other III-nitride-based semiconductors have attracted much attention because of their potential applications, such as blue, green, and ultraviolet (UV) LEDs and laser diodes (LDs) [1]–[4]. The high reflectivity GaN-based distributed Bragg reflector (DBR) is one of the key elements for GaN optical devices, such as resonant cavity RCLEDs [5] and vertical-cavity surface-emitting lasers (VCSEL) [6], [7]. Today, wide-bandgap III-nitride-based material has been applied in flashlights and area lighting to replace the traditional lighting sources. The blue LD can serve as the light source of high-density data storage. However, due to the applications, the efficiency of the light source needs to be improved.

In general, there are two main methods to improve light extraction with photonic crystal structures. One is the use of the photonic bandgap (PBG) to inhibit the propagation of guided modes [8]; the other is utilizing photonic crystal structure to couple guided modes to radiative modes [9]–[13]. In this study, we demonstrated light enhancement of GaN-based 2-D photonic crystals with the ultraviolet AlN/AlGaN DBR at room temperature. This structure combines a 2-D photonic crystal in-plane and a 1-D DBR in vertical direction, which is designed for the UV wavelength region. The DBR structure has center stopband at 375 nm and a width approximately 15 nm. Therefore, it can be acted as a mirror to reflect light from the bottom area and played the role as a lower refracted index layer to control the guided modes.

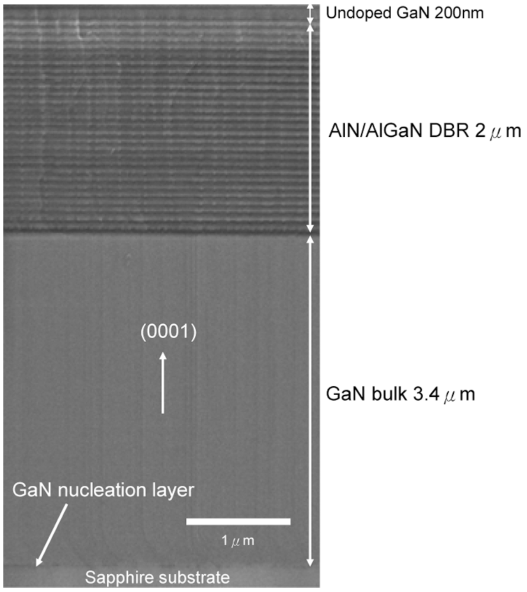

Fig. 1. SEM image of the epitaxial structure from cross-sectional view. The ultraviolet AlN/AlGaN DBR contains 25 periods of $\lambda/4$ pairs.

II. Fabrication

The 2-D photonic crystal square lattices were fabricated in an ultraviolet GaN-based DBR (UVDBR) structure. This AlN/AlGaN DBR structure was grown by a low pressure metal-organic chemical vapor deposition (MOCVD) system. A 2-μm-thick undoped GaN was first grown on a C-plane (0001) sapphire substrate. Then 25-pair AlN/Al$_{0.2}$Ga$_{0.8}$ N structure was grown at 900 °C, followed by a 200-nm undoped GaN gain layer on the top of the epitaxial structure. The schematic structure of the grown DBR is shown in Fig. 1. The structural quality of the UVDBR layers is maintained by compensating the compressive and tensile stress in each $\lambda/4$ pair. This approach results in the lowest elastic strain energy and allows the

---

Manuscript received May 28, 2010; revised September 21, 2010; accepted September 24, 2010. Date of publication October 04, 2010; date of current version November 10, 2010. This work was supported by the Center for Nanoscience and Technology, National Chiao Tung University and the National Science Council of the Republic of China, Taiwan under Contract NSC 96-2628-E009-017-MY3.

C.-C. Chen, J.-R. Chen, M. H. Shih, and H.-C. Kuo are with the Department of Photonics and the Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30050, Taiwan (e-mail: mhshih@gate.sinica.edu.tw; hckuo@faculty.nctu.edu.tw).

M.-H. Shih and Yi-Chun Yang are with the Research Center for Applied Sciences, Academia Sinica, Nankang, Taipei 115, Taiwan (e-mail: mhshih@gate.sinica.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org

Digital Object Identifier 10.1109/JLT.2010.2083634

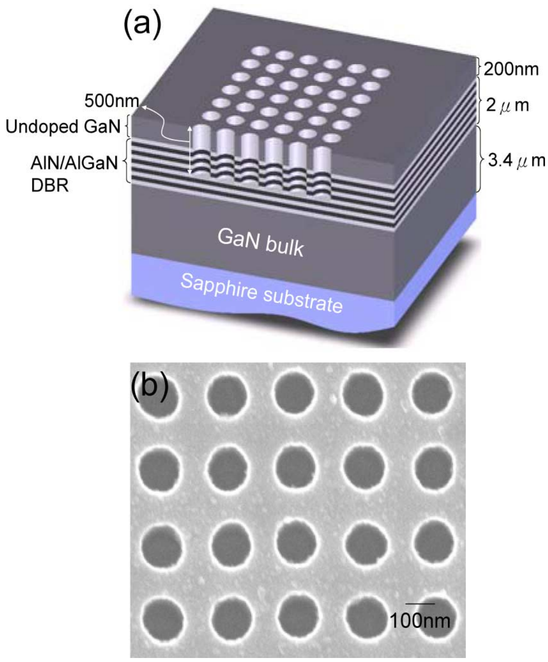

Fig. 2. (a) Schematic structure of the square photonic crystal patterns with a depth 500 nm and total square area of a width about 50 μm. (b) Top view SEM images of the photonic crystal structures with square lattices and circle unit cells.

growth of thick coherently strained DBR. The growth details were reported in our previous works [14], [15].

To fabricate the photonic crystal lattices, a 300-nm Si_3N_4 layer and a 300-nm polymethylmethacrylate (PMMA) layer were deposited as the masks during the process. The photonic crystal square lattice patterns were defined on the PMMA layer by E-beam lithography and the patterns were transferred into Si_3N_4 layer in reactive ion etching (RIE) with CHF_3/O_2 mixture. The structure was then etched by inductively coupled plasma reactive ion etching (ICP-RIE) with Cl_2/Ar mixture. The mask layers were removed at the end of processes. The size of a fabricated photonic crystal pattern is approximately 50 μm $\times$ 50 μm with a lattice constant (a) of 250 nm and a hole radius of $0.28a$. The etch depth of the holes is approximately 500 nm, which is pass through undoped GaN layer into DBR region. The schematic structure of the fabricated photonic crystals in AlN/AlGaN DBR is shown in Fig. 2(a). The top view of an SEM image of a fabricated photonic crystal pattern on the GaN-based structure is shown in Fig. 2(b).

III. CHARACTERIZATION AND MEASUREMENT

Before characterizing the photonic crystal with the AlN/AlGaN DBR structure, the high reflectivity in UV region from the DBR layers was characterized. The UVDBR structure is designed for the UV wavelength around 360 nm. The thickness of AlN and AlGaN layers are 45 and 42 nm decided by the formula $d_{\mathrm{AlN}} = (\lambda)/(4n_{\mathrm{AlN}})$ and $d_{\mathrm{AlGaN}} = (\lambda)/(4n_{\mathrm{AlGaN}})$. Here, n_{AlN} and n_{AlGaN} are refractive indexes of AlN and AlGaN, which are 2.03 and 2.19, respectively. The black curve in Fig. 3 is the simulated reflectivity spectrum from transmission matrix method for the UVDBR. The blue curve in Fig. 3 is the measured spectrum by an n and k spectrum analyzer with a normal incident light from 300 to 420 nm wavelength. The ultraviolet DBR has the highest reflectivity of 85% at the center wavelength of 375 nm, with a stopband width of about 15 nm. A good agreement between simulation and experiment was obtained for the UVDBR structure. The mismatch between calculated and measured reflectivity spectra is attributed to inaccuracy of material indexes in simulation and imperfection of DBR fabrication.

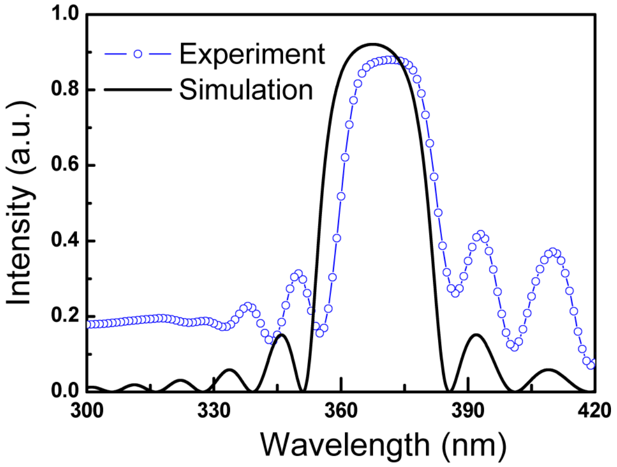

Fig. 3. Calculated (solid) and measured (dash) reflectivity spectra of ultraviolet AlN/AlGaN DBR measured at room temperature with a stopband width of about 15 nm and the center wavelength is 375 nm.

To demonstrate the light enhancement from the photonic crystal structure, the optical pumping was performed by using a frequency-tripled Nd:YVO_4 355-nm pulsed laser with a pulse width of 0.5 ns and a repetition rate of 1 kHz. (The device was pumped by a normal incident laser beam with a spot size of 50 μm, which can cover the whole photonic crystal pattern area. The light emission from the sample was collected by a 15 X objective lens through a multimode fiber and coupled into a spectrometer with a charge coupled device detectors.

Fig. 4(a) shows the measured PL spectrum from the undoped GaN layer. The gain peak of the undoped GaN is located around 360 nm wavelength. Fig. 4(b) shows the measured spectra from the photonic crystal DBR structure (black curve) and nonpatterned region (red curve). The gray region in Fig. 4(a) and (b) is the high reflection region of the bottom UVDBR structure. The reflectivity of DBR might have very small degradation since photonic crystals were etched into top four pairs of AlN/AlGaN layers. The stopband region remains between 362 to 381 nm in wavelength. A strong light emission from the photonic crystal pattern was observed. A strong resonant peak was observed at 374 nm wavelength, which is inside the high reflection region, as expect. A fivefold enhancement in photoluminescence emission was also achieved compared with the emission from the unpatterned area on the same sample, as shown in Fig. 4(b). The slight misalignment between the GaN gain peak and the stopband of UVDBR can be avoided by optimizing geometry of the bottom DBR structure. The better performance from the UV GaN photonic crystals can be expected with higher gain support and better optical properties.

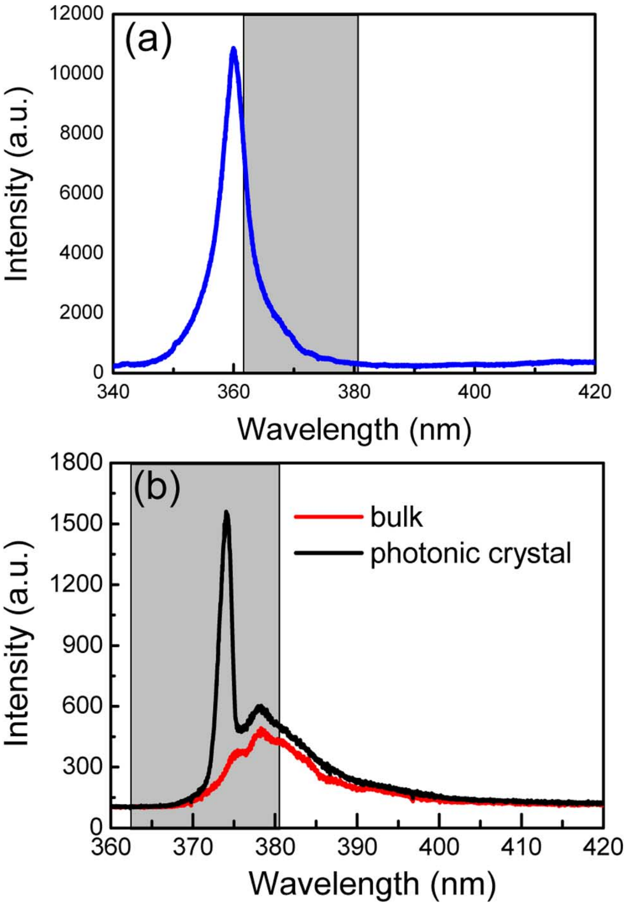

Fig. 4. (a) Photoluminescence spectrum from the undoped GaN layer without the DBR. (b) Photoluminescence spectra of unpatterned (red) and patterned (black) GaN UVDBR structure at room temperature. This peak of the resonant mode is 374 nm wavelength and is located within stopband width (gray region).

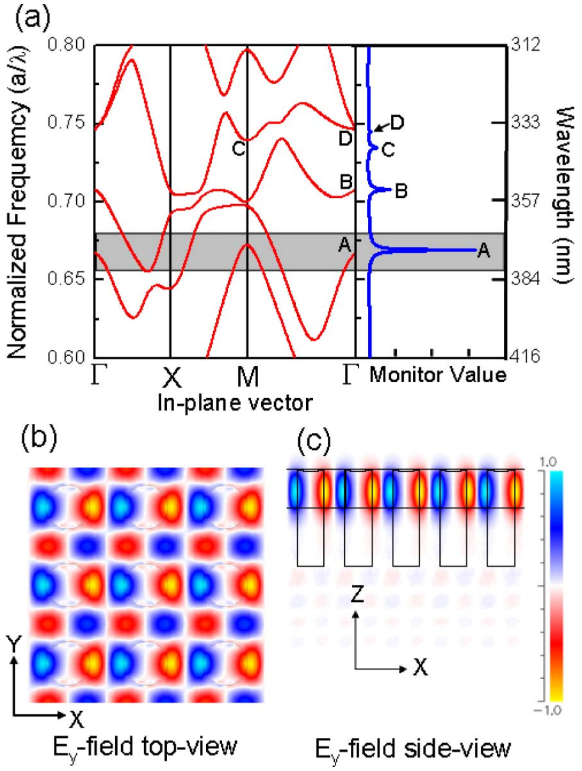

Fig. 5. (a) Corresponding band diagram calculated by the PWE method (red) and the calculated luminescence spectra is presented (blue), corresponding different modes, A, B, C, and D. (b) and (c) are top view and side view of the electric-field distribution, respectively, calculated by FDTD simulation.

IV. Simulation and Model Analysis

In order to understand optical modes of the photonic crystal DBR structure, 3-D finite-difference time-domain (FDTD) and plane-wave expansion (PWE) methods were used to performed simulations for the fabricated structure [16], [17]. The left part of Fig. 5(a) shows calculated band diagram (red) of the photonic crystal structure from the PWE method from normalized frequency (a/λ) 0.6 to 0.8. The right part of Fig. 5(a) is calculated spectrum (blue) from FDTD simulation within the same frequency region. The gray region in Fig. 5(a) indicates the high reflection region due to the UVDBR at the bottom of photonic crystal lattices. Several resonant modes were observed from the FDTD spectrum around the UV region, which are labeled with modes, A, B, C, and D. They are all bandedge modes of photonic crystal lattices because the strong resonances can be observed near these bandedges due to the flat photonic bands and their slow group velocities. By comparing the band diagram and the FDTD spectrum, the mode A, B, and D are bandedge modes at symmetry point Γ, the mode C is a mode at M point. By comparing the measured and calculated spectra, the strong emission at 374 nm wavelength, which is corresponded to a normalized frequency of $\mathrm{a}/\lambda = 0.67$, is verified to be the resonant mode A. Fig. 5(b) shows the calculated in-plane E_y field profile of mode A from the FDTD simulation. We also obtained same mode profile from the PWE simulation. This in-plane mode profile also confirms mode behavior of the bandedge mode at the Γ point. Fig. 5(c) is the vertical E_y field profile of mode A along the y-axis. According to the vertical mode profile, the optical mode is clearly located in the 200-nm undoped GaN layer due to the high reflection of the UVDBR.

The UVDBR plays an important role to select emission wavelength in the GaN-based photonic crystal structure. The gain peak of the GaN without the DBR is around 360 nm wavelength, which is outside the stopband of the DBR. However, the PL peak of GaN on DBR is around 378 nm and the resonant modes are around 374 nm wavelength. There is a 14 nm wavelength difference between the GaN gain peak and the resonant mode. It is mainly attributed to the reflection of the UVDBR mirror on the bottom of photonic crystal lattices. This DBR effect in the GaN epitaxial structure had been observed in our previous works [15], [18]. The amplitude difference between mode A and other modes (mode B, C, and D) in FDTD spectrum also prove stronger optical enhancement within the high reflection region of DBR. The UVDBR also reduces number of resonant modes by tuning its reflection bandwidth. The mode reduction decreases energy waste in modes outside the DBR high reflection region. More emission behavior of the GaN photonic crystals can be obtained with further studies such as far-field pattern characterization [19], [20].

V. Conclusion

In this study, a strong emission from the GaN-based photonic crystal with the AlN/AlGaN DBR structure was achieved in the UV wavelength region. A fivefold enhancement in photoluminescence emission was also observed. This enhancement results from the coupling between electron-hole recombination in the top GaN gain layer and low group velocity modes at the bandedge of Γ point. Experimental results show excellent agreement with the FDTD and PWE simulations. Due to the larger enhancement of the devices, we believe the photonic crystal structure with bottom DBR mirror, which has the potential to light sources for the future applications.

ACKNOWLEDGMENT

The authors would like to thank Prof. T.-C. Lu and Dr. Z.-Z. Li at the National Chiao-Tung University.

REFERENCES

[1] S. Nakamura, T. Mukai, and M. Senoh, “Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting,” *Appl. Phys. Lett.*, vol. 64, pp. 1687–1689, 1994.
[2] S. Nakamura, M. Senoh, N. Iwasa, and S. Nagahama, “High-brightness InGaN blue, green and yellow light-emitting diodes with quantum structures,” *Jpn. J. Appl. Phys.*, vol. 34, pp. L797–L799, 1995.
[3] S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto, and H. Kiyoku, “Room-temperature continuous-wave operation of InGaN multi-quantum-well-structure laser diodes with a long lifetime,” *Appl. Phys. Lett.*, vol. 70, pp. 868–870, 1997.
[4] S. Nakamura, “The roles of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes,” *Science*, vol. 281, pp. 956–961, 1998.
[5] M. Diagne, Y. He, H. Zhou, E. Makarona, A. V. Nurmikko, J. Han, K. E. Waldrip, J. J. Figiel, T. Takeuchi, and M. Krames, “Vertical cavity violet light emitting diode incorporating an aluminum gallium nitride distributed Bragg mirror and a tunnel junction,” *Appl. Phys. Lett.*, vol. 79, pp. 3720–3722, 2001.
[6] T. C. Lu, S. W. Chen, L. F. Lin, T. T. Kao, C. C. Kao, P. Yu, H. C. Kuo, S. C. Wang, and S. Fan, “GaN-based two-dimensional surface-emitting photonic crystal lasers with AlN/GaN distributed Bragg reflector,” *Appl. Phys. Lett.*, vol. 92, pp. 011129-1–011129-3, 2008.
[7] T. C. Lu, C. C. Kao, H. C. Kuo, G. S. Huang, and S. C. Wang, “CW lasing of current injection blue GaN-based vertical cavity surface emitting laser,” *Appl. Phys. Lett.*, vol. 92, pp. 141102-1–141102-3, 2008.
[8] M. Boroditsky, T. F. Krauss, R. Coccioli, R. Vrijen, R. Bhat, and E. Yablonovitch, “Light extraction from optically pumped light-emitting diode by thin-slab photonic crystals,” *Appl. Phys. Lett.*, vol. 75, pp. 1036–1038, 1999.
[9] N. Eriksson, M. Hagberg, and A. Larsson, “,” *IEEE J. Quantum Electron.*, vol. 32, pp. 1038–1047, 1996.
[10] A. L. Fehrembach, S. Enoch, and A. Sentenac, “Highly directive light sources using two-dimensional photonic crystal slabs,” *Appl. Phys. Lett.*, vol. 79, pp. 4280–4282, 2001.
[11] M. Rattier, H. Benisty, E. Schwoob, C. Weisbuch, T. F. Krauss, C. J. M. Smith, R. Houdre, and U. Oesterle, “Omnidirectional and compact guided light extraction from Archimedean photonic lattices,” *Appl. Phys. Lett.*, vol. 83, pp. 1283–1285, 2003.
[12] D. Delbeke, P. Bienstman, R. Bockstaele, and R. Baets, “Rigorous electromagnetic analysis of dipole emission in periodically corrugated layers: The grating-assisted resonant-cavity light-emitting diode,” *J. Opt. Soc. Amer.*, vol. B19, pp. 871–880, 2002.
[13] A. David, T. Fujii, R. Sharma, K. McGroddy, S. Nakamura, S. P. DenBaars, E. L. Hu, C. Weisbuch, and H. Benisty, “Photonic-crystal GaN light-emitting diodes with tailored guided modes distribution,” *Appl. Phys. Lett.*, vol. 88, pp. 061124-1–061124-3, 2006.
[14] G. S. Huang, T. C. Lu, H. H. Yao, H. C. Kuo, S. C. Wang, C. W. Lin, and L. Chang, “Crack-free GaN/AlN distributed Bragg reflectors incorporated with GaN/AlN superlattices grown by metalorganic chemical vapor deposition,” *Appl. Phys. Lett.*, vol. 88, pp. 061904-1–061904-3, 2006.
[15] J. R. Chen, S. C. Ling, C. T. Hung, T. S. Ko, T. C. Lu, H. C. Kuo, and S. C. Wang, “High-reflectivity ultraviolet AlN/AlGaN distributed Bragg reflectors grown by metalorganic chemical vapor deposition,” *J. Crystal Growth*, vol. 310, pp. 4871–4875, 2008.
[16] S. Noda, M. Yokoyama, M. Imada, A. Chutinan, and M. Mochzuki, “Polarization mode control of two-dimensional photonic crystal laser by unit cell structure design,” *Science*, vol. 293, pp. 1123–1125, 2001.
[17] S.-H. Kwon, H.-Y. Ryu, G.-H. Kim, Y.-H. Lee, and S.-B. Kim, “Photonic bandedge lasers in two-dimensional square-lattice photonic crystal slabs,” *Appl. Phys. Lett.*, vol. 83, pp. 3870–3872, 2003.
[18] C. C. Chen, M. H. Shih, Y. C. Yang, and H. C. Kuo, “Ultraviolet GaN-based microdisk laser with AlN/AlGaN distributed Bragg reflector,” *Appl. Phys. Lett.*, vol. 96, pp. 151115-1–151115-3, 2010.
[19] K. McGroddy, A. David, E. Matioli, M. Iza, S. Nakamura, S. DenBaars, J. S. Speck, C. Weisbuch, and E. L. Hu, “Directional emission control and increased light extraction in GaN photonic crystal light emitting diodes,” *Appl. Phys. Lett.*, vol. 93, pp. 103502-1–103502-3, 2010.
[20] S. W. Chen, T. C. Lu, Y. J. Hou, T. C. Liu, H. C. Kuo, and S. C. Wang, “Lasing characteristics at different band edges in GaN photonic crystal surface emitting lasers,” *Appl. Phys. Lett.*, vol. 96, pp. 071108-1–071108-3, 2010.

Cheng-Chang Chen was born in Shalu, Taiwan, in 1981. He received the B.E. degree in physics from the National Chung-Cheng University, Minhsiung, Taiwan, in 2004, and the M.E. degree in photonics technologies from the National Tsing Hua University, Hsinchu, Taiwan, in 2006. He is currently working toward the Ph.D. degree in electrophysics at the National Chiao Tung University (NCTU), Hsinchu, Taiwan.

In 2007, he joined the Semiconductor Laser Technology Laboratory, NCTU, where he is currently with the Department of Photonics and the Institute of Electro-Optical Engineering. His current research interests include III-V semiconductor materials and Si-based material for light-emitting devices and nanostructure for optical devices under the instruction of Prof. Hao-Chung Kuo and Prof. Min-Hsiung Shih.

Jun-Rong Chen was born in Taichung, Taiwan, on October 23, 1980. He received the B.S. degree in physics from the National Changhua University of Education (NCUE), Changhua, Taiwan, in 2004, and the M.S. degree in optoelectronics from the Institute of Photonics, NCUE, Taiwan, in 2006. He is currently working toward the Ph.D. degree in the Department of Photonics and the Institute of Electro-Optical Engineering, National Chiao Tung University (NCTU), Hsinchu, Taiwan.

In 2006, he joined the Semiconductor Laser Technology Laboratory, NCTU, where he was engaged in research on III-V semiconductor materials for light-emitting diodes and semiconductor lasers under the instruction of Prof. T.-C. Lu, Prof. H.-C. Kuo, and Prof. S.-C. Wang. His current research interests include III-nitride semiconductor lasers, epitaxial growth of III-nitride materials, and numerical simulation of III-V optoelectronic devices.

Yi-Chun Yang received the B.S. degree in applied physics from the National University of Kaohsiung, Kaohsiung, Taiwan, in 2006.

In 2007, she joined the Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan, as a Research Assistant. Her current research interests include integrated photonic circuits, photonic crystal lasers and waveguides, and cavity quantum electrodynamics.

Min-Hsiung Shih received the B.S. degree in physics from the National Cheng Kung University, Tainan, Taiwan, in 1995, the M.S. degree in physics from the National Tsing Hua University (NTHU), Taiwan in 1997, and the Ph.D. degree in electrical engineering/electrophysics from the University of Southern California, Los Angeles, in 2006.

In 2007, he joined the Research Center for Applied Sciences, Academia Sinica, Nankang, Taiwan, as an Assistant Research Fellow. His current research interests include integrated photonic circuits, photonic crystal lasers and waveguides, surface plasmonics, and cavity quantum electrodynamics.

Hao-Chung Kuo (S’98–M’99–SM’04) received the B.S. degree in physics from the National Taiwan University, Taipei, Taiwan, in 1990, the M.S. degree in electrical and computer engineering from Rutgers University, Camden, NJ, in 1995, and the Ph.D. degree in electrical and computer engineering from the University of Illinois at Urbana-Champaign, Urbana, in 1999.

He has an extensive professional career both in research and industrial research institutions, which includes as follows: Research Consultant with Lucent Technologies, Bell Labs, Holmdel, NJ, from 1995 to 1997, R&D Engineer with the Fiber-Optics Division, Agilent Technologies, from 1999 to 2001, and R&D Manager with LuxNet Corporation, from 2001 to 2002. Since September 2002, he has been with the National Chiao Tung University, Hsinchu, Taiwan, as a member of the faculty at the Institute of Electro-Optical Engineering. He is the author or coauthor of more than 60 papers published in various national and international journals and conference proceedings. His current research interests include the epitaxy, design, fabrication, and measurement of high-speed InPand GaAs-based vertical-cavity surface-emitting lasers, as well as GaN-based lighting-emitting devices and nanostructures.