Improved Output Power of InGaN LEDs by Lateral Overgrowth on Si-Implanted n-GaN Surface to Form Air Gaps

Shang-Ju Tu, Ming-Lun Lee, Yu-Hsiang Yeh, Feng-Wen Huang, Po-Cheng Chen, Wei-Chih Lai,
Chung-Wei Chen, Gou Chung Chi, and Jinn-Kong Sheu

***Abstract*— In this paper, air gaps were embedded in the n-GaN layer to improve light output power of InGaN-based light-emitting diodes (LEDs). Si ions (Si^{+28}) were implanted on the n-GaN surface, causing a lattice constant disorder. Therefore, the GaN grown on the Si-implanted areas had a lower growth rate than the implantation-free regions. Without using a dielectric thin film, lateral epitaxial overgrowth technique was used to form air gaps above the implanted regions and below the active layers of InGaN LEDs. We proposed the growth mechanisms of GaN layer on the Si-implanted GaN templates and characterized the InGaN-based LEDs with embedded air gaps array. With a 20-mA current injection, experimental results indicate that light output power (LOP) of the proposed LEDs was enhanced by 36%, compared with those of the conventional LEDs. This enhancement can be attributed to the light scattering at the textured GaN/gap interfaces to increase the effective light escape cone in the LEDs. Based on ray tracing simulation, if the height and the width of bottom of gaps were increased to 3 μm, the Lop could be enhanced over 70%.**

***Index Terms*— Air gaps, lateral overgrowth, light output power (LOP), Si-implanted.**

I. INTRODUCTION

GENERALLY, the light output power of a light-emitting diode (LED) depends on the quantum efficiency of the active layer and its light extraction efficiency (LEE). One of the most significant problems with LEDs is the occurrence of trapped light within semiconductors with high refractive indices [1]. Thus, to improve LEE, efforts have been made to overcome the significant photon loss that results from total internal reflection inside LEDs. For GaN/sapphire-based blue/green LEDs, the refractive indices of sapphire and GaN are approximately 1.7 and 2.4, respectively. Therefore, photons emitted from the active layer are virtually trapped within the GaN-based layers if the GaN/sapphire and the GaN/air interfaces are specular. LEE is enhanced by roughening the semiconductor/air and semiconductor/substrate interfaces or, by shaping the LED. Methods to control growth conditions to obtain rough surfaces in situ are theoretically superior to etching methods [2]. To improve the LEE of GaN-based LEDs, the application of naturally textured surfaces, including V-shaped pits or truncated micro-pyramids originating from a change in conditions during the growth of the p-GaN top contact layer, is a well-known and effective approach [3]–[4]. Recently, the growth of GaN/sapphire-based LEDs on patterned sapphire substrates (PSS) to create a rough GaN/sapphire interface and, consequently, to enhance LEE has become a well-accepted technology for mass production [5]–[6]. Tsai et al. demonstrated another approach using in situ SiH_4 treatment to create a naturally textured GaN/sapphire interface in GaN/sapphire-based LEDs. This process led to the formation of a series of gaps at the GaN/sapphire interface, resulting in effective light scattering to enhance LEE [7]. In contrast to the self-assembled texture of top GaN/air and GaN/sapphire interfaces, which are naturally formed during epitaxial growth, the rough GaN/PSS interface needs additional processing. For instance, sapphire is initially patterned by wet chemical etching or plasma etching before epitaxial growth. Moreover, growth conditions are strongly dependent on depth and spacing of the PSS patterns and surface morphology [5]–[6]. In the current study, an approach aimed at achieving guided light-scattering layers beneath the active layer of GaN-based LEDs was demonstrated to improve LEE. The epitaxial layer structures of InGaN/GaN blue LEDs were grown on n-GaN template layers with selective-area Si ion implantation (Si-implanted GaN). The dosage of Si ions used in this study was $5 \times 10^{15}/cm^2$ to selectively create shallow damage areas on the n-GaN templates. During the growth of InGaN/GaN LED structures on the Si-implanted GaN templates, the epitaxial layer was initially grown on the implantation-free area, where as the deposition of GaN on the Si-implanted regions did not occur because the lattice constant of the latter regions was different from that of the

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S.-J. Tu, Y.-H. Yeh, F. W. Huang, P. C. Chen, W.-C. Lai, and J.- K. Sheu are with the Department of Photonics and Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 70101, Taiwan (e-mail: l7897109@mail.ncku.edu.tw; l78001119@mail.ncku.edu.tw; l7897105@mail.ncku.edu.tw; l78991233@mail.ncku.edu.tw; weilai@mail.ncku.edu.tw; jksheu@mail.ncku.edu.tw).

M.-L. Lee is with the Department of Electro-Optical Engineering, Southern Taiwan University, Tainan 71001, Taiwan (e-mail:minglun@mail.stut.edu.tw).

C. W. Chen is with the Department of Physics, National Central University, Taoyuan 32001, Taiwan (e-mail: cwchen@phy.ncu.edu.tw).

G. C. Chi is with the Department of Photonics, National Chia Tung University, Hsinchu 300, Taiwan (e-mail: gcchi@phy.ncu.edu.tw).

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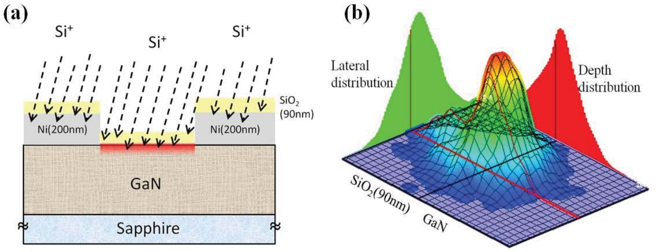

Fig. 1. (a) Layer structure of SiO_2/Ni/n-GaN templates. (b) Calculated ion distribution of Si^{+28} in GaN with SiO2 (90 nm) cap layer. The acceleration energy is 70 keV.

former [8]. As a result, selective growth occurred in the GaN epitaxial layer on the Si-implanted GaN templates, and a series of concaves was formed on the GaN layer. Compared with conventional PSS or SiO_2 nanorod-embedded GaN templates with concaves and/or convexes, which require a critical growth condition for subsequent epitaxial growth [9], the Si-implanted GaN templates were substantially flat, facilitating uncritical growth conditions. In this study, air gaps were created in the InGaN/GaN LED structures grown on the Si-implanted GaN templates to form light-scattering centers for improving LEE of LEDs. The output powers of the bare chip LEDs were measured with an integral sphere. Detailed processing procedures and related results, including electrical and optical properties of the fabricated LEDs, are discussed subsequently.

II. EXPERIMENTS

The samples used in this study were grown on c-face (0001) sapphire substrates in a vertical metal-organic vapor-phase epitaxy (MOVPE) system. Trimethylgallium (TMGa), trimethylindium (TMIn), and ammonia (NH3) were used as sources of gallium, indium, and nitrogen, respectively. A GaN nucleation layer was first deposited on the sapphire at 560 °C, and then a high-temperature (HT) GaN template was grown at 1000 °C in two steps for effective reduction of TD density. Before the growth of the LED structures, n-type GaN epitaxial layers, including a 1 μm thick undoped HT GaN layer and a 2 μm thick Si-doped n-GaN layer, were grown on the sapphire substrates as templates for the subsequent regrowth process. The carrier concentration of the n-GaN template layer was around $8 \times 10^{18}/cm^3$. A 200 nm thick Ni layer, which served as mask layer, was deposited on the n-GaN templates. A series of circular openings on the Ni mask layer with a diameter and spacing of 3 μm was defined using photolithography and wet etching process. Next, a 90 nm-thick SiO_2 layer was deposited on the Ni/n-GaN templates to serve as the ion-stop layer. This SiO_2 layer leads to the implanted Si ions accumulated next to the surface of the GaN layer. Fig. 1(a) shows the layer structure of SiO_2/Ni/n-GaN templates for ion implantation. To fabricate the Si-implanted GaN templates, Si ion(Si^{+28}) implantation, with dosage and energy of $5 \times 10^{15}/cm^2$ and 70 keV, respectively, was performed on the SiO_2/Ni/n-GaN templates. The distribution of the implanted ions at about that depth can be approximated as Gaussian with a standard deviation. The implanted Si ions created a damage layer, with a depth of approximately 50 nm from the GaN surface, which was estimated by simulation using the transport of ions in matter (TRIM) program. Fig. 1(b) shows the ion distributions calculated using the TRIM program

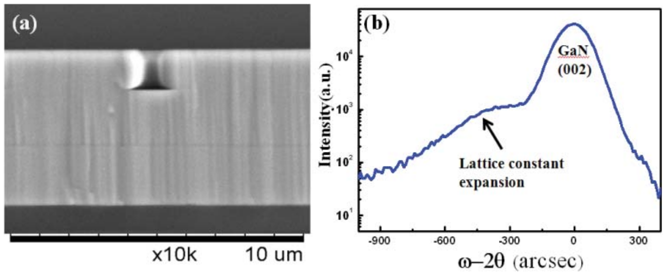

Fig. 2. (a) SEM image of GaN lateral growth on implanted region. (b) X-ray diffraction spectra of ion implanted on GaN surface.

After the ion implantation process and the removal of the SiO_2/Ni layers, GaN templates with selective-area Si implantation were achieved. Next, the Si-implanted GaN templates were loaded onto the MOVPE reactor to regrow the n-GaN epitaxial layer. Growth conditions, such as growth temperature, pressure, and V/III ratio [10]–[12], should be considered in the formation of concaves on ion-implanted regions and air gaps embedded in the GaN layer of LED structures. In this study, growth temperature, pressure, and V/III ratio were at 1030 °C, 100 torr, and 1750, respectively, during the growth of n-GaN layers. Fig. 2(a) shows typical scanning electron microscopy (SEM) images taken from a 2μm thick n-GaN layer grown on Si-implanted GaN templates. Selective area growth can be seen clearly from the images because of the occurrence of concaves on the regrown GaN layer. This could be attributed to the relatively lower growth rate of GaN at the Si-implanted regions than at the implantation-free regions. In general, the crystal structure of semiconductors under high-dose and/or high-energy ion bombardment produces an amorphous layer [8]. Thus, the lattice constant of the Si implanted regions would be different from that of the virgin areas.

To prove the aforesaid contention, high-resolution x-ray diffraction (HRXRD) was performed on the Si-implanted GaN templates. As shown in Fig. 2(b), the XRD spectrum exhibits two peaks, which behave like a two-layer structure. A broad peak located on the low-angle side shows that a lattice disorder and an expansion exist on the GaN layer [13]–[14]. During the ion implantation process, ions undergo a series of collisions with host atoms of the target. These collisions include both lateral and vertical motions, there by resulting in a three-dimensional Gaussian distribution, as shown in Fig. 1(b). Therefore, lattice constant expansion and disorder occur both at in- and normal-plane directions. After the growth of subsequent GaN layers, lateral coalesce eventually results in a continuous layer and leaves air gaps over the Si-implantation regions. Afterwards, a LED structure, including a 1.7 μm thick Si-doped n-GaN layer, a 10-pair $In_{0.3}Ga_{0.7}N$/GaN multiple quantum well (MQW) structure grown at 750 °C, a 0.05 μm thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer, a 0.2 μm thick Mg-doped p-GaN top contact layer grown at 1000 °C, as well as a heavily Si-doped short-period superlattice (SPS) structure, was grown in sequence [15]. As shown in Fig. 3(a), air gaps were embedded in the regrown

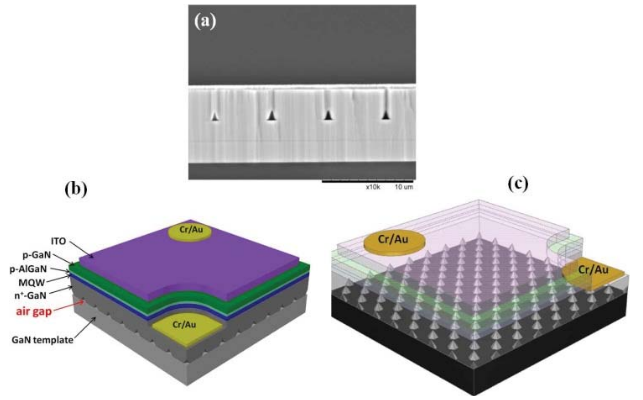

Fig. 3. (a) SEM image of GaN after lateral coalescence to form a series ofair gaps and grown LED structure. (b) Schematic layer structure for GaN-based LED with embedded air gaps. (c) Perspective structure corresponding to (b).

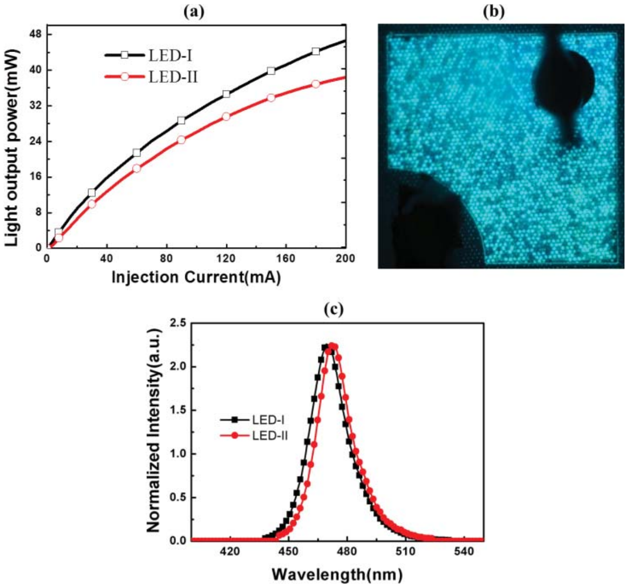

Fig. 4. (a) Light output-current $(L-I)$ are characteristics of LED-I and LED-II. (b) Typical photograph taken from LED-I with a driving current of 20 mA. (c) Typical EL spectra of LED-I and LED-II driven under 20 mA.

GaN layer. Fig. 3(b) shows a schematic layer structure of a GaN-based LED with embedded gaps, where as Fig. 3(c) shows a corresponding perspective structure. Two-dimensional air gap arrays were schematic on the surface of the GaN template layer. In this study, without using a dielectric thin film, the difference in growth rates between the implanted and the un-implanted regions resulted from the difference in their lattice constants. LEDs grown on Si-implanted GaN templates with embedded gaps were labeled as LED-I. LEDs grown on implantation-free GaN templates without embedded gaps were prepared and labeled as LED-II for comparison. All fabricated LEDs had an area of $300\times300\mu$m. Room-temperature current-voltage (I-V) characteristics of experimental LEDs were measured using an HP-4156C semiconductor parameter analyzer. Light output power-current (L-I) of the LEDs was measured with a calibrated integrating sphere.

III. RESULTS AND DISCUSSION

Fig. 4(a) shows light output power as a function of injection current. At an injection current of 20 mA, the output power of LED-I compared with LED-II can be improved by magnitudes of approximately 36%. Usually, photons emitted from the MQW are partially trapped in the LED because of Fresnel loss and total internal reflection (TIR) angle limit. As such, light emitted from the active layer of LED-I experience a shorter average path before the photons escape through the nitride films into the free space. Thus, the enhanced light output was mainly attributed to light scattering around the air gaps, which led to a relatively lower internal absorption in LED-I. Fig. 4(b) shows the micrograph taken from LED-I under an operation current of 20 mA. A periodic feature resulting from the light scattering at embedded air gaps can be clearly observed. To clarify the aforesaid contention, ray tracing simulations were performed. Fig. 4(c) shows the typical electroluminescence (EL) spectra of LED-I and LED-II driven under 20 mA. Peak wavelengths taken from LED-I and LED-II were 469 nm and 472 nm, respectively. In this study, the growth mechanism of n-GaN underlying layer in LED-I grown on the Si-implanted template was similar to the epitaxially laterally overgrowth on GaN (ELOG). Accordingly, LED-I grown on the Si-implanted templates should have relative lower stress in the n-GaN layer [16]. This tentative contention is consistent with the observation of red shift in emission peak of LED-II Fig. 5(a) and 5(b) show cross-sectional ray trajectory images of conventional LED-I and LED-II, respectively. The dimension of the embedded pyramidal gaps was set as 1.5 and 1 μm for the height and the side width of the base, respectively. Compared with LED-II, the extracted ray density through the top face of LED-I was markedly higher. The relatively higher ray density of LED-I was attributed to the emitted light reflected at the GaN/gap interfaces and redirected to the top surface, implying a larger effective TIR angle of the light incident into the air, thereby resulting in a relatively less internal absorption in the LED-I. In principle, the light output of LED-I can be further enhanced by increasing the size of the embedded gaps because the effective area of the GaN/gap interfaces, which creates a refractive index contrast between the gaps and GaN, increases with an increase in gap size. Based on the ray-tracing simulations, if the gap height and the width of the bottom were increased to 3 μm, the light power of LED-I could be enhanced by over 70% compared with that of LED-II, as shown in Fig. 5(c).

However, the gap sizes are strongly dependent on growth conditions and/or the Si-implanted area when GaN-based LEDs are grown on the selective-area Si-implanted GaN templates. Further research on this issue is underway, and related results will be published in the near future. Fig. 6(a) shows the room-temperature I-V characteristics of LED-I and LED-II. With an injection current of 20 mA, the typical forward voltages (V_f) were 3.3 and 3.4 V for LED I and LED II, respectively. This small difference could be attributed to the effect of structure defects on the carrier transport. During the growth of GaN on sapphire substrate, large compressive stress and dense threading dislocation (TD) exist in the epitaxial layer because of lattice and thermal expansion coefficient

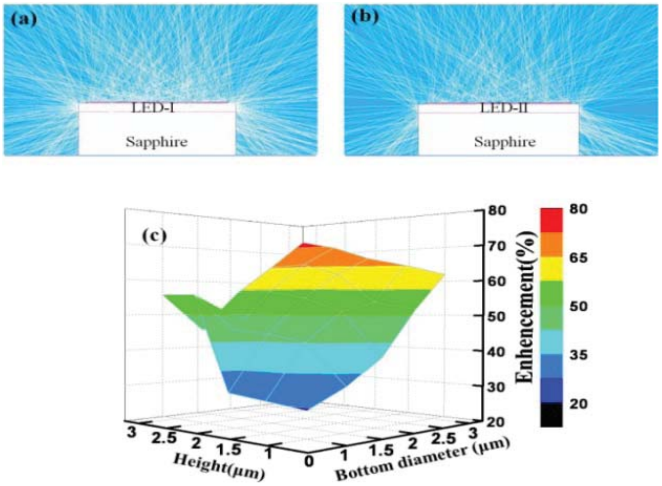

Fig. 5. Cross-sectional view of ray trajectory images by simulation for (a) LED-I and (b) LED-II. (c) Enhancement of output power of LED-I compared with that of LED-II as a function of air gap size.

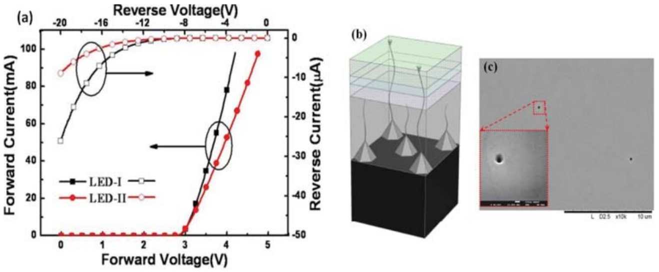

Fig. 6. (a) Typical $I-V$ characteristics of LED-I and LED-II. (b) Schematic diagram of air gaps associated with TD-related surface pits. (c) SEM image taken from the surface of LED-I. Inset: enlarged image of a surface pit.

mismatch between GaN and sapphire. ELOG (epitaxially laterally overgrowth on GaN) technology applied to GaN epitaxial growth can effectively reduce stress and TD density. Although the present case is not completely identical to conventional ELOG cases, the formation of gaps above the Si-implanted regions, as mentioned in the preceding paragraph, implies that lateral growth and dislocation bending might occur above the Si-implanted regions. Therefore, the slight difference in V_f can be tentatively attributed to the relatively higher strain on LED-II. The excess strain causes an additional band tilt in quantum wells (i.e., active layer); hence, there is an effective potential barrier that substantially hinders carrier transport. Meanwhile, in conventional ELOG cases, gaps are often created at coalescence boundaries because of the meeting of laterally growing GaN facet fronts. Further, the coalescence boundary above the gaps shows that high impurity incorporation at the merging crystal planes results in a high carrier concentration [16]–[17]. In this study, the formation mechanism of gaps is similar to that of conventional ELOG cases. Accordingly, the average carrier concentration in the n-GaN layer grown on the Si-implanted GaN templates might be higher than that grown on a conventional sapphire substrate (i.e., n-GaN layer in LED-II). As a result, the relative lower series resistance and V_f were observed in the LED-I. Moreover, the pits that correspond to the underlying gaps have been observed [18]. Fig. 6(b) shows a schematic diagram of the gaps associated with TD-related surface pits. To clarify the aforesaid contention, SEM was performed on the surface of LED-I. As shown in Fig. 6(c), randomly distributed surface pits were observed on the surface of LED-I. This indicates indirectly that the merged crystal planes above the air gaps induce TDs along the growth direction (c-axis), extending to the surface to generate surface pits. Hence, the effect of TD-related pits on the leakage current of the experimental LEDs has been considered. As shown in Fig. 6(a), embedded air gaps cause a marked difference in TD-related surface pit density reflecting on the significant difference of reverse I-V characteristics between LED-I and LED-II. Pit-related TDs, which might contain metalstable acceptor and donor-like states coexisting in the vicinity of dislocations, should be responsible for the locally high reverse leakage current in GaN-based devices [17]–[18]. Although the TD-related surface pits in LED-I induced a relatively higher reverse leakage current compared with those in LED-II, the pits seemed to exhibit an insignificant effect on the emission efficiency of LED-I. This result indicated again that the emission efficiency of InGaN-based blue/green LEDs is relatively insensitive to structural defects [19]–[20]. Although the TD-related surface pits associated with leakage paths deteriorate reverse I-V characteristics, the TD-related surface pits localized above the gaps, as shown in Fig. 6(b), should completely disappear if the thickness of the underlying GaN epitaxial layer is increased or if an insertion layer is added into the LED structure [3], [17], [21].

IV. CONCLUSION

GaN-based LEDs grown on Si-implanted GaN templates to form air gaps beneath the MQW active layer were demonstrated. Experimental results indicated that significant enhancement in LEE of GaN-based LEDs could be achieved. GaN-based epitaxial layers grown on selective Si-implanted regions had lower growth rates compared with those grown on implantation-free regions, resulting in selective growth and subsequent lateral growth over the Si-implanted regions. Accordingly, air gaps were formed over the Si-implanted regions after the meeting of laterally growing GaN facet fronts. The experimental results indicated that the light-output power of LEDs grown on Si-implanted GaN templates was enhanced by 36% compared with conventional LEDs. This enhancement in output power was mainly attributed to the light scattering around the air gaps, which led to a higher escape probability for the photons. In short, there was an increase in light-extraction efficiency instead of an improvement in material quality or internal quantum efficiency.

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Shang-Ju Tu was born in Taiwan. He received the M.S. degree from the Department of Electro-Optical Engineering, Southern Taiwan University, Tainan, Taiwan, in 2008. He is currently pursuing the Ph.D. degree with National Cheng-Kung University, Tainan.

His current research interests include growth and characterization of III–N semiconductors and devices.

Ming-Lun Lee was born in Taiwan. She received the M.S. degree in physics from National Central University, Taoyuan, Taiwan, and the Ph.D. degree in electrical engineering with National Cheng-Kung University, Tainan, Taiwan, in 2002 and 2005, respectively.

She joined the Department of Electro-Optical Engineering, Southern Taiwan University (STU), Tainan, in 2005, as an Assistant Professor, where she is currently an Associate Professor. Her current research interests include characterization of III–N semiconductors and optoelectronic devices.

Yu-Hsiang Yeh was born in Taiwan. He received the M.S. degree from the Department of Electro-Optical Engineering, Southern Taiwan University, Tainan, Taiwan, in 2011. He is currently pursuing the Ph.D. degree with National Cheng-Kung University, Tainan.

His current research interests include growth and characterization of III–N semiconductors and devices.

Feng-Wen Huang was born in Taiwan. He received the M.S. degree from the Institute of Electro-Optical Science and Engineering, National Cheng-Kung University, Tainan, Taiwan, in 2008. He is currently pursuing the Ph.D. degree with the same university.

His current research interests include growth and characterization of III–N semiconductors and devices.

Po-Cheng Chen was born in Taiwan. He received the M.S. degree from the Department of Photonics, National Sun Yat-Sen University, Kaohsiung, Taiwan, in 2011. He is currently pursuing the Ph.D. degree with National Cheng-Kung University, Tainan, Taiwan.

His current research interests include growth and characterization of III–N semiconductors and devices.

Wei-Chih Lai was born in Taiwan in 1970. He received the B.S. degree in electrical engineering from Feng-Chia University, Taichung, Taiwan, in 1993, and the M.S. and Ph.D. degrees in electrical engineering from National Cheng-Kung University (NCKU), Tainan, Taiwan, in 1995 and 2001, respectively.

He was with the Department of Electrical Engineering, NCKU, in 2001, as a Post-Doctoral Associate. He is currently with the Institute of Electro-Optical Science and Engineering, NCKU, as an Associate Professor. His current research interests include growth and characterization of III–N semiconductors and devices.

Chung-Wei Chen is currently pursuing the Ph.D. degree in physics with National Central University, Taoyuan, Taiwan.

His current research interests include growth and characterization of III–V semiconductors and devices.

Gou Chung Chi was born in Kaohsiung, Taiwan, in 1946. He received the B.S. degree from National Taiwan Normal University, Taipei, Taiwan, in 1970, and the M.S. and Ph.D. degrees in solid state physics and materials from the Department of Engineering and Applied Science, Yale University, New Haven, CT, in 1973 and 1976, respectively.

He was a Technical Staff Member with AT&T Bell Laboratories, Murray Hill, NJ, from 1977 to 1990, and from 1990 to 1994, he was a Director of the Division of Optoelectronics Materials and Devices, Optoelectronics and Systems Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan. Since 1994, he has been a Professor with the Department of Physics and the Director of the Optical Sciences Center, National Central University, Taoyuan, Taiwan. He is currently a Professor and Director of the Department of Photonics, National Chia Tung University, Hsinchu. His current research interests include wide-bandgap semiconductor and devices (A1GaInP, InGaAsP, and GaN-based materials) and microoptics integrated systems.

Dr. Chi is a member of the American Physics Society, the Materials Research Society, the Physical Society, and the Electron Devices and Materials Society.

Jinn-Kong Sheu received the Ph. D. degree in electrical engineering from National Cheng-Kung University (NCKU), Tainan, Taiwan, in 1999.

He was a Senior Engineer with Epistar Corporation Ltd ., from 1997 to 2000, specializing in the manufacturing of high brightness light-emitting diode chips and the growth of epitaxial wafers by metalorganic-vapor-phase epitaxy. From 2000 to 2003, he was with the Optical Science Center, National Central University, Taoyuan, Taiwan, as a Post-Doctoral Researcher. From 2003 to 2004, he became an Assistant Professor with the Institute of Optical Science, National Central University. He is currently with the Department of Photonics, NCKU, as a Professor. His current research interests include epitaxial growth and characterization of III-nitride semiconductors and optoelectronics device.