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Lee-Woon Jang

Korea University

Sang-Ik Lee

Korea University

Andrej Kuznetsov

University of Oslo

A.L. Zakgeim

Russian Academy of Sciences

E.B. Yakimov

National University of Science and Technology MISIS

Pil-Kyu Jang

Korea University

Anton E. Chernyakov

Russian Academy of Sciences

Luiza A. Alexanyan

National University of Science and Technology MISIS

M. L. Skorikov

Russian Academy of Sciences

Ivan V. Shchemerov

National University of Science and Technology MISIS

Anton A. Vasilev

National University of Science and Technology MISIS

Alexander Y. Polyakov

National University of Science and Technology MISIS

Ih-Hwan Lee

`ihlee@korea.ac.kr`

Korea University

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Lee-Woon Jang^{a†}, Sang-Ik Lee^{b†}, Andrej Kuznetsov^c, A. L. Zakgeim^d, E. B. Yakimov^{e,f}, Pil-Kyu Jang^b, Anton E. Chernyakov^d, Luiza A. Alexanyan^e, M. L. Skorikov^g, Ivan V. Shchemerov^e, Anton A. Vasilev^e, Alexander Y. Polyakov^{e*}, and In-Hwan Lee^{b*}

† Contributed equally.

^a The Institute for High Technology Materials and Devices, Korea University, Seoul 02841, Republic of Korea

^b Department of Materials Science and Engineering, Korea University, Seoul 02841, Republic of Korea

^c Department of Physics, Centre for Materials Science and Nanotechnology, University of Oslo, P.O. Box 1048 Blindern, N-0316 Oslo, Norway

^d Research & Engineering Center for Submicron Heterostructures for Microelectronics, Russian Academy of Sciences; 26, Politekhnikeskaya 194021, St.-Petersburg, Russia

^e National University of Science and Technology MISIS, 4 Leninsky Ave, Moscow, 119049, Russia

^f Institute of Microelectronics Technology and High Purity Materials, Russian Academy of Sciences, Chernogolovka, Moscow Region 142432, Russia

^g P.N. Lebedev Physical Institute, Russian Academy of Science, 53 Leninsky Ave, Moscow 119991, Russia

*E-mails: ihlee@korea.ac.kr, aypolyakov@gmail.com

ABSTRACT

The efficiency of GaN-based micro-light-emitting diodes (μ LEDs) degrades severely as the device size decreases, a phenomenon known as size-dependent efficiency droop. This degradation is primarily driven by an increased surface-to-volume ratio, where plasma-induced damage during dry-etching generates non-radiative recombination centers at the mesa sidewalls. To clearly elucidate the impact of these process-induced defects, this study investigates the physical extent of sidewall damage and its quantitative effect on the recombination dynamics of blue InGaN/GaN μ LEDs across a size range of 5–100 μm . Spatially resolved micro-cathodoluminescence (MCL) mapping reveals a distinct damaged region approximately 1 μm along the mesa periphery. Furthermore, electrical characterization confirms that leakage current scales inversely with diode diameter, a challenge that is effectively mitigated through KOH wet etching and SiO_2 passivation. By correlating the size-dependent shift in peak quantum efficiency current density (J_{peak}) with the MCL-measured damage width using a modified ABC recombination model, we quantitatively extracted the defect density of the sidewall region. Our analysis indicates that the density of non-radiative recombination centers within the 1 μm -thick sidewall region is approximately 10-20 times higher than that of the bulk material. These results provide a rigorous physical basis for understanding the "efficiency cliff" in μ LEDs and underscore the critical need for defect management in the sub-10 μm regime.

I. INTRODUCTION

InGaN/GaN multi-quantum-well (MQW) micro-light-emitting diodes (μ LEDs) have garnered significant interest because of their superior optoelectronic properties. These devices are typically fabricated by Metalorganic Chemical Vapor Deposition (MOCVD) growth, followed by dry etching to define mesas structures of varying dimensions. This interest is driven by the potential for substantial efficiency improvements and the emergence of new application areas, including micro-projectors, high-resolution micro-displays, diffraction-limited optical microscopy, and advanced optical communication systems [1-6]. The requirements for device dimensions, emission wavelengths, power consumption, and efficiency are dictated by these specific applications. Notably, the most stringent requirements arise from wearables and augmented reality/virtual reality (AR/VR) systems, which necessitate efficient blue, green, and red μ LEDs scaled down to the sub-10 μm or even 1 μm regime.

Despite these advancements, a critical challenge remains: the efficiency of blue μ LEDs declines precipitously, and leakage current increases drastically as dimensions shrink below 20 μm . This phenomenon, graphically termed the “efficiency cliff”, is primarily caused by dry-etching-induced damage at the mesa sidewalls. Detailed studies attribute the performance degradation to increased band bending at the sidewalls and the introduction of non-radiative recombination centers, which significantly enhance surface recombination velocity [6-11].

To quantitatively address this enhanced surface recombination, simplified models—such as the “dead surface region” concept or a modified ABC recombination model incorporating surface effects—have been proposed [6-8, 12, 13]. Physical investigations using transmission electron microscopy (TEM) have identified an enhanced density of dangling bonds at dry-etched surfaces [14]. Furthermore, Deep Level Transient Spectroscopy (DLTS) has associated this degradation with deep electron traps (likely nitrogen vacancy V_N -related acceptors) and non-radiative

recombination centers related to nitrogen interstitials and gallium vacancy (V_{Ga}) complexes. These defects, particularly traps near $E_c - 0.7$ eV in quantum wells and $E_v + 1$ eV in GaN barriers, play a detrimental role by enhancing hole capture and tunneling, thereby reducing injection efficiency as the device diameter decreases [15-21].

Various mitigation strategies, including the physical removal of damaged regions via wet etching (KOH or TMAH) and dielectric passivation (SiO_2 or Al_2O_3), have been discussed to counteract these effects. However, the quantitative impact of these treatments on the internal physics of the sidewall remains to be fully elucidated [6-8, 12-14, 22-24]. In this study, we conduct a comprehensive quantitative analysis of sidewall recombination mechanisms in blue MQW μLEDs with diameters ranging from 100 μm to 5 μm . The optical and electrical properties of the devices are evaluated under different post-etch treatments: as-etched, KOH-treated, and KOH- SiO_2 passivation. By utilizing Micro-Cathodoluminescence (MCL) mapping, we directly visualize the sidewall damage, estimating the damage width to be ~ 1 μm . Furthermore, by correlating the size-dependent shift in peak efficiency current density (J_{peak}) with this spatially resolved damage width utilizing a modified ABC model, we demonstrate that the non-radiative recombination rate in the sidewall region is ~ 19 times higher than that in the bulk. These findings provide a physical basis for the severe efficiency droop and necessity of optimized sidewall management for next generation μLEDs .

II. Materials and Method

The μLEDs were fabricated by dry etching of planar blue InGaN/GaN MQW LEDs grown by MOCVD on a sapphire substrate. The epitaxial structure consists 2.3 μm of undoped GaN, 2.3 μm Si doped n-GaN ($n = 4 \times 10^{18} \text{ cm}^{-3}$), five 4 nm-thick InGaN QWs separated by 14 nm-thick GaN barriers, and 260 nm-thick p-GaN (Mg) layer ($p = 4 \times 10^{17} \text{ cm}^{-3}$ at room temperature). The samples

were patterned into μ LEDs by Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) using Cl_2/BCl_3 mixture down to the etch depth of 1 μm . The mesa diameters of the μ LEDs were 5, 10, 20, 30, 50, 100 μm . Current spreading was facilitated by a thin ITO layer on the p-type emitter, with Cr/Au (10 nm/10 nm) contact rings of 15 μm width. Ohmic contacts to the n-type region were formed by depositing Ni/Au/Cr (10 nm/100 nm/10 nm) rings.

The sidewalls were categorized into three types: as-etched (type S1), KOH treated in a 3 M aqueous solution (type S2), and KOH etching followed by passivation via Plasma Enhanced Chemical Vapor Deposition (PECVD) (50 nm) (type S3) [24]. All samples subsequently underwent Al_2O_3 passivation, and the inter-mesa spacing was filled with spin-on-glass (SOG). Electroluminescence (EL) was extracted through the top sapphire surface, with further fabrication details provided in the Supporting Material (Figure S1 and S2).

Characterization included current-voltage (I-V) measurements at room temperature, photoluminescence (PL) measurements at 10K and 300K, micro-cathodoluminescence (MCL) mapping/spectra measurements at room temperature, and electroluminescence (EL) efficiency measurements. I-V measurements were performed using a semi-automatic probe station Semishare SX-8 (China) for probe positioning and temperature control and Agilent B1500 semiconductor parameters analyzer (Agilent, USA) for current and voltage monitoring.

PL spectra were measured using a Spectra Pro 2500i spectrograph (Acton Research Corporation) equipped with a ZWO ASI294MM Pro CMOS matrix detector. The spectral resolution was about 4 meV; the spectra was not corrected for the response curve of the detector. Luminescence was excited by the second harmonic of a Mira-900D Ti:sapphire laser emitting a train of ~ 3 -ps-long pulses with a repetition rate of 76 MHz at a wavelength of 400 nm (after frequency doubling). The sample was mounted on the Judson ST-500 cryostat, and a confocal setup with a 50 $\times$ Mitutoyo micro-objective was employed for both excitation and collection in a backscattering geometry. The beam power was 15 mW with spatial resolution sufficient to target

the smallest mesas. The ratio of PL intensities at 300 K and 10 K was utilized to estimate the Internal Quantum Efficiency (IQE) [25].

MCL measurements were performed using a Jeol JSM 6490 SEM equipped with a MonoCL-3 system. The electron beam was incident through the ITO contact, with spectra and maps acquired simultaneously with secondary electron (SE) signals to correlate morphology with luminescence intensity along the mesa diameter [21].

EL performance was monitored using a Suss PM-5 probe station coupled with an Avantes spectrometer. External quantum efficiency (EQE), optical power, and power density were quantified using an OL770 high-speed test system, while spatial EL distributions were captured with a Canon EOS 5D CMOS camera. Keithley 2400 source meters were utilized for electrical biasing.

III. RESULTS AND DISCUSSION

The current density-voltage (J-V) characteristics for representative μ LEDs with diode diameters 100, 30, and 5 μm were illustrated in Fig. 1 (a-c). These data compare three distinct surface conditions: immediately following etching (type S1), after subsequent KOH etching (type S2), and following KOH etching with PECVD SiO_2 deposition (type S3). While some spread in parameters exists between individual diodes of a given type and diameter, representative samples are displayed in these figures. It is evident that the primary effects of varying the diode diameter and surface treatments are manifested as changes in reverse current density and specific series resistance in the forward direction. Notably, considerable excess current is observed at low forward voltages for S1 and S2 samples, which are strongly suppressed in type S3 samples.

The variation in reverse current density at -4 V as a function of diameter and treatment type is further detailed in Fig. 1 (d). As shown, reverse leakage uniformly increases as diode diameters

decrease across all samples, primarily due to the heightened impact of sidewall leakage as the periphery-to-area ratio increases. While etching in KOH somewhat alleviates this issue for type S2 samples, the additional SiO_2 passivation via PECVD results in the most significant reduction of reverse current across all diameters for type S3 samples.

For all samples with diameters exceeding 30 μm , the specific series resistance (R_s) remains relatively high on the order of 200 $\text{m}\Omega\cdot\text{cm}^2$, which is attributed to a non-optimal p-type contact fabrication process. However, for diode diameters below 30 μm , R_s values decrease sharply, reaching 10 $\mu\Omega\cdot\text{cm}^2$ for as-etched samples (type S1) and minimizing to 3 $\text{m}\Omega\cdot\text{cm}^2$ for type S2 and S3 samples at smaller diameters, as shown in Fig. 1 (e). This trend is driven by more effective current spreading over the p-type contact as the μLED dimensions decrease [6, 7].

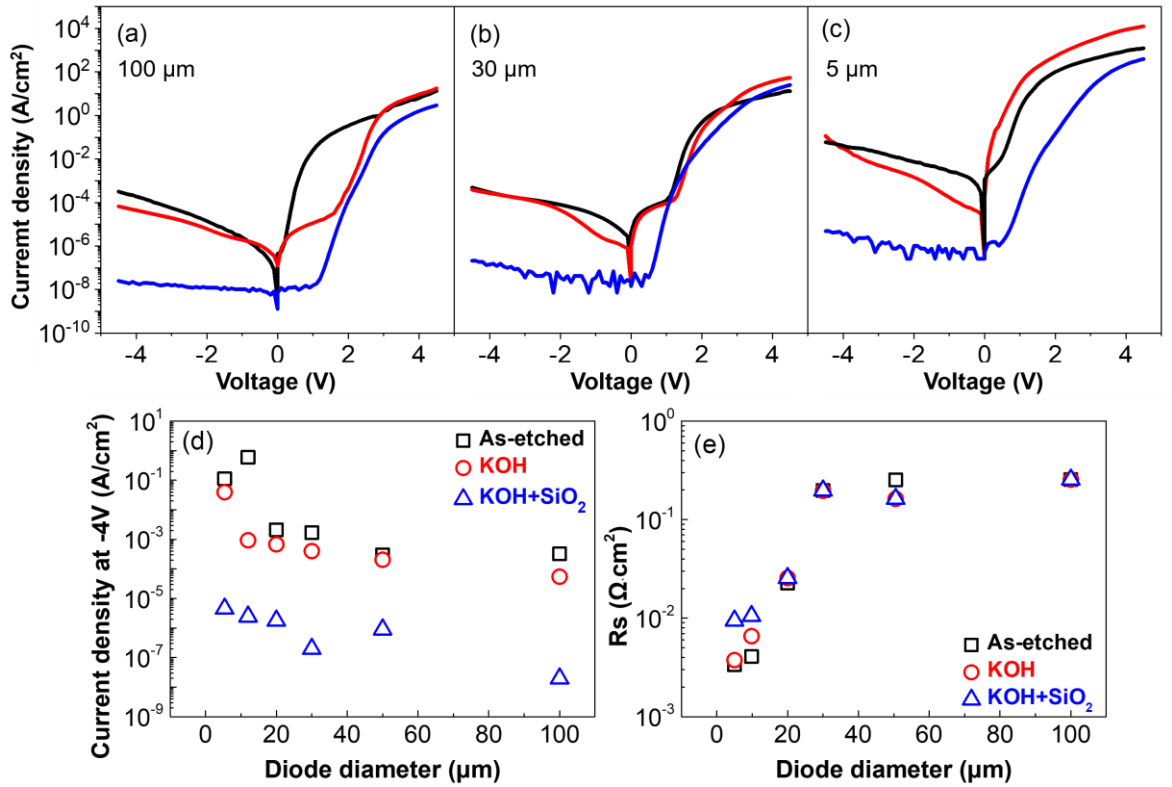


Fig. 1. (Color online) (a) J-V characteristics for type S1 (as-etched, black line), S2(KOH treated, red line), S3 (KOH+PECVD SiO₂, blue line for diode diameter 100 μm) samples; (b) for 30 μm ; (c) for 5 μm ; (d) the current density at -4V for differently treated diodes as a function of diameter; (e) specific series resistance of the studied diodes as a function of diameter and treatment

PL spectra measurements were performed for as-etched (type S1), KOH treated (type S2) and KOH-SiO₂ (type S3) samples. Since no significant differences were observed between types S2 and S3 within the spread of experimental parameters, the following data focuses on type S1 and S3 samples. As mentioned in the Experimental section, the spectra were collected from the top p-GaN side at 10K and 300K. The IQE was estimated from the ratio of the MQW peak intensities at 300K to those at 10K. These absolute IQE values are inherently dependent on the excitation power density (15 μW focused on 10 μm beam diameter, corresponding to $\sim 24 \text{ W/cm}^2$). For mesa diameters larger than the beam diameter (100, 50, 30, and 20 μm), measurements were conducted at both the center and the peripheral edge, with the edge values being utilized for analysis. The observed evolutionary trend across varying diode diameters serves as a robust qualitative indicator of the influence of device scaling and surface treatment on IQE.

The IQE values calculated from 300K/10K MQW peak intensity ratio are illustrated in Fig. 2. For the large diameter devices (100 μm), both sample types exhibit comparable IQE values of approximately 30%. In the as etched (type S1) samples (Fig. S3), however, the IQE begins a sharp decline at diameters below 30 μm , dropping to 2% at 10 μm and 1.5% for 5 μm diodes. In contrast, the KOH treated and passivated sample (type S2 and S3) exhibit an increased IQE of 35% at a diameter of 30 μm . This improvement is due to the relaxation in strain and consequent reduction in the magnitude of the quantum-confined Stark effect (QCSE) [6, 7]. While further scaling leads to a decrease in IQE, the rate of decline is significantly slower compared to the as-etched samples,

likely due to the partial mitigation of dry-etching-induced sidewall damage that otherwise causes high non-radiative recombination [6, 7]. As previously noted, the evolutionary behavior of the IQE remained nearly identical for types S2 and S3.

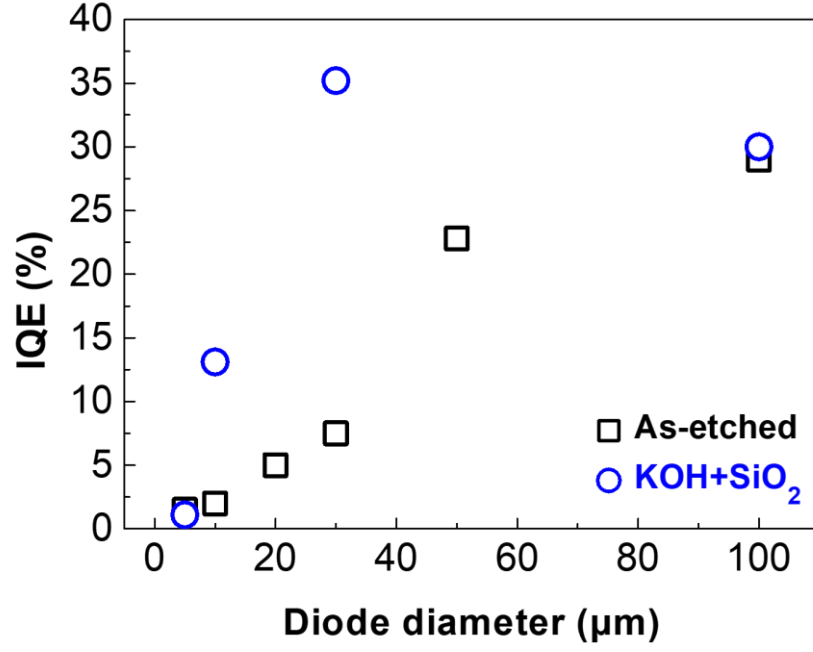


Fig. 2. (Color online) Calculated IQE values of as-etched (type S1) and KOH-SiO₂ treated (type S3) samples.

Further insights into the nature of the physical processes involved were obtained through SEM measurements in both MCL and SE modes. Fig. 3 (a) presents the MCL spectra measured from the top p-GaN surface for as-etched diodes with diameters 50 μm and 100 μm. The MQW emission peak near 450 nm and the GaN near-band-edge peak at 365 nm are clearly observed, and the weak defect related peak near 570 nm, which is attributed to the V_{Ga}-donor centers in the QWs [20, 21, 25]. Comparison of the images of the 50 μm diameter as-etched sample (type S1) taken in MCL mode (monitored at the 450 nm MCL line) and SE mode is shown in Fig. 3 (b) and 3 (c),

respectively. The MCL images clearly shows dark spots with characteristic dimensions of ~ 100 nm and a density of approximately $5\text{-}10 \times 10^6 \text{ cm}^{-2}$, features presumed to be associated with mixed dislocations [25].

Additional information was gleaned from MCL line scans performed at a wavelength of 450 nm corresponding to the emission from the InGaN MQW region. Fig. 3 (c) shows such MCL line scan together with SE mode scan for the 10 μm diameter μLED for as-etched sample (type S1). While the SE profile across the mesa surface is remarkably flat with a measured mesa width of 10.3 μm , the MCL intensity begins to rise and decay exponentially at the mesa edges with a characteristic width of 1.25 μm . This value serves as an estimate for the width of the region affected by enhanced surface recombination at the sidewalls [7, 13]. Variations in MCL intensity across the flat portion of the mesa can be correlated with the dark spots observed in Fig. 3 (b), likely associated with dislocations, a behavior consistent with previous reports [21, 26]. The line MCL profiles obtained for the 10 μm diameter mesas for each sample are compared in Fig. 3 (d). Notably, the mesa width decreases slightly by 0.3 μm after KOH treatment (type S2) and by an additional 0.2 μm following KOH- SiO_2 treatment (type S3). The exponential decay/rise constants at the edges exhibit a subtle decrease to 1.15-1.2 μm for the type S2 and S3 samples, compared to the 1.25 μm observed for the type S1 sample.

The MQW MCL intensity and luminescence lifetime profiles were both found to decay exponentially with characteristic lengths of $\sim 0.5 \mu\text{m}$ and 1 μm , respectively [26]. While our current MCL system is not configured for independent lifetime measurements, the spatial extent of the reduced MCL intensity in our study closely aligns with the region of decreased lifetime [26]. The slight decrease of the mesa width after KOH treatment is consistent with expectations, as the heavily dry etching induced damaged region is either partially or fully removed. Although the width of such damaged layers is typically reported to be in the order of tens of nanometers to 100

nm [7, 13, 27], the damaged region in our case appears slightly more extensive. Furthermore, it is suggested that the additional PECVD process contributes to a further removal of the damaged layer. This effect, in conjunction with SiO₂ passivation, likely accounts for the significantly reduced surface leakage observed in type S3 samples.

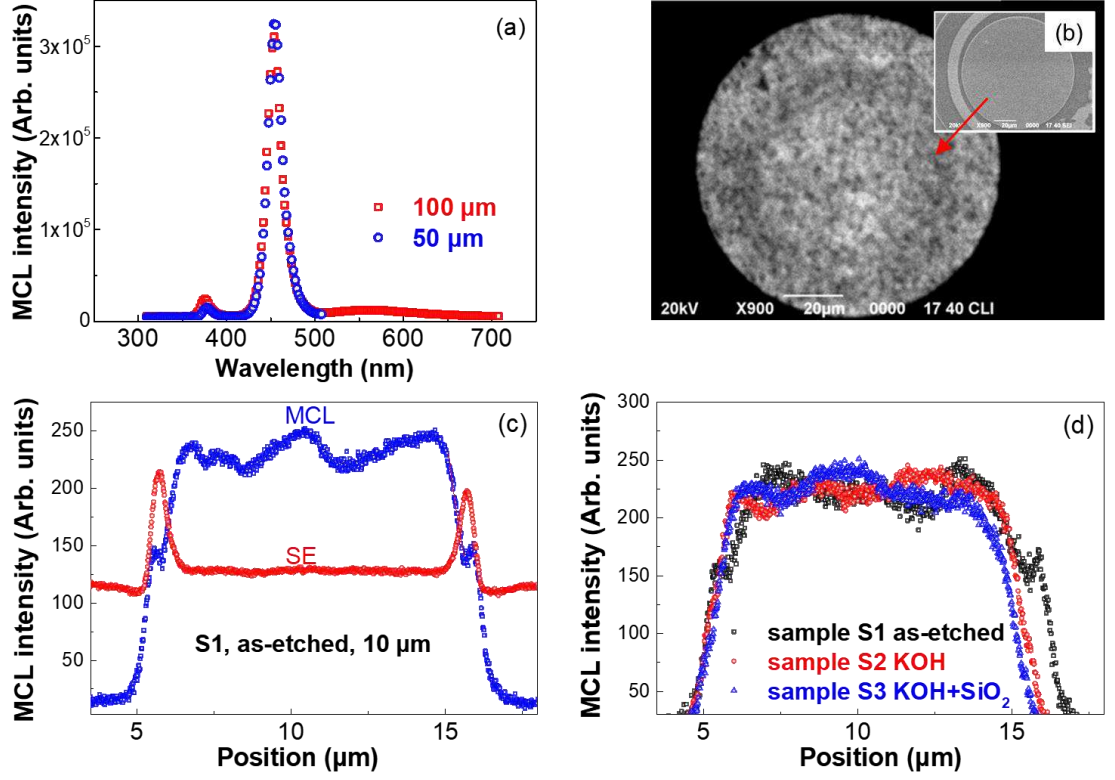


Fig. 3. (Color online) (a) MCL spectra measured from the p-GaN side at accelerating voltage 20 kV and probing beam current 1 nA for type S1 samples with diameters of 50 μm and 100 μm; (b) MCL image of the 100 μm as-etched (type S1) sample, with the inset displaying the p-type contact ring in Secondary Electrons (SE) mode; (c) MCL and SE line scans in as-etched (type S1) with 10 μm diameter; (d) MCL profiles for the as-etched (type S1) (black line), KOH treated (type S2) (red line) and KOH-SiO₂ treated (type S3) sample (blue line)

Recent studies have suggested that the decreased efficiency of micro-LEDs with smaller diameters arises not only from enhanced non-radiative recombination at damaged sidewalls but also from increased leakage current, which compromises injection efficiency [28, 29]. However, this trend was not observed in the present samples. No statistically significant differences in EL performance were found between type S2 and S3 samples, despite the reverse leakage and excess forward current being far more pronounced in type S2 compared to type S3. This discrepancy may be explained by the specific nature of the defects induced by dry etching.

As previously reported, dry etching creates electron traps near $E_c - 0.7$ eV and hole traps near $E_v + 0.8$ eV [20, 21]. The former, associated with interstitial nitrogen acceptors, are believed to be primarily responsible for increased non-radiative recombination. In contrast, the latter mostly account for enhanced leakage current, although they can contribute to losses in injection efficiency through hole trapping in quantum barriers if sufficiently pronounced [18, 20]. In this study, the observed improvements in EL efficiency following both KOH and KOH-SiO₂ treatments are predominantly attributed to a similarly effective reduction in the density of non-radiative recombination centers. This suggests that detrimental effects, such as hole trapping and tunneling-induced leakage, do not play a critical role in the performance degradation of these devices.

Detailed measurements of EL output power and EQE were conducted as a function of forward current density and chip diameter for all samples. Since the results were highly consistent within the statistical spread across the wafers, the following analysis focuses on the type S3 series. The EQE data for diodes of various diameters as a function of current density are presented in Fig. 4 (a). The EQE curves exhibit a characteristic peak, and the position of this (EQE_{peak}) steadily shifts toward higher current densities as the diode diameter decreases. Simultaneously, the peak current density (J_{peak}) is observed to increase as the device dimensions are scaled down. The variation of

EQE_{peak} with diode diameter is illustrated in Fig. 4 (b), while the corresponding shift in J_{peak} is displayed in Fig. 4 (c).

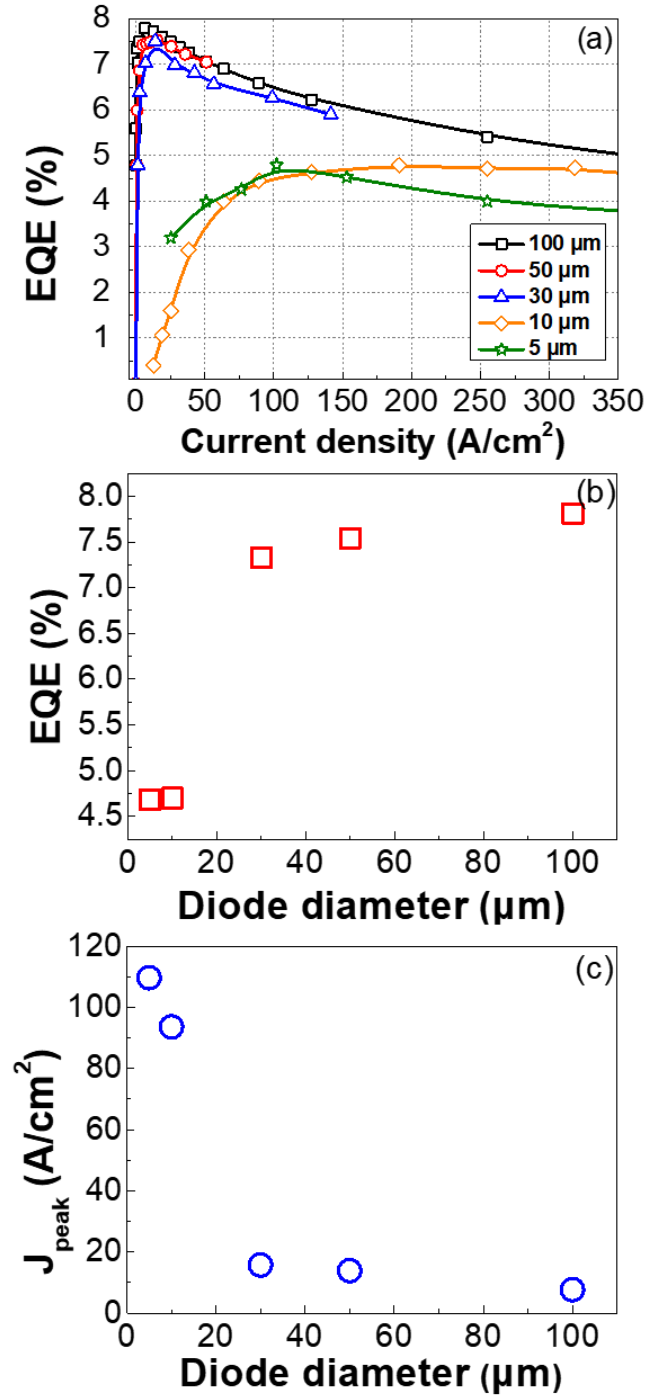


Fig. 4. (Color online) (a) EQE variations for type S3 samples with different diode diameters, (b) the dependence of EQE_{peak} on diode diameter, (c) the dependence of J_{peak} on diode diameter

This behavior of EQE_{peak} and J_{peak} is a widely observed phenomenon in blue InGaN/GaN μ LEDs [6-8, 12, 13]. These trends can be effectively rationalized by the modified ABC theory, which represents the EQE as follows [7, 13]:

$$EQE = \frac{\text{Photons at detector}}{\text{carriers injected}} = \frac{L}{I} \times \frac{e_0}{h\nu} = \eta_e \eta_{inj} \frac{Bn^2}{An + Bn^2 + Cn^3} = \eta_e \eta_{inj} IQE, \quad (1)$$

In this expression, L is the number of detected photons, I is the injection current, e_0 is the elementary charge, h is the Plank constant, η_e is the light extraction efficiency (LEE), η_{inj} is the injection efficiency, A is the coefficient of non-radiative recombination, B is the radiative recombination rate, and C is the Auger recombination rate. The EQE peak emerges from the competition between radiative and non-radiative recombination processes, specifically corresponding to the saturation of non-radiative recombination centers. Conversely, the efficiency droop observed at high current densities is frequently attributed to Auger recombination. In recently adopted models, the peak in the EQE (J) curve is presumed to be primarily governed by the IQE peak, which takes the following form [7, 12, 13]:

$$IQE_{peak} = \frac{P}{P + 2} = \frac{B}{B + 2\sqrt{AC}}, \quad (2)$$

where parameter P is defined as $P = B/(AC)^{1/2}$. Within this framework, the non-radiative recombination coefficient A is corrected to account for the effects of surface recombination velocity (V_s), by expressing it as the sum of the bulk rate, A_0 , and a surface-related component [7, 12, 13, 22, 23]:

$$A = A_0 + V_s \frac{P_{eri}}{S}, \quad (3)$$

where P_{eri} is the diode periphery and S is its area. It has been proposed to express the surface-related recombination term as follows [12, 22, 23]:

$$A = A_0 + \frac{A_s \lambda P_{eri}}{S}, \quad (4)$$

In this model, λ represents the width of the region where non-radiative recombination is influenced by dry-etching-induced defects acting as a sort of effective diffusion length near the sidewalls and A_s is the effective non-radiative recombination constant in this region. Existing literature often assumes that injected carrier concentrations in the "bulk" and "sidewall" regions are identical, attributing the impact of sidewall damage solely to the additional non-radiative recombination velocity (V_s) as described in Eq. (3). Meanwhile, Eq. (4) introduces the effective thickness (λ) for the region where V_s is predominant. As proposed in Ref. [7], the primary process occurring following the chemical removal of crude etching damage is the upwards surface band bending near the sidewall surface, which facilitates the effective drift of non-equilibrium holes to the surface where they recombine with surface states. The width of the affected layer λ , is assumed to correspond to the hole diffusion length or the width of the band-bending area. Admittedly, these constitute significant assumptions. Firstly, the carrier concentrations near the sidewall can differ from the bulk due to excessive tunneling and leakage. However, these factors are disregarded, as in the treatment that follows, one needs to get the expressions for current densities in the “bulk” and damaged sidewall region assuming the injected carrier concentrations in both are the same.

Secondly, the assumption that λ in Eq. (4) represents the diffusion length in “pristine” material is based on the assume that no radiation-induced defects persist after wet etching. However, it has been demonstrated that the penetration of radiation defects beyond the width of the heavily damaged region damaged layer significantly exceeds the width of the region removable by wet etching, as discussed in our recent review [30]. Therefore, a more flexible way to describe the situation is by assuming that the non-radiative efficiency in the damaged region after the wet etching, is increased by the introduction of these “persistent” defects giving rise to non-radiative recombination rate to be equal to A_d down to the depth λ that can be looked upon as effective

diffusion length in the presence of these “persistent” dry etching induced defects. Experimentally this λ is determined to be close to 1 μm . Consequently, the effective non-radiative recombination constant A_{eff} , is due to the non-radiative constant being equal to A_p in the pristine region not affected by RIE and by A_d in the RIE damaged region. The introduction of effective Shockley-Read-Hall (SRH) coefficient within the ABC model framework provides us to estimate IQE behavior as device mesa diameter D changes. Within existing formulation from Ref. [7], we can estimate how peak current density and peak IQE value behave in the presence of damaged region with length λ extended from edge towards mesa center. This damaged region is represented with elevated SRH coefficient A_d attributed to dry etching induced damage. Total device active volume $V_0 = d \cdot S_0$ consists of pristine ($V_p = d \cdot S_p$) and damaged ($V_d = d \cdot S_d$) device volumes, with ratios in terms of mesa diameter (D) and damaged region size (λ) as follows:

$$\frac{S_p}{S_0} = \frac{\pi(D/2 - \lambda)^2}{\pi D^2/4} = 1 - \frac{4\lambda}{D} + \frac{4\lambda^2}{D^2}, \quad \cdot \quad \frac{S_d}{S_0} = 1 - \frac{S_p}{S_0} = \frac{4\lambda}{D} - \frac{4\lambda^2}{D^2} \quad (5)$$

So, total A_{eff} will consist of SRH in pristine region, A_p , and damaged region SRH (A_d) coefficients weighed by contribution portion of damaged volumes:

$$A_{\text{eff}} = A_p \left(1 - \frac{4\lambda}{D} + \frac{4\lambda^2}{D^2} \right) + A_d \left(\frac{4\lambda}{D} - \frac{4\lambda^2}{D^2} \right) \quad (6)$$

For low $\lambda/D \ll 1$ Eq. (6) will coincide with Eq. (4) from [7] (see Fig. S4 of Supporting Material):

$$A_{\text{eff}} \approx A_p + A_d \frac{4\lambda}{D} \quad (7)$$

So, rewriting ABC model with consideration of $A_{\text{eff}} = f(D)$ we now have size dependent η_{IQE} and J :

$$\eta_{\text{IQE}} = \frac{BN^2}{A_{\text{eff}}N + BN^2 + CN^3} \quad (8)$$

$$J = qd(A_{\text{eff}}N + BN^2 + CN^3) \quad (9)$$

where N is the electron-hole pairs concentration, d is the device recombination region, q is the electron charge. Following Ref. [7] one can write the peak values of $\text{IQE}_{\text{peak}} = \eta_{\text{IQE}}$ as:

$$\eta_{\text{IQE}} = \frac{BN^2}{A_{\text{eff}}N + BN^2 + CN^3} \quad (10)$$

And the peak values of current density J_{peak} as:

$$J_{\text{peak}} = \eta_{\text{inj}}qdA \left(\frac{B}{C} + 2\sqrt{\frac{A}{C}} \right) \quad (11)$$

For large-diameter (100 μm) diodes, a good fit of the IQE on current density was obtained through numerical fitting by taking the $A_p = 8 \times 10^5 \text{ s}^{-1}$ and disregarding A_d . In this model, the B value was taken as $10^{-11} \text{ cm}^3\text{s}^{-1}$, and C as $10^{-30} \text{ cm}^6\text{s}^{-1}$ with the product of extraction and injection efficiency ($\eta_e\eta_{\text{inj}}$) close to 0.1 (Fig. S5). These fitted ABC parameters are well within the range commonly reported in the literature [7]. We subsequently attempted to fit the actual J_{peak} dependences on the diode diameter (Fig. 4 (c)) using A_d values determined from A_{eff} values obtained by fitting in which the A_p , B , and C values were kept consistent with those of the 100 μm LED, and $\lambda = 1 \text{ }\mu\text{m}$ (Fig. 5). It is important to note that while B and C parameters can vary as diameter decreases—most notably B due to changing strain—this effect typically remains negligible for diameters above $\sim 2 \text{ }\mu\text{m}$ [7]. However, the experimental values could not be fitted using a single A_d value for all diameters, as the required values ranged from $8.2 \times 10^6 \text{ s}^{-1}$ to $2.2 \times 10^7 \text{ s}^{-1}$.

If these A_d values, fitted from experimental J_{peak} data, are used to calculate the diode diameter dependence for EQE_{peak} (Fig. 4 (b)), the discrepancy becomes considerable, particularly for the low diameters of 5 μm and 10 μm , where the calculated values are

measurably lower than experimental values. This discrepancy likely results from the assumption that the product of injection and extraction efficiency remains constant across all sizes. Injection efficiency may improve at smaller scales due to better current spreading, while extraction efficiency can increase due to the focusing action of small-diameter columns [7]. Consequently, fitting results derived from experimental J_{peak} values are considered more reliable.

These findings suggest that the non-radiative recombination constant A_d is 10 to 20 times higher than the pristine value A_p . Such a disparity indicates a significantly higher density of non-radiative recombination centers within the affected sidewall region. Based on this analysis, it is inferred that the increased apparent densities of electron traps ($E_c - 0.7$ eV) and hole traps ($E_v + 0.8$ eV) observed as diode diameter decreases originate from the defect layer remaining after RIE and subsequent treatments [15, 20]. The ratio of changes in trap density should increase in proportion to the area of the defect ring relative to the total diode area. While this dependence is governed by the width of the damaged region and the density of RIE-induced centers, verifying this for large diodes is challenging. Unlike large-diameter devices where capacitance transient measurements are straightforward, smaller μ LEDs require specialized techniques, such as bunching multiple devices together, to provide sufficient signal for practical DLTS and ODLTS probing.

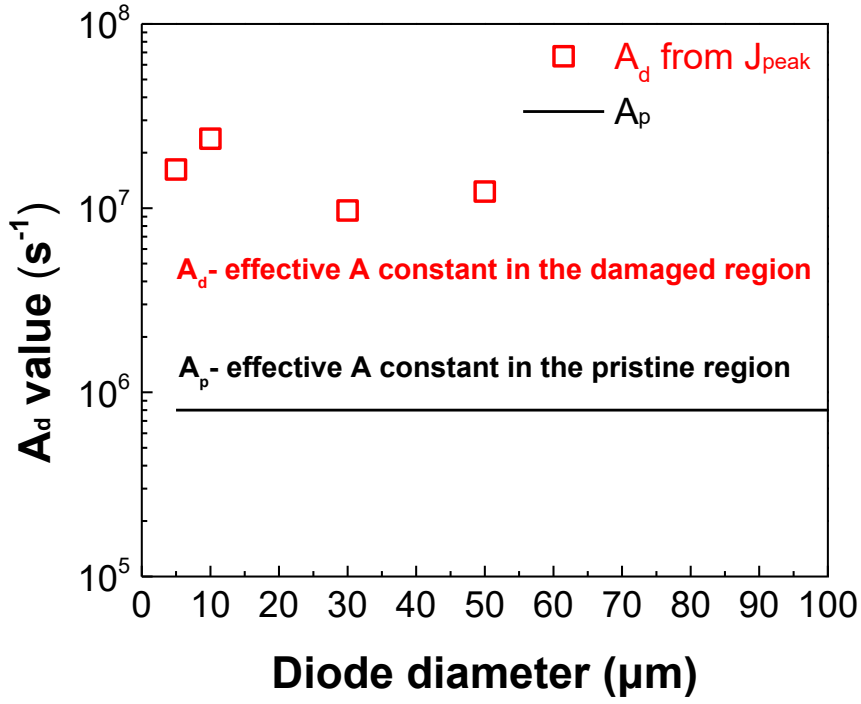


Fig. 5. (Color online) Estimated SRH value of damaged region (A_d is the effective A constant in the damaged region) derived from fitting the J_{peak} dependence on diode diameter, along with the SHR value of pristine region (A_p is the effective A constant in the pristine region) obtained from the experimental data for the 100 μm diode.

It is noteworthy that while EQE_{peak} decreases and J_{peak} increases significantly with shrinking diode diameters, the optical power density (M) as a function of current density changes much more gradually. This stability, attributed to the small footprint of small-diameter diodes, suggests that even devices with a diameter of 5 μm remain viable compared to larger diodes at current densities below 150 A/cm^2 (Fig. 5). These $\mu LEDs$ offer the distinct advantage of operating at much lower driving currents to enable high brightness with reduced electrical power consumption, which represents a feature of utmost importance for practical applications in microdisplays and microprojectors.

Nevertheless, further suppressing the detrimental effects of dry etching on μ LEDs efficiency remains essential. As discussed in recent reviews [6-14, 30], performance improvements are frequently achieved through the successful removal of heavily damaged regions via TMAH or KOH etching. Additional enhancements can be attained through optimized treatments in H_2 , N_2 , or N_2O plasmas [31-33], optimized dielectric passivation routines [24] more radically, by adopting dry etching methods that minimize surface damage, such as Neutral Beam Etching (NBE) [34]. Furthermore, recent studies have reported extremely beneficial effects from decorating μ LEDs sidewalls with nanoparticles. These nanoparticles facilitate the formation of localized surface plasmons that are energetically well-matched with the MQW photoluminescence spectra [35], potentially offering a path to even higher efficiencies in the sub-10 μm regime.

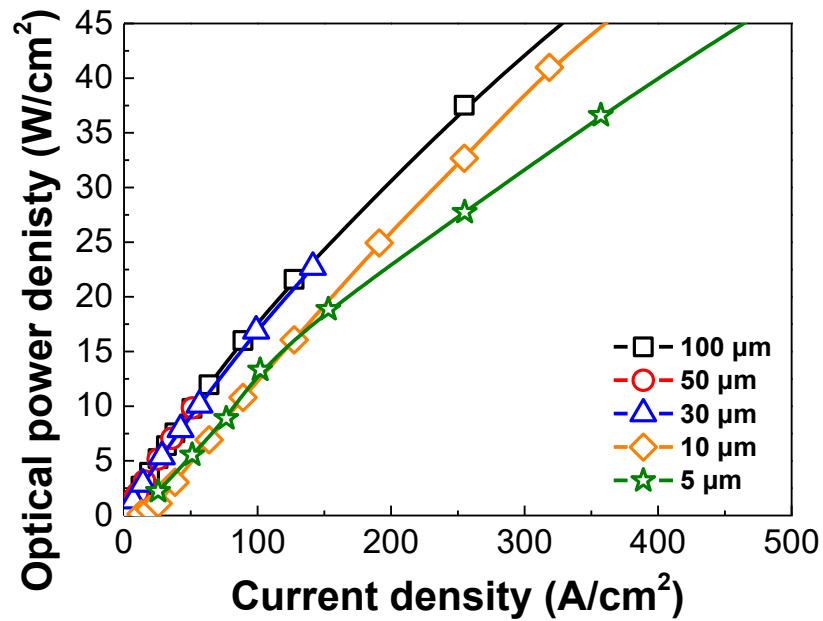


Fig.6. (Color online) Optical power output densities as a function of driving current density for μ LEDs with various diameters

CONCLUSIONS

We have demonstrated that for blue InGaN/GaN μ LEDs prepared by dry etching, the reverse current density increases significantly as diode diameters decrease below 30 μm . This leakage is measurably reduced after KOH treatment, which removes the heavily damaged sidewall region, and is further suppressed by two orders of magnitude after SiO_2 passivation.

The IQE of as etched μ LEDs exhibits sharp drops for diameters below 30 μm and becomes negligible at 10 μm . In contrast, devices treated with KOH or KOH- SiO_2 treatment maintain a reasonably high IQE of approximately 10% even for 10 μm diameter μ LEDs. MCL line profiling of the μ LED diodes indicates that the MCL signal at the edges of the mesa exhibits exponential changes with characteristic length of 1.25 μm for as-etched samples and 1.1 μm for samples with KOH or KOH- SiO_2 treatment.

Measurements of the EQE peak for the treated μ LEDs reveal a reduction from 8 % at a 100 μm diameter to 2.7 % at 5 μm and 10 μm . Concurrently, the peak efficiency current density shifts from 7.6 A/cm^2 at 100 μm diameter to 110 A/cm^2 at 5 μm diameter. The onset of this rapid efficiency degradation and current density shift occurs near a diode diameter of 30 μm .

These experimental results are well explained by the modified ABC recombination model, where the non-radiative recombination coefficient (A) accounts for the enhanced defect density in the sidewall region. Quantitative analysis suggests that the non-radiative recombination lifetime in this ~ 1 μm thick sidewall region is approximately 10-20 times shorter than in the bulk. This indicates that while surface treatments effectively mitigate leakage, the high density of deep-level defects distributed within the sidewall periphery remains the primary limiting factor for the efficiency of sub-10 μm μ LEDs.

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Author contributions: L.W.J. and S.I.L. contributed equally to this work. L.W.J. and S.I.L. conceived the study, performed the experiments, analyzed the data, and wrote the original manuscript. A.K., A.L.Z., E.B.Y., P.K.J., A.E.C., L.A.A., M.L.S., I.V.S., and A.A.V. contributed to experimental characterization, data analysis, and interpretation of the results. A.Y.P., and I.H.L.; supervision was done by A.Y.P. and I.H.L.; and project administration was done by I.H.L.

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Data availability: The data presented in this study are available from the corresponding author upon reasonable request.

DECLARATIONS

Clinical Trial Number: Not applicable.

Ethics, Consent to Participate, and Consent to Publish: Not applicable.

Competing interests: The authors declare no Competing interests.

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