Improvement in the Light Extraction of Blue InGaN/GaN-Based LEDs Using Patterned Metal Contacts

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***Abstract*—We demonstrate a method to improve the light extraction from an LED using photonic crystal (PhC)-like structures in metal contacts. A patterned metal contact with an array of Silicon Oxide (SiO_x) pillars (440 nm in size) on an InGaN/GaN-based MQW LED has shown to increase output illumination uniformity through experimental characterization. Structural methods of improving light extraction using transparent contacts or dielectric photonic crystals typically require a tradeoff between improving light extraction and optimalelectrical characteristics.The method presented here provides an alternate solution to provide a 15% directional improvement (surface normal) in the radiation profile and $\sim$ 30% increase in the respective intensity profile without affecting the electrical characteristics of the device. Electron beam patterning of hydrogen silesquioxane (HSQ), a novel electron beam resist is used in patterning these metal contacts. After patterning, thermal curing of the patterned resist is done to form SiO_x pillars. These SiO_x pillars aid as a mask for transferring the pattern to the p-metal contact. Electrical and optical characterization results of LEDs fabricated with and without patterned contacts are presented. We present the radiation and intensity profiles of the planar and patterned devices extracted using Matlab-based image analysis technique from 200 μm (diameter) circular unpackaged LEDs.**

***Index Terms*—Electron beam lithography (EBL), light emitting diode (LED), patterning, photonic crystal (PC), hydrogen silesquioxane (HSQ).**

I. INTRODUCTION

GROUP III nitride based quantum well LEDs have gained popularity because of their wide bandgap and the ability to emit light over the entire visible spectrum. These optoelectronic devices find applications ranging from everyday light sources to large panel displays [1], [2]. LED-based light sources are gaining acceptance over the traditional incandescent sources because of better energy efficiency [3], lower energy cost, better life span and environmental impact [4]. Despite their benefits, solid state lighting applications still have several fundamental device-level challenges to overcome. These challenges include suboptimal current-voltage characteristics due to high resistivity materials, low light extraction efficiency due to light trapped within the materials, efficiency droop etc. Also, due to the low number and non-uniformity of the activated carriers [5] and low contact resistance, LEDs suffer from current crowding at the contact edges, high turn-on voltages and high leakage currents [6]. Improvements in the electrical characteristics of LEDs could be achieved by altering or improving the material properties [7] to generally increase the internal quantum efficiency of the LED. On the other hand, a major source of optical output power loss is due to light being trapped within the materials due to the optical properties,which affects the light extraction efficiency of the LED. Various methods, such as surface roughening [8], [9], [10], [11], patterned substrates [12], [13], [14], integration of DBRs and photonic crystals [15], [16], [17] are being utilized by research groups to improve LED extraction efficiency [18]. These methods add additional complexities to the fabrication process of the LEDs. Despite the benefits of these techniques, trade-offs between the extraction efficiency and the quantum efficiency must be considered in their application. The use of transparent conducting contacts like Indium Tin Oxide [19] or Zinc Oxide [20] have proven to be viable alternate methods of improving the electrical characteristics mitigating the current crowding issues, increasing the internal quantum efficiency. However, the optimization of such a contact is a tedious process and involves trade-offs between the extraction and quantum efficiencies. On the other hand, transparent conducting contacts also serve to passively increase the light extraction from an LED [20], [21], [22] and a combination with optical elements like photonic crystals have aided in further improving the internal and external quantum efficiency [23], [24]. The main trade off of integrating photonic crystals or surface roughening is to utilize ICP plasma etching which induces etch damage and results in decreased quantum efficiency [25], [26], [27] and hence lift-off techniques are being developed.

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Photonic Crystals (PhC) are uniformly-spaced regions of high and low dielectric regions that offer control over the photonic bandgap [28], [29]. The photonic band gap is a characteristic that can be exploited in a variety of device applications. The propagation of light through a PhC lattice can be engineered by choosing the appropriate geometries and critical parameters of the crystal (lattice parameter, index of refraction, etc.). Groups have utilized dielectric PhC structures (one [15], two [23] and three [17] dimensional) as optical elements of the LED structure to increase the light extraction from the device [14], [30], [24], [18]. Another use of PhC lattice structures is in the creation of diffraction elements. The integration of PhC structures into LEDs using new micro- and nanofabrication techniques improves the light extraction at the cost of degradation to the device's electrical characteristics [25]. Other novel techniques of embedding PhC structures [31], [32] and using self-assembled colloidal microlens structures [33], [34] have proven promising in improving the extraction efficiency of LEDs without compromising on the electrical characteristics of the devices; however, these methods are not directly applicable to common LED architectures and fabrication processes.

In this work, we demonstrate an alternate method to increase the light extraction from the LED using PhC-like lattice structures fabricated in metal contact regions. Our group has utilized the diffraction property of patterned metal to improve light extraction from LED devices [35], [36], [37] rather than using conventional dielectric or transparent conducting materials. Patterning the p-contact with passive photonic crystal-like elements increases the optical output. Device fabrication processes, along with characterization results, are presented in the following sections.

II. Device Fabrication

The fabrication starts with the growth of layers that make up the LED active regions using MOVPE techniques [38], [39]. The LED structure is grown on a sapphire substrate (430 μm thick) and is shown in the Fig. 1. [39], [38]. InGaN/GaN -based quantum wells with a periodicity of 11.90 nm (QW $\sim$ 4 nm, Barrier $\sim$ 8 nm) were grown with 16% indium concentration ($In_{0.16}Ga_{0.94}N$) on n-type (Silicon doped) GaN and followed by p-type (Magnesium doped) GaN. The thicknesses of each layers of the structure are indicated in the Fig. 1. The targeted emission wavelength of this LED structure is around 440 nm. For this experiment, an LED is grown with above mentioned layers over one quarter of a 2 inch sapphire substrate. The fabrication process of planar and patterned devices only differs in the patterning of the metal contact step using electron beam lithography. After this additional metal contact patterning step, devices were fabricated using traditional micro-fabrication techniques. After growth, the quarter piece LED sample was annealed at 800°C for 5 minutes in Nitrogen ambient to mobilize the charge carriers and reduce the resistivity of the p-type GaN films [40].

After this initial annealing process, HSQ (FOX ® - 16 from Dow Corning) is spun on the sample at 3000 rpm for 1 minute resulting in a thickness of approximately 500 nm, followed by

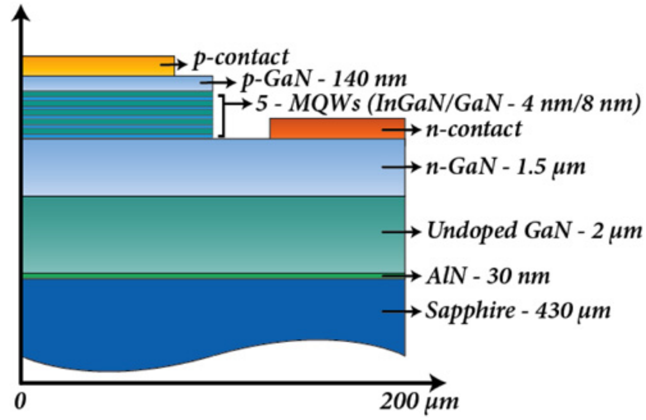

Fig. 1. LED Structure.

4 minute soft-bake at 95°C to evaporate the solvents from the spin on dielectric.

Electron beam lithography was used to pattern an area of 80 x 80 μm^2 in the HSQ layer at a dosage of 320 $\mu C/cm^2$ using a JEOL 7600F Scanning Electron Microscope equipped with NPGS CAD system. The maximum field of view on this system is 104 x 104 μm^2. A drift in the beam focus and alignment was observed when patterning larger areas (> 104 x 104 μm^2). This drift in the system causes uneven exposure resulting in an unresolved pattern at the edges. Due to these issues, an area of 80 x 80 μm^2 was chosen for patterning fully resolved features on our devices.

The exposed resist was developed in Megaposit developer MF-CD 26A for 12 minutes to create pillars of HSQ as shown in the Fig. 2. The HSQ pillars are measured to be 440 nm in diameter with a 1 μm pitch and $\sim$ 500 nm in thickness. The feature sizes are chosen to be on the order of the emission wavelength of the LED. These HSQ pillars are then cured thermally at 400°C for 1 hour to convert them into SiO_x pillars [41], [42], [43]. At this stage, the LED sample contains SiO_x pillars on the surface of the p-type GaN. Further steps involve multiple iterations of photolithography, etch, metal deposition and lift off techniques that are common to both planar and patterned devices.

Photolithography is performed using AZ-5214 E-IR for p-contact patterning. Thep-type contact (Ni/Au – 30 nm/50 nm) is deposited using electron beam evaporation followed by lift-off revealing both unpatterned and patterned metal contacts. The patterned metal contacts have SiO_x pillars that were intentionally left within the contact to prevent collapsing of the patterned contact during the post-annealing process. The resulting p-metal contact is 160 μm in diameter with a patterned area of 80 x 80 μm^2. The patterned p-contact in its final state contains SiO_x pillars (cured HSQ) surrounded by the p-metal stack as shown in Fig. 3(c) and (d).

Photolithography is then performed to create a protective layer of photoresist (AZ 4400) 200 μm in diameter over the patterned p-contact area in preparation for the mesa etch. ICP RIE is then used to etch a mesa in GaN using the hard-baked photoresist as a mask. BCl_3/Cl_2 plasma was utilized to etch into the n-type GaN layer. An etch depth of 600 nm

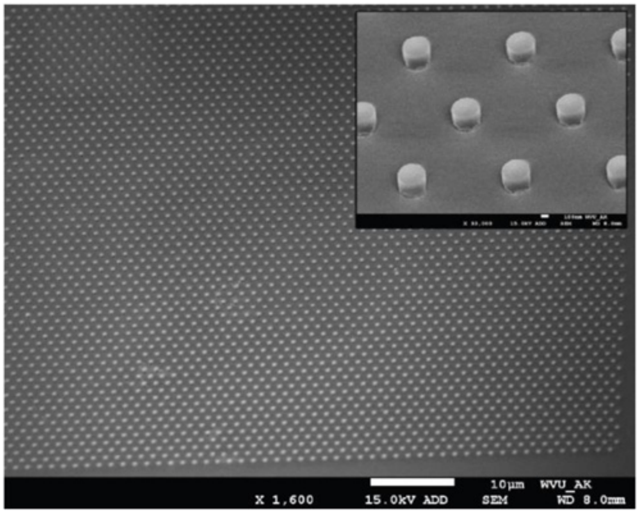

Fig. 2. SEM image of Hydrogen Silsequioxane (HSQ) pillars after 12 minute development (Inset) Zoomed in SEM image of the pillars.

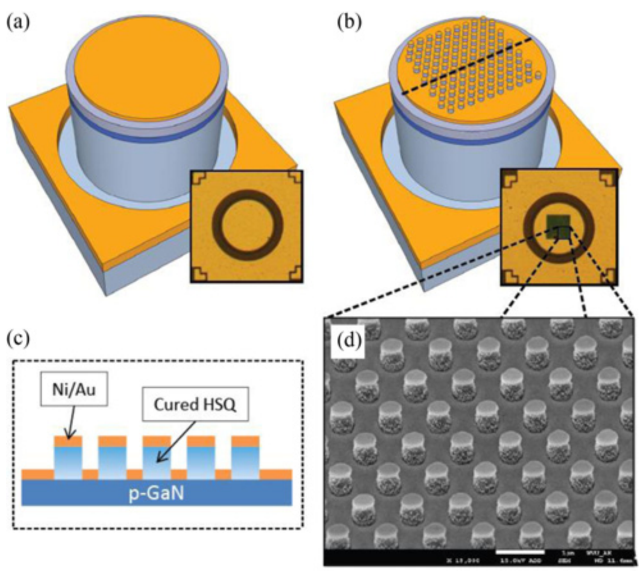

Fig. 3. (a) Schematic of the final fabricated unpatterned device (Inset: Microscope image). (b) Schematic of the final fabricated patterned device (Inset: Microscope image). (c) Cross-section view of the patterned metal contact with cured HSQ pillars intact. (d) SEM image of the patterned metal contact with the cured HSQ pillars intact.

was achieved after 120 seconds of plasma etch. Afterwards, photolithography was used to pattern the n-contact region. The n-contact is created using e-beam assisted metal deposition (Ti/Al/Ti/Au – 2 nm/100 nm/30 nm/50 nm) followed by a lift-off. The fabrication process is completed with a post annealing process performed at 600°C for 3 minutes in air to anneal the contacts. The final fabricated devices with and without patterned metal contacts on p-type GaN are shown in Fig. 3(a) and (b).

III. Characterization & Results

To compare the performance of the metal contact patterning, we characterized planar and patterned devices. Fig. 4 presents

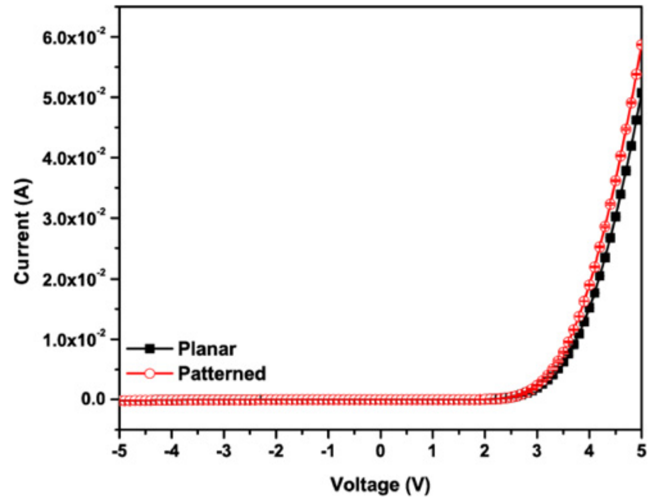

Fig. 4. Current-Voltage Characteristics of 200 μm Mesa Circular LEDs with error bars included.

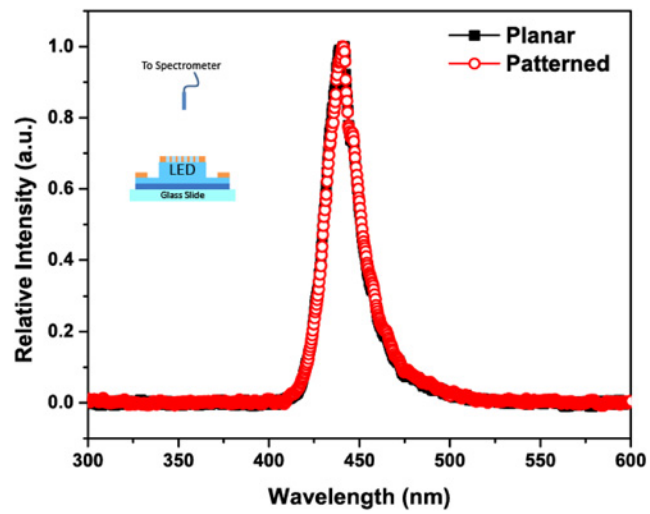

Fig. 5. Normalized EL Spectra of planar and patterned LEDs.

the current-voltage (IV) characteristics of the two device types with their respective error bars included.

The respective normalized electro-luminescence (EL) spectra for the devices are shown in the Fig. 5 which were observed at an injection current of 60 mA using a constant current source. These EL spectra of the planar and patterned devices were taken from the top side of the device using an optical fiber at a constant distance of 1inch, as shown in the inset figure of Fig. 5. The spectra are smoothed using that adjacent averaging method to remove any noise. It is observed from the plot that the peak wavelengths for all the tested devices are close to the expected emission wavelength (440 nm). The peak wavelength for both planar and patterned devices at different injection currents was observed to be within the range of tolerance (<1%).

On the other hand, the radiation patterns of each device are compared to better understand the radial distribution of the light from the devices. Although, these measurements are traditionally done using an integrating sphere, for this work, an

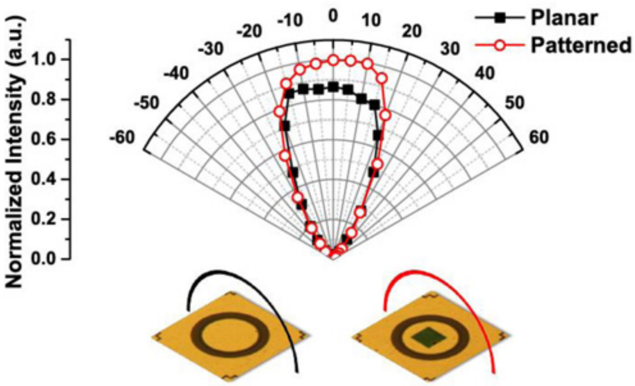

Fig. 6. Radiation plots of the planar and patterned LEDs.

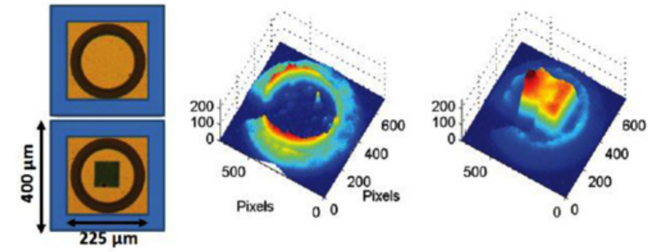

Fig. 7. (a) Cropped areas of the unpatterned and patterned devices, Blue intensity images extracted from Matlab-based image analysis tool. (b) Unpatterned and (c) Patterned devices.

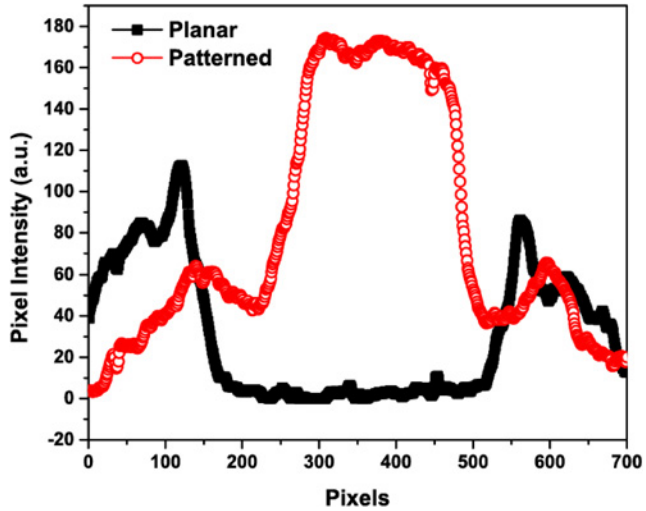

Fig. 8. Row intensity profiles (a) Planar and (b) Patterned.

optical setup was constructed to measure the radiation pattern of each device. The EL spectra of each device is taken at angles varying from -60° to 60° at intervals of 5° using a multimode optical fiber. The optical fiber is maintained at a constant distance (1 inch) from the surface of the LED and rotated about a fixed axis. The intensities at the peak emission wavelength (440 nm) are extracted from the respective EL spectra and normalized by dividing the maximum intensity observed at 0° (surface normal). The normalized intensities are plotted with respect to the angles and summarized in Fig. 6.

From the radiation plots obtained, it is observed that the field of view for both the devices is $\pm 20^{\circ}$. It is also seen the intensity of the patterned LED is approximately 15% higher than that of the planar LED directionally (surface normal). The radiation profiles shown here are constrained to a slice of the solid angle. Since the devices tested are symmetrical, the radiation profiles along any direction would be a replica of the shown result and hence the plots could be rotated to a solid angle perspective. To get more detailed information about the intensity extracted from the device, an alternate method for analyzing the intensity profile is adopted.

A Matlab-based image analysis tool was developed to characterize the top-side emission uniformity. For this analysis, both devices were separately driven with constant currents and images were captured using a Canon 5D Mark II camera mounted on a microscope with a 50x objective. External illumination sources were eliminated to reduce sources of unwanted emission intensity. Images for planar and patterned-LEDs were captured with the following camera settings: the sensitivity of the sensor (ISO) was set to 6400 to capture minimal amounts of generated light. White Balance was set to 10000K Color Temperature, so the sensor is more sensitive to blue colors as we were taking pictures of blue LEDs. A shutter speed of 1/160 was chosen as the best setting for capturing unsaturated images.

Once the parameters were set, images were taken at different injection currents 60 mA, 80 mA and 100 mA. Along with these images, a background image is also taken with the LED powered off to determine the background noise level. Once the images are taken, they were cropped to the edge of the n-type contact of the LED with a cropping size of 700px X 700px as shown in the Fig. 7(a).

These cropped images are then input to the image processing tool to extract the red, green and blue pixels. Since the red and green pixel intensities have relatively insignificant intensities, only the blue pixels are chosen for further analysis as shown in Fig. 7.

The image profiles along the horizontal axes of the images are extracted and the respective pixel intensities are compared, as shown in the Fig. 8. These profiles are smoothed using the adjacent averaging method. The intensity profiles show an increase in the intensity in the patterned area while reducing the intensity around the edge of the contact. The averages of the pixel intensities over the area were also compared and the results are shown in Fig. 9.

The results obtained from the Matlab image processing technique indicate that the patterned p-contact with SiO_x pillars acts as a passive optical component and helps in extraction of light from the top of the LED. This observation may also have been due to a change in the current distribution in the patterned contact, which will be studied in future efforts.

We observe improved extraction from the patterned devices when compared with the unpatterned counterparts. Qualitatively, it is observed that the patterned LED has an average increase of the intensity of 30% when compared with its unpatterned counterpart. Although, this improvement is comparatively low relative to that of the extraction observed

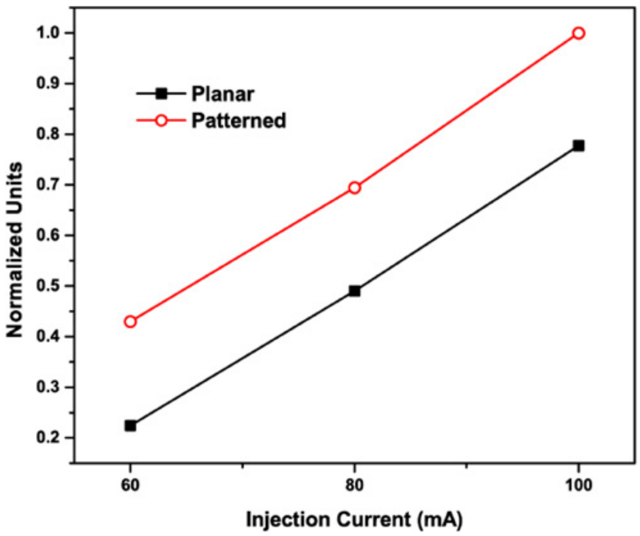

Fig. 9. Normalized average intensities of the images of the two devices observed at injection currents 60 mA, 80 mA and 100 mA.

from other methods [13], [17], [31], [34], our process can be considered complementary to the existing methods and a means to achieve additional performance improvements.

IV. Conclusion

In conclusion, we demonstrate a promising method for increasing light extraction from LED devices using patterned metal contacts with SiO_x pillars. Hydrogen Silesquioxane e-beam resist was used for e-beam lithography and thermally cured to achieve the patterns on the metal contact. Images of each device at 3 injection currents were acquired and a Matlab-based image analysis tool was utilized to analyze the top-side intensity profiles for two different device architectures. The devices with patterned contacts have shown a significant increase in the light extraction from the top side of the device when compared to the planar devices.

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