A Study of Enhancement Techniques for Light Extraction Efficiency of Light Emitting Diodes

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ABSTRACT
Light extraction efficiency has become first order design constraint for LEDs and its enhancement has always been a challenge for researchers. This affects the life of LEDs as well as optical output and various techniques for its enhancement have been reported. Methods for maximizing the efficiency of LEDs are typically based on enhancement of internal and external quantum efficiency. In our paper, we report efficiency enhancement based comparative study of LEDs which are grown by different techniques. Firstly the techniques dealing with improvement of internal quantum efficiency and secondly the techniques for increasing ratio of photons leaving the LED to those created in active region (enhancement of external quantum efficiency) are reviewed.

KEYWORDS
LED, internal quantum efficiency, external quantum efficiency, quantum confined stark effect.

1. INTRODUCTION
Artificial illumination has become one of the fastest emerging areas for research during past few decades. This has facilitated the low cost communication along with enormous bandwidth over fibers, various biomedical and industrial applications. This has evolved Light-emitting diodes (LEDs) which are now entering in domestic and household illumination in addition to the above stated applications. The fraction of applied electrical energy, being delivered as optical energy at the output, is termed as quantum efficiency (QE) of the device. The quantum efficiency or also known as light emitting efficiency dominantly affects the life of device in addition to the determination of available optical energy for application. Techniques for improving the efficiency of an LED fall under two distinct categories namely, increasing the internal quantum efficiency (IQE) and increasing the light extraction efficiency which is also called as External Quantum Efficiency (EQE). Various techniques have been proposed for enhancement of these two quantum efficiencies. A good amount of enhancement in internal quantum efficiency can be obtained by selection and processing of crystal quality and adoption of epitaxial layer structure. A typical IQE value for blue light emitting diode is more than 70% and recently a UV LED grown on a low-dislocation GaN substrate exhibited an IQE as high as 80%.[1,2,3]

This shows that the fairly good (i.e. around 80%) IQE has been achieved whereas on the other hand the typical value of light extraction efficiency of an LED is even less than 10% per crystal face. Hence efforts, being made to increase internal quantum efficiency, results with very low enhancement in the overall light emission efficiency. It is also important to mention that in a nitride based LED there is a large difference between refractive indices of GaN and air (2.5 and 1respectively). The angle of light escape cone is only 23° and hence exhibits very low light extraction efficiency (4.8% per crystal face) [1, 4, 5].

In this paper, we have concentrated our study on various techniques for enhancement of light extraction efficiency which impact more dominantly on the overall quantum efficiency of a LED. The various approaches have been proposed in literature, in order to enhance light extraction efficiency. Brief discussions of techniques for enhancement of internal efficiency have also been made.
The following techniques are studied and analyzed in this context.
1. Surface coating
2. Current spreading layer
3. Reducing quantum confined stark effect
4. Surface patterning

2. SURFACE COATING
The total internal reflection (TIR) severely restricts the delivery of generated photons at output of LED. This not only results in very low light extraction at output but also in heat generation inside an LED. The light as well as the output luminance of LEDs is very adversely affected by TIR. This is mainly contributed by the difference between the refractive indices of crystal material and the output medium (generally air). Hence the increase in the light extraction efficiency can be achieved by decreasing the total internal refection (TIR) of photons [5]. The application of transparent medium having intermediate refractive index between crystal face and output medium can strongly suppress the total internal reflection and further results in better amount of photons at the output of LED. The GaN based LED has low external quantum efficiency as compared to their internal quantum efficiency because the light extraction efficiency of GaN based LED is limited by the total internal refection (TIR) of photons due to the large difference in retraction index between GaN and air [6]. In order to get rid of this drawback of lower external quantum efficiency, a coating of transparent Al_2O_3 powder with an intermediate refractive index (n=1.6), between the GaN film and air is used.

LED coated with transparent Al_2O_3 powder for higher photon extraction is shown in figure 1. This technique of forming Al_2O_3 coating is quite advantageous due to its low cost, large scale production and quite feasible process. Also it does not degrade the electrical characteristics of the LEDs. The 300 nm diameter transparent Al_2O_3 powder is coated on the surface by a spin coating method. As shown in figure 2, an increment in the light output about 4.15 V at 20 mA as compared to conventional LEDs, which have 3.42 V at 20 mA, is achieved with this technique [6, 7].

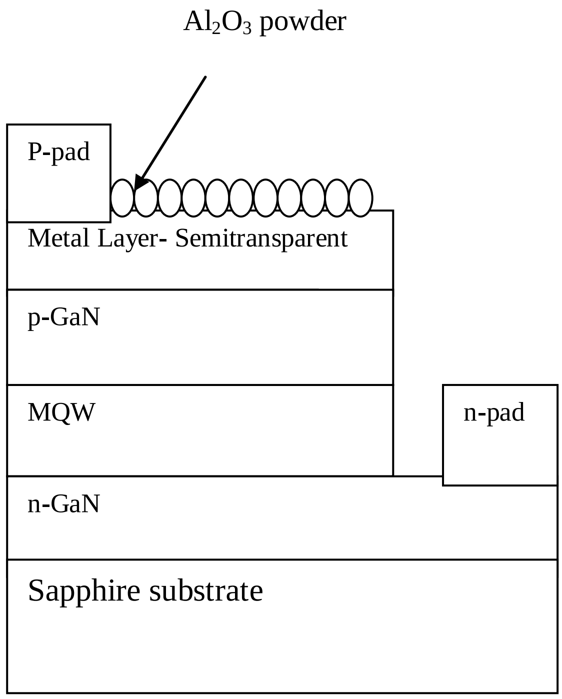

Fig.1: LED Structure Coated with Al_2O_3 Powder [6]

So the light output power increases about 30% as compared to conventional LEDs, mostly contributed by the increase in the area of the effective photon escape cone induced by insertion of Al_2O_3 powder (n=1.6) in between the interface of air and crystal. This is suggested that high extraction efficiency could be achieved at nominal cost by formation of Al_2O_3 coating on p-metal surface of conventional LED [7].

3. CURRENT SPREADING LAYER

The loss in photon delivery is also contributed by their absorption at contacts of LEDs. Improvement in external quantum efficiency can also be achieved by adoption of specific mechanism which can lower down such absorption at the contacts. Making use of semitransparent thin metal layer and transparent conducting oxide current spreading layer can effectively suppress the absorption of photons by in the region of LED contacts [8, 9].

The application of Zinc Oxide (ZnO) films, as transparent current spreading layers for Gallium Nitrate (GaN) LEDs, has proved to be very effective in order to suppress photon absorption in contact region and further to raise the external quantum efficiency. Zinc Oxide (ZnO) provides very high transparency at blue wavelength. A valence band offset of 1.3 eV, which is quite comparable to GaN, induces the possibility of tunneling current across a GaN and ZnO junction. Further, selective etching of Zinc Oxide in various acids is performed in order to allow for fabrication of effective light extraction structures [9].

The aqueous deposition of ZnO at low temperature, as an epitaxial film is preferential method for fabrication of current spreading layer on LEDs, due to its cost effectiveness over the vapor deposition technology. Additionally, the deposition of film at lower temperatures prevents any damage to the active region of LED [9].

Figure 3 clearly shows that the aqueous deposition of ZnO at lower temperatures as a transparent current spreading layer provides the output power 20.7 mW at a current of 20 mA and voltage of 3.32 V with an external quantum efficiency (EQE) of 37.7% as compared to only 19.5% EQE for the LEDs with thin metals. A factor of around 1.93 improvements with this technique, as compared to the LEDs having thin metal electrode is reported [5].

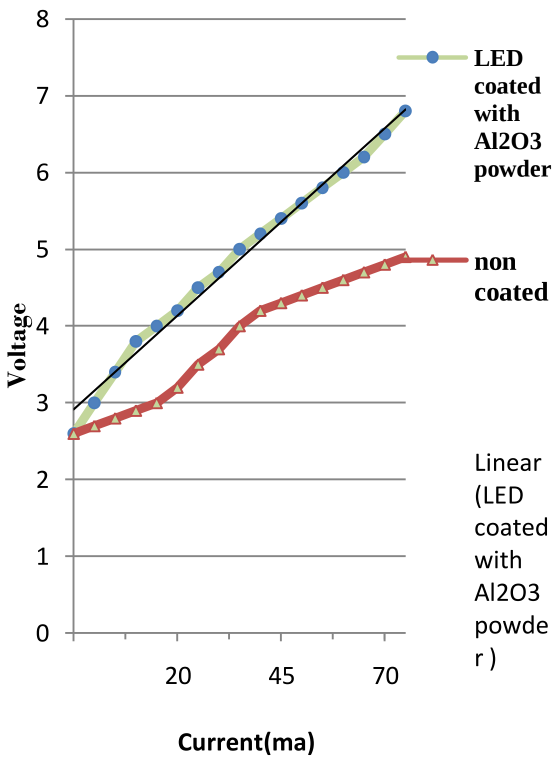

Fig.2: I-V Graph of Conventional LED, with and without Al_2O_3 Coating [6]

4. REDUCING QUANTUM CONFINED STARK EFFECT

The lattice mismatch between active GaInN layer and the underlying GaN layer results in Quantum Confined Stark Effect (QCSE). The quantum confined stark effect reduces the overlap between electron and hole wave functions and further prohibits the recombination of electrons and holes in quantum well (QW) region. The consequence of quantum confined stark effect (QCSE) is degradation of optical efficiency in LEDs [8]. Fabrication of asymmetric quantum well is suggested to minimize quantum confined stark effect [8]. The cutback of this effect increases the overlapping of electron and hole (recombination) in quantum well section and finally efficiency of the LED increases. Lessening of QCSE can be achieved using the fabrication of asymmetric GaN/InN/InGaN quantum well (QW). To avoid the lattice relaxation and serious deteriorations in optical and structural properties of quantum well, the thickness of InN layer must be kept below 2ML [10]. The new structure has been proposed which comprehends high efficiency light emitters operating in blue-green region by employing ~1-ML-thick InN based nano structure [8].

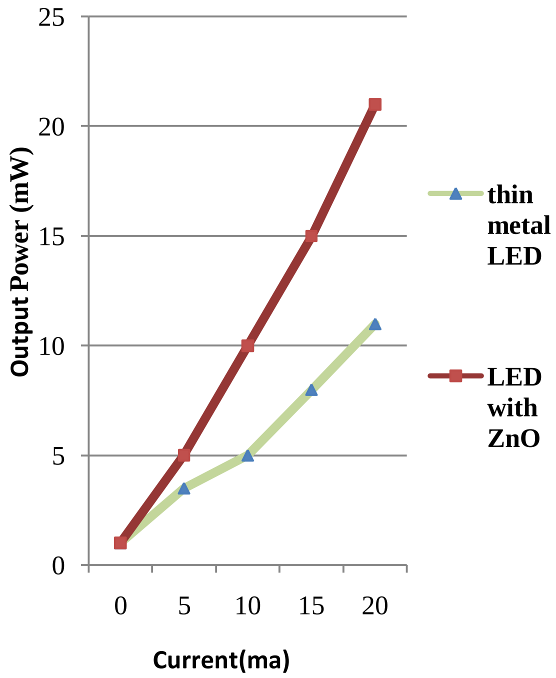

Fig.3: Optical output comparison for thin metal LED and LED with ZnO [5]

Here InGaN layer can be reduced for the design of proposed QW composed of ultrathin InN layer resulting in high crystalline quality of InGaN layer and further suppress the compositional fluctuations [10, 11].

Here it is emphasized that QW must have an asymmetrical structure for achieving a sharp interface in the ultra thin well region. Better interface quality can be achieved for asymmetric QW as compared to the ~1-ML thick InN QWs (symmetric InN). The internal quantum efficiency is hereby strained to increase due to suppression of the QCSC in the ultra thin ~1-ML- InN quantum well layer.

5. SURFACE PATTERNING

Spontaneous and piezoelectric polarizations at hetero-interfaces face discontinuities and contribute the generation of electric fields in quantum well region. Such generation of electric fields causes carrier separation (quantum confined stark effect) and reduces photonic recombination rate within quantum wells [9, 10]. Therefore on backside of GaN substrate, surface patterning is done to improve light extraction outside escape cone [12, 13].

The various types of surface patterning techniques have been proposed where inductively coupled plasma (ICP) etching is rated most successful technique. The ICP is a non equilibrist process where conventional metal organic chemical vapour deposition (MOCVD) is used to grow LED epitaxial layer on double polished semi polar (11$\bar{2}$ 2) bulk GaN substrates with reasonably low extended defect density. As shown in fig. 4 structure of laser diode on a (11$\bar{2}$ 2) plane, a 1mm Si doped n-type GaN layer and active region consist of six period multi quantum well stack with 20nm undoped GaN barrier and 3nm InGaN quantum well ending with an undoped 16nm thick GaN barrier. Then 10 nm undoped $Al_{0.5}$ Ga $_{0.85}$ N electron blocking layer is positioned and a 200nm p-type GaN: Mg layer is placed. With this device 100% increase in output power is obtained before packing and 33% is obtained after packing. Thus this is potentially applied to devices grown on non polar m-or a plane GaN substrate [14].

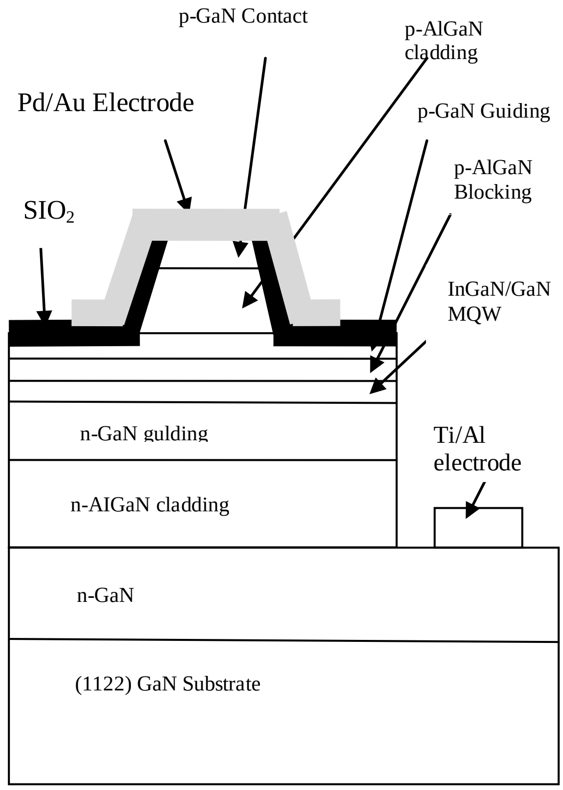

Fig 4: Structure of Laser Diode on a (11$\bar{2}$ 2) Plane GaN Substrate [15]

6. m- PLANE GaInN LEDs ON a-PLANE PATTERNED SAPPHIRE SUBSTRATE

For obtaining high performance blue LED using GaInN, a parallel line and space patterned, striped a-plane sapphire substrate having a stage of 3.0μm (1.5 μm openings) was prepared. The stripe prototype was formed along m-axis of sapphire substrate by means of photolithography [13]. The patterned substrate has horizontal (1 1 $\bar{2}$ 0) sapphire and vertical (0001) sapphire sidewalls. GaN LEDs are developed on a-plane sapphire substrate by metal-organic vapor phase epitaxy (MOVPDE) at ambient temperature.

With this, the reasonably high output power of around 3 mW at peak wavelength of 461 nm from packed chip has been obtained. It has been observed that m-plane LED has polarization anisotropy. This m-plane GaN has high crystalline quality. Further LED device has an active layer with high indium contents forming hetero-substrate and abrupt interface for non polar or semi-polar LEDs [15].

7. CONCLUSION

In conclusion we observed that in case of surface coating of Al_2O_3 powder on GaN based LED, the reported increase in external quantum efficiency about 30% whereas it is reported to be increased by 37.7% in case of current spreading layer of ZnO on a GaN LED. Almost 1.25 time's higher enhancement, using current spreading layer, is achieved as compared to surface coating technique. Reduction in QCSE stimulates recombination of electrons and holes in the quantum well region which contributes to generation of higher number of photons resulting in improved quantum efficiency of LED. In case of surface patterning technique (using MOCVD) used with InGaN device, an ideal increment of 100% in output power can be obtained. But this high quantum efficiency is further reduced up to 33% because of packing process of diode. This provides a good direction for future research for identification and development of packing technology where technological improvement in packing methods are derived for enhancement of light emitting efficiency in LEDs.

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