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Two-step passivation for enhanced InGaN/GaN light emitting diodes with step graded electron injectors

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Enhancement of InGaN/GaN based light emitting diode performance with step graded electron injectors through a two-step passivation is reported. Perimeter passivation of LED dies with SiO_2 immediately following ICP mesa etch in addition to conventional Si_3N_4 dielectric surface passivation leads to decrease in the reverse bias leakage current by a factor of two as well as a decrease in the shunt current under forward bias by an order of magnitude. Mitigation of the leakage currents owing to the two-step passivation leads to significant increase in the radiant intensity of LEDs by more than a factor of two compared to the conventional single step surface passivation. Further, micro-dome patterned surface of Si_3N_4 passivation layer allow enhanced light extraction from LEDs.

1. Introduction

Light emitting diodes (LEDs) based on InGaN/GaN semiconductor structures are widely used as light sources for applications such as general lighting (both indoor and outdoor), backlighting of the display screens, and outdoor LED displays [1,2]. Standard blue LED design is featured by multiple InGaN quantum wells (QWs) separated by GaN or InGaN with relatively lower In content barrier regions, all sandwiched between highly doped n- and p-type GaN layers [1,2]. Use of native substrates for epitaxial growth of GaN films as well as device structures is very limited because of many technical problems for growing bulk GaN resulting in high cost [3]. The use of foreign substrates with lattice parameters and thermal expansion coefficients different from GaN necessitates approaches to minimize density of extended and point defects that form due to lattice and thermal mismatch and result in, among other disadvantages, increased leakage currents. The density of threading dislocations in GaN-based device structures grown by metalorganic chemical vapor deposition (MOCVD) technique on sapphire substrates can be kept below 10^8 cm^{-3} using special techniques such as epitaxial lateral overgrowth (ELO) through in situ deposited Si_3N_4 nanoporous mask (frequently dubbed as nano-ELO technique) [4,5]. Despite such high dislocation densities,

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InGaN/GaN heterostructures exhibit high optical efficiency due to suppression of nonradiative recombination by either localization due to In-rich nanoclusters [6–8] or blockage of carriers from reaching dislocations due to potential barriers formed around V-shaped pits [9,10].

Despite significant industrial progress in InGaN/GaN LED fabrication, problems associated with elimination of leakage currents as well as increasing light output from LED dies still require close attention. Defects and surface states on the surfaces and sidewalls of mesas in light emitters contribute to leakage currents thus degrading the injection efficiency [1]. Elimination of these leakage currents requires a carefully considered complex strategy involving growth and fabrication procedures and LED die design, among others. On the growth side, the strain in epitaxial wafers should be reduced. Otherwise, strain relaxation through defect generation degrades the material quality. The optimum LED die design intended to prevent leakage through surface states at the edge of the LED dies should take into account the limited current spreading due to low hole concentration and the associated low mobility in p-GaN. Thus, the physical distance from the contact pad to the edge of surface emitting LEDs should not be smaller than the current transfer length to prevent current leakage through surface states [11]. Finally, the mitigation of leakage through surface states requires an appropriate passivation of LED dies with dielectric layers that decreases non-radiative recombination and thus results in increased radiative efficiency. For passivation of LEDs based on InGaN/GaN MQWs Al_2O_3 [12–15], SiO_2 [13–16], Si_3N_4 [17], and $SiON_x$ [18,19] have been used. A common passivation approach is a thin layer of dielectric coating covering the entire LED die surface followed by opening windows for contact pads after metalization [12–15,17–20]. Deposition of the aforementioned dielectric layer generally can be done by plasma-enhanced chemical vapor deposition (PECVD) [13,14,17–19], sputtering [12] or atomic layer deposition (ALD) [13]. Passivation is particularly important for elimination of shortening during the packaging step which is characteristic to lateral configuration of InGaN/GaN LED dies on sapphire. These shortening can appear due to the small distance between contact pads to n- and p-type layers particularly in the common interdigitated configuration of electrodes used for high power LEDs [11,21–23].

The damage on the sidewalls of LED mesas (for lateral device configuration) fabricated by inductively coupled plasma (ICP) etching should also be taken into account. Mesa sidewalls can easily be contaminated or adsorb moisture when exposed to air [17]. It is, therefore, important to passivate the surfaces immediately after etching. This may not be an easy task for high power LEDs because of the necessity to use interdigitated configuration for LED dies employed to maximize their effective area [11,21–23].

Passivation of LED dies is also intimately related to the light extraction efficiency. The high refractive index of GaN, 2.25 [24], leads to a small escape cone. Specifically, the critical angle for total internal reflection at the GaN-air interface is equal to 26.4°. Any outward radiation outside the cone with this angle would suffer total internal reflection, which must be encountered in order to collect more of the emission emanating within the solid. In the case of flat GaN surface, only 5.2% of generated light will be emitted into air [1]. One way to improve the extraction efficiency and thus the external quantum efficiency is to roughen the GaN surface. This approach is used effectively in GaAs based LEDs utilizing plasma treatments [25]. In the case of GaN based LEDs, plasma based surface roughening is not suitable because it degrades electrical properties of p-GaN due to plasma induced damage [26]. The plasma damage manifests itself as generation of point defects, primarily nitrogen vacancies, which act as donors [27,28]. There are other ways to improve light output such as using encapsulants with high refractive indices [29,30], patterning of current spreading layer surface [21,31], using patterned sapphire substrates [13], patterning of passivation layer surface [13,14], and employing antireflection optical coatings and two-dimensional photonic crystals [12,32]. One of the practical ways for light extraction improvement of front emitting LED chip that does not degrade its electrical properties is patterning of the passivation layer [13,14].

A bilayer passivation technology with Al_2O_3/SiO_2 for InGaN/GaN based LEDs was proposed in papers [13–15]. Use of ALD grown Al_2O_3 as the first layer was shown to decrease leakage current by two orders of magnitude as compared to PECVD grown SiO_2. Patterned PECVD deposited SiO_2 layer on top of Al_2O_3 was used for increasing light output as material with intermediate refractive index between air and Al_2O_3 [13–15]. This passivation scheme has some drawbacks, because the total internal reflection with Al_2O_3 is relatively high due the fact that its refractive index is much lower than that of GaN (1.75 vs 2.25 for GaN). Silicon dioxide also looks not a good choice as its refractive index is 1.55 [33]. The difference between the refractive indices of GaN and the passivation material causes light entrapment at the layer interfaces. Light entrapping because of high refractive index of top passivation layer can be much weakened with the help of passivation layer patterning.

Using Si_3N_4 for top emitting InGaN/GaN LEDs may be preferred because of its relatively high refractive index of 2.04 [33], which is almost equal to that of ITO ($n = 2$), that is commonly used as a current spreading layer on the top of p-GaN in front emitting LED chips. In such a configuration, the critical angle between ITO and Si_3N_4 will approach 90°. In the case of Al_2O_3 at the interface, the ITO-Al_2O_3 critical angle is only 61.6°. We therefore conclude that use of Si_3N_4 as a passivation layer should minimize light loss at the interface between ITO and Si_3N_4 as compared to the ITO-Al_2O_3 case.

In this paper, we report on the effects of two-step passivation on the electrical and light output characteristics of InGaN based front emitting LEDs. Passivation layers investigated included SiO_2 perimeter passivation of LED dies immediately after mesa etching and Si_3N_4 surface LED passivation with micro-dome fabrication on its surface to improve light extraction.

2. Experimental

InGaN MQW based LED structures grown by metalorganic chemical vapor deposition (MOCVD) on sapphire were used in this work. Epitaxial layers consist of 10 μm undoped GaN grown by in situ nano-ELO technique, followed by a 4 μm thick n-

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