Investigation of GaN-based Micro-LEDs with Sidewall Passivation and KOH Treatment

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ABSTRACT

Micro-light-emitting diodes (Micro-LEDs) with various pixel size and device structures are designed and fabricated based on sapphire substrate. Systematically investigation of GaN-based Micro-LEDs with dielectric layer deposited by atomic layer deposition (ALD) is reported. The devices with ALD passivation and KOH treatment exhibit better I-V characteristics, smaller ideal factor, and better reliability for high-brightness displays.

1 Introduction

GaN-based Micro-LEDs were developed for more than three decades and have been popularly penetrated into applications of visible light communication, sensing, and displays[1]. Especially, Micro-LEDs are considered as one of the most promising candidates for next-generation display application, such as near-eye head-mounted display and large-area emitting display, because Micro-LEDs have advantages in high resolution, high luminous efficiency, brightness and long operating lifetime.

These features make them the most promising platform in high-end display applications, especially for AR/VR displays which requires a 1500ppi because of the human natural eye resolution acuity of about 60 pixels per degree. Such an ultra-high ppi device necessitates the subpixel down to 5μm. Previous reports have shown that the peak external quantum efficiency (EQE) decreases as the dimension decreases[2-4]. Thus, Micro-LEDs with size of less than 5μm may not meet the requirement for brightness in AR/VR display applications. This drop in peak EQE is due to sidewall defects from plasma-assisted dry etching, which induce non-radiative surface recombination. This effect is more significant at small dimension for the surface-volume-ratio increased. Various of methods have been employed to minimize the effect of sidewall damage, such as sidewall passivation and wet chemical[5-7]. Dielectric sidewall passivation by atomic-layer deposition (ALD) and potassium hydroxide (KOH) are commonly used to reduce the surface defects. ALD employs metalorganic precursors that to improve the electrical performances and reduce sidewall damage from dry etching. The lower leakage current and smaller ideality factor were achieved by using ALD passivation and KOH treatment.

In this work, we investigated the effects of ALD sidewall passivation and KOH treatment on the electrical and defect characteristics of Micro-LEDs. This work reveal that the effects of sidewall damage can be minimized by sidewall treatments. Electric characteristic of forward and leakage current can maintain at 10^{-11}A by using treatments.

2 Experiment

The Micro-LEDs structure (from Xiamen Changelight Co., Ltd) were grown on a (0001) c-plane patterned sapphire substrate by metalorganic chemical vapor deposition (MOCVD), as shown in Fig. 1. Multiple quantum wells (MQWs) were formed by 10 pairs of InGaN/GaN, and AlGaN as the electron barrier layer (EBL) under the p-GaN. After the MOCVD growth, 100nm indium-tin oxide (ITO) was deposited via magnetron sputtering as a transparent and ohmic contact layer. 500nm of SiO_2 was blanket deposited using PECVD as hard mask. Then, Micro-LED mesa structures were defined by wet etching of the ITO and dry etching using ICP and etch down to the n-GaN layer. Then passivation layer was deposited by ALD at 300℃ using H_2O/Trimethyl aluminum (TMA), which was patterned by BOE etching. Then, 300nm Ti/Al/Ti/Au was deposited via electron-beam evaporation as negative and positive electrode of Micro-LEDs.

Here we report two kinds of structures for comparing the passivation layer. First is without Al_2O_3 passivation (Fig. 1(a)) and another one is with passivation (Fig. 1(b)). The without passivation layer's structure of the electrode is only on top of the p-GaN. With this structure design, we can investigate passivation effects of minimize the sidewall damage.

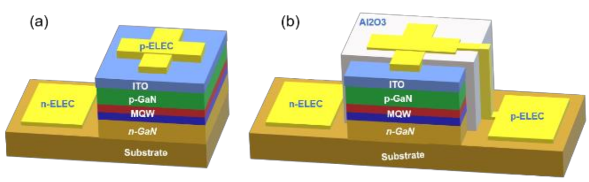

Fig. 1 Cross section schematics of the Micro-LEDs (a) without passivation, (b) with passivation

Another important treatment of improving characteristic of Micro-LEDs was chemical treatment using KOH[8]. After we got mesa structures of Micro-LEDs, BOE was used to remove SiO_2 hard mask. Then, Micro-LED with mesa and ITO structure were soaked in 2M KOH for 30min at 40℃. Then complete the remaining procedure, ALD passivation and electrode deposition. Here we can get with KOH and without KOH treatment samples. It is noticed that Micro-LEDs structure of with KOH and without KOH treatment were all have Al_2O_3 passivation to control the difference of the sidewall effect and obtain smaller devices for testing.

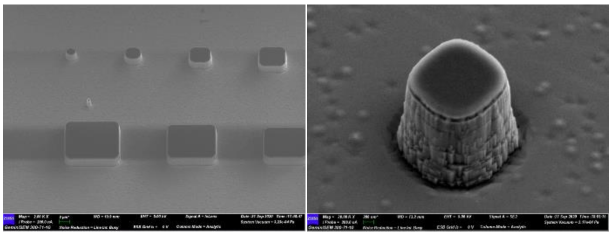

Fig. 2 The SEM images of Micro-LEDs after 30 min etching with KOH at 40℃

3 Results and discussions

The influence of ALD sidewall passivation and KOH treatment to the current-voltage characteristics and the ideality factors of Micro-LEDs were shown in Fig. 3 and Fig. 4. It seems that the sidewall effect is contributed to better threshold voltage in Micro-LEDs devices. Both devices without sidewall passivation treatment yielded orders of magnitude higher forward leakage current than devices with sidewall passivation, indicating the sidewall treatment have suppressed the leakage current of devices.

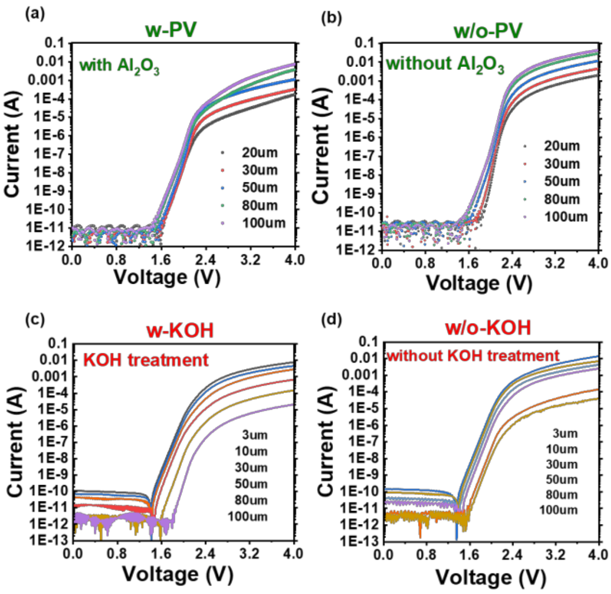

Fig. 3 Dependence of IV characteristic for Micro-LEDs (a) Al_2O_3 passivation, (b)without Al_2O_3 passivation, (c)KOH treatment and (d) without KOH treatment.

The ideality factors of Micro-LEDs were calculated from Eq. (1)[9, 10]

$$n = \frac{q}{kT}\left(\frac{\partial \ln I}{\partial V}\right)^{-1} \quad (1)$$

Where n is the ideality factor, q is the elementary charge, k is Boltzmann constant, T is the temperature, I is the current and V is the voltage. Fig. 4(a) shows the calculated ideality factor of different sized Micro-LEDs with and without passivation, and Fig. 4(b) shows the difference of ideality factor between with and without KOH treatment. For Micro-LEDs with sidewall treatment, the ideality factor of 20μm is about 1.7, lower than without sidewall treatment which is about 2.1. For KOH treatment methods, the ideality factor of devices without KOH treatment were about 2.0. For KOH treatment, the ideality factor of 3μm is 1.6 and 10μm is about 1.8. With the devices' size shrink, the reduction of the ideality factor is more pronounced. It revealed that sidewall treatments and chemical treatments have beneficial effects on the electrical performance.

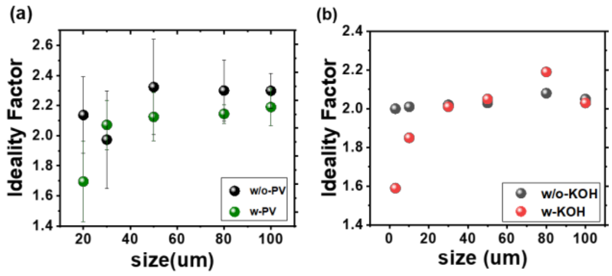

Fig. 4 Ideality factor distribution of different size of Micro-LEDs (a) with and without passivation (b) with and without KOH treatment.

4 Conclusions

In conclusion, we have demonstrated dielectric sidewall passivation by atomic-layer deposition (ALD) and potassium hydroxide (KOH) followed by ALD sidewall passivation to compare with devices without sidewall treatments. Electrical characteristic of forward leakage can be suppressed by using the passivation. The ideality factors of devices can be minimized for sidewall treatment, especially for smaller Micro-LED devices. More systemic analysis of the mechanism of the sidewall passivation and chemical treatment for micro-LED is undergoing.

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