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Use of Aluminum-Doped Zinc-Oxide Film as a Strain-Relief and Schottky Blocking Layer for the Fabrication of Vertical Structure Metal Substrate GaN-Based Light-Emitting Diodes

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1. Introduction

Vertical structure metal substrate GaN-based light-emitting diodes (VM-LEDs) have continuously attracted great attentions for its superior electrical-to-optical power conversion efficiency. In particular, use of metallic substrates significantly improved the thermal management of VM-LEDs and made VM-LEDs even better candidates as a boost to GaN-based LEDs in high-brightness (HB) applications of backlight source, solid-state-lightening (SSL), and vehicle headlights as compared with conventional sapphire substrate GaN-based LEDs [1-4]. To package these vertical HB-LED chips, tin-based solder material is preferable for die-bonding processes due to its better thermal conductivity. However, the temperature variation during die-bonding would be generally over 200°C depending on the alloy composition. This gives rise to additional stresses/strains from essentially large mismatches of coefficient of thermal expansion (CTE) between the epi-GaN and underlying metal layers (Tab. I). Thus the intrinsic polarization states are altered, and in turn electroluminescence (EL) characteristics, and irradiative recombination efficiency are affected [5-7]. In this work, we managed to alleviate this situation by inserting a sputter-deposited aluminum-doped zinc-oxide (AZO) layer between p-side ohmic contacts (oxidized Ni/Au) and the underlying metal layers for its less mismatching CTE and good as-deposited optical properties [8-10]. In addition, the oxidized Ni/Au was patterned to expose p-GaN to form a Schottky blocking region with the AZO layer under the n-electrode area [9]. This will force the current spread outward and enhance current spreading in the periphery area of the proposed device (namely SR-LEDs) [11]. Advantages including simple fabrication, better light output power, and higher power conversion efficiency in comparison regular VM-LEDs were demonstrated. Highly stable EL characteristics confronting temperature variation up to 255°C during die-bonding were reported and investigated as well.

2. Sample preparation

Before fabrication, a circular transmission line method (CTLM) was used to evaluate the as deposited AZO/p-GaN and AZO/(oxidized Ni/Au) contacts. It is found that AZO/p-GaN and AZO/(oxidized Ni/Au) are Schottky and ohmic contacts, respectively [9-10]. Figure 1 illustrates the key fabrication processes of the SR-LEDs. Samples prepared in this work were epitaxially grown on sapphire substrate by metal-organic chemical vapor deposition (MOCVD). For the detailed structure, please refer to ref. 1. Here, the patterned oxidized Ni(2.5 nm)/Au(3.5 nm) were deposited on p-GaN as localized ohmic contact. After that, a 2400Å AZO film was sputter-deposited on the patterned oxidized Ni/Au at an RF power of 90W (Fig. 1(a)). A Ti(15 nm)/Al(400 nm)/Ti(100 nm)/Au(200 nm) metal system was then deposited onto the AZO film to serve as adhesive/mirror layers, followed by 80-μm-thick nickel-electroplating at 1.7 A, patterned laser lift-off (LLO), removal of u-GaN, KOH surface treatment, and n-electrode formation (Fig. 2(b)) [1]. It should be heeded here, the chip size (300×300 μm^2) was defined in the patterned LLO processing stage through the use of a mask and an alignment to the localized ohmic contact layer. Regular VM-LEDs were also fabricated from the same wafer simultaneously for comparisons (Fig. 1(c)). Though the electrical and optical properties of the AZO film could be enhanced by post-deposition annealing, the EL behaviors of the multiple-quantum-wells (MQWs) of the GaN-based LED epilayers would be also affected simultaneously [7], [9]. For a fair investigation on the effectiveness of the AZO CTE matching layer in strain relief, no post-deposition annealing was adopted in the present work.

3. Results and discussion

Figure 2 shows the cross-sectional view of the interfaces between nickel substrates and p-GaN after LLO obtained from focus-ion-beam (FIB). Flat and even interfaces were obtained between AZO/GaN, indicating the proposed structure could sustain the GaN-based epi-layers well through the proposed fabrication processes. The current-voltage (I-V) characteristics of SR-LEDs and VM-LEDs were measured. At 20 mA, the forward voltage (V_F) of SR-LED and VM-LED were 3.38V and 3.27V respectively. The current density distribution in MQWs was calculated with 2D simulator ISE-TCAD in advance and shown in Fig. 3(a). Obviously, the conduction area of the SR-LED was reduced because of the Schottky blocking design. As a result, it leads to a relatively larger V_F, and this is in good agreement with those obtained from I-V measurements [11]. Nevertheless, current spreading in the periphery area of SR-LEDs was promoted due to the Schottky blocking design and this was revealed by the remarkable improvements in light output power (Lop) (Fig. 4) [11]. At an injection current of 20 mA, the Lop of SR-LEDs (10.3 mW) was typically 25% higher than that of VM-LEDs (8.5 mW) on TO-18 package. Taking this advantage, SR-LEDs were 21% superior to

VM-LEDs in power conversion efficiency ($\lambda=P_o/P_e$, the ratio of optical output power P_o to input electrical power P_e). Figure 4(a) showed the thermal profile applied to SR- and VM-LED chips to emulate the crucial temperature variation during die-bonding. The EL characteristics of SR- and VM-LEDs at 20 mA were measured sequentially in 25°C (room temperature), after 165°C for 20s and cooled to 25°C, and in the end of the whole process [12]. The EL characteristics of SR-LEDs remained stable without noticeable change throughout the thermal process. In contrast, the EL peak (W_P) of the VM-LEDs was 464.7 nm in 25°C and shifted to 465.5 nm with 8% degradation in emission intensity after 165°C for 20s. After the whole process, the W_P of VM-LEDs further shifted to 467.0 nm and the degradation in intensity came to 12%. The relatively stable EL characteristics of SR-LEDs throughout high temperature processes could be mainly attributed the AZO layer relieved the thermal stress/strain from CTE mismatch between the underlying metal layers and the epi-GaN, which VM-LEDs suffered from [7].

4. Conclusion

In summary, through the use of AZO CTE matching layers with patterned oxidized Ni/Au, SR-LEDs were fabricated. Due to the p-side Schottky blocking design, the current spreading in the periphery area was promoted and this contributed to the enhancements in Lop and λ of 25% and 21% respectively. With the strain-relief from the AZO layer, SR-LEDs exhibited highly stable EL characteristics confronting a temperature variation up to 255°C during die-bonding. It thus could be expected the SR-LED has great potential to boost vertical GaN-based LED's performance beyond for high-brightness applications in the foreseeable future.

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Tab. I Comparisons on the CTEs of AZO, ITO, GaN, sapphire, and underlying metal layers used in this work [8].

	Aluminum	Nickel	Titanium	Gold	AZO film	ITO film	GaN	Sapphire
Mean Coefficient of Thermal Expansion @ room temperature Unit: 10^{-6}/°C	24	13	8.6	14	6.0	8.5	5.6	7.7

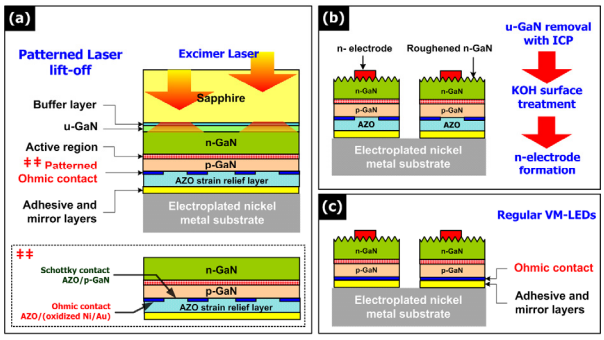

Fig. 1 Key fabrication processes of the proposed SR-LEDs. (a) Samples at the patterned LLO processing stage. (b) At the n-GaN ohmic contact processing stage. (c) The schematic drawing of the regular VM-LEDs.

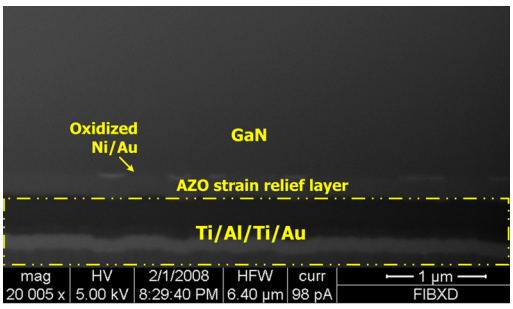

Fig. 2 Cross-sectional view of the fabricated SR-LED on the interfaces between the nickel substrate and GaN.

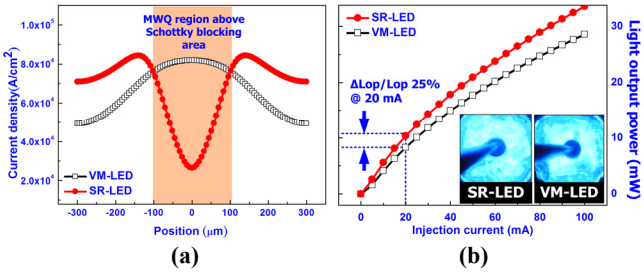

Fig. 3 (a) Theoretical current density distribution of SR- and VM-LEDs at 20 mA. (b)Experimental Lop-I characteristics of SR- and VM-LEDs at 20 mA. The inset shows the emission OM image of SR- and VM-LEDs.

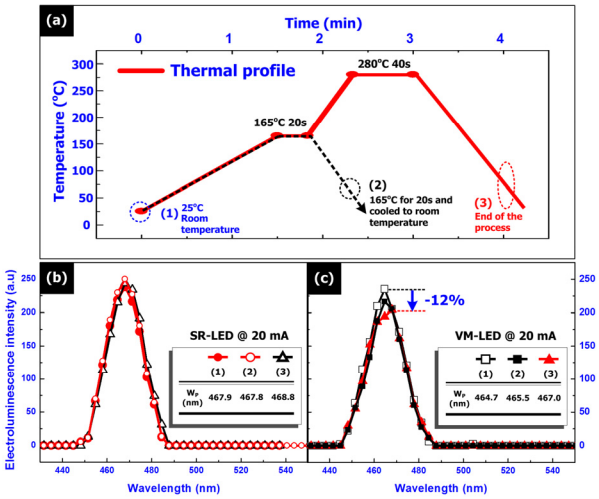

Fig. 4 (a) Profile used for investigations on SR- and VM-LEDs' EL characteristics dependence on temperature variation during die-bonding [12]. (b) Experimental EL characteristics of SR-LEDs and (c) VM-LEDs.

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