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Improved Reliability and ESD characteristics of Flip-Chip GaN-based LEDs with Internal Inverse-parallel Protection Diodes

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Although great improvement in efficiency has been well proven in GaN-based LEDs with ITO upper contact layers, the light extraction efficiency (LEE) is still limited by several factors. For example, the shadow of the bonding pads and wires in conventional face-up devices would result in a reduction of LEE. One possible way to solve the problem is to use flip-chip (FC) technology. Reliability is a crucial factor for different applications such as LCD (liquid crystal display) backlight modules. Aside the decay of light output power, Electrostatic discharge (ESD)-induced electrical pulse is one of the main reliability concerns for LEDs. It is well known that GaN-based LEDs can be electrically connected to Si Zener diodes in order to significantly improve the ESD protection capability [3]. Recent studies have demonstrated that GaN/sapphire LEDs can be electrically protected from ESD damage by using a shunt GaN Schottky barrier diodes (SBDs) connected in parallel to the GaN LED. Since the GaN Schottky diodes were formed by metal contacts deposited on the etched GaN surfaces, the reproducibility and reliability were not perfect. Therefore, the device yield was much lower than typical yield of conventional GaN/sapphire LEDs without the shunt SBDs. In this study, a LED structure featuring electrostatic discharge (ESD) protection function was designed. The design incorporated a GaN-based p-n diode (named ESD diode) instead of the SBD. The p-n diode was electrically connected in inversely parallel direction to the GaN LED. According to the design, the layer structure of the ESD diode was identical to the GaN LED, but the area of the ESD diode was smaller than the area of GaN LED, as shown in Fig.1(a). The idea behind the design was to provide GaN LEDs good protection from the ESD damage. In our design pulsed surge current could flow through the ESD diode in case of reversely electrostatic discharge or an abnormally high voltage. On the other hand, to further improve the output power of the ESD-protected GaN-based LEDs, FC technology was also used in this study.

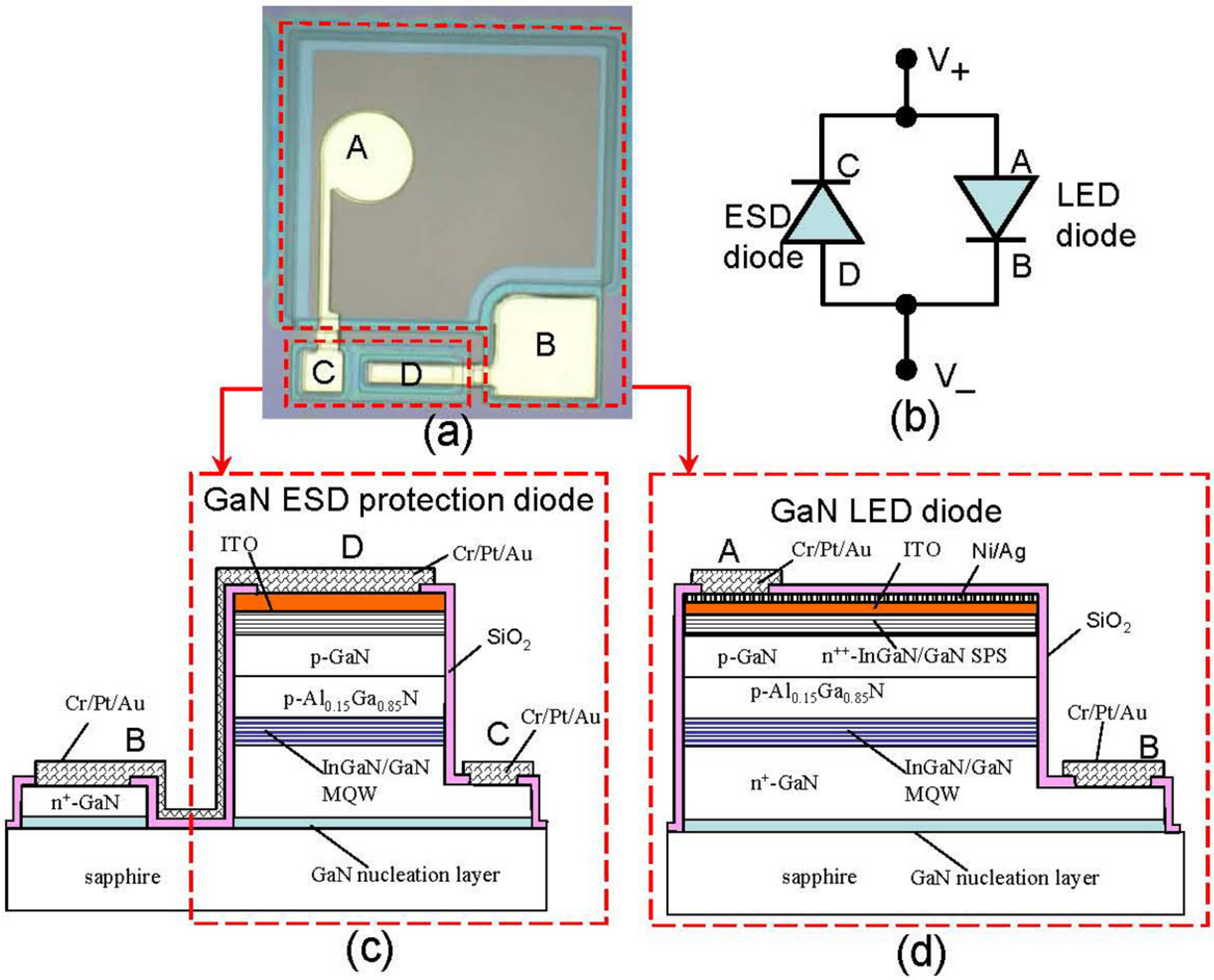

Fig. 1.(a)Bare-chip photograph of the LED-I. (b) Equivalent circuit diagram schematically illustrating LED-II. The schematic layer structure comprises(c) an inverse-parallel-connected GaN ESD diode and (d) a GaN LED

The InGaN/GaN MQW LED wafers used in this study were all grown by MOCVD on c-face sapphire substrates. After the wafer growth procedures, the ITO layer was subsequently evaporated onto the sample to serve as a transparent contact layer. For device process, wafers were partially etched until the n^+-GaN layers were exposed. In order to electrically isolate the GaN LED diodes and the ESD diodes disposed on the same substrate, the n^+-GaN layers were further partially etched away by dry etching until the sapphire substrate was exposed. Next, 1-•m-thick SiO2 films were deposited over the chips to simultaneously serve as the passivation layer and the electrical insulation layer between the two diodes. Following the deposition of the SiO2 films, Cr/Pt/Au (300/100/25•m) were deposited onto the exposed n^+-GaN/ITO contact layers to simultaneously serve as the n-type/p-type electrodes and the interconnection between the GaN LED diodes and the ESD diodes. It should be noted that the above-mentioned LEDs were labeled as LED-I. Figures 1(a), 1(c) and 1(d) show the top-view photograph of the LED-I, the layer structure of ESD diode and the GaN LED diode, respectively. In case of FC samples, Ag-based reflector was performed on the ITO transparent contact layer by e-beam evaporator [4]. Sn/Au(15 μm/5 μm) layers were then electroplated onto the samples to form the P/N bumps. The processed wafers were then lapped down to about 110 μm and then were broken into individual dies with size of 380 μm × 350 μm. It should be noted that FC LEDs were soldered onto Si sub-mounts prior to packaging and they were labeled as LED-II. For comparison, conventional GaN-based LEDs without the inverse-parallel internal diode were also prepared and labeled as LED-III. The ESD characteristics were tested using the Electrostatic Discharge Simulator-Model 910, which consisted of a variable high voltage power supply, a high voltage switch and an R/C discharge network. The device allowed to simulate different electrostatic discharges produced by a human body (Mil Std. 883E)

The analysis of Fig.1(a) shows that it is identical to a circuit diagram schematically illustrated in the Fig.1 (b). One can see that the ESD diode (i.e., C-D junction has inverse-parallel connection to the GaN LED diode (i.e., A-B junction). In general, the shunt ESD diode operates in the reverse region unless it goes into the state of irreversible breakdown due to high reverse bias. Thus the shunt diode remains conducted and exhibits rectification characteristics. When a normal forward bias is applied to the two ends of LED-I (V+ and V-), forward current is generated by the carriers passing the A-B junction and the LED diode emits light. However, when abnormal high reverse voltage or electrostatic charge event occurs, the excessively high voltage can be discharged by the ESD diode that is conducted in the forward-bias regions, and thus high reverse current does not flow to the LED diode. Therefore, we can see that the LED diode is protected from the potential damages resulting from electrostatic discharge, abnormal reverse voltage or excessively high voltage. Fig. 2 shows typical forward I-V characteristics of LED-I, LED-II and LED-III. As shown in the inset of Fig.2, the difference of forward voltage (at 20 mA) between these LEDs does not exceed 0.1 Volt. On the other hand, to judge whether the LEDs failed or not after an HBM pulse stress was applied, the failure criterion was set at a reverse leakage current of 2•A measured at a reverse voltage of -5V. We applied negative ESD stress to the anode, meanwhile keeping the cathode grounded, to evaluate negative ESD levels. As shown in Fig.3, LED-III could only endure negative ESD pulses of around 500V. However, our observations also showed that LED-I could endure ESD pulses as high as negative 3500 V. In other words, we were able to significantly enhance the ESD characteristics of GaN-based LEDs by using a shunt GaN ESD diode connected in inversely-parallel direction to the GaN LED. As shown in Fig. 3, similar results were also observed for LED-II with FC configuration. Fig. 3 also shows typical output power-current (L-I) characteristics of LED-I, LED-II and LED-III. Light output powers of the LEDs with bare-chip form, packaged using epoxy-free metal TO cans (TO-46), were measured under the same conditions. In addition to excellent ESD-protection capabilities, the light output performance of LED-I was also comparable with conventional LEDs (LED-III). When a 20 mA current injection was applied, the output power of LED-I and LED-III, emitting a wavelength of around 465 nm, was around 7.3 mW and 7.5 mW, respectively. However, the LED-II with FC configuration exhibited an output power as high as 12.6 mW. Moreover, the reliability of the LED-II is expected to be superior to the conventional GaN LEDs without the ESD protection function. Reliability tests of LEDs featuring ESD protection were also performed by injecting 20 mA DC current into these devices at room temperature. Fig. 4 shows aging tests of relative luminous intensities, measured for LED-I, LED-II, and LED-III, normalized to their respective initial readings. After 1200 hours of operation, we found that luminous intensities of LED-I, LED-II, and LED-III, decreased by 19 %, 4 %, and 22 %, respectively. It is clear that the degradation trend is comparable between LED-I and LED-III. However, when compared to LED-I and LED-III, thermal path of LED-II was much shorter. Thus, most heat generated in LED chips could easily flow to the heat sink (Si sub-mount) in case of FC LEDs. As a result, we can see that the FC technology allows obtaining LEDs with improved reliability.

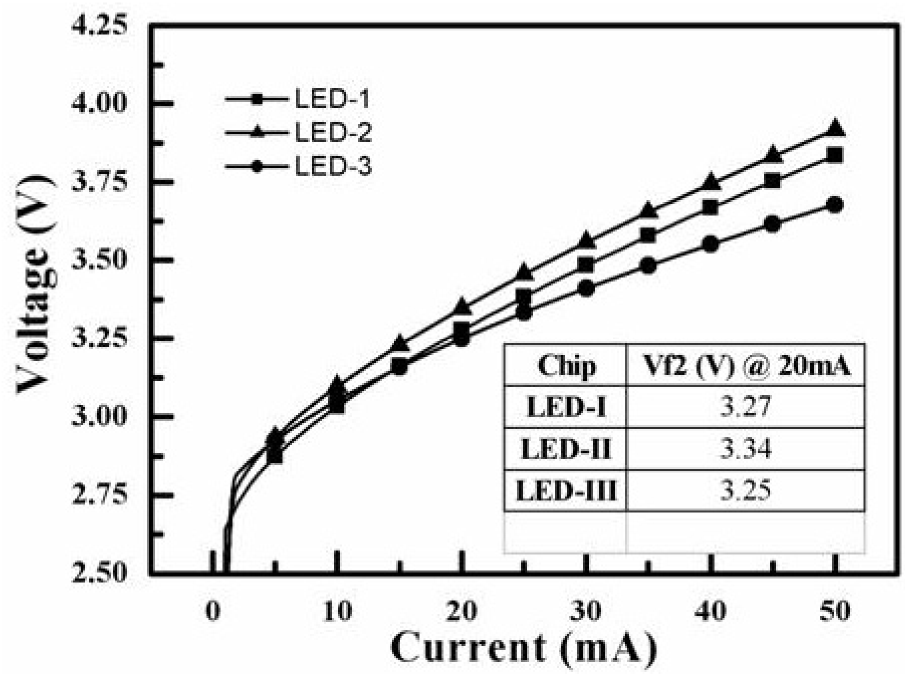

Fig. 2.Typical forward *I-V* characteristics of LED-I, LED-II, and LED-III.

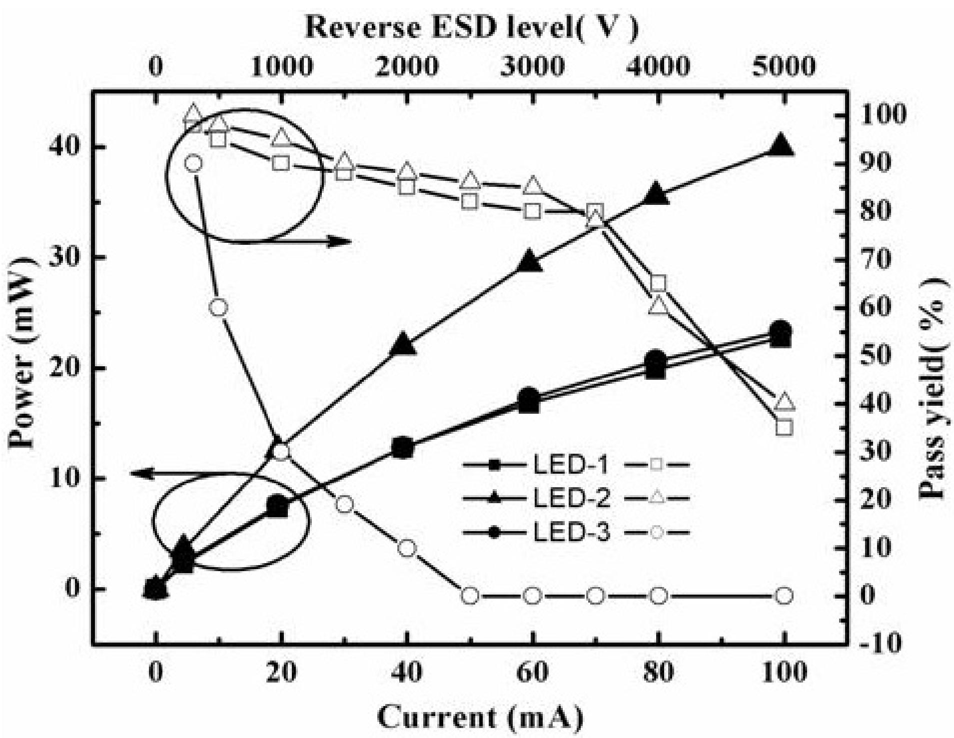

Fig. 3.Measured ESD results as a function of stress voltage and light output power as function of forward current of the LEDs. The values shown in the right-hand vertical axis mean the total tested dvice numbers (100 devices) divided by the non-filed device numbers ofr a given reverse stress voltage.

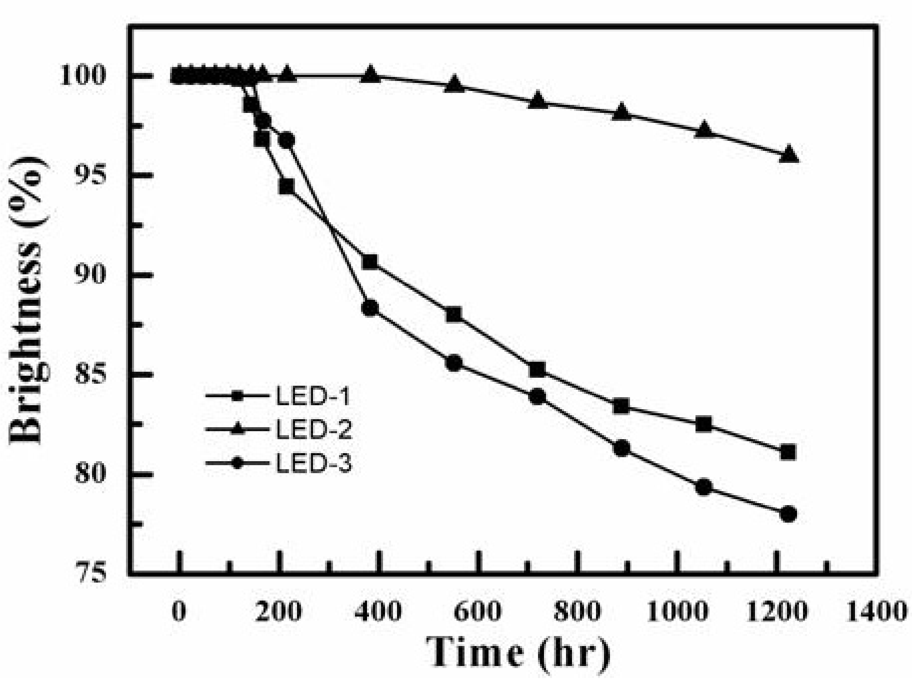

Fig. 4.Room-temperature aging tests of relative luminous intensities, measured from LED-I, LED-II, and LED-III, normalized to their respective inital readings.