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Highly reliable nitride-based LEDs with internal ESD protection diodes

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Abstract

Nitride-based light emitting diodes (LEDs) with internal electrostatic discharge (ESD) protection diodes emitting at 460 nm were proposed and realized. By building an internal GaN p-n junction diode, negative ESD induced pulse current could flow through the protection diode without damaging the major LED. It was found that operation voltage and ESD characteristics of the fabricated LEDs depend on the size of the internal diode as well as the pattern layout design. Furthermore, it was found that we could significantly increase the ESD threshold from 300~400 V to 2000 V. Lifetime of the proposed LEDs could also be improved with proper pattern layout design to enhance current spreading.

KEYWORDS: GaN, LED, ESD, protection diode, current spreading

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I. Introduction

III-V nitrides have some unique properties, such as wide direct band gap, high thermal conductivity and chemical stability [1]. The group III nitrides, especially GaN, are attractive materials for optoelectronic devices. GaN-based blue and green light emitting diodes (LEDs) prepared on sapphire substrates have already been successfully commercialized [2-6]. Such success has opened up the windows of opportunities for using III-V nitrides in varieties of applications, including traffic light, full color display and back light of liquid crystal display (LCD) panels. However, GaN-based devices, such as laser diodes (LD), light emitting diodes (LED) and photodetectors (PD) are still vulnerable to electrostatic discharge (ESD) due to the insulating nature of sapphire substrates [7-11]. For LED applications, reliability is another issue. Although the initial output intensity of GaN-based LEDs is large, it might decay rapidly due to poor current spreading [12-13]. As a result, the internal temperature in GaN-based LEDs will increase to result in short device lifetimes. Thus, we need to overcome both problems to achieve high performance GaN-based LEDs. Although reliability has been extensively studied, however, only few reports on ESD effects of GaN-based LEDs could be found in the literature [7-11]. To our knowledge, no report simultaneously discussing both issues for GaN-based LEDs has been reported yet.

Previously, it has been shown that one can connect GaN LEDs to Si-based Zener diodes through flip-chip process to improve their ESD characteristics since pulse current could flow through Si-based Zener diodes under negative ESD stress [7]. Although such method can effectively improve ESD characteristics of nitride-based LEDs, flip-chip packaging needs extra complex processing steps as compared to conventional packaging. These steps might result in lower production yields and higher production costs. In this study, we propose a new method to improve ESD characteristics of GaN-based LEDs. We built an internal GaN p-n junction diode parallel to the original LED so as to provide a current path when negative ESD voltage was applied. By proper electrical connection, negative ESD induced pulse current could flow through the p-n junction diode without damaging the LED. The fabrication process and characteristics of the fabricated LEDs with ESD protection diodes will also be reported.

II. Experiment

Samples used in this investigation were all grown on c-face (0001) 2” sapphire (Al_2O_3) substrates in a vertical metalorganic chemical vapor deposition (MOCVD) system [14-16]. The LED structure consists of a 50-nm-thick GaN nucleation layer grown at 540^{o}C, a 3-µm-thick Si-doped n-GaN buffer layer grown at 1050^{o}C, an unintentionally doped InGaN/GaN multiquantum well (MQW) active region grown at 750^{o}C, a 50-nm-thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer grown at 1050^{o}C, a 0.25-µm-thick Mg-doped p-GaN layer grown at 1050^{o}C and an InGaN/GaN n^+-SPS tunnel contact structure [17]. The InGaN/GaN MQW active region consists of 5 pairs of 3-nm-thick $In_{0.23}Ga_{0.77}N$ well layers and 7-nm-thick GaN barrier layers. On the other hand, the n^+-SPS tunnel contact structure consists of 4 pairs of n^+-$In_{0.23}Ga_{0.77}N$/GaN (0.5 nm/0.5 nm). By growing such SPS structure on top of the p-GaN cap layer, one could achieve a good "ohmic" contact through tunneling when the n^+(InGaN/GaN)-p(GaN) junction was properly reverse biased [17]. The as-grown samples were subsequently annealed at 750°C in N_2 for 20 minutes to active Mg in the p-type layers.

After the growth, an inductively coupled plasma (ICP) etcher was used to define trench isolation. During ICP etching, Ni was used as the hard mask. The etching depth was about 4 μm, which was about the thickness of the whole LEDs epitaxial layer. We designed our mask so as to divide one chip into two zones. One was the major LED while the other was the slave ESD protection diode. It should be noted that size of major LED was much larger than that of slave ESD protection diode. We then partially etched the sample again with another mask until the n-type GaN layer was exposed. We then deposited a SiO_2 bridge layer for passivation and to prevent electrical short circuit across the p-n junction. Indium-tin-oxide (ITO) was subsequently evaporated onto the sample surface (i.e. Si-doped n^+-SPS) to serve as the p-electrode. On the other hand, Ti/Al/Ti/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-contact.

Figure 1(a) shows cross-sectional diagram of the fabricated devices. With properly designed masks, we could electrically connect p-contact of the major LED, Pm, to n-contact of the slave ESD protection diode, Ns, while connect n-contact of the major LED, Nm, to p-contact of the slave ESD protection diode, Ps. Figure 1(b) shows equivalent circuit of the fabricated devices. Under normal forward bias operation, current could flow across the major LED from Pm to Nm, functioning as a normal LED. On the other hand, if a reverse biased ESD induced electrical pulse occurs, ESD current could flow across the slave ESD protection diode from Ps to Ns, providing a path for the ESD current to release. Thus, such a design could effectively protect the major LED from electrical stress damage during reverse biased ESD induced electrical pulse. These 2-inch epitaxial wafers were then lapped down to about 100 μm. We then used scribe and break to fabricate LED chips. Figure 2 shows top views of the conventional LED (i.e. LED-I) without the ESD protection diode and the LEDs with ESD protection diodes (i.e. LED-II, LED-III and LED-IV) fabricated with three different sets of masks. Table 1 lists the total chip sizes and the sizes of the slave ESD protection diodes of the four fabricated LEDs. Although the total chip sizes were about the same, sizes of the slave ESD protection diodes were very different, i.e. 0, 4200, 10800 and 11500 μm^2 for LED-I, LED-II, LED-III and LED-IV, respectively. Current-voltage (I-V) characteristics of these LEDs were then measured by an HP4155B semiconductor parameter analyzer. The ESD characteristics of these LEDs were measured by an Electro-tech system ESD simulator Model 910, which could produce electrical pulses similar to those originated from human body. During ESD testing, we applied forward and reverse pulse voltages onto the samples. After each test, we measured the electrical characteristics of the samples again. If the measured current varied by more than 30% from its original value, we then concluded that the chip was failed. On the other hand, chips were subsequently packaged with epoxy plastics and cured in high temperatures into LED lamps. The output powers were measured using the molded LEDs with the integrated sphere detector from top of the devices by injecting different amount of DC current into these LED lamps. The reliabilities of these LEDs were then evaluated by injecting 30 mA DC current into the devices for life tests.

III. Results and discussions

Figure 3(a) shows forward I-V characteristics of the four fabricated LEDs. As shown in figure 1(b), we define forward bias as we applied a positive voltage onto Pm (i.e. Ns) with respect to Nm (i.e. Ps). With such definition, the slave ESD protection diodes were turned off under forward bias. With 20 mA forward current injection, it was found that forward voltages of the conventional LED (i.e. LED-I) was 3.32V. In contrast, the 20 mA forward voltages of LED-II and LED-III were 3.38 and 3.58V, respectively. It should be noted that the size of major LED of LED-II (i.e. ~121200 μm^2) was about the same as the size of LED-I (i.e. 120000 μm^2). With the same 20 mA current injection, the current density in the major LED of LED-II should be about the same as that in LED-I. Thus, 20 mA forward voltages of these two LEDs were about the same. On the other hand, size of the major LED of LED-III was about 10% smaller (i.e. ~109200 μm^2). With the same injection current, current density in major LED of LED-III should be larger. We thus achieved a much larger 20 mA forward voltage from LED-III. Such a problem can be solved by better pattern layout design. Previously, it has been shown that one can improve the performances nitride-based LEDs by introducing n-fingers [17] or n-ring [18] during device fabrication. With the n-fingers/n-ring, one should be able to enhance current spreading and thus reduce operation voltage of nitride-based LEDs. As shown in figure 2, LED-IV is a LED with slave ESD protection diode and n-fingers. Although size of major LED of LED-IV (i.e. ~108500 μm^2) was the smallest among the four samples, it can be seen from figure 3(a) that 20 mA forward voltage of LED-IV was only 3.29 V. although the size of slave ESD protection diode was even larger than that of LED-III. The significantly reduced forward voltage of LED-IV should be attributed to the much better current spreading due to the improved pattern layout design. Figure 3(b) shows reverse I-V characteristics of the four fabricated LEDs. During reverse bias, major LEDs were turned off. It can be seen that the reverse current was extremely small for LED-I. In contrast, significant reverse currents were observed from LED-II, LED-III and LED-IV when the applied reverse bias was larger than 3 V. Such large reverse currents could be attributed to turn on of the slave ESD protection diodes. With the same reverse bias, it was found that LED-IV exhibited the largest reverse current, followed by LED-III and then LED-II. Such an order agrees well with the sizes of the slave ESD protection diodes in these three LEDs.

Figure 4 shows room temperature on-wafer electroluminescence (EL) spectra of the four LEDs with 20 mA DC current injection. It was found that 20 mA EL peak positions of these four LEDs were all around 460 nm. It was also found that full-width-half-maxima (FWHM) of the EL peaks were similar. These observations could be attributed to the exactly identical epitaxial structure used for these four LEDs. Figure 5 shows measured intensity-current (L-I) characteristics of the four fabricated

LEDs. It was found that output powers of LED-I and LED-II were both around 10% larger than that of LED-III. This could be attributed to the fact that sizes of the major LEDs of LED-I and LED-II were both larger than that of LED-III. On the other hand, it was found that output power of LED-IV was also slightly larger than that of LED-III. This is probably due to the effects of enhanced current spreading. With 20 mA current injection, it was found that output powers were 8.03, 7.73, 7.18 and 7.45 mW for LED-I, LED-II, LED-III and LED-IV, respectively.

Figures 6(a), 6(b), 6(c) and 6(d) show ESD stressing voltage distribution mappings of the wafers for LED-I, LED-II, LED-III and LED-IV, respectively. During these measurements, we applied negative ESD pulses onto the samples. As shown in figures 6(b), 6(c) and 6(d), it was found that LED-II, LED-III and LED-IV could endure negative ESD stress voltages of 800, 1600, and 2000 V, respectively. In contrast, it was found that conventional LED without the slave ESD protection diode (i.e. LED-I) could only endure negative ESD surge of 300~400 V, as shown in figure 4(a). The much better ESD performance of LEDs fabricated in this study could be attributed to the fact that the slave ESD protection diodes could indeed provide a current path when negative ESD voltage was applied. Among the three LEDs with ESD protection diodes, it was found that ESD characteristic of LED-II was inferior to those of LEID-III and LED-IV. This could be attributed to the fact that size of the slave ESD protection diode for LED-II was much smaller than those of LED-III and LED-IV. With smaller slave ESD protection diode, negative ESD surge current could still damage major LED when the negative ESD stress was larger than 800 V. On the other hand, the much better ESD characteristics of LED-IV, as compared to LED-III, could again be attributed to the much better current spreading due to the improved pattern layout design. It should be noted that we also applied positive ESD pulses onto these LEDs. It was found that all chips could endure positive ESD stress voltage of at least 3500 V. Such a result indicates that the extra fabrication processes used in this study will not degrade the positive ESD performance of the LEDs. Figure 7 shows life test of relative luminous intensity measured from these four different kinds of LEDs, normalized to there respective initial readings. During life test, all four LEDs were driven by 30 mA current injection at room temperature. It was found that EL intensity decayed by about 22% after 1000 hours for LED-I, LED-II and LED-III. Such a result suggests that the extra fabrication processes used in this study also will not degrade reliability of the LEDs. Furthermore, it was found that EL intensity decayed by only 18% after 1000 hours for LED-IV. The slightly better lifetime observed from LED-IV should again be attributed to the enhanced current spreading of the better pattern layout design.

IV. Summary

Nitride-based LEDs with internal ESD protection diodes emitting at 460 nm were proposed and realized. By building an internal GaN p-n junction diode, negative ESD induced pulse current could flow through the protection diode without damaging the major LED. It was found that operation voltage and ESD characteristics of the fabricated LEDs depend on the size of the internal diode as well as the pattern layout design.

Furthermore, it was found that we could significantly increase the ESD threshold from 300~400 V to 2000 V. Lifetime of the proposed LEDs could also be improved with proper pattern layout design to enhance current spreading.

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Figure Captions

Figure 1 (a) Cross-sectional diagram and (b) equivalent circuit of the fabricated devices.

Figure 2 Top views of the LEDs fabricated in this study.

Figure 3 (a) Forward and (b) reverse I-V characteristics of the fabricated LEDs.

Figure 4 Room temperature on-wafer EL spectra of the four LEDs with 20 mA DC current injection.

Figure 5 Measured L-I characteristics of the four fabricated LEDs.

Figure 6 Reverse ESD stressing voltage distribution mappings of the wafers for (a) LED-I, (b) LED-II, (c) LED-III and (d) LED-IV.

Figure 7 Life test of relative luminous intensity measured from these four different kinds of LEDs, normalized to there respective initial readings.

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	Chip dimension (μmXμm)	Slave ESD protection diode dimension(μm^2)
LED-I	300x400	0
LED-II	330x380	4200
LED-III	300x400	10800
LED-IV	300x400	11500

Table I Total chip sizes and the sizes of the slave ESD protection diodes of the four LEDs fabricated in this study.

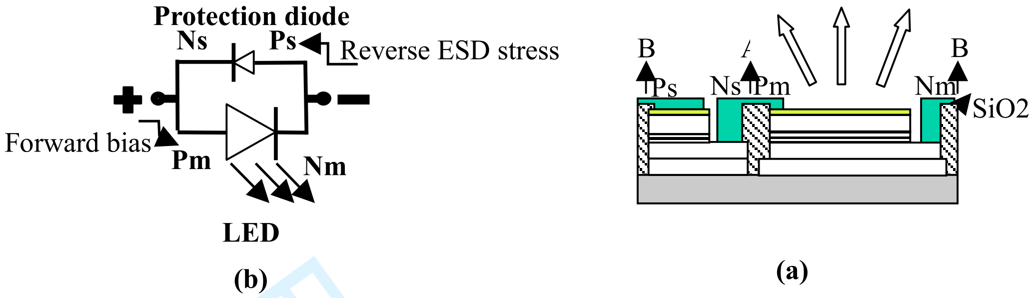


Figure 1.

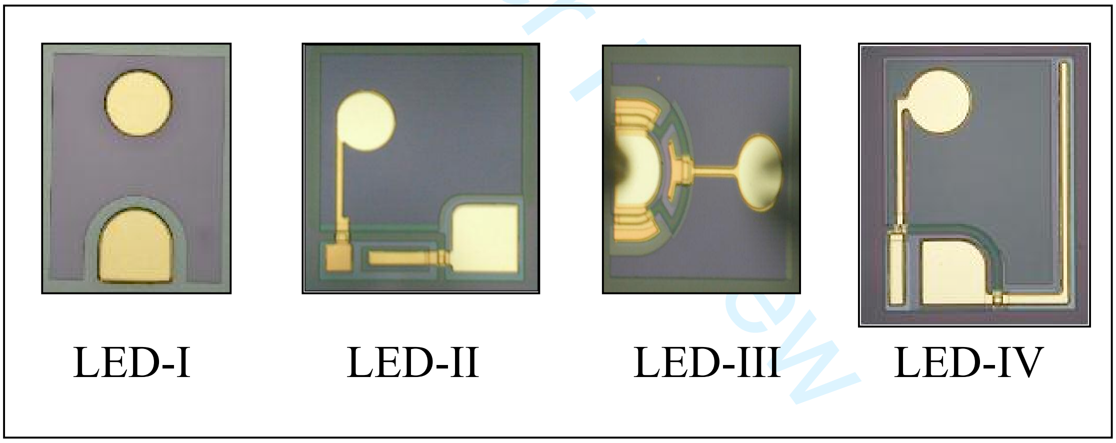


Figure 2.

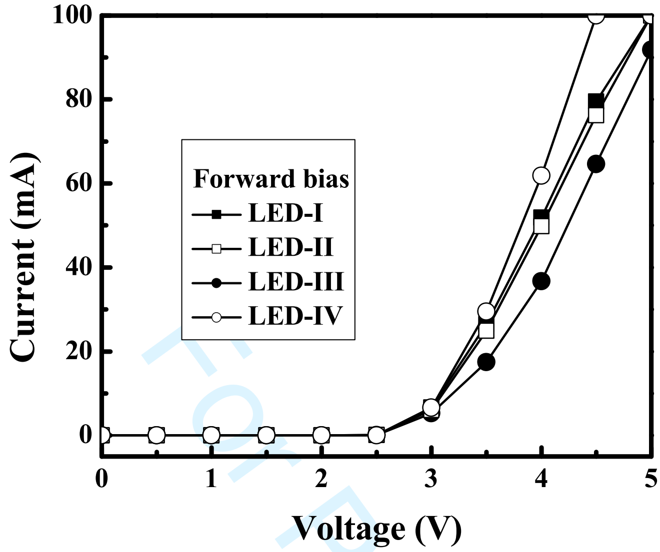


Figure 3(a)

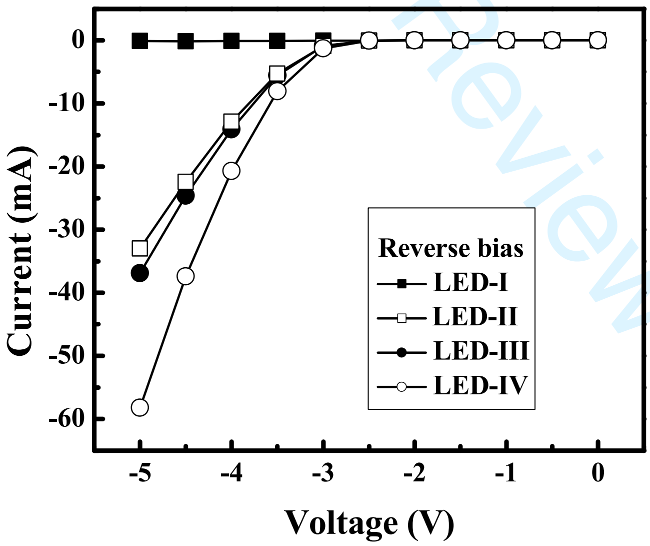


Figure 3(b)

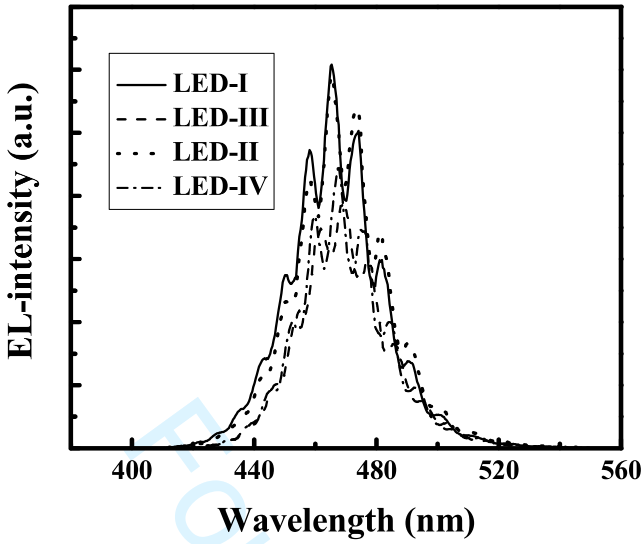


Figure 4

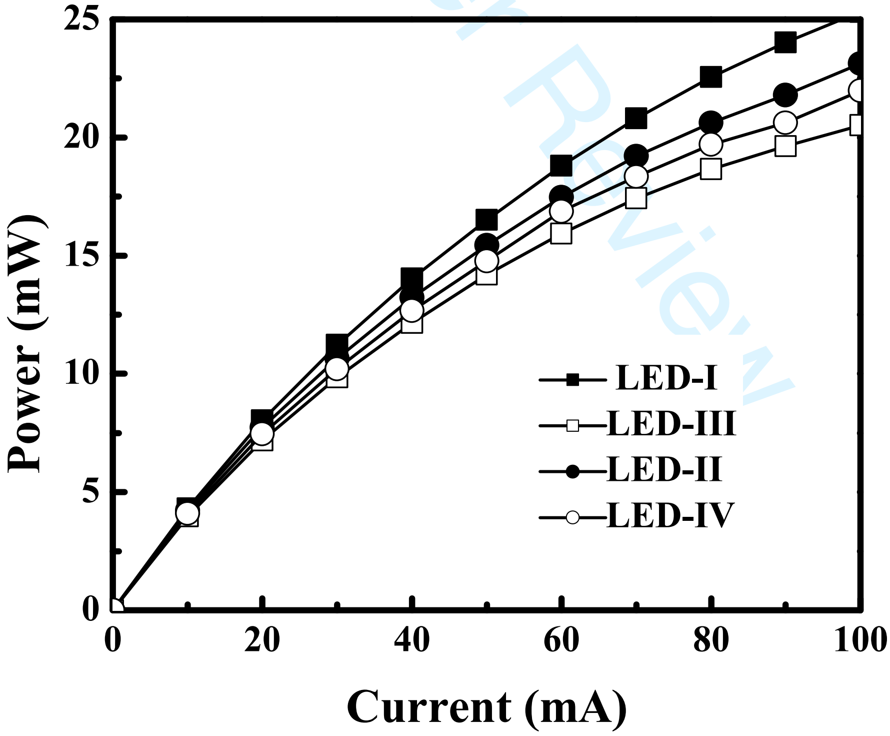


Figure 5

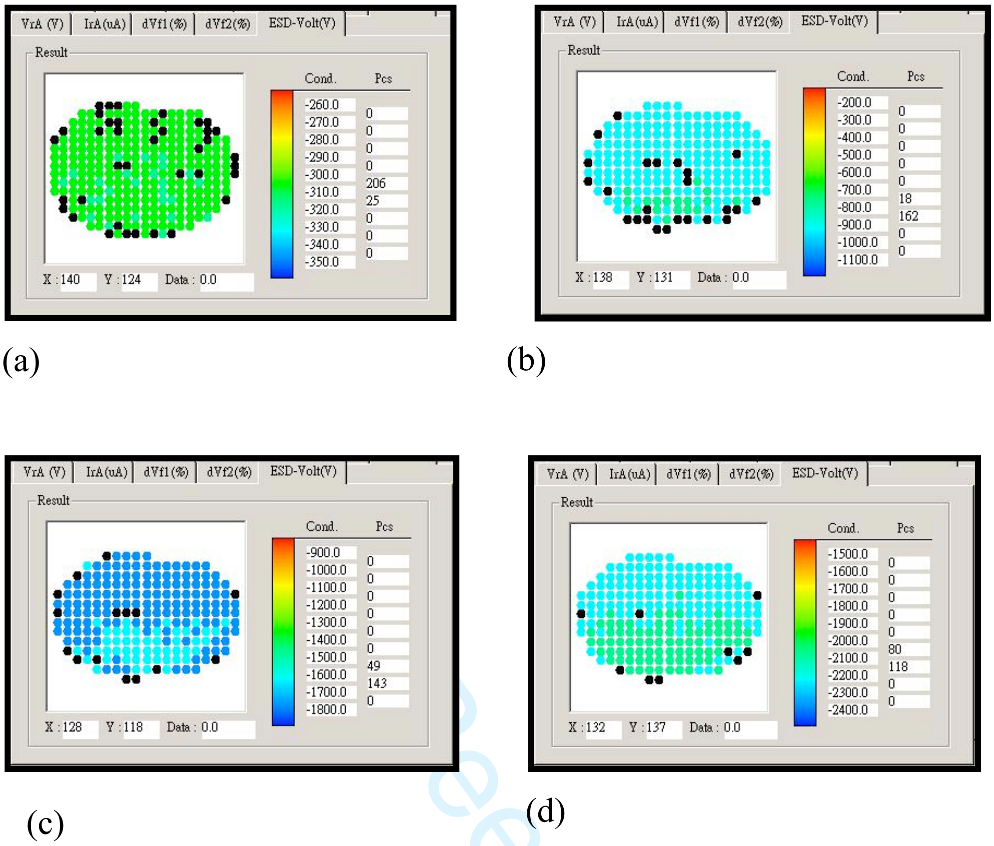

VrA (V)
IrA (uA)
dVf1 (%)
dVf2 (%)
ESD-Volt(V)
Result
Cond.
Pcs
(a)
(b)
(c)
(d)

Figure 6

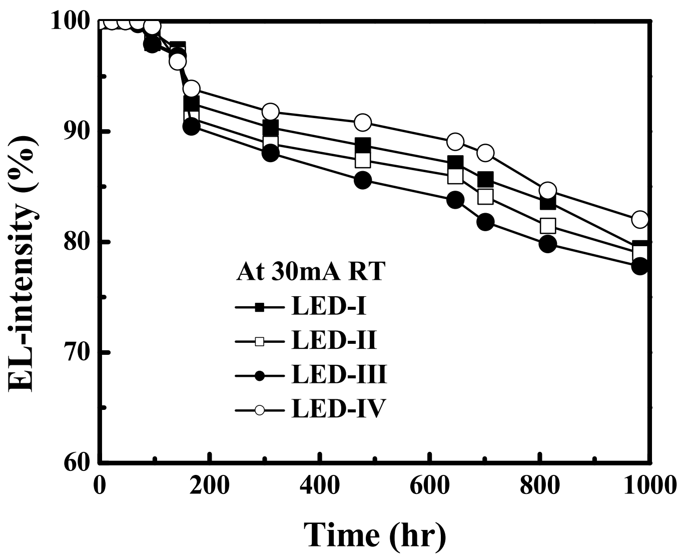
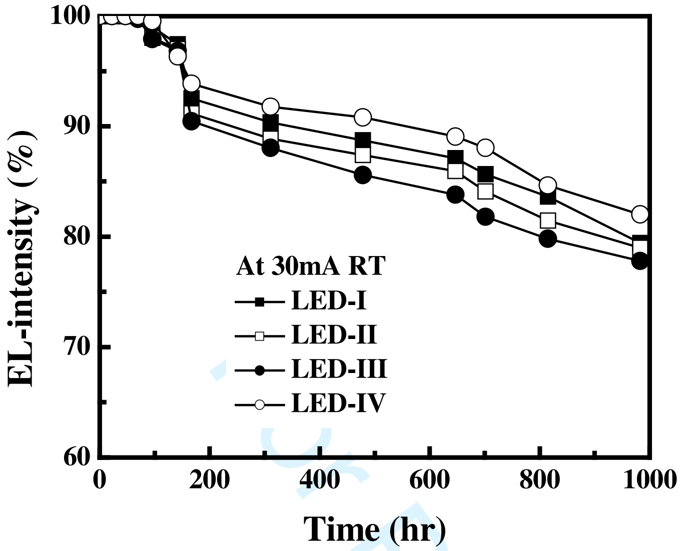

EL-intensity (%)
Time (hr)
At 30mA RT
LED-I
LED-II
LED-III
LED-IV
100
90
80
70
60
0
200
400
600
800
1000

Figure 7



100
90
80
70
60
EL-intensity (%)
At 30mA RT
LED-I
LED-II
LED-III
LED-IV
0
200
400
600
800
1000
Time (hr)

Figure 7