Investigation of GaN-Based Flip-Chip LEDs in Brightness and Reliability

Abstract

In this dissertation, high performance nitride-based flip-chip (FC) light-emitting diodes (LEDs) were investigated and fabricated.

Firstly, to enhance output intensity furthermore, the structure of FC LEDs (280 μm X 360 μm) with transparent ohmic contact and reflective mirror was designed and indium-tin-oxide (ITO)/Ni films and Ag were proper materials for them. Compared with the traditional non-flip-chip (NFC) LEDs, it was observed rapid thermal annealed (RTA) ITO/Ni films could provide good electrical and optical properties to improve powers about 30%, which were 21mW and keep voltages stable for FC LEDs applications, measured were 3.15 V at a 20-mA forward current. Output intensity only decayed by 5% after long-time reliability test.

For power FC LEDs (1000 μm X 1000 μm) in addition, we reported the fabrication with roughened surface of sapphire backside prepared by grinding process could increase output power by about 35%. Reliability of the proposed FC LEDs with rough surfaces was also better, as compared to that with conventional flat surfaces.

On the other hand, heat dissipation is a key issue for power chip LEDs. In our research, Cu sub-mounts were studied to replace conventional ones. With a much higher thermal conductivity, we could achieve a lower operation voltage under high current injections and a lower junction temperature. Compared with the power FC LEDs with Si sub-mount, the reliability of the proposed LEDs was much better. And the EL intensity remained above 90% after operated during long time.

Further, we found the internal ESD protection devices fabricated in Cu sub-mounts could not only avoid lighting area losses for FC LEDs,

compared to those fabricated in LED chips but also provide good ESD protection function. It was achieved that negative ESD thresholds could be notably increased. And the values were about 9 times larger than those of traditional NFC LEDs.

Keywords: light-emitting diodes (LEDs); flip-chip (FC); indium-tin-oxide (ITO); non-flip-chip (NFC).

I. Introduction

1. Background

In the past for lighting applications, incandescent lamps and fluorescent lamps were the two most commonly used light sources in our daily life. However, incandescent lamps consume large power with short lifetime. Fluorescent lamps contain environmentally hazard mercury. Thus, much attention has been focused on generating white light with nitride-based light-emitting diodes (LEDs). In the past two decades, we have witnessed dramatic progress in the area of blue/green light-emitting diodes (LEDs) and laser diodes [1-9]. These developments have propelled the group III-nitride materials to the forefront of semiconductor research worldwide. As observed the applications of LEDs are primarily divided into three fields: solid-state lighting, backlight of liquid crystal display panel, and signal illuminant [10-11]. Doubtless LEDs play a much more principal role in solid stat lighting. In lighting equipments, blue nitride-based LED particularly displays the operative capabilities since it owns flexibility for white lighting whether covered by phosphor or combined with green and red LEDs.

Although the lifetime of LEDs is much longer than those of light bulbs and fluorescent lamps, output power of current LEDs is still low. Nevertheless, about environmental protection and energy crisis issues, we often met a problem how to make LED lighting maintain high output power intensity throughout long-term working in natural climate of out door. Heat is investigated to be a key point because it could incur damaged epitaxy structures, which are like defects and leakage current paths, and current crowding effects and moreover make transform electrons into photons much less effectively. The phenomena mentioned above belong to thermal effect. And in terms of the law of the conservation of energy, if more light is radiated out of LEDs, there is less heat generated in LEDs. Bettering light extraction efficiency, current spreading condition, and multi-quantum well (MQW) efficiency are the main methods to enhance lightness. And ability for conducting heat is also essential equally to LEDs. It's because heat won't be stored in LEDs if it is conducted out successfully. Thus the temperature of LEDs should be decreased to avoid thermal effect occurring.

As integrating the solutions, flip-chip (FC) technology is worth implementing to simultaneously achieve the purposes owing to less light blocking effects (bonding pads or wires exist on top of the devices), more escape cone phenomena, higher thermal conductivity (around 140 W/m-K) of Si sub-mount as compared to that (around 35 W/m-K) of sapphire, and shorter thermal paths [12-16]. However, the refractive indexes of sapphire substrate and air are 1.7 and 1.0 so total reflection and refraction phenomena often happen in the flat sapphire/air interface for FC LEDs to lower output intensities. And in out-door, ESD, which surges a very high voltage generated from everywhere possible will impair LEDs and FC LEDs momentarily. Because LEDs and FC LEDs are usually produced on insulating-natured sapphire substrates and sub-mounts individually, LEDs and FC LEDs could not alone resist ESD effectively. Therefore ESD damage is indeed an issue to FC LEDs.

2. Organization of dissertation

In this thesis, several primary issues for investigating GaN based FC LEDs with improved performance, which are (a) Low operation voltage FC LEDs, (b) High brightness FC LEDs, (c) High reliable FC LEDs, and (d) FC LEDs with electrostatic discharge (ESD) protection, are going to be listed as below and shown in Figure 1:

(1) Low operation voltage FC LEDs

For flip-chip LEDs, it is also important to deposit a reflective metal layer at the bottom to reflect the down emitting photons. However, the specific contact resistance is large and the adhesion is poor between commonly used high reflective metals and GaN. We, thus, need to insert a transparent ohmic layer. Since high work function metals can form good ohmic contacts on p type semiconductor in general, we deposited various high work function metals such as Ni, Pd, and Pt onto n-SPS structure on p-GaN to serve as the transparent ohmic contacts. And work functions of Ni, Pd, and Pt are all around 5.0 to 5.7 eV. And rapid thermal annealing (RTA) was then performed at various temperatures to improve electrical properties of the contacts. In order to simultaneously achieve small operation voltage and high output intensity, combining Ni with ITO as the transparent ohmic contact material of FC LEDs was also studied and realized.

(2) High brightness FC LEDs

Nitride-based flip-chip LEDs with highly reflective metal layers such as Ag, Al, Pt were demonstrated. And RTA was also performed at various temperatures to avoid reflectance decreases of the reflective mirror. Besides owing to high transmittance characteristics of ITO, FC LEDs with ITO layer were designed, too. Furthermore for enhancement of light extraction efficiency, we devise the novel process to manufacture a roughness configuration on light emitting surface, which is the backside of sapphire to extract more light in our design. The process is with non-polishing and with chemical treatment process, which is grinding the backside of wafer while thinning the wafer. But conventional process is with polishing process, which is lapping the wafer.

(3) High reliable FC LEDs

Since thermal path between the MQW active region and heat sink is much shorter for FC LEDs, most heat generated in the MQW active region could flow easily to the Si sub-mount. Therefore less luminous intensity decreases after long-time devices burning were shown in FC LEDs. And with small specific contact resistance and small forward voltage by RTA annealing process, we thus achieved much smaller EL degradation further. On the other hand, because the sub-mount of FC LED is where heat flows out of the device, the conducting ability of it should be greater. Since high thermal conductivity and fabrication feasibility are thought over, copper (Cu) was chosen further as the materials of sub-mount in FC LED. And thermal conductivity of Cu is around 394 W/m-K individually. In my study, reliability influence of Cu sub-mount for FC LEDs were also analyzed.

(4) FC LEDs with electrostatic discharge (ESD) protection

The defense ability for ESD of nitride base LEDs or FC LEDs are still poor, especially in out door. This is due to the characteristics of nitride materials, such as defects or dislocations. And because of the characteristics of p-n junction diodes in LEDs, the forward defense ability is better than the reverse defense ability. In my research silicon (Si)-based complementary metal-oxide-semiconductor (CMOS) transistor was fabricated on up side of Cu sub-mount in FC LED. And the other technologies for ESD protection, like p-n junction diodes were individually fabricated in LED chips and sub-mounts were also investigated and compared.

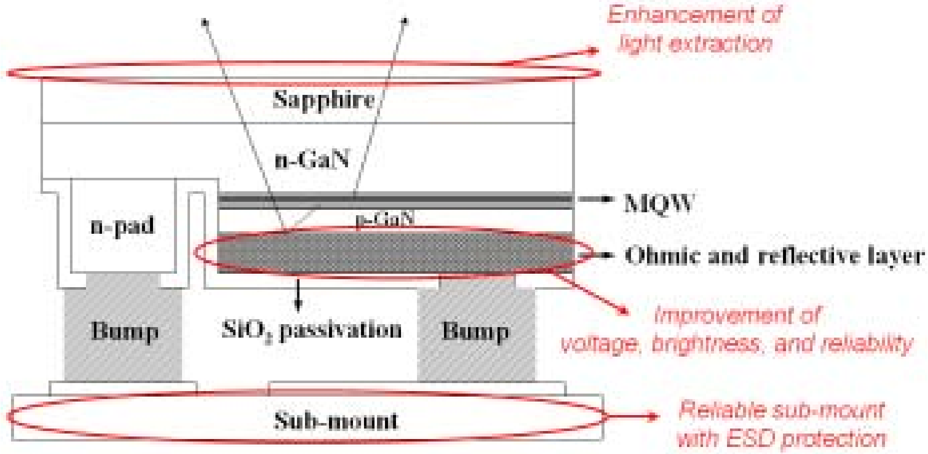


Figure 1 Investigation about GaN based FC LEDs.

II. Literature Review

1. Energy Band Gap of III-Nitride Semiconductor

Recently, Gallium Nitride (GaN) and its related ternary compounds have attracted much attention. These compound materials exhibit direct and wide band gap, high thermal conductivity, and high saturation velocity. At room temperature, energy band gap of AlInGaN varies from 0.8 to 6.2 eV depending on its composition. These properties make nitride-based materials attractive for short wavelength emitters. Indeed, nitride-based blue and green light-emitting diodes (LEDs) are already extensively used in traffic light lamps and full-color displays.

2. P-Contacts of Blue LEDs

Conventional nitride-based blue LEDs used semitransparent Ni/Au on p-GaN as the upper contacts. However, transmittance of Ni/Au is only around 55%–75%. We, thus, need to further increase output power of III-N LEDs for these applications. For top emitting III-N LEDs with indium–tin–oxide (ITO) upper contacts, it was found that specific contact resistance between ITO and p-GaN is larger. As a result, operation voltage is higher with relatively poor reliability for the ITO LEDs in general. Previously, it has been shown that such a problem can be solved by combining the n^+-InGaN/GaN short-period-superlattice (SPS) structure on p-GaN with ITO transparent upper contact.

3. The Dimensions of LED chips

In addition it deserves to be mentioned the penetration rate of lighting in outdoor areas, like street lighting, path lighting, tunnel lighting, parking lot lighting, garden lighting, and architectural lighting, is rising very much in recent years. By the way the lighting usually requires 1-W, 3-W, 5-W, and even 10-W input power hence enlarging chip size is a practicable way to fit in with the specification for packaging modules.

III. Fabrication

1. Metalorganic chemical vapor deposition system

Metalorganic chemical vapor deposition (MOCVD) has become a commonly used technology for production of III-V compound semiconductor optoelectronic devices and electronic devices. The achievement of growing ultra-bright blue light emitting diodes by MOCVD makes this technology be a leading candidate for manufacturing optoelectronics devices. The choice of sapphire substrate resulted from the facts that no bulk GaN substrates are available and a very stable material is required to deal with the high temperature required for GaN growth (around 1000^{o}C). Metalorganic group III sources are either liquids, such as trimethylgallium (TMGa), triethylgallimuu (TEGa), trimethylaluminum (TMAl), and triethylaluminum (TEAl), or solids such as trimethylindium (TMIn). For III-Nitride growth, ammonia (NH_3) is most commonly gaseous hydride source. Dopant materials can be metal organic precursors such as dimethylzinc (DMZn), cyclopenta-dienyl-magnesium (CP_2Mg), and hydrides of silane (SiH_4) or disilance (Si_2H_6).

Basically, the GaN epitaxy process by using MOCVD can be written:

$Ga(CH_3)_3(v) + NH_3(v) \rightarrow GaN(s) + 3CH_4(v)$

Where *v* is vapor and *s* is solid.

InGaN/GaN multi-quantum well (MQW) LED samples used in my investigation were grown by MOCVD on (0001) sapphire substrates. During the growth, trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) were used as the source materials of In, Ga, Al, and N, respectively. Bicyclopentadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p-type and n-type doping sources, individually. The LED structure consists a 30-nm-thick low-temperature GaN nucleation layer, a 2-µm-thick Si-doped n-GaN buffer layer, an InGaN/GaN MQW active region, a 50-nm-thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ layer cladding layer, a 0.25-µm-thick Mg-doped p-GaN layer and a Si-doped n^+-SPS tunnel contact structure. The un-doped InGaN/GaN MQW active region consists 5 periods of 3-nm-thick $In_{0.23}Ga_{0.77}N$ well layers and 7-nm-thick GaN barrier layers. On the other hand, n^+-SPS tunnel contact structure consists of 4 pairs of Si-doped n^+-$In_{0.23}Ga_{0.77}$/GaN (5Å/5Å) shown in Figure 2. The as-grown samples were then furnace annealed at 740^{o}C in N_2 ambient to activate Mg in the p-type layers.

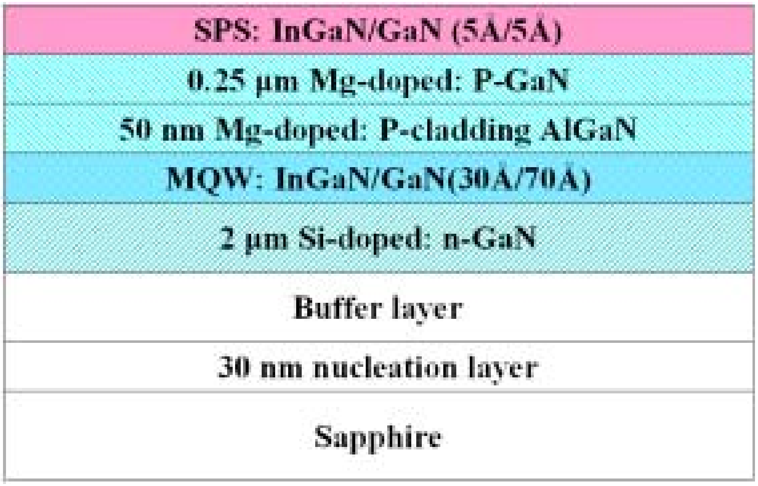


Figure 2 Epitaxy structure of nitride based FC LEDs.

2. The process flow of FC LEDs

The main process flow of FC LEDs is shown in Figure 3. While epitaxial wafers were prepared, firstly we evaporated transparent ohmic layer onto SPS structure on p-GaN by e-beam evaporator, followed by the evaporation of reflective mirror. Rapid thermal annealing (RTA) was then performed at proper temperature to improve electrical properties of the contacts. Then wafers were exposed with SiO_2, grown by plasma enhanced chemical vapor deposition (PECVD) as etching mask and we partially etched surfaces of the wafers by inductively coupled plasma (ICP) until the n-GaN layers. During the ICP dry etching, Cl_2 was used as the etching gas with flow rate 20 sccm. RF coil power and platen power were kept at 500W and 150W, individually. The chamber pressure was kept at 3m Torr. And During the SiO_2 deposition, 60 sccm SiH_4 and 20 sccm N_2O were introduced into the chamber, while the deposition temperature and the process pressure were kept at 250^{o}C and 10m Torr, individually. Ti/Al/Ti/Au contacts were subsequently deposited onto the exposed n-GaN layers to serve as the n-pad. We then deposited SiO_2 films as passivation onto the wafers by PECVD. It should be noted that step coverage of the SiO_2 films should be well controlled to cover the entire chip structure except the positions where the bumps would connect with the chips. Photolithography and HF solution wet etching were subsequently performed to define the designed-pattern for bump electroplating. Sn/Au (15 μm/5 μm) layers were then electroplated onto the wafers before the bumps were formed by lift-off process. We then thin the sapphire substrate to respectively around 110 μm and 90 μm for FC LEDs and power FC LEDs by lapping and polishing. We then used scribe and break to fabricate the 280 μm x 360 μm chips for FC LEDs and 1000 μm x 1000 μm chips for power FC LEDs individually. It should be noted the chips were then soldered onto Si sub-mount prior to packaging, shown in Figure 4, Figure 5, and Figure 6. Figure 4(a) shows photograph of the entire chip after electroplating and liftoff. As shown in this figure, the two Sn/Au bumps were well defined after liftoff. Figure 4(b) shows photograph of the LED after flip-chip. Figure 5 shows photograph of power FC. Figure 6 shows SEM photograph of FC LED from cross-section.

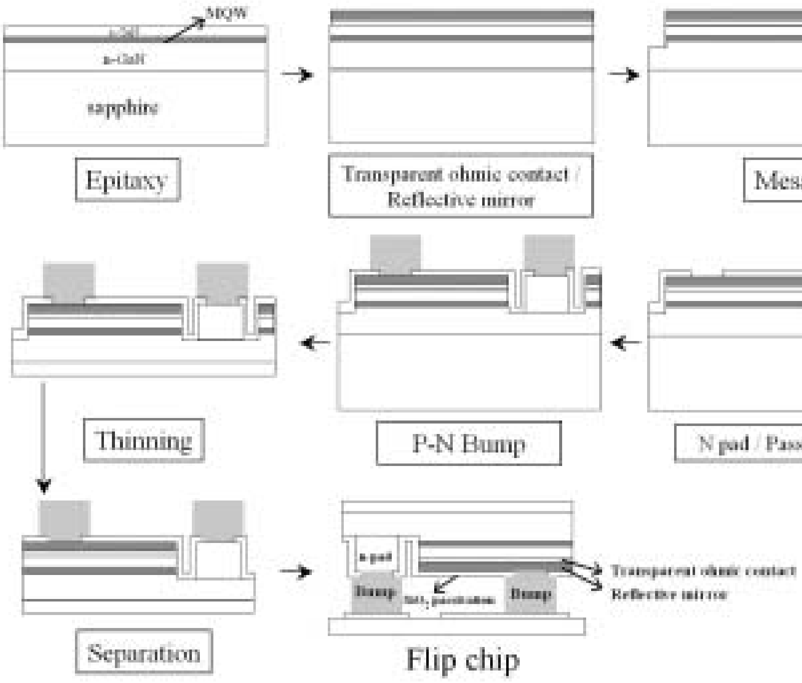


Figure 3 Process flow of FC LEDs fabrication.

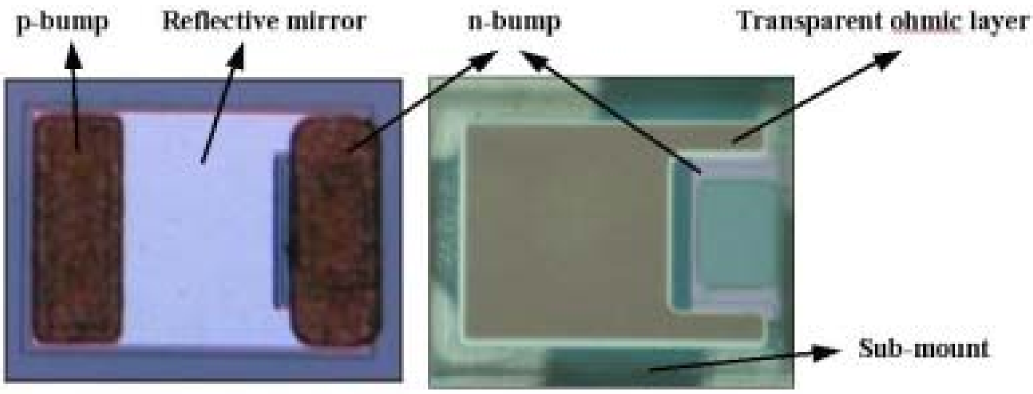


Figure 4 Photographs of the FC (280 μm x 360 μm) (a) after electroplating and lift-off, and (b) after flip-chip.

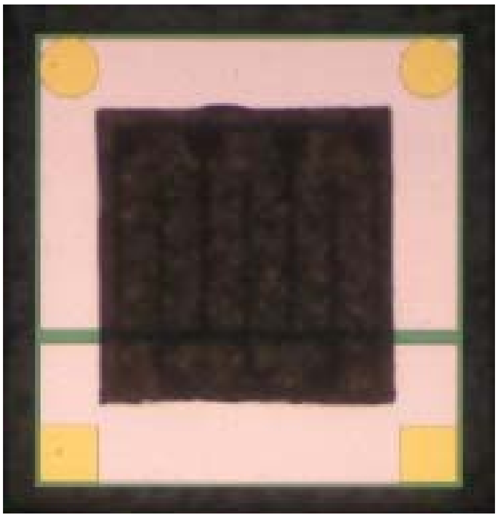


Figure 5 Photograph of the power FC (1000 μm x 1000 μm).

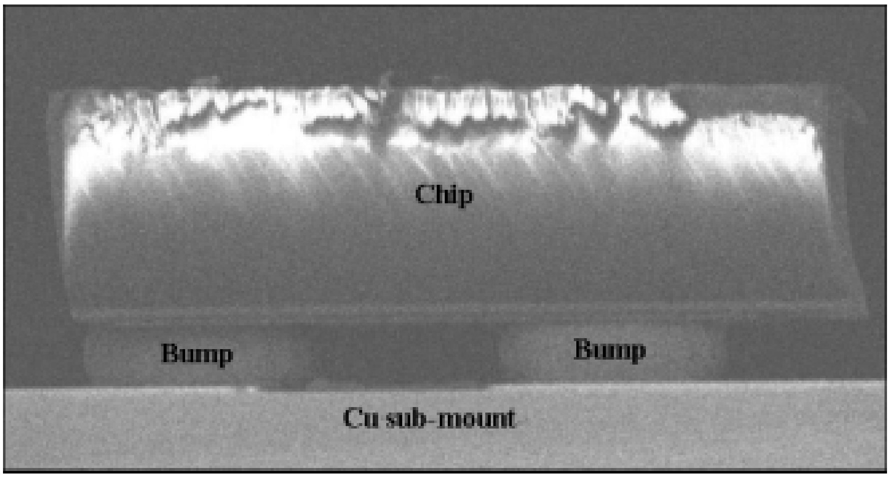


Figure 6 SEM photograph of FC LED from cross-section.

IV. Results and Analysis

1. Low Operation Voltage Nitride based Flip-Chip LEDs

(1) Electrical property of FC LEDs with high work function transparent ohmic contacts

During FC LED process, we deposited 2.5-nm-thick Ni, Pd and Pt layers on top of the sample surface (i.e. Si-doped n^+-InGaN/GaN SPS structure on p-GaN) to serve as transparent contacts. We also deposited 200-nm-thick reflectance metals (Ag, Al, and Pt) onto the transparent contacts to served as the reflective mirror layers. After metal deposition, we also treated the samples at 300^{o}C for 35 seconds with rapid thermal annealing. For comparison of electrical characteristics, flip-chip (FC) LEDs, non-flip-chip (NFC) ITO and NFC Ni/Au LEDs were also fabricated with exactly the same epitaxial structure and the same chip size (280 μm x 360 μm). Finally current-voltage (I-V) measurements of the fabricated LEDs were then performed at room temperature. We also measured performances of flip-chip LEDs with Ni transparent ohmic contact and Ag, Al, and Pt reflective mirrors.

Figure 7 depicts measured I-V characteristics of these flip-chip LEDs and non-flip-chip LEDs. Since the PECVD SiO_2 passivation layer was grown at 250^{o}C, slight interfacial mixing might have occurred in the n^+-SPS structure on p-GaN. We believe such interfacial mixing could result in larger specific contact resistances and larger operation voltage voltages of the flip-chip LEDs. On the other hand, the large operation voltage observed from NFC LEDs (ITO) should be attributed to the larger contact resistance between ITO and the epitaxial surface [15, 28]. Among the three flip-chip LEDs, operation voltage of FC LEDs (Ni+Al) was slightly larger due to the larger specific contact resistance between Ni+Al and n^+-SPS structure on p-GaN.

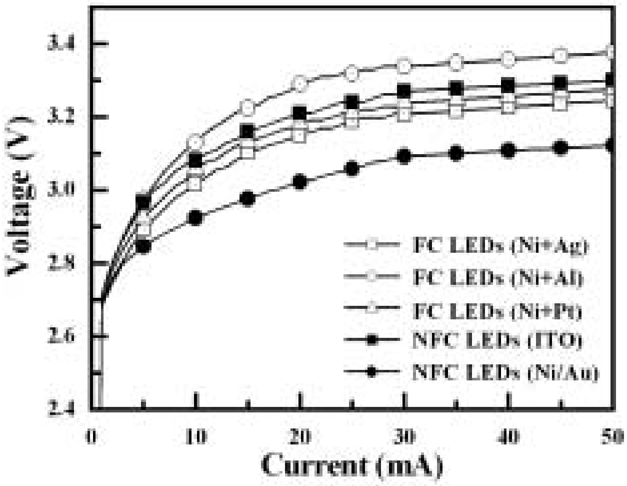


Figure 7 Measured I-V characteristics of the FC LEDs with Ni+Ag, Ni+Al, and Ni+Pt materials and NFC LEDs with ITO and Ni/Au p-contacts.

(2) Electrical property of rapid thermal annealed FC LEDs

In this section, we subsequently evaporated Ni with various thicknesses onto the samples followed by the evaporation of Ag reflective mirrors. Rapid thermal annealing (RTA) was then performed at various temperatures (350°C, 300°C, and 250°C) for 35 seconds to improve electrical properties of the contacts. Circular transmission line model (CTLM) was then used to determine specific contact resistances of the deposited contacts. Standard photolithography process was used to define circular patterns. Transmittance properties of the contacts are also important for practical device applications. For comparison, non-flip-chip (ITO) and NFC (Ni/Au) LEDs were also fabricated with exactly the same epitaxial structure and the same chip size (280 μm x 360 μm). Current-voltage (I-V) measurements of the fabricated LEDs were then performed at room temperature. We also measured the performances of FC LEDs with Ni transparent ohmic contact and Ag (200nm) reflective mirrors annealed at 350°C, 300°C, 250°C, and without RTA.

Figure 8 depicts measured I-V characteristics of these FC LEDs. For comparison, I-V characteristics of NFC LEDs with ITO and Ni/Au upper contacts were also shown in the same figure. It was found that forward voltages of FC LEDs were all higher than that of the LED with the Ni/Au p-contact.

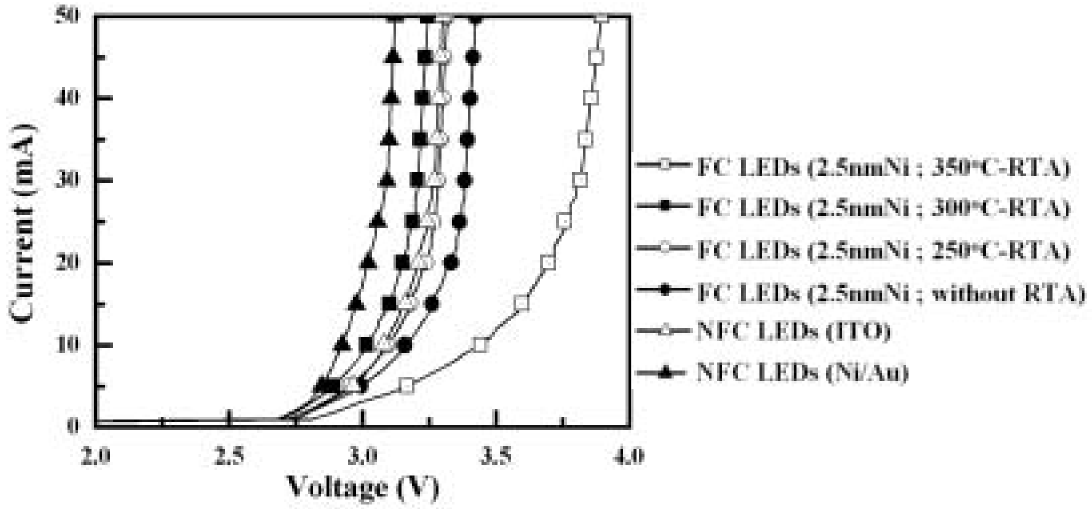


Figure 8 Measured I-V characteristics of FC LEDs at various RTA temperatures and NFC LEDs with ITO and Ni/Au p-contacts.

(3) Electrical property of FC LEDs with ITO / Ni transparent ohmic contacts

In the final part of studying low operation voltage, we subsequently evaporated ITO with various thicknesses onto the samples, followed by the evaporation of a 1-nm-thick Ni interlayer. Rapid thermal annealing (RTA) was then performed at 200^{o}C, 300^{o}C, and 400^{o}C for 35 seconds to improve electrical properties of the contacts. We then used circular transmission line model (CTLM) to determine specific contact resistances of the deposited ITO/Ni(1 nm) layers. Optical properties of the contacts are also important for practical device applications. In order to determine the transmittance of ITO/Ni (1nm), we also deposited these materials onto glass substrates. We then used a Hitachi U3010 spectrophotometer to measure the transmittance and reflectance of these films. For comparison, FC LEDs with ITO transparent ohmic contacts and without the Ni inter layers, FC LEDs with Ni transparent ohmic contacts, NFC ITO LEDs, and NFC Ni/Au LEDs were also fabricated with exactly the same epitaxial structure and the same chip size (280 μm x 360 μm). Current–voltage (I-V) measurements of the fabricated FC LEDs and NFC

LEDs were then performed at room temperature.

Figure 9 shows measured I–V characteristics of the fabricated LEDs. These values indicate that Ni-containing p-contacts can indeed provide lower contact resistances and thus smaller operation voltages for nitride-based LEDs.

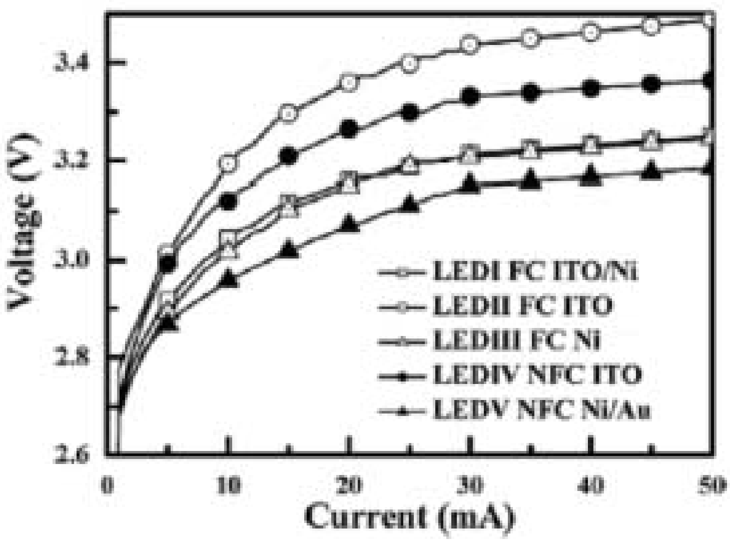


Figure 9 Measured I-V characteristics of the fabricated FC LEDs with ITO/Ni, ITO, and Ni transparent ohmic contacts and NFC LEDs with ITO and Ni/Au p-contacts.

It can be seen clearly that FC LED with ITO/Ni/Ag and Ni/Ag transparent ohmic contact and reflective mirror proposed in this study should be more suitable for applications such as solid state lighting and backlight of LCD panels which simultaneously require high reliability and low operation voltage.

2. High Brightness Nitride based Flip-Chip Light-Emitting-Diodes

(1) Characteristics of FC LEDs with high reflectance mirrors

During FC LED process, we deposited 2000-Å-thick Ag, Al, Pt onto the transparent ohmic contacts of 2.5-nm-thick Ni to served as the reflective mirror layers. Figure 10 shows intensity-current (L-I) characteristics of the flip-chip LEDs and non-flip-chip LEDs. It was found that output power of the non-flip-chip ITO LED was larger than that of the non-flip-chip Ni/Au LED. This is due to the fact that ITO is more transparent than Ni/Au. It was also found that output powers of the flip-chip LEDs were larger than that of the non-flip-chip LEDs. This can be attributed to the fact that no bonding pads or wires exist on top of the flip-chip LEDs. It should also be noted that the refractive indexes of sapphire substrate and GaN are 1.7 and 2.5, respectively. Thus, photons generated in the LEDs should be able to find the escape cone easier from the sapphire/air interface (i.e. flip-chip LEDs), as compared to the GaN/air interface (i.e. non-flip-chip LEDs). In other words, the smaller refractive index of sapphire substrate could also enhance the flip-chip LED output intensity. Overall, these results of optical properties suggest that the 200-nm-thick Ag should be good enough to serve as reflective mirror.

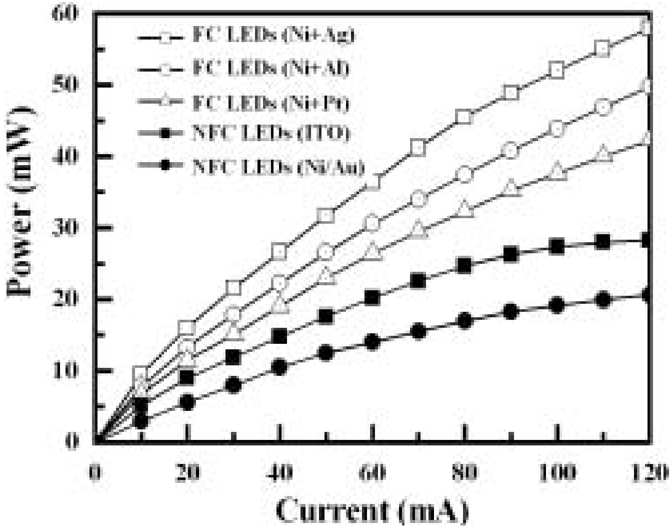


Figure 10 L-I characteristics of the FC LEDs with Ni+Ag, Ni+Al, and Ni+Pt materials and NFC LEDs with ITO and Ni/Au p-contacts.

Figure 11 shows intensity-current (L-I) characteristics of flip-chip LEDs (Ni+Ag) annealed at 350^{o}C, 300^{o}C, and 250^{o}C, and non-flip-chip LEDs with ITO and Ni/Au p-contacts. It can be seen clearly that output powers of the four flip-chip LEDs were larger than those of the two non-flip-chip LEDs. This can be attributed to the fact that no bonding pads or wires exist on top of the FC LEDs. It should also be noted that refractive indexes of sapphire substrate and GaN are 1.7 and 2.5, respectively. Thus, photons generated in the LEDs should be able to find the escape cone easier from the sapphire/air interface (i.e. flip-chip LEDs), as compared to the GaN/air interface (i.e. non-flip-chip LEDs). In other words, the smaller refractive index of sapphire substrate could also enhance the flip-chip LEDs output intensity. Among the four FC LEDs, it was found that flip-chip LEDs (Ni+Ag) annealed at 300°C exhibits the largest output power. This can again be attributed to the highly reflective nature of the 300°C-RTA Ni (2.5 nm)/Ag (200 nm) mirror.

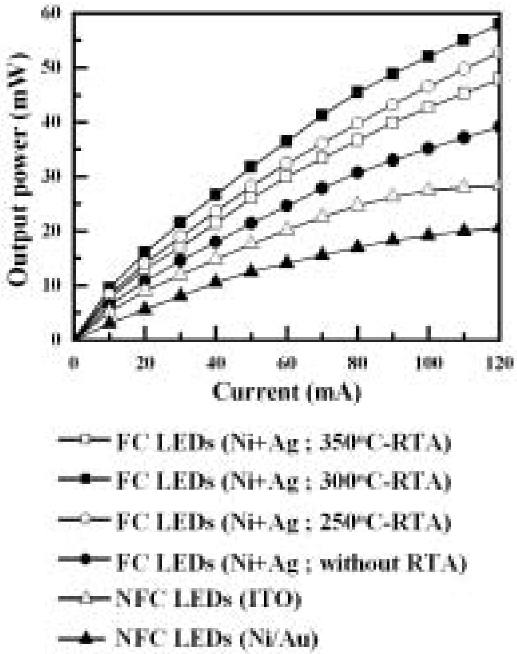


Figure 11 L-I characteristics of FC LEDs at various RTA temperatures and NFC LEDs with ITO and Ni/Au p-contacts.

Figure 12 shows measured intensity-current (L-I) characteristics of flip-chip LEDs with ITO/Ni/Ag, flip-chip LEDs with ITO/Ag, flip-chip LEDs with Ni/Ag, non-flip-chip LEDs with ITO, and non-flip-chip LEDs with Ni/Au, respectively. Flip-chip LEDs with ITO/Ni/Ag is 3.75 times brighter than the conventional non-flip-chip LEDs with Ni/Au upper contact. These values also indicate that output power of flip-chip LEDs with ITO/Ni/Ag is 47% larger than that of flip-chip LEDs with ITO/Ag. The extremely large EL intensity observed from flip-chip LEDs with ITO/Ni/Ag can again be attributed to the highly reflective nature of the 300°C-RTA ITO (15 nm)/Ni (1 nm)/Ag (200 nm) layer. It can be seen clearly that flip-chip LEDs with ITO/Ni/Ag transparent ohmic contact and reflective mirror proposed in this study should be more suitable for applications such as solid state lighting and backlight of LCD panels with high output power owing to higher lighting efficiency.

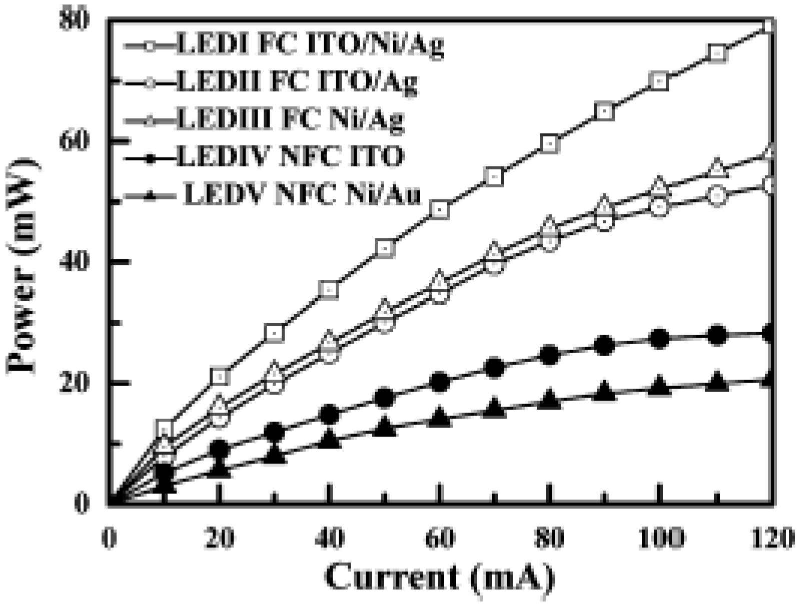
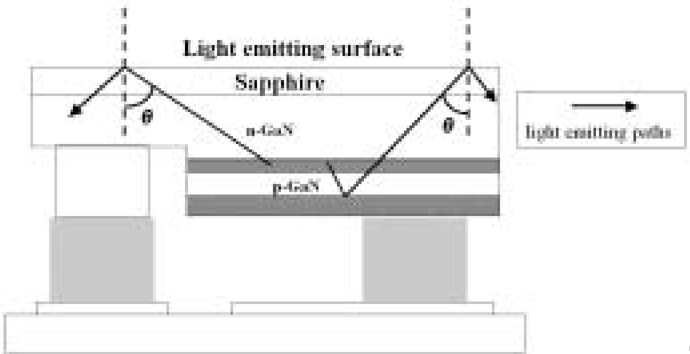


Figure 12 Measured L-I characteristics of the fabricated FC LEDs with ITO/Ni/Ag, ITO/Ag, and Ni/Ag layers and NFC LEDs with ITO and Ni/Au p-contacts.

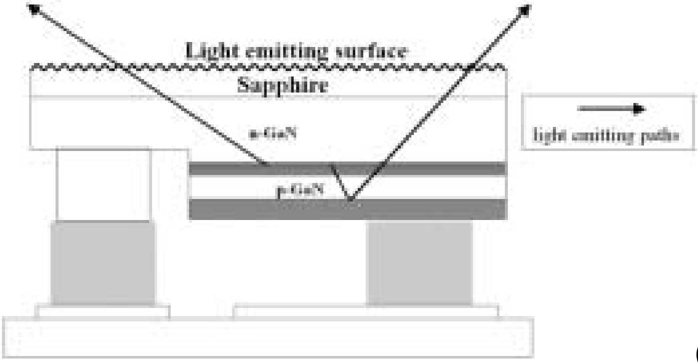
(2) Characteristics of FC LEDs with roughened sapphire backside surface

In this section, we will demonstrate the process and results about the backside roughened power flip-chip (FC) LEDs. After the process of FC LEDs until thinning wafers, we then thin the sapphire substrate to around 90 nm by a SHUWA SGM-8000 grinding system. In order to enhance roughness of the sapphire backside surface, we can increase the rotation rate of the grinding wheel. However, a high rotation rate could break the sapphire substrates easily. We thus controlled rotation speed of the grinding wheel at 900 rpm so as to achieve a grinding speed of 4 μm/min. It should be noted that no polishing was performed after grinding. The samples were chemically treated in H_2SO_4 at 50°C for 90 seconds to remove the remaining contaminant. For comparison, we also used conventional lapping and polishing to prepare FC power LEDs with flat backside surface. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to evaluate morphology of the roughened sapphire backside surface. We then used scribe and break processes to fabricate the 1000 μm x 1000 μm power LED chips. The LED chips were then soldered onto Si sub-mount. For comparison, we also prepared power non-flip-chip (NFC) LEDs with ITO contact and Al backside reflector [48] with exactly the same epitaxial structure and the same chip size (1000 μm x 1000 μm). These chips were then encapsulated with epoxy and packaged into TO cans. Electroluminescence (EL) spectra of these devices were evaluated by injecting 350-mA DC current into the devices. Intensity-current (L-I) characteristics of the packaged devices were measured using the molded LEDs with the integrated sphere detector. To evaluate reliability of these devices and prove roughened sapphire backside surface would not influence the reliability, we attached the packaged LEDs onto a 7 cm x 7 cm board with normal metal heat sink. Burn-in tests of these devices were then performed by measuring their respective EL decays. To show that our results are reproducible, we prepared five 2-inch wafers each for the three different kinds of samples, and randomly picked five chips from each wafer. In other words, the reliability test results shown in the following sections are the average values observed from 25 devices each for the three different kinds of LEDs.

Firstly Figure 13 (a) and 13 (b) show schematic diagrams of power FC LEDs with roughened sapphire backside surface and power FC LEDs with flat sapphire backside surface, respectively.



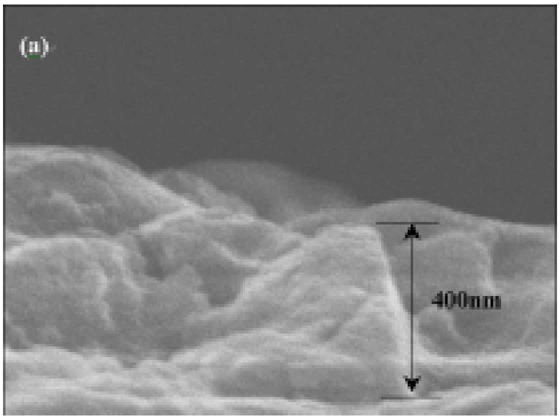
(a)



(b)

Figure 13 Schematics of light emitting paths in flip-chip LEDs with (a) flat sapphire surface and (b) roughened sapphire surface.

And Figure 14(a) and 14(b) shows top-view SEM micrographs of power FC LEDs with roughened sapphire backside surface and flat sapphire backside surface, respectively. Without polishing, it can be seen that numerous rough features exist on the surface of power FC LEDs with roughened sapphire backside surface prepared by grinding. It can also be seen clearly that surface of FC LEDs with roughened sapphire backside surface was rough with a typical peak-to-valley distance of around 400 nm. As shown in Figure 4-13(b), it was found that surface of power FC LEDs with flat sapphire backside surface prepared by lapping/polishing was much smoother with a typical peak-to-valley distance less than 2 nm. We also found that power FC LEDs with flat sapphire backside surface was transparent under optical microscope.



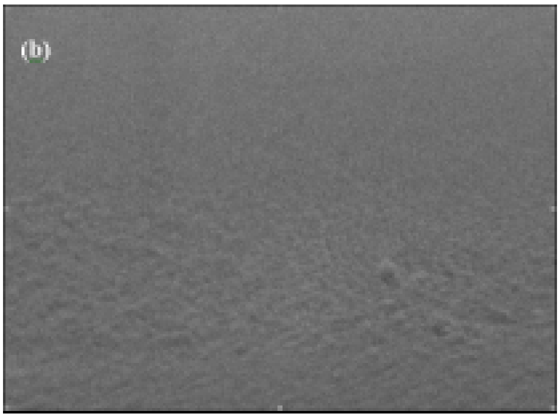


Figure 14 Top-view SEM micrographs of (a) power FC LEDs with rough sapphire backside surface and (b) power FC LEDs with conventional and flat sapphire backside surface.

Figure 15(a), (b), and (c) show height profile, plan-view AFM image, and perspective-view AFM image, respectively, measured from the surface of power FC LEDs with roughened sapphire backside surface prepared by grinding. It can be seen clearly that surface of power FC LEDs with roughened sapphire backside surface was very rough.

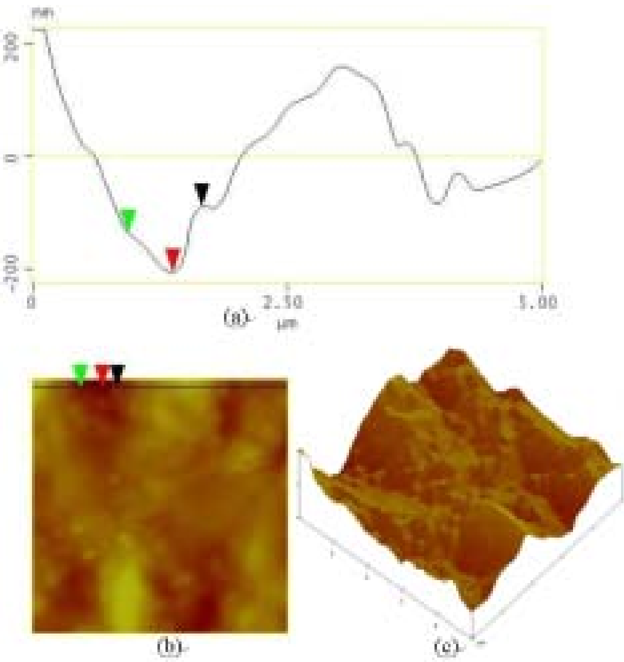


Figure 15 (a) Height profile, (b) plan-view AFM image and (c) perspective-view AFM image measured from the surface of power FC LEDs with rough sapphire backside surface.

Figure 16(a), (b), and (c) show height profile, plan-view AFM image, and perspective-view AFM image, respectively, measured from the surface of FC LEDs with flat sapphire backside surface prepared by lapping/polishing. It was found that surface of FC LEDs with flat sapphire backside surface was smooth. These results indicate that we can indeed significantly enhance the roughness of the backside sapphire substrate by grinding, as compared to conventional lapping/polishing.

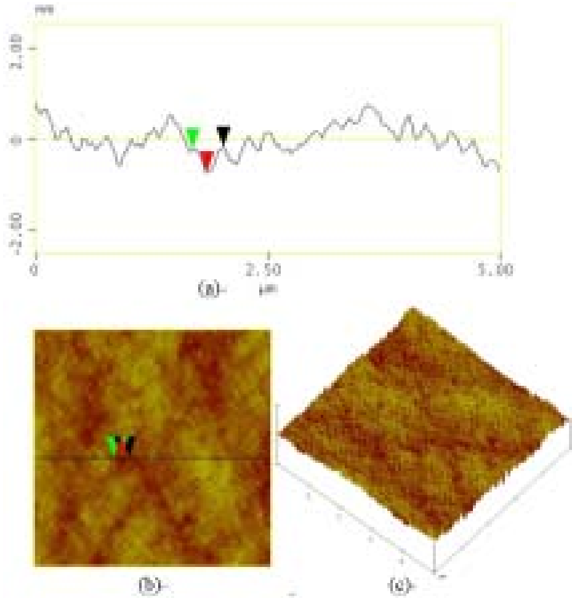


Figure 16 (a) Height profile, (b) plan-view AFM image and (c) perspective-view AFM image measured from the surface of power FC LEDs with flat sapphire backside surface.

Figure 17 shows EL spectra of these three fabricated power LEDs measured at room temperature. Under 350 mA current injection, it was found that EL peak positions of these three LEDs all occurred at around 455 nm. It was also found the full-width-half-maximum (FWHM) of these three LEDs was similar to each other. These results should be attributed to the identical epitaxial structure used in these devices. It was also found that we achieved the strongest EL intensities from FC LEDs with flat sapphire backside surface, followed by power FC LEDs with flat sapphire backside surface. On the other hand, EL intensity observed from power NFC LEDs was significantly weaker. Figure 18 shows measured output power as a function of injection current for these three LEDs. As we increased the injection currents, it was found that output powers of these three LEDs all increased first, reached a maximum and then started to decrease. Under the same injection current, it was found that output powers observed from the two power FC LEDs were larger than that observed from the power NFC LEDs, particular under high current injections. It should be noted that the maximum output intensity occurred at 1400 mA for the two power FC LEDs while occurred at 700 mA for the power NFC LED. These results should be attributed to the much better thermal property of the power FC LEDs. Under 350 mA current injection, it was found that output powers were 366.5, 271.8 and 185.1 mW for power FC LEDs with roughened sapphire backside surface, power FC LEDs with flat sapphire backside surface, and power NFC LEDs, respectively. In other words, we can increase output power of the power FC LEDs by about 35% by roughening backside surface of the sapphire substrate.

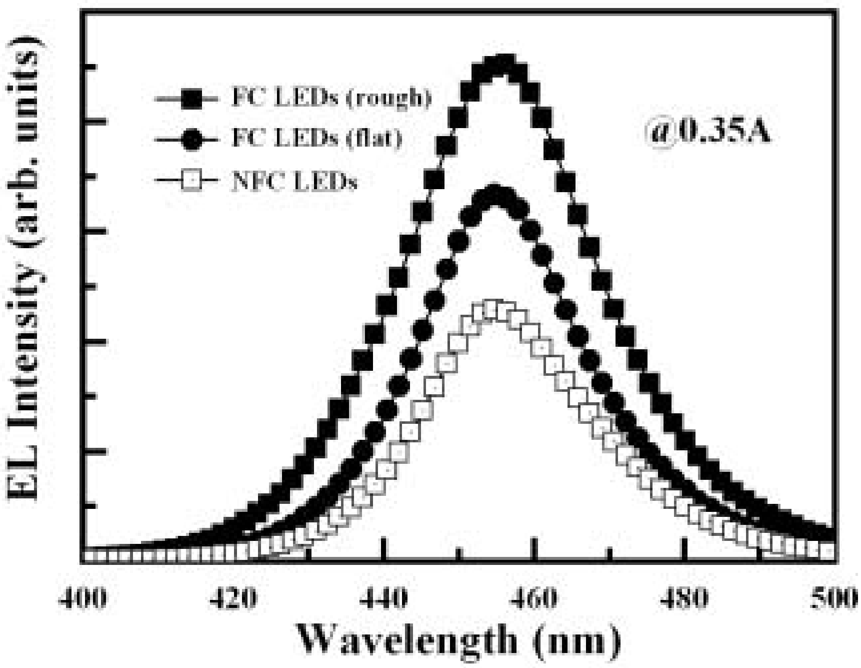


Figure 17 EL spectra of power FC LEDs with rough sapphire backside surface, power FC LEDs with conventional / flat sapphire backside surface, and power NFC LEDs measured at room temperature.

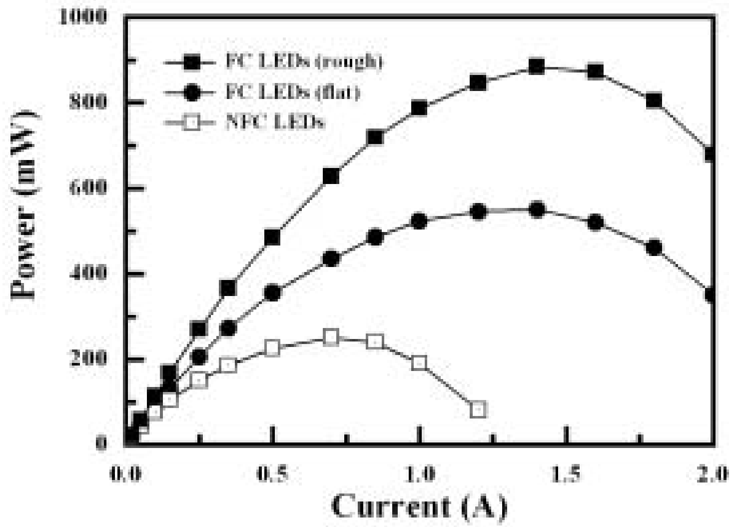


Figure 18 Measured output power as a function of injection current for power FC LEDs with rough sapphire backside surface, power FC LEDs with conventional / flat sapphire backside surface, and power NFC LEDs.

3. High Reliable Nitride based Flip-Chip ight-Emitting-Diodes

Firstly if we could lessen heat produced, thermal effect occurring in FC LEDs would become slighter. To improve electrical properties in the interface between semiconductor and metal material will lower input power directly and then transfer less output heat naturally. And it is worthy of our noting that FC LEDs possesses two advantages: higher thermal conductivity (around 140 W/m-K) of Si sub-mount as compared to that (around 35 W/m-K) of sapphire and shorter thermal paths as compared to those of NFC LEDs.

Furthermore, compared with Si, thermal conductivity of Cu (401 W/m-K) is about 2.7 times higher. If we can replace Si sub-mount with Cu sub-mount, we should be able to enhance heat flow from the device to heat sink and thus further improve the performance of GaN-based high power FC LEDs. In this chapter, we report the fabrication of GaN-based power FC LEDs with Cu sub-mount. And the characteristics of the fabricated power FC LEDs will be also discussed. Moreover fabrication feasibility of power FC LEDs with Cu sub-mount are similar to that of power FC LEDs with Si sub-mount.

(1) Advantages of FC LEDs about reliability

Figure 19 shows life tests of relative luminous intensities measured from FC LEDs with ITO/Ni/Ag, FC LEDs with ITO/Ag, FC LEDs with Ni/Ag, NFC LEDs with ITO, and NFC LEDs with Ni/Au, respectively, normalized to their respective initial readings. During life test, all five LED lamps were driven by 30-mA current injection at room temperature. After 1200 hours, it was found that luminous intensities of FC LEDs with ITO/Ni/Ag, FC LEDs with ITO/Ag, FC LEDs with Ni/Ag, NFC LEDs with ITO, and NFC LEDs with Ni/Au decreased by 5.0%, 10.0%, 4.5%, 29%, and 20%, respectively. Compared with NFC LEDs with ITO p-contact electrode, it was found that NFC LEDs with Ni/Au was more reliable. Similarly, it was found that FC LEDs with ITO/Ni/Ag layer and FC LEDs with Ni/Ag layer were more reliable than FC LEDs with ITO/Ag layer. In other words, we can improve LED reliability by incorporating a thin Ni layer. It can also be seen clearly that intensity decays of the three FC LEDs were much less significant as compared to the two NFC LEDs. We also measured junction temperatures of these LEDs. Using diode forward voltage method proposed by Xi and Schubert, we found that junction temperatures under 30-mA current injection were around 32^{o}C and 43^{o}C for the FC and NFC LEDs, respectively. This can be attributed to the fact that thermal resistance between MQW active region and heat sink is much smaller for FC LEDs. With less thermal effect, we thus achieved a longer lifetime from the FC LEDs. It should be noted that EL intensity of the FC LEDs with ITO/Ni/Ag layer only decays by 5% after 1200 hours. This value was only half of that observed from the FC LEDs with ITO/Ag layer. In other words, we can significantly improve device reliability of FC LEDs with ITO/Ag layer by inserting a thin Ni layer. The 5% decay is only slightly larger than that observed from FC LEDs with Ni/Ag layer. Thus, we can minimize heat generation and achieve longer device lifetime. Although FC LEDs with Ni/Ag layer exhibit the smallest EL intensity decay, the initial output intensity of this particular device is lower due to the lower transmittance of the thicker Ni layer.

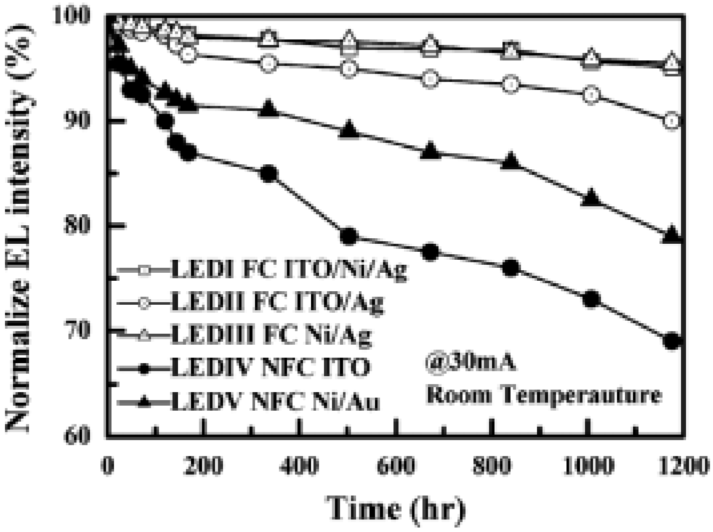


Figure 19 Life tests of relative luminous intensities measured from FC LEDs with ITO/Ni/Ag, ITO/Ag, and Ni/Ag layers and NFC LEDs with ITO and Ni/Au p-contacts, normalized to their respective initial readings.

Table 1 summaries characteristics of the fabricated devices in this section. It can be seen clearly that FC LEDs with ITO/Ni/Ag layer proposed in this study should be more suitable for applications such as solid state lighting and backlight of LCD panels which simultaneously require stable reliability, high output power, and low operation voltage.

Table 1 Characteristics of the fabricated FC LEDs with ITO/Ni/Ag, ITO/Ag, and Ni/Ag layers and NFC LEDs with ITO and Ni/Au p-contacts.

Device description	Voltage @20mA	Power @20mA	1200 hour EL decay @30mA room temperature
FC LEDI ITO (15 nm)/Ni(1 nm)/Ag(200 nm)	3.16V	21.0mW	5.0%
FC LEDII ITO(80 nm)/Ag(200 nm)	3.36V	14.3mW	10.0%
FC LEDIII Ni(2.5 nm)/Ag (200 nm)	3.15V	16.0mW	4.5%
NFC LEDIV ITO (80 nm)	3.26V	9.1mW	29.0%
NFC LEDV Ni(5 nm)/Au(10 nm)	3.07V	5.6mW	20.0%

(2) Characteristics of FC LEDs with Cu sub-mount

In this section, while we finish bump process, then we thinned the sapphire substrate to around 90 nm by backside grinding without polishing. Subsequently, the samples were chemically treated in H_2SO_4 at 50^oC for 90 seconds to remove the remaining contaminant. We subsequently used scribe and break to fabricate the 1000μmx1000μm power LED chips. These chips were then soldered onto Cu sub-mount. Figure 20 shows schematic diagram of the GaN-based power FC LEDs with Cu sub-mount. It should be noted we intentionally roughened backside surface of sapphire substrate so as to reduce total reflection at sapphire/air interface. As a result, photons can experience multiple opportunities to find the escape cone. For comparison, we also prepared power FC LEDs with Si sub-mount, and power NFC LEDs with ITO contact and Al backside reflector. It should also be noted that we prepared these LEDs with exactly the same epitaxial structure and the same chip size (1000μmx 1000 μm). These chips were then encapsulated with epoxy and packaged into TO cans. Current-voltage (I-V) characteristics of these devices were then measured by HP 4156 semiconductor parameter analyzer. Electroluminescence (EL) spectra of these LEDs were evaluated by injecting 350-mA DC current into the devices. Intensity-current (L-I) characteristics of the packaged devices were measured using the molded LEDs with the integrated sphere detector. To evaluate reliability of these devices, we attached the packaged LEDs onto a 7 cm × 7 cm board with normal metal heat sink. Burn-in tests of these devices were then performed by injecting 550-mA DC current at 55^oC and measuring their respective EL decays.

Figure 21 shows life tests of relative luminous intensity measured from these power LEDs, normalized to their respective initial readings. During life test, the three power LEDs were all driven by 550-mA DC current injection at 55^oC. It can be seen that EL intensity decreased by 4%, 24% and 55% for power FC LEDs with Cu sub-mount, power FC LEDs with Si sub-mount, and power NFC LEDs, respectively, after 5000 hours.

Compared with power NFC LEDs, the much better reliability observed from power FC LEDs should be attributed to the used FC technology, which shorten the thermal path between MQW active region and sub-mount. On the other hand, the Cu sub-mount provides a much larger thermal conductivity so that we can rapidly remove the heat generated in the device. As a result, we can achieve a better LED reliability in power FC LEDs with Cu sub-mount.

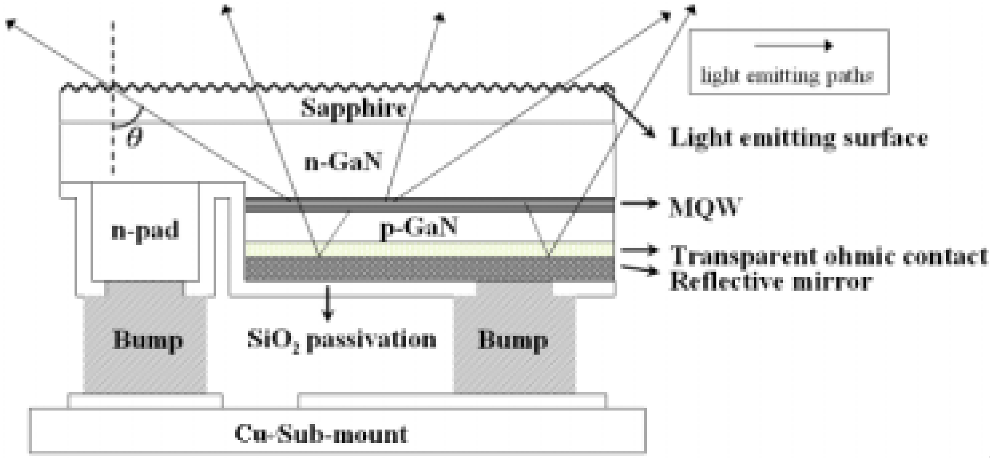


Figure 20 Schematic diagram of the GaN-based power FC LEDs with Cu sub-mount.

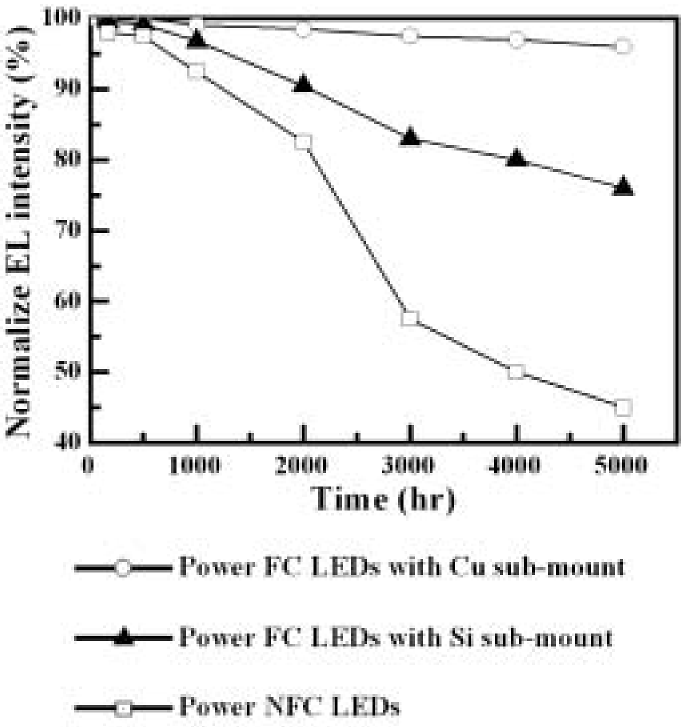


Figure 21 Life tests of relative luminous intensity measured from power FC LEDs with Cu sub-mount, power FC LEDs with Si sub-mount, and power NFC LEDs, normalized to their respective initial readings.

4. Nitride based Flip-Chip Light-Emitting-Diodes with Electrostatic Discharge Protection

Because LEDs are usually produced on insulating-natured sapphire substrates, LEDs could not alone resist ESD effectively. When ESD originated either from human body or machine contacted GaN-based LEDs, surge voltage could destroy the devices instantaneously. Therefore ESD damage is indeed an issue to LEDs. Since ESD protection was thought over, in this chapter silicon (Si)-based complementary metal-oxide-semiconductor (CMOS) transistor was fabricated on up side of copper (Cu), thermal conductivities of which is around 394 W/m-K, sub-mount in power FC LEDs. And wafer-bonding technology was applied for binding the Si-substrate and Cu-substrate in the study. In this investigation, the other technologies for ESD protection, like P-N junction diodes are individually fabricated in LED chips and sub-mounts are also investigated and compared and electro-optical features are going to be analyzed and reported as well as the devices are produced and measured.

In this section, samples used in this section were all grown by metalorganic chemical vapor deposition on c-face 2-inch sapphire (Al_2O_3) (0001) substrates. Details of the other growth flows can be found in section 2.1. While wafer samples were prepared, we partially etched surfaces of the wafers until the n-GaN layers were exposed. Then we subsequently evaporated ITO with 15-nm thickness onto p-GaN with SPS structure, followed by the evaporation of a 1-nm-thick Ni interlayer. And an ITO/Ni layer was used as a transparent ohmic contact. A 200-nm-thick Ag layer was then deposited to serve as the reflective mirror. Rapid thermal annealing (RTA) was then performed at 300^{o}C for 35 seconds to improve electrical properties of the p-contacts. Details of the other processes can be found in section 2.2. For the backside roughened FC LEDs, we then thin the sapphire substrate to around 90 um by a SHUWA SGM-8000 grinding system. To enhance roughness of the sapphire backside surface, we can increase the rotation rate of the grinding wheel. However, a high rotation rate could break the sapphire substrates easily. We thus controlled rotation speed of the grinding wheel at 900 rpm so as to achieve a grinding speed of 4 μm/min. It should be noted that no polishing was performed after grinding. The samples were chemically treated in H_2SO_4 at 50^oC for 90 seconds to remove the remaining contaminant. We then broke all wafers into individual 1000 × 1000-μm chip. On the other hand, Si-based CMOS transistor was fabricated on Si substrates. Details of the design can be found in the thesis, which we have studied and reported. We then thinned the Si substrate to around 90 um. And we used In/Au materials as bonding layer to bond the Si substrate and Cu substrate together. At last we selected the chips to be soldered onto Cu sub-mounts with Si-based CMOS transistor as flip-chips. For comparison, chips soldered onto Cu sub-mount with inverse-parallel Si-based P-N junction diodes, chips with inverse-parallel GaN-based P-N junction diodes soldered onto normal Cu sub-mount, and chips soldered onto normal Cu sub-mount without ESD protection were also fabricated with exactly the same epitaxial structure and the same chip size. Figure 22, 23, and 24 show schematic diagrams of power FC LEDs with Si-based CMOS transistor on Cu sub-mount, power FC LEDs with inverse-parallel Si-based P-N junction diode on Cu sub-mount, and power FC LEDs with inverse-parallel GaN-based P-N junction diode in chip, respectively. It should be noted in Figure 6-3, although a GaN-based P-N junction diode was processed in power FC LEDs with inverse-parallel GaN-based P-N junction diode, the chip (i.e. LED part and P-N junction diode part) area was designed to be the same as those of power FC LEDs with Si-based CMOS transistor Cu sub-mount, power FC LEDs with inverse-parallel Si-based P-N junction diode Cu sub-mount, and power FC LEDs without ESD protection and it should be noted that Metal B1 and Metal B2 were connected together.

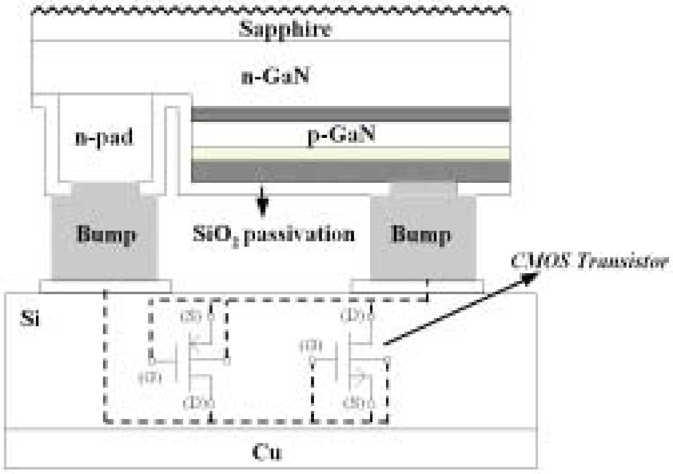


Figure 22 Schematic diagrams of power FC LEDs with Si-based CMOS transistor on Cu sub-mount.

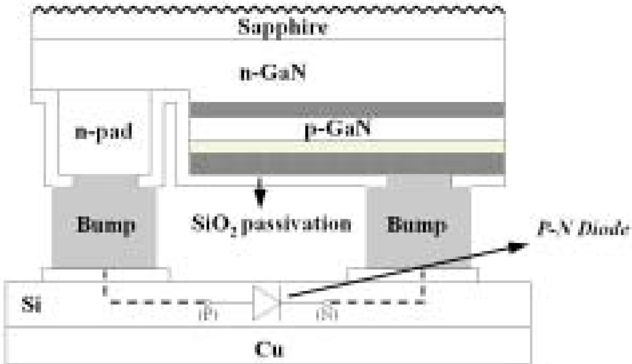


Figure 23 Schematic diagrams of power FC LEDs with inverse-parallel Si-based P-N junction diode on Cu sub-mount.

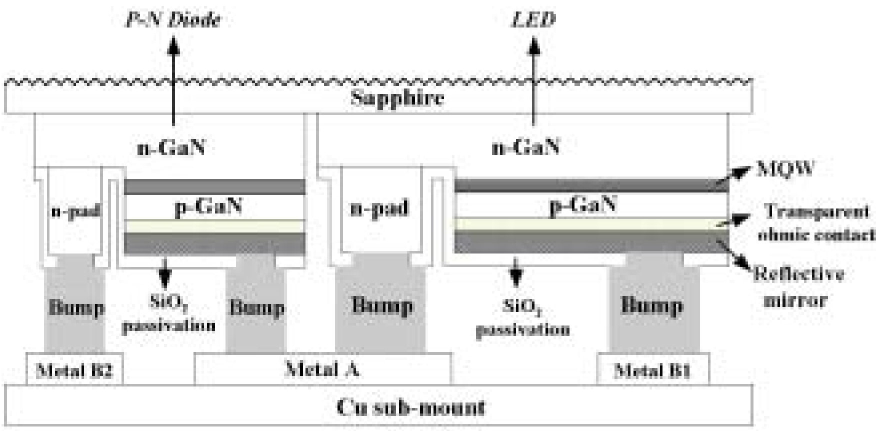


Figure 24 Schematic diagrams of power FC LEDs with inverse-parallel GaN-based P-N junction diode.

Thereupon to investigate the ESD characteristics, the LEDs were stressed by using a tester HANWA HED-T5000, simulating ESD produced by a human body. And in order to judge whether the LEDs had passed or failed, electrical characteristics of the LEDs were measured after ESD stress. If measured currents were varied by more than 25% from the values measured before ESD stress, we judged the LEDs had failed [58]. Then the LEDs were packaged onto TO cans for testing. To begin with measuring Tj, We referred to diode forward voltage method proposed by Xi and Schubert. The forward voltages of the LEDs were then performed at room temperature. The characteristics of Electroluminescence (EL) peak wavelength were also evaluated by injecting 0.35-A currents into these LEDs. The output powers were then measured using the molded LEDs with integrated sphere detector from top of the devices. Prior to the measurements of reliability, we attached the packaged LEDs onto the same 7 cm x 7cm boards with normal metal heat sinks. After that, tests of the boards were performed by injecting 550-mA DC current into these devices at 55^{o}C temperature apart. To show that our results are reproducible, we prepared five 2-inch wafers each for the four different kinds of samples, and randomly picked five chips from each wafer. In other words, the reliability test results shown in the following sections are the average values observed from 25 devices each for every kind of power FC LEDs.

Figure 25 shows ESD characteristics of the four power FC LEDs. It is shown the yields of passed LEDs after ESD stress as functions of negative ESD voltages. It was observed power FC LEDs (without ESD protection) could only endure negative ESD pulses of around 2000V and power FC LEDs with Si-based P-N diode on Cu sub-mount and power FC LEDs with GaN-based P-N diode in chip could endure negative ESD pulses of 12000V. But power FC LEDs with Si-based CMOS on Cu sub-mount could endure the ESD stresses as high as negative 18000 V. It could be attributed the Si-based CMOS transistor is like an equivalent circuit of inverse-parallel three P-N junction diodes while under negative ESD stresses. Accordingly the CMOS transistor in power FC LEDs with Si-based CMOS on Cu sub-mount possesses more current paths to endure stronger ESD stresses significantly than a P-N junction diode in power FC LEDs with Si-based P-N diode on Cu sub-mount and power FC LEDs with GaN-based P-N diode in chip possesses only a single one path.

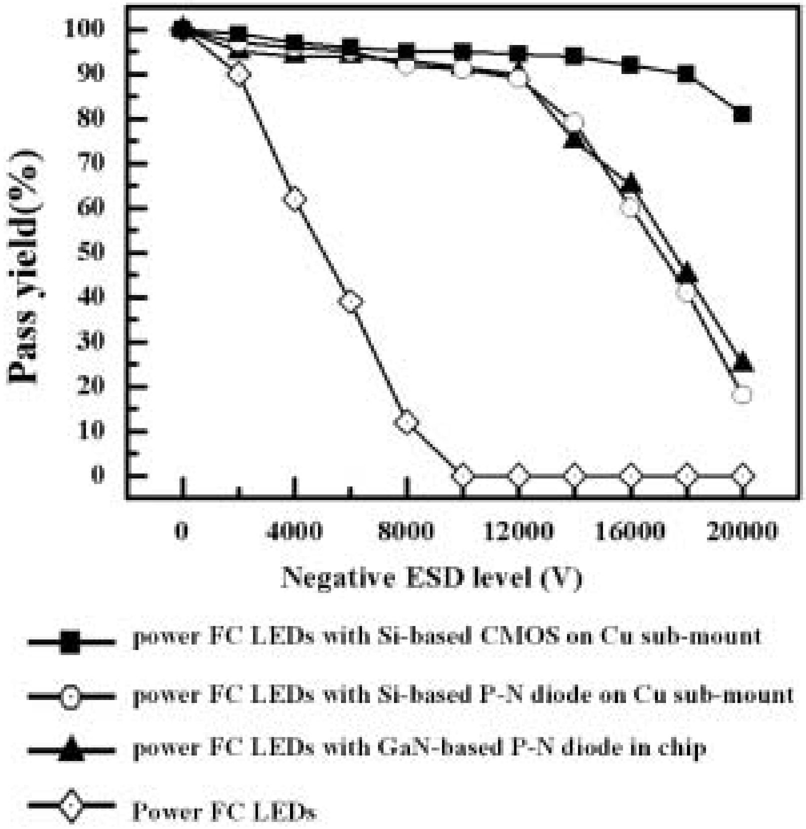


Figure 25 Yield of passed LEDs after ESD stress as a function of negative ESD voltages for these four LEDs.

In summary, It was observed that we can indeed enhance ESD resistive ability by using of Cu sub-mount with Si-based CMOS transistor.

V. Conclusion

1. GaN-based flip-chip LEDs with transparent ohmic contacts and reflective mirrors

Nitride-based flip-chip LEDs with various transparent ohmic contacts and various reflective metal layers were fabricated. It was found that nitride-based flip-chip LEDs with Ni transparent ohmic contact and Ag reflective metal layer could provide us a low operation voltage, a large output power and a long lifetime.

2. Rapid thermal annealed GaN-based flip-chip LEDs

Nitride-based FC LEDs emitting at 465 nm with Ni transparent ohmic contact layers and Ag reflective mirrors were fabricated. With an incident light wavelength of 465 nm, it was found that transmittance of normalized 300^{o}C-RTA Ni (2.5 nm) was 93% while normalized reflectance of 300^{o}C-RTA Ni (2.5 nm)/Ag (200 nm) was 92%. It was also found that 300^{o}C-RTA Ni (2.5 nm) formed good ohmic contact on n^{+}-SPS structure with specific contact resistance of $7.8\text{x}10^{-4}$ Ωcm^{2}. With 20-mA current injection, it was found that forward voltage and output power were 3.15 V and 16.2 mW for FC LED with 300^{o}C-RTA Ni (2.5 nm)/Ag(200 nm). Furthermore, it was found that reliabilities of FC LEDs were good.

3. Highly reliable high-brightness GaN-based flip-chip LEDs

Nitride-based FC LEDs emitting at 465 nm with ITO/Ni transparent ohmic contact layer and Ag reflective mirror were fabricated. With an incident light wavelength of 465 nm, it was found that normalized transmittance of the 300^{o}C-RTA ITO (15 nm)/Ni (1 nm) was 97% while normalized reflectance of the 300^{o}C-RTA ITO (15 nm)/Ni (1 nm)/Ag (200 nm) was 95%. It was also found that 300^{o}C-RTA ITO (15 nm)/Ni (1 nm) forms good ohmic contact on n^{+}-SPS structure with specific contact resistance of $7.9\text{x}10^{-4}$ Ωcm^{2}. With 20-mA current injection, it was found that forward voltage and output power were 3.16 V and 21.0 mW for FC LED with 300^{o}C-RTA ITO (15 nm)/Ni (1 nm)/Ag (200 nm). Furthermore, it was found that we could significantly improve device reliability of FC ITO LEDs by inserting a thin Ni layer.

4. High-brightness GaN-based power flip-chip LEDs

Nitride-based power FC LEDs with roughened sapphire backside surface were proposed and prepared. By grinding the sapphire backside surface without polishing, it was found that we could achieve a 200 times larger peak-to-valley distance on the backside sapphire substrate, as compared to the sample prepared by conventional lapping/polishing. It was also found that we can simultaneously enhance output power and improve device reliability by roughening sapphire backside surface of the power FC LEDs.

5. GaN-based power flip-chip LEDs with Cu sub-mount

Nitride-based power FC LEDs with Cu sub-mount were proposed and prepared. With a much higher thermal conductivity, it was found that we can achieve a lower operation voltage under high current injections and lower junction temperature from the FC LEDs with Cu sub-mount. Compared with the power FC LEDs with Si sub-mount, the reliability of the proposed device was also better.

6. GaN-based power flip-chip LEDs with an internal ESD protection CMOS on Cu sub-mount

Nitride-based power FC LEDs with internal ESD protection Cu sub-mount were proposed and realized. By fabrication Si-based CMOS transistor in Cu sub-mount, it was found that we could improve ESD characteristics from 2000V to 18000V for negative ESD stresses, as compared to conventional power FC LEDs without ESD protection. It was also observed that we can simultaneously enhance ESD resistive ability and improve reliability by using of Cu sub-mount with Si-based CMOS transistor. Moreover, the prepared LEDs were still provided with low operation voltage and enhanced output power under high current injections for solid-lighting application and the electro-optical properties of the other technologies for power FC LEDs ESD protection were also analyzed and compared.

Reference

[1] S. Nakamura, M. Senoh, N. Iwasa and S. Nagahama, "High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes", *Appl. Phys. Lett.*, Vol. 67, pp. 1868-1870 (1995).

[2] S. J. Chang, W. C. Lai, Y. K. Su, J. F. Chen, C. H. Liu and U. H.

Liaw, “InGaN/GaN multiquantum well blue and green light emitting diodes”, *IEEE J. Sel. Top. Quan. Electron.*, Vol. 8, pp. 278-283 (2002).

[3] Y. J. Lee, J. M. Hwang, T. C. Hsu, M. H. Hsieh, M. J. Jou, B. J. Lee, T. C. Lu, H. C. Kuo and S. C. Wang, “Enhancing the output power of Gain-based LEDs grown on wet-etched patterned sapphire substrates”, *IEEE Photon. Technol. Lett.*, Vol. 18, pp. 1152-1154 (2006).

[4] T. C. Wen, S. J. Chang, L. W. Wu, Y. K. Su, W. C. Lai, C. H. Kuo, C. H. Chen, J. K. Sheu and J. F. Chen, “InGaN/GaN tunnel injection blue light-emitting diodes”, *IEEE Trans. Electron. Devices.*, Vol. 49, pp. 1093–1095 (2002).

[5] L. W. Wu, S. J. Chang, T. C.Wen, Y. K. Su, W. C. Lai, C. H. Kuo, C. H. Chen and J. K. Sheu, “Influence of Si-doping on the characteristics of InGaN/GaN multiple quantum well blue light-emitting diodes”, *IEEE J. Quantum. Electron.*, Vol. 38, pp. 446–450 (2002).

[6] C. H. Kuo, S. J. Chang, Y. K. Su, J. F. Chen, L. W. Wu, J. K. Sheu, C. H. Chen and G. C. Chi, “InGaN/GaN light emitting diodes activated in O ambient”, *IEEE Electron. Device. Lett.*, Vol. 23, pp. 240–242 (2002).

[7] T. Mukai, M. Yamada and S. Nakamura, “Characteristics of InGaN-based UV/blue/green/amber/red light-emitting diodes”, *Jpn. J. Appl. Phys.*, Vol. 38, pp. 3976–3981 (1999).

[8] I. Akasaki and H. Amano, “Crystal growth and conductivity control of group III-nitride semiconductors and their applications to short wavelength light emitters”, *Jpn. J. Appl. Phys.*, Vol. 36, pp. 5393–5408 (1997).

[9] S. Nakamura, T. Mukai and M. Senoh, “Candela-class high brightness InGaN/AlGaN double hetrostructure blue light emitting diodes”, *Appl. Phys. Lett.*, Vol. 64, pp. 1687–1689 (1994).

[10] S. J. Chang, C. H. Kuo, Y. K. Su, L. W. Wu, J. K. Sheu, T. C. Wen, W. C. Lai, J. F. Chen and J. M. Tsai, “400nm InGaN/GaN and InGaN/AlGaN multiquantum well light-emitting diodes”, *IEEE J. Sel. Top. Quan. Electron.*, Vol. 8, pp. 744-748 (2002).

[11] C. F. Shih, N. C. Chen, P. H. Chang and K. S. Liu, “Effect of surface electronic states of p-type GaN on the blue-light-emitting diodes”, *J. Electrochem. Soc.*, Vol. 152, pp. G816-G818 (2005).

[12] R. H. Horng, D. S.Wuu, Y. C. Lien andW. H. Lan, “Low-resistance and high-transparency Ni/indium tin oxide ohmic contacts to p-type GaN”, *Appl. Phys. Lett.*, Vol. 79, pp. 2925–2927 (2001).

[13] Y. C. Lin, S. J. Chang, Y. K. Su, T. Y. Tsai, C. S. Chang, S. C. Shei, S. J. Hsu, C. H. Liu, U. H. Liaw, S. C. Chen, and B. R. Huang, “Nitride-based light-emitting diodes with Ni/ITO p-type ohmic contacts”, *IEEE Photon. Technol. Lett.*, Vol. 14, pp. 1668–1670 (2002).

[14] S. J. Chang, C. S. Chang, Y. K. Su, R.W. Chuang, Y. C. Lin, S. C. Shei, H. M. Lo, H. Y. Lin, and J. C. Ke, “Highly reliable nitride-based LEDs with SPS + ITO upper contacts”, *IEEE J. Quantum. Electron.*, Vol. 39, pp. 1439–1443 (2003).

[15] S. C. Shei, J. K. Sheu and C. F. Shen, “Improved reliability and ESD characteristics of flip-chip GaN-based LEDs with internal inverse-parallel protection diodes”, *IEEE Electron Device Lett.*, Vol. 28, pp. 346- 349 (2007).

[16] S. J. Chang, W. S. Chen, Y. C. Lin, C. S. Chang, T. K. Ko, Y. P. Hsu, C. F. Shen, J. M. Tsai and S. C. Shei, “Nitride-based flip-chip LEDs with transparent ohmic contacts and reflective mirrors”, *IEEE Tran. Adv. Packaging*, Vol. 29, pp. 403-408 (2006).