Vol 17 No 7, July 2008
1674-1056/2008/17(07)/2696-05

Chinese Physics B

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Reliability analysis of GaN-based light emitting diodes for solid state illumination*

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(Received 14 November 2007; revised manuscript received 25 January 2008)

In this paper, we have discussed the effect of electrical stress on GaN light emitting diode (LED). With the lapse of time, the LED with an applied large current stress can reduce its current more than without such a stress under a large forward-voltage drop. Its scanning electron microscopy (SEM) image shows that there exist several pits on the surface of the p-metal. With an electrical stress applied, the number of pits greatly increases. We also find that the degradation of GaN LED is related to the oxidized Ni/Au ohmic contact to p-GaN. The electrical activation of H-passivated Mg acceptors is described in detail. Annealing is performed in ambient air for 10 min and the differential resistances at a forward-voltage drop of 5 V are taken to evaluate the activation of the Mg acceptors. These results suggest some mechanisms of degradation responsible for these phenomena, which are described in the paper.

Keywords: GaN based LED, electrical stress, pits, annealing, mechanism of degradation
PACC: 7280E, 8170C

1. Introduction

Group III nitride based semiconductor is one of the most promising materials for optoelectronic applications such as light emitting diodes (LEDs) and laser diodes in blue and ultraviolet ranges, which can be used in full-colour displays, full-colour indicators and light sources for lamps.[1,2]

The band gap energy of $Al_xGa_{1-x-y}In_yN$ varies from 0.7 eV of InN to 6.3 eV of AlN at room temperature. Therefore, one can adjust the emitting wavelength of these group III nitride LEDs by changing the content ratio of aluminium, gallium and indium. At present, the commercial GaN based LEDs have been widely used in market. Recently, the high-power GaN based LEDs have been demonstrated by employing a flip-chip design and their fabrication process has been developed.[3] However, the reliability of the LED has not been deeply studied. So it is necessary for us to make a full study of the reliability. Our interest is focused on failure modes and mechanisms related to the semiconductor material. This paper is devoted mainly to the discussion on the possible failure mechanisms with applied samples.

2. Experiment

$In_xGa_{1-x}N$/GaN multiple quantum well LED structures were grown on c-plane sapphire substrate by metal-organic compound chemical vapour deposition (MOCVD) method. Trimethylgallium, trimethylindium, ammonia, and silane were used as the precursors of Ga, In, N, and Si, respectively. Before growing the nitride films, the substrates loaded into the reactor were thermally cleaned in hydrogen atmosphere at 1100°C for 10 min. A GaN nucleation layer with a thickness of 25 nm was grown on the cleaned substrate at 560°C, and a 2.5 μm-thick GaN:Si ($n = 2\times10^{18}$ cm^{-3}) was then grown at 1100°C. The InGaN/GaN multiple quantum well (MQW) LED structure was grown at 750°C, having a five-period InGaN(3 nm)/GaN(7 nm) quantum well structure. AlGaN cladding layer and a 0.5 μm-thick Mg-doped p-GaN ($p = 1\times10^{17}$ cm^{-3}) were grown finally at 1100°C on the top of a MQW. SiO_2 film was deposited by plasma-enhanced chemical-vapour deposition onto the epiwafer as the etch mask before inductively coupled plasma (ICP) mesa etching. ICP etching was carried out to form a mesa structure by using Cl_2/Ar discharges. Ni (5 nm-thick)/Au (5 nm-thick) bilayer for

*Project supported by the National High Technology Development Program of China (Grant No 2006AA03A108).
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p-ohmic metal was deposited by e-beam evaporation and lifted off, then alloyed at 500°C in air. Ti (30 nm-thick)/Al (70 nm-thick) bilayer for n-type contact was deposited and patterned by lift-off. Etching was performed in a planar-type ICP system, in which the ICP source operated at 13.56 MHz. Figure 1(a) shows the typical structure of the LED, which describes the samples that we used in the experiment. The top view of LED with a planar p electrode and a planar n electrode is shown in Fig.1(b).

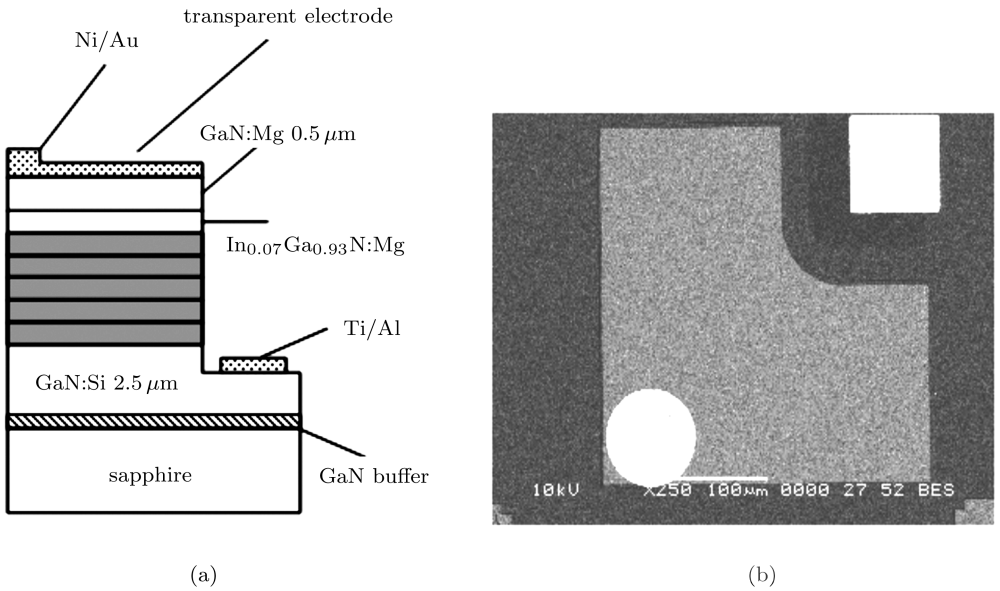


Fig.1. Typical structure of LED in which panel (a) is for the schematic side view of LED and panel (b) for the top view of SEM micrograph of LED.

3. Results and discussion

First, the sample was under the direct current (DC) aging test at 50 mA for 30000 s. The forward I–V curves for different times are plotted as described in detail in Fig.2.

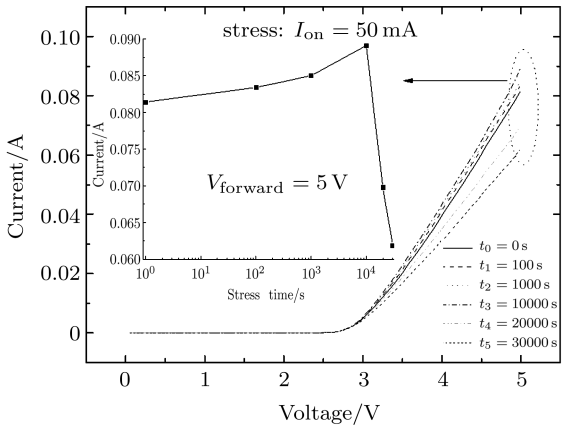
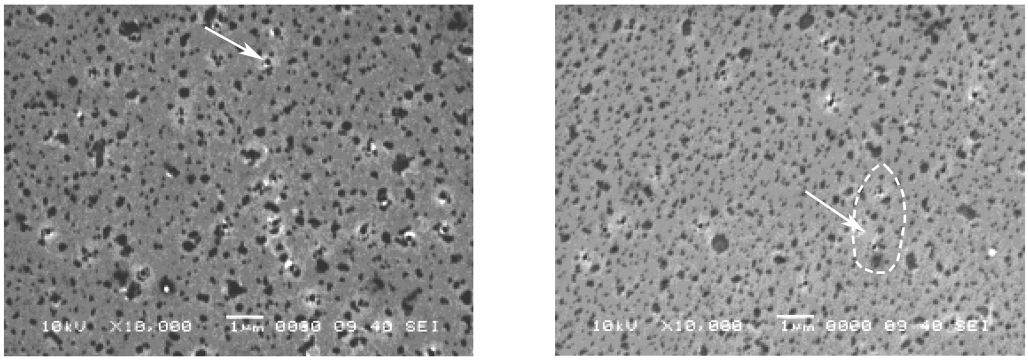


Fig.2. I–V curves of LED under DC aging test at 50 mA for different times.

In the forward region, the variations of I–V curves have the same trends at low voltages but different trends at high voltages. For 5 V, the current varies from 89.1 to 61.9 mA. Without doubt, the optical power will also be decreased. When the aging time is within 10000 s, the current increases with electrical stress. It is because the electrical stress will not arouse enough parasitic series resistance, which has a negative influence on the current. Here, the key factor that leads to an increase of current is the tunnelling current that is due to electrons tunnelling to deep levels in p-GaN, followed by nonradiative recombination, or hole tunnelling via one or more intermediate states to the MQW region, followed by nonradiative and radiative recombinations. When the aging time is longer than 20000 s, these deep levels and intermediate states are saturated and the current obviously decreases. In Fig.2, the inset shows the variation of the forward current with stress time at a forward voltage of 5 V.

Since the layer of Ni/Au is very thin, Au cannot be totally embedded in the layer of NiO. After Ni/Au has annealed in O_2, it can be seen that Au, NiO and Ni are pockety and the arrowhead points to the pit that exists on the top surface in Fig.3(a). Applying a 50 mA electrical stress to Ni/Au surface in 30000 s, we find that the pits increase on the top surface in

Fig.3(b). The number of pits is about two times more than applying no electrical stress (Fig.3(a)). Two or three pits appear in an area as shown in Fig.3(b).



(a) (b)

Fig.3. SEM image without applying a 50 mA electrical stress to Ni/Au surface (a) and with applying a 50 mA electrical stress to Ni/Au surface (b).

In the neighbourhood of the pit there exist no other pits before applying an electrical stress but two or three pits appear there after applying an electrical stress. The neighbourhood of the pit maybe is the foremost degradation region. The increasing pits maybe result from the roughness of surface of p-GaN which is influenced by the electrical stress. We can clearly see these pits on the top surface in Fig.4. With applying a long-time electrical stress, high current and temperature can affect the semi-transparent ohmic contact on the top of device and the top surface of the p-GaN layer, leading to a larger increase in series resistance, thus a decrease in current.

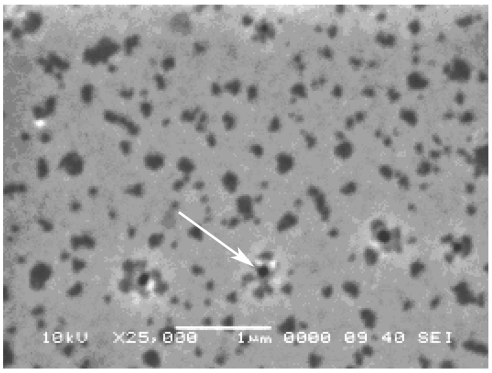


Fig.4. Magnified SEM image with applying a 50 mA electrical stress to Ni/Au surface.

Figure 5 shows a comparison between the doping densities of aged LED after applying a stress and unaged one. We find that the aged LED has a higher capacitance than unaged one. For predigestion, we take p-GaN/n-GaN as p-GaN/n^+-GaN. We can use $C_{\mathrm{T}} = \{\varepsilon q N_{\mathrm{B}}/2\,(V_{\mathrm{D}} - V)\}^{0.5}$ ($\varepsilon = \varepsilon_{\mathrm{r}}\varepsilon_{\mathrm{o}}$) for further discussion, where V_{D} is the electrostatic potential, ε is the permittivity of the semiconductor and N_{B} is doping density. The higher the N_{B} is, the higher the C_{T} will be.

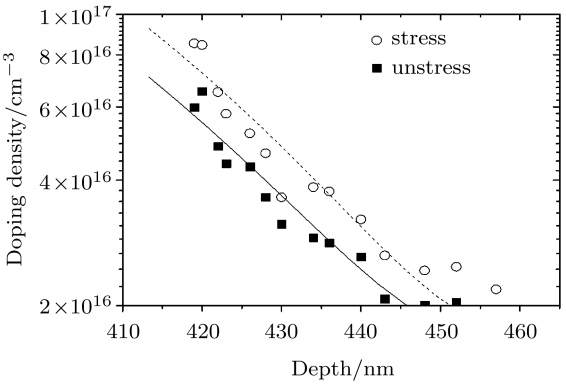


Fig.5. Doping density of the p-layer detected by C–V measurement.

Hydrogen used as a carrier gas in MOCVD is heavily incorporated into Mg-doped GaN. At H concentration greater than the acceptor density, most of the excess H is predicted to exist as interstitial molecular H_2. The MgH can be ionized into isolated Mg^- and H^+, which has little thermal dissociation at room temperature.

All annealings are performed in ambient air for 10 min and the differential resistances at a forward voltage of 5 V are taken to evaluate the activation of the Mg acceptors. Figure 6 shows the differential resistances of GaN-based LEDs, which are annealed in an open-circuit (squares) and annealed under a 5 V

forward bias (dots). For the annealing in the open-circuit, the samples have greater differential resistance even at an annealing temperature between 400°C and 600°C. For the annealing under a forward bias, the differential resistances are significantly reduced. This shows that the bias voltage during the annealing has a major role in reducing the differential resistance.

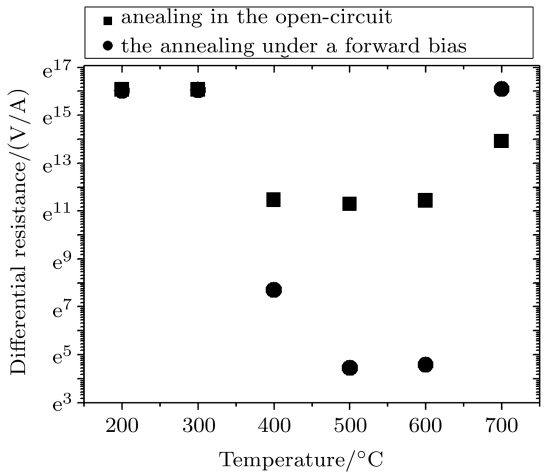


Fig.6. The differential resistance at 5 V as a function of annealing temperature under a forward bias and in an open-circuit.

In the case of thermal annealing, it is supposed that Mg activation occurs through thermal dissociation of Mg–H complexes and the removal of hydrogen.[4] Annealing by using the forward bias method suggests that minority carriers (electronic) have an effect on the dissociation of the Mg–H complexes. Therefore, this indicates that when a forward bias is applied during thermal annealing, the injected current may change the state of hydrogen into another state in which hydrogen does not passivate the Mg acceptor. In high current stresses, even if its junction temperature increases to 500°C above, the impact of electron injection on differential resistance (doping concentration) is still a main factor.

Also, we use the sample that is a chip without encapsulation and so has good heat dissipation. The test room is a super-clean room that has a good constant temperature, constant pressure and ventilation. Therefore, even when applying a large current, its junction temperature will not be too high. As can be seen from the above, we can obtain the conclusions that the decrease of differential resistance (increase of doping concentration) is mainly due to the injection of electrons.

When a forward bias is then applied to the sample, the electrostatic potential across the specimen is changed. The injected electrons are readily captured by hydrogen ion H^+ that has been thermally dissociated from MgH, producing H°. A fraction of the resulting neutral atoms react to form interstitial H_2 before hole capture can restore the ionized state, giving rise to a progressive activation of the Mg acceptors. Then, some of the H° capture second electrons to form some H^- ions, which can be combined with H^+ ions thereby forming more H_2 atoms. The dominant reaction sequence happening in p-GaN are as follows:[5]

$$\begin{aligned}
&\mathrm{MgH} \rightarrow \mathrm{Mg^-} + \mathrm{H^+} \quad \text{(thermal dissociation)},\\
&\mathrm{H^+} + \mathrm{e^-} \rightarrow \mathrm{H^o} \quad \text{(hot-electron capture)},\\
&\mathrm{H^o} + \mathrm{e^-} \rightarrow \mathrm{H^-} \quad \text{(hot-electron capture)},\\
&\mathrm{H^-} + \mathrm{H^+} \rightarrow \mathrm{H_2}.
\end{aligned}$$

At room temperature, thermal dissociation happens. It can be seen that the number of H^+ effectively decreases. Under high electrical stresses, the doping density of the p-layer increases. For n-GaN, some similar reactions also take place. With the increase of doping density of the p-layer, the depletion width further decreases. It is immediate for the thickness of active region (radiation region) to reduce. Therefore, the produced photons decrease, leading to the degradation of the optical power.

With the time of degradation increasing, the leakage becomes larger as shown in Fig.7. The leakage current is much higher than the classical diffusion current and the recombination-generated current, which should be small in magnitude in the wide band-gap materials and weakly voltage dependent. This high reverse current is attributed to defect-assisted tunnelling, or band-to-band tunnelling. At low reverse biases, field-dependent tunnelling via defects located in the space-charge region could be a major contributor. The presence of the defect structure and relatively high density of defects accords with published data.[6,7] At high reverse voltages, the data are in good agreement with those for band-to band tunnelling as predicated by Zener tunnelling model.[8]

With a 50 mA stress applied, electrons are injected to the p-GaN and some Mg–H complexes are decomposed. With the increase of the doping density of the p-layer, the depletion width becomes short and it is easy for the carries to tunnel. At low reverse biases, the influence of tunnelling current is not visible as shown in Fig.7. At high reverse voltages, the influ-

ence of tunnelling current is more and more important and leakage obviously increases as shown in Fig.7.

The inset in Fig.7 shows that the leakage current varies with aging time. With the aging time increasing, the reverse leakage current can increase in the presence of the defect structure and the relatively high density of defects which result from the DC aging test at 50 mA.

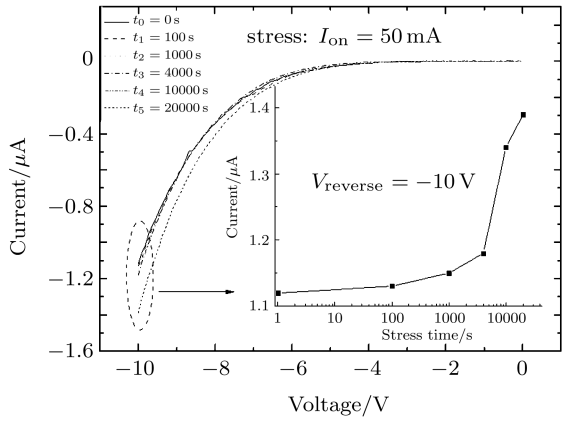


Fig.7. *I–V* curves of reverse leakage current under DC aging test at 50 mA.

4. Conclusions

From the above discussion, we can draw some conclusions that are correlated with the degradation of LEDs under an electrical stress as follows:

(1) The degradation of semi-transparent ohmic contact and the roughness of surface of p-GaN are influenced by an applied electrical stress, which causes the parasitic series resistance to increase.

(2) After applying an electrical stress, the number of pits greatly increases and the pit neighbourhood maybe is the foremost degradation region.

(3) Under high electrical stresses, the dissolution of Mg–H complexes and the increase of doping density affect the degradation of the *I–V* curve. The presence of the defect structure and relatively high density of defects maybe form conductive paths.

(4) The decrease of differential resistance (the increase of doping concentration) is mainly due to the injection of electrons.

(5) The tunnelling current makes a great contribution to the reverse leakage current of GaN based LED, especially at high reverse voltages.

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