Electrical characteristics of a vertical light emitting diode with n-type contacts on a selectively wet-etching roughened surface*

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Abstract: Low resistance and thermally stable n-type contacts to N-polar GaN are essentially important for vertical light emitting diodes (VLEDs). The electrical characteristics of VLEDs with n-type contacts on a roughened and flat N-polar surface have been compared. VLEDs with contacts deposited on a roughened surface exhibit lower leakage currents yet a higher operating voltage. Based on this, a new scheme by depositing metallization contacts on a selectively wet-etching roughened surface has been developed. Excellent electrical and optical characteristics have been achieved with this method. An aging test further confirmed its stability.

Key words: metallization contacts; wet etching; surface roughening; polarization

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1. Introduction

Recently, vertical-injection GaN-based light emitting diodes (VLEDs), which were fabricated by the removal of an insulating sapphire substrate and transferred to a new thermal and electrical conductive substrate, have been investigated extensively. They are undoubtedly considered to be the candidate for future high power and high efficiency LEDs because of their potential better thermal electrical and optical performance compared with traditional lateral light emitting diodes (LLEDS)[1−3]. Generally speaking, both n-type and p-type contacts were formed on Ga-face (0001) GaN for LLEDS. However, for VLEDS, the n-type contacts were formed on the N-face (000$\bar{1}$) GaN after a laser lift-off process. Low resistance and thermally stable n-type contacts to N-polar GaN are essentially important for VLEDS, and many reports have confirmed their degeneration after annealing. Kim *et al.*[4] attributed the degradation of Ti/Al ohmic contacts to N-polar GaN to the presence of the complex surface states of the N-polar GaN, which consists of impurities and process-induced donor-like and acceptor-like defects. Almost all of the articles reported are based on the metallization contacts formed on a flat surface, either an N-polar or a Ga-polar n-type GaN surface, prepared by conventional deposition methods, like molecular beam epitaxial, hydride vapor phase epitaxial, and metal organic chemical vapor deposition, or after some process like laser lift-off (LLO) and dry ICP etching. However, there are limited reports of the characteristics of the metallization contacts to an N-polar surface n-type GaN after surface roughening, which is an effective way to improve the extraction efficiency of light emitting diodes. Based on this, we conclude that it is very important to investigate the electrical characteristics of VLEDs with metallization contacts on a roughened surface.

In this paper, we have compared the electrical characteristics of VLEDs with the metallization contacts on a wet-etching roughened N-polar surface (R-surface) and a flat N-polar surface (F-surface) of n-type GaN. We found that the R-surface samples exhibit somewhat lower leakage currents, higher operating voltage and worse thermal stability than the F-surface samples. The different electrical characteristics are explained in terms of different Schottky barrier heights caused by different ratios of spontaneous polarization of the R-surface and F-surface. The presence of a large number of donor-like defects after the laser lift-off process, such as V_N and O_N also contributes to this. Based on the above results, we have developed a new scheme by depositing metallization contacts before wet-etching surface roughening and protection by SiO_2. Excellent electrical characteristics have been achieved by this

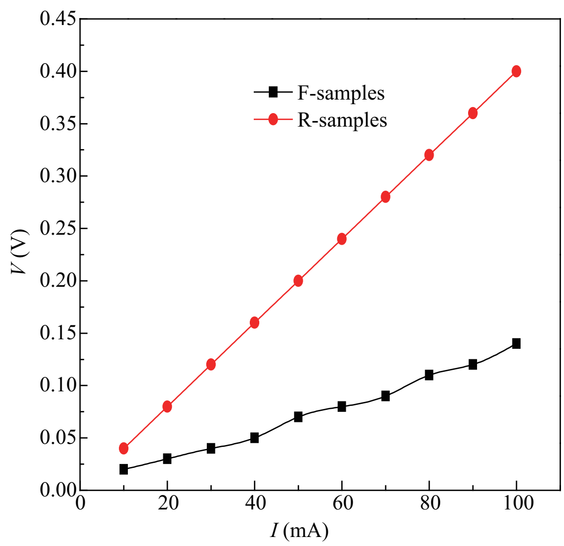

Fig. 1. I–V curves of Al/Pt/Au contacts to R-samples and F-samples. one of the transmission line patterns is shown in the inset.

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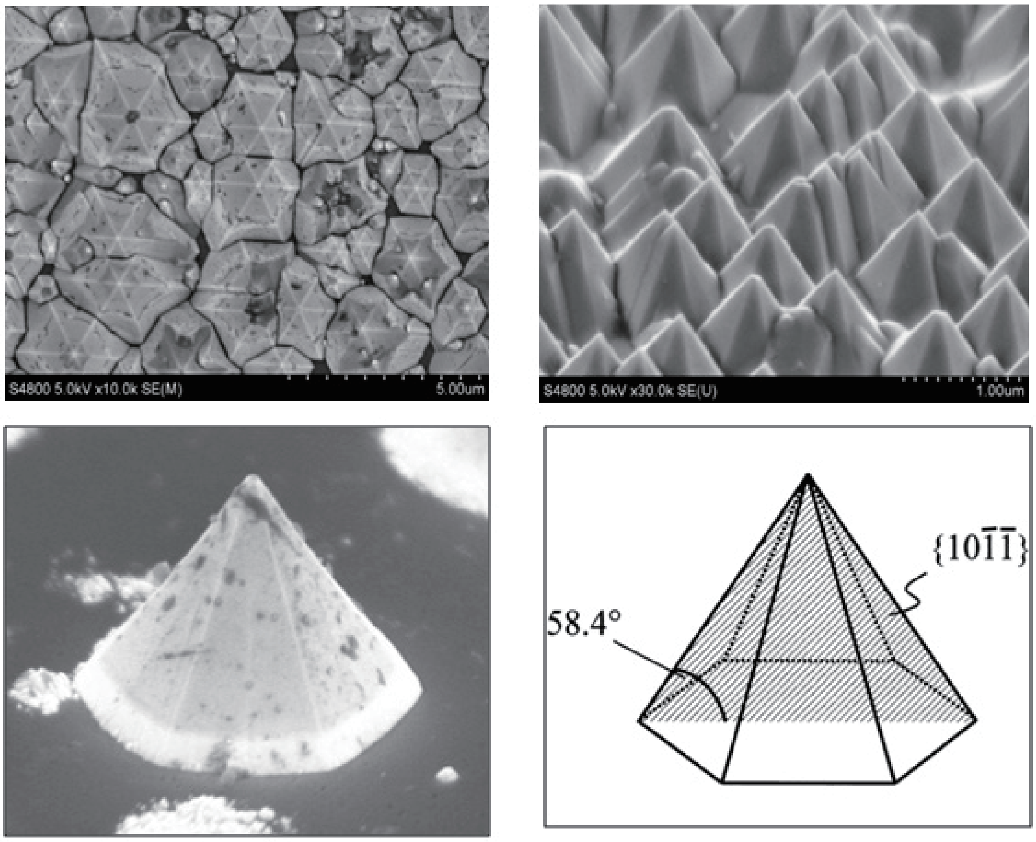

Fig. 2. SEM images of the wet-etching roughened N-polar surface of R-samples.

method, yet without degradation of the optical characteristics of the samples.

2. Experiment

A conventional GaN based epitaxial wafer was grown on a (0001) oriented sapphire substrate by the metal organic chemical vapor deposition (MOCVD) process. After the growth procedure, high reflective metallization contacts were deposited as p-contacts to the p-GaN using an e-beam evaporator. After Cu was electroplated as a new substrate, both samples underwent the LLO process using a KrF exciter laser (248 nm) to separate the sapphire substrate from the GaN layer. The residual Ga droplets on the separated GaN layer were cleared by dipping into HCl solution. After that, an ICP process was performed in order to expose the n-GaN layer. R-samples were then dipped into a hot 2M KOH solution for about 10 min, generating hexagonal cone structures on the n-GaN surface. F-samples were left undo. The N-type contacts consisting of Al (500 nm)/Ti (50 nm)/Au (500 nm) were deposited on both R-samples and F-samples.

3. Results and discussion

3.1. TLM test

We used transmission line method (TLM) patterns consisting of 100 μm^2 ohmic pads with gap spacing of 10, 20, 30, 40, 50 and 60 μm to calculate the resistivity of the contacts. As shown in Fig. 1, we found that contacts to the F-surface exhibited a lower resistivity of 1.3×10^{-6} $\Omega\cdot$cm^2 than contacts on the R-surface, with its resistivity of 2.5×10^{-6} $\Omega\cdot$cm^2. What cannot be neglected is that the contact area of the R-samples was about twice that of the F-samples, as we can see from the SEM images of the roughened surface of the R-samples in Fig. 2. This, of course, reduces the contact resistivity. However, it contradicts the above results. Jang *et al*.[5] compared the band bending on the Ga-face and the N-face GaN films, and found that the Ga-face sample exhibited a higher Schottky barrier height, which was explained by spontaneous and piezoelectric polarization. Karrer *et al*.[6], who investigated the electrical characteristics of Pt contacts to n-GaN with Ga-face and N-face polarity, found that the Schottky barrier height of N-face GaN (0.9 eV) is lower than that of Ga-face GaN (1.1 eV). As to the R-samples, the metallization contact was actually deposited on the m-plane with an angle of about 58.4° to the (000$\bar{1}$) face, as can be seen from the SEM image in Fig. 2. Referring to earlier reports, we concluded that different ratios of spontaneous polarization lead to different band bending on the R-surface and F-surface, which results in different contact resistivities. The presence of large number of donor-like defects on the F-surface, such as V_N and O_N, should also contribute to this. Detailed studies will be reported elsewhere.

3.2. Current–voltage characteristics

Figure 3 shows the I–V characteristics of vertical light emitting diodes with n-type contacts deposited on wet-etching

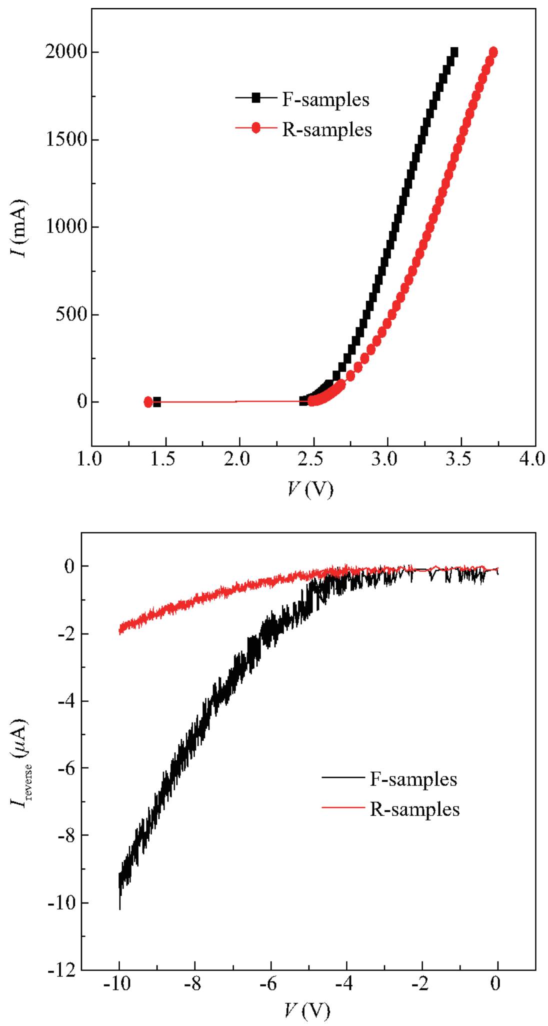

Fig. 3. I–V characteristics of vertical light emitting diodes with n-type contacts deposited on a wet-etching roughened surface (R-samples) and a flat surface (F-samples).

roughened surface samples (R-samples) and flat surface samples (F-samples). Both samples exhibited lower forward voltage compared with conventional lateral LEDs because of their better current distribution with vertical current injection geometry. However, F-samples showed an even more astonishing lower forward voltage of 2.72 V, 3.04 V and 3.44 V at a forward current of 350 mA, 1000 mA and 2000 mA, respectively, lower than the R-samples with 3.28 V at 1000 mA and 3.71 V at 2000 mA. This is of particular significance for high power LEDs. The series resistance of the F-samples and R-samples is calculated to be about 0.4 Ω and 0.43 Ω, respectively. The R-samples and F-samples experience the same process, apart from the n-type contacts being deposited on the wet-etching roughened or unroughened surface. So it is credible that the n-type contact is responsible for the difference in the operating voltage of the two samples. However, the subtraction of the n-contact resistivity does not coincide with the series resistivity of the two samples. This is due to the imprecise calculation of the area of contact and the series resistivity, and variation in the resistivity arising from generating heat.

The reverse characteristics of the two samples are depicted in Fig. 4. The R-samples exhibit superior reverse characteristics with 0.07 μA @ 5 V, and 1.8 μA @ 10 V, in contrast with the R-samples of 0.18 μA @ 5 V, and 7.69 μA @ 10 V. This can be explained in terms of surface defects after the LLO and ICP processes. As to the R-samples, the wet-etching process changed the morphology and surface state, "dissolved" the defects and exposed the new orientation surface, thus reducing the leakage current, which is considered to be dominated by a surface defect-assisted tunneling mechanism.

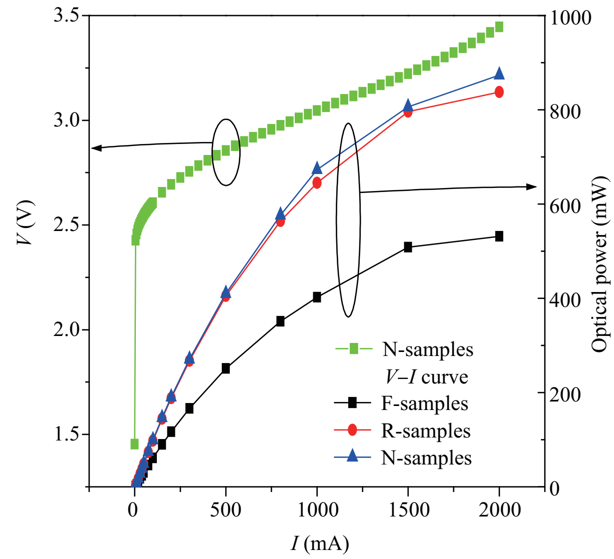

Fig. 4. Voltage and optical output of the N-samples as a function of injection current. Triangle, circle, and black square lines represent the optical output of the N-samples, R-samples and F-samples, respectively.

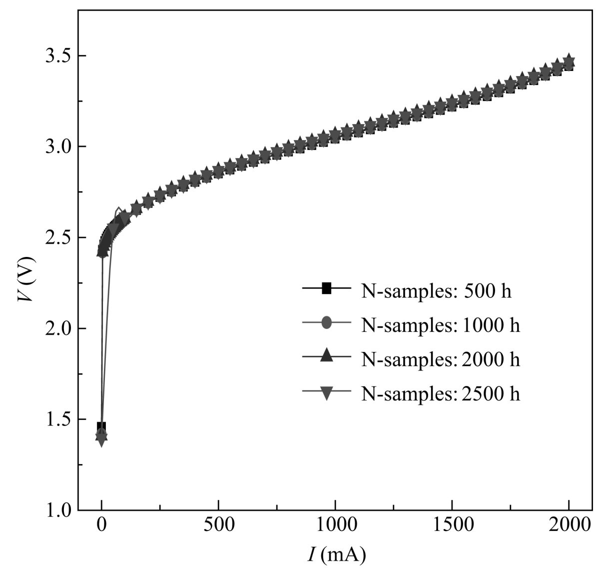

Fig. 5. I–V curves of N-samples after aging for different periods.

3.3. New scheme developed

Considering the optical output, the F-samples with a flat light emitting surface exhibit relatively low optical output compared with the R-samples with a polycone light emitting surface. It is invalid to put F-samples directly into the hot KOH solution, because the deposited metallization contact will be eroded in the solution. In order to best optimize the electrical characteristics yet with no compromise of the optical characteristics of the VLEDs, based on the above experiments, we have developed a new method with n-contacts deposited on a selectively wet-etching roughened surface. New samples (N-samples) underwent the conventional process until ICP etching. After that, a 500 nm-thick SiO_2 patterned n-type contact was deposited by a plasma-enhanced chemical vapor deposition (PECVD) method with the purpose of protecting the contact area from wet-etching roughened in the following step. The samples were then dipped into hot KOH solution for about 10 min to get the surface roughened and then into HF solution to remove the SiO_2 film. The N-type contacts, consisting of Al (500 nm)/Ti (50 nm)/Au (500 nm), were finally deposited by an electron-beam system. N-samples integrate superior characteristics of the R-samples and F-samples with low forward voltage, low leakage current and no compromise of optical output compared with R-samples, as shown in Fig. 4. The increase in optical output was due to surface roughening (compared with the F-samples) and inhibition of leakage current (compared with the R-samples). This further confirmed the above conclusion.

3.4. The aging test

In addition, the aging test conducted at room temperature in air further confirmed the stability of the N-samples. As depicted in Fig. 5, the I–V curve remained almost unchanged after aging for 2000 h. The small decrease in the forward voltage at the first stage was explained by the activation of the Mg acceptors in P-GaN, and the increase in the voltage later may due to the loss of the donor-like defects in the flat surface.

4. Conclusion

In summary, the electrical characteristics of VLEDs with n-type contacts deposited on a wet-etching roughened surface and a flat surface have been compared. Based on this, we have developed a new method with n-contacts deposited on a selectively wet-etching roughened surface. Good electrical and optical characteristics have been obtained by this method. The aging test further confirmed its stability.

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