

Progressive current degradation and breakdown behavior in GaN LEDs under high reverse bias stress*

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The progressive current degradation and breakdown behaviors of GaN-based light emitting diodes under high reverse-bias stress are studied by combining the electrical, optical, and surface morphology characterizations. The current features a typical “soft breakdown” behavior, which is linearly correlated to an increase of the accumulative number of electroluminescence spots. The time-to-failure for each failure site approximately obeys a Weibull distribution with slopes of about 0.67 and 4.09 at the infant and wear-out periods, respectively. After breakdown, visible craters can be observed at the device surface as a result of transient electrostatic discharge. By performing focused ion beam cuts coupled with scan electron microscope, we observed a local current shunt path in the surface layer, caused by the rapid microstructure deterioration due to significant current heating effect, consistent well with the optical beam induced resistance change observations.

Keywords: GaN LEDs, current degradation, breakdown behavior, reverse bias stress

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1. Introduction

Benefitting from the extraordinary high quantum efficiency, GaN-based light-emitting diodes (LEDs) have shown great application potential in optoelectronics.^[1] In practice, when these diodes are incorporated in sophisticated systems, long-term reliability of themselves could become one of the primary concerns for extended operating lifetimes.^[2] Unfortunately, under high field the LEDs usually suffer from a severe electrical failure, e.g., at high reverse biases the LEDs are subjected to a rapid increase in leakage current and eventually a catastrophic breakdown. So far, several constructive models have been proposed to address the time-dependent current degradation and breakdown behaviors. Cao *et al.* suggested that the current degradation could be due to the slow formation of point defects at the boundaries of the space-charge region near pre-existing microstructural defects.^[2] Meneghini *et al.* proposed that the reverse-bias degradation can be attributed to the injection of energetic charges, which interact with the lattice structure at high field, inducing the generation/propagation of defects in the active layer.^[3] Recently, Santi and Buffolo *et al.* performed experimental demonstration of time-dependent breakdown behavior in GaN-based

LEDs, indicating a vertical electrical failure phenomenon.^[4,5] Such studies are certainly very helpful for understanding the failure mechanisms of III–nitride materials and the associated devices. In this study, we further investigate the electrical failure behavior in GaN LEDs under high reverse stress by using a combination of electrical, optical, and surface morphology characterizations. Here, we first demonstrate that: i) the time-to-failure for each failure site is also Weibull distributed with slopes of about 0.67 and 4.09 at the infant and wear-out periods, respectively; ii) instead of a vertical breakdown path, a surface shunt path in the top GaN layers is formed as a result of the defect generation and percolation process, in good agreement with the optical beam induced resistance change observations.

2. Experimental

The samples under test have an InGaN/GaN multi-quantum well structure grown on *c*-plane sapphire substrates using metal–organic chemical vapor deposition, with a mesa size of 300 μm×300 μm. The peak emission wavelength is about 466 nm with a full width at half maximum of 36 nm at 1 mA. The epistructure consists of a 2-μm GaN:Si n-

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contact layer, a ten-period 3-nm undoped $\text{In}_{0.2}\text{Ga}_{0.8}\text{N}$ and 7-nm $\text{GaN}:\text{Si}$ MQW layer, a 70-nm p-AlGaIn electron blocking layer and a 0.2- μm $\text{GaN}:\text{Mg}$ p-contact layer. Annealed Ti/Al/Ti/Au (150/250/50/150 nm) and Ni/Au (3/3 nm) multilayers deposited by e-beam evaporation were employed as n-Ohmic contact and p-type contact, respectively. Thanks to the semitransparent top metal layer, the electroluminescence (EL) spots at the device surface can be spatially resolved by EL mapping technique.

3. Results and discussion

Firstly, a step-bias stress experiment was conducted to characterize the progressive current degradation and breakdown process of the GaN-based LEDs. As shown in Fig. 1(a), the current features a typical “soft breakdown” behavior: when the bias exceeds a critical value of -25 V, the diodes have an unrecoverable increase in current with time, accompanied with a large amplitude of noise. Besides, when the bias approaches as high as -40 V, a sharp current increase takes place suddenly at a short stress time, causing a catastrophic breakdown. The reverse current–voltage characteristics of the LEDs can be well described by trap-assisted tunneling model (not shown here),^[6] which predicts that the excess current will increase proportionally with the volume density of electrical defects within the band gap. So, the current degradation during the stress can be attributed to the generation of new electrical defects in the space-charge region, which could provide additional tunneling path for excess carriers. To obtain direct information, we recorded the spatial distribution of failure sites under a high bias of -40 V by EL mapping. The representative EL images in the pre- and post-breakdown regimes are shown in the inset of Fig. 1(b). It can be seen that, 1) before breakdown, the distribution of EL spots at the top semiconductor surface is inhomogeneous, and thus the leakage current. Physically, each EL spot can be regarded as an independent failure site,^[7] corresponding to a conductive path through the entire diode, which is formed when a critical defect density is reached; 2) as the degradation proceeds, more EL spots grow up from the device surface and gradually percolate to each other; 3) after breakdown, one uniform EL “hot patch” between the two electrodes can be observed even at an extremely low bias.

Further, to reveal the dynamics of the current degradation, the generation and evolution of EL spots were monitored at a low bias of -28 V, at which the leakage current was much smaller than the current at breakdown point so that the spatial overlap of defects during the stress can be neglected, and the failure rate was relatively slow, allowing us to record the generation of new spots. As shown in Fig. 2(a), the leakage current is found to increase approximately linearly with

the accumulative number of EL spots during the stress. Similar relationship was also measured in the time evolution of off-state degradation of AlGaIn/GaN high electron mobility transistors.^[8] Therefore, the time-dependent failure process of the devices can be analyzed by counting the continuous emergence of EL spots, instead of recording the time-to-failure (τ_B) on a large number of samples.^[7] In so doing, we have no need to consider the impacts of the sample difference in the discussion. For failure analysis in device reliability, Weibull distribution model is most frequently used. The corresponding cumulative distribution function is $F(t) = 1 - \exp[-(\tau_B/\eta)^\beta]$, where η is the scale parameter representing the characteristic failure time, and β is the Weibull slope (or shape parameter) denoting the change of failure rate with time.^[8] In principle, for $\beta < 1$ the failure rate decrease and for $\beta > 1$ it increases with time.^[8] As shown in Fig. 2(b), the time to failure for each site is indeed Weibull distributed, where $F(t)$ values are approximately estimated by median rank, similar to the usual time-dependent dielectric breakdown. By fitting the data point, the β values are extracted to be about 0.67 and 4.09 at the infant and wear-out periods, respectively. During the infant period with $\beta \sim 0.67$, the failure is associated with the external factor, such as macro manufacturing defects; while during the wear-out period with $\beta \sim 4.09$, the failure arises from the intrinsic factor, such as the generated defects in the materials.^[8]

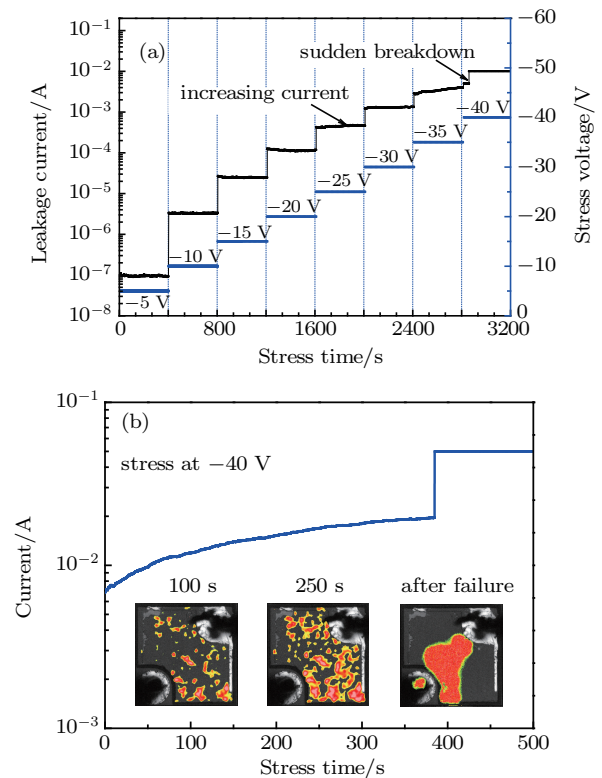


Fig. 1. (color online) (a) The current evolution during the step-stress experiments of the GaN-based LEDs, and (b) the catastrophic failure process as a function of time at a high reverse bias of -40 V. The inset shows the spatial distribution of the EL spots before and after device failure.

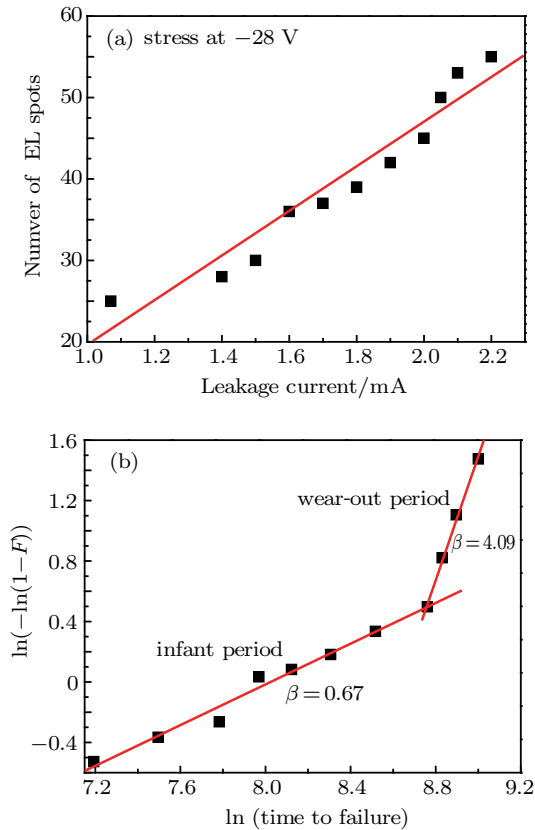


Fig. 2. (color online) (a) Number of EL spots as a function of leakage current stressed at $V = -28$ V, and (b) Weibull plot of the time-to-failure for each failure site, with the Weibull slopes of about 0.67 and 4.09 at the infant and wear-out periods, respectively.

Next, we will identify the possible breakdown path. Figure 3(a) shows the morphology of the LEDs after breakdown, where visible craters can be observed at the device surface, which is a typical result of significant current heating effect. For more detailed investigation, we performed focused ion beam (FIB) cuts around the initial breakdown point (highlighted by red spot) along the white dashed line [see Fig. 3(a)]. The scan electron microscope (SEM) of the cross section exhibits an obvious microstructure change at the failure site in the surface layer [see Fig. 3(b)], confirming the formation of a surface runaway path. Figure 3(c) is the SEM of the mesa side observed from a slight tilt angle, which also shows a crystal burnout phenomenon. All these results point towards that, the catastrophic breakdown should be caused by a transient electrostatic discharge behavior in the device surface. After breakdown, an optical beam induced resistance change (OBIRCH) measurement is immediately performed to confirm the detailed breakdown path without any treatment. As illustrated in Fig. 3(d), high leakage current firstly conducts along a surface defect path, and then flows through the vertical defect path on the mesa side into the n-type electrode, in good agreement with our preceding observations.

Finally, from the above analyses, we are able to explain the progressive current degradation and breakdown behaviors

of the LEDs as follows: 1) when the high reverse voltage is initially applied, the leakage current is inhomogeneously distributed through the didoes, related to the spatial distribution of electrical defects in the materials. It is believed that, the defect-assisted tunneling mechanism should dominate the reverse local current, and the primary conduction path is along the electrical dislocation threading through the space charge region; 2) because of the heat dissipation caused by the reverse current at high reverse voltage, the local temperature increases. In turn, this temperature increase leads to the generation and percolation of new electrical defects, possible by a heat accelerated electrochemical migration regime,^[9] and the rapid degradation of leakage current, showing increasing EL spots number and area; 3) as the degradation processes further, the defect density in the p-GaN surface will quickly approach to a critical value, which will trigger a preferred surface conductive path. Under a high field, the material microstructure will deteriorate rapidly due to considerably higher local temperature, giving rise to a surface shunt path for electrostatic discharge (catastrophic breakdown).

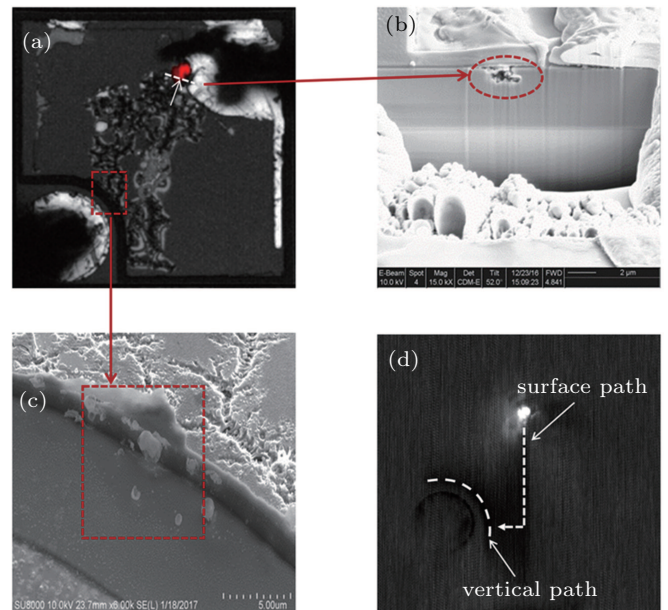


Fig. 3. (color online) (a) Surface morphology of the GaN LEDs, (b) SEM images of the cross section after FIB cuts and (c) of the mesa side observed from a slight tilt angle, and (d) OBIRCH image after breakdown failure.

4. Conclusions

The gradual current degradation and breakdown behaviors of GaN LEDs under high reverse bias stress are studied by various characterization techniques. The current increase shows a linearly dependent relationship with the number of EL spots, and the time-to-failure for each failure site is Weibull distributed. By performing FIB cuts with SEM, a surface current shunt path is detected for electrostatic discharge,

confirmed by OBIRCH measurement. The underlying physical process for the progressive failure behavior of the LEDs is finally discussed. Based on our failure picture, one effective method for improving the device reliability is to depress the generation rate of the surface electrical defects by surface treatments.

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