



Damage of light-emitting diodes induced by high reverse-bias stress

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ABSTRACT

The ability of a nitride light-emitting diode (LED) to withstand electrostatic discharge (ESD) is important because of the insulating property of the sapphire substrate. Therefore, damage caused by ESD to a nitride LED is a valuable subject. However, damage is caused by ESD in a very short period, so monitoring its evolution is very difficult. Accordingly, ESD experiments are performed and the effects of a high reverse current (HRC) on devices are investigated. Damage caused by ESD and HRC and their other effects on devices are compared. Four distinct effects of the ESD on devices are illustrated.

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1. Introduction

Since the successful commercialization of GaN-based light-emitting diodes (LED), GaN-based LEDs have been applied extensively in several different fields [1–6]. Comparing to the previously extensively used devices such as GaAsP, AlGaAs or AlGaInP LEDs that are grown on lattice-matched conducting substrates, most GaN-based LEDs are heteroepitaxially grown on lattice-mismatched insulating substrates. Thus, GaN-based LEDs have many unique characteristics that arise from the substrates, such as lateral current spreading, a high density of dislocations, lattice mismatch, thermal mismatch and others. In particular, in a low-humidity environment, since the substrate is an insulator, static charge created in the device during process is easily accumulated over a very long period. When these accumulated charges are eventually released, the device may be damaged or destroyed. Accordingly, GaN-based LEDs are more sensitive to electrostatic discharge (ESD) than other similar devices [7–9]. Although some investigations have established that the sensitivity of the device to ESD can be efficiently suppressed [10–14], since breakdown by ESD occurs in a very short period, its progress cannot be effectively monitored and the mechanism of failure due to ESD is more difficult to study than other properties. Hence, a more controllable method of producing similar ESD effects on the devices is helpful. In this study, in

addition to the ESD test procedure, a high reverse current (HRC) was applied to the devices to simulate charge release in an ESD test. Damage caused by both methods was compared and significant conclusions were drawn.

2. Experiment

Multiple InGaN quantum-well (MQW) LED structures were grown on 2-in *c*-plane sapphire substrates by low-pressure metal organic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylaluminum (TMAl), Trimethylindium (TMIn), ammonia (NH₃), SiH₄ and bis(cyclopentadienyl)magnesium (Cp₂Mg) were used as the precursors for Ga, Al, In, N, Si and Mg, respectively. The wafer structures comprised in order a low-temperature-grown nucleation layer, a 2.7 μm-thick undoped GaN layer grown at 1050 °C, a 2.5 μm-thick n-type Si-doped GaN layer also grown at 1050 °C, eight pairs of quantum wells, consisting of 3 nm InGaN/12 nm GaN grown at 800 °C and a p-type Mg-doped GaN layer grown at 960 °C. These wafers were then processed into LED chips for further study. The ESD was simulated using a Model 910 electrostatic discharge simulator from Electro-Tech Systems, Inc., which meets all of the testing requirements specified in Mil-Std-883E, Method 3015.7, ESD-S5.1 and JEDEC TEST METHOD A114.A for human body model of the ESD from personnel and ESD-S5.2 for machine model of the ESD from machines. The HRC was forced using Keithley 2430 source-meter unit; and the effects of ESD and HRC on the devices were examined using an Agilent E5270 modular source-monitoring unit.

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3. Results and discussion

Since the devices studied herein are only slightly sensitive to the human body mode and the forward machine mode up to the highest voltage of the simulator, only the reverse machine mode is studied. Fig. 1 plots the effect of gradually increasing the voltage of the ESD on the current–voltage (*I*–*V*) curves of a chip. At under 650 V, the reverse leakage current was even smaller than that without ESD stress, indicating that some leakage paths were obstructed by the discharge. Since the reverse leakage current in GaN-based LEDs that were heteroepitaxially grown on sapphire substrate is mostly associated with the tunneling of carriers through the dislocations [15], and the density of these dislocations was completely set by the crystal growth, the ESD reduced the conductivity of the dislocations for leakage current. As the ESD voltage was increased to 700 V, the leakage current increased by three to five orders of magnitude. Accordingly, this device had been damaged by the ESD at 700 V. Further applying 700 V ESD to the device again further increased the leakage current, and the device exhibited an unstable behavior. The hollow circles in Fig. 1 represent the *I*–*V* curve measured immediately following the second 700 V ESD stress. Although the leakage current was very large, the device still glowed under forward bias. However, when the *I*–*V* measurements were repeated, the device behaved like a resistor and was thoroughly destroyed. These observations indicate that the conductivity of the leakage paths was unstable as the device was seriously damaged by ESD stress. When the device was destroyed, all forward current flowed through the pn junction via these leakage paths, and so explaining why the device behaved like a resistor.

Details about the leakage paths and the unstable conductivity should be studied. Nevertheless, the instability of the conductivity and the unreproducibility of the *I*–*V* curve discourage the drawing of a reliable conclusion directly from the ESD experiments. However, the charge accumulated in the capacitor of the ESD simulator should reversely pass through the pn junction of the device when discharging. Some damages caused by the ESD should be related to the high reverse current. Hence, the effects of the HRC on the devices were examined. The inset in Fig. 2(a) shows the voltage–time relation of a device under –0.5 mA HRC stress. The voltage was decreased from –45 to –41 V after 40 s of stress, indicating that HRC made the leakage paths in the device leakier. Similar effects were also observed in Fig. 2(a), which plots *I*–*V* curves of a chip that has been stressed by HRC that was

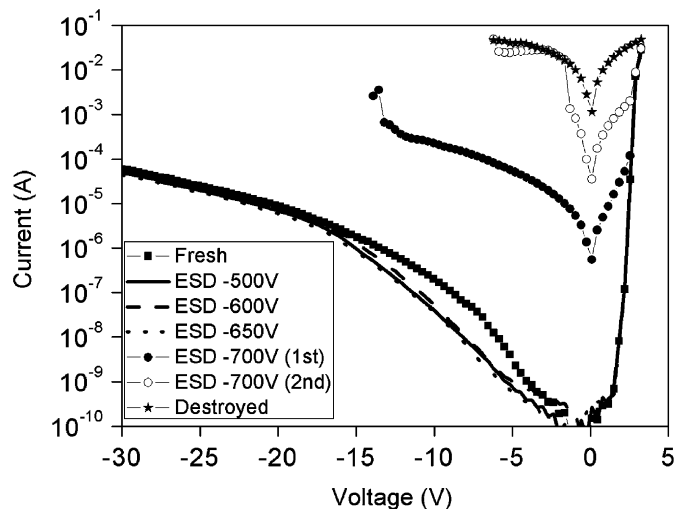


Fig. 1. Effects of sequentially increasing electrostatic discharge (ESD) voltages on current–voltage curves. All curves were obtained from the same device.

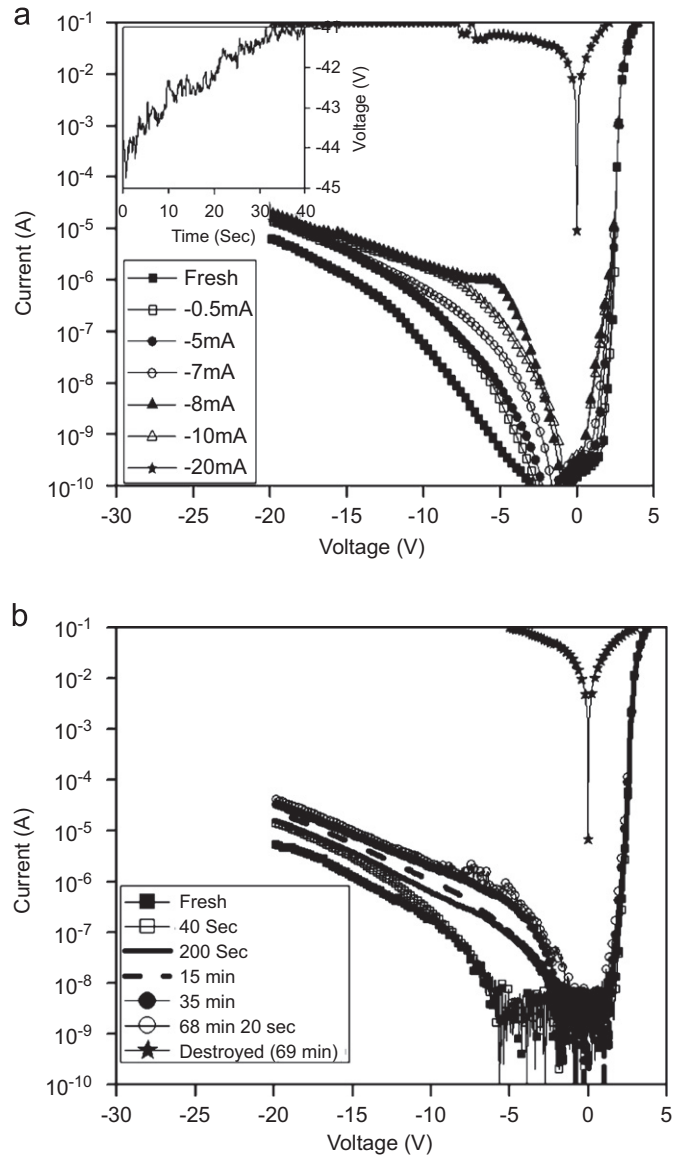


Fig. 2. (a) Effects of sequentially increasing high reverse current (HRC) on current–voltage curves. All curves were obtained from the same device and the stress time for each HRC was 40 s. Inset plots voltage–time curve of this device during –0.5 mA HRC stress. (b) Effects of duration of HRC stress on current–voltage curves. Stress current is –5 mA.

increased from –0.5 to –20 mA in steps that were each held for about 40 s. The leakage current increased with the stressing reverse current. At HRC = –20 mA, the device was destroyed. Therefore, the conductivity of the dislocations, the predominant leakage paths in GaN-based LEDs, was enhanced by the HRC. Fig. 2(b) further shows the *I*–*V* curves of a device stressed at –5 mA for various durations. Before 35 min had passed, the leakage current monotonically increased. When 68 min and 20 s had passed, the *I*–*V* curve seemed to be slightly unstable. This observation indicated that the conductivity of the leakage paths was unstable after the HRC stress. However, after 69 min, the device was destroyed. Since the stress current was constant, damage caused by HRC were accumulated and caused a latent damage.

When the device was subjected to a HRC, a curious phenomenon was also found: the device dimly glowed under the HRC, as shown in Fig. 3. Since the device is under strong reverse bias, this

light should be resulted from the impact ionization and carrier recombination in the active layer [16]. Accordingly, these light spots should correspond to the leakage paths of the device. Cao et al. [15] had grown nitride LEDs on sapphire and GaN substrates. Using conductive atomic force microscopy, they found that threading dislocations are the major leakage paths in the heteroepitaxially grown LED. Therefore, these randomly distributed light spots should correspond to the crystal defects with

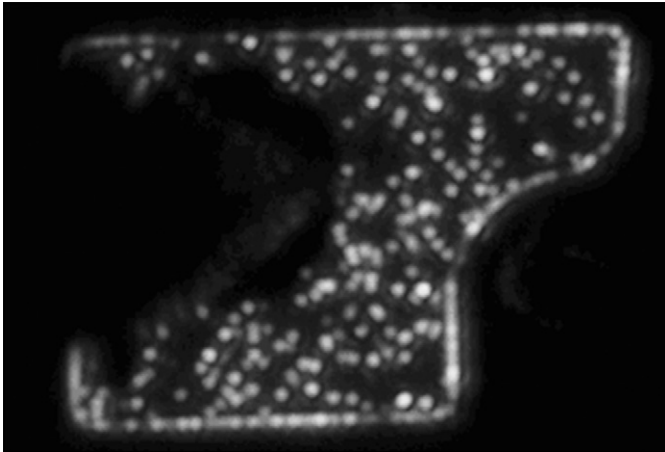


Fig. 3. Image of device under high reverse current stress. Light spots are randomly distributed on device and correspond to leakage paths.

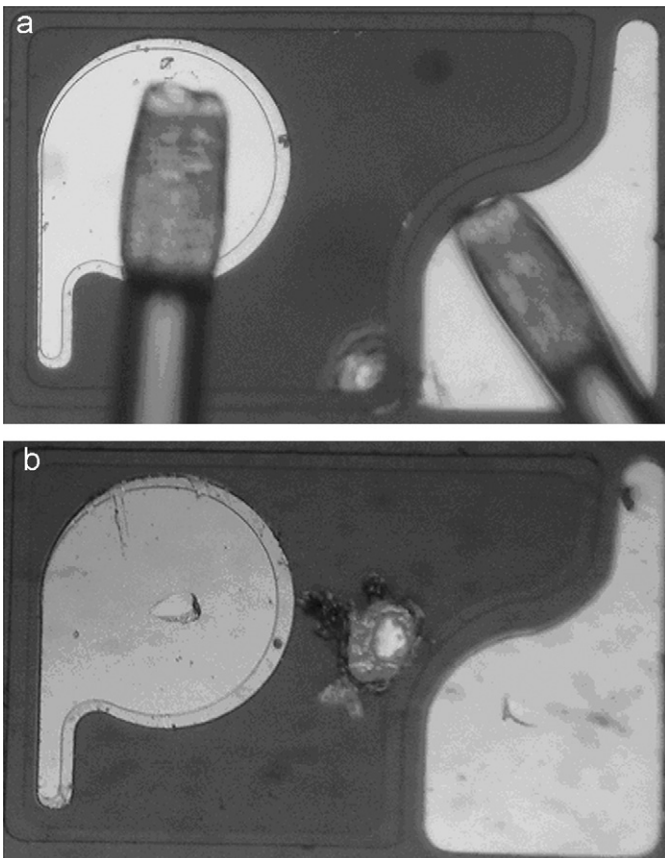


Fig. 4. (a) Image of device damaged by a 700V electrostatic discharge and (b) image of device damaged by high reverse current. Burst voids are observed on both devices.

higher conductivity that thread through the active layer. The density of the light spots was gradually increased with time. Besides, some spots become brighter, and some spots become darker under stress until the device was suddenly failed. These observations show that the conductivity of the leakage paths was gradually increased by the HRC and the fluctuation of the conductivity among these leakage paths results in brightness competition among these spots. However, when the conductivity of some paths became very large, the voltage substantially decreased and the device failed.

ESD and HRC not only caused electrical damage but also destroyed the morphologies of the devices. Fig. 4(a) shows the photograph of a chip after 700 V ESD stress had been applied and a burst void had formed on the device. The chip that was damaged by HRC, shown in Fig. 4(b), also shows the similar void. Since these voids were mechanical defects, the mechanical stress was very high and concentrated near these locations before these voids were formed. This concentrated stress is related to the aforementioned randomly distributed leakage paths with fluctuating conductivities. When the conductivity of one leakage path sufficiently overwhelms that of the others, most of the current is concentrated on that most conductive path. Accordingly, the concentrated thermal power that accompanies the concentrated current exerts a concentrated stress around the leakage path by thermal expansion.

4. Conclusion

In conclusion, four distinct effects of the ESD on devices are found: (1) Suppression of the conductivity of the leakage paths in the initial stage of ESD stress. (2) Unstable conductivity of the leakage paths when device was seriously damaged by ESD. (3) Increase in conductivity of the leakage paths. (4) Formation of burst voids on the device. These effects are further studied by performing the HRC experiments. Since effect (1) is not found in the HRC experiments, it resulted from the high voltage of the ESD. In the HRC experiments, the leakage current of the device was randomly distributed. The conductivity of the leakage paths was increased by the large leakage current that flowed through them. Thus, effect (3) is caused by the flow of charge through the leakage path during ESD, and the effect can be accumulated and has a latent damage. Effect (4) is caused by the highly concentrated discharging power, which accompanies the highly concentrated discharging current, and is a power effect of the ESD.

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