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Defect generation in InGaN/GaN light-emitting diodes under forward and reverse electrical stresses

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Abstract

Electrical and optical degradations of GaN/InGaN single-quantum-well light-emitting diodes (LEDs) under high-injection current (150 A/cm^2) and reverse-bias (−20 V) stresses were investigated. A substantial increase in the tunneling components of both forward and reverse currents was observed in the devices subjected to reverse biases. However, the stressed LEDs exhibited minimal degradation of optical characteristics. For devices subjected to high forward currents, a monotonic decrease in light intensities with stress time, accompanied by an increase of forward leakage current, was observed in the low-injection region, but a positive stress effect was found on the light output measured at high currents. These degradation behaviors can be explained by slow generation of point defects in the LEDs via different mechanisms, i.e., thermally induced defect formation in the InGaN active region in the devices subjected to high-injection currents, and destructive microstructual changes as a result of impact ionization in the cladding layer in the devices under high reverse-bias stress.

1. Introduction

III–V nitride materials are very attractive for the fabrication of light-emitting diodes (LEDs) and laser diodes (LDs) operating in the short-wavelength part of the spectrum [1]. The requirement of long-term reliability is one of the primary concerns for these emitting sources to be incorporated in sophisticated systems for many optoelectronic applications. Early studies showed that degradation of GaN-based LEDs under high-current aging tests was associated with growth of the pre-existing dark-spot defects [2] or contact metal electromigration [3]. Such rapid degradation has been substantially reduced in state-of-the-art LEDs as a result of continuous improvement of material growth and device processing techniques. It has been predicted that the dislocation mobility in GaN and its alloys is extremely small compared to that of conventional III–V materials, and the operational lifetime of GaN-based LEDs are much longer [4]. However, as conventional III–V LEDs, GaN-based LEDs commonly also exhibit degradation characterized by a gradual, uniform decrease in light emission. While this slow failure mode is widely believed to be associated with generation and diffusion of point defects [5–7], the physical mechanism, especially in GaN-based LEDs, is not yet completely understood.

In this work, we investigate the changes in electrical and optical characteristics of GaN/InGaN single-quantum-well (SQW) LEDs subjected to high-injection current and reverse-bias stresses. The gradual degradation of device performance is attributed to defect generation in the InGaN active layer or the AlGaN/GaN cladding layers. These defects act as nonradiative recombination centers and carrier tunneling channels. We believe that similar degradation mechanisms are also applicable to commercial GaN/InGaN-based LEDs.

2. Experimental

The LED samples were grown on sapphire(0 0 0 1) substrates using low-pressure metalorganic chemical

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vapor deposition (MOCVD). The device structure was similar to a typical commercial InGaN/GaN LED. It consisted of a 30 nm low-temperature GaN buffer, a 3.5 μm Si-doped GaN layer, a 3 nm undoped InGaN SQW active layer sandwiched by a Si-doped and a Mg-doped cladding layers consisting of alternating layers of AlGaN (5 nm)/GaN (5 nm), followed by a 0.5 μm Mg-doped GaN epilayer. Room temperature p-doping and n-doping concentrations in the p-GaN and the n-GaN were measured to be $\sim 5\times10^{17}$ and 2×10^{18} cm^{-3}, respectively. A standard technology for GaN-based LED fabrication was used, i.e. the p-GaN was partially etched to form mesas of 300×300 μm^2 using an inductively coupled plasma (ICP) etching system. Thin Ni/Au films were deposited on the p-GaN layer by electron beam evaporation, and followed by a 550 °C anneal in air to form semitransparent p-type ohmic contacts which also serve as current-spreading layers [8]. Fig. 1 shows the typical electroluminescence (EL) spectrum of the LEDs at 75 A/cm^2, which exhibits a peak around 405 nm, with a full width at half maximum of about 14 nm.

The LEDs were then stressed under a forward-current density of 150 A/cm^2 or a reverse bias of −20 V for up to 120 h. The tests were performed on wafer level at ambient temperature. The average junction temperature of the devices under forward-current stress was estimated to be >120 °C based on the change of forward voltages. The evolution of current–voltage (*I–V*) characteristics and optical output of the LEDs were recorded using a HP 4145 semiconductor parameter analyzer and a silicon photodiode-array fiber-optic spectrometer. To ensure accurate measurements of the changes in light output, the testing setup remained constant during the stress period.

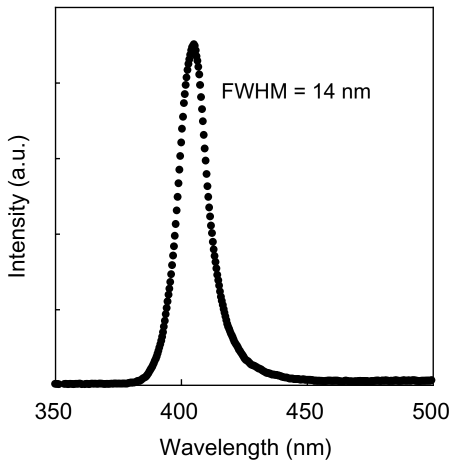

Fig. 1. EL spectrum of the GaN/InGaN SQW LED measured at 75 A/cm^2.

3. Results and discussion

The forward *I–V* characteristics of the LEDs before and after stress are shown in Fig. 2. In the control sample, the low-injection characteristics are dominated by carrier tunneling to the active region. This tunneling behavior has been extensively observed in GaN-based LEDs because of the highly doped junction and high-density defects in the space-charge region [9,10]. In the cases of both the forward and reverse stresses, the *I–V* curves show remarkable increase in the tunneling components. The changes take place most pronouncedly at the early stage of the stress test, and slow considerably as the stress is continued. Especially in the LEDs subjected to reverse bias, the forward currents increase by almost two orders of magnitude within the first 4 h of stress. However, the distribution of emission intensity on the surface of the stressed LEDs remained uniform, and the dark spots and contact failure which were observed in earlier GaN-based LEDs did not develop [2,3]. The degradation of the *I–V* behavior is therefore more likely

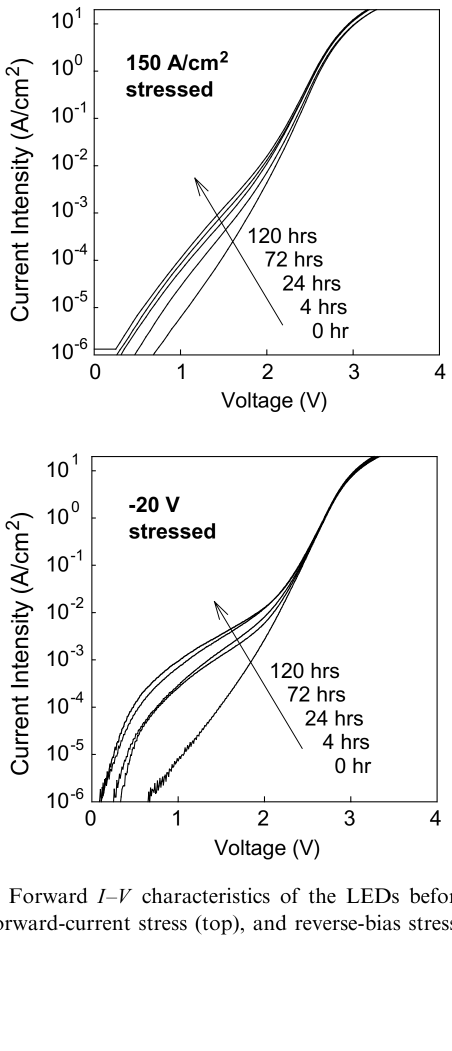

Fig. 2. Forward *I–V* characteristics of the LEDs before and after forward-current stress (top), and reverse-bias stress (bottom).

a manifestation of slow generation or reaction of defects in the space-charge region, especially point defects such as vacancies and interstitials, which result in more carrier tunneling into the SQW region. At a high-current density, large amounts of heat generated in the active layer where the majority of carriers recombine, result in a high junction temperature. Hot carriers can transfer enough energy to the lattice displacing the atoms and breaking the metal–N bonds. It is plausible that the thermally assisted defect formation occurs primarily in the InGaN layers because the bonding energy of InN is considerably smaller. The defect formation could also be enhanced by a nonradiative recombination process in the active region [5].

In the devices subjected to reverse-bias stress, the physical model for defect creation could be different. The LEDs were biased at −20 V, which is very close to avalanche breakdown voltage in these devices. The electrical field inside the QW region is estimated to be as high as 10^7 V/cm. Hot carriers injected to the boundaries of the space-charge region have enough energy to cause impact ionization, and may create deep-level states in the cladding layers. We have found inhomogeneous avalanche breakdown luminescence in these devices, which is indicative of a nonuniform spatial distribution of reverse leakage currents. In the areas with a high density of structural defects, the electric field, and therefore the impact ionization rate, is higher. The heat generated by the large localized current may enhance the defect generation. The increase of forward current in the low-injection regime can be ascribed to the enhanced localized carrier tunneling via the generated defect states in the cladding layers. It is known that GaN-based LEDs are highly susceptible to damage by electrostatic discharge (ESD) [11]. The mechanism of device degradation under the reverse-bias stress we observed in this work is believed to be similar to the destructive mechanism associated with ESD in LED devices. In the latter case, a short high-amplitude voltage pulse generates high current and high temperature in localized regions (near microstructural defects), leading to deterioration of the material and creation of a shunt path in the junction.

Fig. 3 shows the reverse *I–V* characteristics of the LEDs before and after 120 h stress. A significant increase in leakage current is only seen in the devices after reverse-bias stress. The different stress effects on the reverse *I–V* behaviors of the LEDs are further indication of different physical mechanisms for defect generation under forward and reverse stresses. As discussed earlier, defects are primarily generated in the thin (3 nm) InGaN SQW during forward stress. These defects should have minimal influence on the reverse characteristics. In contrast, defects formed in the cladding layers of the devices under reverse stress may increase both band-to-defect and band-to-band tunneling at reverse biases.

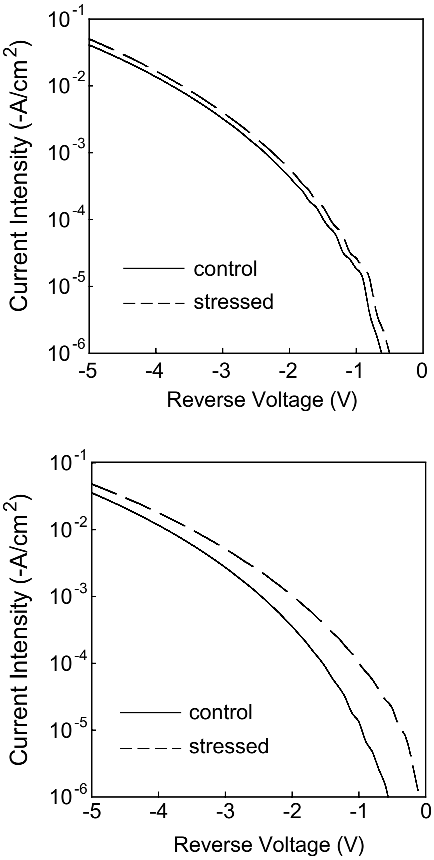

Fig. 3. Reverse *I–V* characteristics of the LEDs before and after forward-current stress (top), and reverse-bias stress (bottom).

The EL spectra of the control LEDs show two luminescence bands centered at about 405 and 580 nm, which correspond to the band-edge emission and defect-related yellow emission, respectively. The relative intensity of the two bands is a strong function of the injection current. The emission band associated with pre-existing defects in the LEDs offers us the chance to observe defect migration and generation during the stress tests. Fig. 4 illustrates the spectra of the LEDs measured at low-injection current (4 A/cm^2) and high-injection current (75 A/cm^2) before and after 120 h forward stress. The intensity of the band-edge emission at 4 A/cm^2 decreases by 20% after stress, suggesting the generation of nonradiative recombination centers in the InGaN SQW. A striking feature in Fig. 4 (top) is that a significant decrease in intensity is only observed for the high-energy part of the defect-related emission, and the location of the main peak shifts toward the longer wavelength region. This behavior suggests that the broad defect emission band consists of two components: a low-energy component centered at $\sim$600 nm which is the yellow

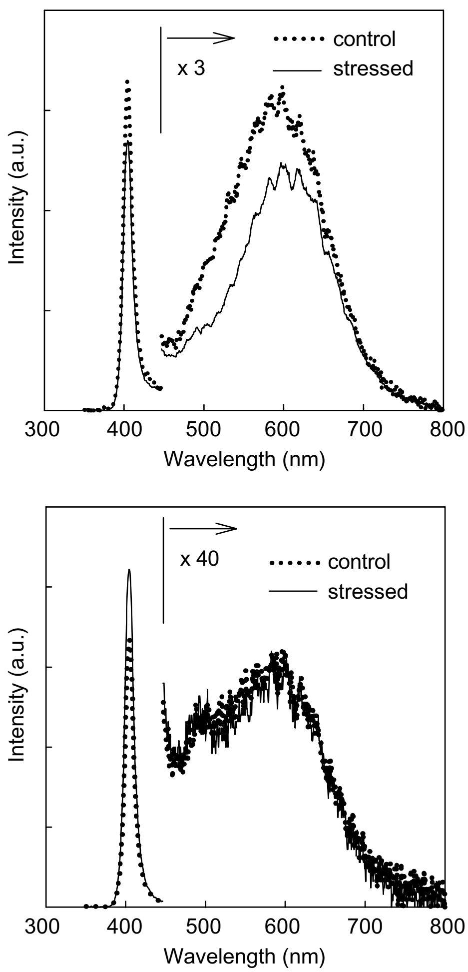

Fig. 4. EL spectra of the LEDs measured at 4 A/cm^2 (top) and 75 A/cm^2 (bottom) before and after 120 h forward-current stress.

band in InGaN (similar to the famous yellow band in GaN), and a high-energy component centered near 560 nm which is yellow emission from the AlGaN/GaN cladding layers. The latter results from electrons tunneling to the space-charge p-type region, which are then captured by the defect levels [12]. The intensity of the yellow band in this region is strongly affected by the defects in the active layer. As the lifetime of the injected carriers in the InGaN SQW decreases with increasing density of nonradiative recombination centers, far fewer electrons can tunnel through the InGaN layer. An alternative explanation for the peak shift of the defect emission is that the optical quality of the cladding layer was improved after the stress test. Similar results have been reported in a GaAs/AlGaAs double heterostructure LED, where gradual migration of defects from the cladding layer to the active layer during the aging test was proposed to be responsible for the decrease in intensity of defect-related deep-level emission for the cladding layer [13].

From Fig. 4 (bottom), we can see a significant increase of the intensity of the band-edge emission measured at 75 A/cm^2 after the stress test. This beneficial effect of aging, which was also observed in AlInGaP-based LEDs [14], indicates that different degradation processes, such as dopant activation [6], and defect generation occur simultaneously and compete with each other during the applied stress. At high-injection currents, the generated nonradiative recombination centers are saturated; therefore the positive stress effect becomes evident in the luminescence spectrum. As the stress continues, more and more defects are generated in the active region. We can expect that the negative stress effect will become dominant at a certain point, and the EL intensity will exhibit a gradual decrease. In addition, defect accumulation and interaction could cause a further increase in junction leakage and eventually lead to junction shorting. Fig. 5 illustrates the light output–current (L–I) characteristics of the LEDs before and after the forward stress. The deterioration of the light intensity in the low-current region is well correlated with the changes of I–V curves at low biases as shown in Fig. 2. The optical power measured at $\sim$10 A/cm^2 remains unchanged after the stress.

We did not observe any significant changes of the optical characteristics of the LEDs subjected to reverse-bias stress. This further confirms that defects generated in the cladding layer rather than in the active layer in this case. Fig. 6 shows the normalized light output of the LEDs plotted against stress time (t). It is evident that the most pronounced changes of the light output of the

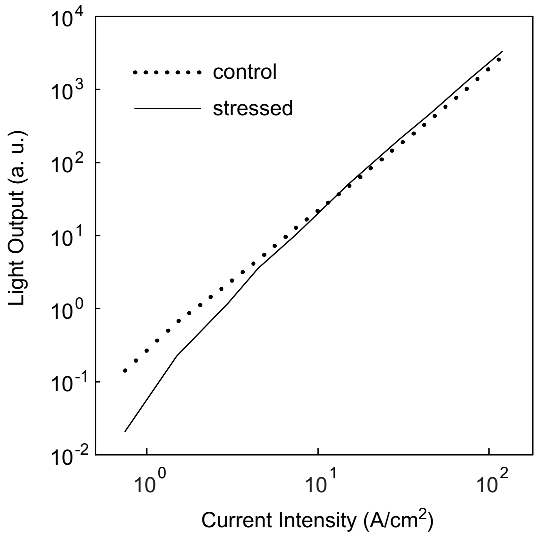

Fig. 5. L–I characteristics of the LED before and after 120 h forward-current stress.

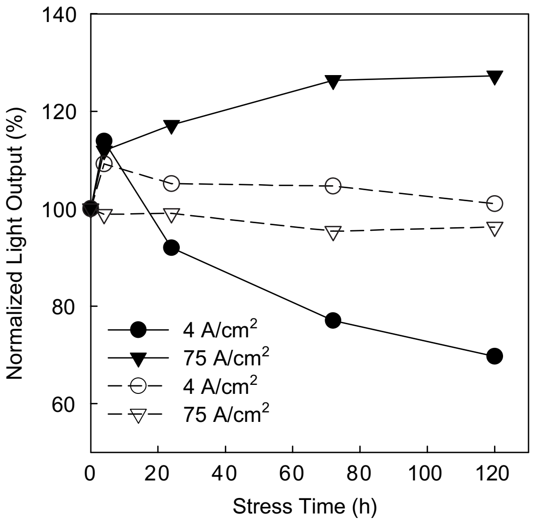

Fig. 6. Normalized light output of the LEDs as a function of time under forward-current stress (solid lines) and reverse-bias stress (dotted lines).

LEDs under stress current density of 150 A/cm^2 take place within the first 24 h of the test. The decay behavior of light output power measured at 4 A/cm^2 as a function of the stress time is roughly an exponential function, i.e. $L = L_0 \exp(-\beta t)$, which is a typical feature of slow LED degradation under a constant driving current [15]. The value of the degradation rate β was determined to be 3.1×10^{-3} h^{-1}. We have found similar degradation rate in a different set of LEDs which have the same epitaxial structure but one order of magnitude higher dislocation density. This suggests that no essential link between the degradation rate under forward stress and the density of pre-existing threading dislocations, and excludes efficient point defect generation and diffusion near dislocation cores as the major degradation mechanism. Note that while the existence of the high-density dislocations (10^9–10^{10} cm^{-2}) reaching the SQW active layer does not affect the device operational lifetime, they may accelerate device failure under high reverse biases.

4. Conclusions

In summary, we have investigated the degradation of the GaN/InGaN SQW LEDs subjected to high-injection current and high reverse bias. The gradual changes of *L–I–V* characteristics indicate the slow formation of point defects, which enhance nonradiative recombination and low-bias carrier tunneling. We have presented two different models for the defect generation. In the LEDs under high forward-current stress, it is possibly through thermally assisted and recombination-enhanced processes in the InGaN layer; while in the LEDs under high reverse voltage, material changes result from avalanche breakdown at the boundaries of the space-charge region near pre-existing microstructural defects.

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