Reliability study on green InGaN/GaN light emitting diodes

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Abstract. Although InGaN/GaN green light-emitting diodes (LEDs) are widely available, it is still challenging to grow green LED structures for emission at longer wavelengths due to the difficulty associated with the incorporation of In. The higher concentration of In may also affect the performance and reliability of the device. The reliability of green GaN LEDs with three different indium doping concentrations, with centre-wavelength of 520 nm, 540 nm and 550 nm, is studied in this paper. The electrical properties, including $I-V$ characteristics, leakage current and $1/f$ noise were measured. The optical performance of the devices was also evaluated. The devices were subsequently subjected to a 1000 hours continuous stress test. The defect densities of the LED structures were also determined. Our results show that the 520 nm LED, which contains the lowest indium concentration in its quantum wells, produces highest optical output power at 20 mA. It also degrades slower than 540 nm and 550 nm LEDs.

1. Introduction

The development of phosphor-free white light emitting diodes (LEDs) relies on high quality green LEDs at longer wavelengths. Green LEDs are preferred for their high photonic response. LEDs with wavelengths centred at around 555 nm are particularly important for high-brightness, red-green-blue (RGB) based white-lighting systems that coincide with the peak photonic response of the human eye. However, it is challenging to grow InGaN/GaN LED structures for emission at longer wavelengths due to the difficulty associated with the incorporation of indium (In). This difficulty originates from the strain condition in the quantum wells (QWs) which can control the extent of indium incorporation [1].

On the other hand, higher indium composition is essential for realizing longer wavelength emission; it also becomes a threat to the device performance and reliability. Firstly, the presence of higher In concentration in multiple QWs (MQWs) can introduce large piezoelectric fields induced by the large strain. This piezoelectric field reduces the overlap of the electron-hole wave functions, and so results in reduced internal quantum efficiency in green LEDs [2]. Secondly, the large lattice mismatch can give rise to high defect concentrations in the structure in the form of dislocations, which results in a degraded material quality. As a result, the higher dislocation densities of green LED introduced by the indium incorporation can often decrease the performance and device reliability.

In this study, we focus on studying the reliability of green LEDs by correlating defect concentrations in devices of different wavelengths ranging from 520 nm to 550 nm with their low frequency noise spectrum and 1000 hour lifetime data. Atomic force microscopy (AFM) surface scans are used to detect the exposed defects after Reactive Ion Etching (RIE) has been conducted to compare the defect densities in different wafers. The electrical properties of the different devices, including $I-V$...
characteristics, leakage current, 1/f noise spectrum were measured. The optical performance of the devices was also evaluated. The devices were subsequently subjected to a 1000 hours continuous stress test. A physical model has been constructed to explain the observed phenomenon.

2. Experimental details
The structure of wafers for LED devices include a GaN buffer layer grown on c-plane sapphire substrate, an n-type GaN layer, the active layers with InGaN/GaN as the quantum well structures, capped by p-type GaN as top contact. The wavelengths of the wafers are 520 nm, 540 nm and 550 nm obtained by varying the In composition. Details of the growth will be reported elsewhere. The LEDs were fabricated using a standard micro-fabrication process beginning with the deposition of a semi-transparent current-spreading layer composed of Ni/Au (10nm/10nm) deposited by e-beam evaporation and annealed in an oxygen environment at a temperature of 550 °C for 5 minutes. The 500 \times 500 \mu m^2 emission active area was defined by photolithography and dry etched by RIE using a chemistry comprising CHF_3 and Ar to expose the n-contact regions. Photolithography was carried out to define the p-pad and n-pad areas. A bi-layer of Ti/Al (50nm/350nm) was deposited as p-pads and n-pads and annealed in N_2 at 350 °C for 1 min. The chips were diced by laser micro-machining and packaged into TO (transistor outline)-cans. Following wire-bonding, a silicone encapsulant was applied to protect the device.

The electrical properties, including \textit{I-V} characteristics, leakage current and 1/f noise spectra were measured. The \textit{I-V} characteristics of the packaged devices were measured with an HP 4156A precision semiconductor parameter analyzer. Optical performance of the devices was also evaluated by an Ocean Optics HR2000 fibre-coupled spectrometer. The 1/f noise spectrum was measured by a BTA 9603 FET Noise Analyzer. The devices were subsequently subjected to a 1000 hours continuous stress test. The defect densities of the LED structures were also determined by AFM using a Seiko Instruments Nanopics system, after plasma exposure.

3. Results and discussion
The left part of Fig. 1 shows the measured \textit{I-V} characteristic from the three LEDs. The leakage currents of the devices have been extracted at a reverse bias voltage of −4 V. As the wavelength of the LEDs increases, the leakage current also increases from 0.99 \mu A in the 520 nm LED to 2.29 \mu A in the 540 nm LED and 4.45 \mu A in the 550 nm LED. The slope of the linear region of the \textit{I-V} curve (in the forward bias region) has been extracted to determine the device static resistance. As evident from the \textit{I-V} plots, the slopes increase as the wavelength increases. The extracted static resistances are 23.5 \Omega , 33.3 \Omega and 52.6 \Omega for the 520 nm, 540 nm and 550 nm LEDs, respectively. This consistent trend in leakage current and static resistance can be linked to the increasingly higher defect concentration as the In incorporation increases. The dislocations act as vertical current leakage pathways, while the defects lead to carrier scattering and thus higher resistance. To verify our postulations, additional experiments are conducted to study the carrier properties.

Since low frequency noise is closely related to the presence of impurities and defects in the semiconductors, it can more accurately represent the internal crystal quality than any other electrical parameters. Noise spectra of the three LEDs were measured and are plotted in the right part of Fig. 1. The system floor calibration was conducted for DC bias calculation and 1/f noise correction. The range of frequencies was between 3.15 Hz and 105 Hz. The slope can be extracted by the supplied software automatically. From this figure, both the magnitude and slope for the 520 nm LED are lower than for the 540 nm LED and 550 nm LED.
In an LED structure, the current spectral density can be expressed by the following equation [3]:

\[
S_I(f) = \frac{\alpha q I_D}{f \tau} + \left( \frac{q n_i A}{I_0} \right)^2 \cdot B \cdot \frac{k T N_i}{\ln(\tau_2/\tau_1)} \cdot \frac{1}{f} \cdot f^2 \tag{1}
\]

where \( n_i = n_i \cdot \exp\left( \frac{E_i - E_r}{kT} \right) \) \tag{2}

The first term of equation (1) represents the near-equilibrium steady state conditions whereby there is no net accumulation of charge and the generation rate is equal to the combination rate. \( \alpha \) is the Hooge parameter [4], which depends on the quality of the crystal [5], and on the scattering mechanisms. A larger \( \alpha \) value generally implies poorer crystal quality, and increases the magnitude of the noise spectrum. \( I_D \) is the diode current through the device, \( \tau \) is the lifetime of the minority carrier lifetime, \( N_i \) is the trap density, which can increase the magnitude of the noise spectrum when the trap density increases, while the other terms have their usual meanings. The measured 1/f noise spectrum thus indicates that the crystal quality deteriorates as the emission wavelength increases from 520 nm to 550 nm, supporting the theory of enhanced defect densities with increasing In incorporation. A further observation from the slopes of the noise spectra also supports this theory. Moreover, according to the Number Fluctuation Model [6], there is a variation in the generation-recombination rate. The occupation of traps must be taken into account which also affects the total noise spectral density. When the defect density in the InGaN/GaN QW increases, the transitions between traps become more frequent, leading to a drop in the electron mean free time and an increase in the electron number fluctuations. In the noise spectrum, it corresponds to an increase in the slope, consistent with our measured data.

**Figure 1.** Left: Current-voltage (I-V) characteristics and leakage currents of LEDs with different wavelengths. Right: Noise spectrum of LEDs with different wavelengths.

**Figure 2.** AFM surface scans of the 520 nm, 540 nm and 550 nm wafers (left to right).
The dislocation densities of the wafers are estimated by obtaining AFM scans of plasma-exposed samples. The LED wafers were exposed to plasma in an RIE system to remove about 50 nm $p$ type GaN, thus exposing the defects. This is a valid and convenient method of defect estimation since defects propagate through the structure. The densities of etch pits at the surface accurately represent the densities of defects generated underneath [7]. In the AFM surface scans shown in Figure 2, the dark dots are the etch pits propagating from the defects generated at the GaN/sapphire interface due to lattice mismatch, and also from defects generated within the MQWs due to strain. By counting the number of the dark dots within regions of identical areas, a comparative defect density can be obtained. It is estimated that the defect density of the 520 nm, 540 nm and 550 nm wafers are about $1.4 \times 10^7$ / cm$^2$, $1.75 \times 10^7$ / cm$^2$ and $2.22 \times 10^7$ /cm$^2$ respectively. These numbers tie in well with the prediction that increased In incorporation leads to increased defect densities, correlating well with the electrical characteristics presented earlier.

The results can also be correlated to the lifetime of the devices. Figure 3 shows the results of a 1000-hours reliability test, whereby a constant bias current of 20 mA was applied to the various devices. While the 520 nm LED maintains 95% of its initial optical power after 1000 hrs, the number drops to 91% and 82% for the 540 nm and 550 nm LEDs, respectively. Our results show that green LEDs with increasing wavelengths are expected to have increasingly short lifetimes. At the same time, the lifetime of LEDs can be predicted from electrical parameters, particularly from the noise spectrum.

4. Conclusions

In summary, the role of indium incorporation in green InGaN/GaN LED has been studied. While higher indium concentrations in the quantum wells produce LEDs with longer wavelengths (particularly wavelengths around 550nm with high photonic response phosphor-free white LEDs), defects are introduced into the devices. These defects will increase the leakage current, the static resistance and the low frequency noise level, degrading the lifetime of the devices.

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