ROLE OF NANOPIPES IN DEGRADATION OF AlGaN/InGaN/GaN DEVICES OPERATING AT HIGH VOLTAGE

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ABSTRACT

We argue that the nanopipes recently observed in device-quality GaN grown on sapphire play an important role in degradation of nitride-based devices requiring high driving voltage, such as diode lasers or high-power electronics. The nanopipes offer a preferential path for the top (*p*-side) contact metal to migrate down towards the *p-n* junction under high-voltage operation, eventually causing a short and device failure. The metal migration process is enhanced by high voltage (tens of volts) required to drive high-current pulses through the device, and its elimination is of critical importance for achieving reliable GaN-based power devices and diode lasers.

INTRODUCTION

Wide-bandgap GaN/AlGaN/InGaN semiconductor system is now considered to be a prime candidate for short-wavelength (blue-green to UV) diode lasers. Spectacular progress has been reached in improving the device performance and longevity over the last two years. Less than a year elapsed between the first demonstration of room-temperature cw lasing action with devices living only a few seconds [1], and the announcement of diode lasers with lifetime exceeding 300 hours [2]. Within those few months, nitride-based diode lasers have surpassed the performance of their II-VI counterparts that seem to have reached the ceiling of their lifetime at 100 hours back in early 1996 [3]. However, this progress has been limited to only one particular company, namely Nichia Chemical Industries in Japan. While a number of other groups have succeeded in achieving pulsed operation of nitride-based diode lasers, so far none of them has been able to overcome the problem of rapid degradation. The purpose of this paper is to shed some light on what may be causing the failures of nitride-based lasers, and to explain why Nichia has switched from laser structures grown on sapphire to laterally overgrown structures.

BACKGROUND

We have begun extensive studies of nitride-based optoelectronic devices back in Spring of 1994, soon after the first high-brightness blue light-emitting diodes (LEDs) manufactured by Nichia became commercially available. Epitaxial growth of group-III nitrides on various substrates had been known to result in a large density of dislocations, due to the absence of a substrate that would match the lattice constant and thermal expansion coefficient of GaN, and to non-availability of bulk GaN substrates. Sapphire is the most commonly used substrate, and the best performance of LEDs and diode lasers (invariably reported by Nichia) has always been obtained with structures grown on sapphire. The questions that we wanted to address at that time were:

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1. Are Nichia LEDs better from crystallographic point of view than typical nitride material grown on sapphire in other laboratories?
2. How does the presence of defects affect the LED lifetime under close-to-normal operating conditions?
3. What predictions can be made with respect to possible problems with reliability of nitride-based diode lasers?

As described in more detail below, we found out that the LEDs were made of material containing enormous density of extended defects that in other III-V compounds would only qualify as reject. Yet, the LEDs seemed to perform very well, and our extensive life testing, including devices driven cw at currents twice exceeding the maximum rating and at temperatures surpassing the maximum allowed in the manufacturer specifications, failed to produce any damage inside the semiconductor material. A more detailed recent account of that part of our work can be found in [4].

The answer to the third question is the subject of this paper. We show that our early predictions, formulated back in 1995 [5], were confirmed by recent observations on both the operating laser devices and the nitride material itself.

DEVICES UNDER STUDY

Our early studies began with investigations of double-heterostructure (DH) Nichia NLPB-500 blue LEDs, shown schematically in Fig. 1. More recently, we focused our attention on newer generations of Nichia LEDs of the NSPB and NSPG series with single-quantum-well (SQW) active region, emitting in the blue and green spectral range. Their structure is very similar to that shown in Fig. 1, except for the obvious change in the active-region thickness and composition.

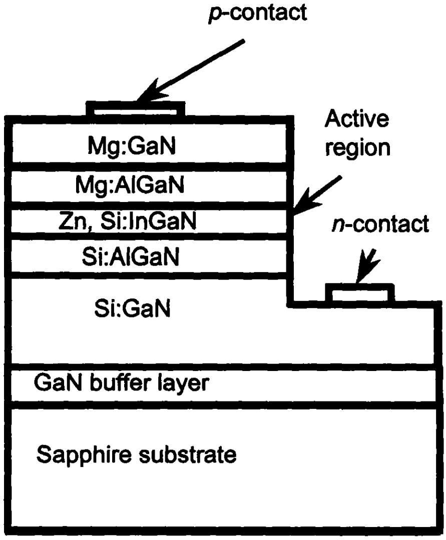

Fig. 1. Schematic structure of Nichia NLPB-500 DH blue LED. The layer thicknesses are: GaN buffer - 30 nm; *n*-type Si-doped layers: GaN - 4 μm, $Al_{0.15}Ga_{0.85}N$ - 150 nm; $In_{0.06}Ga_{0.94}N$ active region co-doped with Zn and Si - 50 nm; *p*-type Mg-doped layers: $Al_{0.15}Ga_{0.85}N$ - 150 nm, GaN - 500 nm. The ohmic contact materials are: Ti-Al on *n*-side, and Au-Ni on *p*-side. After Ref 6.

HIGH-ELECTRICAL STRESS EXPERIMENTS

In order to simulate laser-like conditions, we subjected the LEDs to low-duty-cycle high-amplitude rectangular voltage pulses of 100 ns duration and 1 kHz repetition rate. Even though the LEDs were not packaged for that type of testing and their maximum rating under pulsed conditions was only 100 mA, we were able to drive pulses up to ~1.5 A in the case of DH LEDs, and as much as 6 A for SQW LEDs, before nearly instantaneous degradation would occur. The corresponding current densities varied between 2 and 7 kA/cm^2, thus exceeding the level required to reach threshold in nitride-based lasers.

RESULTS

Double-heterostructure LEDs

Electrical and optical characteristics of blue DH LEDs were relatively stable up to moderately high-bias pulses. Noticeable changes were recorded at currents approaching 1.5 A. Minor and partially reversible diode damage manifested itself in changes in the *I-V* characteristics and in small reduction in the light emission efficiency. These changes can be interpreted in terms of a micro-shunt formation resulting from localized overheating by high-density current. The main signatures of this process are a decrease in the zero-bias differential resistance and an increase in the reverse-bias current. When the added shunt resistance is larger than 7-8 kΩ, it is manifested mostly at the bias below 2.7 - 2.9 V, hence there is only a minor degradation of light emission at higher bias. Table 1 summarizes the results of electrical stress tests of DH LEDs.

Table 1. Results of high-current tests on Nichia NLPB-500 DH LEDs

Sample	Stress conditions	Shunt resistance [kΩ]
Unstressed	None	>10^6
Stressed	Up to 1.5 A 100-ns pulses	5 - 8
Degraded	Pulses over 1.8 A, few s	0.001-0.020

The LEDs would become heavily degraded, with great loss of light emission efficiency, within seconds of applying current with amplitude in the range of 1.8 – 2 A. After degradation, the *I-V* curves would become linear, indicating presence of a short. However, no obvious sign of damage to contacts was apparent; thus, the damage was likely associated with internal diode properties and not with the electrode wires. Failure analysis was performed on these devices in order to identify the degradation mechanism [5]. The main results of those investigations are described in the "Failure Analysis" section.

Single-quantum-well LEDs

Compared to DH devices, high-electrical-stress testing of SQW LEDs turned out to be more difficult. Instantaneous degradation, with massive damage to the *p*-contact area, was observed at currents exceeding 6 A. In order to produce samples with less damage, more suitable for identification of the degradation mechanism, we lowered the pulse current amplitude to ~5 A. The LEDs would then operate for tens, even hundreds of hours with very little degradation of the light output (~0.03%/h). Without any prior warning in the optical or electrical characteristics, a sudden short would occur at the end of device operating lifetime, shutting down the diode. We identified the origin of this behavior to be package-related [7]. At those high pumping levels, the encapsulating plastic would itself degrade due to local overheating at the *p*-contact region. Thus, rather than inducing the damage to semiconductor, we observed shorting of the diode that took place through carbonized pieces of damaged plastic [7]. We now continue further testing of SQW LEDs without any encapsulation, but it is already obvious that they can sustain much higher current densities than earlier DH devices. We address this point further in the "Discussion" section.

FAILURE ANALYSIS OF DH LEDs

Degraded DH LEDs were subjected to extensive post-mortem testing. DLTS, output spectrum, and admittance spectroscopy measurements on stressed (not shorted) devices indicated that the degradation was not caused by the formation of deep levels or other charge trapping mechanisms. We also noticed that the short was to some extent reversible. It could be removed, and light emission restored, by either biasing the LED in the reverse direction, or by driving it with sinusoidal voltage with no pre-bias. EBIC analysis of a failed LED indicated that the short was localized in a couple of spots on the *p*-contact side. We then removed the top Au layer of the contact metal, still leaving Ni metallization intact, and examined closer the region identified by EBIC. Fig. 2 shows what we consider to be the evidence of contact metal entering into the body of the semiconductor crystal.

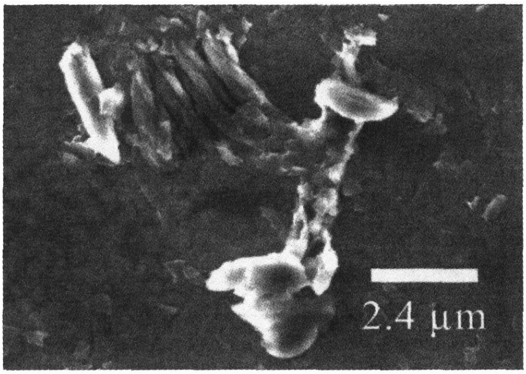

Fig. 2. High-resolution SEM secondary image micrograph of the damaged region on the surface of *p*-side contact in a Nichia NLPB-500 LED shorted by high electrical stress. Note multiple fingers of Ni penetrating into the underlying crystal. Magnification is 7500×. After Ref. 5.

In order to further elucidate the process of metal penetration into GaN, we have examined the Nichia DH LED material by TEM. A thin (~1000 Å) sample was prepared using a focused ion beam (FIB) system. A careful three-step process of FIB milling was devised, aimed at minimizing the damage the FIB process itself could induce. As shown in Fig. 3, TEM observa-

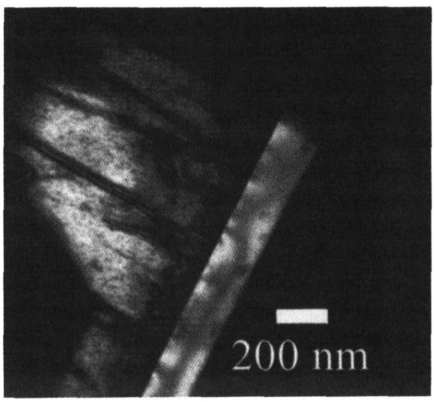

Fig. 3. TEM micrograph of defects threading through the epitaxial layers of a Nichia NLPB-500 blue LED sample. The image was taken with a two beam condition and **g** = (0331). After Ref. 5.

tion revealed the presence of threading dislocations in the sample, with density estimated to be at least 2.2×10^9 cm^{-2} [5]. Even higher count of dislocation density, in excess of 2×10^{10} cm^{-2}, was reported in other samples of Nichia DH material [8]. The presence of those defects led us to hypothesize that under the high voltage (70-80 V) required to drive the current pulses through the LED, the metal from the top (*p*-side) contact would migrate down along clusters of such defects or defect tubes [5], eventually shorting the junction.

DISCUSSION

Our early study of the role of defects in degradation of DH LEDs under high electrical stress [5] indicated that two factors will play a key role in reliability of nitride based diode lasers:

1. The voltage required to operate the laser would have to be kept at minimum, as the metal migration would be much slower at lower voltages.
2. The presence of defects will ultimately limit the laser lifetime, hence it will be necessary to eliminate those defects.

It should be noted that recently developed short-lived nitride-based diode lasers were reported to cease their operation by developing a short [2],[9]. This is consistent with our earlier prediction that nitride lasers would suffer from the metal migration problem. The success of Nichia in extending the laser lifetime to 300 h was primarily due to reduction of threshold voltage to as little as 4.3 V [2], compared to 34 V in their first lasers [1].

It is important to identify the defects that are particularly harmful from the point of view of degradation process involving metal migration. Recently, in addition to dislocations, two other types of filamentary defects were discovered in device-quality GaN, using a combination of TEM and convergent beam electron diffraction techniques: hollow nanopipes and inversion domains [10]. The nanopipes with typical diameter of 5 to 25 nm are of particular relevance to the metal migration process. We suggest that it is not that much dislocations themselves as the nanopipes that are responsible for metal migration, offering a preferential path for metal atoms to move towards the *p-n* junction.

The presence of nanopipes at the density 10-100 times smaller than that of threading dislocations may well have been signaled in the morphology of *n*-GaN surface in early Nichia devices, as illustrated in Fig. 4. Significantly, the *n*-GaN surface in SQW LEDs is smooth, indicating much lower density of the nanopipes. This may well explain why the SQW LEDs display a much better tolerance to high-voltage pulses [7]. The ultimate GaN-on-sapphire laser lifetime of 300 h achieved in [2] is also consistent with the behavior of SQW LEDs.

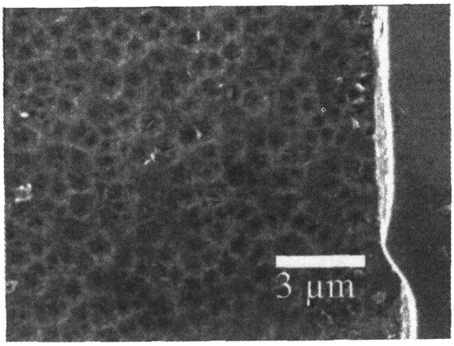

Fig. 4. SEM micrograph of hexagonal shaped etch pits on the *n*-GaN surface of Nichia NLPB-500 blue LED, exposed during the fabrication process. The etch pit density is approximately 3×10^8 cm^{-2}. After Ref. 5.

CONCLUSIONS

We argue that nanopipes in GaN grown on sapphire substrates are responsible for rapid degradation of GaN-based devices operating under high voltage (tens of volts). Elimination of those defects, by adopting lateral overgrowth techniques (as practiced by Nichia at present) or by using bulk GaN substrates in the future, is critical for extending the device lifetime beyond a few hundred hours.

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