Available online at www.sciencedirect.com

ScienceDirect

Solid-State Electronics 52 (2008) 968–972

SOLID-STATE ELECTRONICS

www.elsevier.com/locate/sse

Degradation of AlGaN-based ultraviolet light emitting diodes

S. Sawyer *, S.L. Rumyantsev [1], M.S. Shur

Department of Electrical, Computer, and Systems Engineering, Center for Broadband Data Transport Science and Technology, CII 9017,
Rensselaer Polytechnic Institute, Troy, NY 12180-3590, United States

Received 14 September 2007; received in revised form 17 January 2008; accepted 31 January 2008
Available online 1 April 2008

The review of this paper was arranged by Prof. E. Calleja

Abstract

Aging the LEDs by driving at high current, results in the decrease of optical power proportional to the reciprocal square route of stress time. With aging time, change in the current–voltage characteristics indicates decrease of the current at low voltage below the light emission threshold, decrease of the forward voltage drop at high currents and usually no change in the series resistance. No change in the peak wavelength and half bandwidth were found with aging. Low frequency noise measured at low and high currents either did not depend on aging time or decreased. No correlation between noise, the device power, and the rate of the power degradation were found. These results are in strong contrast to previous studies of longer wavelength GaN-based LEDs. The possible degradation mechanism is the diffusion of the Al atoms out from the p-type cladding layer and lowering of the cladding layer potential barrier as a result.
Published by Elsevier Ltd.

Keywords: Ultraviolet; Light emitting devices; Degradation; Low frequency noise; AlGaN; Optoelectronics

1. Introduction

Light emitting diodes (LEDs) have penetrated today's market as the most efficient sources of light with the wavelength from far infrared to deep ultraviolet (UV). Recent developments of the AlInGaN-based UV LEDs opened their new applications in medicine, security and defense, counterfeit detection, high resolution optics, displays, semiconductor manufacturing and solid state lighting. The growing market for UV LEDs requires higher reliability. Therefore, understanding the degradation mechanisms that hinder reliability of these devices is paramount. Recent publications [1–4] discovered several mechanisms of GaN-based LEDs degradation and pointed out the long lifetime of theses devices. However, degradation for deep UV LEDs ($\lambda < 290$ nm) has not been studied before.

In this paper, we use a number of methods including low frequency noise to characterize aging of AlGaN/AlInGaN UVTOP®-280 LEDs with the peak wavelength of 280 nm from Sensor Electronic Technology, Inc.[2] We find results in strong contrast to previous papers dealing with longer wavelength GaN LEDs [1–4].

2. Experimental details

The LED structures were grown on basal-plane sapphire substrates with a custom-designed vertical metalorganic chemical vapor deposition (MOCVD) system using proprietary MEMOCVD® process. The LED chips with junction area $\sim 10^{-3}$ cm^2 were flip-chip packaged using commercial TO-39 headers. The peak wavelength was 280 ± 5 nm.

Devices were aged at the forward current of 20 mA without additional heat sink for the header. The junction temperature in course of aging, (estimated using the MIL-STD-750 3100 series method) was in the range 35–45 °C.

---

* Corresponding author. Tel.: +1 5182762164; fax: +1 5182762990.
E-mail address: sawyes@rpi.edu (S. Sawyer).

[1] On leave from Ioffe Institute of Russian Academy of Sciences, 194021 St-Petersberg, Russia.

[2] www.s-et.com.

0038-1101/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.sse.2008.01.027

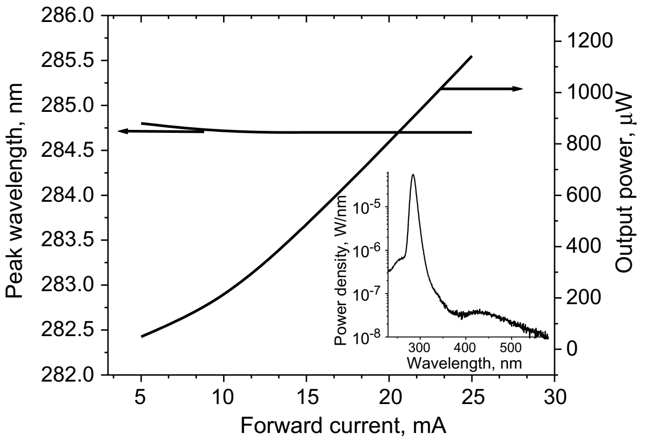

Fig. 1. Current dependence of power and peak wavelength. The inset shows the typical spectrum of the studied LEDs.

Nine identical LEDs were used in the experiment. Before the aging procedure and at the intermediate stages the following parameters of the LEDs were monitored:

1. output power
2. peak wavelength
3. full width at half magnitude (FWHM)
4. current–voltage characteristics
5. low frequency current noise at low and high currents.

Typical current dependencies of power and peak wavelength are presented in the Fig. 1. The inset in Fig. 1 shows the typical spectrum of the studied LEDs.

For the noise measurements, the LED was connected to a low noise battery using a load resistor which varied from 100 Ω to 10 kΩ, depending on the LED current. Voltage fluctuations, S_v, across the load resistors were measured by a SR 770 Network Analyzer.

3. Results and discussion

Fig. 2 shows the LED output power as a function of aging time. As seen, the power follows a linear relationship with the square root of time. This type of time dependence for device parameters during degradation is known and usually associated with diffusion. For example, it may be diffusion of contact metal to the device structure or diffusion of the dopant atoms [5].

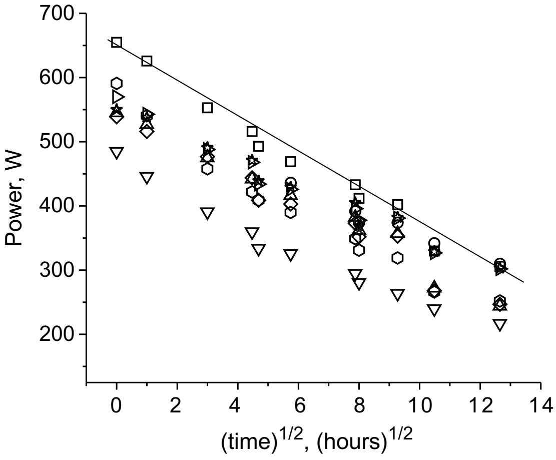

Fig. 2. Output optical power as a function of the aging time.

Approximation of the output power by exponential function as it often proposed [1] requires our LEDs to be characterized by more than one time constant, i.e. first a relatively fast drop of the power is followed by a slower process. After several tens of hours of aging, the time dependence of the output power can be reasonably well described by the exponential function with the time constant of ~500 h.

While power decreased with time, we did not find any change in the peak wavelength and FWHM with accuracy of ±0.1 nm. This suggests that the properties of the quantum wells do not change with time.

There are several mechanisms of LED degradation known for GaN-based LEDs. These mechanisms include degradation of the contacts due to the electromigration of the metal, generation of the point defects and dislocations in the active region, and thus generation of non-radiative recombination centers, and degradation related to the passivation layers and packaging [2]. For these mechanisms of degradation the decrease of the output power is accompanied by the increase of the forward voltage drop at high currents [3] and increase of the non-radiative recombination at low currents [4].

Our measurements differ from the characteristics listed above. Fig. 3 shows an example of the typical

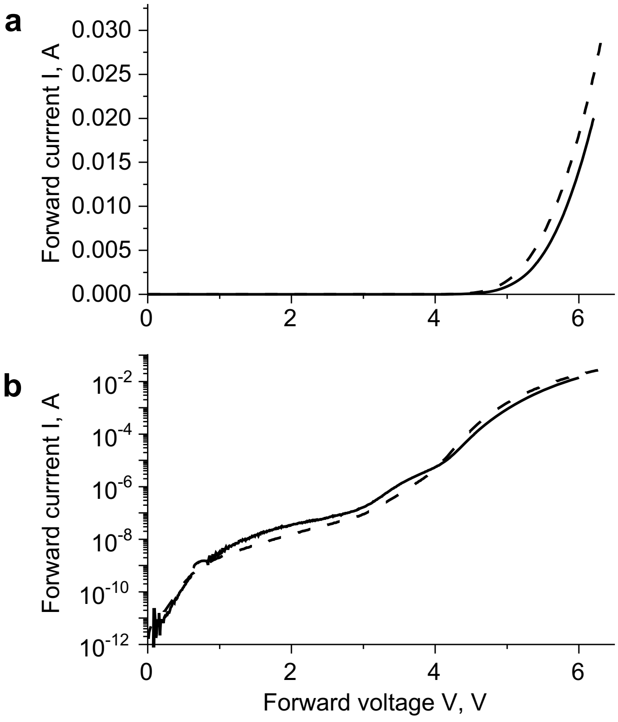

Fig. 3. A typical example of the current–voltage characteristics measured before aging (solid line) and after 160 h of the stress (dashed line) in the linear (a) and semi-logarithmic (b) scales.

current–voltage characteristics measured before (solid line) and after the 160 h of aging. The current at low voltages either decreased or remained unchanged for some LEDs during aging. At high currents the voltage drop always decreased as a result of aging. Fig. 4 shows the voltage drop measured at the current $I = 20$ mA as a function of aging time for several LEDs. As seen the decrease of 5–6% in the voltage drop during the first ~20 h of aging was found for all devices. Differential resistance at high current associated mainly with contact resistance remained unchanged or even decreased for some LEDs during aging.

These tendencies in the influence of aging on the current–voltage characteristics were found for all measured devices varying from the device to device only quantitatively. While Fig. 3 is an example for the average device, the current–voltage characteristics for the LEDs experienced the highest change are shown in Fig. 5. In this figure, the photodetector current which is proportional to the output optical power is also shown as a function of the voltage. As seen the kink on current–voltage characteristic corresponds approximately to the light generation threshold voltage (Fig. 5b). This threshold current always decreased as a result of the stress.

One of the most sensitive indicators of the semiconductor devices degradation and LEDs in particular is low frequency noise [6–9]. For LEDs and semiconductor lasers, the low frequency noise measured at low bias is sensitive to degradation of the barrier layer (active region) [9,10]. At high bias, the measured noise reflects the degradation of the contacts and/or semiconductor layers contributing to the series resistance [9,10]. For example, the increase of the 1/*f* noise as a result of degradation was found either only at low currents (active region degradation) or both at low and high currents (active region and contact degradation) for the AlGaInP based laser [10]. The influence of the aging on noise in GaN-based LEDs was studied in Ref. [9]. While noise at low currents was not significantly affected by aging, the strong increase in noise related to series resistance was found in stressed devices. This result of Ref. [9] is in agreement with the previous study [2,3], indicating that the main degradation mechanism of GaN-based LEDs is the worsening related to the series resistance due the electromigration of the contact metal through the defects [2] or diffusion of the hydrogen from the passivation layer to the p-type region [3].

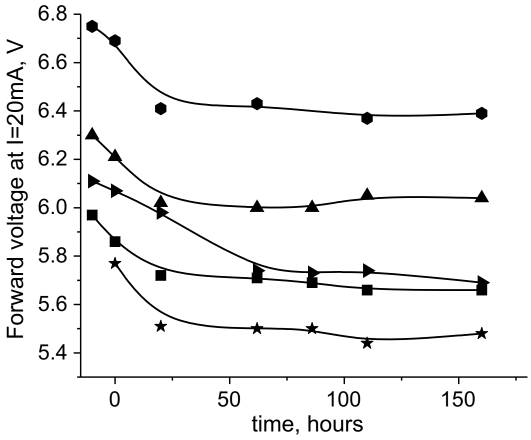

Fig. 4. Voltage drop at $I = 20$ mA as a function of the aging time for several LEDs.

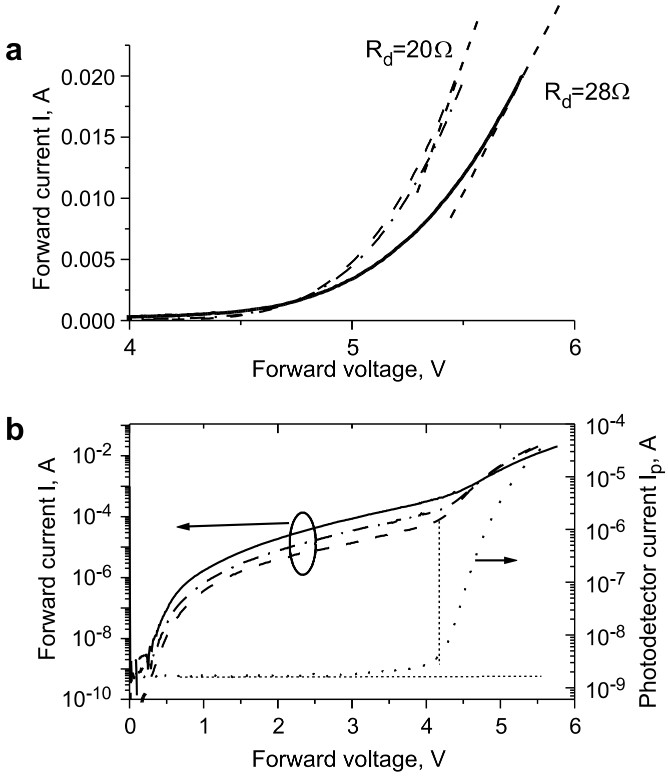

Fig. 5. Current–voltage characteristics of the LED D1 before aging (solid line), after 90 h of aging (dashed-point line) and after 160 h of aging (dashed line). Dotted line shows the photodetector current measured after 160 h of aging. Horizontal and vertical dashed lines show the photodetector dark current and the position of the light generation threshold voltage.

The low frequency noise in the present study was measured in a wide range of currents from 1 μA to 20 mA. At low currents, $I < 10$–50 μA, the noise spectra were close to the 1/*f* noise and spectral noise density of the short circuit current fluctuations, S_I, was proportional to the first power of the current. At the intermediate currents 50–100 μA < I < 1–3 mA the Generation–Recombination (GR) noise was found in many devices. For this current range the nonmonotonic dependence of S_I on current was typical. At higher currents the 1/*f* noise again dominated the spectra and S_I increased as $S_I \sim I^2$. The current dependence of noise in this type of LEDs was analyzed in details in Ref. [11]. In this paper, for the characterization of the degradation we choose only the noise measured at the lowest and the highest currents, i.e. at $I = 1$ μA and $I = 20$ mA.

Fig. 6 shows the spectral noise density at $f = 10$ Hz as a function of the aging time for low and high currents. Note first of all a high dispersion in the noise level for both low

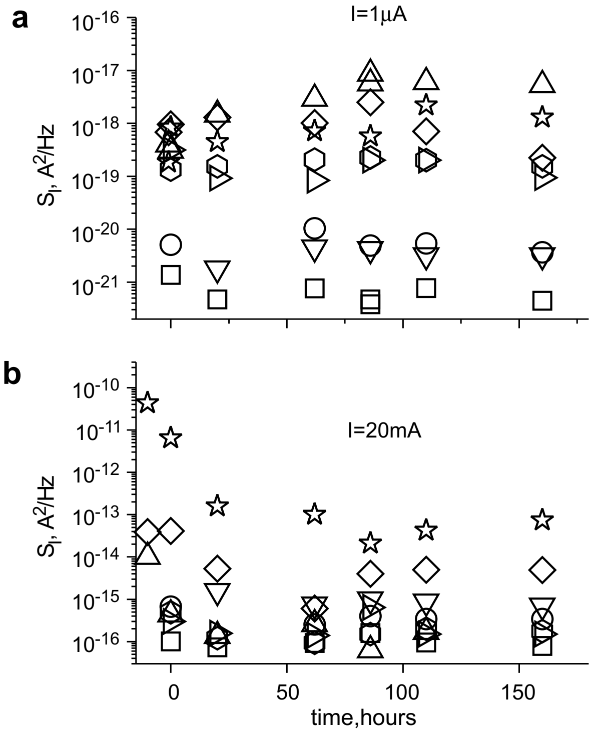

Fig. 6. Spectral noise density S_I as a function of the aging time measured at $I = 1$ μA (a) and $I = 20$ mA. Different symbols correspond to different LEDs, $f = 10$ Hz.

and high currents. In Figs. 2 and 6, the same symbols correspond to the same devices. No correlation between the noise level and the output power can be seen. For example, devices marked as down triangles and squares have similar noise level both at $I =$ μA and $I = 20$ mA (Fig. 6a) but the difference in the output power is the maximal for them among all LEDs (Fig. 2).

In spite of the different noise level, the rate of the degradation was the same for all LEDs, see Fig. 2. Although some LEDs demonstrated an increase of the noise at low currents (up-triangles in Fig. 6a), the aging behavior was identical to all devices. Some LEDs demonstrated a decrease of the noise measured at $I = 1$ μA at the aging time $t > 100$ h, see LEDs marked as stars, diamonds, and squares.

The noise level at high currents either remained unchanged or decreased with aging time. In Fig. 6b, stars correspond to the same LED for which current–voltage characteristics are shown in Fig. 5. This LED demonstrated the highest decrease of the current at low voltage and decrease of the differential resistance at high currents during aging. As seen from the Fig. 6b, this LED demonstrated also the highest drop of the noise level as a result of aging. Assuming that the noise at high currents is caused by the contact resistance, these two observations indicate that properties of the contact are actually improving during the stress.

Note also that dispersion in the noise level from device to device increases for $I = 1$ μA and decreases for $I = 20$ mA.

The decrease of the current at low bias (see Fig. 3 and Fig. 5, $V < 4$ V), stable peak wavelength and FWHM altogether provide a clue that the active region (quantum wells) remained unchanged or even improved as a results of the aging. Table 1 summarizes the observations of the present study and those made in other publications. As seen from the Table 1, we found that stress affects current–voltage characteristic and noise completely differently than was reported before for GaN-based LEDs with longer peak wavelengths. The only exception is a very small decrease in the voltage drop at high forward current that is seen in Fig. 6 of Ref. [3].

Therefore, the mechanism of the degradation of the devices under investigation is different from those reported earlier. This mechanism cannot be related to degradation of the light extraction. In this case, gradual degradation of the output power with time under stress would be of the same rate for different currents. Fig. 7 shows the power

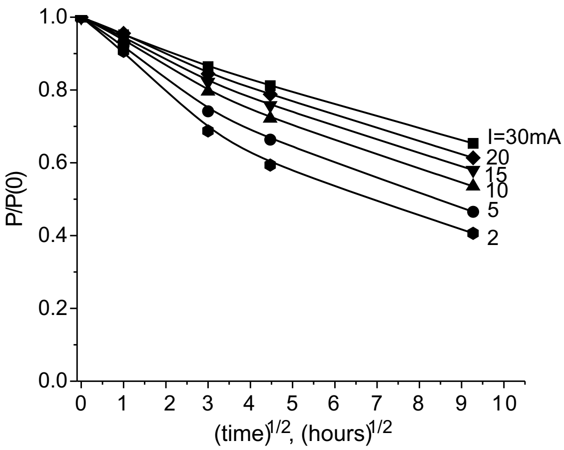

Fig. 7. Optical power normalized to the power of the unstressed LED as a function of time for different currents.

Table 1
Change in current–voltage characteristics and noise as a result of the stress from different publications for GaN-based LEDs

	[3], $\lambda \approx 500$ nm	[9], blue	[4], blue	Present paper, $\lambda \approx 280$ nm
Forward voltage drop at high current	Increase[a]	Increase	Increase	Decrease
Differential resistance at high current	Increase	Increase	Increase	No change or decrease
Non-radiative recombination current	–	Increase	Increase	Decrease
Noise at low current		No change		No change or small initial increase and decrease at $t > 100$ h
Noise at high current		Increase		No change or decrease

[a] For the devices without passivation a very small decrease of the forward voltage drop is seen in Fig. 6 of Ref. [3].

normalized to the power of unstressed device for different currents as a function of time. As seen, power at low currents decreases faster. Therefore, we conclude that the degradation is due to the decrease of the internal quantum efficiency.

The possible location of the degradation process might be the barrier layer associated with compositionally graded p-AlInGaN layer in the vicinity of the p-type contact. The mechanism of the degradation might be the diffusion of the Al atoms to the adjoining layers with the smaller Al mole fraction. As a result, the potential barrier lowers, the concentration of the carriers inside the quantum well decreases (light power decreases) and the current increases due to the increase of the number of electrons passing the cladding layer.

4. Conclusions

The AlGaN-based UV LEDs with the peak wavelength of 280 nm were aged by driving at high forward current. As a result of the stress, the gradual decrease of the optical output power was observed. For all devices the decrease of power followed the law

$$P_{\mathrm{out}} \propto 1/\sqrt{\mathrm{time}}.$$

While the output power decreased with aging time, the following observations have been made:

1. Series resistance either does not depend on the degradation stage or decreases with time.
2. Current at low bias often decreases with time.
3. Voltage drop at high currents decreases.
4. Knee on the current–voltage characteristic which corresponds to the light turn-on moves to the lower voltages with the aging time.
5. Peak wavelength and half bandwidth do not depend on time.
6. Noise at low current only weakly depends on time and even decreases for some devices at $t > 100$ h.
7. Noise at high current often decreases with time for the first 20–40 h.
8. Dispersion in the noise level from sample to sample is high and increases for $I = 1\ \mu\mathrm{A}$ and decreases for $I = 20$ mA.
9. There is no correlation between noise, the device output power and the rate of the power degradation.
10. Power at low currents decreases faster than at high currents.

These results show that the mechanism of degradation of these UV LEDs is different from that reported earlier for other GaN-based LEDs. In contrast to several publications on noise and degradation of GaN-based and other LEDs we found that there is no correlation between degradation and noise in these devices.

Nitride-based light emitting structures typically include electron and hole supplier layers, a light emitting structure, and an electron blocking layer. As shown in Ref. [12], the electron blocking layer can be eliminated using a graded composition AlInGaN layer between the hole supply layer and the light emitting structure. In both cases, the degradation mechanism might be related to the diffusion of the Al atoms into to the adjoining layers with a smaller Al mole fraction. As a result, the potential barrier for electrons becomes smaller, leading to the current increase and decrease of the electron concentration inside the quantum wells in the light emitting structure (light power decreases).

Acknowledgment

The standard UVTOP-280 LEDs for this study were supplied by Sensor Electronic Technology, Inc. The work at RPI has been supported by the National Science Foundation under “Connection one” I/UCR center. The work of S.L. Rumyantsev was partially supported by Russian Foundation for Basic Research.

References

[1] Reliability of gallium arsenide MMICs. Christou A, editor. John Wiley & Sons; 1992 [Chapter 5].

[2] Mukai T, Morita D, Yamamoto M, Akaishi K, Matoba K, Yasutomo K, Kasai Y, Sano M, Nagahama S. Phys Stat Sol (c) 2006;3(6):2211–4.

[3] Kim H, Yang H, Huh C, Kim S-W, Park S-Ju, Hwang H. Electron Lett 2000;36(10):908–10, 11th May.

[4] Meneghini M, Trevisanello L, Meneghesso G, Zanoni E, Rossi F, Pavesi M, Zehnder U, Strauss U. Superlattices Microstruct 2006;40:405–11.

[5] Meneghesso G, Levada S, Zanoni E, Podda S, Mura G, Vanzi M, Cavallini A, Castaldini A, Du S, Eliashevich I. Phys Stat Sol (a) 2002;194(2):389–92.

[6] Ursutiu D, Jones BK. Semiconductor Science and Technology 1996;11(8):133–1136. August.

[7] Berntgen J, Lieske T, Schineller B, Deufel M, Heuken M, Juergenson H, Heime K. In: Proceedings of the 10th international conference on indium phosphide and related materials, 11–15 May 1998, p. 741–4.

[8] Pralgauskaite S, Palenskis V, Matukas J, Petrulis J, Kurilcik G. In: Fourth SPIE international symposium on fluctuations and noise, 20–24 May, Italy: Florence; 2007.

[9] Bychikhin S, Pogany D, Vandamme LKJ, Meneghesso G, Zanoni E. J Appl Phys 2005;97:123714.

[10] Chen XY, Pedersen A, van Rheenen AD. Microelectron Reliab 2001;41:105–10.

[11] Sawyer S, Rumyantsev SL, Shur MS, Pala N, Yu Bilenko, Zhang JP, Hu X, Lunev A, Deng J, Gaska R. J Appl Phys 2006;100:034504.

[12] Gaska R, Zhang J, Shur M. Nitride-based light emitting heterostructure, Patent Application Publ., No.: US2006/0118820 A1, 2006.