Status of Performance and Reliability of 265 nm Commercial UV-C LEDs in 2023

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***Abstract*—In the last years, the research on ultraviolet-C (UV-C) light emitting diodes (LEDs) focused its efforts on the solution of major problems that limited the emitted optical power (OP) and that caused the sudden failure of the devices. This led to the availability in the market of some devices with interesting electro-optical characteristics and promising lifetimes. In this article, we decided to study the reliability of four commercial UV-C LEDs with a nominal wavelength of 265 nm, in order to study their lifetime and their possible implementation in disinfection systems. We submitted the devices to an accelerated lifetime test of 20 000 min, at the absolute maximum current indicated in their respective datasheets. During the tests, we carried out electrical and optical measurements, and we evaluated their spectral characteristics before and after aging. Once identified the best sample, we compared it with the best sample at 275 nm studied in our previous work, in order to show all the problems to consider if these LEDs have to be used in machinery that will be placed on the market.**

***Index Terms*—Degradation, disinfection, reliability, ultraviolet (UV) light-emitting diodes (LED).**

I. Introduction

THE improvement of deep ultraviolet (UV) light-emitting diodes (LEDs) has been a crucial research topic in semiconductors for a couple of decades [1], in particular those able to emit radiation in the ultraviolet-C (UV-C) spectrum. UV-C LEDs are a valuable tool in the fight against the spread of diseases, particularly in the current global health crisis caused by COVID-19. UV-C radiation has been shown to be effective in killing SARS-CoV-2 [2], the virus that causes COVID-19, and can be adopted in several ways to limit the spread of the pandemic condition.

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Since the development of the first UV-C LEDs, they have been the best candidate to replace low-pressure mercury tubes because they are smaller, lighter, and more compact, have a tunable wavelength, and have a faster startup [3], [4]. In the following years, great progress has been made in terms of LED performance, but nowadays they still suffer from low wall plug efficiency [1], self-heating, spectral impurities [5], [6], and difficulty in contact fabrication, and the p-doping [7], [8].

UV-C LEDs are based on the compound semiconductor aluminum gallium nitride (AlGaN). By increasing the Al content in the alloy, it is possible to increase the bandgap of the semiconductor and thus reduce the wavelength of the emitted radiation. Unfortunately, as the aluminum ratio increases the material quality, doping incorporation and lattice mismatch worsen, resulting in all the problems previously described in the above paragraph. The inevitable effect is that, to reduce the emission wavelength of the UV-C LEDs, new technological issues have to be addressed in order to achieve good device efficiency and lifetime. For some years, the most popular UV-C LEDs on the market had an emission wavelength of around 275–280 nm; this wavelength is a good balance between disinfection effects and LED's efficiency and reliability. However, recent works have suggested that, also for SARS-CoV-2, the maximum disinfection efficacy would be achieved at around 260 nm [2]. Lately, devices emitting at 265 nm are made available on the market by different manufacturers, increasing the efficiency of these devices and decreasing their price. This allowed a stronger implementation of UV LEDs in disinfection systems, however, a limited lifetime [9] is the main limiting factor in reducing their adoption in continuous virucidal apparatus, large volume systems, and wastewater treatment applications.

The aim of this article is to study the reliability of four commercial UV-C LEDs, with a nominal wavelength of 265 nm, submitting them to an accelerated lifetime test at their absolute maximum current for 20 000 min, i.e., about 330 h, in order to extract their characteristic lifetime parameters of L90, L80, and L70 (the time required to reduce the radiation emitted by the device to 90%, 80%, or 70% of its initial value). After that, we decided to compare the characteristics of a 265 nm LED with those of 275 nm LED, to examine the advantages of reducing the emission wavelength in disinfection systems, and finally propose an exhaustive comparison in application terms.

TABLE I
LEDs Characteristics Extrapolated From Datasheets

Device	T1	T2	T3	T4
Absolute Maximum Current [mA]	500	150	200	350
Peak Wavelength [nm]	265	265	265	265
Typical Radiant Efficiency [%]	0.8	1.7	2	5.7
Chip Size [mm^2]	0.8	0.25	1.21	1.43
Package Size [mm x mm]	3.5 x 3.5	3.5 x 3.5	4.5 x 4.5	6 x 6
Thermal Pad Area [mm^2]	*No*	3.84	6.72	*No*
Contact Area [mm^2]	7.68	2.88	8.5	31.9
Nominal OP at current [mW @ mA]	25 @ 440	10 @ 100	18 @ 150	100 @ 250
Estimated price [€]	113.20	25.33	20.64	36

II. Experimental Details

In Table I, we report the most relevant characteristics of the devices selected for the reliability test of this article. The LEDs are commercial off-the-shelf UV-C devices with a nominal emission peak at 265 nm available through the main electronic component distributors, they are produced by three different manufacturers. They were selected with different nominal electrical and optical characteristics to study different internal structures. All the devices are flip-chip type on a surface mount device (SMD) package; they were soldered on a proper metal core printed circuit board (PCB) to dissipate the generated heat. We tested one sample per type, at the absolute maximum current indicated by the manufacturer in the datasheet. It is worth noticing that LED T2 and LED T3 came from the same manufacturer.

Our measurement system was composed of a source meter, a photodiode, and a compact array spectrometer, to provide the electrical (Current versus Voltage: I–V), optical (Optical power versus Current: L–I), and spectral (Power Spectral Density versus Current: PSD-I) measurements, while the devices were temperature controlled by a thermo-electric plate. The accelerating lifetime test of 20 000 min (about 330 h) was interrupted at exponentially spaced time steps to provide the electrical and optical measurements as a function of temperature, from 15 °C to 75 °C with 10 °C steps. Instead, the spectral characterization was carried out before and after the tests. The stress current is set equal to the absolute maximum current indicated in the datasheets; instead, the current limits for device characterization were chosen to be close to the nominal current value, to not further stress the devices during the measurement phases. They are reported in Table II.

III. Experimental Results

A. Optical Characterization

Fig. 1(a) shows the optical characteristics of the devices under test. The first thing to observe is the lower current densities of the LED T3, which suggests that the LED was subjected to a stress condition much lower than the other devices. This is probably due to a manufacturer's conservative choice in the indication of the absolute maximum current, possibly related to power dissipation issues. For this reason, with respect to other devices, a lower degradation in all the parameters analyzed is expected. Each LED shows a decrease in optical power at all current levels, the degradation is more prominent at low current densities where Shockley-Read-Hall (SRH) recombination prevails [10]. This behavior suggests an increase in the defectiveness of the active region, as already reported in similar UV devices [7]. At higher current levels, i.e., the typical operating current levels at which the devices work, the optical performance degradation is less evident, these trends are reported in Fig. 1(b) where we plotted the gradual variation of the OP at the maximum measurement current. It is commonly correlated with the decrease in injection

TABLE II
Summary of the Experimental Details

Device	Stress Current Density [A cm^{-2}]	I-V current limit [mA]	OP-I Current limit [mA]	PSD-I at [mA]
T1	62.5	300	300	0.01, 0.1, 1, 10, 100
T2	60	100	100	0.001, 0.01, 0.1, 1, 10, 100
T3	16.5	150	150	0.001, 0.01, 0.1, 1, 10, 100
T4	24.5	300	300	0.01, 0.1, 1, 10, 100

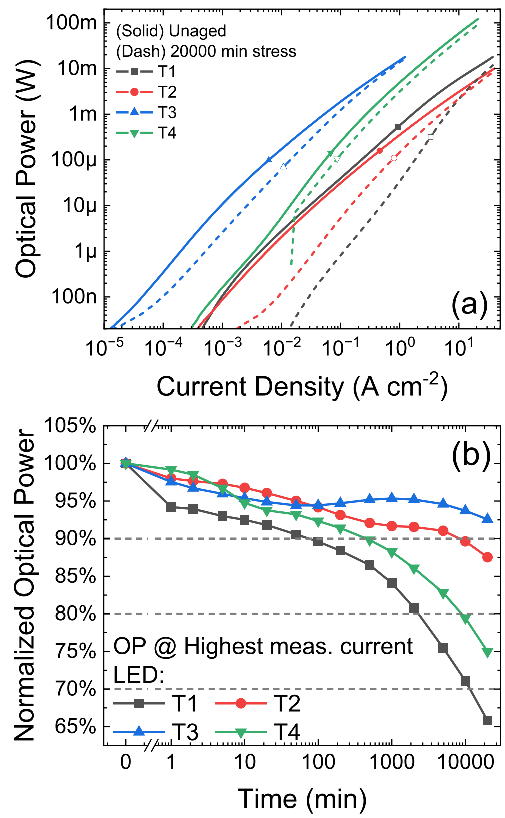

Fig. 1. (a) Optical characteristics (L–J) of the devices on a full logarithmic scale before and after 20 000 min of stress. (b) Optical power behavior at the maximum measurement current as a function of time.

TABLE III
SUMMARY OF THE LIFETIME OF THE DEVICES

Device	L90 [min]	L80 [min]	L70 [min]
T1	71	2300	11500
T2	8400	110000*	-
T3	47000*	-	-
T4	433	8800	39000*

* Extrapolated with a logistic fit

efficiency in the active region [11], [12], [13] and the increase in non-radiative recombination events [14], [15]. As we can observe, after 330 h LED T1 reached 66% of the initial optical power, LED T2 87.5%, LED T3 92.5%, and LED T4 75%. In Table III, we calculate and extrapolate, if possible, the L90, L80, and L70 of each device, i.e., the time at which the measured optical power reached 90%, 80%, and 70% of its initial value, respectively; where experimental data were not available an extrapolation was done by means of a logistic fit of the data, as proposed in [16].

These results are very promising, especially for LED T2 which is submitted to an aging test at high current densities (60 A cm^{-2}) and has an L80 of about 1800 h. On the other hand, LED T3, which comes from a similar series of the same manufacturer, shows an even longer lifetime, but was stressed at a current density almost four times lower. The much higher extrapolated lifetime of the LED T3 could be related to an initial recovery or stable phase which is not concluded after the stress time analyzed; its degradation level cannot be compared with the same value from other LEDs, so we decided to neglect its lifetime estimation in the following analysis.

The recovery in the optical power degradation kinetic showed by LED T3 and partially by LED T2 is of particular interest. This behavior was already observed in 275 nm UV-C LED [17] and it seems to be more outstanding for the 265 nm wavelength range. A hypothesis regarding this recovery could be given by a reduction of the quantum confined stark effect (QCSE) in the quantum wells (QWs), which leads to an increase in the superimposition of electron and hole wavefunctions. Further studies and analysis are in progress to confirm or deny this hypothesis.

B. Electrical Characterization

From the electrical characteristics reported in Fig. 2(a), we observed an increase in subthreshold leakage current in all devices, which can be ascribed to an increase in defects that create parasitic conduction paths through the active region [18], [19]. This increase is more prominent in LED T1 and it is well correlated with the higher decrease in OP at low current levels shown in Fig. 1(a). The turn-on voltage is similar for all the LEDs and is about 4.5 V, while the operating voltage is about 6 V, except for LED T4 which requires 8 V at 300 mA. The latter implies that during stress the LED should dissipate an elevated amount of heat compared to other devices, which could be a cause of a faster decrease in the optical power [20], [21]. To evaluate the impact of heat on the degradation, we also calculated the junction temperatures of the devices, establishing a similar T_j for LED T2, LED T3, and LED T4 of 44 °C, 46 °C, and 44 °C, respectively, and a T_j for LED T1 of 84 °C.

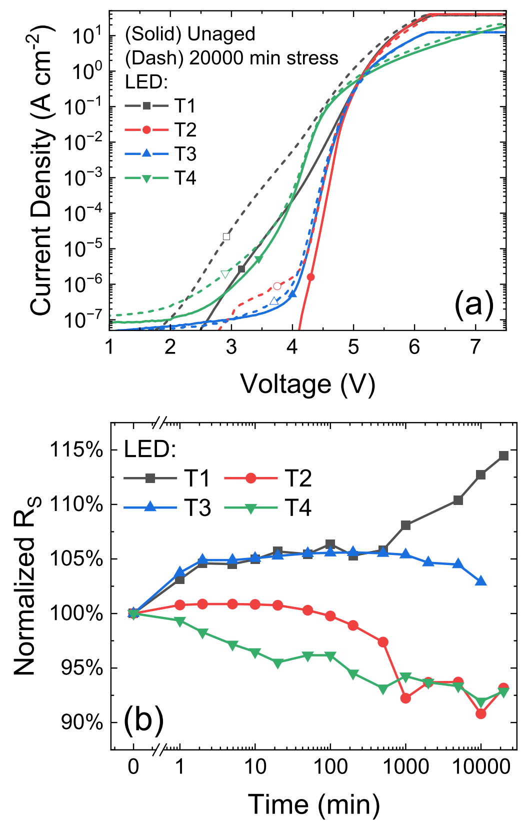

Fig. 2. (a) Electrical characteristics (J–V) of the devices on a semi-logarithmic scale before and after 20 000 min of stress. (b) Normalized series resistance in function of time.

In Fig. 2(b), we reported the normalized series resistance during the aging. We observed a different behavior for the LEDs: LED T2 and S had a decreased series resistance, probably due to an increase in localized defects that lower the conductivity of the device [22]; LED T3, after an initial increase, followed the trend of LED T2 that is similar but with a smaller area; LED T1 showed instead an increase in series resistance, possibly correlated to activation of Mg during the stress, as already proposed in [7].

C. Spectral Characterization

Fig. 3 reported the spectral characteristics of the devices, for the parasitic band interpretation we refer to our previous work in the literature, where the analyses were carried out for 275 nm devices [17]. What stands out from these plots is the fact that these devices had several parasitic spectral bands that need to be taken into account if the device is running at low current levels. The optical power emitted by the device is then partly, or totally composed of the parasite peaks, thus using the OP to calculate the disinfection effect of the LEDs at low currents can be misleading. For the analyzed samples, this condition is particularly relevant for LED T4 and critical for LED T1, whose spectrum is constituted only of yellow band luminescence [23] after the stress test, when measured at 10 μA. The presence of parasitic bands in the same order of magnitude as the main peak explains also the decrease in the slope of optical power at very low current levels [Fig. 1(a)] for LED T2 and T3, because at such low currents, the PSD is dominated by the parasitic emission which then saturates at higher currents.

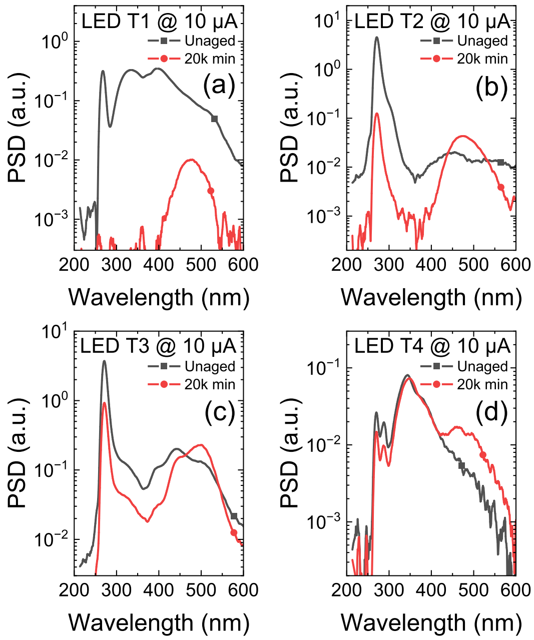

Fig. 3. PSD spectrum at room temperature (25 °C) and at 10 μA of (a) LED T1, (b) LED T2, (c) LED T3, and (d) LED T4.

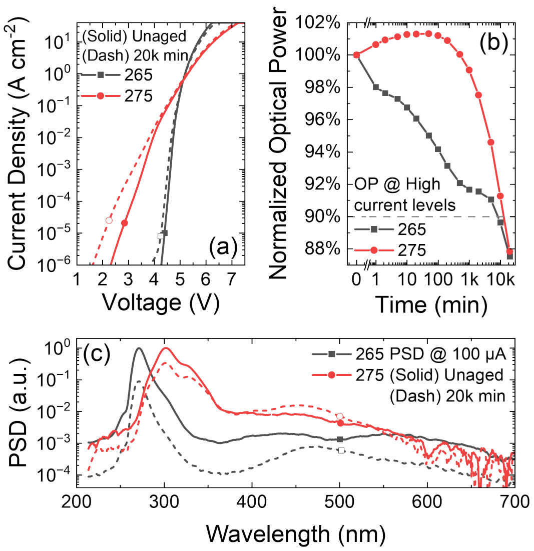

Fig. 4. Comparison of (a) electrical, (b) optical, and (c) spectral characteristics between LED T2 and LED B.

IV. Comparison Between 265 and 275 nm Devices

At this point, we decided to compare the characteristics of the most promising analyzed 265 nm LED (LED T2), and the most promising 275 nm LED investigated in our recent work on the reliability of 275 nm LEDs [17] (LED B). They are made by different manufacturers, and both devices had the same absolute maximum current (150 mA) and the same area (0.25 mm^2); the 265 nm LED presented a thermal pad and it cost 25.33€ against 3.99€ of the 275 nm LED. In Fig. 4(a), we appreciate that 265 nm LED had an operating voltage of 1 V lower than 275 nm and present a lower increase in subthreshold leakage current during the aging. From Fig. 4(b), we can observe better stability in terms of optical power over the first 1000 min of stress for 275 nm device, but almost the same degradation at the end of the test. Comparing the nominal radiant flux, 275 nm had a slightly higher OP at 100 mA, 12 mW, compared to 10 mW of 265 nm. In conclusion, in Fig. 4(c), both devices showed several similar parasitic emission peaks and bands, correlated with the yellow band emission in GaN [23], [24], [25], the charge accumulation in some barriers in the structure [26], and to carrier escape and current overflow in the active region [8]. It is worth noticing that the parasitic emission, with respect to the main peak, of 275 nm LED is an order of magnitude higher than that of the 265 nm device.

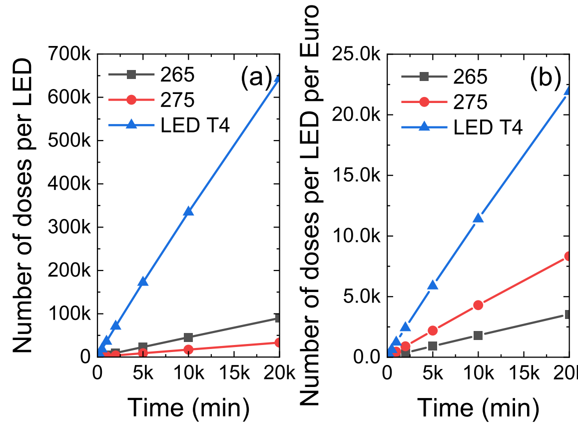

Fig. 5. (a) Number of doses and (b) number of doses per euro that each LED can provide in 20 000 min (330 h) at the absolute maximum current.

Evaluating these three characteristics altogether, we can state that 265 nm LED is a better device in terms of reliability, because it has a lower drive voltage, its optical power decreases with a slower kinetic, and it has lower parasitic emission components.

Considering that for an LED with a nominal wavelength of 265 nm, an optical power dose to reach the virus disinfection of 99.9% (log3) is 3 mJ/cm^2, instead of the 275 nm LED is 10 mJ/cm^2 [27]; in Fig. 5, we calculated how many doses each LED can provide in 330 h of operation at its absolute maximum current. We could notice that at the same current density condition, the LED at 265 nm can provide 2.7 times the doses of the 275 nm one. On the other hand, if we normalized these numbers to the cost of the devices, we obtained the opposite result, where the LED at 275 nm can provide 2.3 times the doses per Euro with respect to the 265 nm device. This is an important parameter to take into account in the implementation of disinfection systems based on these LEDs because if with 265 nm, LED we can provide the same number of doses in 1/3 of the time, the cost of these doses is higher (0.42€ per 1000 doses at 265 nm, 0.18€ per 1000 doses at 275 nm). For this reason, during the development phase of the system, a trade-off must be achieved between the LEDs' cost, the time spent to reach a certain number of doses, and the salary of the operator who has to follow the procedures.

To conclude, we decided to insert in this comparison LED T4, that have the same cost as LED T2 and a lower lifetime, but has a radiant flux ten times higher than LED T2. We obtained that this LED T4 can provide in 20 000 min 7.2 times the number of doses per LED with respect to LED T2, and 2.7 times the doses per LED per Euro provided by LED B. With its 0.05€ per 1000 doses, at the expanse of a lower lifetime, LED T4 is the best solution for implementation in UV-C disinfection systems.

The other two LEDs investigated, LED T1 and LED T3, can provide 202k and 17k doses per LED, respectively. This implies a number of doses per Euro of 1.8k and 800, respectively, and a higher cost of the doses, with 0.56€ and 1.23€ per 1000 doses.

V. Conclusion

In this article, we presented an exhaustive analysis of the reliability of state-of-the-art 265 nm UV LEDs, exploring the most important parameters for their implementation in commercial systems. These devices show promising characteristics, as long lifetimes (not yet close to visible counterpart) and limited electrical and optical degradation can be observed in short-duration stress tests, although they still present important aging indicators like different parasitic bands and peaks.

By comparing the two LEDs, one emitting at 265 nm and the second at 275 nm, offering the best reliability in their class, we demonstrated that the device emitting at 265 nm can achieve a greater number of disinfection treatments, even with a lower lifetime due to the improved efficacy of its radiation. However, the 275 nm device still has a reduced cost of operation due to its lower cost. It is interesting to notice that if we take the most powerful 265 nm UV LED tested in this comparison, its improved irradiance compensates for its reduced lifetime, thus delivering a much greater number of disinfection treatments during its lifetime as compared to the two previous devices. In this case, the shorter lifetime is more than compensated by the shorter irradiation time to achieve the required energy dose. This particular conclusion should be an important design consideration for a disinfection system developer; all these analyzed parameters must be taken into account for the realization of the best possible disinfection system, and optical power and reliability should be combined to estimate the energy that a device can emit during its operative lifetime.

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