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Research Article

^{60}Co γ-irradiation of AlGaN UVC light-emitting diodes

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ABSTRACT

270 nm AlGaN UV Light-Emitting Diodes (LEDs) were exposed to 1–5 Mrad fluences of Co-60 γ-rays. The effect of the exposure to radiation was a ~40% reduction in optical output after the highest fluence. No significant midgap emission was induced in the electro-luminescence spectra of the irradiated LEDs. We ascribe the decrease in optical output to creation of non-radiative states within the active regions. There were small (5–10%) increases in forward and reverse current as a result of irradiation with an effective carrier removal rate of <1 cm^{-1}. The irradiation did not produce any increase in degradation rate of the LEDs output power under high drive current (95 mA) compared to unirradiated devices, which is consistent with the lack of midgap emission. The relatively small changes in electrical and optical properties, along with the resistance of the $Al_xGa_{1-x}N/AlN$ to displacement damage effects indicate these devices may be well-suited to harsh terrestrial and space radiation applications.

1. Introduction

Deep-UV Light-Emitting Diodes (LEDs) are a promising technology with a wide range of potential applications, including sterilization, water purification, and medical diagnostics [1–5]. These LEDs emit light in the deep-UV wavelength range (230–300 nm), which is strongly absorbed by DNA and RNA, making them effective at inactivating a variety of microorganisms [3–5]. The external quantum efficiency (EQE) of $Al_xGa_{1-x}N$-based deep-UV LEDs is typically $<0.5\%$, but this can be improved by optimizing the device structure and fabrication process [6]. Recent advances in deep-UV LED technology have enabled the impressive development of devices with EQEs exceeding 10% [6–15], which is sufficient for many applications [6].

These LEDs have several advantages over conventional UV sources, such as mercury lamps and excimer lasers [1–15]. They are more compact, have a longer lifetime, and can be modulated at much higher frequencies. These LEDs are also expected to have applications in the Laser Interferometer Space Antenna (LISA), the first gravitational wave detector in space, for discharge capability on free-flying test masses to minimize the effect of electrostatic forces caused by cosmic rays and solar particles [16–20].

However, there is still much to understand in terms of the response of these materials to various radiation environments, including total ionizing dose conditions where ionization energy deposition dominates and single event upsets during heavy ion strikes [18,21–28]. Sun et al. [18] reported experiments in which UV LEDs were irradiated with ~63 MeV protons to fluences of 2×10^{12} protons/cm^2, equivalent to ~100 years of radiation dose in the LISA orbit. The light output from the LEDs did not show significant changes. The strong atomic bonding and high defect recombination rates at room temperature are reasons why these materials also display strong resistance to radiation damage displacement effects and highlights their potential for operation in harsh space or terrestrial environments [28]. However, the response to other sources of radiation, including gamma rays, neutrons, and electrons must be established. Radiation damage in photonic devices can cause several problems, including a decrease in the emission intensity, increase in the leakage current and a decrease in the breakdown voltage and creation of defects in the device, such as vacancies and interstitials, which can trap carriers and lead to non-radiative recombination. Wang et al. [21] reported that γ -ray irradiation accelerated degradation caused by

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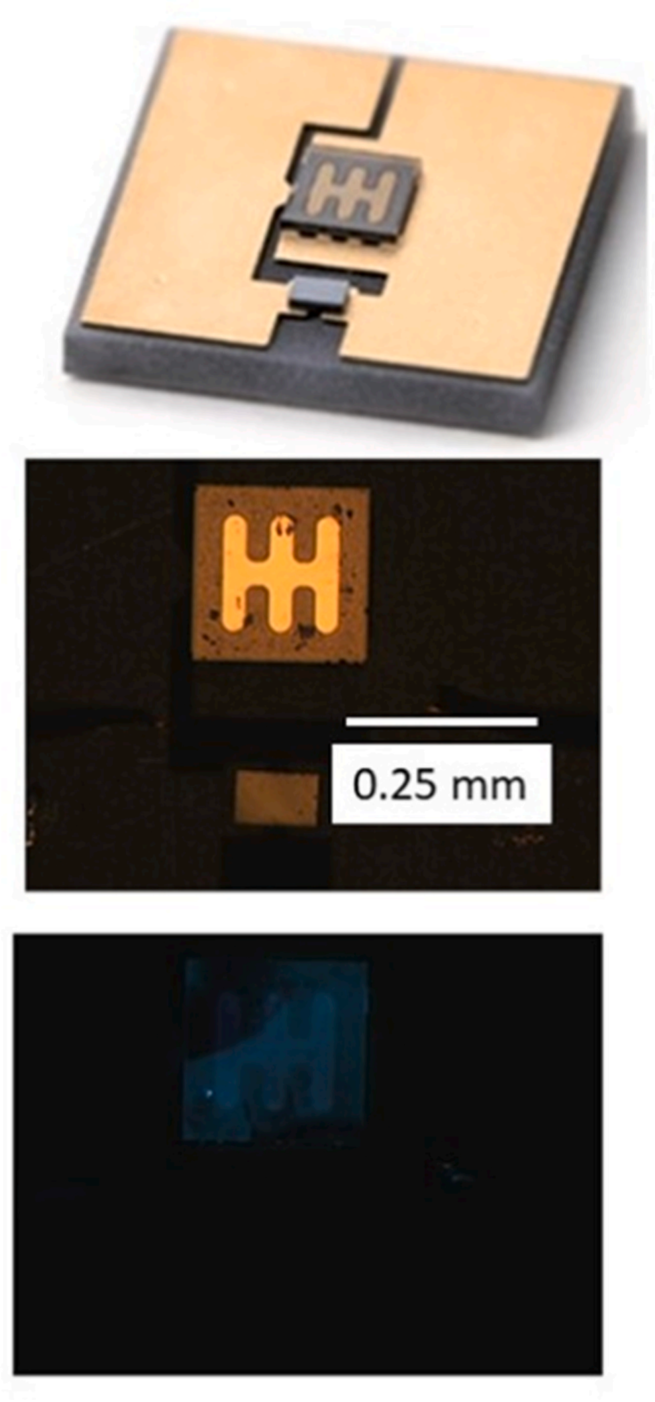

Fig. 1. (Top) Optical microscope image of packaged UV LED (center) image of device at zero bias and (bottom) small amount of visible light observed under bias in the dark. In the top image the chip area is 3.5 × 3.5 mm^2.

electrical stress in AlGaN-based UVC LEDs. Typically, UV LED aging rate is inversely proportional to the third power of drive current density [30–36], and part of the degradation in optical output is due to Auger-Meitner recombination, in which electrons and holes recombine across the semiconductor band gap [37]. This leads to a transfer of energy via the Coulomb interaction to another electron or hole, which is excited to a higher energy state.

The presence of resistive layers within the UVC LED raises the question of the possible susceptibility of such devices to ionizing radiation, which can be conveniently studied using gamma rays [38]. Total Ionizing Dose (TID) testing using Co-60 γ sources remains the standard test method for space craft instrumentation qualification [39].

The main energy loss mechanism at the energy of Co-60 γ-rays is Compton scattering. This can lead to secondary electrons able to displace lattice atoms [40,41]. The primary displacement defects created in AlGaN by gamma-irradiation are Frenkel pairs, produced by these Compton electrons. The Non-Ionizing Energy Loss (NIEL) for gamma rays is much less than for ions, with only a few percent of the gamma photon flux creating secondary Compton electrons.

In this paper we report on the response of UVC LEDs to Co-60 gamma rays. Even to fluences of 5 Mrad, no midgap emission is introduced and only modest decreases in band edge emission are observed. This fluence does not increase the degradation rate of output power under high drive currents.

2. Experimental

The 270 nm packaged LEDs (Klaran LA Series) with peak emission between 260 nm and 270 nm, >80 mW output power and mounted in 3.5 mm × 3.5 mm surface mount diode packages were purchased from Crystal IS. The basic structure consists of epi layers from by Metal Organic Chemical Vapor Deposition on a (0001) AlN single crystal substrate. The buffer layer is ~0.5 μm of $Al_{0.7}Ga_{0.3}N$, followed by a multi-quantum well structure consisting of pairs of $Al_{0.58}Ga_{0.42}N$/$Al_{0.7}Ga_{0.3}N$ wells/barriers. There is an electron blocking layer prior to the p-GaN top contact layer. More details are described elsewhere by the supplier [42]. The bowing parameters and emission wavelength for AlGaN QWs as a function of Al composition are described elsewhere [43,44]. A photograph of one of the LEDs is shown at the top of Fig. 1, while the center and bottom shows the difference in the same device under bias without room illumination to show the almost complete absence of visible emission from midgap states. The current–voltage (I–V) characteristics were recorded with an Agilent 4156C parameter analyzer was used for forward and reverse current and capacitance–voltage (C–V) measurements. The emission spectra were measured using an Avantes AvaSpec-ULS2048XL-EVO spectrometer, which was fiber-coupled the spectrometer to the UV LED with a 600 μm diameter fiber optic cable. Total output power measurements were made by coupling the LEDs to a Si photodetector in series with a 55 Ohm resistor, measuring the resistor voltage, and calculating the resultant power. The statistical spread in spectral characteristics of large batches of these LEDs has been reported previously [29,30].

Packaged devices were irradiated by a Co-60 irradiation facility within a 1 MW TRIGA facility at the RSEC, Penn State, with a dose rate of 180 krad/h (±~10%), resulting in total fluence of 1 or 5 Mrad (Si). The isodose region was used to ensure isotropic gamma dose. The TID was calculated using the relation 1 rad (Si) = 2.0 × 10^9 photons. cm^{-2}, which represents the energy lost to ionization over mass. No secondary irradiation was induced in the AlGaN/AlN by Co-60 gamma rays. The LEDs were unbiased during the approximately 30-h exposure, and the generation rate in the AlGaN quantum wells was estimated to be ~10^{15} e-h pairs/Gy.cm^3 based on reported threshold energies for pair creation. The gamma rays pass through the entire packages structure, as evidenced from the mean-free path shown in Fig. 2 (top). This was obtained from the EpiXS code for photon attenuation [45]. The linear attenuation coefficients are dominated by Compton scattering for the energies of Co-60 γ-rays, as shown at the bottom of Fig. 2 [45].

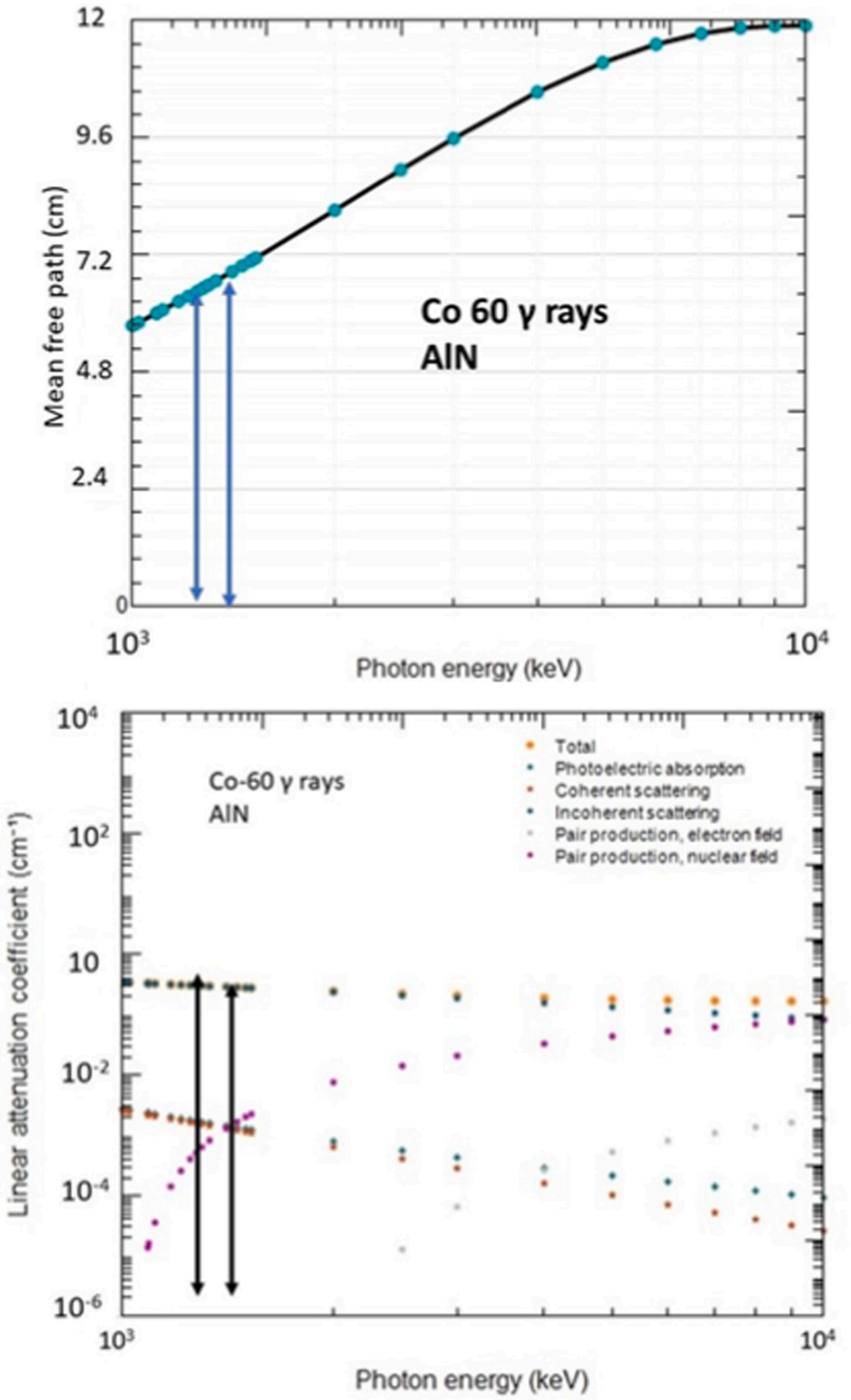

Fig. 2. (Top) Mean free path of γ-rays as a function of energy in AlN (bottom) linear attenuation coefficients as a function of photon energies. The specific case of specific case of Co-60 γ-ray energies are indicated by the vertical lines in both plots.

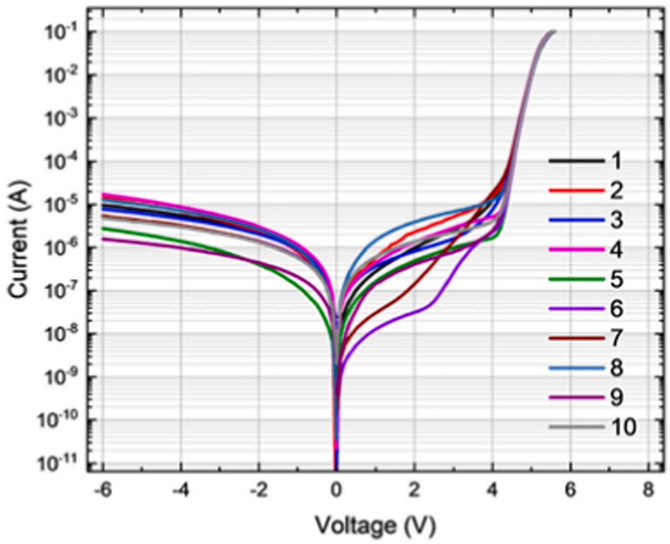

Fig. 3. Collection of I–V characteristics from 10 different UV LEDs prior to irradiation.

3. Results and discussion

It is important to establish the statistical spread in the initial performance of the LEDs so that the change in performance after irradiation can be quantified. Fig. 3 shows the I–V characteristics of 10 individual devices prior to irradiation, with outliers removed. The spread in their performance is comparable to the radiation-induced changes, so we identified each individual LED and kept track of their characteristics before and after the radiation exposure. We were very careful to compare the same devices before and after irradiation, and that's why we kept track of the individual device number. We therefore feel very confident the changes seen after irradiation are representative. The I–Vs are typical of previously published reports, with turn-on voltages around 4 V [29,30]. Outlier devices can be excluded by selecting for figures of merit, such as the UV power at 1 mA or 20 mA, the ratio of optical power within the main spectral peak to total optical power at low drive currents, reverse leakage current at a drive voltage of −6 V, ideality factor before turn-on, and ideality factor after turn-on [29,30]. The ideality factors are generally >2 due to the presence of multiple current conduction mechanisms [46–48].

Fig. 4 shows the electro-luminescence spectra from a typical LED before and after 1 or 5 Mrad fluence. The panel at top shows the data in linear form, where it is clear the peak intensities have decreased by ~10 and 35%, respectively, for 1 and 5 Mrad exposures. Noteworthy is the data in the bottom panel, where the log scale plots reveal there is no increase in the midgap emission from 400 to 600 nm. These transitions are usually ascribed to the presence of deep trap states, which degrade the optical and electrical performance of the LEDs [47,48]. This has important implications for the subsequent aging kinetics of the LEDs, as discussed later. The increase in non-radiative recombination centers in the quantum wells and barriers, and this behavior has been ascribed to Al or Ga vacancy complexes [32–34].

Fig. 5 shows the integrated power from the LEDs as a function of drive current before and after the fluences of 1 Mrad (top) or 5 Mrad (bottom). These were measured by the Si photodetector. The changes in output power support the small changes seen in peak bandedge intensity observed in the spectra.

Fig. 6 shows the I–V characteristics from LEDs before and after irradiation with either 1 Mrad (top) or 5 Mrad (bottom). Within experimental error, there is no change in the I–V characteristics for the low fluence condition. For the 5 Mrad condition, we were able to find an LED with low initial reverse leakage and that showed an increase in both reverse and forward current after irradiation for voltages <4 V forward and <6 V reverse bias. This is consistent with previous report for devices where their performance was degraded by forward bias stressing [21]. This was ascribed to generation of point defects which form deep levels and act as non-radiative Shockley–Read–Hall recombination centers [32,49,50]. From the reverse bias capacitance change after irradiation, we found the carrier removal rate was $<1\ \mathrm{cm}^{-1}$. This is consistent with the small amount of displacement damage created by the γ-rays. We want to emphasize that the reverse current increase was only visible in a limited number of LEDs. These were devices with a lower initial reverse leakage, and we were able to see an increase with irradiation. Most devices did not show any significant increase after irradiation because of their higher initial reverse current. We did this to emphasize the

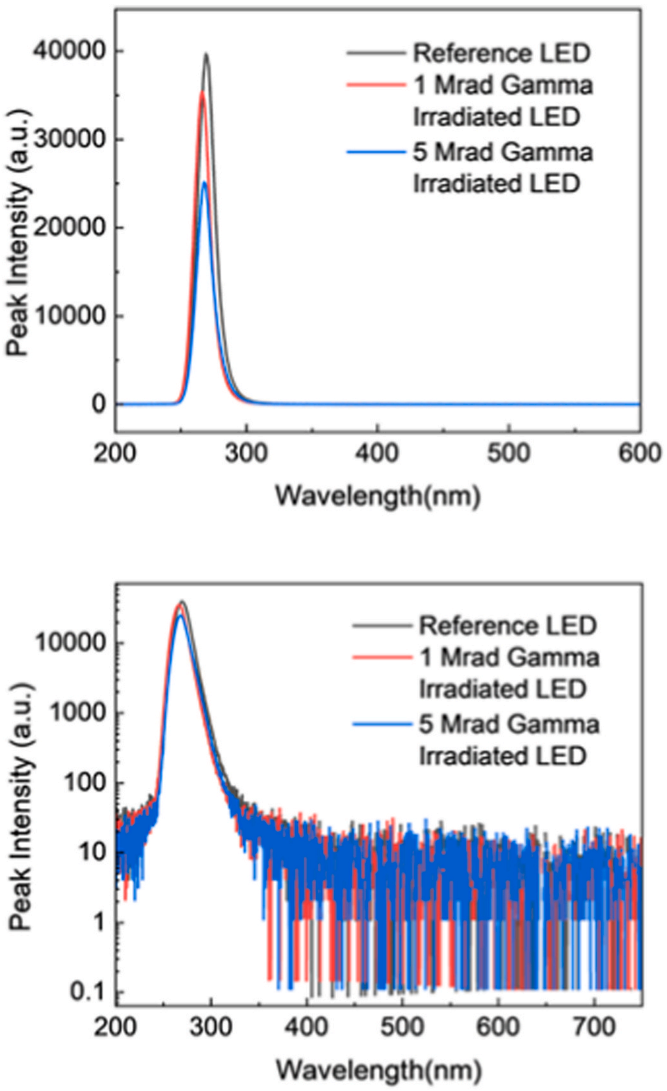

Fig. 4. (top) Output spectra from UV LED before and after irradiation with 1 or 5 Mrad fluence (bottom same spectra, shown on log-scale. Note the absence of midgap emission, even after irradiation.

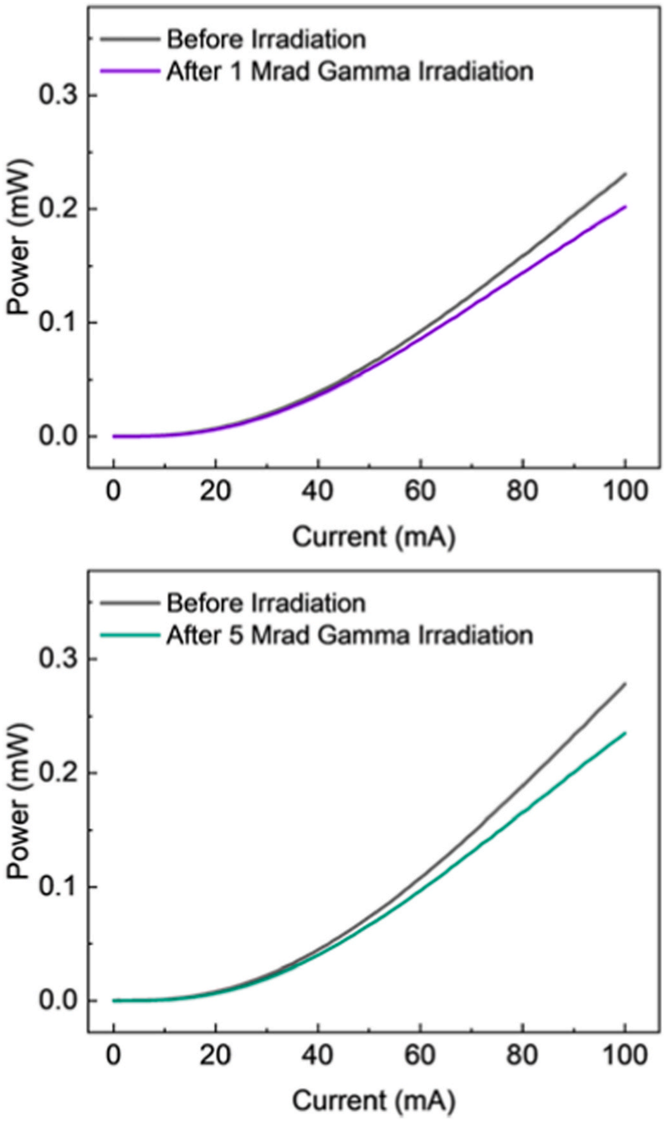

Fig. 5. Output power as a function of drive current before and after (top) 1 Mrad fluence or (bottom) 5 Mrad fluence.

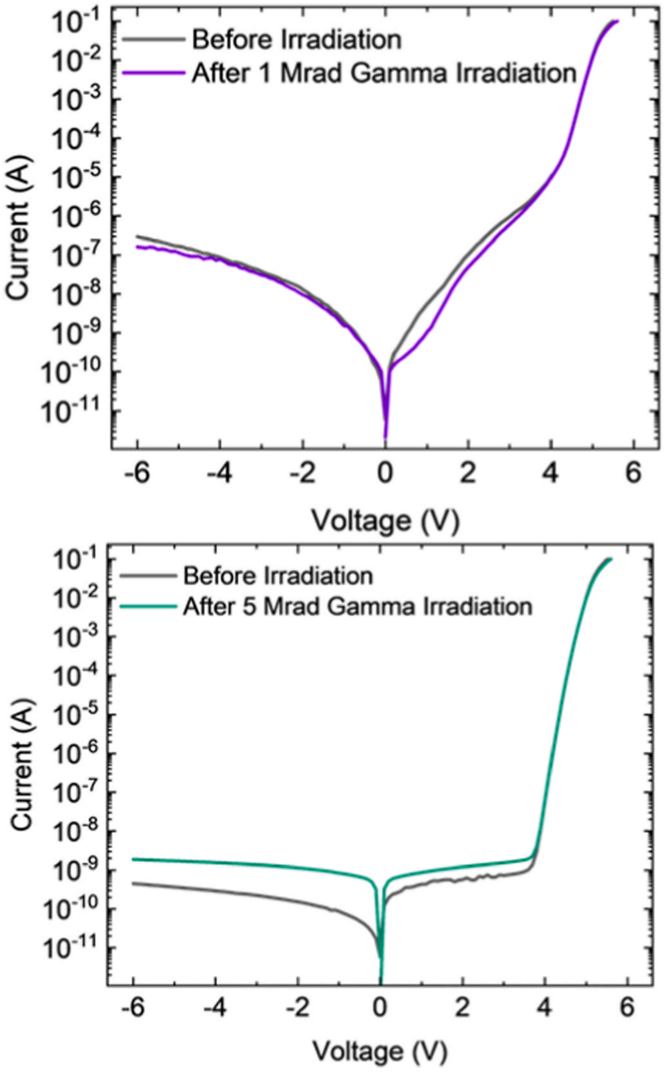

Fig. 6. I–V characteristics from UV LEDs before and after irradiation with (top) 1 Mrad or (bottom) 5 Mrad.

relatively small changes induced by even the highest gamma ray fluence.

Fig. 7 shows that the aging characteristics of the LEDs under a high forward current of 95 mA was unaffected within experimental error by the irradiation fluence of 5 Mrad. This is consistent with the low concentration of midgap states evident from the emission spectra after irradiation. Wang et al. [21] reported that γ -irradiation accelerated the degradation of UVC LEDs induced by electrical stress. They employed lower Co-60 fluence of 1.75 Mrad (Si) but did use LEDs grown on sapphire substrates, which will have higher dislocation densities than the devices in this study and may have made the devices more prone to degradation during forward bias stressing. Our results show the benefit of advanced AlN substrates for growth, which improve LED performance (external and internal quantum efficiency) as well as LED lifetime.

4. Summary and conclusions

UVC LEDs grown on AlN substrates show robustness against Co-60 γ-rays to fluences of 5 Mrad (Si) and show their applicability to operation in radiation environments such as space or nuclear plants. The devices show a decrease of ~40% in peak emission intensity as a result of the irradiation, with relatively small changes in the electrical characteristics due to trap-assisted tunnelling. The absence of midgap emission in the unirradiated LEDs is an advantage, since it is clear that a threshold density of midgap states are needed to affect the subsequent aging characteristics and starting with a low number means the introduction of traps by irradiation doesn't reach this threshold.

Given the previously established radiation hardness of UV LEDs to proton irradiation, our results add to the notion that these devices will be well-suited to space-borne applications.

CRediT author statement

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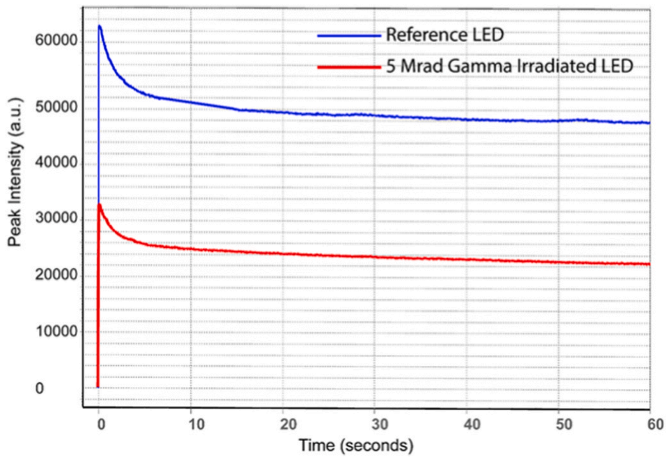

Fig. 7. Time dependent peak intensity under forward 95 mA bias for reference (unirradiated) and 5 Mrad fluence exposed LEDs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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