Destruction of LED heterostructures under high-current electron beam irradiation

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Abstract. This paper presents the experimental results of the fracture morphology of InGaN / GaN heterostructures and epitaxial GaN layers deposited on sapphire substrates after irradiation with high current electron beams. A special type of damage - microspheres, ~1-5 μm was discovered and studied. The results show that the microspheres act as diffractive optical elements redistributing the stimulated emission of InGaN/GaN in space.

1. Introduction

The study [1] reveals the prospects of luminescent control of light-emitting InGaN/GaN heterostructures on sapphire substrates by high-energy high-current electron beams (HCEBs). In view of this, it is necessary to elucidate the mechanisms of breaking the light-emitting heterostructures during their HCEB diagnostics. As is known, the HCEB irradiation of dielectrics and semiconductors is accompanied by their fracture [2-4]. Threshold electron beam energy density H* required for breaking macrosamples with a size over the electron beam penetration depth in a material is determined by the type of a solid and increases at the transition from ionic crystal dielectrics to semiconductors. It was established that the main mechanisms of the HCEB initiated fracture of dielectrics and semiconductors are thermal shock [2, 3] and electrical breakdown [4]. Both mechanisms are related to the features of the HCEB effect on materials—specifically, high rates of charge and energy input (10^{10}–10^{11} C m^{-3} s^{-1} and 10^{11}–10^{13} Gy s^{-1}, respectively) [5]. The discharge mechanism of dielectric fracture is implemented, as a rule, in the regime of multipulse irradiation of samples by a low-density ($H \approx 0.1$ J/cm^2) electron beam; the thermal shock is implemented in the regime of single irradiation by an electron beam of higher density ($H \geq 0.6$ J/cm^2). These mechanisms can be experimentally distinguished by the characteristic morphology of fractures [4]. This article considers the morphology of electron-beam-initiated fracture of light-emitting diode heterostructures (HSs) based on InGaN/GaN quantum wells grown on sapphire substrates and determines possible mechanisms of their fracture.

The purpose of this work is to study the destruction patterns and features of GaN / InGaN LED heterostructures under irradiation by a high-current electron beam.

2. Methods

In this work, three LEDs with InGaN / GaN quantum wells, grown by various manufacturers using organometallic gas-phase epitaxy on sapphire with (0001) orientation, were investigated (figure1).The samples had a dislocation density of 10^7 - 10^9 cm^{-2}. The samples were irradiated in atmospheric air at room temperature.

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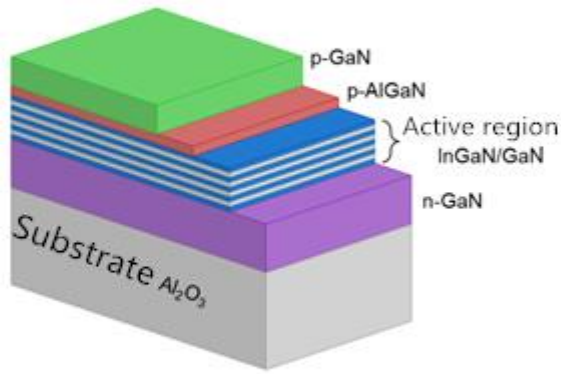

Figure 1. Sample LED heterostructure

The excitation source was an electron accelerator with a GIN-600 generator (350 keV, 2 kA, 15 ns). The electron beam energy density was varied in the range of 0.05–0.25 J / cm^2.

The spatial distribution of luminescence over the sample surface was photographed by a SONY DSLR-A500 digital camera in the "Bulb" mode during a single excitation pulse through an MBS-10 microscope (figure 2). The morphology of residual damage resulting from multipulse irradiation of HCEB was detected using a μVizo-101 transmission microvisor.

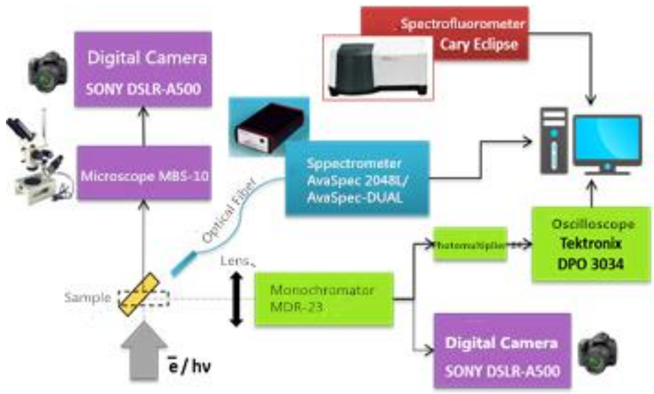

Figure 2. Source of excitation: HCEB (U = 350 keV; t = 15 ns; 0.02 - 1 J/cm^2);

3. Results and Discussion

Figures 3 and 4 show the morphology of damage, two mechanisms characteristic destruction of the HS by an electron beam. It can be seen that for thermal shock, the typical type of damage is cracks in both crystallographic planes and in other directions (figure 3). For the electrical breakdown, GaN's electrical breakdown channels and local micro-region damage are typical damage (figure 4).

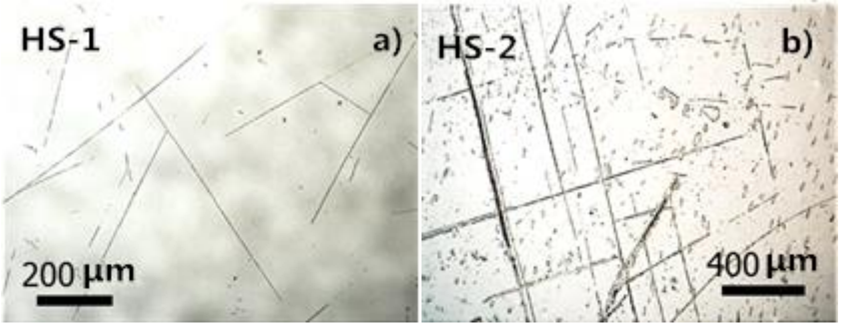

Figure 3. Cracks, formed in the samples after 10 pulses of the HCEB, H = 1 J/cm^2

Table 1 The angles between the cracks formed in the samples under the action of the HCEB

Sample	Angles between cracks, degrees
HS-1	2; 3; 4; 5; 6; 8; 9; 10; 12; 13; 15; 17; 22; 24; 31; 33; 37; 46; 62; 65; 71; 74; 75; 77; 80; 82; 83; 84; 86; 87; 88; 92; 93; 95; 108; 117; 119; 132
HS-2	1; 2; 9; 13; 28; 37; 41; 50; 92; 93; 94; 105; 106; 107; 133; 134; 135; 142; 143; 144

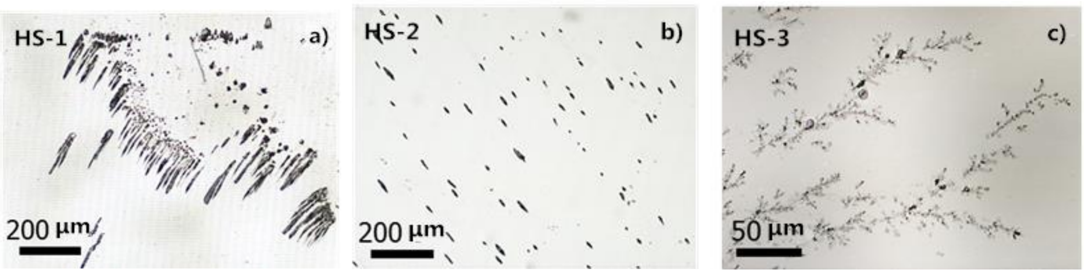

Figure 4. Photographs of micro destruction in the heterostructure samples after 100 irradiation pulses of HCEB (H = 0.25 J/cm^2)

A special type of degradation of the HS, recently discovered by us, is a spherical region with diameters of 1-10 microns (microspheres). The photograph of microspheres obtained on sample HS-3 is shown in Fig. 5. Similar structures were previously observed on the samples of Alkali Halide Crystals (AHC) irradiated by a HCEB. Studies have shown that these microspheres are formed as a result of the impact of a stretching wave on a crystal. As a result, spherical pores form in a solid. In our case, such pores are formed in HS-3.

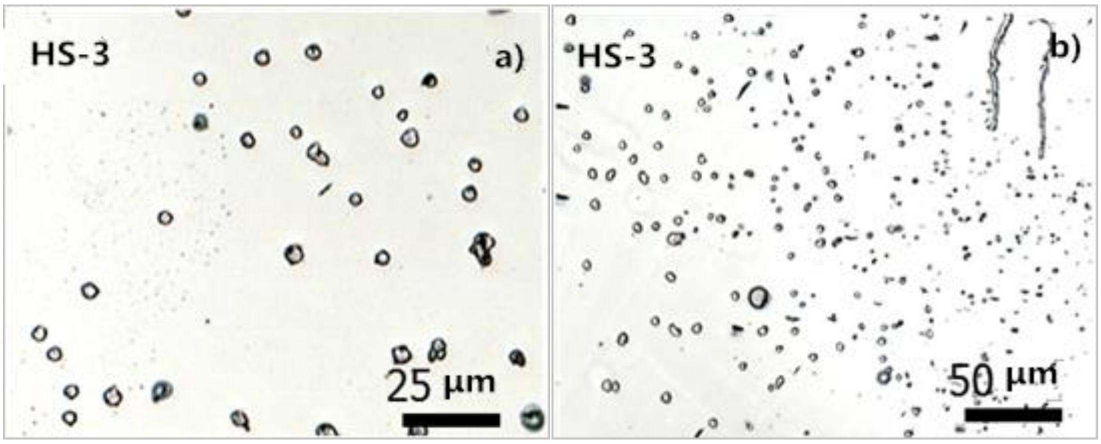

Figure 5. Destruction morphology of sample HS-3 after 100 pulses irradiation by HCEB at H = 0.6 J/cm^2

When photographing the spatial distribution of pulsed cathodoluminescence (PCL) over the surface HS-3, we observed stimulated radiation diffraction on the microspheres. Photographs of PCL diffraction on microspheres are shown in Figure 6.

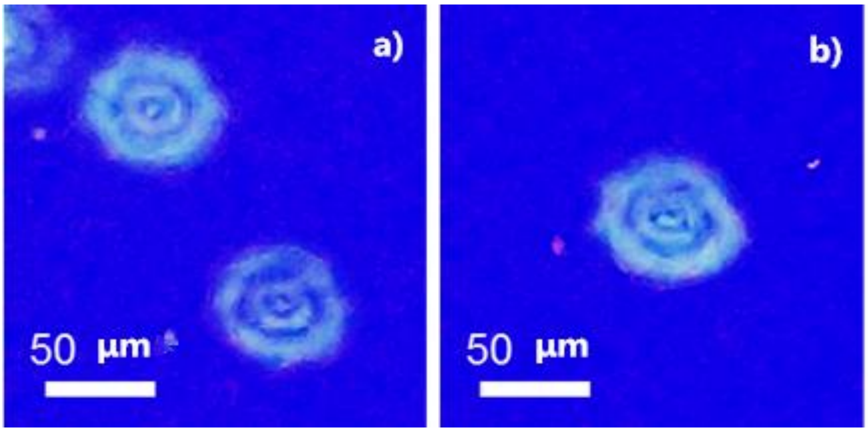

Figure 6. The pulsed cathodoluminescence photographs of the sample HS-3 with microspheres by excitation HCEB (H = 0.6 J/cm^2)

The diameter of the outer ring is 50 µm, and the diameter of the central spot is ≈ 5 µm.

The formation of microspheres (pores in a solid) during the irradiation of HCEB was observed by us in other samples: in polymethyl methacrylate (PMMA) and in glass with a protective film sprayed onto the surface (figures 7-8).

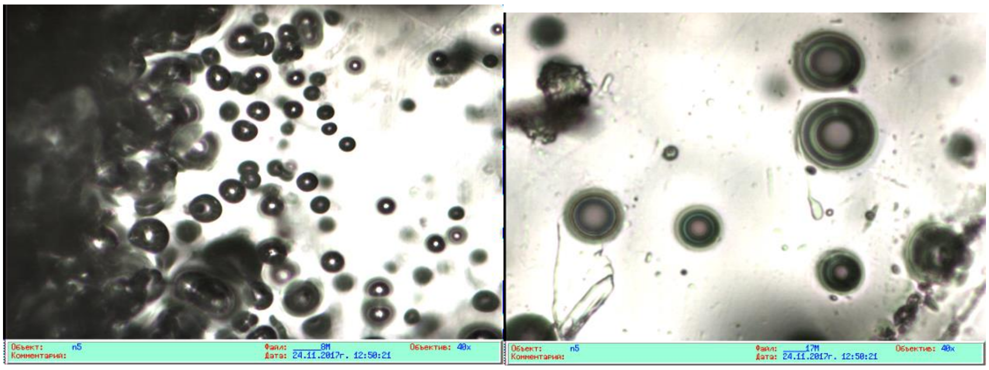

Figure 7. Diffraction of light on microspheres formed in PMMA when exposed to HCEB

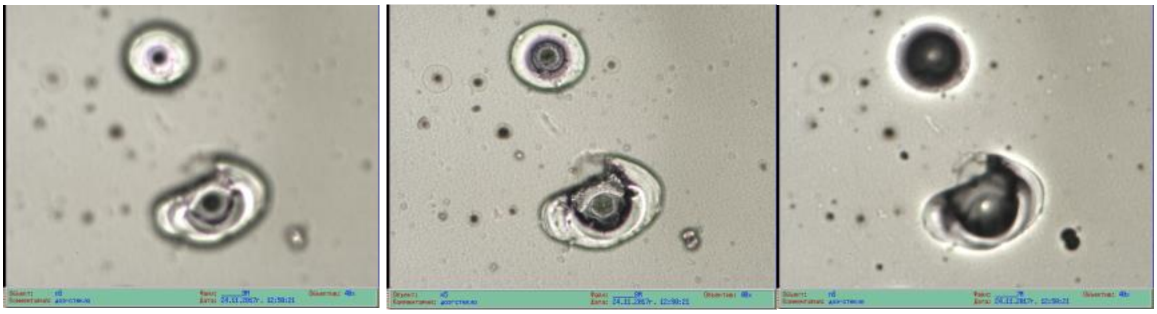

Figure 8. Diffraction of light on microspheres formed in glass with a protective film when exposed to laser radiation

An analysis of the experimental data obtained in this work suggests that the formation of microspheres is associated with the action of stretching acoustic wave on a solid. Acoustic waves with a high amplitude, sufficient for the destruction of solids, can be formed as a result of the HCEB, and laser radiation.

Microspheres play the role of local “mirrors” for stimulated InGaN quantum wells PCL: bright luminous microzones are characteristic of samples in whose luminescence spectra recorded stimulated InGaN quantum wells emission. It has been established that the spatial distribution of luminous microzones coincides with the localization regions of electron-beam microspheres. The spectral composition of the luminescence HS-3 before and after the electron-beam damage formation does not change.

4. Conclusion

As a result of the research, it was established that during the irradiation of the HS by an electron beam, three types of fracture structures are formed: cracks, electrical breakdown channels and microspheres. The electrical breakdown channels are formed as a result of the electrical discharges development in the HS. Cracks and microspheres are formed by the interaction of a bipolar acoustic wave with free surfaces of the irradiated samples. It is shown that microspheres can play the role of passive optical elements (local “mirrors” and diffractive optical elements) that do not affect the spectral composition of the luminescence, but only redistribute the stimulated emission of the quantum-well active InGaN / GaN region in space.

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