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Acoustic emission and fluctuations of electroluminescence intensity in light-emitting heterostructures

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Abstract. It was shown that in the GaAsP/GaP and InGaN/GaN heterostructures during current passage redistribution of electroluminescence intensity on the structure surface takes place simultaneously with radiation of acoustic emission. Local (on surface area) fluctuations of electroluminescence intensity are observed together with general degradation of electro-physical parameters.

Keywords: acoustic emission, light-emitting diodes, electroluminescence.

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1. Introduction

Evolution with time and change of current of non-uniform distribution of electroluminescence (EL) intensity on radiating surface of light-emitting diodes (LEDs) based on the InGaN/GaN and GaAsP/GaP heterostructures was already described by us [1, 2] and many other researchers, for example in [3-6]. Active processes of defects formation and fluctuation in these heterostructures in excess of the density of direct current (J), which is specified by the manufacturer as maximal density of the direct current $J_{\max}$, impose the certain restrictions on their field of application, because EL intensity could be several times higher with J increase [1, 2, 7-10]. A similar possibility for the pulse current (pulse duration 3 and 0.3 μs, off-duty factor $\sim 3\cdot 10^3$) was shown in [11].

To solve these problems, many physical mechanisms of the active processes, in particular, dynamics of defects development, transformation of functional parameters of LEDs and also their interrelation should be investigated [1-12].

Increase of the integral EL intensity I in LEDs, caused by injection current density J increase, leads to non-uniform distribution of I [3-10] on the active area of the structure and on any cross-section of the current tube [8-10], in particular, due to effect of current crowding [3, 5], and also to significant additional local overheating of the active area [1, 2, 5-10]. These and other factors considerably decrease LEDs efficiency.

In the InGaN/GaN LED active area, the gradient $\Delta T(r)/\Delta r$ reaches a considerable value (by our estimations not less than 10^3-$7\cdot 10^3$ °C/cm [1, 10], according to [5, 12] – $\sim 10^4$-$2\cdot 10^5$ °C/cm). This fact, taking into account distinction of the thermal expansion coefficients α_i and lattice constants a_i of individual layers, leads to formation of local inelastic thermo-mechanical stresses in *p-n* junction [1, 2, 5, 7-10, 12]. At the same time, it is known that ultra-fast relaxation of these induced mechanical stresses in LEDs results in appearance of spontaneous chaotic acoustic radiation – acoustic emission (AE) of materials [1, 2, 7-10, 13].

The purpose of this work was to analyze dynamics of local processes in relaxation and defects formation in the light-emitting InGaN/GaN and GaAsP/GaP heterostructures, induced by the direct current, which leads to simultaneous changes in the EL intensity distributions on a surface of the structure $I(S)$, AE occurrence, oscillation of I, and also fluctuations of current and general degradation of electro-physical parameters of heterostructures.

2. Experimental

Research of correlation of AE, fluctuations of EL intensity ΔI and current was carried out using technique described in [1, 2]. AE signals were registered by the piezoelectric transducer of the specialized acoustic-emission device AF-15, integrated I was registered by photodiodes. These signals and current noises were processed by ADC. Objects of researches were low-sized (GaAsP/GaP) (Fig. 1b, d) and nanosized (InGaN/GaN) (Fig. 1b, d, f) structures.

The EL intensity distribution at surface *I*(*S*) (Fig. 1a, c and Fig. 2a, c, e), and along the selected section (Figs 3 and 4) were obtained by frame-by-frame computer analysis of digital video (or directly from original digital photos) of the structure surface taken using microscope with zoom ×98.

3. Results

In Fig. 1a, c distributions *I*(*S*) for the GaAsP/GaP heterostructure are presented in the spectral range 410-700 nm at different injected currents. It is seen that an increase of intensity distribution *I*(*S*) with current becomes more heterogeneous on the surface – intensity is concentrated near electrode, and on edges of the structure intensity decreases that can be connected with decrease of the *p*-*n* junction resistance, relative decrease of the lateral component of the current and, probably, with crowding of the current between electrodes [3-5]. Similar results were obtained for InGaN/GaN heterostructures.

In Fig. 2a, c, e *I*(*S*) of the InGaN/GaN heterostructure in the same spectral range measured in an orderly sequence at 80 ms interval are presented. In the process changes of the intensity in separate local areas of the structure surface $\Delta I(S_i)$ were observed during AE. Similar results were obtained for GaAsP/GaP heterostructures.

In Fig. 3 and Fig. 4 distributions of the EL intensity on radiating surface along the selected direction (section) on it *I*(*l*) are presented. Distributions *I*(*l*) in the GaAsP/GaP heterostructure in Fig. 3 correspond to consecutive change of over-threshold density of the heterostructure current J_{th} (for AE appearance). Distributions *I*(*l*) of the InGaN/GaN heterostructure in Fig. 4 correspond to the consecutive moments at over-threshold J_{th} (similar to those shown in Fig. 2a).

As follows from Fig. 3, local areas of radiating surface (Fig. 3b) exist in which dynamics of degradation differs essentially from dynamics of the basic area.

In Fig. 4, local areas of radiating surface are also seen in which essential monotonous degradation (B) during three consecutive moments, EL fluctuation (A), and also areas (C) and (D) in which *I*(*l*) change does not exceed the measurement errors are observed.

It should be noted that at subsequent decrease of *J* after AE termination final degradation of *I* on the LED surface was also non-uniform, and degradation of *I* as a whole was sharply asymmetric about the electrode and individual dynamics of *I* in various local areas was observed.

For these structures, at $J = 110$ A/cm^2 integrated (corresponding to the whole radiating surface of the structure) fluctuations of ΔI and fluctuations of the current were registered simultaneously with AE signals and $\Delta I(S_i)$ fluctuations. Usually, the following correlation between them was observed: fluctuation of the excessive current noise and $\Delta I(S)$ corresponded to each group of AE signals [1, 2]. Moreover, essential changes of current-voltage

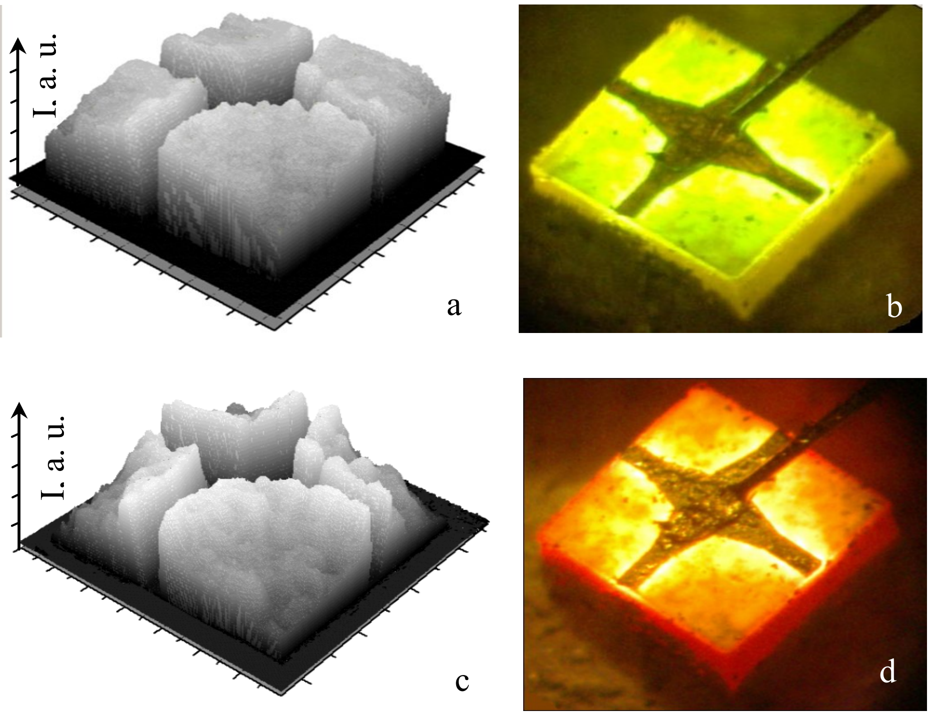

Fig. 1. EL intensity surface distribution *I*(*S*) for the GaAsP/GaP heterostructure at 68 A/cm^2 (a) and 172 A/cm^2 (c) and their micrographs (b, d).

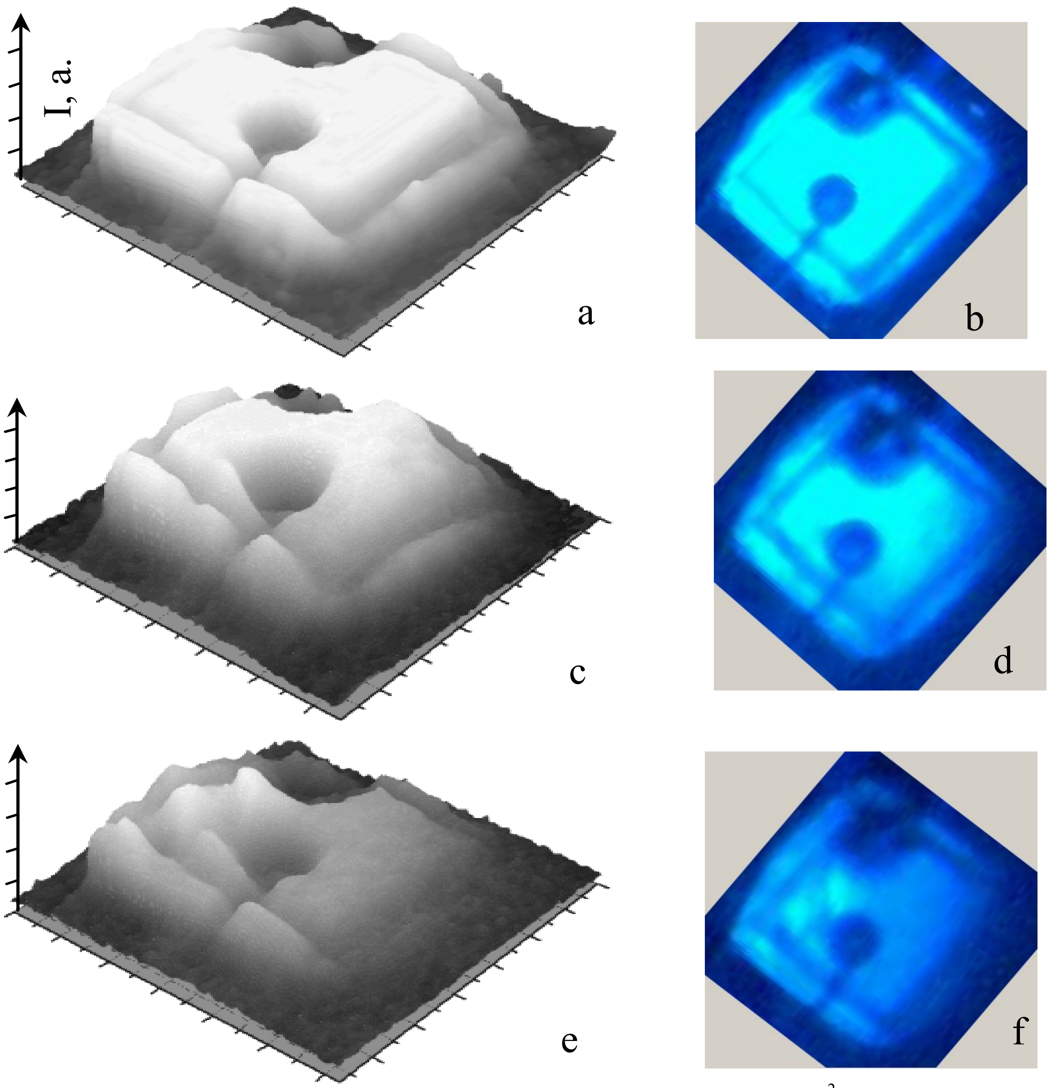

Fig. 2. EL intensity surface distribution *I*(*S*) for the InGaN/GaN heterostructure at 110 A/cm^2 at sequential moments (a, c, e) and their micrographs (b, d, f).

characteristics (CurVC) and capacitance-voltage characteristics (CVC) took place, which were similar to those described by us earlier in [10].

4. Discussion

One of the problem of fabrication and operation of these structures, in which the average value of internal mechanical stresses reaches ~10^9 Pa [2], is local heterogeneities in conductivity, thermal resistance, difference of elastic modules [1, 2, 7-10], and also α_i and a_i, mentioned above. At current passage, it leads to formation of the temporary additional local thermo-mechanical stresses (>10^7-10^8 Pa), which are distributed in unpredictable manner (chaotically) in the structure bulk and on its interfaces, areas and lateral surfaces adjoining them due to a complex spatial distribution of the temperature gradients.

The complex of these reasons leads to individual dynamics of degradation in local areas of the heterostructures. Degradation and fluctuations of electro-physical properties and integrated EL intensity [1, 2, 7-10] as well as the current noises of the locally non-uniform thermo-stressed heterostructures, simultaneous with AE, are integrated manifestations of this fact.

Defects formed or changed their state in the active area due to formation of additional system of the energy levels in the area of hetero-junction act as both the additional scattering centers of the charge carriers and their tunneling centers. At *J*, exceeding AE appearance threshold, *I* decreases and changes in separate local areas because of activation of defects-formation processes, thus a redistribution of relative *I*(*S*) on the structure surface takes place.

Intensive appearance of the structural defects as well as changes in their energy state, accompanied by

AE, lead to local ΔJ_i fluctuations due to fast local changes of heterostructure resistance. In turn, ΔJ_i leads to fluctuations of carriers injection into the quantum well, which recombine there with radiation. It causes fluctuations $\Delta I(S_i)$ in local areas of radiating surface S, and appearance of the dependences I and ΔI on S and t – $I(S, t)$ and $\Delta I(S, t)$.

Let us note that the factors influencing the dependences $I(S, t)$ and $\Delta I(S, t)$ are also temporary local appearance of conductive channels (shunting *p-n* junction) and their subsequent breakings [4, 6]. Fluctuations of recombination current due to redistribution of recombination and tunnel components of current, caused by growth of leakage current at crossing of the *p-n* junction area by defects (dislocations) and decrease of injection factor due to capture of carriers on the traps at defects formation in the field of contacts are also possible. In paper [6], fluctuations were observed in GaN resonant-cavity LEDs, which correlated with CurVC changes that also corresponds to our researches [2, 8, 10]. Authors of [6] explain this effect by metal atoms migration along threading dislocations and nanopores.

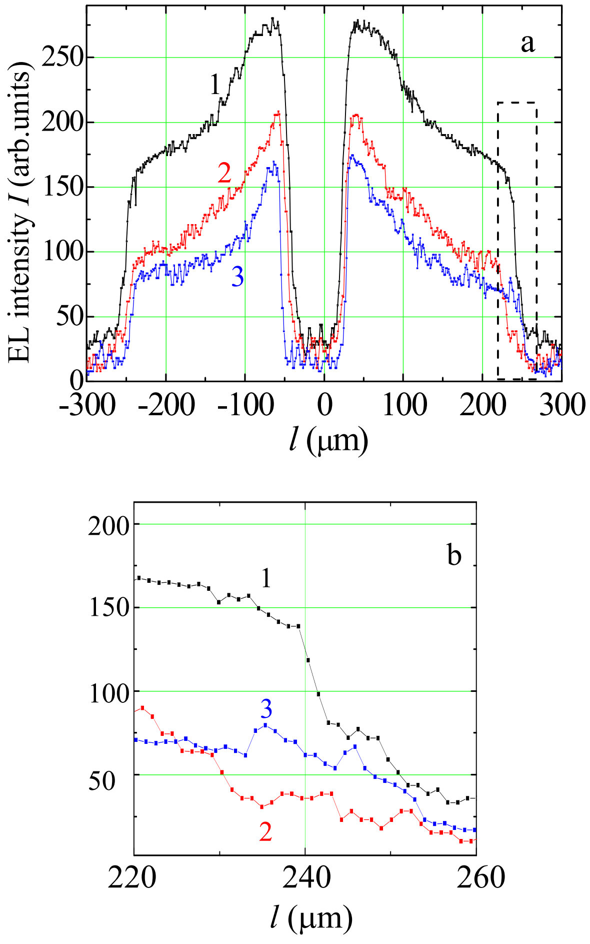

Fig. 3. Distribution $I(l)$: 1 – J = 80 A/cm^2; 2 – 140 A/cm^2; 3 – 80 A/cm^2 after AE (a) and selected area (b) from (a).

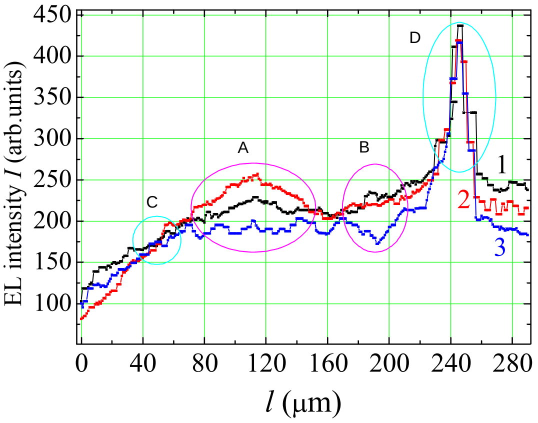

Fig. 4. Distribution $I(l)$: 1 – t = 0, 2 – t = 40 ms, 3 – t = 80 ms; J = 110 A/cm^2.

Shown by us (see Figs 1-4) non-uniform distribution of EL intensity and formation of local areas with unique dynamics of degradation correlates well with definition of AE source as area of object under investigation in which transformation of any form of energy into mechanical energy of AE [13] takes place. Thus, defects formation processes accompanying with AE radiation can result in fluctuations of EL intensity on LED radiating surface.

There are at least two ways of degradation (change of the efficiency of the "quantum yield") depending on changes in the defect structure of light-emitting heterostructure. In one of them, chaotic vibrational-translatory motions of the single dislocations, which cause appearance of continuous low-energy AE, do not change essentially a "degree of deficiency" of the structure, *i.g.*, the density of dislocations remains approximately at the initial level. Vibrational-translatory motion of dislocations in this case is only a part of the mechanism of super-fast relaxation of excessive local mechanical stresses accompanying by AE occurrence and, consequently, determines only redistribution of $I(S)$ and appearance of $\Delta I(S)$.

Other way supposes substantial increase of both dislocations density and three-dimensional defects, and, consequently, irreversible individual reduction for each $I(S_i)$ area and also $\Delta I(S_i)$ appearance.

Distribution $I(S)$ in Fig. 1 corresponds to the first of described ways, and distribution in Fig. 2 corresponds to the second one.

5. Conclusion

It was shown that at current increase in the GaAsP/GaP and InGaN/GaN heterostructures not only integrated but also local degradation of the electroluminescence intensity takes place simultaneously with acoustic emission appearance. Thus, evolution of electroluminescence intensity surface distribution, which is related with integrated degradation of other electro-physical characteristics, including CurVC and CVC, can bear witness to local changes of electro-physical characteristics in surface and subsurface layers of the heterostructures.

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