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Dynamics of acoustic emission in light-emitting A_3B_5 structures

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Abstract. In light-emitting A_3B_5 structures, a correlation between the process of acoustic emission (AE) occurrence and fluctuations of the electroluminescence intensity and current has been revealed, which indicates a common mechanism of their origin. It has been shown that in these structures, including InGaN/GaN structures with quantum wells, the probable reason of it is the consecutions of physical processes leading to correlation of three various pulse sequences. Revealed is the presence of several activation mechanisms (sources) of AE, which are corresponded by various scenarios and physical processes of local reorganization of material structure with different values of the activation energy.

Keywords: acoustic emission, electroluminescence, fluctuation, light-emitting structures.

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1. Introduction

Any determined external influence leads to determined reaction of any linear system [1], for which initial conditions (prehistory) usually have only a week influence on the shape of the functional dependence "influence-reaction". At the same time, some nonlinear systems possess a high sensitivity to initial conditions, which can result in chaotic behavior of these systems in time (their evolution) and is in fact a manifestation of certain dynamic regularities set by their prehistory [1].

The majority of physical processes, both in solids and in complex semiconductor structures is determined, that is, within the framework of this or that system of equations, they can be described starting from the initial conditions set in advance [1]. One of the most known exceptions is the threshold, nonlinear, spontaneous and chaotic phenomenon known as acoustic emission (AE) in materials [2-10].

Traditional theoretical (and simplified technical) approaches to AE define it either as a nonlinear, or as is absolutely-chaotic, noise process. It is caused by complexity to accurately formulate the task of AE and, even, tasks for initial enough simple functional relations influence-reaction. Therefore, AE cannot be described within the framework of a joint theory (absent up to date) valid for the majority of known AE manifestations.

The nature of AE in materials is related with some non-equilibrium processes in local areas of materials (solid state), as well as with various defect-formation processes in them. Related to these processes are movement and duplication of dislocations [3-6] and cracks [6-8], changes in a state (the size, the form, structure, a aggregate state) of separate local areas under threshold external influence of various nature [6, 9, 10]. For semiconductors and semiconductor structures, they are, first of all, mechanical stress and electric voltage or processes of heating-cooling [3, 4], including those leading to melting fusible metallic non-homogeneities in the form of microinclusions in the layers prepared by liquid-phase epitaxy and vapor-phase epitaxy [11, 12].

The problem of identification of acoustic emission sources (in fact, defects and non-homogeneities) for some kinds of influences (basically, static mechanical) was partially solved for some homogeneous and non-homogeneous materials [3-5, 13].

It is obvious, that under the analysis of AE dynamics (at establishment of its quantitative interrelations with other phenomena) application of nondestructive method (AE) for complex researches, modern light-emitting low-dimensional and quantum-dimensional semiconductor devices and structures based on the A_3B_5 compound, development of methods of their control and diagnostics, studying of influence of defects and non-homogeneities on their electrophysical characteristics, revealing of laws of their genesis and dynamics for creation of new technologies of synthesis crystals and structures with improved parameters is possible.

However for today similar researches practically completely are absent, except for [3,14-21,30], the same as both a trustworthy information about the nature and mechanisms of formation and operation of AE sources, in particular, at work of structures both in their nominal (worker) and in maximal-critical modes.

The goal of this work is analysis by AE method dynamics of local processes of relaxation and defects formation in light-emitting InGaN/GaN and GaAsP/GaP heterostructures, induced by the direct current, leading to simultaneous appearance of acoustic emission, oscillation of electroluminescence (EL) intensity, current fluctuations and the general degradation of electrophysical parameters of heterostructures.

2. Experiment

Objects of researches were light-emitting structures GaAsP/GaP and InGaN/GaN with $In_xGa_{1-x}N$ quantum well in width 30 Å. Structures had the heterojunction area (300…400)x(300…400) μm^2.

As well as in [14-17] AE signals were registered piezoelectric transducers and acoustic-emission device in a frequencies band 200-500 кHz at the common amplification 69-75 dB, recorded by computer and for analysis of AE signals, EL oscillation and current fluctuation were processed.

Step-by-step change of current was made according to empirical dependence $I(n) = an^2+b$, where I - current, n - a step of change, a and b - constants [20]. This dependence has been established on researches more than 300 light-emitting structures based on the InGaN/GaN, GaAsP and GaAlAs, lead in [14-17].

AE was measured at constant I_i to operation of the majority potentially active (for this I_i) AE sources, i.e. to AE termination, or to sharp reduction in its intensity. It corresponded to performance of Kaiser law, and also allowed to make the certain comparisons, because hetrostructure after AE termination were in a metastable condition. Time between current changes made 300 s.

In most cases, both in initial records, and after computer processing of AE signals (fig. 1, 2), reducing influence of equipment of registration, time conformity with processes of the different physical nature is observed.

So, EL intensity oscillation (2) usually there correspond groups of continuous AE signals (1) or (less often) sequence of discrete AE signals with a delay 25-75 μs (fig.1), that will be agreed with the results received earlier [18]. Time EL intensity oscillation (2) on fig.1 usually look like “an integrating curve” to (1) - to AE signals (oscillation) and formally correspond to concept “AE event” - to a time interval of elastic waves radiation, corresponding act of operation of AE source (group of cooperating AE sources).

On fig.2 current fluctuations and AE are presented. A face of these time conformity some another. To time borders of AE signals group (AE event), i.e. the beginning-ending of AE source operation (fig.2, site I), correspond significant individual explosive fluctuations of current, and the greatest density of continuous current noise is achieved later - at AE attenuation (fig.2, a site II).

Despite of significant distinctions in the form of registered EL intensity oscillation, current fluctuations and acoustic emission, time conformity between them more than are obvious, as interval of time between AE events and, accordingly, between observable time conformity usually in 10^2-10^4 times exceeds time of AE events.

It is known, that the acoustic emission signals amplitude A characterizes mechanical energy, radiated AE source. In particular, at cracks movement, A sometimes proportional to length of jump and change of the microcrack area [6-8]. At dislocations movement A determined by number of dislocation segments moving simultaneously, and also their parameters. Therefore face of AE amplitude distribution and its change characterizes dynamics of local processes of relaxation and defects formation.

Earlier [15,17] has been allocated some characteristic script of development (dynamics) of AE for which some basic AE parameters [17] have been calculated. On fig.3 amplitude distribution of AE signals for three such scripts are resulted: abrupt degradation of electrophysical parameters heterostructures (fig.3 a), degradation with melting of contact (fig.3 b), degradation and structure breakdown with ohmic CVC occurrence (fig.3 c). Thus it is necessary to note, that in our experiments breakdown occurred mainly in InGaN/GaN mesastructures, and for GaAsP/GaP structures - degradation to melting contact (fig.3 d).

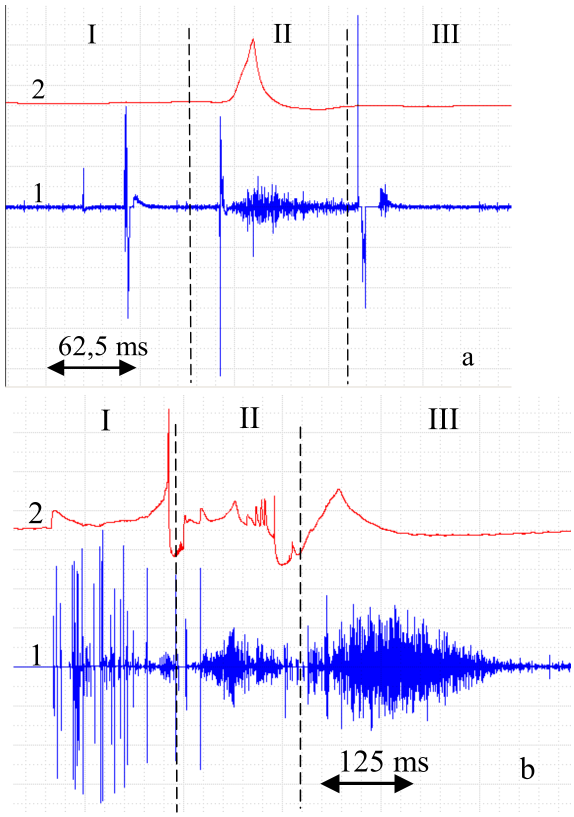

Fig. 1. AE (1) and EL intensity oscillation (2) at degradation and destruction of structure at 7 V, 200 mA.

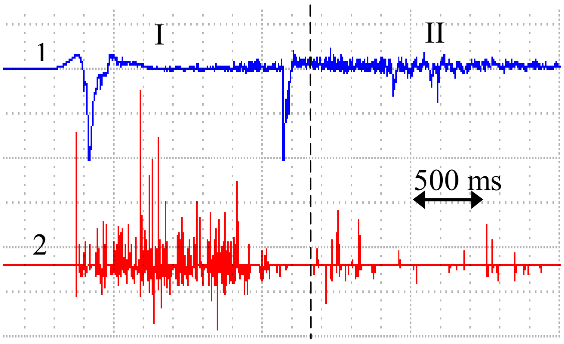

Fig. 2. Correlation of fluctuations of current (1) and AE (2) in *InGaN/GaN* structure.

On fig.4 photos of surface of structures GaAsP/GaP corresponding different stages of degradation and destruction are presented. Microcracks and both the fused and break contact on a surface of failed at I = 450 mA GaAsP/GaP structures are visible (fig.4 b), and also working at 200 mA structure after partial melting of contact at 400 mA (fig.4 c). AE amplitude distribution for process fig.4 c, corresponds fig.3 d.

It is necessary to note, that various dynamics of AE, as well as in [17] it was shown in dependences of AE intensity on time at constants I: at current increase up to destruction current, for various samples time of a delay of occurrence maximal intensive AE t_d concerning time of establishment I or decreases, or from the moment of achievement of AE occurrence threshold I_{th} it neglected little.

Such dynamics of AE process will well enough be agreed with the basic assumptions stated earlier [21] - AE parameters, in particular delay time of AE occurrence t_z and AE duration depend on a level of the external fixed loading and number of AE sources activated by this influence during time of its action.

3. Discussion

One of essential problem of manufacturing and operation (especially - at critical modes) the investigated structures in which the average size of mechanical stresses achieves ~ 10^9 Pa [22] are local heterogeneity of conductivity in volume [12,23], a difference of elastic constants modules, factors of thermal expansion and lattices on heterojunction interface [24], thermal resistance of active area and a heat-conducting path [25,26], the phenomenon “current crowding” [27]. It leads at current passage to formation of temporary local gradients of temperatures (10^3 – $7\cdot10^3$ °C/cm) and thermo-mechanical stresses (> 10^7 - 10^8 Pa), is unpredictable (chaotically) distributed in the structure and adjoining areas.

The complex of these reasons considerably accelerates degradation of electrophysical parameters with various dynamics in each of local areas of

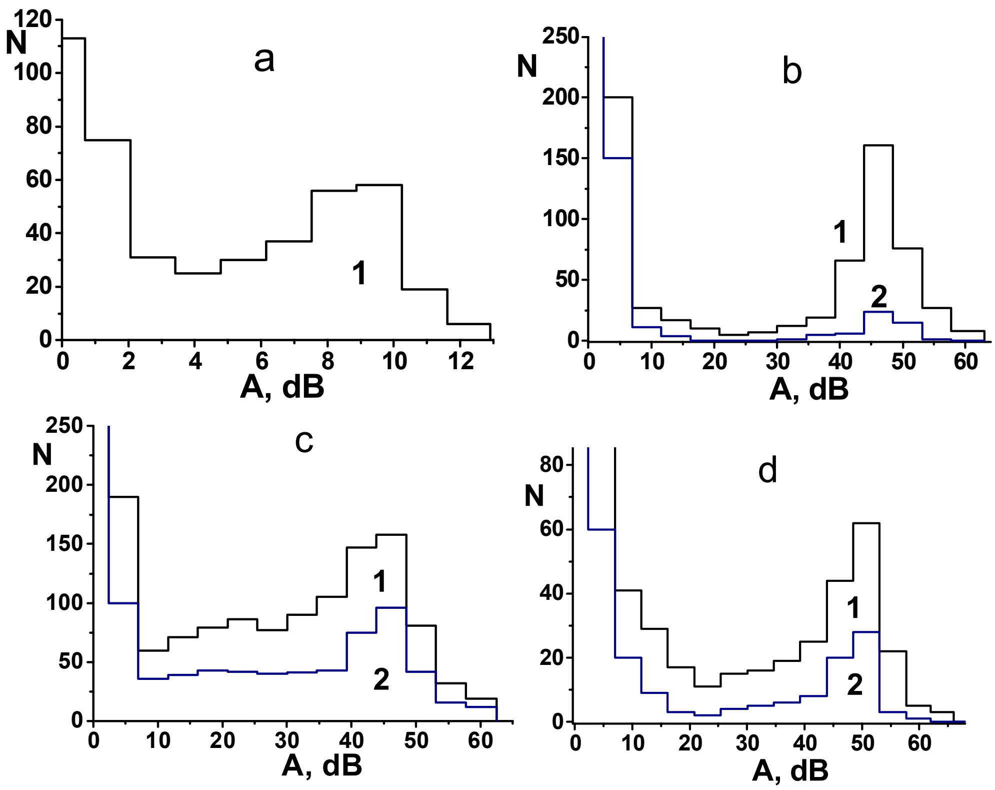

Fig. 3. AE amplitude distribution of InGaN/GaN structure: a – I = 100 мA, degradation; b - I = 200-250 mA, melting of contact; c - I = 200-250 mA, breakdown; d - GaAsP/GaP structure, I = 400 мA, melting of contact. Accumulation time: 300 s (1) and 120 s (2).

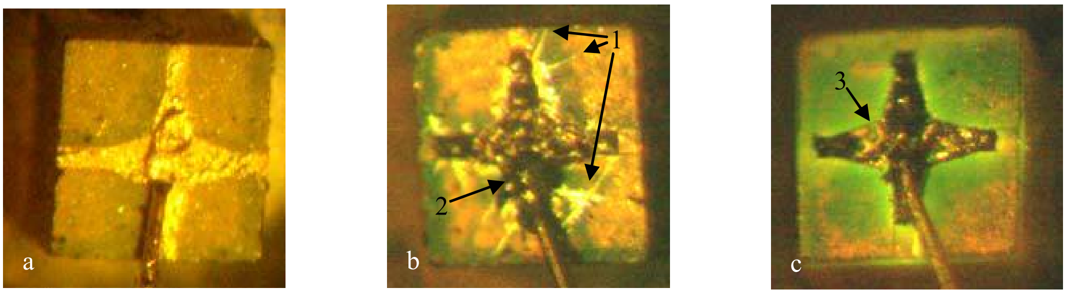

Fig. 4. Surfaces of GaAsP/GaP structures: a - typical initial structure; b - I = 450 mA, the micro-cracks (1), the melted and failed contact (2) in the sample 1; c - I = 200 mA, after partial melting of ohmic contact (3) at I = 400 мA in the sample 2.

heterostucture. Display of it are simultaneous with AE degradation [3,28,29] and fluctuation [16,19] of electrophysical parameters (in particular – EL intensity), and also current and optical noise locally-is non-uniform thermo-strained diode and laser heterostructure based on the A_3B_5 compounds [30].

It is obvious, that because complexity of reasons of AE occurrence it is very difficult to construct hierarchy of rather various physical mechanisms leading observed time parities (correlation, [31]) between both current and EL fluctuations with AE. These time parities cannot be shown to functional as any two values depend on other, additional factors which for today are unknown.

Despite of significant divergences in the form of registered EL intensity oscillation, current fluctuations and acoustic emission (fig.1 and 2), which do not allow us to enter correctly a numerical measure (correlation function, [31]), possible is calculation correlation value for separate sites of these signals where their correlation takes place.

On fig.5 (a, b) are resulted initial (for I and II areas) sites of AE signals and light oscillation fig.1. Accordingly on fig. 5 (c, d) - corresponding dependences correlation value from Lag Index.

Difference from zero correlation value in time interval of existence of these signals (near Lag Index=0) addition confirms interrelation AE and EL intensity oscillation. Similar dependences are received for current fluctuations and AE.

One can see from fig.1 and fig.2 observed correlation between AE signals, EL intensity oscillation and current fluctuation "some unequal". So, correlation AE and oscillation EL is a little short AE impulses and one "integrating" fluctuation.

It allows assuming, that the following sequence of processes is carried out. During the moments of occurrence and reorganization of defects in any semiconductor structures, leading to AE occurrence, are possible not only significant changes of CVC [15], but also fluctuations of differential resistance of structure, and accordingly a current. As not to each act of occurrence and reorganization of structural defects correspond AE, AE signals are divided by time intervals (fig. 1, 2). Significant fluctuations of current in the beginning and in the end of process of occurrence and reorganization of defects are connected with changes of differential resistance. Any process of occurrence and reorganization of defects is accompanied enough by the long relaxation, passage in separate local areas more slowly, and individually, so therefore as a whole on the sample - is more continuous.

It also leads to occurrence of the greatest density continuous current noise later - at AE attenuation, when AE, at even processes of reorganization becomes improbable process because of non-simultaneity of these processes of reorganization in various local areas of structure and substrate. We shall note that for formation of AE impulse practically simultaneous operation of several AE sources (in dislocation models [5] up to 10^3-10^4 dislocation segments) is necessary. During intensive AE, occurrence of significant current fluctuations connected with fluctuations of differential resistance of structure is improbable. First of all - because of amount processes, not coherent neither in space, nor in time, proceeding in time AE in a significant part of heterostructure volume.

Actually EL oscillations are formed at enough long (continuous) processes of reorganization and with taking account of special role of thin active layer and - at enough intensive processes in it or near. Therefore, performance of these conditions which, generally, are not enough for formation AE, leads to individual EL oscillation, simultaneous with several, divided time intervals AE signals.

Actually, with the reasons of EL oscillation formation there can be some mechanisms. So, for example, in investigated nano-sized InGaN/GaN structures, at current fluctuation, arise fluctuations of injection carriers in a quantum well, where carriers radiation recombine and as consequence - there are the fluctuations of quantum yield observable simultaneously with AE. It is known also, that coherent heterogeneity in epilayer with variable composition reduce diffusion length of charge carriers and influence to processes non-radiative recombination [11]. On [28] follows, that at degradation InGaN/GaN structure the leakage current increases, and instability given components of current is connected with recharge boundary state in sites which

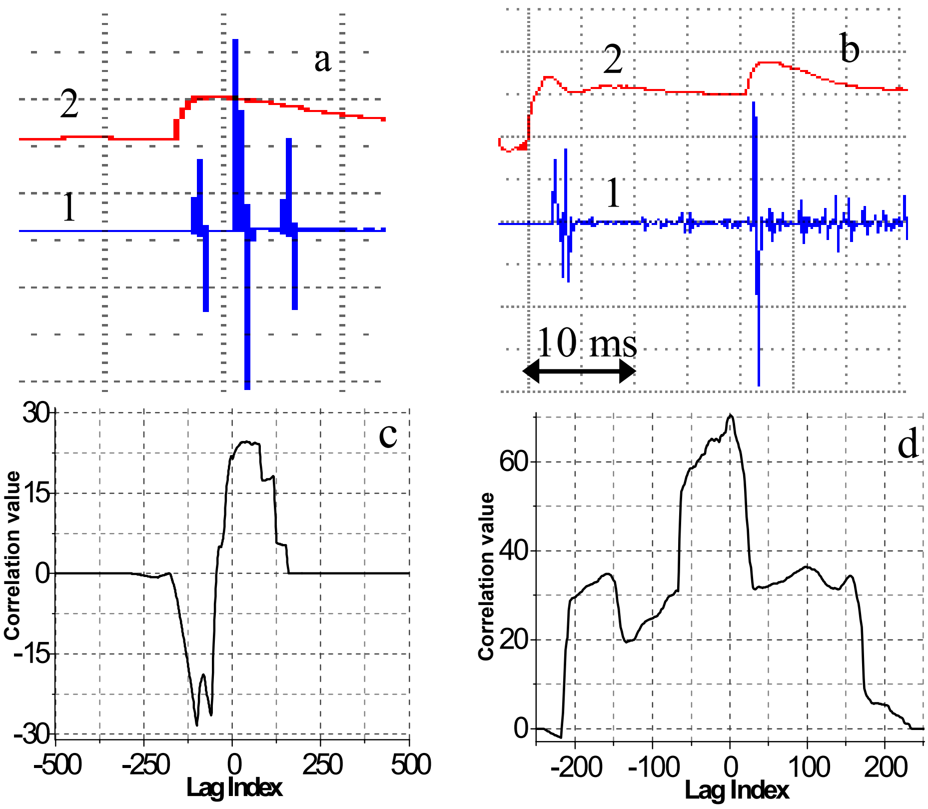

Fig. 5. AE (1) and EL intensity oscillation (2) at degradation and breakdown of structure at 7 V, 200 mA (a, b) and their correlation value (c, d).

play a role of channel "shutter". At moments of occurrence and reorganization of structural defects growth of instability of processes recharge is obvious, that increases probability, both fluctuations of quantum yield and its correlation with AE.

Also it is impossible to exclude some additional mechanisms, for example-local temporary shunting *p-n*-structures due to occurrence and break of current channels [28], and the given process can be dominating in formation quantum yield oscillation.

It is necessary to note also, that non-uniform distribution of current density through *p-n*-transition and in sub-contact areas, its localization in separate channels equivalent to reduction of effective area of transition (area of energy generation). At significant density of current the temperature of local areas increases more quickly and non-uniformly, heat exchange with crystal volume is carried out insufficiently effectively and at achievement of critical current, there is a local thermal damage metal contacts and structure which is accompanied AE and corresponding fluctuations of current and quantum yield. It confirms the analysis fig.3 and 4.

So, occurrence of peak on the AE amplitude distribution in the field of 10 dB (fig.3, a) is observed at direct current through heterostructure I = 100 mA which in 10 times exceeds its nominal current. From [3,29] is known, that in the given area current loading of light-emitting structures (70-120 mA and more) there is an origin structural extended defects and non-uniform movement of dislocations. It specifies also a site of irreversible increase of resistance on CVC of these structures [15]. Thus, the maximum of AE amplitude distribution in the field of 10 dB possibly corresponds to generation and collective non-uniform movement (to oscillation near to initial position [5]) dislocation segments in gradients of thermal, elastic and electric fields in active area of heterostructure.

AE amplitude distributions at destruction (melting) of contact (fig.3 b, d) have a characteristic maximum in the field of 45 - 50 dB that specifies at process with essential greater activation energy of AE sources. Thus in the field of from 15 up to 35 dB the number of AE impulses is essential - at 6-12 time less. Stable enough radiation of AE signals of the certain amplitude can be connected with repeated absorption and radiation in the form of AE energy liberated at processes of local phase transition a solid state-liquid state in ohmic contacts based on the Au and subcontact area, oversaturated impurity which essentially influence to average sizes and concentration non-homogeneities. Thus accompanying processes, in particular - the accelerated diffusion from metal contact, disintegration oversaturated matrix metal of solid solution at sharp cooling, etc. are important [11].

The possibility of AE occurrence at the similar phase transitions, investigated in [9,10], is possible at change of density (or - initial and final volume) substances. Contacts of investigated by us GaAsP/GaP structures are made from AuZn, AuNi eutectic alloys (a wire) and $Au_{99}Zn_1$, $Au_{99}Ni_1$, $Au_{98}Si_2$, AuIn ohmic contact made by thermal evaporation, fig.4. Density in a solid and liquid phase of pure components: Au - 19,32 g/cm^3 and 17,24 g/cm^3, (at T=1100 °C) accordingly, In - 7,36 g/cm^3 and 7,07 g/cm^3 (at T=160 °C), Zn - 7,14 g/cm^3 and 6,66 g/cm^3 (at T=419,5 °C) [32], and corresponding relative change of volume $\Delta V/V$ for Au - 5,19 %, for Zn - 6,9 %, for In - 2,5 %.

On [9,10], in this case, AE signals with amplitude 45-50 dB (fig.3 b, d) for two-componential alloys for which criterion of AE occurrence is reduction of volume (increase in density) correspond to phase transition liquid-solid phases, i.e. to hardening. The stable amplitude of AE signals connected by that local volumes in which occurs phase transitions, are geometry similar (fig.4) and are determined by wire section and a film of ohmic contact.

At intensive degradation and breakdown (fig.3) AE amplitude distribution have more uniform distribution in all range, however also have a small maximum in the field of 45-50 dB that specifies simultaneous action of several independent AE mechanisms. During the moment of intensive degradation and breakdown the crystal temperature can reach 600°C [25], therefore possible there is a local thermal breakdown; partial short circuit *p*-and *n*-areas; local fusion over-stoichiometry inclusion (enriched gallium or indium) with much more below melting temperature than basic materials [11]; intensive occurrence of structural defects that leads to increase tunnel component of current.

Except for this usually takes place AE after destruction of structure which is connected with formation of dislocations at relaxation thermal stresses after sharp cooling.

4. Conclusion

Correlation between process of acoustic emission occurrence and fluctuations of electroluminescence and current which specifies on common mechanism of their origin is found out. The probable reason of correlation is the consecutive physical processes, defining dynamics of various-dimensional defects and leading to correlation of the given values.

Revealed some scripts of degradation light-emitting structures to which there correspond activation mechanisms (sources) AE, i.e. physical processes of local reorganization of materials structure: AE at structure degradation - origin and movement of dislocations in active area of structure; AE at degradation and destruction of contact area - crack formation on a structure surface and tear of contact at repeated melting-solidification; AE at degradation and breakdown – avalanche duplication of dislocations, crossings of active area by them, local fusion of micro-volumes with *p-n*-transition breakdown.

It is shown that physical processes of intensive defect formation are connected with dominating (in the certain scripts of degradation) mechanisms and forming characteristic maxima in AE amplitude distribution, in particular: low-energy, corresponding origin and movement of dislocations, and also high-energy, corresponding local phase transition (solidification). Besides there are some more mechanisms with relative's energy of AE radiations, to distinguish which it was not possible.

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