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Fluctuations of current, electroluminescence and acoustic emission in light-emitting A^3B^5 heterostructures

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Abstract. It is shown, that in heterostructures based on A^3B^5 compounds acoustic emission occurrence, current and light fluctuations, evolution electroluminescence spectrums, current-voltage characteristics degradation occur simultaneously and has the common origin.

Keywords: acoustic emission, light fluctuation, current fluctuation, electroluminescence spectrum, CVC.

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1. Introduction

The question on the superfluous electric noise nature of semiconductor devices remains opened though the sufficient attention is paid to it. Character of these noises allows assuming, that their source can have not electric nature. For example, in [1] it was observed, as a result of nonlinear acoustoelectric transformation (convolutions of external ultrasound with a flowing alternating current, [2]), occurrence wide electric noise spectrum in semiconductor devices at influence on them is essential more narrow-band acoustic noise. In paper [3] in light-emitting structures at direct current passage correlation between optical and electric fluctuations and acoustic noise - acoustic emission (AE) materials was observed. Later, by authors [4] it was observed at long external influence of ultrasound monotonous reduction of intensity and distortion of electroluminescence (EL) spectrum of light-emitting structure and their restoration after the stopping of external influence.

AE - spontaneous chaotic radiations of the pulse acoustic waves [5, 6], caused by failure of the superfluous internal mechanical or induced thermomechanical strains at additional superthreshold external influence. AE at current flowing in semiconductor devices it is characterized by short-term creation of thermomechanical strains in microvolumes of epitaxial structures, especially on border of heterojunction, and also probable in the top layers of a crystal (substrate) which failure is accompanied by acoustic impulses radiation. The local strain value before failure by different estimations achieves 10^6-10^8 Pa. Also it is known, that the average value of mechanical strain in a GaN film on a sapphire substrate achieves ~10^9 Pa [7]. Thus, AE it can be considered as the source of internal acoustic (ultrasonic) fluctuations comparable, or surpassing on power external sources [1], changing electrophysical characteristics of structure, and, simultaneously, as the process which has arisen at external influence [3, 6, 8, 10, 11], in particular – mechanical [11].

Arising (at AE) short-term mechanical strains can lead to spontaneous current oscillations of various value, which is lead to change of own noise level of the device.

It is necessary to note, that distinguish high-energy burst (discrete) AE, which is caused usually by change of a condition ("operation") dislocations complexes, two- or three-dimensional defects, and low-energy continuous AE, which is caused by usually synchronous movement (fluctuation, with tearing-fastening on stoppers) groups of dislocations loops.

AE occurrence means that irreversible changes took place in local areas of a crystal, i.e. there arising new defects or metastable conditions already existing defects have changed. At enough intensive AE such local changes simultaneously cover a significant part of crystal volume, is irreversible changing its "integrated" properties, in particular there is electrophysical parameters degradation. Similarly, various extended defects cardinally change electrophysical properties of semiconductor crystals and structures [12, 13].

In [8, 9] dependence of spectral position of electroluminescence (EL) strips from current density heterojunction J of light-emitting $GaAs_{0.15}P_{0.85}$:N,Zn-

O/GaP heterostructures during the different consecutive moments of time - before and after AE is established. Researches in [9] specify presence of connection between evolutions of EL spectrums specified heterostructures, degradation their current-volt characteristics (CVC) and AE occurrence.

It specifies that additional sources of superfluous noise of semiconductor devices, in particular light-emitting heterostructures, can be various physical mechanisms. For example – transformation, owing to tensoresistive effect [14, 15] or acoustoelectric transformations [1, 2], acoustic noise (AE signals) in a superfluous current. The common for the set forth above phenomena non-equilibrium processes, and also defects-formation in complex structures based on the semiconductors compounds, induced by a current more possibly.

Considering similar to noise character of AE signals, is obviously important and actual complex research of acoustic emission, optical and electric current fluctuation of light-emitting heterostructures, and also – changes of their electroluminescence spectrum and current-volt characteristics.

2. Experiment

As samples were used light-emitting epitaxial n^+-n-p structures based on the A^3B^5 compounds: $GaAs_{0.15}P_{0.85}$:N,Zn-O/GaP, GaP:N/GaP and InGaN/GaN structures. Research of time correlation dependences was carrying out on apparatuses and by a technique similar [6, 8, 9]. AE signals were registered by the piezoelectric transducers and specialized acoustic-emission device AF-15. For record of EL spectra it was used monochromator, and the signal from a photodetector was processed by a computer. Current-volt characteristics of structures were measured simultaneously with record of AE spectra and AE registration. Through epitaxial structures with the area (400-450)×(400-450) µm and the maximal direct current density of recommended by the manufacturer J_n = 4 A/cm^2 the density current J_i = (2-200) A/cm^2 was passed, which increased at a walk – in everyone (i+1) increase J_i+1 = (2-1.2)·J_i. Time between changes of a current was defined on AE termination (2-15 min after J_i increase), or on AE absence within 5 min.

Prominent feature of observed acoustic emission, at the set mode of current change, was occurrence of AE signals through 3-30 s (or more) after sharp increase (jump) of a current of heterojunction. Thus in some cases burst AE it was registered (attenuated) within 5-10 min as groups of impulses, the time interval between which achieved sometimes 3-5 min. It specifies that AE sources relatively inertial, and local microstrains in a crystal till the failure moment developed at least during 3-30 s. During too time already achieved heterojunction current of the investigated samples only in some cases (at repeated loading) caused repeated failures of microstrains that corresponds to performance of the Kaiser law. Regular AE control, in particular, has allowed to achieve direct current density of the given structures up to 30-50 times above, declared by the manufacturer.

The AE, electric and “optical” fluctuations (noises) had been registered simultaneously under direct current of heterojunction. Following correlation was always observed: actually to each group of burst AE signals there corresponds increase superfluous current noise (Fig. 1a, c). To “optical” noise (short-term change of EL intensity) always there correspond AE signals (Fig. 1b) and superfluous current noise.

It is necessary to note, that at registration by means of analog-to-digital converter group of AE signals are registered with a delay 25-75 µs to quantum yield fluctuations (Fig. 1b), and have more “difficult” form, than at registration by a recorder (Fig. 1a). Time quantum yield fluctuations in Fig. 1b look like an integrating curve to AE signals (oscillations) and actually correspond to concept “AE event” – to the certain time interval of elastic waves radiation which answers the act of operation of AE source. Also EL degradation after intensive AE was observed.

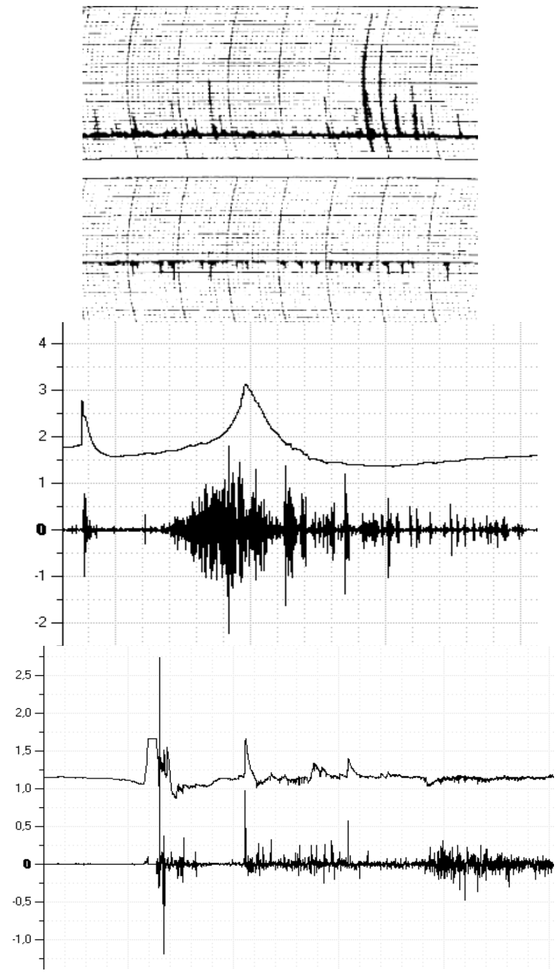

Fig. 1. Correlation of acoustic emission signals (*1*), current fluctuations (*2*) and a quantum yield fluctuations (*3*).

As well as in [8, 9], AE in epitaxial light-emitting $GaAs_{0.15}P_{0.85}$:N, Zn-O/GaP structures it is accompanied by EL strips displacement (Fig. 2). These displacements for small currents had character of fluctuations (1-5 min) at constant *J* (Fig. 2a, b) or were reversible at reduction *J* [8].

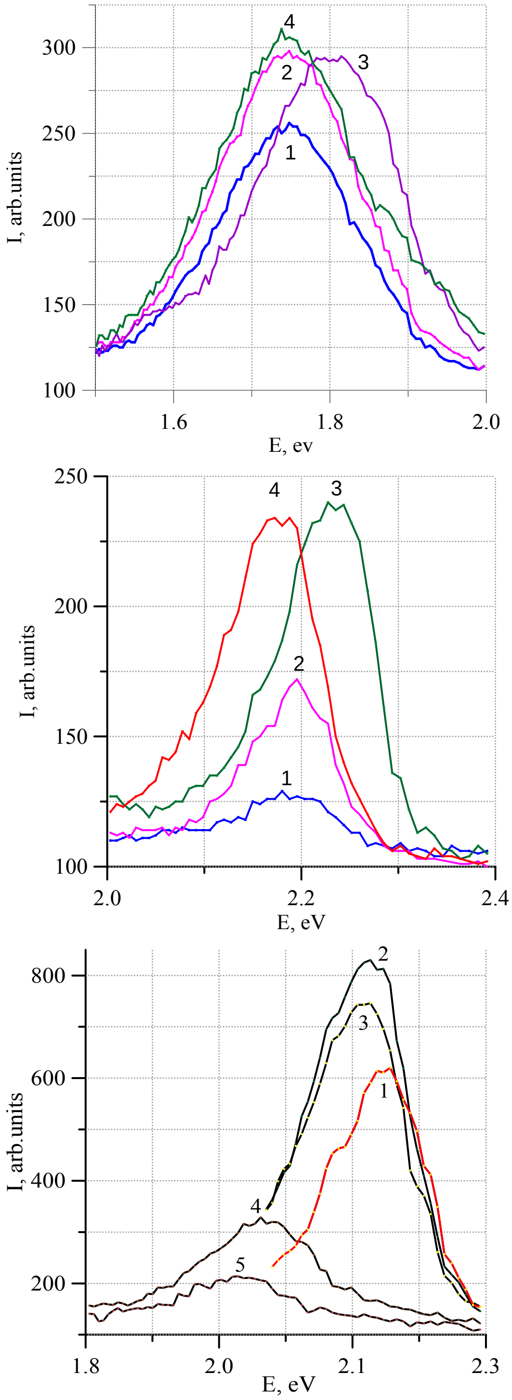

Fig. 2. EL spectra displacement: a, b – temporary, c – irreversible; a – red strip, b, c – green strip. Current density (A/cm^2): a) *1* – 6, *2* – 12 (without AE), *3* – 12 (with continuous AE), *4* – 28; b) *1* – 6, *2* – 12, *3* – 28 (with continuous AE), *4* – 28 (without continuous AE); c) *1* – 60, *2* – 80 (before burst AE), *3* – 80 (after burst AE), *4* – 130 (before burst AE), *5* – 130 (after burst AE).

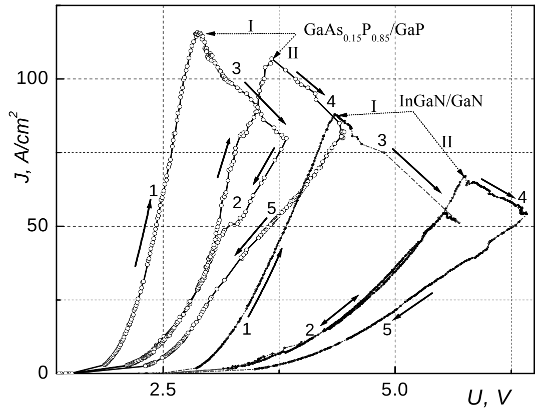

Fig. 3. CVC degradation GaAsP/GaP and InGaN/GaN heterostuctures at acoustic emission.

For big *J*, after intensive AE and formations infrared (I) EL strips, this process of displacement of EL strips could end differently. In some cases (as well as in [8]) was restoration of initial position red (R) and green (G) strips of a EL spectrum of $GaAs_{0.15}P_{0.85}$:N, Zn-O/GaP structures at reduction *J* up to the previous value. In others – there was a degradation, displacement of a green strip (Fig. 2c) with 2.2 up to 2.0 eV and irreversible disappearance of a R-strip even at small J_i.

Structures degradation in which it was observed AE, is shown and in their change of CVC. In Fig. 3 shown are typical CVC GaAsP/GaP and InGaN/GaN structures for two cycles (I and II) changes *J*, arrows specify a direction of change *J*. The site 1 (for each of structures) corresponds to the first cycle increase of current J_i. A site 2 – reduction J_i to zero and repeated increase J_i. The site 1, site 2 and site 5 (repeated reduction J_i) are qualitatively similar – actually is three (consecutive in time) CVC of structure that degraded.

It is necessary to note, that fast (during 30-90 s) degradation, at the first (sites 3) and the second (sites 4) increase, it was accompanied intensive burst AE and current fluctuation. AE last up to spontaneous reduction $J_i \sim$ 80 A/cm^2 for GaAsP/GaP and $J_i \sim 55$ A/cm^2 for InGaN/GaN structures.

3. Discussion

Performed estimations of efficiency of transformation of acoustic signals in electric, it is similar [1, 2], and also the comparative analysis of the AE signals form and current noise have shown (Fig. 1a, b), that in this case AE signals cannot be an original cause of current noise occurrence. Losses at such transformation are too great (up to 10^5-10^6 times), and the current noise amplitude was less amplitudes of electric AE signals no more, than in 10^2 times, thus the signals form not corresponded transformation according to tensoresistive mechanism.

As an interval between AE events it is usual in 10^2-10^4 times exceeds time of AE event despite of significant mismatches in the form of the registered quantum yield fluctuations ("optical" noise), current noise and acoustic emission, time coincidence (correlation) between them more than obvious though these dependences cannot be shown to functional as the named values, obviously, depend on others, additional (for today – up to the end unknown) factors which are defined by the common nature of these phenomena. Big integrated intensity of current noise is defined, possibly, also the contribution of the mechanisms which have been not connected with AE occurrence. As a whole, it agrees with the results received earlier [3].

The reason of such phenomena conformity could be both development of microcracks, and development of linear defects (dislocations) in a crystal that are accompanied by AE. Consequence of it would be current jumps at crossing by defects of heterojunction area, and also jumps and degradation of EL intensity. It is necessary to notice, that AE at change of a condition of separate dot defects, as is known, now it is not registered at all because of obviously too small (probably radiated) mechanical energy.

It is known, that degradation of structure parameters, in particular current-volt characteristic, capacitance-volt characteristic and EL intensity at flowing of critical currents density is accompanied by occurrence of a grid of dislocations in active area – *p-n* junction [13, 16]. The lead studying of change of a light output in GaP light-emitting diodes [10] by AE method also explains dislocations distribution in active area of the device. Due to [10], in light-emitting diodes in which it was AE observed the greatest dislocations density has been found out.

We had been made an estimation of probable change of dislocations density $\Delta\rho$, proportional, according to dislocation AE theories [5, 18], total AE. At the sizes of crystal $V \sim 400\times400\times300$ μm^3, average total AE for a cycle of measurements $N \sim 10^3$-10^4, average length $l \sim 1$-20 μm dislocation loops (the minimal AE source on sizes), and also the estimated ratio known on [18]: 1 AE impulse correspond $n \sim 10^3$-10^4 dislocations (dislocation loops), changed the condition simultaneously, $\Delta\rho$ can be defined from

$$\Delta\rho \approx N \cdot l \cdot n / V \qquad (1)$$

Then, on the average on a crystal volume, $\Delta\rho \sim 10^{10}$-10^{13} cm^{-2}, and for active area (nanolayer in case of InGaN/GaN) and adjoining areas up to 10-100 times more, thus are known, that in the industrial light-emitting InGaN/GaN structures which have been grown up by a metal-organic chemical vapor deposition (MOCVD) method, initial dislocation density on [19] $\rho \sim 10^7$-10^8 cm^{-2}, and for $GaAs_{0.15}P_{0.85}$/GaP on [13, 17] $\rho \sim 10^6$-10^8 cm^{-2}.

On the other hand, intensive development of microcracks also should result not only to degradation, but also to fast destruction of structures, however, as is noted above, they kept working capacity at $J \sim$ (20-50) J_n.

Obviously, observed features in EL spectra also demand additional explanations. It is known, that in structures $GaAs_{0.15}P_{0.85}$:N,Zn-O/GaP radiating recombination in a red strip which influence in structures GaP:N/GaP slightly is determined by Zn-O complexes. Absence in the last I-strips in EL spectrum confirms (stated in [8, 9]) the assumption, that EL growth in an I-strip can be connected with process which leads to disintegration of Zn-O complexes (and fast degradation of structures) at high J_i and is accompanied by AE.

Thus, the observed complex of the phenomena cannot be shown to one – to two typical mechanisms in light-emitting structures, therefore us the following sequence of mechanisms which lead, in particular, to AE occurrence is offered.

At current flowing through *p-n* structure in it temporary are formed areas of a temperature gradient, and there is a redistribution of electric field gradients. In turn, local areas of a temperature gradient which were formed through a complex of the reasons – geometry of contacts, the current crowding phenomenon [22], conductivity heterogeneity of structure and others, cause formation of temporary local areas of thermomechanical strains (TMS).

The relaxation (failure) superfluous TMS is accompanied burst ("high-energy") acoustic emission – radiation of pulse acoustic waves (creation of attenuating local mechanical strain). It leads to current noise due to fast local changes (in particular owing to temporary deformations of energy zones) resistance, electronic and hole a current component that leads to fluctuations of injection of carriers in a quantum well whit radiation recombination and, in turn, create EL intensity oscillation. The termination burst AE means transition of a defect system in other, more stable condition.

Dislocations, others linear and extended defects considerably – up to two or three orders lower strength of semiconductors crystals [21]. Therefore, action TMS which have achieved critical value in the certain local area of structure, and also duplication and change of a condition (in particular – movement) this defects at which own elastic field [21] is summarized with local TMS, are initiators of occurrence (generation and movement) new defects of different dimension or change of a energy condition existing defects. As these defects are the centers of carriers dissipation of and them tunneling [13], additional local growth of temperature and acceleration of degradation of electrophysical characteristics is probable.

Change dislocation subsystems of a crystal at enough high density of dislocations can occur under powerful enough pulse influence (burst AE) under several scripts – first, continuous growth of dislocations density owing to their duplication which is less probable because of mechanical (brake) fields of already existing dislocations [21], and, secondly, redistribution in volume of existing dislocations (their movement) [18]. Possibly, registered by us continuous "low-energy" AE which traditionally connects with dislocation mechanisms of

AE [10, 18], can be explained by a following sequence of processes: burst (explosive) AE, fast local redistribution of mechanical strains, fast local spatial redistribution (shift) of dislocations, relaxation processes connected with the subsequent movement of dislocations and pairs of their loops in fields of elastic strain (continuous AE).

It is obvious, that thus nevertheless there is an accumulation of local mechanical strains and duplication of defects, in particular dislocations, especially in the area of *p-n* junction [20], in particular, because of its significant own electric field and due to the depletion which has the high resistance. It correspond researches [16], and allows explaining available degradation processes (CVC degradation and EL intensity).

Received by formula (1) “formed at AE” the additional dislocation density $\Delta\rho \sim 10^{10}$-10^{13} cm^{-2} actually only displays quantity of dislocation loops pairs (or dislocation), which have participated (first of all owing to their movement near to a source burst AE) in formation of signals of continuous AE, it is probable – repeatedly.

Actually local areas of microplasticity of structure at critical current density in which there is a relaxation of the superfluous mechanical and created thermo-mechanical strains, are acoustic emission sources in complex semiconductor structures which operation corresponds to their change luminescent that of electric characteristics. It explains and noted irreversible shift of G-strip of EL connected, apparently, with irreversible accumulation of residual mechanical strains (accumulation of plastic deformation) which lead to deformations of local energy zones, to change of bandgap width and, possibly, to change of distribution of probability of radiating recombination.

4. Conclusion

From the lead complex researches of light-emitting GaAsP/GaP, GaP/GaP and InGaN/GaN structures at current density which exceed a threshold of burst AE occurrence, follows, that simultaneously take place: AE sources operation, reversible and irreversible change of EL spectra, CVC degradation and fluctuations of quantum yield and current. It specifies the common mechanism of their origin – processes of occurrence and changes of energy condition and structure extended, in particular linear, and dot defects, in particular – the centers of radiating and nonradiating recombination.

It is shown, that changes of EL spectra heterostructures which traditionally connect with change of a condition of dot defects, can it is determined not only a material and heterojunction structure and relaxed condition of dot defects (impurity), but also momentary, in particular nonequilibrium, a condition of crystal defect structure as a whole and momentary operating non-uniform thermomechanical strains which at a relaxation change a structure of energy zones and levels in separate local areas of a crystal.

The high density direct current of light-emitting heterostructure is the initiating factor for changes in distribution of their internal local mechanical strains and in defect structure heterojunction and substrates which determine AE occurrence speed and value of degradation of basic parameters, in particular – CVC, spectrum and EL intensity.

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