512. Defect diagnostics in devices via acoustic emission

A. Bogorosh[1a], S. Voronov[1], V. Roizman[2], A. Bubulis[3], Ž. Vyšniauskienė[3]
[1]*National Technical University of Ukraine "Kyiv Polytechnic Institute", Ukraine*
[2]*Khmelnitsky National University, Ukraine*
[3]*Kaunas University of Technology, Lithuania*
E-mail: [1]*fondfti@ntu-kpi.kiev.ua,* [3]*lgimantas.Bubulis@ktu.lt*

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Abstract. The research was conducted to explore conditions triggering degradation and deterioration processes in heterostructures using methods of acoustic emission. Current, flowing through materials, causes significant temperature gradients and thermo-mechanical stress (up to 10^7 Pa) that contributes to the development of undesirable microplasticity of the material. The research disclosed peculiarities of acoustic emission in *n+-n-p-* and *p+-p-n-* structures of A^3B^5 compounds under direct current in a process of their natural deterioration, and interdependence between the acoustic emission and developments in their electrical characteristics. The research facilitates direct and timely detection of defects and microcracks in different devices operating under threshold parameters and being influenced by external physical/mechanical forces generated from direct current and ultrasonic fluctuations.

Keywords: Heterostructures, defect formation, acoustic emission, current, ultrasound, deterioration

1. Introduction

Reliability of devices, including electronics, operating under extreme environment of maximum possible physical/mechanical overloads is a nowadays problem for engineers and scientists. Deterioration of materials and individual elements of device (also nanoelectronics) generates degradation and defect formation processes in materials of the device. Unclear threshold parameters of devices being affected by external physical/mechanical forces impose limitations on their practical use.

2. Research task

Defect formation and dynamics of their growth, transformation of functional parameters in nanoelectronic devices, and paragenesis in materials under various physical effects have been researched in a number of works. In line with delicate local indestructible ferromagnetic methods, used for the detection of places that may be defected in near future [1], scientists have recently started to use acoustic emission methods [2]. Acoustic emission (AE) is an inductive radiation of natural noise-type acoustic waves, present in dynamical transformation of solid physical bodies, accompanying the formation and breakdown of local mechanical stresses under the effect of various external forces. AE is a set of noise-type acoustic impulses recorded from internal sources of a material, including internal static or dynamic loads, basically in a phase of initiation or movement of defect locations, breakdown of internal mechanical pressure, destruction of granules, etc. [3]. Independent experimental studies indicate that AE method may be used for detection and investigation of defect formation processes in granular materials as well as in functional structures of electronic devices [4, 5].

Using solid heterostructures, LEDs and semiconductors under threshold conditions, the researchers take into account heterogeneity of electric current that flows through the whole structure of the element and the contact points, as well as different modules of elastic constants, coefficients of linear thermal expansion, lattice distance at the interface of heterogeneous junctions, thermal resistance of active environment, and heat-conducting path. [6]. These factors and their physical interactions must be helpful in determining interior defects accumulating at intergranular space and forming clusters and microcracks. Empirical testing of such assumptions is one of the main tasks of this work.

3. Problem solving

It is known that current, flowing through a material, courses significant temperature gradients, and thus, thermo-mechanical stress (up to 10^7 Pa) and undesired microplasticity of materials. Such changes in structure of materials take place particularly under the threshold density of current in Joule self-heating environment [7]. Such parts of material where relaxation of mechanical stress takes place in presence of current and heat become sources of AE [8]. Microplasticity of nanostructures may be also defined on the basis of the main components [9] and additives present.

The aforementioned phenomena significantly accelerate deterioration and degradation of electric, luminescent and other characteristics of devices, and reduce performance, efficiency and trouble-free operation. Detecting degradation processes at the very beginning, via AE methods, is one of the most relevant and important tasks of diagnostics and control over the nanoelectronic devices.

From a scientific point of view, examining and implementing AE processes in physical investigations may solve one of the main problems in solid-state sciences – run-time diagnostics and detection of the main defect formation processes, natural or stimulated by external physical/chemical forces, including plastic deformations of granular materials. It is important to underline, that this is almost the only one non-destructive express method for monitoring the dynamics of continual defects and spatiotemporal evolutions of defective subsystem at the moment. Previously, multiple attempts to recognize the beginning of defect formation processes in materials, led by various external physical forces, via acoustic methods and with a use of special non-destructive devices [10] allowed noticing microcracks that had already reached 0.1 mm; this is not enough in field of nanoelectronics.

The research [11] disclosed peculiarities of AE formation in LEDs on basis of Gap, GaAs and GaN junctions in a process of their natural deterioration under the influence of direct current, and the establishment of interconnection between the acoustic emission and developments in their electric and optical characteristics. However, this research poorly examined the dynamics of AE and the influence of direct electrical current on the interconnection between the threshold fluidity characteristics of joints between separate units of micro- and nano-electronics changing the amplitude of inductive acoustic response in presence of physical radiation, what became the main object of our research.

Therefore our research was focused on examination of AE processes triggered by structural degradations and relaxations on basis of GaAsP, GarAIAs and GaN under the effect of direct current and in semi-conduction joints GaAs and CdTe affected by impulses of ultrasonic field.

AE method was the main tool in experimental research; however other contemporary measuring tools were also used in order to measure structural characteristics (optical microscopy), electrical parameters (volt-ampere characteristics (VAC)), and other data of researched devices.

AE signal recording was performed using piezoelectric sensors of bi-channel acoustic device AF-15 within the frequency ranges 20-200 kHz, 200-500 kHz, and 500-1000 kHz. The boost of AE electrical signals (70-85dB), as the intensity, has been recorded using the integrated electronic accumulator of the AF-15. Signals of discrete high-energy AE at the output of peak detector AF-15 were recorded using automatic recorder or PC and processed by appropriate software.

A non-destructive express control method applicable in ferrielectric and LED structures and devices, which allows run-time detection of degradation and relaxation processes on a threshold of AE in both durably stored and actively used heterostructures under the effect of direct current, was also used. This method facilitates forecasting reliability and helps determining individual threshold parameters of devices, including threshold current density preceding the destruction of materials.

4. Experimental setup

After gradual application of direct current on heterostructures on basis of GaAsP, GaAIAs, and GaN, it was recognized that typical threshold current density J_{thre}, which is necessary for occurrence of AE in examined p+-p-n structures on basis of $Ga_{0.7}Al_{0.3}As$, $Ga_{0.65}Al_{0.35}As$, and $GaAs_{0.15}P_{0.85}$ (Fig 1a), is 70-75, 80-87, 53-66 A/cm^2 respectively, what significantly exceeds J_{norm} of such structures (Table 1).

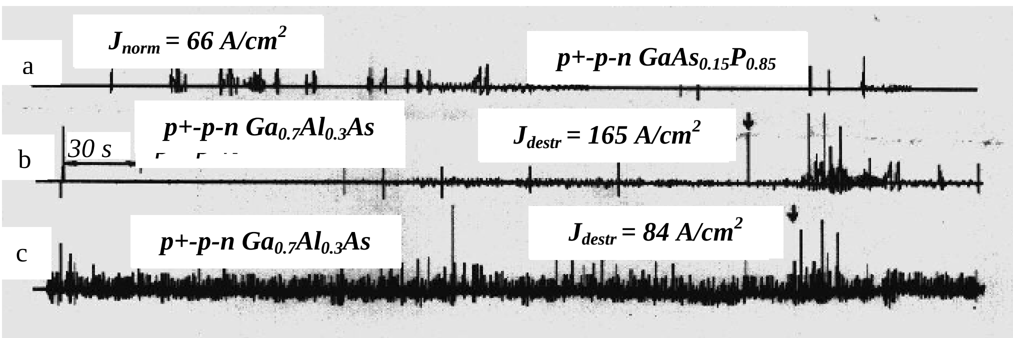


Fig. 1. Discrete AE: a – close to defect formation threshold; a – typical beginning of destruction; c – destruction under rapid gradual increase of current ↓ – current supply point

Experimental results are presented in Table 1.

Table 1. AE occurrence thresholds and destructive current

Material	Nominal current density A/cm^2	AE threshold, A/cm^2	Destructive current density A/cm^2
$Ga_{0.7}Al_{0.3}As$	3.9	75.0	165.0
$Ga_{0.65}Al_{0.35}As$	3.9	84.0	201.9
$GaAs_{0.15}P_{0.85}$	3.9	66.9	165.0

It is important to notice, that, comparing to the results of previous experiments conducted in a time period $2.5x10^8$s (~8 years) [8], present research exposed significant increase of AE threshold (J_{thre}) and destructive current ($J_{destruc}$). Since the manufacture of researched devices – $(5-6)x10^8$s (16-18 years) – their J_{thre} has changed from 2-20 A/cm^2 in example [8] to 66.9-201.9 A/cm^2 in our experiment. Moreover, in some $Ga_{0.65}Al_{0.35}As$ type structures AE was detected at the beginning of destruction only. Such a wide range of results may be explained by the fact that direct current density was hard to measure at the end of XX century [7], and, besides, AE and accompanying threshold processes in materials were poorly examined. Our research also disclosed that destructive current density J_{destr}, which brakes down most of the structures, exceeds J_{thre} and is equal to 160.5 A/cm^2 in n+-n-p structures on basis of $GaAs_{0.15}P_{0.85}$, p+-p-n on $Ga_{0.7}Al_{0.3}As$ (Fig 1b), and p-n on GaP; and 201.9 A/cm^2 in p+-p-n structures on a basis of $Ga_{0.65}Al_{0.35}As$ (see Table 1).

In order to compare occurrences of AE threshold in ultrasonic field, researchers performed an experiment on semi-conductive compounds GaAs and CdTe under impulsive ultrasonic (US) radiation applied in both gradual and step-like modes using methods described in paper [12]. Under the acoustic pressure of US field, which reaches $2x10^5$ MPa with an intensity $1.5-2x10^4$ W/m^2 and frequency 22 kHz (on the surface of a radiator), and is applied 0.5-1.0 hour, Seignette material $KOOC(CHOH)_2COONax4H_2O$ was destroyed and reduced at 20-25 percent; when the intensity of US was increased, the material completely broke down. Another experiment was performed on modified Seignette-electric substance used in non-cooled thermovision cameras with hybrid detectors. Basic materials of this substance are lead zirconate titanate ($PbZr_{0.58}FeO_2NbO_2Ti_{0.03}$:U) and semi-conductor silicium. During the same period of time, this material was destroyed at 12-21 percent, and broke down completely under the increased intensity of US. As it is known, structures produced on the basis of A^3B^5 get such defects as microinclusions of another phase: matrix metals, solvent metals, and oxides, as well as good few of surface and massive defects related to technological processing, already during the manufacture [9,13]. Such 'technological' bi-dimensional and three-dimensional defects, under the effect of direct electrical current, may change their status and become active sources of powerful discrete AE (see Fig 1).

System analysis of experimental data demonstrates that formation of AE sources in heterostructures greatly depends on velocity of incremental changes in current load – increasing the step and reducing the time application, AE formation threshold moves to the area of minor current, and the total emission and the intensity of AE significantly increases, however the destructive volume of current, significantly declines. This happens due to the interaction and replication of defects that are active sources of AE (Fig 1c).

Thus, further experiment was conducted on electro-acoustic memory devices (EAMD), representing herostructures for analog and digital data storage and processing, that are made from layers of different materials (Fig 2).

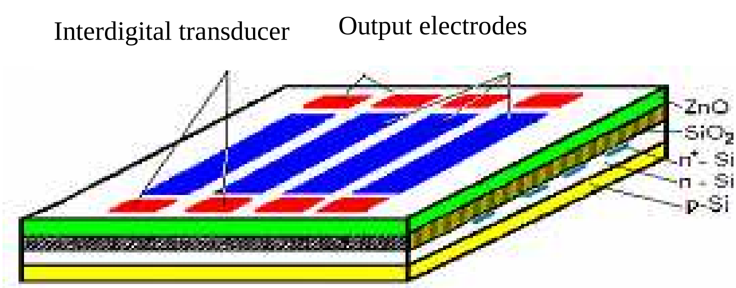


Fig. 2. Bi-dimensional memory device with matrix addressing scheme ZnO-Si

Such a ‘sandwich’ device has high-density memory and high data transfer speed. For example, memory device consisting of n+-n-p structures ZnO-Si and LiNbO3 and Si diode matrix, where binary information is recorded as non-uniform charge distribution captured in trap centers on ZnO films (Fig 2), also experienced erosive destruction of external layers at 8-12 percent after the analogical ultrasonic treatment. Relative increase of J_{thre} and J_{destr}, which was observed in that case, may be compared to deterioration processes that occur in much shorter time, due to the effect of external physical forces, but local and linear defects on material are more intensive and clusters-like. Such defects get three-dimensional structures what limits the number of potentially active sources for continuous AE and simultaneously leads to formation of complex defects (new sources of AE).

Having analyzed volt-ampere characteristics that are common to areas of simultaneous reduction of current and increase of voltage, under the occurrence of AE (Fig 3), the researchers determined average measures of threshold current density, under the occurrence of AE, and structure destructive current.

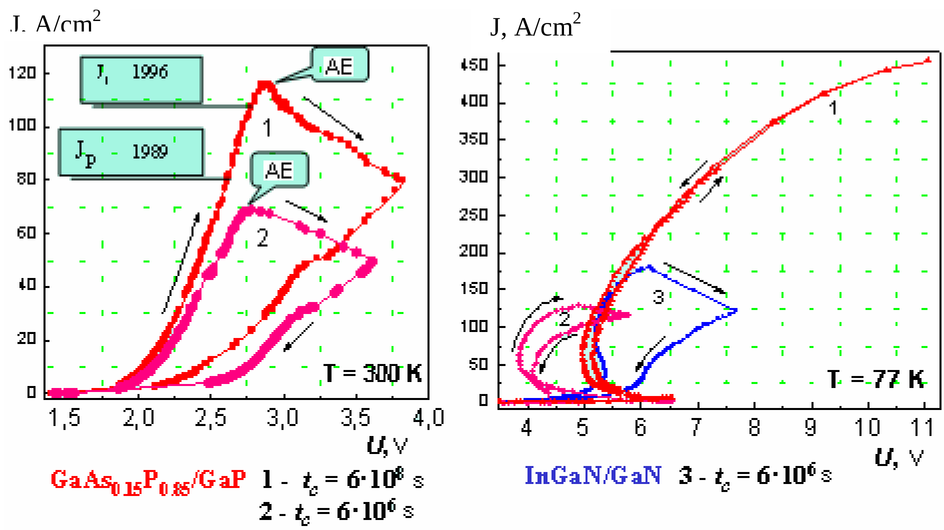


Fig. 3. Change of volt-ampere structures during degradation: deterioration time of GaAs0.15R0.85/GaP structure $6x10^8$ s (1) and $6x10^6$ s (2), when T=300 K

Average values of threshold current density that triggers AE in heterostructures GaAs0.15R0.85/GaP under various temperatures and operation time (τ = $6x10^8$ s and $6x10^6$ s) are exposed in Table 2.

Table 2. Average values of threshold current density

τ, s		**300-310 K**	**280-290 K**	**180-200 K**	**77 K**
$6x10^6$	1, mA	120	147	174	291
	J, A/cm^2	75	93	111	183
$6x10^8$	1, mA	192	300	354	507
	J, A/cm^2	129	192	228	309

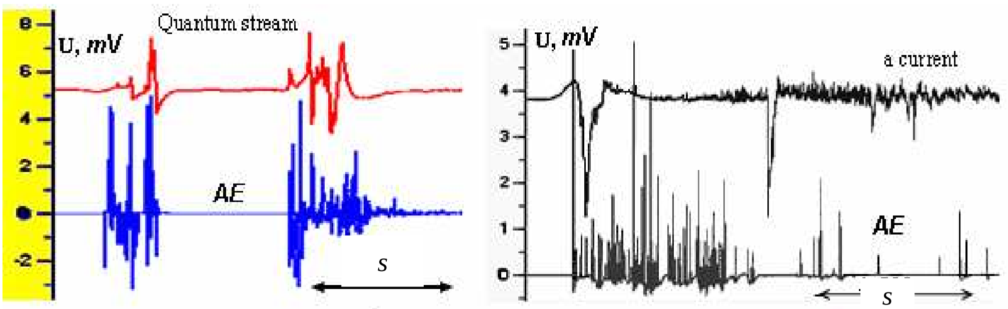
Average values of current density that constantly destructs heterostructures InGaN/GaN under various operation conditions (temperature and current power) in different periods of time are listed in Table 3.

Table 3. Average values of destructive current density

τ, s		**280-290 K**	**77 K**
$6x10^6$	1, mA	250-300	400-450
	J, A/cm^2	160-190	250-280
$6x10^8$	1, mA	450-500	600-730
	J, A/cm^2	280-310	375-460

Developments observed during the experiment correspond to that of plastic deformations, therefore their localization triggers AE. The experiment exposed correlation of AE as well as fluctuations of quantum output and current in structures under threshold current loads (Fig 4).

The achieved result may be explained in such a way: intensive formation of structural defects and developments in their power status courses relax of non-uniform thermal pressures and the acoustic emission. Intensive formation of defects under threshold current density leads to current fluctuations what happens due to rapid developments in structure resistance, therefore current deviations lead to fluctuation of injection carriers under the heterotransfer, what recombines analogical fluctuations of quantum output.



U_{kr}=5V, J=110 A/cm^2 U_{kr}=7V, J=131-150 A/cm^2

a) **b)**

Fig. 4. Correlation of AE, fluctuations of quantum output *I(a)* and current *J(b)* in heterostructure InGaN/GaN under 110 A/cm^2 at the moment of rigid degradation and appearance of microcracks

Value of acoustic pressure *P* depends on absorption factor α and thermoresistance value *I* in a time period τ:

$$P = \frac{\beta_1 c^2}{2C_p}(1-R)I\alpha\tau,$$

where β_t is coefficient of volume expansion, c – velocity of elastic waves, Cp – thermoabsorption, R – reflection ratio.

Evident reason for this is the increase of static reflection ratio due to gradual accumulation of defects.

A non-linear dependence between the amplitude of acoustic response and the intensity of physical effect under the excess plasticity threshold may occur due to summing up of acoustic impulses induced by rigid changes in volume under the plastic deterioration, as well as the acoustic emission at the moment of defect formation and phase transformation from solid to liquid and from liquid to solid.

5. Conclusions

1. The experiment disclosed that nature of AE in heterostructures on basis of A^3B^5 junctions may be determined by time of their natural deterioration. Namely, the increased deterioration time changes the nature of AE from continuous to discrete one and decreases its intensity, but increases density of current forming AE as well as density of destructive current, which indicates the movement of defective subsystem into more stable status.
2. The experiment revealed that defect formation processes in heterostructures on basis of A^3B^5 junctions, stimulated by direct electrical current and AE, may be determined from current status of their defect system and velocity of step-like changes in current.
3. The research indicates that activation of AE sources, irreversible degradation of volt-ampere characteristics and fluctuation of quantum output take place simultaneously, if current density exceeds the threshold of discrete AE (in heterostructures on basis A^3B^5 junctions), what confirms common mechanism of their origin – emerging and moving the power status of continuous defects.
4. The research demonstrates that non-linear dependence between the amplitude of acoustic response and intensity of one-time nanosecond physical effect, radiations in area of transparency and fundamental absorption of granules may help to detect a threshold of plastic deformation in monogranules of semiconductor junctions A^3B^5.

Acknowledgements

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