Вісник Одеського нац. ун-ту.– 2006.– Т. 11, вип. 7. Фізика.– С. 3–18

PACS: 85.30, 61.72.F, 71.55.E; УДК 621.315.592

A. A. Ptashchenko*, F. A. Ptashchenko **
* I. I. Mechnikov National University of Odessa
** Odessa National Sea Academy

DEGRADATION OF SEMICONDUCTOR DEVICES: NON-DESTRUCTIVE DIAGNOSTICS

Наведено огляд механізмів деградаційних процесів у напівпровідниках та експериментальних даних про деградаційні явища у напівпровідникових приладах оптоелектроніки. Представлено неруйнівні методи діагностики деградаційних процесів, що базуються на аналізі електричних і світлових характеристик та поляризації випромінювання в різних діелектричних середовищах, вимірюванні просторового розподілу випромінювання та фоточутливості, аналізі низькочастотного спектру шумів.

Приведен обзор механизмов деградационных процессов в полупроводниках и экспериментальных данных о деградационных явлениях в полупроводниковых приборах оптоэлектроники. Представлены неразрушающие методы диагностики деградационных процессов, основанные на анализе электрических и световых характеристик и поляризации излучения в различных диэлектрических средах, измерении пространственного распределения излучения и фоточувствительности, анализе низкочастотного спектра шумов.

General insight into mechanisms of degradation processes in semiconductors is given, as well as some of experimental data on degradation phenomena in optoelectronic semiconductor devices. Non-destructive techniques for diagnostics of degradation processes are presented, based on analysis of electrical and light output characteristics, as well as polarization of emission in different dielectric mediums, measurements of spatial distributions of emission and photosensitivity, analysis of low-frequency noise spectrum.

Introduction. Degradation processes, changing the performance parameters of a semiconductor device during its operation, reflect general properties of solids: interactions between exited states of atomic and electronic subsystems, as well as relations between order and chaos. Excitation of these subsystems is usually produced by electric field, current, ionizing radiation, and interactions with the ambient atmosphere.

There are several reviews of degradation phenomena [1-8]. Numerous studies showed that degradation processes in semiconductor devices have some specific features. The recombination-enhanced defect reactions (REDRs) and charge-state dependent defect reactions between contamination impurities (such as Cu, Li, Au, Fe, O), doping atoms (Zn, O, Al etc.), and intrinsic defects (vacancies, interstitials, antistitials, such as As_{Ga}, and their clusters), as well as multiplication of dislocations, occur in heterogeneous and inhomogeneous systems, in presence of potential barriers, in strong and non-uniform electric fields and under non-uniform mechanical strain. Such techniques as deep-level transient spectroscopy (DLTS), thermally stimulated currents (TSC), and *C-V* measurements, giving average characteristics of an actual structure, have a very restricted application to the reliability diagnostics of semiconductor devices.

The purpose of this paper is to give a general insight into mechanisms of degradation processes in semiconductors and to present some of experimental data on degradation phenomena in semiconductor devices, as well as to refer to some non-destructive techniques for diagnostics of degradation processes.

1. Degradation mechanisms due to reactions of point defects. In early studies on degradation phenomena, it was established that degradation processes are connected with transformations in the spectrum of point defects [9]. Vacancies and interstitial atoms were produced in alkali halides by ionizing irradiation. It was clear that these phenomena have a subthreshold character [9-15]. The binding energy of atoms in most semiconductor materials amounts >10eV. According to the momentum conservation law, a direct displacement of atoms in a semiconductor can occur under irradiation by photons with energy > 300keV. And the experiments showed that point defects were generated by photons with energies of few eV.

The fundamental cause of subthreshold degradation effects in solids is the Frank-Condon principle. Transitions between the electronic states due to photo-excitation or recombination require such a short time Δt, that atoms practically do not change their positions for this time. Thus the electronic transition causes an impact excitation of the atomic subsystem. On the other hand, because of a strong difference in mass between electrons and atoms, the full energy of the electronic subsystem plays a role of a potential energy component of the atomic subsystem. Therefore the electronic transitions change binding energy of atoms and the energies of their vibrational states.

The mechanisms of quasi-chemical defect reactions caused by an excitation of the electronic subsystem are connected with (a) ionization of intrinsic and/or impurity atoms in a crystal [11, 12]; (b) creation of a short radius exciton and subsequent predissotiation of a quasimolecule [13-15]; (c) by impact excitation of the vibrational subsystem of a quasi-molecule by nonradiative recombination of electrons and holes [16, 17]. The ionization model [11, 12] takes into account a change in the effective charge of an intrinsic or impurity atom as shown in Fig.1*a*. In the ground state, a negative ion (in an ionic crystal) is surrounded by positively charged atoms. When an electron is removed from its orbit at the central ion A, the surrounding atoms begin to vibrate between new equilibrium positions. If the vibrational energy is concentrated at one of the atoms, this can result in a shift of the atom into a new position in the crystal. A similar process in a covalent crystal [18] is shown in Fig.1*b*. The central atom A is bound to four other atoms by electron pairs. And when a bond (dashed line at the left) is broken, the atom can be "thrown" off by three other bonds. An edge atom A at a dislocation can be displaced in a similar way, as shown in Fig. 1*c*.

Fig.1*d* represents a configuration diagram for an explanation of such a quasi-chemical defect reaction. The curve depicts the dependence of the "potential" energy U of the quasi-molecule on some configuration parameter x. The equilibrium state of the quasi-molecule corresponds to $x=A$ and the vibrational energy E_0. An additional energy ΔE_0 is required for a transition to the state localized at $x=C$. A recombination enhanced defect reaction (REDR) [5] can occur, when, as a result of an electronic recombination- (or excitation) transition, the quasi-molecule goes to a point A^1 above the ground state. The probability of the $A^1 \rightarrow C$ transition can be written as

$$w = w_0 \exp\left[-(\Delta E_0 - E_e)/(kT)\right], \qquad (1)$$

where E_e is an energy contribution caused by electronic excitation [19] (it is implied $E_e < \Delta E_0$). The coefficient w_0 is different in several models [5, 6]. In the optimum case, when the electronic energy is transferred directly to the vibrational mode required for the $A \rightarrow C$ transition of the atom, E_e is equal to the energy released by the electronic transition. This case is realized for a number of defects in III-V compounds [5]. According to Eq. (1), in the case of $E_e<\Delta E_0$, an electronic excitation reduces the thermal dissociation energy of a quasi-molecule. When the energy of the electronically excited state of the quasi-molecule is higher than $E_0+\Delta E_0$, the dissociation can be athermal. Athermal dissociation can also take place, when the electronically excited state of the quasimolecule has a $U(x)$ curve without minimum.

It is evident that different charge states of a quasimolecule should have different $U(x)$ curves. Therefore changing of the charge state of point defects by doping, injection or photo-excitation changes (under some conditions) the thermal dissociation energy of photochemical reactions. The role of these "steady-state" effects (as compared to "dynamical" effects, REDRs) should be enhanced with increasing temperature.

Fig.2 represents the spectrum of deep levels in the energy gap of degraded III-V semiconductors, studied by DLTS (deep level transient spectroscopy) [20–21], thermo-stimulated currents [22–23], tunnel spectroscopy [23]. The most important of these levels are ascribed to centers containing Cu, As_{Ga} (E_2 - center), Si, O, Zn [6]. But the nature of a great number of centers and their role in degradation phenomena is unknown.

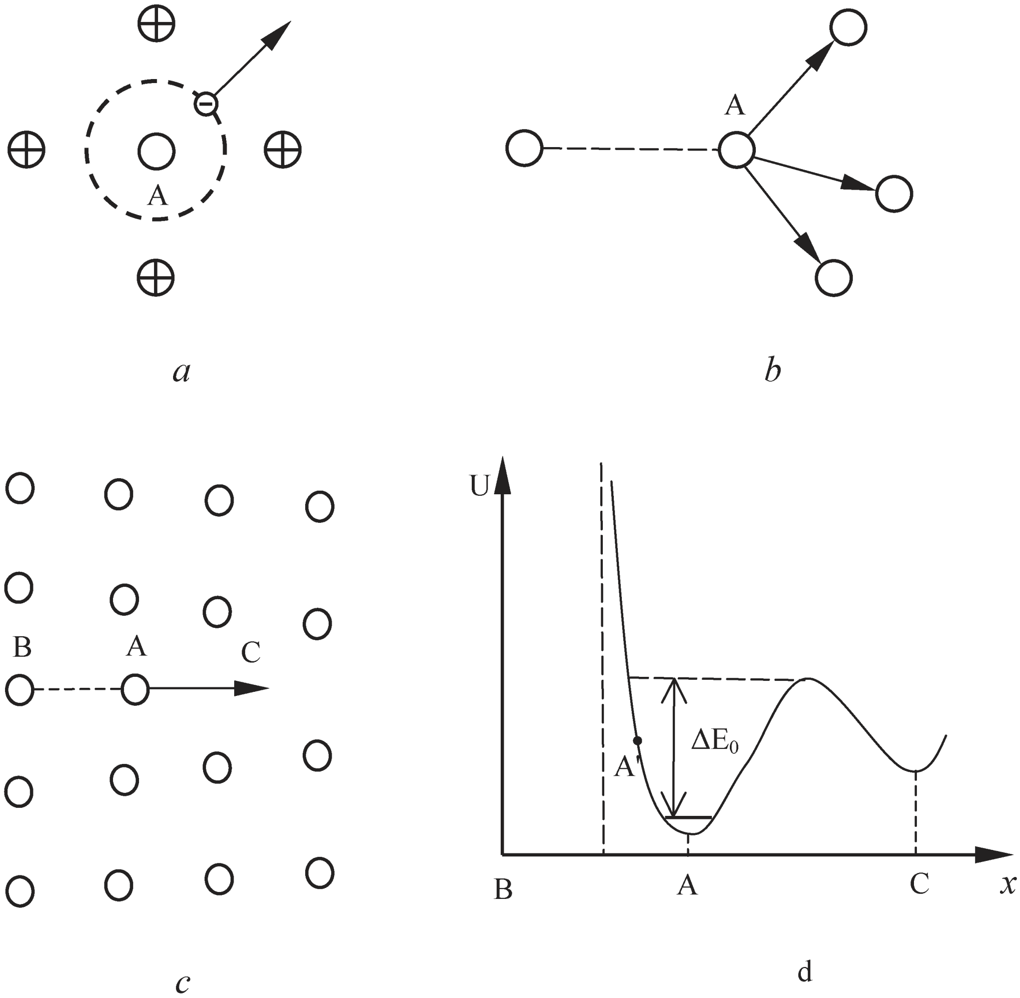


Fig. 1. Schematic of defect reactions in (a) ionic crystal; (b) covalent crystal; (c) at a dislocation. Section (d) presents the corresponding configuration diagram

2. Degradation mechanisms due to dislocations. Degradation of diode lasers and light-emitting diodes is often associated with the development of dark line defects (DLDs) [1–3]. DLDs are usually observed as sets of lines with lowered brightness of photo-, cathode- or electroluminescence. The nature of DLDs in III-V compounds is well studied by transmission electron microscopy (TEM) [24-25]. It has been established that DLDs are formed by 3-dimensional sets of dislocations, containing dipoles of a length of 1–5μ, dislocation loops of 2–30nm and helicoidal dislocations. The Burgers vectors of the most dislocations in DLDs are usually directed along <110> or <100> axes.

The first model of dislocation multiplication was proposed by Frank and Read [26]. The Frank–Read dislocation source is a dislocation segment pinned between two points *A* and *B* in a glide plane. Under an inhomogeneous stress, the dislocation segment is bent by glide, and finally a dislocation loop is formed encircling points *A* and *B*, while the dislocation segment *AB* is regenerated. The primary glide planes in III-V semiconductors are the {111} ones and the dislocation glide occurs in <110> directions by formation of a double kink on the dislocation line and its subsequent propagation along the dislocation line [3]. The models of the electronically enhanced dislocation glide invoke a change in the charge of dislocation states (or double-kink states) [27, 28], or a contribution of non-radiative recombination to the activation of the double kink nucleation (or its propagation along the dislocation line) [29]. The α- and β- dislocations gliding in appropriate <110> directions in III-V compounds have different energy bands, different recombination activities and different recombination enhanced mobility's. Some important features of recombination-enhanced degradation processes in GaAs – AlGaAs heterostructures were studied in [26] by TEM and cathode-luminescence observations, using laser illumination combined with indenting the structure by a Wickers pyramid. Laser illumination with a photon energy of $h\nu > E_g$, generating electron-hole pairs, substantially enhanced only one of the two <110> glide directions (the β one) in the *p* - GaAs (or *p* - AlGaAs) "active" layer of a laser-like GaAs–AlGaAs heterostructure [32, 33]. Therefore local stresses could only be partly released by the glide. The second step of the stress relaxation authors [32, 33] attribute to <100> DLDs formation as a result of dislocation climb. The <100> DLDs only developed under light illumination, and their development required a certain time (10 to 15 hours) [33], which was observed earlier in [34]. The point defects needed for the climb process may be generated by previously developed dislocations [32]. The inhomogeneous stress, required for the photo-activated dislocation glide, may be produced by fluctuations of the material composition in heterostructures [35], or induced during processing of a device [36].

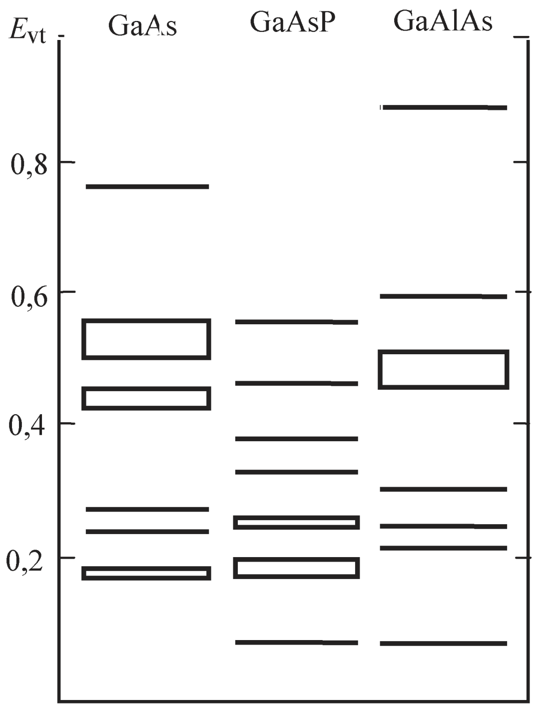


Fig. 2. Spectrum of deep levels changing their concentration in degraded devices on III-V compounds. E_{vr} is the distance of the corresponding level from the *V*-band.

3. Degradation and dislocations in semiconductor devices. A substantial decrease in the light output of degraded light-emitting diodes (LEDs) and diode lasers (DLs) was usually observed, while DLDs covered a small part of the active region [1, 2, 6–8]. Therefore it was interesting to know, whether DLDs cause the observed reduction in the light intensity, or they are a by-product of degradation processes. The second question was in what way DLDs affect the steady-sate and transient characteristics of semiconductor devices. And the third problem was the features of degradation processes in semiconductor devices in comparison with those in bulk materials. We studied effects of passing direct and reverse currents [22, 23, 37–43], laser illumination [44], γ and *X*-irradiation [45,46], O^+ and A_r^+ ion bombardment [47], axial pressure [49, 50] and indentation by a Wickers pyramid at room temperature [50 – 52] on electric, photoelectric and electroluminescent characteristics of *p-n, p-i-n, n-i-n* structures and Shottky diodes on III-V semiconductors. The most important result of these studies was that the degradation processes are spatially inhomogeneous. The most sensitive to the degradation processes is the "excess" current, which is dominant at low forward bias voltages and has tunnel-recombination nature [53, 54], as well as the tunnel-breakdown reverse current. The averaged thickness of the depletion region in the studied structures was too high for tunnel processes. Therefore we concluded that the most sensitive to degradation are the inhomogeneities of p-n and metal-semiconductor junctions, which cause local narrowing of the depletion region [6]. *I-V* characteristic of the tunnel-recombination current can be written as

$$I = I_t \exp\left(eV/(n_t kT)\right); \qquad (2)$$

where the "nonideality coefficient" is [53, 54]

$$n = 2\left\{1 - \hbar^2/\left[6m_t W_1^2 (kT)^2\right]\right\}^{-1}, \qquad (3)$$

where m_t is the effective mass of a tunnelling carrier; W_1 is the coefficient in the expression for the local thickness of the depletion region

$$W = W_1 (V_0 - V)^{1/2}, \qquad (4)$$

V_0 is constant. An analysis of *I-V* characteristics, based on Eqns. (2)–(4), permitted to estimate the effective local thickness of the depletion region in the corresponding inhomogeneities of degraded p-n-junctions to be of 5–30 nm.

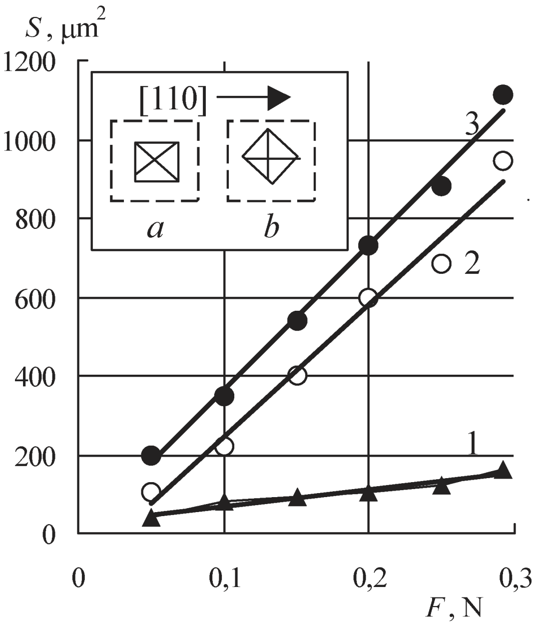


Fig. 3. Dependence of the area of the indentation spot (1) as well as the dark area in electroluminescence immediately after indentation (2) and after degradation (3) on the indenter load. The insert shows orientation of the dark area (dashed lines) at different orientations of the indenter pyramid (crossed squares) [50]

The observed decrease in the light output of LEDs at a fixed current, resulting from current aging [23, 37] or local laser illumination [44], was quantitatively explained by the increase of local nonradiative current component. The selective etching of degraded structures showed that the local laser irradiation created dislocations crossing the *p-n* junction [44]. Therefore it was concluded that the main effect of dislocations (and the corresponding DLDs) in degradation of LEDs was connected with the nonradiative tunnel recombination in the depletion region at these defects. This conclusion was reinforced by the study of the effect of dislocations, introduced by indentation with a Wickers pyramid at room temperature, on the *I-V* characteristics and the electroluminescence (EL) of LEDs on AlGaAs double heterostructures [50, 51]. The Wickers pyramid was oriented with diagonals in <100> or <110> directions, as shown by crossed squares in the insert in Fig. 3, while the surface was of (100) orientation [50]. When passing the direct current, the near field of electroluminescence (EL) was photographed. The dark areas surrounding the indentations were always practically square, and their orientation was independent of the orientation of the indenter, as is shown by dashed squares *a, b* in the insert in Fig. 3. The dark areas were formed by dark lines of <110> predominant orientation like DLDs created by passing direct current [1], illumination [33], or electron-beam bombardment. Curves 1 and 2 in Fig. 3 represent the effect of the indenter load *F* on the area *S* of the indentation spot and the dark area, respectively. Linearity of the curve 2 and the independence of the dark square orientation of the indenter orientation suggest that the edge of the dark squares corresponds to a fixed stress, which was found to be of 200MPa, while the destruction threshold, corresponding to the indentation area, was of 1.2GPa. Curve 3 in Fig. 3 illustrates the effect of the indenter load *F* on the dark area formed around the indented spot as a result of current passing during 100 hours. An analysis of curve 3 gives the threshold stress of 160MPa for fast degradation of the active layer.

Curves 1 and 2 in Fig. 4*a* represent the dependence of the light output on the current in an AlGaAs LED double heterostructure (DHS), measured before (1) and after (2) a number of indentations [51]. It is seen that the dislocations introduced at room temperature reduce the light output, especially at low injection levels. Curves 1 and 2 in Fig.4*b* show the corresponding *I-V* characteristics, which are exponential, obeying Eq. (2). Taking into account that the entire area of the introduced dark squares is

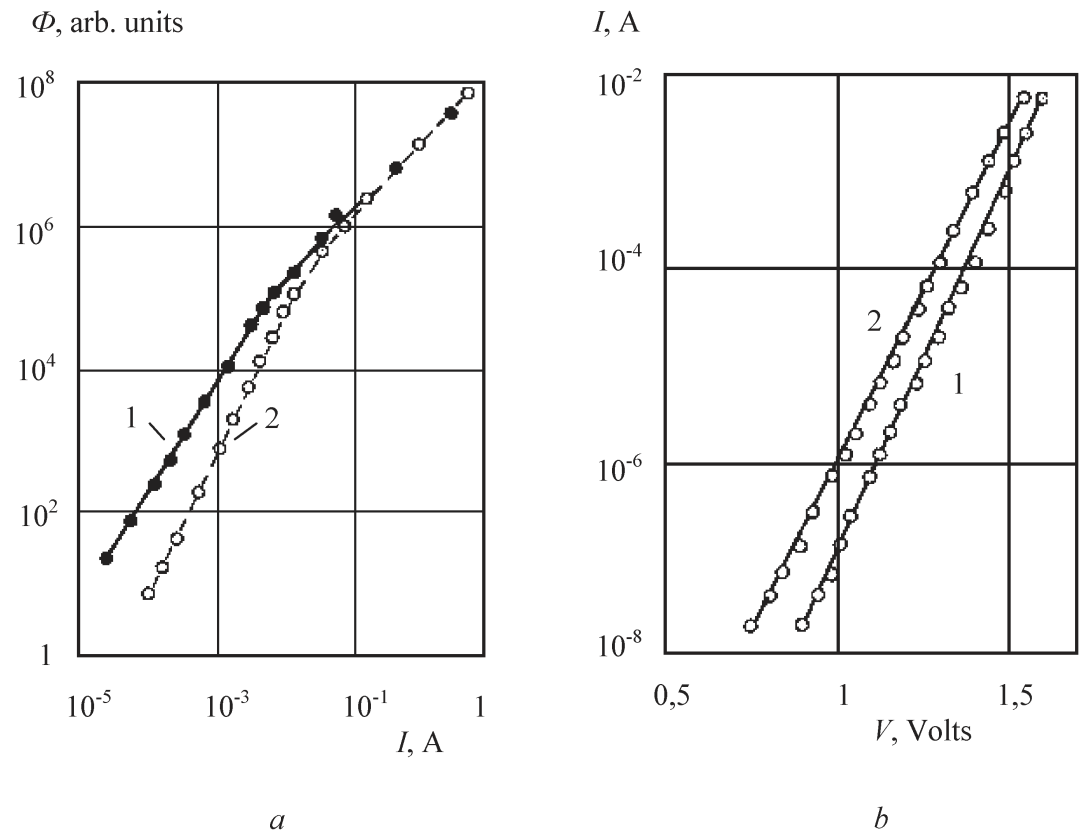


Fig.4. Dependences of the light output on the current (*a*) and *I-V* curves (*b*) of an AlGaAs p-n heterostructure before (1) and after indentations (2), correspondingly [50]

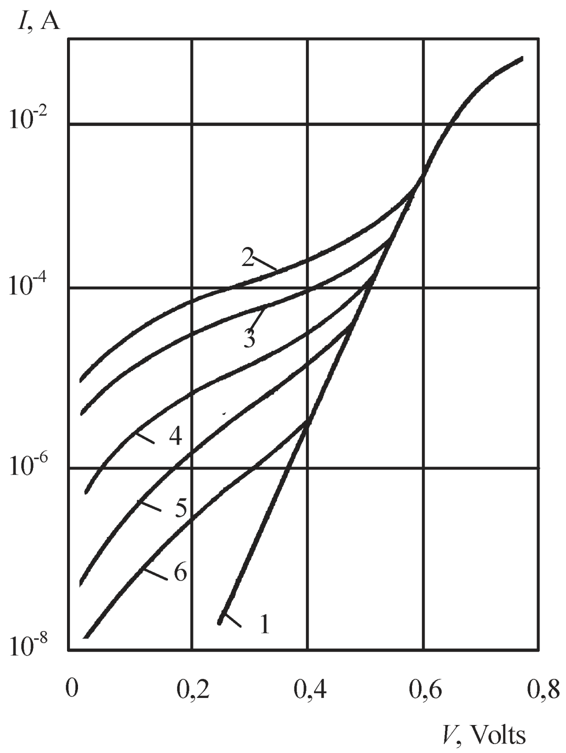
$$S_d << S_j , \tag{5}$$

where S_j is the *p-n* junction area, we can conclude that the lowering of the light output at a fixed current is caused by an increase in the non-radiative current component. The dashed curve 2 in Fig.4*a* is calculated from the curve 1 assuming that the difference between *I-V* curves 1 and 2 in Fig.4*b* is only caused by the additional non-radiative current resulting from indentations. A good agreement between the experimental points and the dashed curve 2 in Fig.4*a* reinforces the conclusion [51] that the non-radiative current component is concentrated at DLDs in the *p-n* junctions studied.

The main question of our work [48] was under what conditions mechanical stress can produce dislocations in semiconductor devices in the absence of excess minority carriers. The effects of axial pressure, passing forward and reverse current and heat treatment on the electric and photoelectric characteristics of barrier structures Au–GaAs, Sn–GaAs, Au–GaAlAs were studied [48]. Fig.5 shows *I-V* characteristics of an Au–nGaAs structure, measured before treatment (curve 1), after keeping the structure under axial pressure of 1,5MPa for 2000 h (2) and after annealing for 10 minutes at various temperatures. A comparison between curves 1 and 2 shows that a pressure of 1,5MPa is enough for degradation of Shottky diodes without electronic excitation. A similar pressure-aging of bare GaAs crystals resulted in generation of dislocation sets, observed by the selective etching.

The "excess" forward and reverse currents in Shottky diodes, produced by pressure-aging, were subject to annealing. The "excess" currents, produced by indentation of p-n junction in III-V compounds, also could be partly annealed [51].

Fig.6 represents the time-dependence of the forward current measured at V= 0,3V in



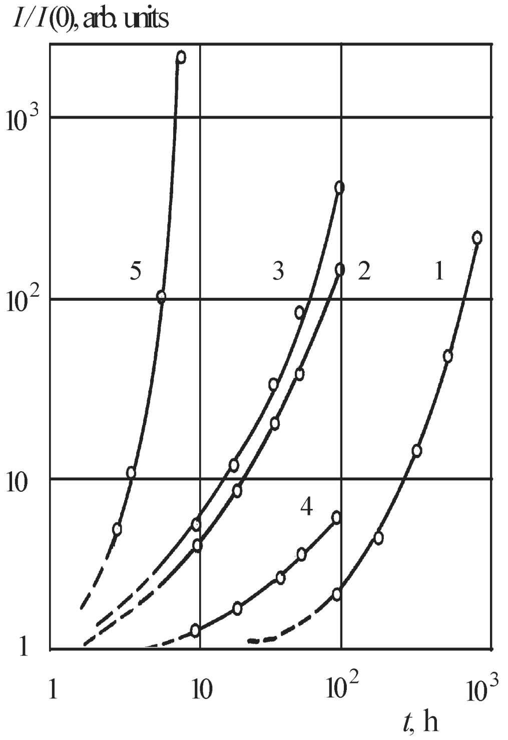


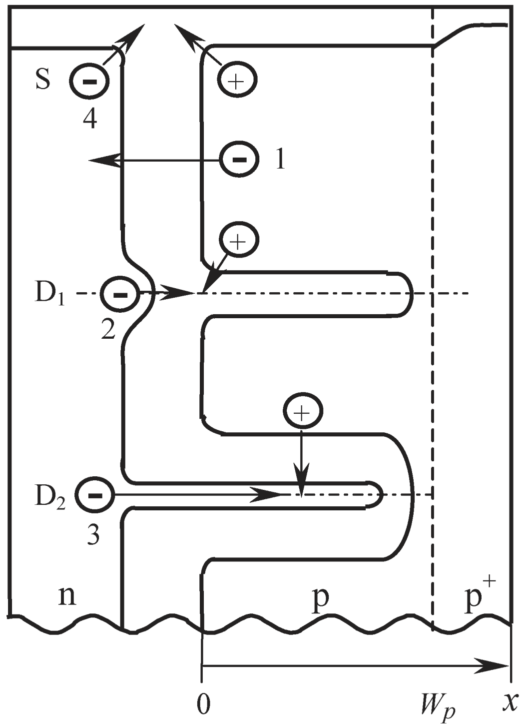
Fig.5. *I-V* characteristics of the direct current in an Au - GaAs junction: 1 - initial; 2 – after pressure-aging and after the subsequent isochronal annealing at $250^0\,C$ (3), $300^0\,C$ (4), $350^0\,C$ (5), and $400^0\,C$ (6) [48].

Fig.6. Time-dependences of the forward current measured at V= 0,3 V in junctions: Au–nGaAs (curves 1,2,5); Sn– nGaAs (3), and Au–pGaAlAs (4), subjected to an axial strain of 3,5 MPa (1); 180 MPa (2); 4,3 MPa (3); 200 MPa (4), and 160 MPa (5). Curve 5 was obtained for a combined pressure + current aging [48]

Shottky diodes, subjected to various axial stresses (curves 1-4) and, additionally to the stress, to passing a current of 10mA (curve 5) [48]. A comparison between curves 1 and 2, measured on Au–n-GaAs junctions, shows that an increase in the pressure from 3,5MPa to 180MPa accelerates the degradation process by more than one order of magnitude. Passing the forward current of 10mA during the pressure-aging causes a further strong acceleration of the degradation, as evident from curves 2 and 5. At the current density of $\cong$1 A/cm^2, used for the aging of a Shottky diode, the minority carrier injection could be neglected. Therefore this observation showed that degradation of stressed Shottky diodes can be substantially enhanced by current passing without recombination of electron-hole pairs. A comparison between curves 1, 3 and 4, obtained on Au–nGaAs, Sn–nGaAs and Au–pAlGaAs junctions, respectively, shows that degradation can be accelerated or suppressed by the choice of metal and semiconductor material in Shottky diodes [48].

4. Degradation and EL decay time in LEDs. Degradation of LEDs causes shortening of the decay time τ_e of EL [6]. We proposed a model of this phenomenon, taking into account that the non-radiative tunnel recombination is located at DLDs and the surface [52]. Diffusion of electrons, injected into the active region, in the junction plane cannot substantially shorten τ_e because of relation (5).

Fig. 7 is a schematic of a *p-n* structure [52] containing dislocations. There are a surface depletion layer *S* and dislocations D_1 and D_2, the latter of which is assumed to be deco-



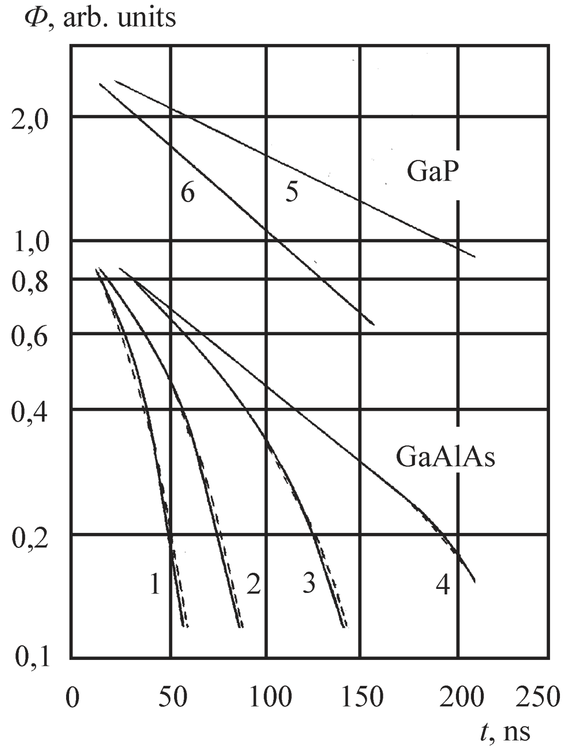


Fig. 7. Schematic diagram of a p-n structure with a surface depletion layer (*S*) and dislocations (D_1 and D_2) crossing the p-n junction [51]

Fig. 8. EL decay curves measured for GaAlAs DHS (curves 1–4) and GaP LED structure (curves 5, 6) by using current pulses: 1 – 50 mA; 2 – 100 mA; 3 – 400 mA; 4 – 1 *A*; 5,6 – 2 *A*. Pulse duration was 400 ns for curves 1–5 and 20ns for curve 6. The dashed curves are calculated [51]

rated by shallow donors. The shortest way for an electron, injected into the *p*-region, to recombine with a hole at the dislocation after an injection current pulse is to pass back into the *n*-region, as shown by arrow 1. Because of the neutrality condition, practically simultaneously electron 2 (or 3) recombines with a hole at a dislocation or at a deep level in the depletion layer at the surface (arrow 4). We simulated these processes in approximations of a thick ($W_p >> L_n$) and thin ($W_p << L_n$) active layer, where W_p is the thickness of the p-layer; L_n is the electron diffusion length [52].

Fig.8 shows the EL decay curves Φ(t) obtained for two LED structures. Full curves 1–4 were measured on GaAlAs DHS after passing current pulses of duration of 400 ns and various amplitudes. The dashed curves were calculated. Curves 5 and 6 in Fig.8 represent the EL decay measured in a dislocated (by indentation) GaP LED structure after passing current pulses I= 2 A of a duration of Δt=400 ns ($\Delta t > \tau$, where τ is lifetime of electrons) and Δt=20 *ns* ($\Delta t << \tau$), respectively. Such measurements were made on a number of GaAlAs, GaAsP and GaP LED structures, some of them were degraded by passing current or laser illumination, and others were indented by a Wickers pyramid [52]. The experimental data indicate that the local non-radiative recombination at dislocations leads to a non-exponential EL decay. The dislocations shorten the EL decay, especially on its "fast" stage. A comparison of calculated EL (or PL) decay curves with experimental data can be used for estimations of the bulk lifetime and some parameters of the non-radiative current component [52].

5. Polarization- and spatial characteristics of degraded laser heterostructures. The most sensitive methods for detection of strain in semiconductor structures and, particularly, in DLs and LEDs are based on polarization-resolved measurements of photo- and electroluminescence [36, 49, 55–58]. These methods, which use splitting of the heavy- and light-hole subbands in a deformed III–V crystal, enable to measure an elastic deformation of 0.01%. Fig.9 represents the degree of polarization ρ of the electroluminescence of an AlGaAs double heterostructure DL, measured under different pressures at various temperatures, as a function of the current I [49]. Curve 1 was obtained before, and curves 2–4 after passing a direct current of 60mA under an axial pressure of 25MPa for 4 h. A comparison between curves 2 and 4 shows that the degree of polarization ρ substantially changes with stress, which enables to estimate the strain in the active layer. And the "excess" polarization at low currents (I<10mA), which appears after degradation, can be explained as a result of the tunnel radiative recombination at inhomogeneities of the *p-n* junction [49]. Such inhomogeneities leading to deviations from the planarity of the depletion layer, as well as to a local thinning of this layer may be located at dislocations crossing the p-n junction. An inverse phenomenon – the Franz-Keldysh effect at dislocations in degraded III–V semiconductors was reported in [32].

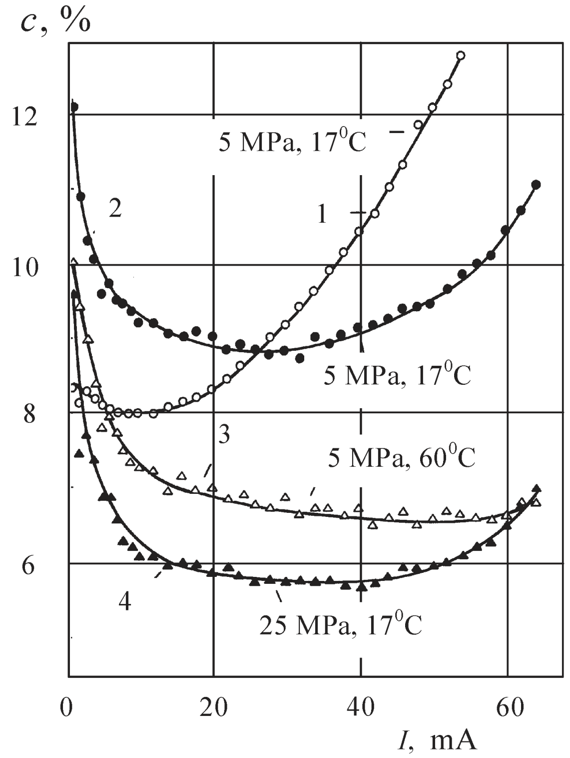


Fig. 9. Degree of polarization as a function of current in DL: 1 – before degradation; 2–4 – after degradation. Pressures and temperatures are indicated on the curves [59]

Degradation processes in semiconductor lasers are inhomogeneous. The profile of the radiation intensity on a resonator mirror (the near-field distribution) of a laser with stripe-geometry is shown in Fig. 10*a* and *b*, accordingly, before and after degradation [59]. The stripe width was 15 μ. It is seen that degradation leads to a significant narrowing of the near field. Degradation strongly affects the angular distribution (the far field) of laser emission as shown in Fig. 11 [59]. Curve 1 measured before degradation has two symmetric maximums which are characteristic for stripe-geometry lasers. Curve 2 measured after degradation is not symmetrical and has a number of maximums. This effect can be ascribed to one of two different mechanisms: non-uniform degradation of the mirrors or bulk degradation of the active layer. These mechanisms can be discriminated by measuring the output characteristics of the laser in air and in a dielectric liquid [60]. The threshold current of a laser is determined in one-dimension approximation as

$$I_t = I_0 + \frac{1}{\beta}\left(\alpha + \frac{1}{\Gamma L}\ln\frac{1}{r}\right), \tag{6}$$

where I_0 is the current which corresponds to the forming of inverse population; β is the differential pumping efficiency, which is the coefficient in the relation

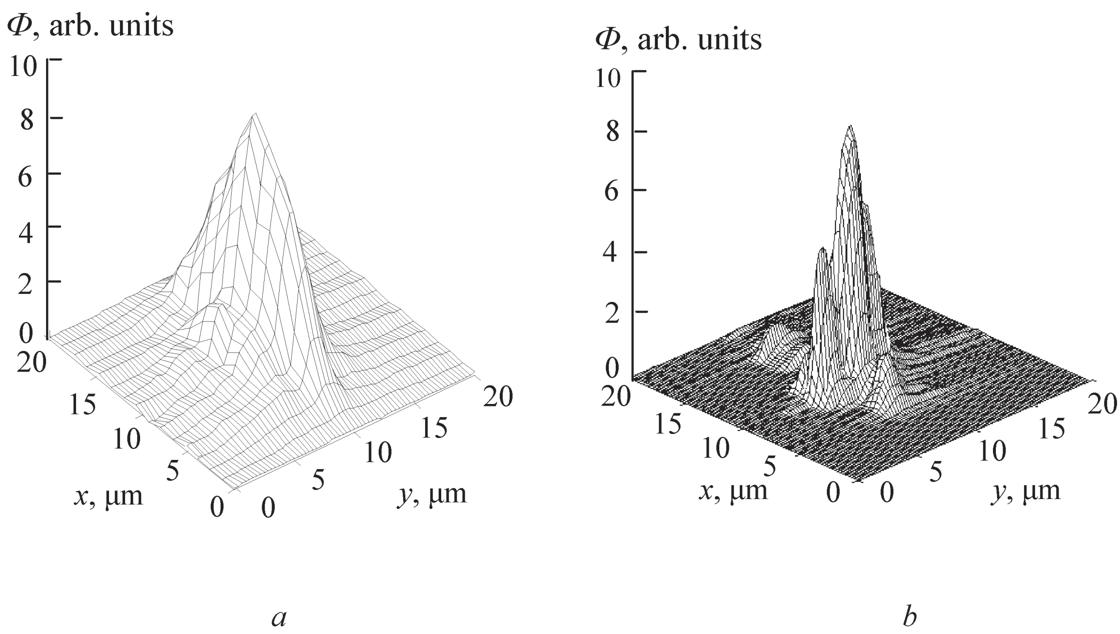


Fig.10. Near-field distribution of the laser emission: a – initial; b – after degradation

$$g = \beta\left(I - I_0\right), \tag{7}$$

g is the gain coefficient; Γ – the filling coefficient; L is the resonator length; r is the reflectivity of the laser mirrors

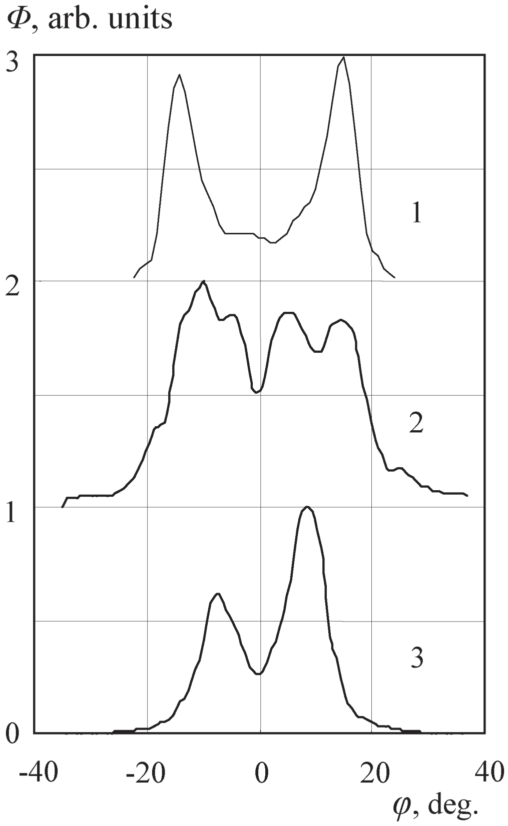
$$r = (n_s - n)^2/(n_s + n)^2, \tag{8}$$

n_s and n are the refractivity coefficients of the semiconductor and the ambient medium, correspondingly. It is seen from (6) and (8) that enhancing n by placing the laser in a transparent liquid increases the threshold current. This leads to an increase in the concentration of current carriers injected into the active layer and as result to reaching the inverse population in degraded places of the active layer. Therefore, if degradation is located in the active region (and not in the mirrors), placing the laser in a dielectric liquid must destroy the additional maximums in the far field. It takes place in the studied degraded lasers, as seen comparing curves 2 and 3 in Fig. 11 [59].

Curves 1 and 2 in Fig 12 represent the output characteristics of a laser diode, measured in air (n=1) and in turpentine (n=1.47), respectively, before degradation. From an analysis of these characteristics, using equations (6)–(8), we estimated the differential pumping efficiency β=0.40 ma^{-1}cm^{-1} and the absorption coefficient α=18 cm^{-1} [60, 61]. Similar measurements give for the laser after degradation α=100 cm^{-1} and β=0.68 ma^{-1}cm^{-1}.

6. Local breakdown of p-n junctions. Degradation processes in p-n junctions under passing reverse currents were studied in [42, 62]. When the reverse current used for aging was low enough, this treatment resulted in some increase in the avalanche breakdown voltage and stabilization of the breakdown in *p-n* junctions in III–V semiconductors and Si [42, 62]. Passing higher reverse currents, in a regime of limited avalanche breakdown, lowers the breakdown voltage.

Fig. 13 represents the reverse branches of the *I-V* characteristics of a *Si* p-n junction, measured before and after degradation [62]. Before degradation *I-V* curve 1 exhibits avalanche breakdown at V=380V. Curves 2-4, obtained at temperatures 296K, 333K, and 373K, correspondingly, after degradation, show gradual breakdown, and the current increases with the temperature. The noise spectrum of the reverse current of this *p-n* junction, which was monotonous before degradation, has a maximum, as seen from Fig.14. Curves 1–3, measured at temperatures 296K, 333K and 373K, respectively, illustrate lowering the noise



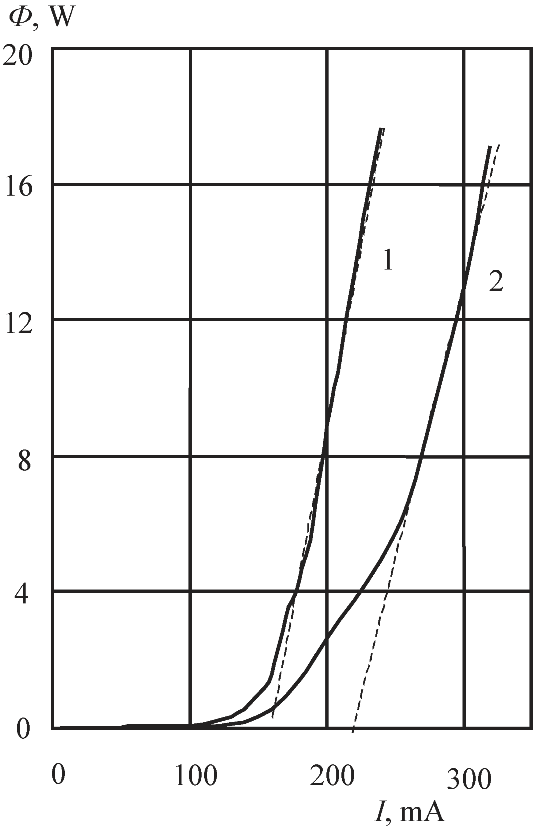


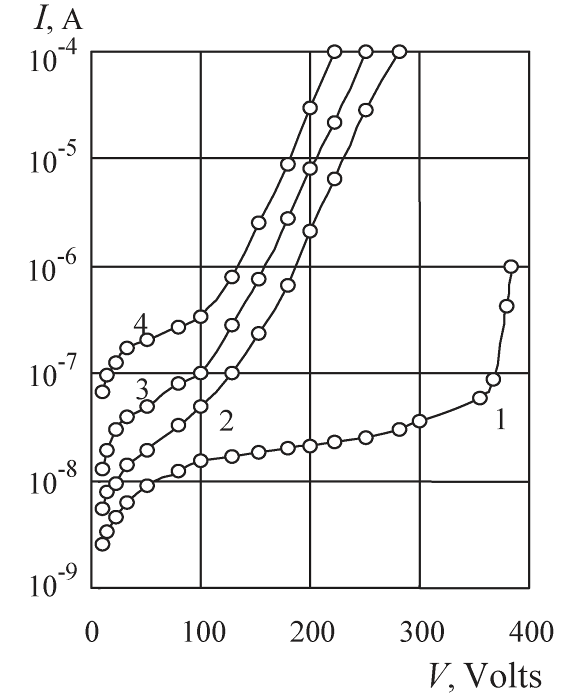
Fig. 11. Far-field distribution of the laser emission: 1 – initial; 2 – after degradation; 3 – after degradation, measured in turpentine

Fig. 12. Output characteristics of a laser diode, measured in air (1) and in turpentine

maximum with rising temperature. Analogous results were obtained for III–V LED structures, and sometimes low-frequency noise maxima were observed before degradation, in samples exhibited higher "excess" currents. A model of the reverse current oscillations in a *p-n* junction was developed [62], taking into account tunnel transitions from deep centers to the conduction band and the impact ionization of these centers in some inhomogeneities in the depletion region. Presence of these oscillations may be used in the reliability diagnostics of *p-n* structures and integrated circuits.

Inhomogeneities in *p-i-n* photodetectors can be studied by photoscanning techniques [63]. Fig. 15 displays a distribution of the photocurrent over a section of the photosensitive area of a Si *p-i-n* photodiode, measured at a pre-breakdown voltage. In this regime the inhomogeneities, at which the avalanche multiplication of the photocurrent occurs at lover voltages, are seen as "mountain ranges". Another kind of inhomogeneities is connected with deep levels located in *i*-layer of a *p-i-n* structure [63]. These inhomogeneities are detectable only at low reverse voltages, where the changing occupation of the related centers gives a substantial contribution to the space charge distribution (and voltage profile) in *i*-

region. At low voltages, these inhomogeneities are seen as areas of a lower photosensitivity, and at higher voltages they do not affect the photocurrent.



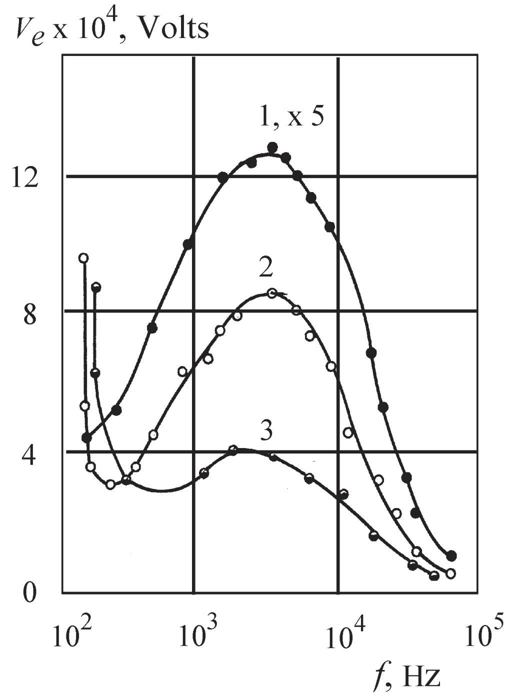


Fig. 13. Reverse branches of *I-V* characteristics of a Si p-n junction, measured before (1) and after degradation (2–4) at temperatures 296K (1, 2), 333K (3), and 373K (4) [62]

Fig.14. Noise spectrum of the inverse current in a degraded Si p-n junction, measured at temperatures 296 K (1), 333 K (2) and 373 K (3) [54]

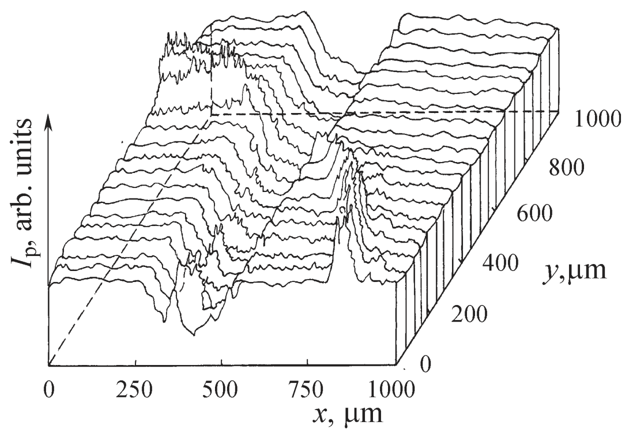


Fig. 15. Photo-current map, measured in a Si p-i-n photodiode under pre-breakdown voltage [55]

Conclusions. Degradation processes in semiconductor devices usually originate at inhomogeneities of the depletion region (associated with dislocations, surface, precipitations etc.). The cause of this is high local strain, high local impurity concentrations (>10^{19} cm^{-3}) and their gradients, high local electric fields (10^4 –10^6 V/cm), high local current densities (>10^4 A/cm^2). Besides REDRs and related effects, the non-uniformity of the current flow leads to the agglomeration of mobile ions at the inhomogeneities. These processes can create a positive feedback: an inhomogeneity → enhanced field and current density → REDRs + ion agglomeration → inhomogeneity development (an increase in the local defect density and generation of dislocations).

Dark line defects (DLDs) generated in LEDs and DLs during their work take small part of the active layer area and cannot significantly affect the life time of injected minority carriers. Generation of dislocations and related DLDs causes an increase in excess currents due to phonon assisted tunnel recombination at related deep states. The decrease in EL intensity of degraded LEDs is quantitatively explained by non-radiative nature of such recombination.

The most sensitive techniques for detecting of inhomogeneities in semiconductor structures with potential barriers are based on an analysis of *I–V* characteristics of excess forward currents due to phonon assisted tunnel-recombination and tunnel reverse currents. These currents exponentially depend on the local depletion region thickness and, consequently, on the local impurity (defect) concentration.

A significant role in the degradation of semiconductor devices plays mechanical stress. A stress of 1,2 GPa is destruction threshold for GaAs in (100) plane; 200 MPa corresponds to DLDs generation within minutes, 150 MPa – during 100 hours of current ageing. An uniform pressure of 1,5 MPa causes strong degradation of GaAs bulk material and Au–GaAs Shottky diodes within 1000 hours without passing current. Passing forward current (without minority carrier injection) in stressed Shottky diodes strongly accelerates degradation processes.

Local recombination at dislocations and surface significantly shortens the decay time of electroluminescence due to extraction of injected minority carriers and subsequent capture by related states. Time-resolved electroluminescence measurements give information about the local non-radiative recombination and can be used especially at high injection levels, where *I-V* characteristics are affected by bulk resistance.

The polarization- (especially, polarization- + spatially) resolved electroluminescence measurements give valuable information on strain in the active region of diode lasers and LEDs, as well as information on tunnel radiative recombination at inhomogeneities leading to local narrowing of p-n junction.

Measurements of near- and far-field distributions of laser emission of DLs with stripe geometry can be used for a study of non-uniform degradation of the active region. Bulk- and mirror-mechanisms of degradation of DLs can be discriminated by measuring the output characteristics of the laser in air and in a dielectric liquid. These measurements can be used for estimation of phenomenological parameters of the laser, such as absorption coefficient α and differential pumping efficiency β.

An analysis of the low-frequency noise spectrum can be used for diagnostics of degradation processes in complex systems. And very informative for reliability diagnostics of optoelectronic devices are measurements of the spatial distribution of photosensitivity in pre-breakdown regime.

1. **Bergh A.A. and Dean P.J.** Light emitting diodes. – Oxford: Clarendon Press, 1976.– 591 P.
2. **Gribkovskij V. P., Kononenko V. K., Pak G. T.** et al. Degradacija injekcionnykh laserov i elektroluminescentnykh diodov.– Minsk: Preprint Instituta Fiziki AN BSSR, 1976.– 66 P.
3. **Milvidskij M.G., Osvenskij V.B.** Zakonomernosti defektoobrazovaniya v heteroepitaksialnykh strukturakh soedinenij A^3B^5 dlya optoelektroniki (obzor)// Kristallografija.– 1977.– V. 22, P. 431–447.
4. **Shishiyanu F.S.** Diffuzija i degradatsija v poluprovodnikakh i poluprovodnikovykh priborakh.– Kishinev: Shtiinca, 1978.– 232 P.
5. **Kimerling L.C.** Recombination enhanced defect reactions// Solid–St. Electron.– 1978.– V. **21**, №12.– P. 1391–1401.
6. **Ptashchenko A.A.** Degradacija svetoizluchajushchikh diodov (obzor)// Zhurnal Ppikladnoj Spectroskopii.– 1980.– V. 33, №5.– P. 781–803.
7. **Torchinskaja T.V., Sheinkman M.K.** Phizicheskaya priroda degradatsii svetodiodov i poluprovodnikovykh lazerov// Zhurnal prikladnoj Spectroskopii.– 1983.– V. 38, №3.– P. 371–382.
8. **Eliseev P.G., Kochetkov A.A.** Nadezhnost heterolaserov // Itogi nauki i tekhniki. Ser. Elektronika. – M.: VINITI. – 1989. – V. 23. – P. 53 – 94.

9. **Seitz F.** Color centers in alkali halide crystals// Rev. Mod. Phys. – 1946. – V. 18, №3. – P. 384 – 408.
10. **Seitz F.** Speculation on the properties of silver halide crystals// Rev. Mod. Phys. – 1971.– V.23, №4.– P. 328–352.
11. **Varley J.H.O.** A mechanism for the displacement of ions in an ionic lattice// Nature – 1954. – V.174, №4436. – P. 886–887.
12. **Varley J.H.O.** Discussion of same mechanisms of F–centre formation in alkali halides // J. Phys. Chem. Sol. – 1962.– V. 23, №7.– P. 985–1005.
13. **Lushchik C.B., Lijdja G.G., Elango M.A.** Elektronno–dyrochnyj mekhanizm sozdaniya centrov okraski v ionnykh kristallakh // Sov. J. Solid State Phys. – 1964. – V.6, №6.– P.2256–2262.
14. **Pooley D.** Center production in alkali halides by radiationless electron hole recombination // Solid – St. Comm. – 1965. –V.3, №9. – P. 241–243.
15. **Hersh H.N.** Proposed excitonic mechanism of color–centers formation in alkali halides // Phys. Rev. – 1966.– V. 148, №2.– P .928–932.
16. **Weeks I.D., Tully I.C., Kimerling L.C.** Theory of recombination–enhanced defect reactions in semiconductors// Phys. Rev. B.– 1975.– V. 12, №8.– P. 3286–3292.
17. **Dean P.I., Choyke W.J.** Recombination–enhanced defect reactions. Strong new evidence for an old concept in semiconductors// Advances in Physics. – 1977. – V.26, №1.– P. 1–30.
18. **Iskanderova Z.A., Kiv A.E., Malkin A.A.** Podporogovye udarnye mekhanizmy obrazovahiya radiatsionnykh defektov v poluprovodnikakh // Sov. Phys. and Techn. of Semicond.– 1973.– V. 7, №9.– P. 1755–1759.
19. **Vinetskij V.L., Kholodar G.A.** Statisticheskoje vzaimodejstvie elektronov i defektov v poluprovodnikakh.– Kiev: Naukova Dumka, 1969.– 188 P.
20. **Lang D.V.** Deep-level transient spectroscopy: A new method to characterize traps in semiconductors // J. Appl. Phys.– 1974.– V. 45, №7.– P. 3023–3032.
21. **Lang D.V., Hartmann R.L., Schumaker N.E.** Capacitance spectroscopy studies of degraded $Al_xGa_{1-x}As$ DH stripe-geometry lasers // J. Appl. Phys.– 1976.– V. 47, №11.– P. 4986–4992.
22. **Ptashchenko A.A., Sushkov V.P., Litovchenko L.F**. et al. Issledovanie mechanizmov degradatsii svetoizluchajushchikh diodov na osnove $GaAs_{1-x}P_x$ i $Ga_{1-x}Al_xAs$ pri nizkikh urovnyakh inzhekcii // Elektronnaja tekhnika.– 1976.– Ser.2, №8.– P. 41–54.
23. **Ptashchenko A.A., Litovchenko L.F., Tepljakov V.A., Baranov V.M**. Dvizhenije primesnykh centrov pri komnatnoy temperature v p-n perekhodakh na osnove GaAs, $Ga_{1-x}Al_xAs$, $GaAs_{1-x}P_x$ // Ukr. Fiz. Zhurnal.– 1978. – V. 23, №1.– P.100–108.
24. **Petroff P., Hartman R.L.** Rapid degradation phenomenon in heterojunction GaAlAs–GaAs lasers // J. Appl. Phys.– 1974.– V. 45, №9.– P. 3899–3903.
25. **Hutchinson P.W., Dobson P.S.** Defect structure of degraded GaAlAs–GaAs double heterojunction lasers // Philos. Mag. – 1975.– V. 32, №4.– P. 745–754.
26. **Frank F.C., Read W.T.** Multiplication processes for slow moving dislocations // Phys. Rev. – 1950. – V. 79, No 4. – P. 722 – 723.
27. **Haasen P.** Kink formation and migration as dependent on the Fermi level // J. Phys. France). – 1979. – V. 40, No 6. – P. – 111–116.
28. **Hirsh P.B.** A mechanism for the effect of doping on dislocation mobility // J. de Physique. – 1979. – V.40, № 6. – P. 117 – 121.
29. **Maeda K., Sato M., Kubo A., Takeushi S.** Quantitative measurements of recombination enhanced dislocation glide in gallium arsenide // J. Appl. Phys. – 1983. – V. 54, № 1. – P. 161 – 168.
30. **Wosinski T., Figielski T.** Electronic properties of dislocations and associated point defects in GaAs // Inst. Phys. Conf. Ser. – 1989. – No 104; chapter 2. – P. 151 – 162.
31. **Wosinski T., Figielski T.,** Energy levels and electrical activity of dislocation electron states in GaAs // Acta Physica Polonica A. – 1993. – V. 83, No 1. – P. 51 – 58.

32. **Farvacque J.L., Vignand D., Depratere E.** et al. Electrical and optical properties of dislocations in GaAs // Inst. Phys. Conf. Ser. – 1989. – 104; chapter 2. – P. 141 – 149.
33. **Depratere E., Vignaud D., Farvacque J. L.** et al. The photoplastic effect in GaAs, a model for device degradation phenomena // Philosophical Magazine A – 1990 – V. 61, №6. – P. 893 – 907.
34. **Imai H., Fujiwara T., Segi K.** et al. Degradation of optically-pumped GaAlAs–double heterostructures at elevated temperature // Jap. J. Appl. Phys. – 1979/ – V.18, No 3. – P. 589–598.
35. **Sieber B., Farvacque J.L., Wang J., Steeds J.W**. Possible origin of degradation mechanisms in AlGaAs/GaAs laserlike structures// Appl. Phys. Lett. – 1992. – V. 60, №5. – P. 2654 – 2656.
36. **Colbourne P.D., Cassidy D.T.** Bonding stress measurements from degree of polarization of facet emission of *AlGaAs* superluminescent diodes// IEEE J. Quant. Electron. – 1991. – V.27, №4. – P. 914 – 920.
37. **Baranov V.M, Vorontsov L.F, Ivanov V.S.** et al. Issledovanie stabilnosti izluchajushchikh diodov na osnove $Ga_{1-x}In_xAs_{1-y}P_y$// Radiotekhnika i electronika.– 1979. – V. 24, №11.– P. 2342–2349.
38. **Ptashchenko A.A., Sushkov V.P., Irkha V.I**. et al. Issledovanie mechanizma degradatsii elektrolyuminestsentsii $Ga_{1-x}Al_xAs$ // Pis'ma v Zhurn. Tekhn. Fiz. – 1979.– V.5, №10.– P. 624–627.
39. **Ptashchenko A.A., Timokhov F.P.** Osobennosti degradatsii opticheskikh izluchateley na osnove n^+–i–n–heterostruktur GaAs – $Ga_{1-y}Al_yAs$ – $Ga_{1-x}Al_xAs$ // Zhurnal Ppikladnoj Spectroskopii.– 1979.– V.31, №3.– P. 453–454.
40. **Baranov V.M., Ivanov V.S., Irkha V.I.** et al. Rol neodnorodnosti p–n–perekhodov v degradatsii izluchajushchikh diodov na osnove InGaAsP // Zhurnal Ppikladnoj Spectroskopii.– 1981.– V.35, №2.– P. 338–343.
41. **Ptashchenko A.A., Marjutin V.I.** Degradatsiya p–ν–n–svetodiodov na osnove GaAs(O)// Zhurnal Ppikladnoj Spectroskopii.– 1982.– V. 36, №2.– P. 317–319.
42. **Abramov V.S., Golembievskij N.N., Ptashchenko A.A., Sushkov V.P.** "Zalechivanie" neodnorodnostej p-n perekhodov v svetodiodakh pri propuskanii obratnogo toka // Electronnaja Tekhnika.– 1987.– Ser.2, №4.– P.16–49.
43. **Abramov V.S., Ajriyan Yu.A., Kudashov V.N.** et al. Statisticheskije zakonomernosti degradatsii svetodiodov na osnove $GaAs_{0,6}P_{0,4}$ i GaP:N pri impulsnykh rezhimakh pitaniya // Electronnaja Tekhnika.– 1990.– Ser.2, №4.– P. 83–87.
44. **Ptashchenko A.A., Tsap B.V.** Degradatsiya p–n perekhodov na osnove GaAsP i GaAlAs pod dejstviem lazernogo izlucheniya// Zhurnal Prikladnoj Spectroskopii.– 1989.– V. 50, №6.– P. 897–901.
45. **Irkha V.I., Ptashchenko A.A., Chapnin V.A.** Vliyanie γ–radiatsii na $Ga_xAl_{1-x}As$ izluchajushchie diody. Elektrovakuumnye pribory dlya metrologicheskogo obespecheniya bystroprotekayushikh protsesov// Sbornik Nauchnykh trudov VNIIFTRI.– 1984.– P. 56–63.
46. **Ptashchenko A.A., Irkha V.I.** Osobennosti generatsii defektov v GaAs i GaAlAs pod dejstviem rentgenovskogo izlucheniya// Ukr. Phys. Zhurn.– 1981.– V. 26, №11.– P. 1881–1883.
47. **Ptashchenko A.A., Fusik M.** Vliyanije ionnogo obluchenija na fotoelektricheskije svojstva i elektroluminescenciju p–n–heteroperekhodov na osnove $GaAs_{1-x}P_x$.– Odessa, 1989.– P.20.– Dep. in UkrNIINTI, № 2770–Uk89.
48. **Ptashchenko A.A., Em Ren Sik.** Rol dislokatsij v degradatsii struktur metall–GaAs // Optoelectronika i poluprovodnikovaja tekhnika.– 1989.– №16.– P. 33–36.
49. **Ptashchenko A.A., Ptashchenko F.A.** "Excess" polarization of the spontaneous emission in laser heterostructures // Solid–State Electronics. –1996. – V. 39, № 10. – P. 1495–1500.

50. **Ptashchenko A.A., Ptashchenko F.A., Maslejeva N.V., Sadova G.V.** Mecanical strain and degradation of laser heterostructures // Proc. SPIE. – 2000. – V. 4355. – P. 79 – 86.
51. **Ptashchenko A.A., Moroz N.V.** O roli dislokatsij v degradatsii svetodiodov// Zhurnal Ppikladnoj Spectroskopii.– 1986.– V. 45, №3.– P. 474–478.
52. **Ptashchenko A.A., Melconyan D.V. , Moroz N.V., Ptashchenko F.A**. Effect of local nonradiative recombination on time-resolved electroluminescence of p–n junctions // Phys. Stat. Sol.(a). – 1997. – V. 159, №2. – P. 523–534.
53. **Ptashchenko A.A.** Kharakteristiki tunnelno–termicheskikh tokov v p–n perekhodakh // Ukr. Phys. Journ. – 1982.– V.27, №12.– P.1829–1833.
54. **Ptashchenko A.A.** Vliyanie tunnelnogo zakhvata s ispuskaniem phononov na primesnuyu rekombinatsiyu nositelej zaryada v p–n perekhodakh // Ukr. Phys. Journ.– 1984.– V. 29, №4.– P. 575–581.
55. **Vekua V.L., Dzhiojev R.I., Zakharchenja B.P.** et al. Poljarizatsija luminescencii i rasshcheplenije aktseptornykh urovnej pri deformatsii v kubicheskikh kristallakh // Sov. Solid St. Phys. – 1975. – V. 17, №4. – P. 1096 – 1103.
56. **Averkijev N.S., Gorelenok A.T., Tarasov I.S.** Osobennosti poljarizatsii luminestcentsii i konstanty deformatsionnogo potentsiala v InP n- i p-tipa provodimosti // Sov. J. Phys. and Technics Semiconduct. – 1983. – V.17, №6. – P. 997 – 1002.
57. **Cassidy D.T., Adams C.S.** Polarization of the output of InGaAsP semiconductor diode lasers // IEEE J. Quantum Electron. – 1989. – V. 25, № 6. – P. 1156 – 1160.
58. **Peters F.H., Cassidy D.T.** Spatially and polarization resolved electroluminescence of 1.3μm InGaAsP semiconductor diode lasers // Applied Optics. – 1989. – V. 28, № 17. – P. 3744 – 3750.
59. **Ptashchenko O.O., Ptashchenko F.O.** Degradatsija diodnykh laseriv I prostorovi charakterystyky jikh byprominjuvannja // 1 Ukrajins'ka naukova konferentsija z fizyky napivprovidnykiv. Tezy dopovidej. V. 1. – Odesa. – 2002. – P. 208.
60. **Ptashchenko A.A., Ptashchenko F.A., Volkov I.A., Grupp A.G.** Vlijanije okruzhajushchej dielektricheskoj sredy na charakteristiki poluprovodnikovykh laserov // Fotoelektronika. 2000. – V. 9. – P. 103 – 107.
61. **Ptashchenko O.O., Ptashchenko F.O.** Refraktometrychni kharakterystyky napivprovidnykovykh laseriv // Fotoelektronika. 2002. – V. 11. – P. 76 – 80.
62. **Ptashchenko A.A., Moroz N.V**. Model nizkochastotnykh oscilljacij obratnogo toka v p–n perekhodakh.– Odessa, 1996.– P.14.– Dep. in GNTBU 01.02.96, № 412 –Uk96.
63. **Ptashchenko A.A., Zekhov L.A.** Neodnorodnosti fototoka v kremnijevykh solnechnykh elementakh.– Odessa, 1995.– P. 15.– Dep. in GNTBU10.06.95, № 1463–Uk95.