Semiconductor Physics, Quantum Electronics & Optoelectronics, 2016. V. 19, N 1. P. 14-22.
doi: 10.15407/spqeo19.01.014

PACS 61.72.Ff, 78.55.Cr, 78.60.-b

Physical mechanisms and models of the long-term transformations in radiative recombination observed in *n*-GaAs under microwave irradiation

G.V. Milenin, R.A. Red'ko
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine,
41, prospect Nauky, 03680 Kyiv, Ukraine

Abstract. Simulation of long-term changes in photoluminescence of *n*-GaAs after microwave treatment by using the analysis of random events underlying the processes of evolution of the defect structure has been performed. We have shown the agreement of the experimental and theoretical time dependences of the changes in the photoluminescence intensity provided that the distribution of the random variable – time to a random event – obeys the Weibull–Gnedenko law. The mechanisms of transformation of the defect structure, which are based on the dynamics of behavior of dislocations and impurity complexes owing to microwave irradiation, have been presented.

Keywords: photoluminescence, dislocation, impurity complex, random variable, distribution function of the random variable, resonance, ion-plasma frequency.

Manuscript received 23.10.15; revised version received 03.02.16; accepted for publication 16.03.16; published online 08.04.16.

1. Introduction

Improving the structural perfection of epitaxial films of semiconductor structures by means of non-thermal action of external fields, including the electromagnetic one, is a promising direction of modifying their physical characteristics. In its turn, the control of change in the microstructure of semiconductor materials is possible with understanding the mechanisms that underlie the processes of evolution of structural and impurity defects under the influence of microwave radiation. To date, these mechanisms are not well studied and are mainly related to the thermal heating of the substance by microwave field [1-4]. Therefore, this work is, to a certain extent, aimed at eliminating this gap and at the analysis of the mechanisms and time regularities of transformation inherent to the defect subsystem of semiconductor structures based on GaAs, which is stimulated by non-thermal effect of microwave radiation.

2. Experimental procedure

The study involved the structures of n-n^+-GaAs with the thickness of epitaxial n-layer close to 3 μm and that of n^+-substrate 300 μm doped with Te. To reduce the influence of environment on atomic composition of surfaces in the studied samples, the surface of GaAs was covered with a thin layer of gold (~100 Å) by using electron beam evaporation in vacuum. The concentrations of free carriers in the epitaxial film and substrate were $\sim 5 \cdot 10^{22}$ and $\sim 1 \cdot 10^{24}$ m^{-3}, respectively.

Semiconductor Physics, Quantum Electronics & Optoelectronics, 2016. V. 19, N 1. P. 14-22.
doi: 10.15407/spqeo19.01.014

We studied the photoluminescent (PL) spectra at 77 K within the spectral range 0.6…2.0 eV, when exciting with $h\nu \geq 2$ eV light. The PL spectra were measured from the thin metal layer during the extended period after microwave treatment (up to 90 days). Microwave treatment of the samples was carried out inside air in the operation chamber of the magnetron at the frequency 2.45 GHz and output power 7.5 W/cm^2. The duration of exposure was 60 s. To prevent heating the sample, ranging the irradiation dose was carried out by stages, namely: the exposure time was 2 s, while the intervals between treatments reached 5 s.

3. Experimental results and their discussion

The observed features in PL spectra of the initial samples were as follows: the edge band with $h\nu_{\max} \approx 1.52$ eV and broad bands caused by local states in the forbidden band with $h\nu_{\max} \approx 1.02$ and 1.21 eV, which is typical for this type of the samples (Fig. 1). Like that in [5-9], we will associate these bands with radiative recombination on donor-acceptor (DA) pairs formed by vacancies of gallium and impurities (Cu).

Time dependences of the frequency position of the observed peaks are plotted in Fig. 2. It is seen that the frequency position of the edge peak does not change with time after microwave treatment, whereas after treatment the impurity bands are slightly shifted to the shorter wavelengths and further return to their initial state. The intensity of the PL bands after microwave irradiation increase as a whole, but for some relaxation time they return to the initial value or close to it.

The observed long-term non-monotonic changes in the intensity of photoluminescent bands after microwave treatment can be explained being based on understanding the dynamics of behavior of dislocations or defect complexes in subsurface region.

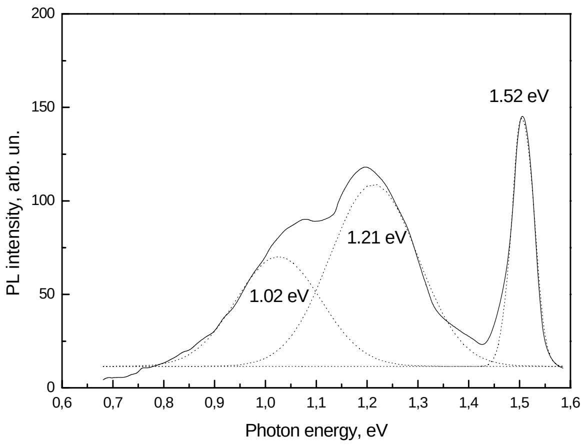

Fig. 1. Typical PL spectrum of the studied samples in the initial state.

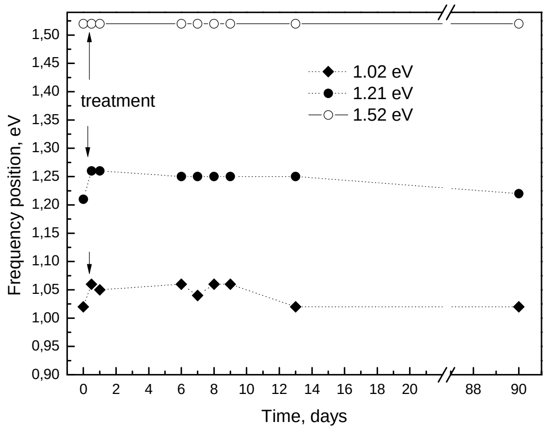

Fig. 2. Time dependence of the frequency position of the observed PL peaks in *n*-GaAs after microwave irradiation.

Thus, in the first scenario, it is assumed that, in the initial state, the dislocations are fixed by stoppers, and as a result of the microwave treatment and action of the fields of residual stresses on them, the elastic fields of other defects as well as the attractive force of dislocations to the crystal surface [10], the dislocations detached from local obstacles and moved from the subsurface layer to the surface (the subsurface area is taken to mean the thickness of layer, in which electron-hole pairs are generated when the crystal is exposed to light exciting photoluminescence).

In the forbidden gap, dislocations create dislocation levels, transitions to which are of predominantly non-radiative nature in the GaAs crystals [11]. It was noted in [12] that the transitions to the states of dislocation nature in the gallium arsenide crystals lead to optical quenching of both photoconductivity and substantial decrease in the intensity of the edge and donor-acceptor PL bands. Finally, condensed on dislocations are defects, such as gallium vacancies that are centers of non-radiative recombination [13]. In summary, we can conclude that the dislocations effectively increase the channel of non-radiative recombination.

Therefore, reducing the concentration of dislocations in the subsurface area analyzed using photoluminescence should lead to an increase in the intensity of all the observed bands – the edge, donor-acceptor and impurity ones. Furthermore, movement of the dislocation from the epitaxial layer into the subsurface area results in the fact that the intensity of PL bands, when peaking, decreases.

Let’s consider a second scenario based on the behavior of complex of defects under the influence of microwave treatment. It is known that in the doped GaAs crystals containing copper, the donor-acceptor complexes are formed. The ionized Te^+ and Si^+ atoms in the As sublattice are donors, and the uncontrolled Cu^- and Cu^{2-} impurity in the Ga sublattice acts as an acceptor [13].

Let's assume that under the action of microwave radiation, destruct of these complexes in the subsurface area takes place, and, consequently, the diffusion of copper is mainly observed on the interstices (Cu is a fast diffusing impurity) [13] to the surface under the influence of concentration gradient. Then, with the progress of time after microwave treatment, as a result of formation of new donor-acceptor pairs [$V_{Ga}Te_{As}$] (with account of released copper), we will see an increase in the intensity of PL band in the vicinity of 1.2 eV, which is accompanied by quenching the band at 1.3 eV [5]. When copper diffuses to the surface, it periodically fills the gallium vacancies (embedded into gallium sites [13]), that is, diffuses according to the dissociative mechanism. Since the gallium vacancies are centers of non-radiative recombination, when their number decreases, the intensity of both the edge and impurity PL band increases. Subsequently, on the one hand, with account of the movement of copper (released from the impurity complexes) to the surface, the concentration of the gallium vacancies is restored, and, on the other hand, due to the diffusion of copper into the subsurface area from the epitaxial layer, the impurity tellurium-copper complexes is also recovered. Accordingly, the intensity of PL bands will tend to its initial state. That is, in addition to changes in the intensity of the observed bands, in accord with this mechanism their reversible frequency shift to long-wave region is suggested.

Observed in our data is a shift of the impurity band to the shorter wavelengths, i.e., in our case, the initial prevailing concentration of the complexes [$V_{Ga}Te_{As}$], as a result of the filling with copper atoms diffused from the bulk, temporarily decreased together with firing the band at 1.3 eV, for which the complexes [$Cu_{Ga}Te_{As}$] are responsible. Because of it, the high-energy shift of the impurity band is observed (the peak at 1.25 eV observed for a long time after the microwave treatment is a superposition of two radiating centers – at 1.21 and 1.3 eV). The appearance of point defects Cu_{Ga} leads to increase in the intensity of the band at 1.02 eV, and the decrease in the concentration of gallium vacancies – to decreasing the channel of non-radiative recombination that results in increasing the intensity of all the PL bands, which is observed in the experiment.

Within the details of these mechanisms responsible for changes in the intensity of the PL bands, it is necessary to solve two problems. The first one concerns the mathematical description of the time regularities in changes of the PL intensity after microwave treatment, and the second one – the sense of mechanisms leading to detachment of dislocations and destruct of impurity complexes under the influence of microwave radiation.

3.1. Probabilistic-physical modeling of the evolution of the defect semiconductor structure due to microwave treatment

To solve the first problem, we used the results of [14], where it was shown that the physical processes are caused by random events, and the corresponding random variables – times to events – obey to the distribution by Weibull–Gnedenko.

We introduce the following random events: random event of movement of a defect (dislocations, gallium vacancies) from the subsurface area to the surface (boundary) and random event of defect motion to the subsurface area from the epitaxial layer (source) adjacent to this subsurface area and commensurate with the sizes of the latter. We emphasize once again that the subsurface area is considered to mean the thickness of the layer in which the electron-hole pairs generate when the crystal is exposed to light of photoluminescence excitation. Then, the random variable is the time to a random event. Accordingly, $F_1(t)$ is the distribution function of time before movement of a defect from the subsurface area to the boundary (the probability of motion from the subsurface area to the boundary); $F_2(t)$ is the distribution function of times before movement of a defect into the subsurface area from the source (the probability of movement into the subsurface area from the source).

Let's consider a new random event – the absence of a defect in the subsurface area. This event is complex and consists of a random event – movement of a defect from the subsurface area to the boundary – and of random one – the lack of movement of a defect into the subsurface area from the source. Let us assume these events are independent. Then, the probability of the given complex event is equal to the product of probabilities for the constituent events:

$$P_{1-2}(t) = F_1(t)[1 - F_2(t)] \ . \tag{1}$$

Being based on [14], we use Weibull-Gnedenko distribution as $F_1(t)$ and $F_2(t)$. Then, in the general case $F_1(t)$ and $F_2(t)$ can be expressed as [14]:

$$F_1(t) = 1 - e^{-\left(\frac{t}{\tau_1}\right)^{m_1}} , \tag{2}$$

$$F_2(t) = 1 - e^{-\left(\frac{t}{\tau_2}\right)^{m_2}} , \tag{3}$$

where τ_1, τ_2 are the time constants of random events; and m_1 and m_2 are the form factors of the distribution function of time to a corresponding random event.

Thus,

$$P_{1-2}(t) = \left[1 - e^{-\left(\frac{t}{\tau_1}\right)^{m_1}}\right] e^{-\left(\frac{t}{\tau_2}\right)^{m_2}} . \tag{4}$$

Accordingly, the higher the $P_{1-2}(t)$ value, the greater the value of the intensity of the photoluminescence band $I(t)$, that is, $I(t)$ is in proportion to $P_{1-2}(t)$:

$$I(t) = I_{in} + I_0 \left\{ \left[1 - e^{-\left(\frac{t}{\tau_1}\right)^{m_1}}\right] e^{-\left(\frac{t}{\tau_2}\right)^{m_2}} \right\} , \tag{5}$$

Semiconductor Physics, Quantum Electronics & Optoelectronics, 2016. V. 19, N 1. P. 14-22.
doi: 10.15407/spqeo19.01.014

where I_{in} is the initial value of the intensity of the photoluminescence band, I_0 is the proportionality factor.

This function has an extreme (maximum). In the particular case, when $m_1 = m_2 = m_3$ and $\tau_1 = \tau_2 = \tau$, the extremum condition

$$\frac{dI(t)}{dt} = 0 \tag{6}$$

is fulfilled at

$$t_{\max} = (\ln 2)^{m^{-1}} \tau . \tag{7}$$

In a general case, it is impossible to represent $t_{\max}$ in the analytical form.

In particular, Fig. 3 shows the graph of function $I(t)$ in absolute values at τ_1 = 6 days, τ_2 = 8 days, $m_1 = 3$, $m_2 = 4$, $I_{in} = 100$, $I_{in} = 1000$.

Let's consider the second group of random events: random event of the movement of a defect from the subsurface area to the boundary and random event of the movement of a defect into the subsurface area from the distant areas of the epitaxial layer (remote source).

By analogy with the above, for this group of events the probability of the lack of a defect in the subsurface area has the form:

$$P_{3-4}(t) = \left[1 - e^{-\left(\frac{t}{\tau_3}\right)^{m_3}}\right] e^{-\left(\frac{t}{\tau_4}\right)^{m_4}} , \tag{8}$$

where τ_3 and τ_4 are the time constants of random events; m_3 and m_4 – form factors of the distribution function of time to a corresponding random event.

For the case, when overlapping functions $P_{1-2}(t)$ and $P_{3-4}(t)$ can be ignored (incompatible events), the probability of absence of a dislocation is equal to the sum of probabilities for the constituent events, that is, it obeys the relation:

$$P(t) = P_{1-2}(t) + P_{3-4}(t) . \tag{9}$$

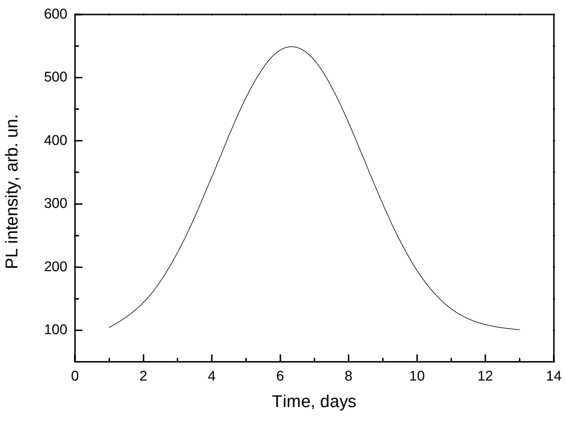

Fig. 3. Graph of the function (5). Empirical parameters are given in the text.

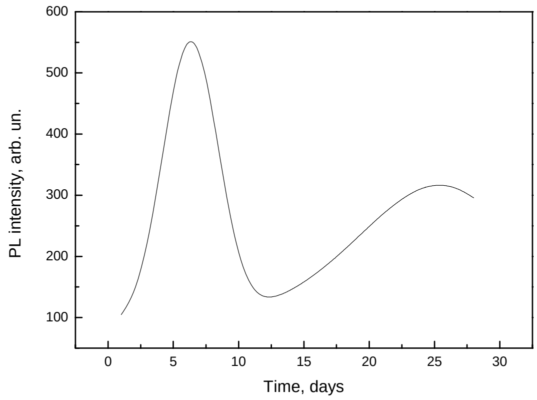

Fig. 4. Graph of the function (10). Empirical parameters are given in the text.

Respectively,

$$I(t) = I_{in} + I_0 \left\{ \left[1 - e^{-\left(\frac{t}{\tau_1}\right)^{m_1}}\right] e^{-\left(\frac{t}{\tau_2}\right)^{m_2}} + \left[1 - e^{-\left(\frac{t}{\tau_3}\right)^{m_3}}\right] e^{-\left(\frac{t}{\tau_4}\right)^{m_4}} \right\} . \tag{10}$$

Fig. 4 shows the change in this function with time at τ_1 = 6 days, τ_2 = 8 days, τ_3 = 30 days, τ_4 = 28 days, $m_1 = 3$, $m_2 = 4$, $m_3 = 4$, $m_4 = 5$, $I_{in} = 100$, $I_{in} = 1000$.

Thus, the probabilistic approach predicts the presence of one or several extrema in the long-time changes in the intensity of photoluminescence bands, which were observed in the studies [6-9].

Figs. 5 and 6 present the results of the least squares approximation with the expression (5) of change in the intensity of integrated PL for the edge and impurity bands of epitaxial *n*-GaAs structure with the parameters τ_1 = 7.06 days, τ_2 = 100 days, $m_1 = 2.48$, $m_2 = 1.88$, $I_{in}^{edge} = 7.11$, $I_{in}^{impurity} = 25.25$, $I_0^{edge} = 17.98$, $I_0^{impurity} = 55.05$, respectively. It is easy to note a good agreement between the experimental and theoretical results, as well as the fact that all the parameters of this approximation, beside the purely empirical (I_{in} and I_0) ones, are identical for both the impurity and edge PL, which evidences in favor of the same nature of defect transformations responsible for the observed changes in the edge and impurity radiative recombination.

We estimated the parameters that characterize transformation of the defect structure. If the movement of defects has diffusive character, in accordance with [14], $\tau_1 = d^2/D$, where D is the effective diffusion coefficient, and d – thickness of the layer in which the electron-hole pairs are generated under exposure to light of photoluminescence excitation. In our experiments, for the latter d is of the order $10^{-7}...10^{-6}$ m. Then, D ranges within $1.6\cdot10^{-20}...1.6\cdot10^{-18}\,\mathrm{m^2/s}$. The resulting value agrees well with similar estimations of the diffusion coefficients for migrating impurities due to weak magnetic-field processing the Si-SiO_2 and GaN-Al_2O_3 structures [15, 16]. The latter fact may indicate some generality of non-thermal mechanisms of interaction of microwave waves and weak magnetic field with semiconductor structures. If the movement of dislocations is carried out according to the gliding mechanism, then assuming that $\tau \approx d/\upsilon$, where υ is the velocity of the movement of dislocations, we obtain the estimation for the latter $1.6\cdot10^{-13}...1.6\cdot10^{-12}$ m/s.

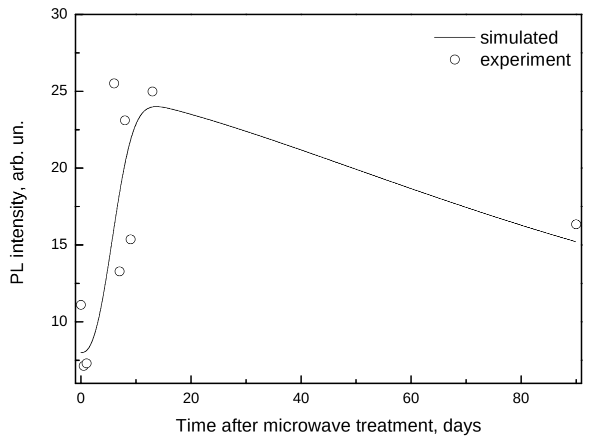

Fig. 5. Simulation of experimental results for time changes in the integrated intensity of edge photoluminescence, by using the function (5).

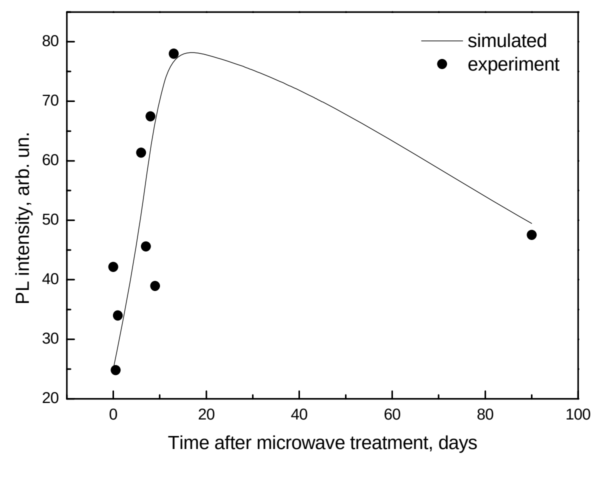

Fig. 6. Simulation of experimental results for time changes in the integrated intensity of impurity photoluminescence, by using the function (5).

3.2. Possible mechanisms of interaction of microwave radiation with semiconductor material

The existing up to date models of interaction of microwave radiation with semiconductor material in the vast majority are based on microwave-induced heating the studied material [1-4] or have some limitations that do not allow use their full usage [17, 18]. At the modes selected by us, thermal heating is excluded, so, the questions remain open concerning the non-thermal mechanisms of detachment of dislocations and destruct of impurity complexes under the influence of microwave radiation. Let us discuss them.

3.2.1. The mechanism of detachment of dislocations caused by electronic transitions

The essence of this mechanism proposed by these authors are the electron transitions from the dislocation core onto ionized impurities on the assumption that the dislocation is held near the stopper by the strong Coulomb interaction, which is turned off as a result of these transitions. The role of the Coulomb interaction in the dislocation-stopper system was discussed in many works, in particular [19, 20]. Indeed, the dangling bonds of dislocation have acceptor properties and capture electrons [21, 22]. When stoppers are positively charged impurities, the Coulomb interaction is set between the dislocation core and the stopper.

This mechanism is also valid if between the portion of dislocation core and stopper a covalent bond (quasi-molecule) forms, which is the cause of inhibition of the dislocation [23].

Just as a dislocation creates an energy level in the forbidden gap, so a point defect (stopper) forms its own level. If the ΔE value of the energy gap between the levels is equal to the quantum energy of microwave radiation (in our case ν_{em} = 2.45 Hz, $\nu_{em} = 1.54\cdot10^{10}$ Hz and $\Delta E = \hbar\nu_{em} = 1.01\cdot10^{-5}$ eV), and the acceptor level of the dislocation will be either below or above the level of the stopper, then the transition of electrons will be possible with absorption of a quantum of microwave radiation from the lower lying dislocation levels onto the overlying levels of stoppers or induced by electromagnetic field, forced transition of electrons from higher lying dislocation levels onto the lower lying levels of stoppers. The latter transition is energetically favorable for the crystal, since its energy drops in this case. As a result, the Coulomb interaction will disconnect or the covalent bond will break, and dislocation will detach from stoppers and shift.

It is also possible another scenario that is as follows. The movement of dislocations in the gliding plane in accord with the Peierls mechanism begins with the transfer from one valley of the Peierls potential to another one under action of thermal fluctuations of a short section of the dislocation [21]. That is, the movement of the dislocations takes place as a result of formation of a double kink, and its enhancement along the dislocation line. If the dislocations are fixed on the stoppers, the double kinks between the stoppers are also created, because, firstly, the number of stoppers is significantly less than the number of atoms in the dislocation, and secondly, not all the broken bonds in the dislocation core are filled with electrons, that is, are involved in the Coulomb interaction. The probability of filling of dislocation state obeys the Fermi–Dirac statistics and depends on the positions of the Fermi level and dislocation level [11, 22]. However, the stoppers prevent the spread of a double kink along the dislocation line.

It is known that under the influence of the kink the displacement occurs, particularly, the displacement of acceptor levels of dislocations closer to the middle of the forbidden gap of semiconductor [21]. This movement, like to the process of kink formation, occurs in time. It is likely that, in some point in time of this transformation, such a situation may be realized, when the value of the energy gap between the levels is equal to the quantum energy of microwave radiation ($\Delta E = 1.01\cdot10^{-5}$ eV), and the acceptor level of the dislocation will be located either below or above the level of the stopper. And then, again, the mentioned electron transitions will be possible. As a result, the Coulomb interaction will disconnect (breaking the covalent bond), and double kinks spread along the dislocation, and the dislocation itself will detach from stoppers and move.

We will discuss the problem concerning candidates for stoppers. As the stoppers, oxygen can act, it leads to appearance of deep donor levels E_c – (0.70…0.78 eV) in the forbidden gap of gallium arsenide [13]. On the other hand, in [12] it was noted that the dislocations in gallium arsenide create particularly the acceptor level E_V + 0.7 eV. Location of this level may also undergo changes. It is likely that either in its initial state, or as a result of the above transformation of position of the dislocation level, the conditions may appear when the analyzed electron transitions will be possible.

3.2.2. The mechanism of detachment of dislocations caused by their oscillations

As shown in [6], the dislocations anchored at the ends have their own (basic) frequency of vibration ω_1 equal to

$$\omega_1{}^2 = \pi^2 \frac{G}{L^2 \rho_v}, \tag{11}$$

where G is the shear modulus, ρ_v – bulk density of material, L – dislocation length.

When the dislocation is electrically charged and fixed by two stoppers at the ends, the frequency of the electromagnetic radiation ω_{em} is equal to the frequency of intrinsic oscillations of dislocation ω_1, then under the influence of the electric component of an electromagnetic wave, the phenomenon of resonance is observed. At the resonant frequency, the amplitude and energy of oscillations sharply increase at low damping. As soon as the energy of oscillations exceeds the binding energy of the dislocation with stoppers, the dislocation detaches and becomes able to move. However, this effect is characterized by strong selectivity of lengths of detached dislocations to the frequency of microwave radiation. For example, for GaAs at $\omega_{em} = 1.54\cdot10^{10}$ Hz and $\rho_v = 5.317\cdot10^3$ kg/m^3 [24], G =32.85·10^9 Pa [25], in accordance with (11), only the dislocation with $L = 5.07\cdot10^{-7}$ m detached.

The proposed mechanism of detaching the dislocations is based on the fact that, on the one hand, in the microwave generator operation, in particular a magnetron, when switching it, the so-called pre-generational phase of transition period takes place [26]. The spectrum of the output signal of the magnetron has quasi-noise character in the early stage of pre-generational phase, and the signal is chaotic. Its size to several tens of decibels is less than that in the generation mode [26]. This signal contains the frequencies from ν_{min} to ν_{max}, and here ν_{min} may be about 1 GHz and ν_{max} is about 4.8 GHz.

An additional factor is that, when the magnetron operates, the side oscillations are excited in the vicinity of the carrier frequency [27].

On the other hand, the studied samples were processed in the resonator. Any resonator is characterized by a large number of oscillation modes [28]:

$$\lambda = \frac{2}{\sqrt{\left(\frac{m^2}{a^2} + \frac{n^2}{b^2} + \frac{p^2}{l^2}\right)}}, \tag{12}$$

where λ is the wavelength; m, n, p are the whole numbers; a, b, l – length, width and height of the resonator, respectively.

As it can be seen from (12) at relatively low frequencies (low values of integer parameters), the spectrum of oscillation frequencies has a discrete character with a minimum frequency for the resonator used $\nu_{em\,\min}$ = 0.307 GHz (in the formula (12), a = 48.9 cm, m = 1, n = p = 0). In the direction of higher frequencies (with the growth of the integer parameters), the density of the oscillation modes increases, tending to infinity to the continuous spectrum, i.e., the resonant frequencies are arranged denser.

The resonator can operate at any of the resonant frequencies. The operating frequency of a resonator is determined by the carrier frequency of magnetron (ν_{em} = 2.45 GHz) and the quality factor Q of resonator at a given frequency.

In the frequency range that is often close to the resonance frequency of the resonator, the amplitude of microwave oscillations in this resonator is equal to [28]:

$$U = \frac{U_p}{\sqrt{\left\{1 + \left[\frac{2Q(\nu_p - \nu)}{\nu_p}\right]^2\right\}}}, \tag{13}$$

where ν is the frequency of the excitation signal, ν_p – resonant frequency, U_p – amplitude of oscillations at a resonance, Q-factor for the applied resonator, it is not high – less than 100.

As can be seen from (13), the higher the quality factor, the narrower the frequency band, in which excitation of resonator can be possible. Due to the low quality factor of a resonator, significant are oscillation types that are generated at other resonant frequencies (side resonances). Their frequency positions are determined by the formula (12), and the oscillation amplitudes at them vary within wide limits. In their magnitude, they are smaller than the amplitude of oscillations at the operating frequency. Within the frequency range in the vicinity of the given resonances, the oscillation amplitude is determined by the expression (13) with different values Q and U_p, which are smaller than those at the operating frequency. The maximum frequencies of excited resonances are limited by the losses in the resonator.

Thus, the total electric field formed by superposition of all oscillation modes can be complex, but through alternating the directions it will contain maxima and zero points.

Summarizing all the foregoing, one can say that in the resonator, there is a wide range of microwave oscillations with the frequencies $\nu \ge \nu_{em\,\min}$. Therefore, all the dislocations, anchored by two stoppers at the ends and with the intrinsic frequencies $\omega_1 \ge \omega_{em\,\min}$ = 1.93 GHz, detached. The lengths of detached dislocations obey the relation $L \le 4.05 \cdot 10^{-6}$ m, in accordance with (11).

A similar situation takes place, if the dislocation is fixed by n stoppers, dividing it into segments with a number of $(n-1)$. When the intrinsic frequencies of oscillations of all the set of segments satisfy the condition $\omega_1 \ge \omega_{em\,\min}$, then the dislocation detaches from the stoppers.

We note that, in relation to the above mechanism of dislocation detachment caused by electron transitions, the presence of oscillation frequency spectrum in the resonator allows making the following notation. Electron transitions between the levels of dislocations and stoppers are available in a wide energy range, the lower boundary of which is $\Delta E = \hbar\omega_{em\min} = 1.27 \cdot 10^{-6}$ eV.

3.2.3. The mechanism of the impurity complexes destruct

Without loss of generality review, let's analyze, in particular, the destruct of complexes of defects formed by ionized tellurium and copper impurities in n-GaAs epitaxial structures doped with tellurium. To do this, we examine the features of their behavior under the influence of the electromagnetic field.

In metals, in the system of charged point ions of the same sign, the long-wave ion-plasma oscillations are observed [29]. One can assume that in the bulk of doped semiconductors outside the limits of near-surface area of the space charge, there are also possible oscillations with a frequency ω_p that by analogy with that of metal is equal to [29]:

$$\omega_p^2 = \frac{N(Ze)^2}{\varepsilon_0 \varepsilon M}, \tag{14}$$

where N is the ion concentration (in this case, it is the concentration of tellurium ions, since it is significantly higher than that of copper uncontrolled); Z_e – charge of ions (for Te ions $Z = 1$); e – elementary electrical charge; M – mass of ion; ε – dielectric constant of semiconductor; ε_0 – electric constant.

Thus, the dynamics of behavior of Te ions at low damping is described by the equation of simple harmonic motion [30]:

$$\frac{d^2x}{dt^2} + \omega_p^2 = 0, \tag{15}$$

where x is displacement of ions relatively to the equilibrium position.

Under the influence of the electric component of microwave radiation, motion of ions is described by the equation of forced oscillations [30]:

$$\frac{d^2x}{dt^2} + \omega_p^2 = \frac{F_m}{M}\cos\omega_{em}t, \tag{16}$$

where $F_m = e\,E_m$, and E_m is the amplitude of oscillations of the electric component of the electromagnetic wave.

For the amplitude of ion oscillations x_m, we have [30]:

$$x_m = \frac{eE_m}{M\left|\omega_p^2 - \omega_{em}^2\right|}. \tag{17}$$

Thus, if the frequency of the electromagnetic wave coincides with the plasma frequency of tellurium ions, we will observed a resonance phenomenon accompanied by a significant increase in the amplitude of oscillations of tellurium ions relatively to copper ions executing the forced oscillations with a small amplitude in the opposite direction. The destruct of impurity complexes will be result.

We calculated ω_p for the epitaxial structure n-GaAs with the concentration of a doped tellurium impurity $N = 5 \cdot 10^{22}\,\mathrm{m}^{-3}$. Taking into account that ε = 12.9 [24], and the mass of tellurium ion (coincides with the atom mass) $M = 2.119 \cdot 10^{-25}$ kg, according to (14), we obtain ω_p = 7.28 GHz (ν_p = 1.16 GHz). The obtained value of the ion-plasma frequency is sufficiently close, but, nevertheless, differs from the radiation frequency of microwave generator ν_{em} = 2.45 GHz. However, as mentioned above, in the resonator the oscillations with the frequency equal to the calculated one are also observed. Therefore, oscillations of tellurium ions will be accompanied by resonant phenomena, which can lead to destruct of tellurium-copper complexes.

Let's consider else another possible scenario of destruct of impurity complexes. Assume that these associates are combined in electrically neutral clusters. We assume that the concentrations of Te^+ and Cu^- in these clusters are the same and equal to the volume concentration of tellurium *N*. Then, such a cluster in the subsurface area of semiconductor, where depleting bending of bands takes place, is similar to an ion crystal, and the equation of motion of ions has the form of the harmonic oscillator [31]:

$$\frac{d^2x}{dt^2} + \omega_{p1}^2 = 0 , \tag{18}$$

wherein the ion plasma frequency is [31, 32]:

$$\omega_{p1}^2 = \frac{e^2 N}{\varepsilon_0 \varepsilon \mu_1} , \tag{19}$$

where μ_1 is the reduced mass of the ion pair [31, 32]:

$$\mu_1 = \frac{M_1 M_2}{M_1 + M_2} , \tag{20}$$

where M_1 is the mass of tellurium ion, M_2 – mass of copper ion.

Then, the amplitude of oscillations of ions under the influence of the electric component of an electromagnetic wave is as follows:

$$x_{m1} = \frac{eE_m}{\mu_1 \left| \omega_{p1}^2 - \omega_{em}^2 \right|} . \tag{21}$$

The coincidence of the frequency of electromagnetic wave with the ion-plasma frequency will be accompanied by resonance increase in the amplitude of oscillations of ions as well as destruct of the $\left[\mathrm{Cu}_{\mathrm{Ga}}^{-}\mathrm{Te}_{\mathrm{As}}^{+}\right]$ complexes and clusters consisting of them.

We will generalize the results to the $\left[\mathrm{Cu}_{\mathrm{Ga}}^{2-}\mathrm{Te}_{\mathrm{As}}^{+}\right]$ complexes, from which the clusters form. Formally considering two ions of tellurium as one ion with a charge +2*e*, mass $2M_1$ and concentration *N* (it is assumed that for fulfilling the condition of electrical neutrality of a cluster, they do not consist as bound in complexes of tellurium ions, the number of which is equal to their number in these complexes), we obtain:

$$\omega_{p2}^2 = \frac{4e^2 N}{\varepsilon_0 \varepsilon \mu_2} , \tag{22}$$

Moreover,

$$\mu_2 = \frac{2M_1 M_2}{2M_1 + M_2} . \tag{23}$$

According to x_{m2}, we have

$$x_{m2} = \frac{2eE_m}{\mu_2 \left| \omega_{p2}^2 - \omega_{em}^2 \right|} . \tag{24}$$

Let's calculate ω_{p1} and ω_{p2}. Taking into account that the mass of copper ion (the same as the mass of copper atom) $M_2 = 1.055 \cdot 10^{-25}$ kg, using (20) and (23) it yields $\mu_1 = 0.7043 \cdot 10^{-25}$ kg, $\mu_2 = 0.8447 \cdot 10^{-25}$ kg. Then, for epitaxial structure *n*-GaAs with the concentration of tellurium dopant $N = 5 \cdot 10^{22}\,\mathrm{m}^{-3}$, in accordance with Eqs. (19) and (22), we have ω_{p1} = 12.6 GHz (ν_{p1} = 2.01 GHz) and ω_{p2} = 23.1 GHz (ν_{p2} = 3.67 GHz).

As one can see, both frequencies, especially the first one, are close to the carrier frequency of the microwave generator ν_{em} = 2.45 GHz. Since in the resonator there are oscillations with the indicated frequencies, the oscillations of ions of two considered types of complexes will be accompanied by resonance phenomena, which can cause destruct of these associates and clusters.

4. Conclusions

Thus, the used probabilistic-physical approach of the analysis of transformation of the defect structure in time after the microwave treatment enables to explain the observed long-term changes in the radiative recombination of gallium arsenide. In its turn, to justify the reasons for evolution of defect subsystem, we have proposed the mechanisms of detachment and movement of dislocations caused by electron transitions and resonant oscillations of dislocations as well as destruct of the impurity-defect complexes caused by coincidence of the frequencies inherent to ion-plasma vibrations of impurity atoms with the frequency of external forced power, the role of which the electric component of microwave radiation plays. In conclusion, it is worth noting that the proposed mechanisms have athermal nature, that is, do not suggest a significant heating of the studied samples, which in itself is a major contribution to the creation of detailed and subsequent picture of the interaction of microwave radiation with semiconductor material.

The authors thank V.V. Milenin for useful discussions and critical comments.

References

1. S.W. Kingman, N.A. Rowson, Microwave treatment of minerals – a review // *Minerals Eng.* **11**(11) p. 1081-1087 (1998).
2. T.L. Alford, D.C. Tompson, J.W. Mayer, N. David Theodore, Dopant activation in ion implanted silicon by microwave annealing // *J. Appl. Phys.* **106**(11), p. P114902-01 – P114902-08 (2009).
3. A.V. Kliuchnik, Influence intense of MW radiation on the structure of sea ice // *Zhurnal tekhnicheskoi fiziki*, **62**(7), p. 99-107 (1992), in Russian.
4. E.V. Vinnik, V.I. Guroshev, A.V. Prokhorovich, M.V. Shevelev, Application of powerful MW

radiation for fast annealing of gallium arsenide // *Optoelektronika i poluprovodnikovaia tekhnika*, №15, p. 48-50 (1989), in Russian.

5. N.S. Averkin, A.A. Gutkin, V.E. Sedov, Photoluminescence of $Cu_{Ga}Te_{As}$ and $Cu_{Ga}Sn_{As}$ complexes in *n*-GaAs under resonance polarized excitation // *Semiconductors*, **35**(2), p. 170-181 (2001).
6. I.B. Ermolovich, G.V. Milenin, V.V. Milenin, R.V. Konakova, R.A. Red'ko, Modification of the defect structure in binary semiconductors under action of microwave radiation // *Technical Physics*, **52**(9), p. 1173-1177 (2007).
7. N.S. Zayats, R.V. Konakova, V.V. Milenin, G.V. Milenin, R.A. Red'ko, S.N. Red'ko, Microwave-radiation induced structural transformations in homo- and heterogeneous GaAs-based systems // *Technical Physics*, **60**(3), p. 432-436 (2015).
8. I.B. Ermolovich, V.V. Milenin, R.V. Konakova, R.A. Red'ko, Influence of microwave irradiation on radiative recombination in A^3B^5 compounds // *Fizika i khimiya obrabotki materialov*, № 5, p. 12-18 (2006), in Russian.
9. V.V. Milenin, R.A. Red'ko, S.N. Red'ko, Effect of microwave irradiation on radiative recombination in GaAs // *Radioelectronics and communications systems*, **8**(9), p. 77-80 (2006).
10. J. Friedel, *Dislocations*. Oxford-London-Edinburg-New York, 1964.
11. E.F. Venger, M. Grendel, V. Danishka et al. / Ed. by Yu.A. Tkhorik, *Structural Relaxation in Semiconductor Crystals and Device Structures*. Publ. "Phenix", Kiev, 1994 (in Russian).
12. E.G. Bagduev, M.Sh. Shikhsaidov, Influence of dislocations on optical and photoelectrical properties of gallium arsenide // *Fizika tverd. tela*, **30**(1), p. 155-162 (1988), in Russian.
13. V.F. Masterov, B.E. Samorukov, Deep centres in $A^{III}B^{V}$ compounds (Review) // *Fizika i tekhnika poluprovodnikov*, **12**(4), p. 625-652 (1978), in Russian.
14. G.V. Milenin, Analysis of random events in the physical and chemical processes flowing in materials of semiconductor products under external influences and thermal aging // *Semiconductor Physics, Quantum Electronics & Optoelectronics*, **18**(3), p. 233-247 (2015).
15. M.N. Levin, Yu.O. Lichmanov, V.M. Maslovskii, Changes in charge stability of MDS structures induced by pulse magnetic field // *Pis'ma v zhurnal tekhnicheskoi fiziki*, 20(4), p. 27-31 (1994), in Russian.
16. R.A. Red'ko, R.V. Konakova, V.V. Milenin, V.V. Shvalagin, S.M. Red'ko, Yu.N. Sveshnikov, Long-term transformation of GaN/Al_2O_3 defect subsystem induced by weak magnetic fields // *J. Luminescence*, **153**(9), p. 417-420 (2014).
17. A.L. Buchachenko, Magnetoplasticity of diamagnetic crystals in microwave fields // *Journal of Experimental and Theoretical Physics,* **105**(3), p. 593-598 (2007).
18. K.I. Rybakov, V.E. Semenov, Possibility of plastic deformation of an ionic crystal due to the nonthermal influence of a high-frequency electric field // *Phys. Rev. B*, **49**(1), p. 64-68 (1994).
19. A.L. Buchachenko, Effect of magnetic field on mechanics of non-magnetic crystals: The nature of magnetoplasticity // *Journal of Experimental and Theoretical Physics,* **102**(5), p. 795-798 (2006).
20. M.B. Goldfarb, M.I. Molotskii, Electron interaction between donors and dislocation // *Fizika i tekhnika poluprovodnikov*, **24**, p. 1330-1332 (1990), in Russian.
21. T. Suzuki, X. Yoshinaga, S. Takeucti, *Dislocations Dynamics and Plasticity*. Springer-Verlag, 1985.
22. H.F. Mataré, *Defects Electronics in Semiconductors*. John Wilet & Sons Inc. 1971.
23. Yu.I. Golovin, Magnetoplastic effect in solids (Review) // *Physics of the Solid State*, **46**(5), p. 789-824 (2004).
24. *http://www.ioffe.ru/SVA/NSM/Semicond/GaAs/basic.html.*
25. *http://www.ioffe.ru/SVA/NSM/Semicond/GaAs/mechanic.html.*
26. O.V. Gritsunov, Excitation of electromagnetic oscillations with an arbitrary spectral composition by using short-circuited electron flows in systems with crossed fields. *Author's abstract for Dr Thesis* (Phys. & Math. Sci.), Kharkiv, 2006 (in Ukrainian).
27. O.V. Betskii, K.I. Palatov, M.B. Tseitlin, Yu.D. Il'in, *Side Oscillations in Electron MW Devices* / Ed. by M.B. Tseitlin. Publ. House "Radio i Sviaz'", Moscow, 1984 (in Russian).
28. H. Meinke, F.W. Gundlach, *Radiotechnical Handbook*, in 2 vol. Vol. 1. Publ. House "Gosenergoizdat", Moscow, Leningrad, 1961 (in Russian).
29. N.W. Ashcroft, N.D. Mermin, *Solid State Physics*. Mir, Moscow, 1979 (in Russian).
30. H. Kuchling, *Handbook of Physics*. Mir, Moscow, 1982 (in Russian).
31. P.V. Pavlov, A.F. Khokhlov, *Solid State Physics*. Vysshaia shkola, Moscow, 2000 (in Russian).
32. R.A. Smith, *Semiconductors*. Cambridge University Press, Cambridge, New York, 1978.