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Identification of the main recombination channels in lightly doped layers of GaAs $p-i-n$ diodes before and after irradiation with 1 MeV neutrons

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High-voltage GaAs $p^+-p^0-i-n^0-n^+$ diodes, fabricated by liquid-phase epitaxy in a hydrogen environment, were studied before and after irradiation with neutrons with an energy of 1 MeV and a fluence of $2.9 \cdot 10^{13}\,\text{cm}^{-2}$. The main channels of recombination of minority carriers in the base n^0-layers of high-voltage GaAs diodes before and after neutron irradiation were determined using methods of deep-level transient spectroscopy and control of the dynamics of reverse recovery of diodes. The correspondence of the lifetime values of nonequilibrium charge carriers determined using both methods has been found. It was revealed that $HL2$ defects are the main recombination centers in diodes before irradiation, determining their dynamic characteristics and the lifetime of minority carriers in the lightly doped base layers. It has been established that after neutron irradiation, the dynamics of forward and reverse switching processes is determined by recombination through deep acceptor-like D^- states of three-charged centers of radiation defect bands. It is found that in lightly doped GaAs layers, a damage defect surrounded by a large Coulomb barrier exhibits configurational metastability controlled by optical illumination.

Keywords: GaAs, neutron irradiation, capacitance spectroscopy, p^0-i-n^0 junction, liquid-phase epitaxy, reverse recovery of diodes.

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1. Introduction

It is common knowledge that gallium arsenide has long been used in the production of optoelectronic and microwave electronic devices. In recent years, bipolar high-voltage diodes based on GaAs structures, which have been first manufactured and studied by Zh.I. Alferov and his colleagues from the Ioffe Institute approximately 50 years ago [1], are also finally starting to attract the attention of manufacturers of high-power high-frequency diodes. Crystals of such diodes have the capacity to operate reliably and efficiently at temperatures up to 250°C and frequencies ranging from a hundred kilohertz to several megahertz, which is needed for the construction of modern lightweight and compact energy-efficient power converters. Owing to the high quality of gallium arsenide substrates, their relatively low cost, and the simplicity of liquid-phase epitaxy (LPE) setups, several companies have already initiated pilot production of GaAs $p-i-n$ diodes and device structures, which are to replace relatively expensive devices based on SiC [2].

Most applications in the current high-frequency power electronics market require diodes with blocking voltage levels ranging from tens of volts to a couple of kilovolts and reverse recovery times < 100 ns. At the same time, one of the main requirements for modern high-speed power diodes is softness of switching from the conducting state to the blocking state [3,4]. This requirement ensures a reduction in the amplitude of high-voltage surges at inductors in power circuits with such diodes and prevents the emergence of high-frequency parasitic oscillations and the generation of electromagnetic interference, which may result in damage to components of electronic circuits or just lead to a high level of radio-frequency interference in operation.

It is known that defects in the active layers of crystals, which form in the process of epitaxial growth of structures [5–8] and have deep levels (DLs) in the band gap through which generation and recombination processes proceed, exert the primary influence on the dynamic (temporal) characteristics of bipolar diodes (the times of conductivity modulation and dissipation of electron-hole plasma in the base layers of diodes) and on the parameters of their steady-state current–voltage curves (CVCs). The modern manufacturing route for the majority of power bipolar diodes normally involves minimization of the number of defects with DLs in the production of device structures (i. e., long minority carrier (MC) lifetimes are achieved). To enhance the dynamic parameters of diode structures, they are usually subjected to irradiation with high-energy particles after manufacture. Irradiation provides precise controlled introduction of point radiation defects into semiconductor structures, reducing the MC lifetime and improving the frequency characteristics of diodes to the required level.

At the same time, modern semiconductor devices (power ones included) are also subject to the requirement of a high resistance to the effects of ionizing radiation. This resistance is governed not only by the material chosen for production of a semiconductor structure, but also by the parameters of device structure fabrication processes, which may exert a significant influence on, among other things, the total number and the characteristics of deep traps in the base layers of power devices [9–12].

In the present study, bipolar diodes based on high-voltage GaAs p^0-i-n^0 structures grown by LPE in a hydrogen atmosphere with a controlled distribution of residual impurities and intrinsic defects with DLs [5–8] were examined. This technology provides an opportunity to produce devices capable of operating at temperatures up to 300°C in high-frequency (up to 100 kHz) circuits. A certain fraction of diode chips were irradiated with neutrons with an energy of $E \sim 1.0$ MeV in order to raise the operating frequencies of these diode structures to ~ 1 MHz through a corresponding reduction in the MC lifetime in the base layers of the structures. The irradiation dose for the examined samples was as high as $2.9 \cdot 10^{13}$ neutrons/cm^{-2}. This provided an opportunity to expand our understanding of both the mechanisms and possibilities of controlling the frequency characteristics of device structures in the process of their growth through growth defect engineering and further opportunities for improving the frequency characteristics of diodes by neutron irradiation. The obtained results also allow one to evaluate the level of radiation resistance of the examined diodes, which is quite important, since it is the response to fast neutrons that is normally used to determine the resistance of electronic components to ionizing radiation.

Defects involved in nonradiative recombination were studied using deep-level transient spectroscopy (DLTS) [5-14]. The determination of parameters of DL defects, such as thermal activation energies (E_t), capture cross-sections (σ_p), and concentrations (N_t), is needed to gain a complete understanding of their role in generation and recombination processes and to perform an accurate quantitative calculation of MC lifetimes in semiconductor materials (in particular, materials subjected to irradiation). The method of monitoring the processes of reverse recovery of diodes switching from the conducting state to the blocking one [15–21] was used as a second technique for estimating the MC lifetime in bipolar pulse devices with $p-i-n$ junctions. A comparison of the MC lifetimes determined in DLTS measurements with the reverse recovery (RR) times allows for a more accurate identification of recombination centers shaping the MC and RR lifetimes of diode structures. The results of a thorough examination of traps with DLs in a GaAs diode with a p^0-i-n^0 junction grown by LPE in a reducing hydrogen environment have been presented in our earlier study [12]. Despite this, a number of questions remained regarding the type and nature of deep traps, which could be the main recombination centers that specify the dynamic characteristics and lifetimes of minority carriers in lightly doped base layers before and after neutron irradiation, in the studied structures. In the present paper, we report the results of a DLTS study of deep traps that satisfy the above criteria.

Thus, this paper is focused on the experimental study of the effect of neutron irradiation on the formation of DL defects and the relation between the MC lifetime measured using DLTS and the RR in lightly doped base layers of high-voltage GaAs $p^+-p^0-i-n^0-n^+$ diodes grown by LPE in a hydrogen atmosphere.

2. Experimental results and discussion

2.1. Reverse recovery characteristics of diodes

The time of reverse recovery of the blocking capacity of diodes (t_{rr}), maximum current amplitude $I_{R\text{-max}}$ in reverse recovery, and the degree of „softness“ of switching were determined for two groups of samples (non-irradiated and subjected to neutron irradiation) by examining the oscilloscope records of diode witching from the conducting state to the blocking one (Figures 1 and 2). The process of recovery of the blocking capacity of diodes was monitored in regimes similar to those set in measuring the MC lifetime by the Lax method [22,23] in the case of equality of the amplitudes of pulses of forward and reverse currents. The duration of the reverse recovery process of a $p-n$ diode depends on the total excess charge of minority carriers accumulated in the base under forward bias. The specific shape of the time dependences of current and voltage is set by the distribution of excess carriers in the diode and the electrical circuit parameters.

The RR process may be divided into two phases, which are easy to distinguish in Figure 2. In the initial phase, the polarity of voltage at the $p-n$ junction of the diode remains corresponding to the forward bias for time t_1, while the direction of current in the circuit gets reversed. In the idealized case, the current through the diode is controlled by the external circuit (i. e., the supply voltage and the load resistance in the diode circuit) in this phase up to the point of excess carrier resorption at the $p-n$ junction. This phase is also called the retention one. At this stage, the concentration of excess non-equilibrium holes in the base and at the $p-n$ junction decreases both due to their escape through the $p-n$ junction into the p-region and due to their recombination in the n-region, reaching zero at the end of the first phase. From this moment on, an opposite polarity of voltage is established at the $p-n$ junction, and a space-charge layer (SCL) starts to form at the $p-n$ junction of the diode. The increasing electrical resistance of the expanding SCL starts to limit the flow of reverse current. The magnitude of this current ($I_{R\text{-min}}$) eventually reaches extremely low levels (in the present case, several microamperes). $I_{R\text{-min}}$ (leakage current of the diode structure under reverse bias) is specified by the sum of thermal generation current through DLs in the SCL and „leakage“ along the surface of the edge circuit of the diode structure. Time t_2 is commonly defined as the interval from the moment when the reverse current amplitude reaches its maximum value $I_{R\text{-max}}$ to the moment when the reverse current decreases to 25% of $I_{R\text{-max}}$.

The diode RR time ($t_{rr} = t_1 + t_2$) prior to neutron irradiation was 115 ns (Figure 1). After irradiation, the t_{rr} values decreased to 8.5 ns (Figure 2). Thus, irradiation

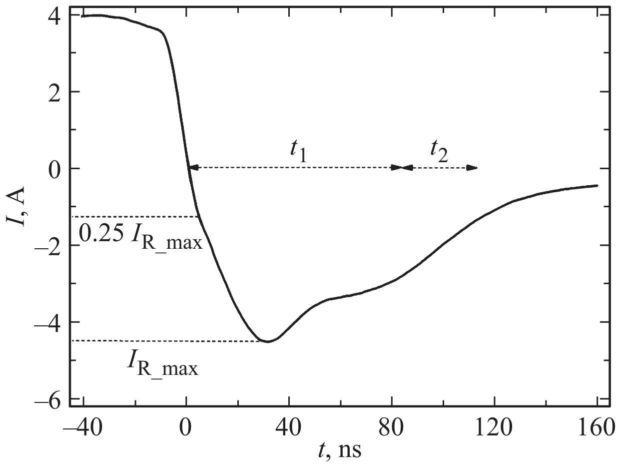

Figure 1. Oscilloscope records of switching of a GaAs $p^+-p^0-i-n^0-n^+$ diode prior to neutron irradiation.

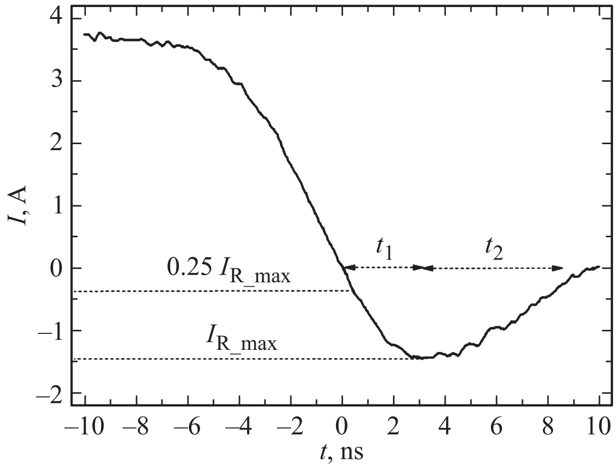

Figure 2. Oscilloscope records of switching of a GaAs $p^+-p^0-i-n^0-n^+$ diode after neutron irradiation.

with neutrons with a fluence of $2.9 \cdot 10^{13}\,\mathrm{cm}^{-2}$ leads to a significant (by more than an order of magnitude) reduction in time t_{rr} and a many-fold reduction in the amplitude values of reverse recovery current $I_{R\_\max}$ of diodes, which corresponds to a $\sim$ 50-fold decrease in the reverse recovery charge (Q_{rr}) of diodes. In the case of a transient diode switching process with an accumulation phase, times t_1 and t_2 are related by transcendental equations to average lifetime τ_h of minority carriers (holes), which are extremely difficult to measure and impractical as a means to characterize switching diodes. A new approach to characterization of diode switching with easily measurable parameters has been proposed in [22–24]. The authors of these papers analyzed the reverse switching transient process and new equations for the switching time of a diode with a $p-n$ junction, which were obtained by relating the reverse $(I_{R\_\max})$ and forward (I_F) currents to minority carrier charge Q accumulated in the base diode region within retention time t_1. Minority carrier (hole) lifetime τ_h may be estimated in this case using the following relation within the reverse recovery method [22–24]: $t_h = t_1/\ln(1 + I_F/I_{R\_\max})$. The oscilloscope records for non-irradiated GaAs diodes reveal non-ideality in the recovery current waveform: a certain variation of the amplitude of reverse current I_R is observed within the retention phase, which may be caused, as was noted in [17], by the presence of parasitic inductances and delay and reflection in the transmission line. This, however, does not preclude one from estimating the t_1, t_2 and τ_h times based on the oscilloscope records shown in Figures 1 and 2. Time $t_1 \sim 85$ ns for non-irradiated GaAs diodes switching from a forward current of 4 A to a reverse current of 4.5 A. The average minority carrier lifetime is ~ 133 ns in this case. Following neutron irradiation, the phase of high reverse conductivity becomes significantly shorter (Figure 2): t_1 dropped to ~ 3 ns at $I_F \approx 4$ A and $I_{R\_\max} \sim 1.45$ A. A single peak is observed instead of a plateau. As was demonstrated in [17], the plateau width depends on the edge steepness of a blocking pulse, and the plateau may converge to a point as the switching front duration decreases. The average lifetime of minority carriers (holes) in the base layer of the GaAs diode after neutron irradiation was 2.3 ns. Following neutron irradiation, „hard“ diode switching from the conducting state to the blocking one gives way to „soft“ switching. This becomes evident if one compares Figure 1, where softness factor S (defined as t_2/t_1) is ~ 0.35, and Figure 2 with softness factor $S \sim 1.8$, which should ensure a relatively low level of pulse electromagnetic interference in electrical circuits with such diodes.

2.2. DLTS measurements for $p^+-p^0-i-n^0-n^+$ diodes

This section presents the results of a detailed study of traps with DLs in a GaAs diode with a p^0-i-n^0 junction grown by LPE in a reducing hydrogen environment. DLTS spectra were measured at different bias voltages V_r and fill pulse voltages V_f both before (Figure 3) and after (Figure 4) neutron irradiation (Figure 4 from [12] was used in preparing the figures). Fill pulse voltages V_f were positive, which allowed us to identify deep levels for majority and minority carriers in p^0- and n^0-layers of the studied structures.

The DLTS spectra measured with $V_f = +0.5$ V and $V_r = -1.0$ V for the non-irradiated samples featured one positive DLTS peak, which was attributed (with the use of the Arrhenius dependence) to the $HL5$ deep defect level [11,12,16]. The emergence of this level was associated (Figure 3) with the capture and emission of holes to acceptor traps of minority carriers in the n^0-layer. The $HL5$ defect level concentration was $\sim 10^{14}\,\mathrm{cm}^{-3}$. A high-temperature narrow negative DLTS peak was also observed in the DLTS spectrum of the studied non-irradiated sample. This peak was easy to attribute to the $HL2$ deep defect level [16]. Deep level $HL2$ had the following parameters:

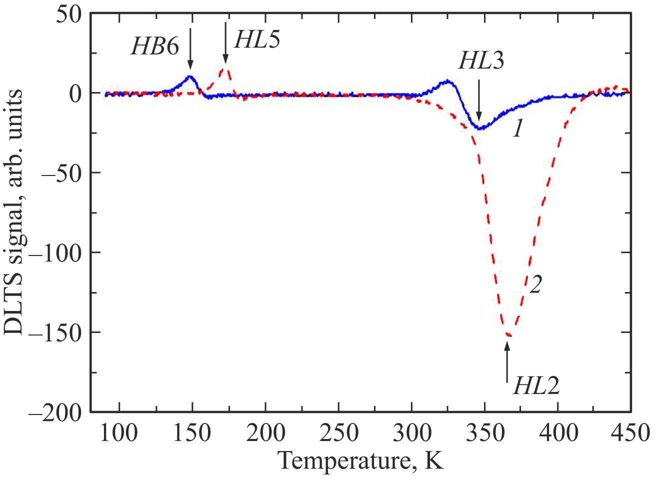

Figure 3. DLTS spectra of a non-irradiated GaAs $p^+-p^0-i-n^0-n^+$ diode measured at a window rate of $200\,\mathrm{s}^{-1}$, bias voltage $V_r = -1.0\,\mathrm{V}$, and the following fill pulse voltages V_f: *1* — +0.01, *2* — +0.5 V. Measurements were performed without illumination.

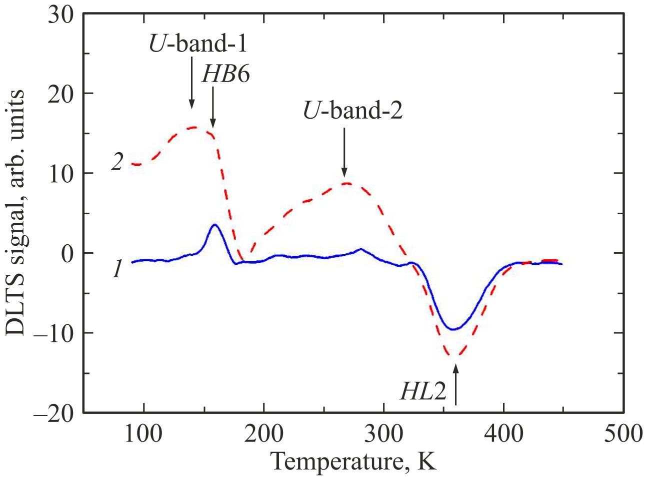

Figure 4. DLTS spectra of a GaAs $p^+-p^0-i-n^0-n^+$ diode measured after neutron irradiation at a window rate of $200\,\mathrm{s}^{-1}$, bias voltage $V_r = -1.0\,\mathrm{V}$, and the following fill pulse voltages V_f: *1* — +0.01, *2* — +0.5 V. Measurements were performed without (*1*) and with (*2*) white-light illumination.

thermal activation energy $E_a = 649\,\mathrm{meV}$ and hole capture cross-section $\sigma_h = 6.44 \cdot 10^{-16}\,\mathrm{cm}^{-2}$.

As was demonstrated in [12], a peak with its maximum in the region of forward bias voltage ($V = 0.14\,\mathrm{V}$) emerged in the $C-V$ characteristic profile after neutron irradiation of the studied structure grown in a hydrogen atmosphere. The formation of such peaks is attributed to the presence of electrically active deep traps in the $p-n$ junction region [12,25–27] and to the flow of space-charge-limited current (SCLC), which is the sum of drift and diffusion currents. When the structure was illuminated with white light at 300 K, the capacitance and, consequently, the thickness of the SCL of the $p-n$ junction decreased [12]. As was noted in [12], the probable causes of changes in the SCL thickness induced by neutron irradiation and illumination are, first, a reduction in the concentration of electrically active $HL5$- and $HL2$-type acceptor levels in the i-layer and, second, the formation of a cluster of spatially localized acceptor-like negatively charged traps in epitaxial layers of the $p^+-p^0-i-n^0-n^+$ structure [9,10]. Damage clusters with acceptor-like negatively charged traps and their characteristics and features have been examined thoroughly in [9,10,12].

The DLTS spectra of GaAs $p^+-p^0-i-n^0-n^+$ diodes irradiated with neutrons featured broad bands (U-band-1 and U-band-2 in Figure 4) associated with the emission of carriers from the n^0-layer, which are typical of neutron-irradiated GaAs [9–12]. U-bands emerged only under illumination with white light at reverse bias $V_r = -1.0\,\mathrm{V}$ and fill pulse voltage $V_f = +0.5\,\mathrm{V}$ in the DLTS spectra for the GaAs diode irradiated with neutrons with a fluence of $2.9 \cdot 10^{13}\,\mathrm{cm}^{-2}$ (Figure 4, spectrum *2*). Note that a broad band emerged without illumination in the spectrum for the GaAs diode produced in an argon atmosphere and irradiated with neutrons, and illumination did not affect the spectrum shape [12,14]. We attribute this to a higher doping level of the base regions (the concentration of uncompensated impurities in the p^0- and n^0-layers fell within the $10^{16}-10^{17}\,\mathrm{cm}^{-3}$ range) grown in an argon atmosphere [12]. For comparison, the concentration of uncompensated impurities in the p^0- and n^0-layers for lightly doped irradiated GaAs structures grown in a hydrogen atmosphere is $\sim 10^{15}\,\mathrm{cm}^{-3}$ [12]). When the DLTS spectrum was measured with $V_r = -1.0\,\mathrm{V}$ and $V_f = +0.01\,\mathrm{V}$, a U-band did not emerge (Figure 4, spectrum *1*). The nature of DLTS signals with a broad U-band has been investigated thoroughly in [9,10]. It was demonstrated there that neutron irradiation of GaAs layers results in the formation of cascades of damage defects, which are surrounded by large Coulomb barriers that prevent the complete filling of traps in damaged areas. Barriers exist for both n- and p-GaAs. Negative and positive charges should accumulate in n-GaAs and p-GaAs, respectively; i. e., the defect band is acceptor-like in nature above the midgap and donor-like below the midgap [9,10].

However, the characteristics and features of damage clusters with acceptor-like negatively charged traps revealed in our study [12] and [9,10] turned out to be insufficient to gain an understanding of the recombination process associated with this trap forming in the base lightly doped layers after neutron irradiation.

The results of our studies of DLTS signals associated with the damage cascade induced by neutron irradiation of GaAs demonstrate that the model proposed in [9,10] may be supplemented by the assumption that the defect band consists of three charge states: D^+, D^0, and D^- [28]. If the defect band is initially in the fully ionized state (D^+), it may capture two electrons. The first electron is captured following reaction $D^+ + e^- \to D^0$, and the second one is captured as $D^0 + e^- \to D^-$. The capture of the first electron corresponds to a donor level that will be charged positively when it is above the Fermi level and will be neutral when it is below the Fermi level. Likewise, the second level will be an acceptor one. Owing to the Coulomb interaction between electrons, the second electron will be bound less tightly than the first and, consequently, the acceptor level will lie higher than the donor one. We assume that the Hubbard correlation energy in the examined case is positive: $U > 0$ [29]. In our studies of DLTS spectra of GaAs $p^+-p^0-i-n^0-n^+$ structures, the diode was cooled with $V_f = +0.5\,\text{V}$ to a temperature of $\approx 80\,\text{K}$ before the measurement. This should result in sequential filling of the lower donor state D^+ with the first electron ($D^+ + e^- \to D^0$) and capture of the second electron by the acceptor state ($D^0 + e^- \to D^-$). The cooling procedure eliminates uncertainties that may arise if the defect turns out to be bistable. The DLTS spectra were then measured at $V_r = -1.0\,\text{V}$ and $V_f = +0.5\,\text{V}$. When the fill pulse is turned on, the $p-n$ junction capacitance increases as a result of recharging of the defect states ($D^0 + e^- \to D^-$). When the fill pulse is turned off, reverse bias $V_r = -1.0\,\text{V}$ is applied to the GaAs $p^+-p^0-i-n^0-n^+$ diode, the SCL expands deeper into the n^0-layer, and the defect eventually emits two electrons closely following each other. Since the empty donor level is positively charged, the capture cross-section for the first electron exceeds the cross-section of capture of the second electron to the neutral empty acceptor level. Since the emission of the first electron takes up much more time than the emission of the second electron, the emission rate for this radiation will be essentially the same as the one for the electron emission from the acceptor level, which then becomes neutral. The capacitance of the $p-n$ junction decreases in the process. This implies that the DLTS signature of the U-band level derived from the Arrhenius dependence will correspond to the deep acceptor-like state of the U-band, which is a trap for majority carriers. All this eventually leads to the emergence of a positive DLTS signal associated with the U-band. When the GaAs $p^+-p^0-i-n^0$ diode is cooled with reverse voltage $V_r = -1.0\,\text{V}$ before the DLTS spectra measurement, a broad U-band is not observed.

The differences between the DLTS spectra measured under different cooling conditions (with $V_r = -1.0\,\text{V}$ and $V_f = +0.5\,\text{V}$) are apparently attributable to the fact that the damage defect surrounded by a large Coulomb barrier features controlled configurational metastability [30,31]. It may assume a neutral or negatively charged state configuration, and the transition from one state to the other may be transformed reversibly via thermal annealing cycles with the bias voltage turned on or off. Electrons need to overcome the Coulomb energy barrier to complete this transition. When annealed with $V_f = +0.5\,\text{V}$, the defect assumes a configuration in which levels are capable of capturing and emitting electrons in the process of DLTS measurements. In the case of pre-cooling of the diode with $V_r = -1.0\,\text{V}$, the U-bands are in a configuration with neutrally charged levels. In the process of subsequent DLTS spectra measurements with $V_r = -1.0\,\text{V}$ and $V_f = +0.01\,\text{V}$, the electron energy is not sufficient to overcome the barrier and fill the energy levels; therefore, DLTS signals associated with the U-band are not detected in the spectra.

The DLTS spectra measured with $V_r = -1.0\,\text{V}$ and $V_f = 0.5\,\text{V}$ for the GaAs $p^+-p^0-i-n^0$ structure grown in a hydrogen atmosphere, which has lightly doped epitaxial layers, featured a U-band signal only when the measurements were performed under white light illumination. The specifics of emergence of DLTS signals from damage defects in this structure are associated with the flow of SCLC [12,25,26]. In the case of annealing with $V_f = +0.5\,\text{V}$, the current in the diode is drift in nature, carrying carriers out of the epitaxial i- and n^0-layers. The damage defects in these layers will assume a configuration with neutrally charged levels. Optical illumination may convert a defect into a configuration with negatively charged levels. The emergence of positive peaks in the DLTS spectrum (Figure 4, spectrum *2*), which are associated with the emission of electrons from deep acceptor-like defect bands of the GaAs n^0-layer located above the midgap, differs strongly from what is usually found in the DLTS spectra for majority carrier traps, which produce a negative DLTS signal of majority carriers. A DLTS signal with a positive-sign peak has been observed previously for the negatively charged state of a DX center in n-type $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layers [7,8] and dislocations [5,6]. The first band (U-band-1) formed at the site of the low-temperature peak; the second (high-temperature) band denoted as U-band-2 was not visible in the DLTS spectrum before irradiation.

2.3. Identifying the relation between the measured values of recovery time and carrier lifetime

In the previous section, we investigated the changes in dynamic characteristics before and after neutron irradiation using the diode reverse recovery method [22–25]. This method provided an opportunity to examine the waveform of recovery current (Figures 1 and 2) and measure reverse recovery time t_{rr} and softness factor S, which depend on the physical parameters of diode structures (thickness of the base layer of the diode, resistance, lifetime of minority carriers) and on the external circuit [3,4]. In order to reduce t_{rr}, one needs to reduce minority carrier lifetime τ in the base layers, which is associated with the presence of defects with DLs. One way to adjust the DL concentration and lifetimes is to introduce radiation defects [3,4]. The $C-V$- and DLTS studies of GaAs $p^+-p^0-i-n^0-n^+$ diodes subjected to neutron irradiation allowed us to identify changes in the composition of intrinsic and radiation defects in the base layers and estimate the lifetime of minority carriers (τ_h) in these layers before and after irradiation with neutrons. It was assumed that the main hole trap in the GaAs n^0-layer of the non-irradiated GaAs $p^+-p^0-i-n^0-n^+$ diode is the $HL2$ defect with thermal activation energy $E_a = 649\,\text{meV}$, hole capture cross-section $\sigma_h = 6.44 \cdot 10^{-16}\,\text{cm}^2$, and concentration $N_A \approx 6.36 \cdot 10^{14}\,\text{cm}^{-3}$. This defect sets the lifetime of minority carriers in this GaAs layer. Taking these facts into account, one may estimate the lifetime of minority non-equilibrium carriers (τ_h) in *n*-type GaAs using relation

$$\tau_h \approx 1/\sigma_h \upsilon_h N_T, \tag{1}$$

where N_T is the concentration of deep levels filled with electrons and υ_h is the average thermal velocity of holes in GaAs [32,33]. Thus, time τ_h, which is governed by the process of capture and emission of non-equilibrium holes to the $HL2$ defect level, turned out to be equal to $\approx 136\,\text{ns}$ for non-irradiated *n*-type GaAs. The average lifetime of minority carriers in the base of GaAs diodes measured by the reverse recovery time method was 133 ns. This is quite close to the values estimated using relation (1) under the assumption that the $HL2$ defect governs the dynamic processes in non-irradiated GaAs diodes produced in a hydrogen atmosphere. A certain discrepancy between the values of τ_h determined by the reverse recovery method and with the use of relation (1) may be attributed both to a possible inaccuracy of determination of the cross-sections of carrier capture by traps based on DLTS measurement data and to the presence of additional traps that were not taken into account in processing of the DLTS measurements.

When evaluating the lifetimes of minority carriers (τ_h) in the base n^0-layers of GaAs $p^+{-}p^0{-}i{-}n^0$ diodes after neutron irradiation, we assume that the recombination process proceeds mostly through the defect band consisting of three charge states: D^+, D^0, and D^- with positive correlation energy $U > 0$. Notably, the D^+/D^0 state should be positioned lower than state D^0/D^- [14]. It should be noted that a damage defect surrounded by a large Coulomb barrier exhibits controlled configurational metastability of the U-band trap states, and the U-band states are never completely filled in the process of DLTS measurements due to the presence of a significant Coulomb barrier. However, it is known that the concentration of neutron-induced traps is $\sim 1 \cdot 10^{18}\,\text{cm}^{-3}$ at a fluence of $1.0 \cdot 10^{14}\,\text{cm}^{-2}$ [9], and the cross-sections of electron capture by this trap are strongly dependent on temperature and vary from $6 \cdot 10^{-17}$ to $3 \cdot 10^{-16}\,\text{cm}^2$. When the reverse recovery time is measured, forward current is passed through the diode, and the D^- states are filled with holes. The capture cross-section for them is 3 orders of magnitude greater than the one for electrons, and the defect goes into the D^0 state, which is filled in a stable manner under the passage of forward current. When the forward pulse voltage is switched to the reverse one, holes captured at the D^0-level are emitted, and the reverse recovery time will be determined by lifetime τ_h of minority carriers (holes) in the base n^0-layer. Before estimating the τ_h lifetime, let us try to estimate cross-sections σ_h of hole capture to the neutral D^0-state and the concentrations of traps induced by neutrons. Since the RR method [17–24] is a direct way of determining the average lifetime of non-equilibrium carriers in the base layers of a diode, one may use its value (8.5 ns in the base n^0-layer of a GaAs $p^+{-}p^0{-}i{-}n^0{-}n^+$ diode after neutron irradiation) to calculate the capture cross-section if the concentration of neutron-induced traps involved in the recombination processes is known. It has been demonstrated in [34] that a large capture cross-section arises from the process of nonradiative capture by phonons. Owing to this, the capture cross-section values fall within the range from 10^{-17} to $10^{-15}\,\text{cm}^2$ for neutral centers and from 10^{-15} to $10^{-12}\,\text{cm}^2$ for attracting Coulomb centers. Assuming that cross-section σ_h of hole capture to the neutral D^0-state may assume a value of $\approx 4.0 \cdot 10^{-16}\,\text{cm}^2$, we find that the concentration of neutron-induced traps involved in recombination processes is on the order of $N_T \sim 1.7 \cdot 10^{16}\,\text{cm}^{-3}$ at $\tau_h = 8.5\,\text{ns}$.

3. Conclusion

The methods of DLTS and monitoring of the dynamics of diode reverse recovery were used to identify the main channels of minority carrier recombination in lightly doped base n^0-layers of high-voltage GaAs $p^+{-}p^0{-}i{-}n^0{-}n^+$ diodes, which were fabricated by a modified liquid-phase epitaxy method with autocompensation by background impurities in a hydrogen environment, before and after irradiation with neutrons with an energy of 1 MeV.

The reverse recovery times of GaAs $p^+{-}p^0{-}i{-}n^0{-}n^+$ diodes decreased significantly after neutron irradiation, and their switching behavior changed from „hard“ to „soft“.

The average lifetime of minority carriers in the base of non-irradiated GaAs diodes measured by the reverse recovery time method was 133 ns. This is quite close to the value calculated under the assumption that the $HL2$ defect governs the dynamic processes in non-irradiated GaAs diodes produced in a hydrogen atmosphere.

After neutron irradiation, broad bands associated with the emission of electrons from states, which are located above the midgap, of a defect cluster with acceptor-like negatively charged traps were found in the DLTS spectra of the n^0-layer of GaAs structures. It was found that this electron emission is associated with a defect band consisting of three charge states (D^+, D^0, and D^-) and having a positive Hubbard correlation energy.

The estimates of minority carrier lifetimes and neutron-induced trap concentrations in the base n^0-layer of the GaAs $p^+{-}p^0{-}i{-}n^0{-}n^+$ diode, which were obtained under the assumption that the dynamics of switching processes is governed by recombination through deep acceptor-like D^--states of three-charge centers of radiation defect bands, did also agree with the average lifetime determined using the reverse recovery method. Therefore, it is fair to conclude that dynamic processes in an irradiated diode are controlled by defect clusters consisting of three charge states (D^+, D^0, and D^-) with configurational metastability that is governed by the conditions of cooling (with or without reverse bias voltage $V_r = -1.0\,\text{V}$) before the measurement of DLTS spectra and optical illumination.

Conflict of interest

The authors declare that they have no conflict of interest.

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