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Deep-level defects in high-voltage AlGaAs *p–i–n* diodes and the effect of these defects on the temperature dependence of the minority carrier lifetime

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ABSTRACT

The variation of the effective lifetime of minority carrier lifetime τ_{eff} with temperature has been studied in the temperature range 300–580 K in $Al_xGa_{1-x}As$ base regions of p^+–p^0–i–n^0–n^+ high-voltage GaAs–AlGaAs diodes grown by liquid-phase epitaxy. It was found by using deep level transient spectroscopy that the emission/capture of electrons and holes in $Al_xGa_{1-x}As$ p^0–i–n^0 epitaxial layers is governed by the DX^- states of the DX center formed by Se/Te background impurities. The Arrhenius plots associated with the τ_{eff} were used to determine the activation energy of the hole capture to the DX^- level to be $E_c = 159$ meV. It is shown that the thermal capture of holes to the DX^- level determines the relaxation time of nonequilibrium carriers in the $Al_xGa_{1-x}As$ base layers as well as its temperature dependence.

I. INTRODUCTION

The operation of semiconductor *p–n* structures for pulsed power electronics is based on the processes of accumulation and resorption of excess carriers.[1] Therefore, the resorption time of nonequilibrium carriers (τ_i) accumulated in the diode base in the mode of switching to the equilibrium concentration after the perturbation is eliminated is one of the most important characteristics of high-voltage *p–i–n* diodes. This process is associated with the disturbance of the thermodynamic equilibrium state, which is favored by the presence of deep levels (DLs) associated with impurities and defects in the forbidden gap. Closely related to the relaxation time τ_i is such a fundamental characteristic as the minority carrier lifetime $\tau_{n,p}$, which is determined by the equilibrium properties of a material and is related to the nature of recombination centers and to the density of these. Therefore, the information about the nature of deep centers in the base regions and specific features of their recharging is exceedingly important for the development of fast pulse devices operating at increased working pulse repetition frequencies, which are commonly examined by capacitive spectroscopy, capacitance–voltage (*C–V*), and deep level transient spectroscopy (DLTS).

Another important characteristic of high-voltage *p–i–n* diodes is the possibility of their operation at elevated temperatures. These requirements are satisfied by structures based on GaAs and its solid solutions and, in particular, AlGaAs, which have, in comparison with Si, a wider energy gap. Devices fabricated from these materials can operate at increased working pulse repetition frequencies and temperatures of up to 250–300 °C and more.[2–4]

The high-voltage *p–i–n* structures based on GaAs and its solid solutions are mostly fabricated by liquid-phase epitaxy (LPE) with controlled distribution of residual impurities and intrinsic defects with DLs, formed in the course of epitaxial growth of *p–i–n* structures.[2–6] In our preceding studies,[2–4,7,8] we demonstrated the possibility of raising the operation speed of high-voltage high-power *p–i–n* structures based on InGaAs/GaAs and GaAsSb/GaAs heterostructures with uniform networks of mismatch dislocations formed in the course of the epitaxial growth. In these layers, deep dislocation traps of the acceptor type, similar to HD3,[7–10] are responsible for the decrease (by a factor of up to 100) in the relaxation time of nonequilibrium carriers in the base regions of InGaAs/GaAs and GaAsSb/GaAs heterostructures. Further choice of LPE-grown semiconductor structures may be associated with a *p–i–n* structure based on AlGaAs/GaAs heteroepitaxial layers in which the relaxation of nonequilibrium carriers and temperature characteristics are largely determined by the presence of mutually compensating donor/acceptor impurities and defects with DLs.

When $Al_xGa_{1-x}As$ layers are investigated, it is necessary to take into account the circumstance that the presence in these layers of such donor impurities as, e.g., Si, Sn, and Te, results in that configuration-bistable DX centers are formed.[11] It has been shown[12–14] that this defect has a negative effective correlation energy (negative *U*). The occupancy of the DX^- level that is in thermal equilibrium with the conduction band states is in good agreement with the kinetics of thermal capture and emission if it is assumed that a deep DX state is of the two-electron type. The capture of an electron from the conduction band to the DX level must occur via a single-electron neutrally charged DX^0 state, which is metastable.[12,13] The DX^0 state is not an effective-mass X- or Γ-like excited state of the DX center, it lies higher than the negatively charged DX^- state, and has a small barrier for relaxation into the substitution configuration. In the opinion of the authors of Ref. 14, this state is strongly bound, similarly to the ground DX^- state, which is a state of the distorted lattice configuration. In a layer of the solid solution $Al_xGa_{1-x}As$ with $x > 0.22$, the localized state of the donor becomes deeper than the effective-mass state, and a deep DX^- level is formed, with Si (Se, Te) displaced into the interstitial position and their bonds thereby ruptured.

In this communication, we present the results of a study of how the effective lifetime of minority carriers (τ_{eff}), found from the reverse recovery time of $Al_xGa_{1-x}As/GaAs$ $p^+–p^0–i–n^0–n^+$ diodes, depends on the temperature. In addition, results are presented of an examination by the DLTS method, aimed to find defects and impurities in the base epitaxial $Al_xGa_{1-x}As$ $p^0–i–n^0$ layers of the diode under study. Electron (E1) and hole (H1) traps associated with the capture of electrons and holes to the DX^- level were found. An analysis of the results obtained made it possible to relate the temperature dependence of the lifetime of nonequilibrium carriers to the capture by states of the DX center of holes, which are minority carriers in the n^0 region of the $Al_xGa_{1-x}As$ $p^0–i–n^0$ layer.

II. EXPERIMENTAL SAMPLES

Samples of $GaAs/Al_xGa_{1-x}As$ $p^+–p^0–i–n^0–n^+$ heterostructures used in the study were grown in the single technological process by the modified LPE method[2–4] in a piston-type graphite container from two solution-melts in the hydrogen atmosphere. The high-voltage lightly doped graded $p^0–i–n^0$ junction was epitaxially grown on a (100) p^+-GaAs substrate doped with zinc to 5×10^{18} cm^{-3}, which was followed by the growth of a heavily tellurium-doped to 2×10^{18} cm^{-3} n^+-GaAs emitter layer. The thickness of the $Al_xGa_{1-x}As$ $p^0–i–n^0$ layer was 44 μm, that of the n^+-GaAs emitter layer was 15 μm, and the thickness of the p^+-GaAs substrate was about 200 μm. Figure 1 shows the AlAs distribution obtained on a sample cross section with a Camebax x-ray fluorescence microanalyzer. The content of AlAs in the $Al_xGa_{1-x}As$ $p^0–i–n^0$ layer monotonically decreases across its thickness from the substrate ($x \approx 0.45$)

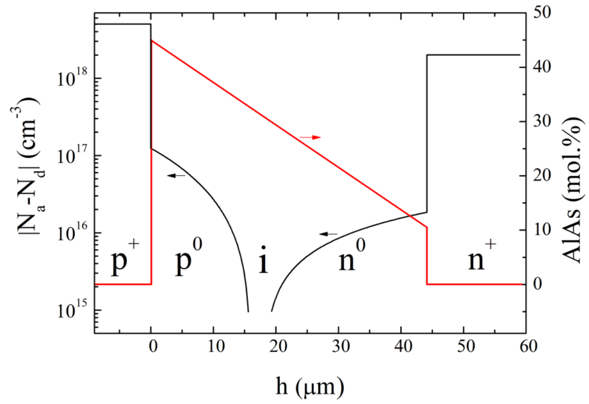

FIG. 1. Distribution of the AlAs composition *x* and free carrier concentration profile across the thickness of a p^+-GaAs substrate, graded $Al_xGa_{1-x}As$ $p^0–i–n^0$ junction and n^+-GaAs emitter layer.

to the emitter layer ($x \approx 0.10$). In the space charge layer (SCL), the AlAs content is $x \approx 0.3$.

The procedure used to obtain graded $Al_xGa_{1-x}As$ $p^0–i–n^0$ junctions from the same solution melt via autodoping with background impurities is mostly similar to that used to fabricate GaAs (InGaAs, GaAsSb) $p^0–i–n^0$ junctions, previously described in Refs. 2–4, 7, and 8: in this method, it is possible to vary the free carrier concentration and the conduction type of an epitaxial layer without using any direct doping, but by only changing the technological process conditions, and layers with a *p–n* junction can be produced from the same solution melt. However, obtaining graded $Al_xGa_{1-x}As$ $p^0–i–n^0$ junctions has its specific features. These are associated with the fact that Al is a chemical element characterized by a high affinity to oxygen, and, therefore, the presence of Al in the melt leads to a decrease in the concentration of donors associated with oxygen and, accordingly, to a change in the relative concentrations of donors and acceptors in the layers. A distribution of the free carrier concentration across the thickness of a graded $Al_xGa_{1-x}As$ $p^0–i–n^0$ junction is also shown in Fig. 1. The free carrier distribution profile was obtained by a layer-by-layer etching-off the structure and measuring *C–V* dependences of a reverse-biased Schottky barrier with a mercury probe.

III. RESULTS AND DISCUSSION

For the $p^+–p^0–i–n^0–n^+$ diode structure, DLTS spectra were measured with different values of the filling pulses, $V_f = -0.50$ and +0.50 V, at bias voltages $V_r = +2.40$ V at which the DLTS spectra in Fig. 2 were obtained. The duration of the filling pulse used in DLTS measurements was $\tau_p = 100\,\mu s$. These spectra demonstrated the existence of two DLTS peaks, E1 and H1, both of the positive sign. The positive DLTS peak H1 can be attributed to a trap for minority carriers in the n^0 layer because of its formation at $V_f = +0.50$ V, when minority carriers are injected into this layer. At the same time, the positive sign of the DLTS peak E1 is unusual for the DLTS spectrum measured for a filling pulse with $V_f = -0.50$ V.

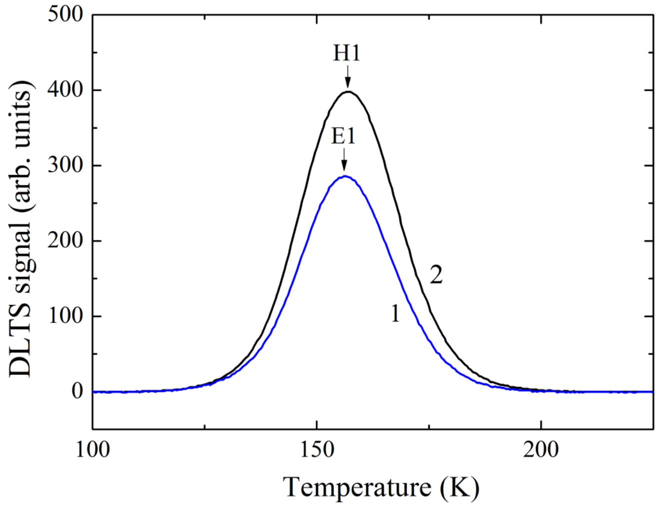

FIG. 2. DLTS spectra of a $Al_xGa_{1-x}As/GaAs$ $p^+–p^0–i–n^0$ diode with a rate window of $200\,s^{-1}$ at reverse voltages $V_r = -2.44$ V [(1) and (2)] and filling pulse voltages $V_f = -0.50$ V (1) and +0.50 V (2).

Our studies of the $C–V$ characteristics of the $GaAs/Al_xGa_{1-x}As$ $p^+–p^0–i–n^0–n^+$ structure (Fig. 3) demonstrated that DX centers are to be contained in $Al_xGa_{1-x}As$ epitaxial layers because temperature dependences of $C–V$ characteristics typical of DX centers were observed. In addition, the $C–V$ characteristic remained unchanged during a long time at a low temperature after the illumination was switched off, which was attributed to the so-called persistent photoconductivity (PPC) effect.

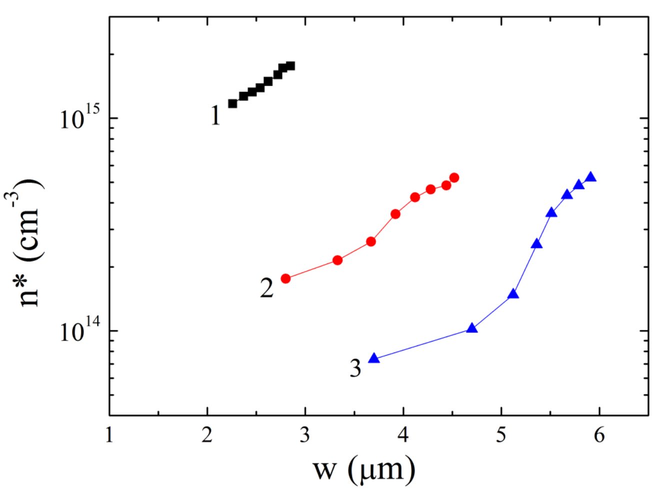

FIG. 3. Distribution profiles of the effective free carrier concentration n^* across the SCL thickness w of a $p^+–p^0–i–n^0–n^+$ diode based on $Al_xGa_{1-x}As$ layers, measured at various temperatures T, K: (1)–141; (2) and (3)–87; in the dark [(1) and (3)] and under optical illumination (2).

It was shown in Refs. 12–15 that the DX center is a donor with a negative correlation energy U and has three charge states: that of a shallow donor DX^+ and two levels with electrons in neutral (DX^0) and negatively charged (DX^-) states (acceptor-like level). It was shown in Ref. 14 in a study of the photoionization, thermal ionization, and electron capture kinetics for the DX center of the $Al_xGa_{1-x}As$ ($0.25 < x < 0.55$) by photocapacitance measurements that, first, there are different relaxation times for two DX^0 and DX^- states and, second, that the DX center in the ground state binds two electrons and forms a negative U system. The intermediate state of the process is the neutral (DX) state, rather than the effective-mass X- or Γ-like excited state of the DX center. This neutral state is strongly coupled to the lattice in the same way as the ground (DX) state. The DX^0 state is thermodynamically unstable and serves as an intermediate state. As shown in Refs. 12–16, the DX^0 states plays an important role in the process of carrier capture and emission. For the defect with a negative U, the emission and capture of electrons must occur in two stages (Ref. 14): $2e^- = 2D^+ \to DX^- + DX^0$, $DX^- \leftrightarrow DX^0 + e^- \leftrightarrow DX^- + 2e^-$.

For $GaAs/Al_xGa_{1-x}As$ $p–n$ structures containing DX centers, which are donors with a negative correlation energy U, the DLTS spectra measured for a filling pulse with $V_f = -0.50$ V may show a positive sign of the DLTS peak E1, which seems unusual at first sight. For the defect that is a majority carrier trap, the DLTS peak must have a negative sign at a filling pulse with $V_f = -0.50$ V, whereas in our measurements, it is positive. A reasonable question arises, why? In our opinion, this is due to the nature of the DX center, which is a donor with a negative correlation energy U and has three charge states: that of a shallow donor DX^+ and two levels with electrons in neutral (DX^0) and negatively charged (DX^-) states (acceptor-like level).[12–15] For the ordinary donor defect with DL, emission of electrons occurs upon application a reverse bias voltage. These electrons are carried away by the strong electric field in the SCL, the donor becomes positively charged, with the capacitance increasing. When a filling pulse with $V_f < 0$ is applied, donors situated in the SCL of the n-layer are filled by electrons, which are majority carriers, and become neutrally charged, with the capacitance decreasing. The whole process gives rise to a DLTS peak with a negative sign in the DLTS spectra. Everything occurs alternatively in $p–n$ structures containing DX centers. When DLTS spectra are measured for defects with a negative U at a reverse-biased $p^0–i–n^0$ junction with $V_r = -2.44$ V, a space charge region (SCR) is formed, in which the DX levels, donor level, and deep DX^- level (acceptor-like level) are emptied due to the emission of electrons from states of the DX center and to their carryover by the strong electric field in the SCR. The donor level designated as D^+ becomes positively charged with the large electron capture cross section, whereas the deep level (DX) becomes neutral with a carrier capture cross section smaller than that for the donor level D^+. In the process, the capacitance of the $p–n$ junction decreases. After a filling pulse with $V_f = -0.50$ V is applied, the SCR boundary shifts toward the p^0 layer, and at a filling pulse duration sufficient for capture of two electrons to the D^+ and DX^0 levels, the first to be captured to the positively charged donor level will be an electron. As a result, the defect becomes DX^0 in accordance with the requirements of the reaction $D^+ + e^- \to DX^0$. After that, the defect nearly immediately captures a second electron and becomes DX^- ($DX^0 + e^- \to DX^-$).

In the process, the capacitance of the p–n junction increases as a result of the recharging of the states of the DX center when the filling pulse is switched on. Then, after the filling pulse and a reverse bias are switched on with $V_r = -2.44$ V, two electrons are emitted closely following each other. Because the emission of the first electron takes a substantially longer time than that of the second electron, the observed emission rate will be in fact the same as that of the first electron.[16] This means, first, that the DLTS signature of E1 level, found from the Arrhenius dependence (Fig. 4) will belong to the DX$^-$ state and, second, deep states of the DX center, which are traps for majority carriers, give a positive DLTS signal. The appearance in the DLTS spectra of positive peaks associated with the emission of electrons from a deep DX$^-$ state in the $Al_xGa_{1-x}As$ n^0 layer (Fig. 2, spectrum 1) (as well as that for quantum-dot states[17,18]) strongly differs from that commonly observed in DLTS spectra of distributed traps for majority carriers, for which the DLTS of majority carriers has a negative sign. The thermal activation energies, capture cross sections, and concentrations of the E1 trap were found from the Arrhenius dependence to be $E_t = 280$ meV, $\sigma_e = 3.17 \times 10^{-14}$ cm^2, and $N_t = 5.4 \times 10^{14}$ cm^{-3} (Fig. 4). The parameters of this DX$^-$ state can be related to the manifestation of Se and Te donor impurities. It has been found previously[12] that the donor impurities Se and Te form in $Al_xGa_{1-x}As$ epitaxial layers DX centers with activation energy $E_t = 280$ meV for emission of electrons from the deep DX level into the conduction band.

The Se and Te impurities may appear in the $Al_xGa_{1-x}As$ layers under study because Ga is used as a solvent to grow base layers of a diode, and high-purity Ga (99.9999%) contains elements that can be incorporated into the epitaxial layer grown from the melt and strongly affect the impurity background of these layers. These elements include such donor impurities as Se and Te. The mass fraction of Se and Te in Ga (99.9999%) does not exceed

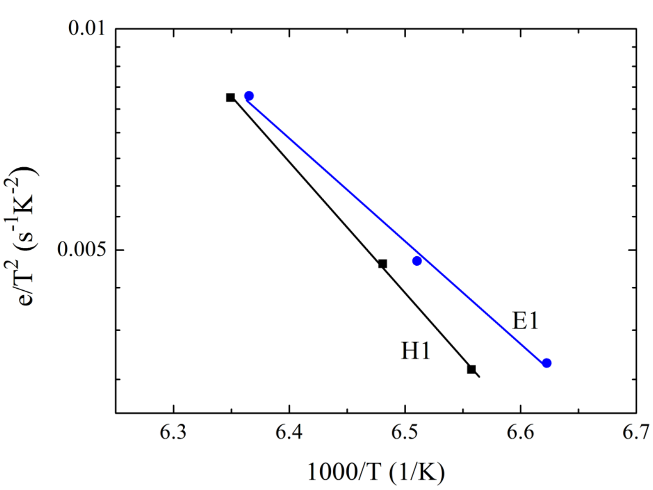

FIG. 4. Arrhenius temperature dependences of the thermal emission rates e of electrons and holes from deep traps H1 and E1 in $Al_xGa_{1-x}As/GaAs$ p^+–p^0–i–n^0 structures.

(according to the results of a chemical-spectral analysis) value of 1×10^{-7} for both Se and Te. However, because of the large values of the distribution coefficient,[19] their concentrations in intentionally undoped AlGaAs epitaxial layers under study can reach values of $\sim 10^{16}$ cm^{-3}. The distribution coefficients reported for these elements in Ref. 19 were used to estimate their maximum possible content in the layers grown due to the incorporation from the liquid gallium: these calculated values are within the range of $(0.5–2) \times 10^{16}$ cm^{-3} for Se and $(0.8–4) \times 10^{15}$ cm^{-3} for Te. The concentration of Se and Te in $Al_xGa_{1-x}As$ p^+–p^0–i–n^0 layer increases, respectively, from 5×10^{15} cm^{-3} and 8×10^{14} cm^{-3} near the p^+–p^0 interface to 2×10^{16} cm^{-3} and 4×10^{15} cm^{-3} near the n^0–n^+ interface.

A positive DLTS peak H1 was found in the DLTS spectrum measured at $V_f = +0.50$ V and $V_r = -2.44$ V in the dark. This peak appears because of the emission of holes from a minority carrier trap in the $Al_xGa_{1-x}As$ n^0 layer. The parameters of the H1 trap were (Fig. 4) $E_t = 353$ meV, $\sigma_h = 8.53 \times 10^{-13}$ cm^2, and $N_t = 8.4 \times 10^{14}$ cm^{-3}.

It should be noted that, on the whole, application of DLTS measurements to examine defects and impurities with the DL is correct when the doping concentration exceeds the trap concentration at least by 10%, which provides an exponential relaxation of the capacitance in measurement of DLTS spectra. Figure 3 shows the distribution of the effective carrier concentration profile across the thickness at $T = 87$ and 140 K. When the electric field at $T > 140$ K is applied to the p–n junction, DX centers in the region of centers in the depletion region of the SCL are thermally ionized, and, because all the donors are ionized, the total donor concentration can be determined from the results of C–V measurements. It varies across the thickness of the n^0 layer within the range from 1.2×10^{15} cm^{-3} to 1.8×10^{15} cm^{-3}, which exceeds by $\sim$30% the concentration N_t of the traps under study: for E1 trap, $N_t = 5.4 \times 10^{14}$ cm^{-3}, and for H1 trap, $N_t = 8.4 \times 10^{14}$ cm^{-3}.

Let us discuss the possible nature of the H1 level. It is well known that the epitaxial GaAs and AlGaAs layers of LPE-grown p^0–i–n^0 structures characteristically contain HL5 and HL2 defects,[20] which are hole traps and have concentrations dependent on the growth conditions.[6] The DLTS spectra of these compounds may also show the signals HB1, HB3, HB4, and HL12, which are associated with transition metal impurities, such as Cr, Fe, Cu, and Zn, respectively, and are minority carrier traps in n-type materials.[20] The parameters of these all these known levels do not coincide with those of the H1 trap. In Ref. 21, the authors found, when studying the nonradiative recombination via DLs in an epitaxial layer with $x = 0.30$ by the DLTS method, that the DX level can capture not only electrons but also holes, with the capture cross section of holes, σ_h, to the DX level being approximately four times that of the electron, σ_e. In addition, strong temperature dependences of σ_h and σ_e were observed, which suggest, in particular, that there is a barrier of 0.14 eV for capture of holes. It was found in Ref. 22 that the capture of holes by the DX center is responsible for the quenching of the near-bandgap photoluminescence in silicon-doped $Al_xGa_{1-x}As$. In Refs. 23 and 24, measurements of the thermally stimulated capacitance in an epitaxial layer of silicon-doped n-$Al_xGa_{1-x}As$ in relation to the conditions of isochronous annealing and subsequent cooling were used to observe the transition kinetics of the DX center from the stable configuration (DX^- state) to that of the metastable type (DX^0 state) and back.

We have a hypothesis that the appearance of the H1 DLTS peak may be due to the emission of holes from the acceptor-like DX^- state related to Se or Te impurities, preliminarily filled with holes on applying a filling pulse with $V_f = +0.50$ V (Fig. 2, spectrum 2). As already noted, states of the DX center are emptied after the reverse bias $V_r = -2.44$ V is applied. In this case, the donor level D^+ is positively charged, and the lower deep DX^- level becomes neutral. When the filling pulse $V_f = +0.50$ V at which the SCR becomes quasi-neutral is switched on, there occurs the injection of minority carriers (holes) into the base n^0 region of the diode. The first electron is rapidly captured to the donor level $D^+ + e^- \rightarrow DX^0$ and the defect passes to the DX^0 state, nearly immediately captures the second electron, and the defect passes to the negatively charged DX^- state ($DX^0 + e^- \rightarrow DX^-$). Simultaneously and rapidly, holes for which the capture cross section is three orders of magnitude larger are captured by the DX^- level, and it is transformed to the DX^0 level. As a result of its replenishment with injected holes during the filling pulse, this level will be stable. After the pulse voltage is changed from forward to reverse, holes captured to the DX^0 level are emitted, and this is observed in the DLTS spectra as the H1 peak.

On revealing by the DLTS method, the electron (E1) and hole (H1) traps associated with the capture of electrons and holes to the DX^- level in p^0–, i–, n^0–$Al_xGa_{1-x}As$ layers, we examined the temperature dependences of the effective lifetime of minority carriers (τ_{eff}) on the basis of the reverse recovery[1–4] of $Al_xGa_{1-x}As/GaAs$ p^+–p^0–i–n^0–n^+ diodes.

This method based on successively applying to the diode rectangular pulses of a forward (J_F) and reverse current (J_R) with a certain ratio between the amplitudes of signals and their durations makes it possible to rather accurately estimate τ_{eff} in the base layers of the diodes. The time in which a diode is switched from the forward to the blocking direction (reverse recovery time) is constituted by the durations of phases of a high reverse conductivity t_1 (with a constant J_R observed) and reverse current decay t_2. The full recovery time $t_r = t_1 + t_2$ primarily depends on the effective lifetime of minority carriers and, consequently, on the density of defects and impurities with DLs and on their cross sections. To measure the temperature dependences of τ_{eff} when switching the diode into the blocking state, samples were placed with a pressure contact in a 50 Ω matched strip holder. The total time in which the current changed from forward to reverse did not exceed 7–8 ns, the amplitude of J_F was not higher than 10 A/cm^2, and the ratio between the amplitudes of the forward J_F and reverse J_R currents was maintained at $J_F/J_R \approx 5$–6, at which the phase duration $t_1 \approx \tau_{eff}$.[1] Our measurements demonstrated a significant (by up to a factor of 6) increase in the phase duration t_1 (and, accordingly, in τ_{eff}) in the temperature range 300–580 K.

These temperature dependences of τ_{eff} can be attributed to the presence of a DX center in the base n^0 layer. Because, as shown above, the cross section of hole capture by the DX^- level exceeds that for electrons, this level will be trap for holes. Then, the capture time (lifetime) can be written as

$$\tau_h \approx 1/\sigma_h \upsilon_h N_{DX}^-, \tag{1}$$

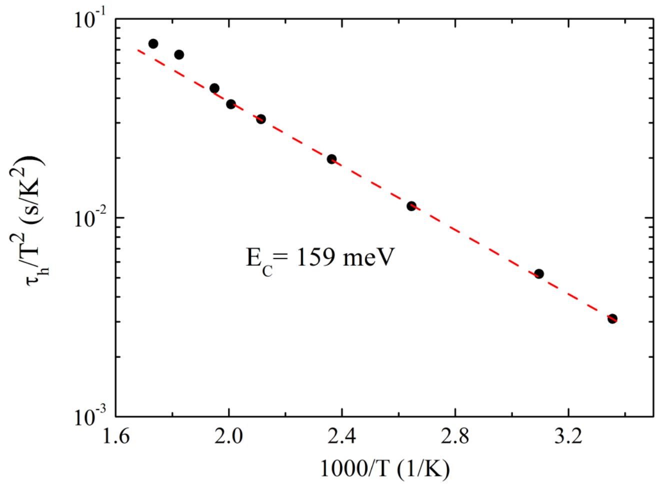

FIG. 5. Arrhenius temperature dependence of the capture time/lifetime of a hole to the DX^- level in $Al_xGa_{1-x}As/GaAs$ p^+–p^0–i–n^0 structures.

where N_{DX}^- is the concentration of DX^- levels filled by electrons and υ_h is the average thermal velocity of holes.[12] Relation (1) is valid if the DX^- level is related to the only impurity with DL, the injection level is low, and the trap concentration is high. If the capture is temperature-dependent and occurs via a multiphonon process, the capture cross section is described by the following formula:

$$\sigma_h = \sigma_\infty \exp\left(-\frac{E_c}{kT}\right), \tag{2}$$

where σ_∞ is the capture cross section at infinite temperature and E_c is the activation energy for thermal capture of holes. After appropriate transformations, relation (1) can be written as (Ref. 12)

$$\tau_h \propto T^{-2} \exp\left(-\frac{E_c}{kT}\right). \tag{3}$$

Relation (3) characterizes the thermal capture of holes to the DX^- level and plot of $\ln(\tau_h/T^2)$ against T^{-1} is a straight line with the slope ratio E_c. The effective lifetime $\tau_{eff} \approx \tau_h$ for a $Al_xGa_{1-x}As/GaAs$ p^+–p^0–i–n^0–n^+ diode was measured by the above method for various temperatures in the range of 300–580 K. The result of this experiment is shown as the Arrhenius dependence $\tau_h/T^2 = f(T^{-1})$ in Fig. 5. The slope ratio of the straight line describing this dependence was used to determine the activation energy of hole capture to the DX^- level to be $E_c = 159$ meV, which is close to the value reported in Ref. 21 (140 meV). Measurements in Ref. 21 were made by the DLTS method in injection of holes into the AlGaAs n-layer at various filling pulse amplitudes.

IV. CONCLUSIONS

High-voltage p–i–n diodes based on a $GaAs/Al_xGa_{1-x}As$ p^+–p^0–i–n^0–n^+ heterostructure grown in the single technological process by a modified LPE method with controlled distribution of residual impurities and intrinsic defects with deep levels were fabricated. The diodes retain their rectifying properties up to at least 600 K. The methods of C–V and DLTS spectroscopy were used to reveal in $Al_xGa_{1-x}As$ p^0–i–n^0 layers with Se/Te background impurities a DX center with negative correlation energy U, which strongly affects recombination processes in these layers. Two peaks were observed in the DLTS spectra of the n^0 layer, measured at two different filling pulses with $V_f = -0.50$ and +0.50 V. One of these, E1, attributed to the electron emission from the level of the DX^- state, is commonly observed in the DLTS spectra of n-type $Al_xGa_{1-x}As$ layers. The other peak, H1, is related to minority carrier traps and associated with the emission of holes from the level related to the DX^- state. An analysis of the dependence of τ_{eff} on the basis of the reverse recovery time of GaAs/$Al_xGa_{1-x}As$ p^+–p^0–i–n^0–n^+ diodes for various temperatures (300–580 K) made it possible to determine the activation energy of a hole capture to the DX^- level to be $E_c = 159$ meV. This enables us to conclude that the thermal capture of holes to the DX^- level defines the relaxation time of nonequilibrium carriers (holes) in the $Al_xGa_{1-x}As$ base layers as well as its temperature dependency.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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