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PHYSICS OF SEMICONDUCTOR DEVICES

A Study of Deep Centers in Microplasma Channels in GaP Light-Emitting Diodes with Green-Emission Spectrum

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Abstract—The statistical delay of microplasma breakdown in GaP light-emitting diodes with the green-emission spectrum is studied. The unusual profound effect of deep centers on the statistical delay of avalanche breakdown is observed in the temperature range of 300–380 K; this effect is caused by a variation in the charge state of these centers due to a reduction in the reverse bias applied to the *p*–*n* junction. Four deep levels are revealed and their parameters are determined.

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1. INTRODUCTION

Avalanche breakdown in real *p*–*n* junctions is conventionally highly localized and is of microplasma nature. As a rule, microplasma appears at sites of the accumulation of different structural defects and imperfections. The characteristics and reliability of semiconductor devices depend to a large degree on the properties of different defects and are determined by the microplasma set in the diode.

A delay in the breakdown is observed if a reverse voltage, which exceeds the breakdown voltage of microplasma with the lowest voltage, is applied to the *p*–*n* junction [1]. A relaxation-related delay in breakdown is observed at a high concentration of deep-level centers (DLCs) [2]. If the concentration of DLCs is low, the emission of charge carriers from these centers affects the statistical delay of microplasma-related breakdown [3]. In contrast to known traditional methods (capacitance spectroscopy, the Hall effect, photoconductivity, and so on), the delay in the avalanche breakdown makes it possible to study the characteristics of local sites where defects are concentrated, which is very important for predicting the properties and reliability of semiconductor devices.

Previously, several attempts were undertaken to determine the parameters of DLCs from the statistical delay in the avalanche breakdown [4–6]. However, as was noted in the above publications, the obtained results were ambiguous and contradictory.

The aim of this study is to evaluate the method of the microplasma-related spectroscopy of deep levels in the case of its application to GaP:N light-emitting diodes; this method makes it possible to study deep levels (DLs) in microplasma channels of *p*–*n* junctions since these levels can be responsible for processes of nonradiative recombination.

The charge state of DLCs was changed by partial lowering of the reverse voltage applied to the *p*–*n* junction. In this case, the DLCs are filled by majority charge carriers. In addition, the DLCs are occupied only in a limited part of the space-charge region (SCR) in the vicinity of its boundaries, where the electric-field strength is relatively low. We consider the possibility of determining the DLCs parameters from measurements of the distribution function for the duration of statistical delay in the microplasma-related breakdown (the Laue curve) in GaP light-emitting diodes with green emission.

Previously, studies of GaP light-emitting diodes with the red emission spectrum [3] and Si diodes [7] were undertaken

An analysis of previous studies [3, 7, 8] makes it possible to conclude that the method under consideration features a very high sensitivity to the DLC concentration in comparison with other methods; in particular, this sensitivity is even higher than that in the case of Q-DLTS.

2. EXPERIMENTAL

In this study, we have chosen, as most efficient, the pulsed method of studying the delay in the avalanche breakdown in a *p*–*n* junction [3]. The block diagram of the measuring installation is shown in Fig. 1.

The source of direct-current voltage (*1*) feeds the generator (*2*), which produces rectangular voltage pulses with an amplitude continuously adjustable from 0 to 300 V for both the lower and upper levels. The pulse duration can be varied from several microsec-

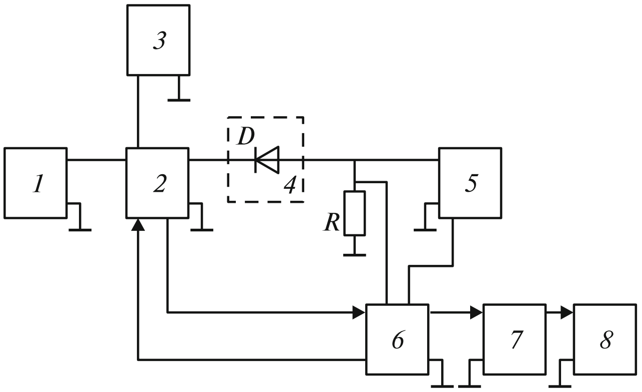

Fig. 1. Block diagram of the setup for measuring the breakdown delay: (*1*) adjustable source of direct-current voltage, (*2*) generator of rectangular pulses, (*3*) voltmeter, (*4*) cryostat, (*5*) oscilloscope with memory, (*6*) control unit, (*7*) time meter, and (*8*) PC; *R* denotes a resistor and *D* denotes the diode under study.

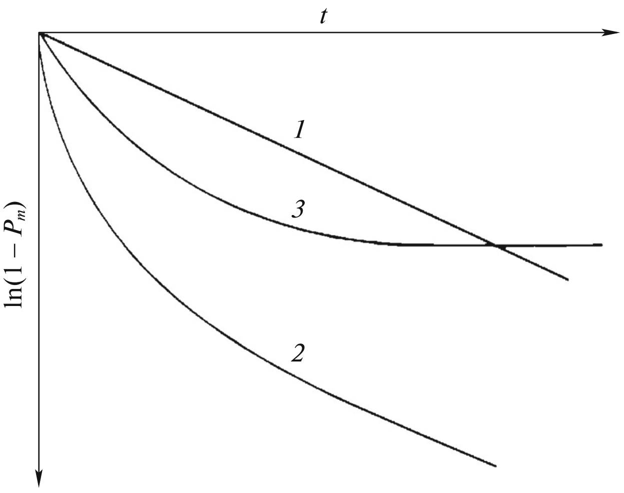

Fig. 2. Distribution function for the statistical delay in the breakdown with regard to duration: (*1*) without the occupation of deep-level centers (DLCs), (*2*) with the occupation of DLCs, and (*3*) the difference curve.

onds to tens of minutes. The level of noise at the output of the generator (*2*) does not exceed 0.5 mV; the voltage was kept constant with an accuracy of no worse than 1 mV. The durations of the upper and lower levels of the voltage are specified independently; the duration of the upper level can be also specified by the duration of the delay of avalanche breakdown in the *p*–*n* junction. The rise time of the voltage pulse does not exceed 1 μs. All types of control of the generator of rectangular pulses are implemented using the control unit (*6*). The sample under study is placed in an opaque cryothermostat. The latter makes it possible to vary the sample temperature in the range of 77–380 K and maintain it with an accuracy of ±0.1 K. We used a TSPN-5 resistance thermometer for measuring the temperature with high precision.

A detailed theory of the method is reported in [3]. For example, let a deep level be located in the upper half of the band gap and let this level be occupied with majority charge carriers (electrons) from the side of the *n*-type region in the course of short-time lowering of the reverse voltage at the *p*–*n* junction. The duration of the voltage pulse giving rise to occupation of the level was determined by the time of establishment of a steady state in the microplasma channel. For a level located in the upper half of the band gap, the coefficient of electron emission from a DLC is, as a rule, much larger than the coefficient of emission for holes, $e_n \gg e_p$. Therefore, at the initial moment of time ($t = 0$), after the voltage jump $V > V_M$, where V_M is the voltage corresponding to the breakdown of microplasma, deep-level centers in the region of their occupation become located in the SCR and are found to be completely occupied with electrons. The function of the distribution of the delay in microplasma breakdown over its duration (the probability of the fact that the microplasma is not restored during the time *t* after application of the discharge voltage), in the semilogarithmic system of coordinates (1) consists of linear (2) and nonlinear (3) parts

$$\ln(1 - P_M) = \ln(1 - P_{M0}) + \ln(1 - P_{Mt}), \tag{1}$$

$$\ln(1 - P_{M0}) = -S_M N_t \frac{e_n e_p}{e_n + e_p}\left[\int_{-L_p}^{L_n} (P_n(x) + P_p(x))dx\right]t, \tag{2}$$

$$\ln(1 - P_{Mt}) = -S_M N_t \frac{e_n^2}{(e_n + e_p)^2} \times \left[\int_{L_m}^{L_n} P_n(x)dx + \frac{e_p}{e_n}\int_{L_m}^{L_n} P_p(x)dx\right]\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{3}$$

where P_M is the probability of the appearance of microplasma under the effect of overvoltage ($V - V_M$); e_n and e_p are the coefficients of the emission of electrons and holes from the DLC, respectively; P_n and P_p are the probabilities of initiation of an avalanche by the above process; N_t is the DLC concentration; S_M is the cross section of the microplasma channel; $\tau = (e_n + e_p)^{-1}$ is the time constant for establishment of the DLC steady state; L_p and L_n are the boundaries of SCRs of the *p*–*n* junction from the *p*- and *n*-type regions, respectively; and L_m is the SCR boundary from the side of the *n*-type region at the voltage V_M of occupation of deep levels.

The typical shape of the distribution functions under discussion is shown in Fig. 2.

The linear term (2) represents the thermogeneration-related mechanism of avalanche initiation via the deep level under consideration. The nonlinear

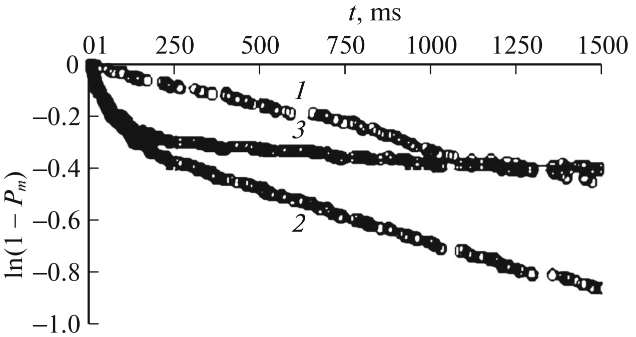

Fig. 3. Typical curves describing distribution functions for the statistical delay in the breakdown with regard to duration at a temperature of 354.2 K: (*1*) without occupation of DLCs, (*2*) with occupation of DLCs, and (*3*) the difference curve.

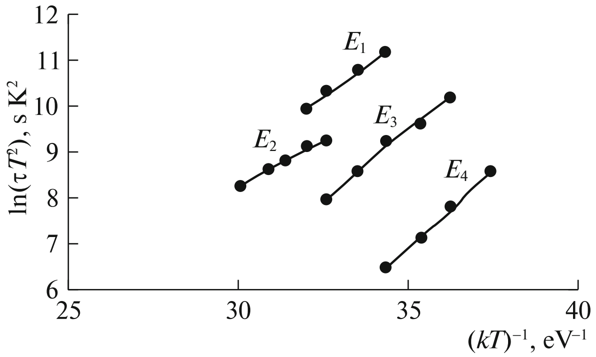

Fig. 4. Arrhenius curves.

term (3) is responsible for avalanche initiation facilitated by the re-emission of charge carriers from DLCs.

The linear term can be excluded from consideration if the distribution function without occupation of DLCs is measured. In that case, $1 - P_{M0}$ is exactly measured at low overvoltages $L_m \approx L_n$. Thus, the problem can be reduced to an analysis of the function $1 - P_{Mt}$, which includes the main information about the effect of DLCs on the breakdown delay and can be represented as

$$1 - P_{Mt} = \exp\left[A\left(1 - \exp\left(-\frac{t}{\tau}\right)\right)\right], \tag{4}$$

where

$$A = -S_M N_t \frac{e_n^2}{(e_n + e_p)^2}\left[\int_{L_m}^{L_n} P_n(x)dx - \frac{e_p}{e_n}\int_{L_m}^{L_n} P_p(x)dx\right]. \tag{5}$$

If there are several simple two-charge deep levels in the SCR of the p–n junction, the emission of charge carriers from these levels is bound to proceed independently; as a result, the distribution function for the breakdown delay will be represented by the sum of individual components in semilogarithmic coordinates.

In real p–n junctions, there are other mechanisms (in addition to the emission of charge carriers from DLCs), which deliver charge carriers for the initiation of an avalanche. In this case, the right-hand side of expression (2) must be complemented by yet another, most commonly linear, term. The contribution of the latter can also be taken into account in measurements of the distribution function for the breakdown delay without the occupation of DLCs.

3. RESULTS

We studied the delay in the avalanche breakdown using AL341G commercial GaP light-emitting diodes. For measurements, we chose samples, which revealed all the signs that they include "classic" microplasma: the appearance of current pulses, a characteristic kink in the current–voltage characteristic, and a fairly wide range of overvoltage for the first microplasma.

The crystal of a GaP:N light-emitting diode is an epitaxial p–n structure. Two layers with n- and p-type conductivity are formed by the method of liquid-phase epitaxy on a single-crystal n-GaP substrate doped with Te. The n-type layer was doped with nitrogen and residual donors while the p-type layer was doped with zinc and nitrogen.

The model of a graded p–n junction with the concentration gradient $a = 2.1 \times 10^{22}$ cm^{-3} is more justified for the p–n junction under consideration. The distribution of the doping impurity in the region of the metallurgical junction corresponds to a typical diffusion p–n junction. The steady-state breakdown voltage for the first microplasmas in various diodes amounted to 18–19 V at room temperature. The voltage of activation of the second microplasma differed from the corresponding voltage for the first microplasma by more than 1.2 V (at various temperatures).

Studies were performed in the temperature range of 300–380 K, the overvoltage was 1.1 V, and the voltage needed for occupation of deep-level centers amounted to 10 V.

Typical experimental distribution functions for the duration of statistical delay in the microplasma breakdown are shown in Fig. 3. In the range of temperatures under study, the resulting curve *3* was described by a single exponential function or by a sum of exponential functions of the form (4). This made it possible to determine the time constants τ for establishment of the steady state for deep-level centers. Figure 4 shows the dependences of τ on T in the form of an Arrhenius plot. The obtained parameters of the energy levels are listed in the table.

We changed the charge state of deep-level centers by partial lowering of the voltage at the p–n junction and used the data on statistical delay of the micro-

Parameters of detected energy levels

Designation of the energy level	Energy ΔE_t, eV	Capture cross section, cm^2
E_1	0.52	1.23×10^{-18}
E_2	0.41	9.5×10^{-20}
E_3	0.60	1.44×10^{-16}
E_4	0.68	2.9×10^{-14}

plasma breakdown to determine the energy spectrum of deep levels in the microplasma channels of the GaP:N light-emitting diodes. We revealed the effect of four deep levels in the temperature range of 300–380 K. The first level features an energy of 0.52 eV and a capture cross section of 1.23×10^{-18} cm^2, the second level features an energy of 0.41 eV and a capture cross section of 9.5×10^{-20} cm^2, the third level features an energy of 0.60 eV and a capture cross section of 1.44×10^{-16} cm^2, and the fourth level features an energy of 0.68 eV and a cross section for the capture of minority charge carriers equal to 2.9×10^{-14} cm^2. Since the *p*–*n* junction under study features a symmetric structure, it is found impossible to determine from which band positions the levels are counted.

We failed to determine the concentration of deep-level centers. In order to determine this concentration, it necessary to calculate the probability of the initiation of an avalanche by charge carriers originating from the region of filling, i.e., from the boundary of L_m to L_n. If we calculate the probability of the initiation of an avalanche (for linear GaP linear *p*–*n* junctions with a breakdown voltage of 18–19 V) using the method reported in [1], we receive a value, which is smaller by many orders of magnitude than that necessary for obtaining reasonable values of the concentration of deep-level centers. Thus, an anomalously high probability of initiation of an avalanche by charge carriers is observed in GaP light-emitting diodes with the green emission spectrum (the same is observed for GaP light-emitting diodes with the red emission spectrum [9]). Deep-level centers in the light-emitting diodes under study were not detected by capacitance-related methods including, in particular, the DLTS method. This is indicative either of the low concentration of these centers or of their localization in microplasma channels.

The obtained values of the level energies E_2 = 0.41 eV, E_3 = 0.60 eV, and E_4 = 0.68 eV coincide with the levels observed in GaP by other methods and related to the presence of copper (E_v + 0.68 eV) and to the presence of cobalt (E_v + 0.41 eV); the level E_c – 0.6 eV is of unknown origin. The level with the energy of 0.52 eV in GaP is not mentioned in the previous publication [10]. The measurements performed by us are not sufficient for precise identification of the observed levels. These levels can belong to both impurity centers and to structural defects. It cannot be excluded that the found levels manifest themselves only in microplasma channels and, correspondingly, are not detected by other methods.

4. CONCLUSIONS

The results presented above show that the delay in the avalanche breakdown in the GaP:N light-emitting diodes is affected profoundly by deep-level centers (DLCs). A variation in the charge state of DLCs even at a small reduction in the reverse voltage (approximately, by 4–5 V relative to the breakdown voltage of the first microplasma) leads to a significant increase in the turning-on of microplasma. It is shown that a variation in the charge state of DLCs by partial lowering of the voltage at the *p*–*n* junction, the statistical delay makes it possible to determine the parameters of SLCs located in the microplasma channel.

The considered method does not impose restrictions on the geometry of the *p*–*n* junction and can be used for studying deep-level centers in the region of microplasma localization in which case capacitance-based methods become inapplicable.

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