Раздел третий

КОНСТРУКЦИОННЫЕ МАТЕРИАЛЫ РЕАКТОРОВ НОВЫХ ПОКОЛЕНИЙ, РЕАКТОРОВ НА БЫСТРЫХ НЕЙТРОНАХ И ТЕРМОЯДЕРНЫХ УСТАНОВОК

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NEUTRON IRRADIATION INFLUENCE ON THE SILICON VOLTAGE LIMITER PARAMETERS

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The influence of neutron irradiation on breakdown voltage (U_{bd}) and limitation voltage (U_{lim}) is investigated in silicon voltage limiter. The coefficient K_ρ is basic radiation parameter, forming dependences $U_{bd} = f(F)$ and $U_{lim} = f(F)$, which determines the dependence of basic charge carriers concentration in silicon from neutron fluencies. The mechanisms, which form the U_{lim} value after neutron irradiation are determined. On basis of obtained results analysis is proposed the model, which makes it possible to forecast changes in the breakdown voltage and limitation voltage, which occur as a result the neutron irradiation of voltage limiter.

INTRODUCTION

In view of continuous enhancement of radio-electronic equipment (REE), increase in the number of carried out functions and decided tasks, the requirements for its reliability and failure-free operation sharply grew. One of the basic factors which decreases reliability and failure-free performance of REE is the influence of unregulated electric pulses such as atmospheric electricity, powerful switching noise, etc. Therefore the guaranteed protection of radio-electronic equipment (or its separate elements) of the influence of such pulses is one of the basic ways of its reliability growth. The overwhelming majority of known protection ways is that at the moment of action of “dangerous” electric pulse the protective element "cut away" the peaks of voltage pulses up to a safe level, and so the excess electrical energy is dissipated on protective element. One of perspective protective elements is the semiconductor voltage limiter (VL); it is the semiconductor diode, where the most important parameter is limiting voltage (U_{lim}). The voltage is the maximum voltage which provides overpowers protection of the REE [1]. If $U_{lim} > 20$ V one can consider that the avalanche breakdown of *p-n* junction [2] is the basic mechanism forming the U_{lim} value. In this case one of the parameters characterizing VL should be also avalanche breakdown voltage (U_{bd}). U_{bd} is the voltage since which voltage limiting at protected REE (or its element) begins. Limiting voltage (U_{lim}) and avalanche breakdown voltage are connected by the relation:

$$U_{\lim} = U_{bd} + I_{\lim}(R_{dif} + R_{ser}), \qquad (1)$$

where I_{lim} is the current passing through VL when the overvoltage pulse appears; R_{dif} and R_{ser} - differential and series resistances of VL, respectively.

This current value characterizes of the excess electrical energy dissipated on VL in the “limitation” regime which does not lead of VL parameters to destruction or degradation. VL is in so-called “waiting” mode in the absence of an overvoltage pulse. The reverse voltage (U_{rev}) is fed to VL which equal to working voltage of the protected REE (or its element). *Apriori* $U_{rev} < U_{bd}$, and reverse current (I_{rev}) of VL at this voltage characterizes power losses in VL when working in "waiting" mode.

It is evident that the dependence of the VL parameters on the external influencing factors (EIF) (the most important of which are ambient temperatures [2, 3, 4] and radiation) defines its efficiency as an element of electrical circuit under the actual conditions of REE operation.

Radiation influence on U_{bd} and I_{rev} of rectifier diode and stabilitron is described in variety of works (for example [5-8]). At the same time radiation influence on U_{lim} and connection of this parameter with U_{bd} are not investigated practically. First of all it concerns neutron radiation which is the strongest factor influencing on semiconductors and semiconductor devices parameters. The present work is dedicated to study of neutron irradiation influence on limiting voltage and its connection with breakdown voltage under radiation influence.

INVESTIGATED SAMPLES AND EXPERIMENTAL TECHNIGUE

The VL were studied with voltage limitation $U_{lim} = 50$ V. The construction of the investigated VL is schematically shown in Fig. 1 (two-layered protection of crystal surface by organic materials is not shown). The schematic construction of the active part of the voltage limiter crystals used in the experiment, some of its geometric dimensions (in millimeters) are presented in Fig. 2.

Detail description of crystal making technology basic principles for the VL is given in [2]. The most important physical characteristics of the VL structure and technological regimes fabrication will be given.

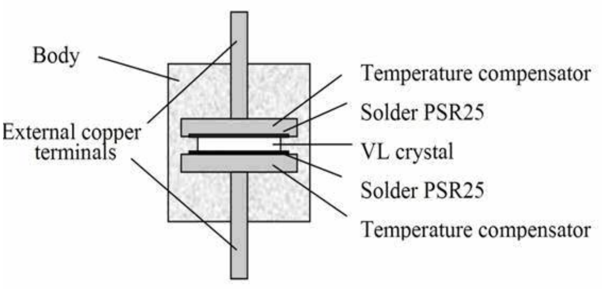

Fig. 1. VL construction (schematic)

They are the following:

– the area of *p-n* junction is ~ $9.3 \cdot 10^{-2}$ cm^2;

– for crystal VL making *n*- type silicon with specific resistance of 0.3 Ohm·cm was used;

– p+ and n+ layers were created by the boron and phosphorus diffusion, respectively;

– diffusion was carried out by the package method [2] at (1250 ± 5) ºC during 1 h. At this diffusion method the distribution of the diffusing admixture is obeyed to the errors addition function [2].

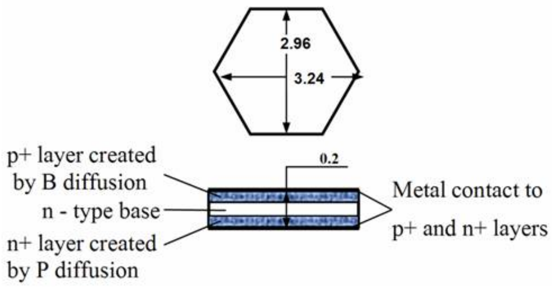

Fig. 2. VL crystal construction (schematic)

The calculations carried by formulas [9] and initial data [2, 9] (diffusion coefficients, surface concentrations) showed that:

– *p-n* junction occurrence depth Xj (boron diffusion depth) is ~ (37±1) µm;

– concentration gradient of impurity which crea-tes *p-n* junction at x= Xj is ~ $(1.0 \pm 0.2) \cdot 10^{20}$ cm^{-4};

– n-n junction occurrence depth (phosphorus diffusion depth) is ~ 45 µm.

Neutron irradiation of samples was carried out at the research reactor. Neutron fluence dosimetry was realized by the sulfuric indicators ^{32}S (E > 3 MeV) followed by reduction (using reactor spectrum) to the neutrons fluence with the E ≥ 100 keV energy. The average neutrons energy was ~ 1.5 MeV and dosimetry error − ± 20 %.

U_{bd}, U_{lim}, I_{rev} and voltage dependence of barrier capacity (volt-farad characteristics) were measured at VL before and after radiation. U_{bd} was measured in accordance with the State Standard 18986.2 by the bend of voltage-current characteristic (under sharp decrease of differential resistance and the reverse currents which exceed I_{rev} not less than 10 times over the prebreakdown region). U_{lim} was measured in accordance with the procedure described in [1] by compensation method with the error not more than 5 %; the current I_{lim} was 50 A. I_{rev} was measured according to the State Standard 18986.1 under the assigned reverse voltage with the error not exceed 5 %. The barrier capacity from voltage dependence (volt-farad characteristics) at investigated VL was measured by bridge method at the 1 MHz frequency according to the State Standard 18986.4 with the error not more than 5 %. The samples (selection consisted of 20 VL) were irradiated and the mentioned parameters were measured. For reactor time economy and reduction of the reactor startup number the sample selection were divided into 5…6 groups (by 3…4 VL). Each sample group was irradiated into two stages (by two neutron fluxes) followed by measurement of parameters after each irradiation stage. For the analysis of parameters dependence from neutron fluence (Φ) the average values of the parameters were used. The VL experimental parameters values were processed by the least-squares method. Obtained graphic dependences, their analytic equations (y = f (x)), quantity coefficient of approximation (R^2) and experimental points are given in all subsequent figures.

BASIC RESULTS AND DISCUSSION

The $\ln [U_{bd}(\Phi / U_{bd}(0)] = f(\Phi)$ and $\ln [U_{lim}(\Phi) / U_{lim}(0)] = f(\Phi)$ dependences are presented in Fig. 3.

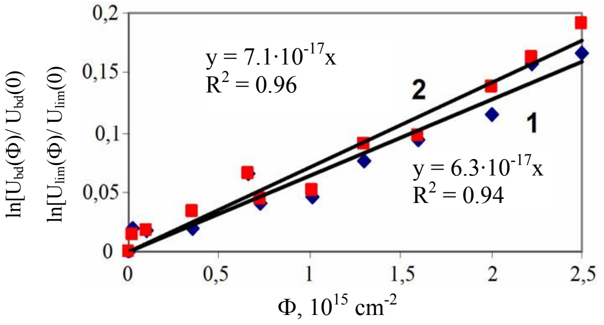

Fig. 3. Neutron fluence dependences of avalanche breakdown voltage and limiting voltage: 1 – $\ln[U_{bd}(\Phi / U_{bd}(0)] = f(\Phi)$; 2 – $\ln[U_{lim}(\Phi)/U_{lim}(0)] = f(\Phi)$

From the figure one can see that the dependences are straight lines with sufficiently high ($R^2 \geq 0.9$) reliability of approximation and, therefore, for investigated VL the relations $U_{bd}(\Phi) / U_{bd}(0)$ and $U_{lim}(\Phi) / U_{lim}(0)$ exponentially depend on the neutron fluence:

$$U_{bd}(\Phi) = U_{bd}(0) \exp(K_1 \Phi), \qquad (2)$$

$$U_{\lim}(\Phi) = U_{\lim}(0) \exp(K_2 \Phi), \qquad (3)$$

where K_1 and K_2 – coefficients which are determined by slope of lines in Fig. 3 are represented in table1.

Table 1

K_1, cm^2	K_2, cm^2
$6.3 \cdot 10^{-17}$	$7.1 \cdot 10^{-17}$

So, K_1 and K_2 values are near each other and are distinguished less than 10 %. Themselves the values of breakdown voltage change on ~ 12…13 % and of limiting voltage on ~ 20…23 % even at the maximum neutron flux (~ $2 \cdot 10^{15}$ cm^{-2}). In Fig. 4 the $\ln [U_{bd}(\Phi)/U_{bd}(0)] = f(\Phi)$ dependence, built according to experimental data, is presented. Fig. 4 shows that the U_{bd} dependence on neutron fluence Φ is exponential nature which is typical [6, 7]. K_1 coefficient value in exponent and its independence of specific resistance of silicon which is used for creation of *p-n* junction, and from the structure is novel (within certain degree): according to [6, 7] this coefficient is $K_1 = 0.75\,K_\rho$, where K_ρ is a constant of the specific resistance change of semiconductor under radiation influence.

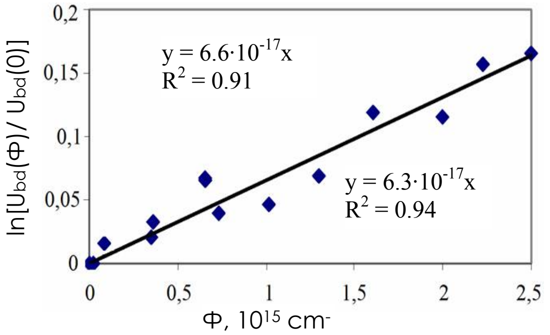

Fig. 4. The dependence of $\ln\,[U_{bd}(\Phi) / U_{bd}(0)] = f\,(\Phi)$

It is known [5, 6, 10] that if neutron irradiation weakly influences on carriers mobility the relation occurs:

$$K_\rho = \frac{dn / d\Phi}{n_0}, \qquad (4)$$

where dn/dΦ – carriers removal rate; n_0 – initial concentration of equilibrium basic current carriers.

In accordance with [6], for the initial silicon specific resistance of $\rho_0 \sim 2$ Ohm·cm ($n_0 \sim 2.5\cdot10^{15}$ cm^{-3}) dn/dΦ can be within the limits of 1.5…4 cm^{-1}. In this case the coefficient K_ρ must be $\sim (1.1\pm0.5)\cdot10^{-15}$ cm^2 and, therefore, according to [6,7] the coefficient K_1 must be $\sim (0.8\pm0.4)\cdot10^{-15}$ cm^2. But for the investigated VL samples this value is approximately by an order less and is $\sim 6.6\cdot10^{-17}$ cm^2 (Fig. 5). It is the most probable that such discrepancy in the K_1 value is related to the fact that in the works [6, 7] the sharp *p-n* junctions were investigated but in the present work the *p-n* junctions with the linear distribution of impurity in the base (Fig. 5, curve 1) are examined.

The mentioned reason for discrepancy is probable sufficient because the authors [5] showed that for the diffusion p-n junctions U_{bd} practically does not change under irradiation, and they explained this effect by fact that at the large reverse voltages the quasi Fermi level in the space charge region of *p-n* junction falls below energy of the deep acceptor levels injected by irradiation. As a result the ionization degree of these deep levels becomes negligible and the properties of the space charge region are determined only by ionized initial donors and acceptors. However in the mentioned work the quantitative data were not given which confirm both the explanation and statement about the U_{bd} (Φ) weak dependence of diffusion diodes. Therefore the mechanisms will be considered in more detail which form the dependences described by formulas (2) and (3).

According to [3, 11, 12], the avalanche breakdown voltage of *p-n* junction is directly related to the width of space charge region (SCR) of the *p-n* junction:

$$U_{bd} \sim \left[\omega(U_{bd})\right]^m, \qquad (5)$$

where ω (U_{bd}) – VCR width at the reverse voltage equal to U_{bd}; m – exponent equal to ~ 0.84 [11, 12].

Dependence (5), given in the literature, relates to the *p-n* junctions which were not being exposed to irradiation. It is very interesting to determine possibility of existence of similar dependence in the *p-n* junctions which were neutron irradiated. Note that the characteristics of the space charge region can undergo sufficiently noticeable changes as a result of radiation exposure. It is illustrated by Fig. 5: in this figure the typical volt-farad characteristics (VFCh) of the VL before and after irradiation are presented on the log-log scale [13]:

$$U_d = \frac{2kT}{3q}\ln((a^2\varepsilon\varepsilon_0\frac{kT}{q})/8qn_i^2), \qquad (6)$$

where U_d – gradient potential; k – Boltzmann constant; T – absolute temperature; q – electron charge; a – impurity gradient which creates *p-n* junction; ε – silicon dielectric constant; n_i – intrinsic concentration of carriers in silicon. Fig. 5 shows that before irradiation the barrier capacitance of *p-n* junctions in VL is proportional to $\sim U^{-0.33}$ (where U – reverse voltage), which is typical for linear *p-n* junction [13].

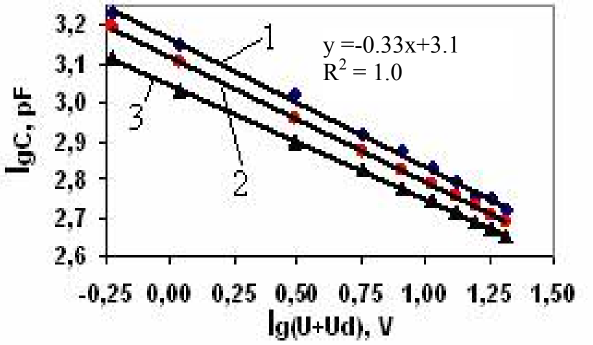

Fig. 5. Volt-farad characteristics of VL:
1 – before and 2, 3 – after irradiation with neutron fluence of $7\cdot10^{14}$ *and* $2\cdot10^{15}$ cm^{-2}*, accordingly*

But after irradiation exponent has a tendency to decreasing. At increasing reverse voltage the slope angle of the lg [C (Φ)] - lg ($U+U_d$) dependences after irradiation approximates to the slope angle of these dependences before irradiation.

ln[ω(Φ)/ω(0)] = f(Φ) (if $U_{rev} \approx U_{bd}$) dependence is presented in Fig. 6.

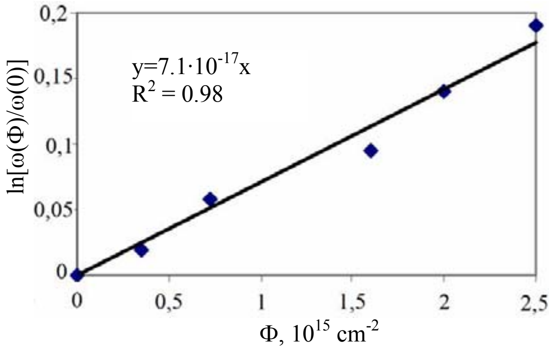

Fig. 6. Dependence of ω(Φ)/ω(0) ratio
on neutron fluence

It is possible to see that for the studied VL the next relation is carried out with quite large reliability ($R^2 \approx 1$):

$$\omega(\Phi) = \omega(0)\, exp(K\Phi), \qquad (7)$$

where K – the coefficient equal to $7.1\cdot10^{-17}$ cm^2 ($U_{rev} \approx U_{bd}$).

Dependence (7) is general for the studied type of VL and the obtained graph is described well by formula:

$$\omega(\Phi) = \omega(0)\, exp(7{,}1\cdot10^{-17}\, \Phi). \qquad (8)$$

Using data given in Fig. 4 and 6 it is possible to build the dependence $U_{bd}(\Phi)/U_{bd}(0) = f(\omega(\Phi)/\omega(0))$ (if $U_{rev} \approx U_{bd}$) which on the log-log scale is given in Fig. 7. It follows from this figure that after irradiation, in spite of a change in the structure of diffusion *p-n* junction, the avalanche breakdown voltage also obey of the universal dependence (5) with the quite large reliability ($R^2 = 0.91$), and therefore this formula may be used for calculating U_{bd} after irradiation.

It is of certain interest to confirm the experimental dependence (8) by calculations.

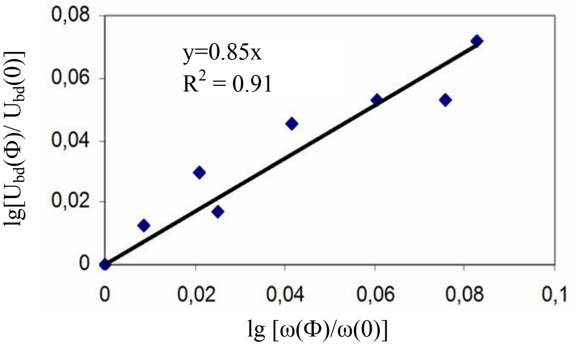

Fig. 7. Dependence of ratio $U_{bd}(\Phi)/U_{bd}(0)$ on ratio $\omega(\Phi)/\omega(0)$

At that let us assume that both before irradiation, in entire range of reverse voltages, and after irradiation at the rather high reverse voltages ($U \sim U_{bd}$) of the SCR width can be calculated by the known formula for the graded *p-n* junction [13]:

$$\omega = \left(\frac{12\varepsilon\varepsilon_0(U+U_d)}{qa}\right)^{\frac{1}{3}}, \qquad (9)$$

where a – impurity gradient which creates *p-n* junction.

If to consider that the *p-n* junction is formed by linear distribution of impurity: $N_0(x) = ax$, then after irradiation, according to [5, 6, 10], this dependence is:

$$N(x,\Phi) = N_0(x)\exp(-K_\rho\Phi),$$

(10)

where Kρ – coefficient determined for the linear junction; x – depth of impurity arrangement (depth of the *p-n* junction position);

$$K_\rho(x) = \frac{1}{k(ax)^{0{,}77}},$$

(11)

where k – number which for n- type silicon varies from 387 to 3300 depending on the specific resistance and neutron spectrum [10].

Differentiating (10) by the «x» coordinate we obtain:

$$\frac{dN(x,\Phi)}{dx} = a\,(1+0.77K_\rho\Phi)\exp(-K_\rho\Phi).$$

(12)

If $0{,}77K_\rho\Phi < 1$ (it is not difficult to see that this condition is carried out practically for entire range of neutron fluences used in the experiment), then:

$$\frac{dN(x,\Phi)}{dx} = a\ \exp(-0.23K_\rho\Phi).$$

(13)

Using (13) and (7), it is easy to obtain:

$$\frac{\omega(\Phi)}{\omega(0)} = \exp(0.077K_\rho\Phi) \qquad (14)$$

at that $U_{rev} \approx U_{bd}$.

By comparing (8) and (14) one can see that these exponential dependences are identical and experimental value of the coefficient is $K_\rho \approx 0.9\cdot10^{-15}$ см^2. In this case the question arises: to what initial (before the irradiation) carriers concentration can be related this coefficient value. In our opinion, it should be related to the average carrier concentration that forms of VCR width of in *n*-region (ω_n). In the first approximation the average carriers concentration is equal to $\sim n(\omega_n)/2$, where ω_n is VCR width in the n- region. The results of ω, ω_n, $n(\omega_n)$ and K_ρ calculation are presented in table 2.

Table 2

Name of calculated value	Calculation result for VL with $U_{rev} \approx 50$ V	Calculation procedure
Total width of VCR (ω), cm	$2.5\cdot10^{-4}$	[14]
Width of VCR in *n*-region (ω_n), cm	$1.36\cdot10^{-4}$	[14]
Carriers concentration (ω_n), cm^{-3}	$8.2\cdot10^{15}$	[12]
Average concentration of main carriers in ω_n, cm^{-3}	$4.1\cdot10^{15}$	$n_{av} = n(\omega_n)/2$
Carriers removal rate, cm^{-1}	3.7	By formula (4) at carriers removal rate of 2.5 cm^{-1}

As can be seen from the calculation results (table 2), the values of the carriers removal rate, obtained from the experimental dependence ω (Φ) (Fig. 6 and formula (8)) and also from its design model expressed by the formula (14), it is very close to the value K_ρ given at [5] for the value of the carriers removal rate of 1…4 cm^{-1}. This value lies inside the interval of its possible values. So, formula (14) may be used in practice for calculating the ω(Φ) dependence and its following application for calculation and predicting the dependence $U_{bd} = f(\Phi)$ according to formula (5).

Let us consider in more detail the dependence of limiting voltage (U_{lv}) upon neutron fluence. In accordance with formula (1) the value of this parameter is related by linear dependence with breakdown voltage, differential resistance of *p-n* junction in limitation regime and series resistance of semiconductor structure in this regime. As already mentioned, the limitation regime is characterized by the current of $I_{\lim} = 50$ A for VL. *Apriori* one can state that in this case the *p-n* junction is located in "deep" breakdown, and in accordance with the Miller formula [9]:

$$\frac{I_{\lim}}{I_R} = M = \left(1-\left(\frac{U}{U_{bd}}\right)^{C}\right)^{-1},$$

(15)

where M − coefficient of carriers multiplication; C = 5 for the silicon *p-n* junction; I_R − reverse current of *p-n* junction if $U << U_{bd}$.

We will obtain from (15) that:

$$R_{dif} = \left(\frac{U_{bd}}{C I_{\lim}}\right)\left(\frac{I_R}{I_{\lim}}\right)\left(\frac{I_{\lim}}{I_{\lim}-I_R}\right)^{\frac{C-1}{C}}.$$

(16)

For the considered regime of limitation and for real values of reverse currents in the waiting regime ($I_R \leq 5\cdot10^{-5}$ A) we obtain that $R_{dif} \approx 10^{-5}$ Ohm and so in the formula (1) the R_{dif} value can be neglected. As regards the value of series resistance (R_{ser}) (in formula (1)), it consists of two parts [16]. The first part is resistance the part of SCR in which impact ionization does not occur. This part is named "transit-time region" and, in accordance with [15], its resistance (R_{ttr}) is determined by the relation:

$$R_{ttr} = \frac{(\omega-\omega_m)^2}{2\varepsilon\varepsilon_0 S V_{sat}}, \qquad (17)$$

where ω_m – width of the part of VCR in which impact ionization occurs, S-area of *p-n* junction; V_{sat} – saturation rate of carriers in silicon, which, in accordance with [14], is 10^7 cm/s. The second part is the ohmic resistance of neutral base of VL:

$$R_{base} = \rho_{nb}\frac{d_{nb}-\omega}{S},$$

(18)

where ρ_{nb} – specific resistance and d_{nb} – width of neutral base.

Note that ω_m value calculating for the diffusion *p-n* junctions is realized by various expressions for each concrete case but the results of ω_m calculating are single-valued for the sharp *p-n* junctions [16].

At the same time taking into account that R_{dif} and, therefore, voltage drop across the ω_m section is negligibly little, it follows from formula (1):

$$U_{\lim} - U_{bd} = I_{\lim}(R_{base} + R_{ttr}),$$

(19)

where R_{base} and R_{ttr} are determined by formulas (17) and (18), respectively.

According to formulas (17–19), using initial (before irradiation) experimental values of $U_{\lim} - U_{bd}$, the values of SCR width ω (for $U \approx U_{bd}$]) calculated by formula (9), the neutral base width (d_{nb}) and its specific resistance (ρ_{base}), one can calculate the ω_m value. Calculation gave $\omega_m \approx 1.3\cdot10^{-4}$ cm. It is interest to note that in [16] for sharp *p-n* junctions it is obtained $\omega_m \approx 0.5\cdot10^{-4}$; at that the *p-n* junctions have been prepared using silicon with the same initial specific resistance (~0.3 Ohm·cm) that the investigated VL. The fact that the length of avalanche multiplication region in the smooth *p-n* junctions is larger than in the sharp ones is completely regular, and it, in our opinion, confirms reliability of the obtained values of ω_m for the VL structures under study.

Subsequently we will consider that the ω_m value does not depend upon irradiation. In this case R_{ttr} (17) depends on irradiation only because during irradiation, in accordance with formula (14), value ω changes. In the table 3 the results of the voltage drop calculation at the transit-time part of SCR in dependence on neutron flux (Φ) at the current $I_{\lim}$ are presented.

Table 3

Neutron flux (Φ), cm^{-2}	Voltage drop at the transit-time part (U_{ttr}),V
0	0.7
1.0·1014	0.72
3.5·1014	–
7.3·1014	0.85
1.3·1015	0,93
1.6·1015	–
2.0·1015	1.1
2.5·1015	1.2

Using calculation data given in table 3 and experimental dependences $U_{bd}(\Phi)$ and $U_{\lim}(\Phi)$ (Fig. 3) it is possible to find the dependence of voltage drop at neutral base (U_{base}) on neutron fluence:

$$U_{base}(\Phi) = I_{\lim} R_{base}(\Phi) =$$
$$= U_{\lim}(\Phi) - U_{bd}(\Phi) - U_{ttr}(\Phi).$$

(20)

The dependence $\ln[U_{base}(\Phi)/U_{base}(0)]$ on neutron fluence (Φ) is presented in Fig. 8. The similar method of the dependence representation permits to exclude the poorly controlled values of d_{nb} and ω and to bring them to the dependence $\rho_{base}(\Phi)/\rho_{base}(0)$ by (18). Fig. 8 shows that for the investigated VL the relation $U_{base}(\Phi)/U_{base}(0)$ and consequently the relation $\rho_{base}(\Phi)/\rho_{base}(0)$ exponentially depend on neutron flux.

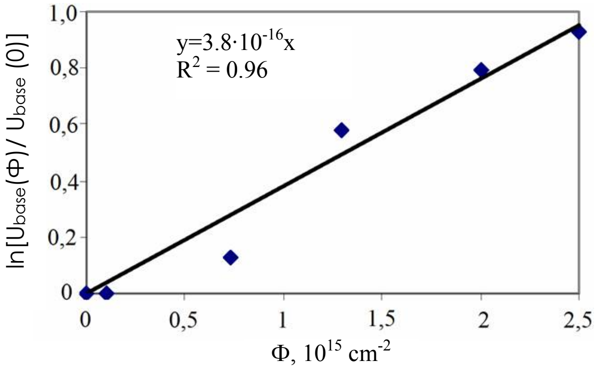

Fig. 8. Dependence $U_{base}(\Phi)/U_{base}(0)$ on neutron fluence

At that, for the VL $K_\rho = 3.8 \cdot 10^{-16}$ cm^2. This value of the coefficient K_ρ corresponds to the carriers removal rate under neutron irradiation (4) which is 7.6 cm^{-1} for *n*-type silicon used when making VL with $\rho_{base} \approx 0.3$ Ohm·cm. This carriers removal rate value is sufficiently near literature data [17]: $dn/d\Phi \approx 9$ cm^{-1} for silicon with $\rho \approx 0.3$ Ohm·cm, and it permits to consider that the proposed calculation procedure can be used for predicting of the radiation resistance U_{lim} – the most important parameter of VL. It is reasonable that for the similar prediction it is necessary the knowledge of the structure of *p-n* junction of VL, the electro physical properties of silicon on which it is prepared and also the K_ρ value of used silicon (or the carriers removal rate under irradiation).

CONCLUSIONS

As a result of study of neutron irradiation influence on the breakdown voltage (U_{bd}) and the limiting voltage (U_{lim}) of the silicon voltage limiters the following is established:

– the experimental dependences $U_{bd} = f(\Phi)$ and $U_{lim} = f(\Phi)$ for VL with the 50 V limiting voltage before irradiation are obtained;

– it is shown that the relation $U_{bd}(\Phi)/U_{bd}(0)$ practically does not depend on the breakdown voltage value of VL before irradiation;

– it is shown that in the relation $U_{bd}(\Phi)/U_{bd}(0) \approx [\omega(\Phi) / \omega(0)]^m$ (if $U_{rev} \sim U_{bd}$) the exponent "m" does not change after irradiation and is equal to ~ 0.84;

– it is shown that the coefficient K_ρ is the basic radiation parameter which forms the dependences $U_{bd} = f(\Phi)$ and $U_{lim} = f(\Phi)$ which determines the dependence of the concentration of basic charge carriers in silicon on neutron fluence;

– mechanisms which form the U_{lim} value after irradiation are determined;

– the model is suggested and is calculated which takes into account "smoothness" of the investigated *p-n* junctions and which makes it possible to predict changes in the breakdown voltage and limiting voltage which occur as a result of neutron irradiation of VL.

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ВЛИЯНИЕ НЕЙТРОННОГО ОБЛУЧЕНИЯ НА ПАРАМЕТРЫ КРЕМНИЕВЫХ ОГРАНИЧИТЕЛЕЙ НАПРЯЖЕНИЯ

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Влияние нейтронного облучения на напряжение пробоя ($U_{\text{проб}}$) и напряжение ограничения ($U_{\text{огр}}$) исследовано в кремниевых ограничителях напряжения. Коэффициент K_ρ является основным радиационным параметром, формирующим зависимости $U_{\text{прб}} = f(\Phi)$ и $U_{\text{огр}} = f(\Phi)$ и определяющим зависимость концентрации основных носителей заряда в кремнии от флюенса нейтронов. Определены механизмы, формирующие величину $U_{\text{огр}}$ после нейтронного облучения. На основе анализа полученных результатов предложена модель, позволяющая прогнозировать изменения напряжения пробоя и напряжения ограничения, которые происходят в результате нейтронного облучения ограничителя напряжения.

ВПЛИВ НЕЙТРОННОГО ОПРОМІНЕННЯ НА ПАРАМЕТРИ КРЕМНІЄВИХ ОБМЕЖУВАЧІВ НАПРУГИ

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Вплив нейтронного опромінення на напругу пробою ($U_{\text{проб}}$) і напругу обмеження ($U_{\text{обм}}$) досліджено в кремнієвих обмежувачах напруги. Коефіцієнт K_ρ є основним радіаційним параметром, що формує залежності $U_{\text{прб}} = f(\Phi)$ і $U_{\text{огр}} = f(\Phi)$ і визначає залежність концентрації основних носіїв заряду в кремнії від флюенса нейтронів. Визначені механізми, що формують величину $U_{\text{обм}}$ після нейтронного опромінення. На основі аналізу отриманих результатів запропонована модель, що дозволяє прогнозувати зміни напруги пробою і напруги обмеження, які відбуваються в результаті нейтронного опромінення обмежувача напруги.