INFLUENCE OF PRODUCTION TECHNOLOGY AND DESIGN ON CHARACTERISTICS NEUTRON-SENSITIVE P-I-N DIODES

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This paper presents the results of tests on neutron-sensitive p-i-n diode with local p-n junction, which allows to measure not only the integral dose by nonionizing energy loss (NIEL), but also the real-time dose and dose rate because of ionizing energy losses (IEL). The influence of design and process parameters and the lifetime of minority carriers on the radiation characteristics of the device considered. Sensitivity at low doses (from one to ten rad) is limited due to a decrease in the lifetime because of influence of lateral sides of cut. The sensitivity and accuracy of dose can be increased by moving of p-n junction away from the cut surface. The dependence of the voltage drop across the diode on the neutron dose irradiation up to 5 krad received, and the sensitivity was 2 - 3 mV/rad. We have demonstrated that replacement of the bulk p-i-n diode with total p-n junction by new diodes with local p-n junction allow for increase sensitivity, accuracy of dose and application in NIEL and IEL measurements simultaneously. Explanation for the extinction of a direct current through the diode with increasing doses of neutron irradiation proposed.

1. Introduction

The use of p-i-n diodes for determining of neutron dose by measuring parameters related to damage of the crystal structure of a semiconductor material under irradiation, is attractive due to the small size of the detector, a simple measuring circuit, a low (or zero) supply voltage, high mechanical strength. Despite the disadvantages of this method (fading, the temperature dependence, the dispersion), it is widely used in neutron dosimetry [1 - 7].

The measurement of the dose based on the effect of damages of the semiconductor detector material crystal structure in the interaction with neutrons, which in the case of p-i-n diode leads to increased forward voltage across the diode U_F with increasing doses of neutron irradiation. Formation of various point defects and defect clusters in silicon irradiated with neutrons leads to a change of two key characteristics of the material. First, a change in the concentration of deep levels in the band gap of silicon, which leads to a change in the lifetime τ of minority carriers in the base [8]. Second, a change in the effective concentration of shallow donors and acceptors, which leads to a change in resistivity ρ in the base [1]. Changing either of these parameters (ρ and τ) under irradiation contributing to the change in the current-voltage characteristics (I-V). Both parameter can influence on the accuracy of the dose, the sensitivity and the minimum threshold of the measured dose. And given the high sensitivity τ to the effects of technological factors, it is necessary to investigate its behavior in the manufacturing process of the diode, influence on the I-V characteristics of the diode and contribution to the error in determining the dose that was done in this study. In addition, it is important to know the influence of p-i-n diode geometry on the τ, to predict described above electrical and radiation parameters of the detector. Therefore, when designing the diodes we specified various geometries of the sensitive area of diodes to create different conditions for the generation-recombination processes in the edge regions. The studies were conducted during testing and experimental operation of several batches neutron-sensitive p-i-n diodes.

2. The bulk neutron-sensitive p-i-n diode with long base and total implanted layer.

The traditional structure of neutron-sensing p-i-n diode wth long base is presented in [1] and shown in Fig. 1. Initial material - silicon of zone melting (FZ) n-type with a resistivity $\rho_o \geq 10^3$ Ohm·cm, the samples with a thickness (length) of the base 1,2; 2,2; and 3,2 mm and a cross section of the base 1x1 mm were investigated. The lifetime of the initial silicon τ_o~300 μs. Formation of p-n junction (p +-region) conducted by ion implantation of boron totally over the whole surface of the wafer, the depth of the p-n junction was 0,8 μm. The wafers were divided into individual chips with a cross section 1x1 mm by cutting directly on the p-n junction. To reduce surface recombination and other negative consequences of cutting side surfaces of the crystal diodes were etched and protected with a special varnish. Minority carrier lifetime in the base, defined by [8] and the experimental data, was 10 μs. Diodes were irradiated in the central channel of the reactor BR-1 by neutrons with an average energy 1,25 MeV in quasistatic and pulsed mode.

The sensitivity of the diodes according to the data [1] was 200mV/Gy for a diode with a thickness of base 1,2 mm and increased with increasing thickness of the base.

One drawback of the design and technology is disruption of the p-n junction by cutting, which leads to an increase in dark current leakage through the p-n junction, the appearance of regions with increased generation-recombination activity in the p-n junction, the growth of the saturation current of the p-n junction I_S, which reduces the sensitivity of the diodes to violations introduced by neutrons, i.e., to raising the threshold for the detection of small doses. In addition, because of the large leakage current these diodes cannot be used for the measurement of ionization currents in reverse bias p-n junction for the detection of gamma-, X-rays or other ionizing radiation or particles.

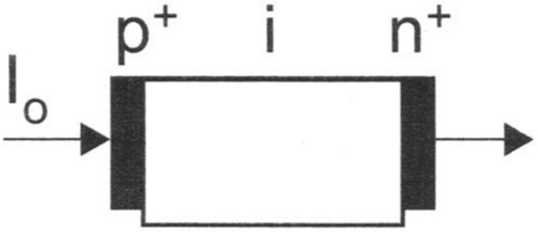


Fig. 1. Design of the bulk neutron-sensitive p-i-n diode with long base according to [1].

3. Design and technology of the new bulk p-i-n diode with local p-n junction

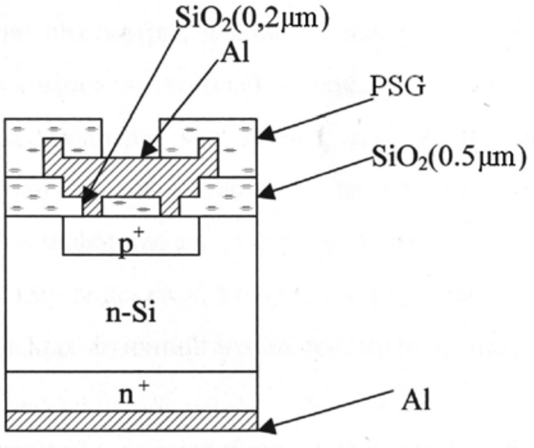


Fig. 2. Design of the new bulk neutron-sensitive p-i-n diode with thick base and local p-n junction.

Given the above, we have proposed the design of a neutron-sensitive p-i-n diode with the formation of a local p-n junction, using planar technology of integrated circuits (IC), shown in Fig. 2. To provide high sensitivity used high-resistance n-type silicon (FZ) with ρ_o~2 × 10^3 Ohm · cm, with an initial value of τ_o ~ 300 µs. Thickness of the base of the diode was 1200 µm. Cross-section of the crystal 1000 × 1000 µm. The boundaries of the p+-region moved away from the side surfaces (cutting planes) at 200 (300) µm, the size of the p+ region was 600 × 600 (400 × 400) µm, respectively (Table). Also, we have been made inspection lot diodes with n-type silicon of high quality with ρ_o = 1 kOhm · cm and an initial τ = 1700 µs and wafers thickness of 375 µm (see Table).

Technological features making p-i-n diodes, presented in Fig. 2 are described in [9 - 10], process provides high reproducibility of manufacturing the devices for leakage current, lifetime, breakdown voltage and other parameters due to processes through the use of soft-temperature conditions, cleaning, gettering impurities and suppress the defect formation. Fig. 3, *a* shows the crystal p-i-n diodes with different sizes of p+-region (600 × 600 and 400 × 400 µm), and Fig. 3, *b* - assembled neutron-sensitive devices.

Change in the lifetime of minority carriers in silicon at different stages of manufacturing p-i-n diode and neutron irradiation

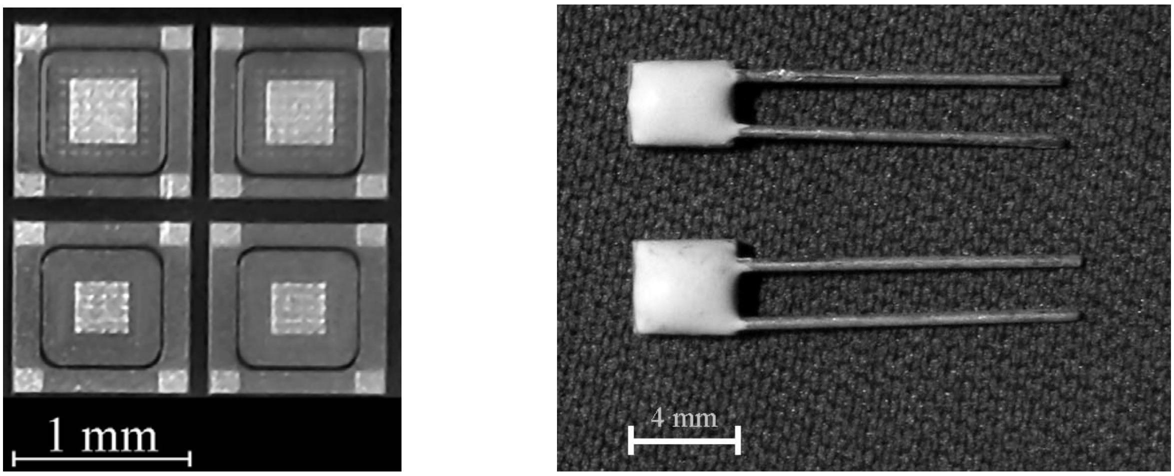
The geometry of the p-i-n diode	Minority carrier lifetime τ, µs				
The size of p +-region and wider. diode, µm	In the initial silicon, (ρ_o~2 KOhm × × cm)	After production (before cutting)	After cutting, the average over the diode	Without the contribution of cutting edges ***	After neutron irradiation **
400 × 400 × 1200	300	~275	23	190	10**
600 × 600 × 1200	300	~ 275	23	190	10
600 × 600 × 375	1700****	~1200	30	300	-
5000 × 5000 × 375	1700****	~1200	220	400	15
1000 × 1000 × 1200*	300****	~ 275	10	-	-

* p-i-n diode with the formation of p+-region of the p-n junction by implantation of boron totally over the whole surface and separated into chips by cutting (size 1000 × 1000 µm) [1].

** Neutron irradiation dose 3500 rad (E = 1,25 MeV).

*** Measurements at dipping of the cut diode in liquid polar dielectric with ε = 81.

**** silicon with a resistivity ρ_o~1,0 KOhm · cm.



a *b*

Fig. 3. Crystals of new p-i-n diode with thick base and local p-n junction (*a*) and assembled neutron-sensitive devices (*b*).

4. The lifetime of minority carriers in silicon at different stages of p-i-n diode manufacturing and neutron irradiation

Analysis of the results of the effect of geometry, technology and irradiation on the lifetime of minority carriers in silicon τ given in the Table, led to a number of conclusions about the relationship τ with these factors. From the Table it is clear that in comparison to the technology of total doping and cutting of the p-n junction, the technology of local p-n junction formation gives τ increase about 2 - 3 times (23 - 30 μs compared to 10 μs) by moving aside the boundaries of the p+-region from the edges of the crystal, even without any treatment side surfaces of the cut. In addition, measurements τ before cutting and after cutting the crystals show a very strong influence of this operation, leading to a decrease in τ on the order of magnitude (e.g., from 275 μs to 23 - 30 μs). On the other hand, dipping of the cut crystals in a liquid with a high dielectric constant increases τ and almost restores it to the original value (190 μs). These facts suggest the existence on the cut edges of crystal the regions with increased generation-recombination activity due to the presence of deep levels with high concentrations, making a major contribution to the reduction in the measured lifetime by generation-recombination processes (Fig. 5).

5. Effect of the lifetime on current of directly-biased p-i-n diode and shape of the I-V characteristic

The effect of lifetime on the currents of direct-biased p-n junction and shape of the I-V can be seen from Fig. 4, which shows the direct branch of the I-V studied p-i-n diodes with a different value of the lifetime: lower curves for the samples on the wafers before cutting (τ ~ 275 - 300 μs) and upper curves for the same samples after cutting (τ ~ 20 - 30 μs). It is seen that with decreasing τ I-V has shifted towards increasing of the "heel" and the decrease in the slope of the I-V.

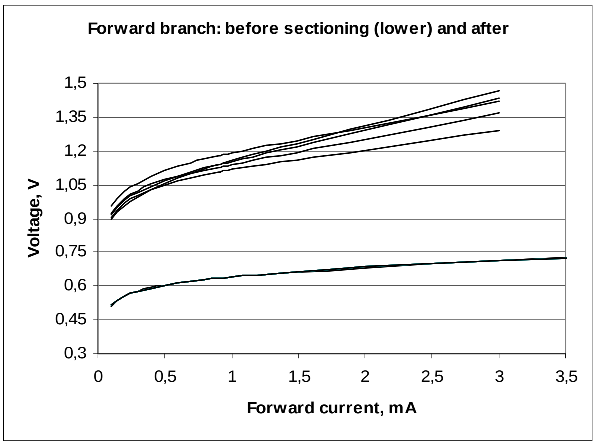


Fig. 4. Direct branches of I-V characteristics for p-i-n diodes with different value of the life time: before cutting (lower curves) and after cutting (upper curves).

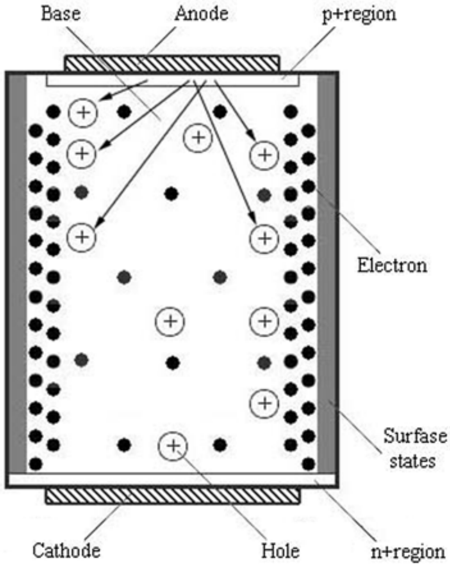


Fig. 5. The depletion of the base due to the effects of surface state at the cut sides leading to a decrease in conductivity base and preferential recombination of injected holes at the side faces. Arrows indicate the preferred direction of motion of the carriers.

Forward voltage U_F on pin-diode is the sum of voltages on p-n junction and on base (V_i) and is described by [11]:

$$U_F = U_{p-nS} + V_i = \varphi_T \ln \frac{I_F}{2qp_n \frac{DS}{\sqrt{D_p \tau_p}}} + \frac{3\pi kT}{8q} \exp\left(\frac{W}{2\sqrt{D_a \tau_a}}\right), \qquad (1)$$

where D_a – ambipolar diffusion coefficient; τ_a – ambipolar lifetime; $L_p = \sqrt{D_p \tau_p}$ for holes; p_n – hole concentration in the n-base; φ_T – temperature potential; I_F – current through the diode; W – width of the base of a diode; S – area of p+-region; expression $I_S = 2qp_n \frac{DS}{\sqrt{D_p \tau_p}}$ characterizes the saturation current, $L_a = \sqrt{D_a \tau_a}$ – ambipolar diffusion length.

Expression (1) shows that the voltage across the diode depends essentially as on the length of the base of diode, and on the lifetime τ. Similar relations for ΔU_F are given in [12]. When you use the right branch of a parabolic relationship, described in [12], for estimation ΔU_F under irradiation using the value of ratio W_b/L_a close to 2,75, get the value ΔU_F, harmonizing with the received experimental sensitivity at neutron dose measurements. According to given in [11, 12] dependences for our construction 600 × 600 × 1200 mm, τ at the point of conversion should be ≈ 190 μs, and at W_b/L_a = 2,75 - 100 μs, in this case original U_F will be about 0,6 V. A further increase in sensitivity of the diode is possible by increasing τ while maintaining (W_b/L_a = 2,75). The easiest way to increase τ is moving of p-n junction away from the cut surface of the crystal at the distance 3*L* considering τ, measured on a wafer. It is necessary to implement in the following modifications of the device. Really, the Table shows that for the diodes with the size of 55 × 0,375 mm, in which p-n junction is away from the cut surface at a distance 500 μm, has value of τ ~ 220 μs in comparison with 30 μs for the diode with the distance from the p-n junction to the cut surface 200 μm.

Described above the deep levels in the cut crystal surfaces also have the ability to capture the majority carriers, obtaining a negative charge, and thus depleting the base (see Fig. 5). This was evidenced by the increase in own base resistance, which turned out when it was measured, more than 30 % higher than the calculated value specified of the geometry of the crystal.

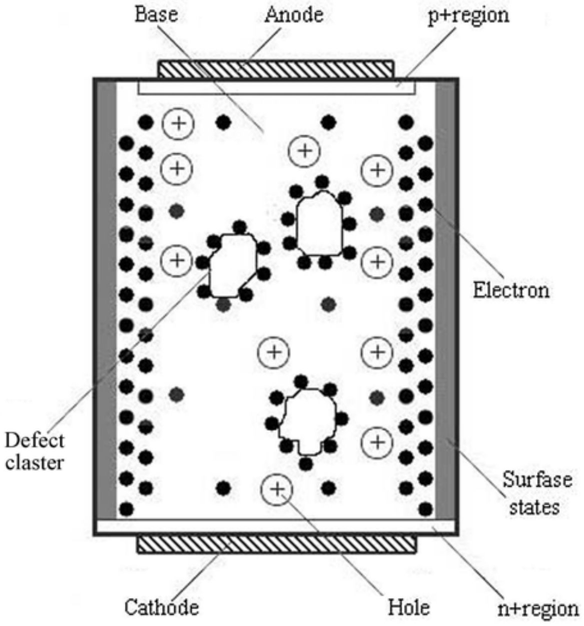


Fig. 6. Recombination of injected holes on defects and damage caused by radiation and on surface state at the cut faces.

The interaction with the flow of particles contributes to the semiconductor as point defects, and the whole cluster of disordering with the size of the space-charge region to 200 nm [13 - 14], (Fig. 6). These areas collect the majority carriers, immobilizing them, causing the growth of the resistivity and the increase in the recombination of minority carriers in the base, which reduces τ. Appearance of similar defects is expected also at the sides after cutting, as confirmed by the similarity of growth patterns U_F after cutting and after irradiation. With increasing doses of neutron irradiation effect is observed when the p-i-n diode is non-conductive, so that only an intrinsic current measurements are possible. According to the authors this is due to the fact that the concentration of clusters of defects increases with irradiation until they overlap over the section of base, so that the base is fully depleted region and does not pass current in direct inclusion as in the diode cannot begin the process of setting current. This effect was observed in diodes that have received large doses of neutron irradiation. For in this article pin-diodes, this effect occurs beginning doses of 3000 - 5000 rad. With further increase in the voltage across the diode can beginning field breakdown, leading to the appearance of the current in the diode just as is the case with latch-up.

6. Effect of the lifetime on characteristics of reverse-biased p-i-n diode and the measurement of ionizing energy losses

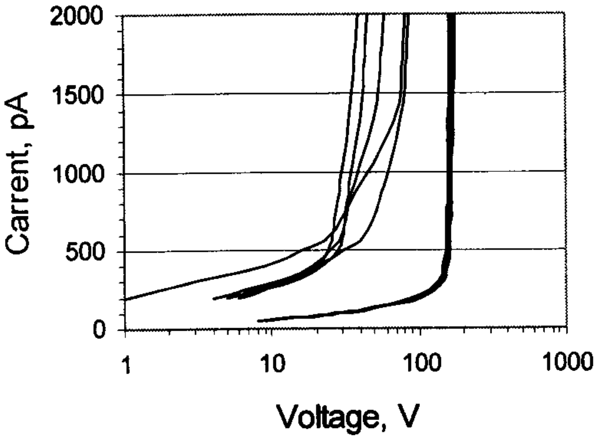


Fig. 7. Current-voltage characteristic reverse-biased p-i-n diode (size of the p+-region 600 × 600 mm^2).

Developed in this paper, the neutron-sensitive p-i-n diodes are also planned for the measurement of ionization currents in mode of reverse-biased p-n junction at the gamma-irradiation, X-rays or other ionizing radiation or particles.

In Fig. 7 shows the current-voltage characteristic reverse-biased p-i-n diode with the size of the p+-region of 600 × 600 mm^2, which shows that the decrease in τ after cutting has led to an increase in leakage current of p-i-n diode and their spread, reduce the breakdown voltage and the appearance of a soft (field) breakdown in prebreakdown area. If the initial leakage current is a few pA, after cutting it increased by an order.

Due to such low dark leakage current at a sufficiently low capacitance of diode (0,5 - 1 pF/mm^2) becomes possible registration of gamma-ray, X-rays with low energies in the spectrometric mode. In [15] presented minidozimeter used in low dose rate brachytherapy with isotope ^{125}I, in which was applied reverse-biased p-i-n diode (fully depleted) with cross-section base less than 1 mm^2, similar to that described above, which resolved ^{125}I isotope peaks in the energy range 22 - 35 keV when measuring the spectral characteristics. In [10] the results of spectrometry by pin-diode, with close to the above parameters (leakage current of ~ 10 pA/mm^2, capacity ~ 0,5 - 1 pF/mm^2), but has a relatively large capacity (~ 50 pF) which at the direct detection diodes of X-ray radiation of the isotope ^{241}Am resolved peak 59.5 keV. Thus, the use of local p-n junction allows dosimetry and spectrometry in real-time reverse-biased p-n junction, provided sufficiently small leakage currents. This allows to measure not only the integral dose by NIEL, but also the real-time dose and dose rate of IEL simultaneously by one diode.

7. Dose characteristics of p-i-n diodes under the neutron irradiation

Made p-i-n diodes were exposed by two sources of fast neutrons - reactor BR-1 with an average energy 1.25 MeV neutron doses up to 600 rad and reactor GIR - 2 with an average energy of 0.9 MeV neutron doses up to 5000 rad.

Prior to the exposure the diodes of the same type were divided into three groups. Group 1 consisted of a number of diodes, selected by the close values of τ and initial base R_{B0}. Group 2 consisted of a number of devices that simply satisfied the 20 % variation of electrical parameters. Both groups were exposed to low doses in the first reactor. The group division was to determine the influence of τ and R_{B0} scatter to repeatability of $U_F(D)$. The third group also consisted of diodes with a 20 % variation of electrical parameters and was exposed in the second reactor. Dosimetry support ensured track dosimeter DINA.

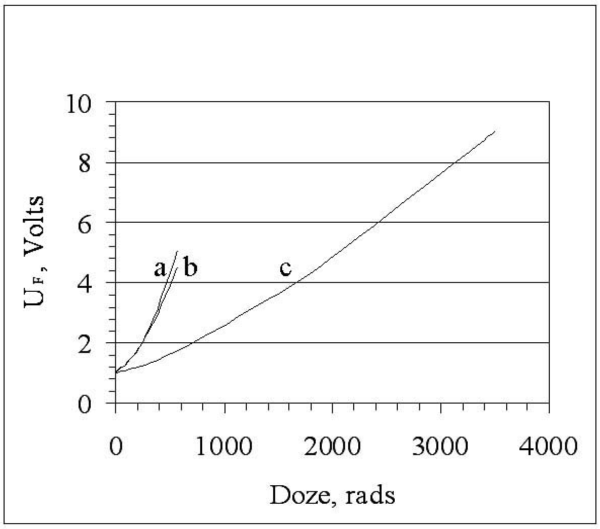


Fig. 8. The dependence of the forward voltage drop on the p-i-n diode on the dose of neutrons: *a* – the first group; *b* – second group ($E_{av\,n}$ = 1,25 MeV); *c* – the third group ($E_{av\,n}$ = 0,9 MeV).

The top difference of measured U_F in the first group was within 2 %, and U_F of the first group and the worse of the second – 13%.

Dependences of U_F on the dose of neutrons are different for different reactors. The slope of the curve (and hence sensitivity) determined by the spectrum of the neutron energy in the flow and flow power that are unique to each reactor. For example, in [7] was observed differences in the sensitivity of p-i-n diode under neutron irradiation in various reactors. But for a good repeatability of the dependence $U_F(D)$, that allows you to use a correction factor KERMA [16] for the dose correction, you can use the final random calibration of the devices used to make with the features of the energy spectrum of the neutron source for the measurements.

Also of interest is a dependence of R_{B0} on the dose. As can be seen from Fig. 9 base resistance first increased with increasing dose because of defects, leading to a decrease in the concentration of majority carriers in the base, and then the value of R_{B0} is stabilized as approaching intrinsic values [14, 17].

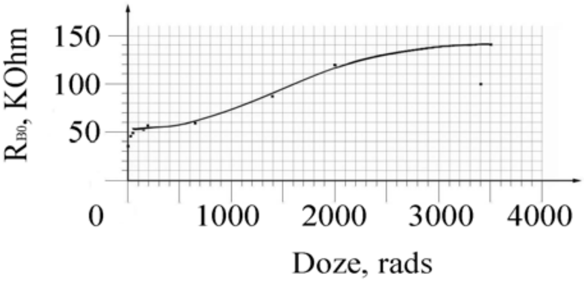


Fig. 9. The resistance of the p-i-n diode base on the dose of neutrons.

The measurement of the base resistance was carried out by the pulse method, by feeding the diode by an amplitude of 30 V, 1mA, registering drop voltage on the diode in conduction mode.

8. Conclusions

Restrictions of the bulk p-i-n diode with total p-n junction in the measurement of small neutron doses were analyzed. Presented the results of tests on neutron-sensitive pin-diode with local p-n junction, which allows to measure not only the integral dose by nonionizing energy loss (NIEL), but also the real-time dose and dose rate because of ionizing energy losses (IEL). The influence of design and process parameters and the lifetime of minority carriers on the radiation characteristics of the device considered. Sensitivity at low doses (from one to ten rad) is limited due to a decrease in the lifetime because of the influence of lateral sides of cut. The sensitivity and accuracy of dose can be increased by moving of p-n junction away from the cut surface. The dependence of the voltage drop across the diode on the neutron dose irradiation up to 5 krad received, and the sensitivity was 2 - 3 mV/rad. Replacement of the bulk p-i-n diode with total p-n junction by new diodes with local p-n junction allow for increase sensitivity, accuracy of dose and application in NIEL and IEL measurements simultaneously. Explanation for the extinction of a direct current through the diode with increasing doses of neutron irradiation proposed.

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