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Static and dynamic parameters trade-off of Si p-n–junctions irradiated by fast electron under reverse bias at low temperature (*77 K*)

ABSTRACT

Low temperature electron (E =4 MeV) irradiation influence on the static (forward voltage drop U_F) and dynamic (minority charge carriers lifetime τ_P) characteristics trade-off of diffused p-n–junctions manufactured on the basis of *CZ*-growth *P*-doped Si (ρ = 32 Ω·cm) has been investigated. The investigated samples were irradiated in passive and active modes of operation. Irradiation was performed at temperatures T_i = 77 K and 300 K.

It was established that passive mode irradiation at 77 and 300 K do not make differences in $U_F(j_F)$ dependencies. In the active mode irradiation there was the significant shift of the $U_F(j_F)$ dependency as compared with passive mode irradiation both at 300 K and 77 K. At 300 K irradiation this results in static and dynamic parameters trade-off

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deterioration (1.5 times) and at 77 K irradiation it results in trade-off improvement (1.5 times) as compared with passive mode irradiation.

The peculiarities of the $U_F(j_F)$ dependencies behavior during active mode irradiation are caused by primary defects charge state change into the spatial charge region (SCR) and by their drift in SCR electric field.

1. INTRODUCTION

The semiconductor devices (diodes, transistors and thyristors) can operate in fields of penetrating irradiation in different modes of operation with a reverse bias applied to a p-n–junction (strong electric field) or a current passing through a device (injection of charge carriers). The irradiation during operation can result in changing both the radiation defects (RD's) distribution type in a space charge region of p-n–junctions and the RD's accumulation rate in devices quasi-neutral base regions. The fact of the RD's profile formation in SCR during irradiation of the reverse biased p-n–junctions had been pointed out elsewhere in literature [1, 2], but its influence on the power device parameters was not investigated. But such results are of interest both for prediction of the devices parameters degradation during irradiation and for investigating the opportunity of regulating their static and dynamic parameters trade-off.

2. EXPERIMENTAL

In the given work the data gained during investigations of parameters of power diodes irradiated in different modes of operation (with applied reverse bias, during charge carriers injection and at different temperatures) are submitted. The p^+-n-n^+ structures manufactured on the conventional diffusion technology were used as samples in our investigations. Their area was 20 mm^2, the p$^+$-region depth was 100 microns, n-region

depth – 200 microns, n^+-region depth – 20 microns. The diodes irradiation was performed by the pulsed electron accelerator with electron energy $E = 4$ MeV, and on a gamma-rays Co^{60} irradiation installation. The electron beam pulse repetition rate was 200 Hz, one impulse duration was 5 mks, an electron beam average density was $2{\cdot}10^{12}$ electron.$cm^{-2}{\cdot}c^{-1}$. The irradiation intensity of the gamma-quantums irradiation installation was $5{\cdot}10^{11}$ quantum$\cdot cm^{-2}{\cdot}c^{-1}$. Samples were irradiated at irradiation temperature $T_i = 77$ and 300 K, in three modes of operation: in passive mode, with a forward current passing and with applied reverse bias. As the pulsed electrons beam intensity made $2{\cdot}10^{15}$ electron$\cdot cm^{-2}{\cdot}c^{-1}$ it was necessary during electron irradiation with applied reverse bias to allow for the influence of the non-equilibrium charge carriers (NCC) generation in SCR caused by electron beam on a resistance of a reverse-biased p-n–junction. It was experimentally determined that the SCR width during electron irradiation with applied reverse bias U_R equals the SCR width in electrons beam absence when we have utilized the voltage source with low output resistance ($R < 1\ \Omega$).

3. RESULTS AND DISCUSSION

The diode forward voltage drop (U_F) dependencies on the forward current density j_F (current-voltage characteristic) for samples irradiated in different conditions with electrons and gamma-quantums are submitted in Figure 1 and Figure 2. It is seen from the Figure 1 that the current-voltage characteristic of diode irradiated with gamma-quanta with applied reverse bias $U_R = -100$ V shifts in the field of the larger U_F values as compared with irradiation in passive mode and it shifts in the field of the smaller U_F values when irradiation was performed during current passage. It is seen from the Figure 2 that for diodes irradiated with electrons without the applied reverse bias (curves 1,1’) the current-voltage

characteristics behaviour does not depend on the irradiation temperature T_i. For samples irradiated with reverse bias applying such a dependence is observed. It is necessary to pay attention to the fact that the irradiation at T_i = 300 K and U_R = –100 V (curve 2) results in considerably larger U_F changes than at irradiation in passive mode (U_R = 0) providing diodes had the identical speed level (the NCC lifetime equals 1.8 μs for all cases of irradiation modes shown in Figure 2 and was measured by the Lax method at the high injection level.) The irradiation at T_i =77 K to the contrary, shifts the $U_F(j_F)$ dependence in the field of smaller U_F values improving thus the diode static and dynamic characteristics trade-off.

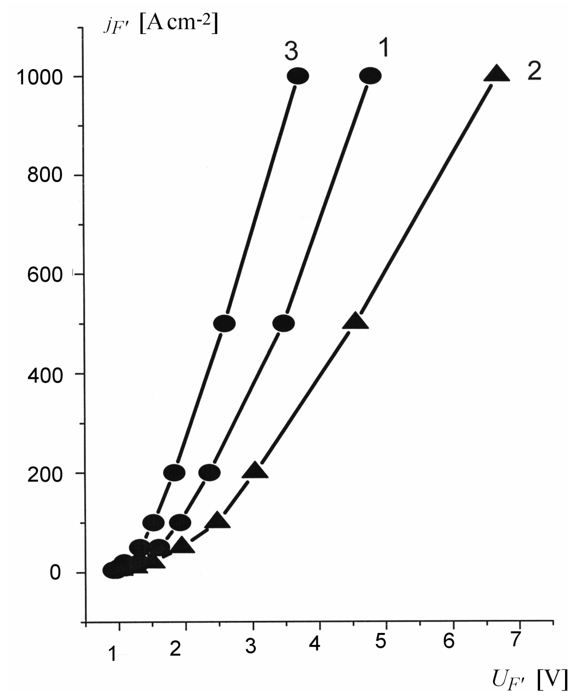

Fig. 1. Current-voltage characteristics of p-n–junctions, irradiated with gamma-quanta Co^{60}: $F = 8\cdot10^{16}$ Quantum cm^{-2}. 1 – without reverse bias; 2 – under reverse bias U_R = –100 B; 3 – forward current j_F = 20 $A\cdot cm^{-2}$ passage. T_i = 300 K. τ_p =1.8 μs

As it was shown in [3] the diode static and dynamic parameters trade-off depends on the effective recombination centers (RC) distribution pro-

file at the depth of the high-resistivity base. And the optimum static and dynamic characteristics trade-off is obtained in the case when RC concentration maximum can be created in the vicinity of a p-n–junction. The SCR electric field can essentially influence the accumulation of the basic radiation defects in this region as compared with their accumulation in the remaining part of a structure. The authors of [1, 2] consider that the basic reason of the lower vacancy-related RD's introduction efficiency (V–O – centers and divacances) in SCR consists in the change of the primary defects (vacancies and interstatials) charge state in this region (the vacancy becomes neutral instead of negatively charged as it is in the quasi-neutral region) and the probability of its annihilation with neutral or negatively charged interstatials and also their drift in SCR electric field into the most likely annihilation regions increases.

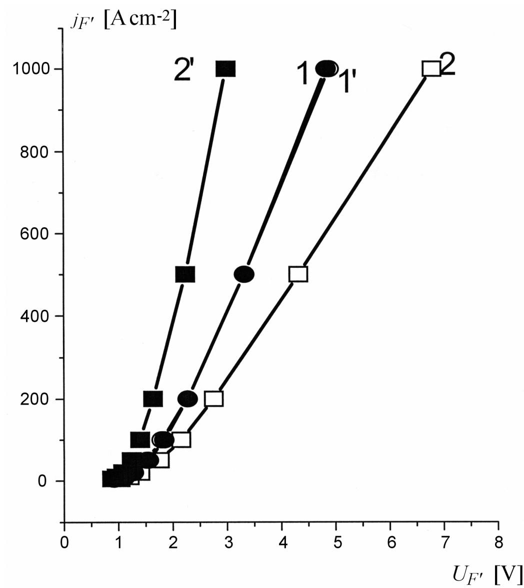

Fig. 2. Current-voltage characteristics of p-n–junctions, irradiated with electrons:1,1' – witout reverse bias 2,2' – under reverse bias $U_R = -100$ V. 1,2 – T_i=300 K, 1',2' – $T_i = 77$ K. $F = 1\cdot10^{15}$ cm^{-2}, $\tau_p = 2\cdot1$ μs

In this case the vacancy-related RD’s concentration decrease is observed in SCR as compared with their concentration in quasi-neutral region. At T_i = 77 K this dependence increases by a factor of more than 2 as compared with irradiation at T_i = 300 K. Taking into account the stated above the results obtained by us can be interpreted in the following manner. The reverse bias applying during irradiation, as it can be expected, should result in diodes static and dynamic characteristics deterioration in both cases of electron and gamma irradiation. It is related with the RD’s concentration decrease in the vicinity of p-n–junction. Accordingly to [1, 2] improving of a diode static and dynamic characteristics trade-off at diode irradiation in the injection mode is stipulated, apparently, by RD’s concentration increase in the vicinity of p-n–junction as the applied positive bias reduces the p-n–junction contact potential voltage that in turn reduces the SCR width. On the basis of data, obtained in [3] one can predict that irradiation of the reverse-biased diode at 77 K should result in more considerable deterioration of the static and dynamic parameters trade-off than its irradiation at 300 K. But as it can be seen in the Figure 2 the irradiation of reverse-biased diodes at the liquid nitrogen temperature (Fig. 2, curve 2’) results, contrary to the predictions, in the static and dynamic parameters trade-off considerable improving (almost on 50%) as compared with results of diode irradiation in a passive mode (Fig. 2, curve 1,1’).

To elucidate the above results we had measured the *C–V* dependencies of the investigated p-n–structures at the measurement temperature $T_M = 77$ K. At this temperature all deep RD’s levels in the upper part of Si forbidden gap are filled and from the *C–V* curve behaviour we can consider the RD’s concentration distribution in SCR. The SCR width dependencies (h_{SCR}) on the applied reverse voltage U_R calculated on the basis of measured *C–V* dependencies are shown in Figure 3 and 4. As it can be seen from the Figure 3 in the case of electron irradiation at $T_i = 77$ K with applied reverse bias $U_R = -100$ V (curve 2) the shift of the $h_{SCR}(U_R)$ curve to the curve calculated for the initial sample at $U_R > 0.5$ V

is observed. The curves for other modes of electron irradiation have the same form as for initial sample. All this allows one to consider that RD's concentration in the SCR depth for electron irradiation under reverse bias at $T_i = 77$ K are reduced in comparison with the other cases of electron irradiation. And this correlate with voltage-current characteristic behavior shown in Figure 1. But the reasons of such features in RD's accumulation at the given irradiation conditions are not quite understood by that moment.

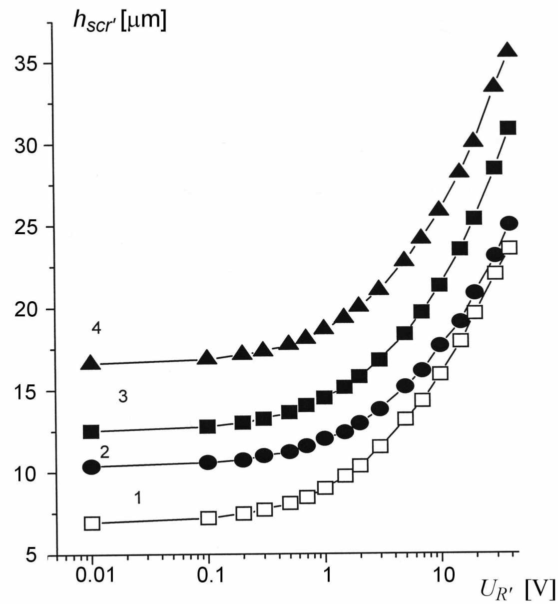

Fig. 3. Electron irradiated p-n–junctions space charge region width dependence on the applied reverse voltage. $T_M = 77$ K, $F = 1{\cdot}10^{15}$ electron·cm^{-2}, 1 – unirradiated sample; 2 – $T_i = 77$ K, $U_R = -100$ V; 3 – $T_i = 77$ K, $U_R = 0$ V; 4 – $T_i = 300$ K, $U_R = -100$ V. τ_p=1.8 μs

As for the gamma-quanta irradiation than in spite of differences in $U_F(T)$ dependencies (Fig. 1) for different modes of irradiation there are no differences in $h_{SCR}(U_R)$ dependencies behaviour that testify to the absence of significant differences in compensating impurities distribution in SCR. The comparison of dependencies shown in Figure 4, for electron

and gamma irradiated samples with the same τ_P value irradiated at room temperature in passive mode (curves 3 and 5 accordingly) indicates that in the case of electron irradiation the RD's concentrations in the vicinity of p-n–junction are higher than in the case of gamma-quantum irradiation. It can explain the well known fact that the utilization of electron irradiation instead of gamma-quantum irradiation allows one to gain the better devices static and dynamic parameters trade-off.

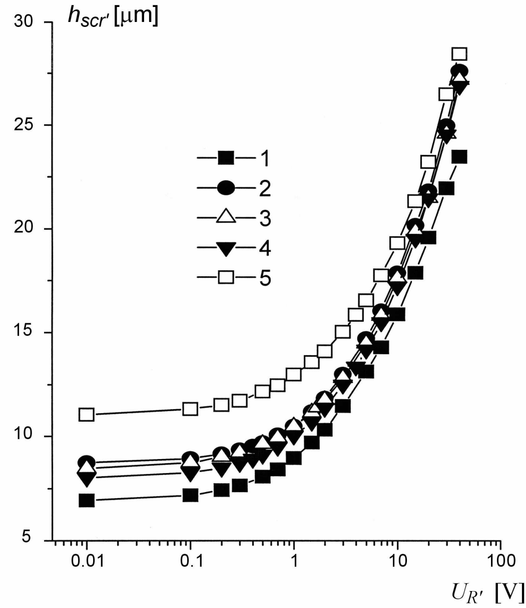

Fig. 4. Gamma-quanta irradiated p-n–junctions space charge region width dependence on the applied reverse voltage. T_M=77 K, T_i = 300 K; $F = 8{\cdot}10^{16}$ quantum·cm^{-2}, 1 – unirradiated sample; 2 – U_R= –100 V; 3 – , J_F = 20 A; 4 – irradiated in passive mode τ_p = 1.8 μs; 5 – electron irradiated in passive mode $F = 1{\cdot}10^{15}$ electron·cm^{-2}; τ_p = 1.8 μs

It is possible to explain the observed in this work absence of the correlation between voltage-current characteristics and $h_{SCR}(U_R)$ dependencies behavior and the contradiction of gained in this work data with those obtained in [1, 2] supposing that there exists the essential contribution in recombination processes in this case not only the vacancy-related com-

plexes, but also complexes containing interstatials alone and also by defects with energy levels situated in the lower part of the Si forbidden gap. For more complete understanding of the above data further investigations are required.

4. CONCLUSIONS

The work shows that the irradiation conditions influence consists in both the deterioration of the diode static and dynamic parameters trade-off and in its significant improvement.

ACKNOWLEDGEMENT

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