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ON THE CHARGE MULTIPLICATION MECHANISM IN SILICON RADIATION DETECTORS

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О механизме мультипликации заряда в кремниевых детекторах ядерных излучений

Проведен анализ экспериментальных данных, полученных при облучении различных типов кремниевых детекторов тяжелыми заряженными частицами в широком диапазоне их масс и энергий. Показано, что экспериментальные данные хорошо согласуются с моделью, основанной на накоплении заряда вблизи входного электрода детектора в процессе его собирания. Накопление плотного облака носителей тока приводит к кратковременному возникновению высокого электрического поля, которое может вызвать ударную ионизацию носителей тока.

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On the Charge Multiplication Mechanism in Silicon Radiation Detectors

The analysis of the experimental data obtained for different silicon detector types irradiated by heavy charged particles in wide range of its masses and energies was carried out. It is shown that the experimental results are in good agreement with model based on the charge accumulation close to entrance detector electrode in course of the charge collection process. The accumulation of the dense cloud of current carriers leads to temporarily creation of high electric field, which can cause an impact ionization of charge carriers.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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Two peculiarities significantly limiting the spectrometric performance of the silicon radiation detectors have been revealed at the registration of heavy charged particles. The first one is the pulse height defect caused by the loss of the generated carriers in the course of the charge collection process and by losses of energy converted to electron-hole pairs. Much attention has been paid to the investigation of the pulse height defect, and at present about one hundred papers have been published. The second peculiarity consists in the anomalous increasing of the pulse height, when the electric field intensity within the detector is many times smaller than the electric field intensity required for avalanche multiplication of the current carriers. This effect was called "the charge multiplication phenomenon". Systematic investigations of this phenomenon have not been carried out yet. The existing results on charge multiplication obtained with various detector types at the registration of different heavy charged particles can be found in the following publications [1-11]. To explain the multiplication mechanism a number of models has been proposed [2,5,7,9-11]. The main points of this models are as follows:

a) the charge multiplication is determined by electron tunneling injection from the metallic electrode through a thin oxide layer [2];

b) the charge multiplication is determined by impact ionization or by carrier injection in the high electric field arising due to accumulation of a dense cloud of charge carriers close to the entrance electrode of the detector in the course of the charge collection process [5,7,11];

c) the charge multiplication is determined by impact ionization in the high electric field arising at the pole of the extended ellipsoidal track [9,10].

At the same time, a detailed analysis of the obtained experimental results gives the possibility to distinguish the most probable mechanism of the charge multiplication phenomenon. Such analysis has been carried out in the present work. Assuming the identical nature of the multiplication mechanism in the different detector types, the tunnel electron injection from the metallic electrode can be excluded from consideration. This conclusion is based on the fact that the region of the high electric field at the p-n junction of ion-implanted detectors is at the distance of 500 - 2000 Å from the metallic electrode (for energies of the implanted ions - 15 - 50 keV [5]). The electron penetration probability through the barrier with the pointed out widths is practically equal to zero.

Let us consider the multiplication model based on impact ionization at the strong electric field arising at the extended ellipsoidal track pole [9,10]. The main suggestion of this model is that at the pole of the track the electric field intensity causing the avalanche multiplication of the carriers is equal to

$$F_m = \frac{R}{r_0}F, \qquad (1)$$

where R is the track length, r_o - the curvature radius at the ellipsoid pole, F - the field intensity in the unperturbed by track region of the space charge of the detector. Because the electric field distribution in the p-n junction is not uniform, the authors of ref.[9] have used the value of the electric field at a point related to the track pole which is determined by the relation

$$F = \frac{2V}{d(V)}(1 - \frac{R}{d(V)}), \qquad (2)$$

where V is the bias voltages applied to the detector, $d(V)$ - the width of space charge region ($d = k\sqrt{V}$, k - a constant for a given detector).

From the relations (1) and (2) for particles with energies E_i, E_k and ranges R_i, R_k the following expression can be written:

$$R_i F^i_{th} - R_k F^k_{th} = K(R_i^2 - R_k^2), \qquad (3)$$

where F^i_{th} and F^k_{th} are the threshold multiplication electric field intensities depending on the applied detector bias voltages, and K is a proportionality coefficient ($K > 0$). For example, if $R_k < R_i$, then it follows from eq. (3) that :

$$F^k_{th} < \frac{R_i}{R_k}F^i_{th}. \qquad (4)$$

From eq. (4) it can be concluded that the multiplication process for small range particles takes place at lower field intensities. The experiments show an opposite dependence - the charge multiplication starts at higher values of the field intensity for particles with shorter ranges.

In the model based on charge accumulation taking place close to the entrance detector electrode, the electric field intensity causing the charge multiplication is defined by the expression:

$$F_m = \frac{\sigma}{\epsilon\epsilon_0}, \qquad (5)$$

where $\sigma = Q/S$ is the surface density of the accumulated charge, ϵ and ϵ_0 are the relative electric penetrability of Si and the dielectric penetrability of vacuum, respectively, Q is the accumulated charge (the accumulated charge of holes in the case of detectors based on n-Si), $S = \pi r^2$ is the projection of the plasma column area on the entrance detector surface. If the variable r is assumed equal to the mean square root radius of the ambipolar diffusion determined by the formula

$$r^2 = 4D_a T_p, \qquad (6)$$

(here D_a is an ambipolar diffusion constant, T_p is the plasma time) and if the dependence of the plasma time on the particle parameters and on the intensity of the electric field acting on the track according to [12] is supposed have the following form

$$T_p = k(\frac{E^2}{R})^{1/3}F^{-1}, \qquad (7)$$

then, we can write

$$F_m = K(ER)^{1/3} F_{th}, \tag{8}$$

where K is a proportionality coefficient, and F_{th} - the threshold field intensity in the detector. According to (8) the following ratio

$$\frac{(E_i R_i)^{1/3}}{(E_k R_k)^{1/3}} = \frac{F^k_{th}}{F^i_{th}} \tag{9}$$

can be written for particles with energies E_i, E_k and ranges R_i, R_k. The predictions of this model are in a good agreement with experimental results. Evidences of this statement are presented bellow. Here it is worthwhile noting that the expression (9) gives the possibility to obtain not only qualitative conclusions on the multiplication mechanism but also to obtain quantitative estimations.

The threshold electric field intensity as a function of $(ER)^{1/3}$ earlier obtained by us and reported in [7] for of two surface barrier detectors irradiated by monoenergetic ^{40}Ar ions in the energy region 175 -320 MeV are shown in Fig.1.

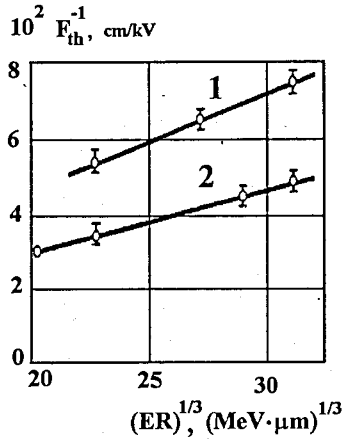

Fig.1. Inverse threshold electric field intensity as a function of $(ER)^{1/3}$ parameter for ^{40}Ar ions (1-$\rho = 500$ Ohm·cm, 2 -$\rho = 245$ Ohm·cm)

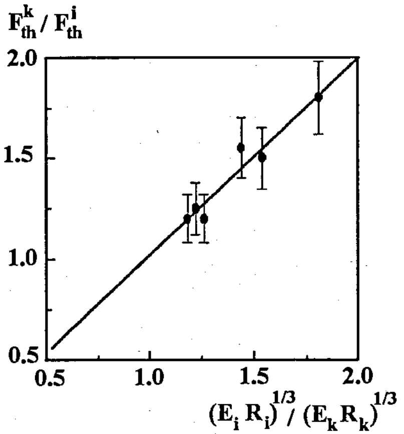

Fig.2. Threshold electric field intensity ratios as a function of the $(ER)^{1/3}$ ratios for ^{16}O ions (Data taken from work [13])

From Fig.1 one can see that the experimental dependence corresponds to the one expected from (8), i.e. the dependence of the threshold electric field intensity on the particle parameters satisfies the multiplication model based on charge accumulation in the course of the collection process. Another very important experimental fact, confirming the mentioned above suggestion, is also reported in ref. [7]. This fact means that the threshold multiplication intensity is lower for channeling particles with longer ranges in comparison with the one for the same type of particles registered in the same registration conditions but not channeling.

The investigations of the multiplication in silicon epitaxial detectors irradiated by spontaneous fission fragments [11] have also shown that the experimental threshold field intensities ratio for heavy and light fission fragments satisfies relation (9). The experimental ratio F^h_{th}/F^l_{th} is equal to 1.17 ±0.05. It is in a good agreement with the calculated value $(E^l R^l / E^h R^h)^{1/3}$, amounting to 1.19 (the scripts l and h are related to light and heavy fission fragments, respectively).

We have obtained the next experimental evidence of this multiplication mechanism from the experimental data shown in ref. [13]. In this work the pulse height response for monoenergetic ^{16}O ions was studied in ion-implanted silicon detectors with high internal electric field. The threshold electric field intensity ratios as a function of the $(ER)^{1/3}$ ratios are shown in Fig.2 for ^{16}O ions in the energy range from 2.804 to 8.085 MeV. The fluctuations of the points in Fig.2 are caused by inaccuracy at transferring these points from [13], where the values of electric field intensities are given in a logarithmic scale. Due to this reason the value of the error bars for threshold field intensities was taken equal to 10%.

Thus, the analysis of the accessible experimental information carried by us shows that accumulation of a dense cloud of current carriers at the entrance detector electrode is the most probable reason responsible for the charge multiplication process. The accumulation of the dense cloud of current carriers leads to the creation of a high electric field, which can cause an impact ionization or a carrier injection. It is quite probable that the observed in experiments [8,11] fine structure in the pulse height distributions of multiplied signals appears as a consequence of the combined effect of the suggested above charge multiplication mechanisms. From our point of view, the further experimental investigation of charge multiplication in semiconductor detectors is of significant interest for the physics of hot carriers as well as for clarifying the charge multiplication mechanism itself and for selection of optimal detector operating conditions.

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References

1. H. C .Britt, H. E. Wegner, Rev. Scie. Instr. **36** (1963) 627.
2. F. J. Walter, IEEE Trans. Nucl. Scie. **NS-11** (1964) (3) 232.
3. E. Belcarz, P. Siffert, JINR communication **13-74-90**, Dubna (1974).
4. V. F. Kushniruk, Yu. P. Kharitonov, Prib. Tekh. Exper. **4** (1977) 76.

5. H. M. Heijne, E. Belcarz, J. C. Muller, IEEE Trans. Nucl. Scie. **NS-25** (1978) (3) 378.
6. A. A. Alexandrov et al., "Metody experimentalnoy yadernoy fiziki v issledovaniyah processov i produktov deleniya", Moscow, Energoatomizdat (1983) 33, in Russian.
7. V. F .Kushniruk, Thi Ha Guin, Yu. S. Tsyganov, Prib. Tekh. Exper. **3** (1989) 57.
8. Yu. Tsyganov, V. Kushniruk, A. Polyakov, JINR preprint **E7-95-388**, Dubna (1995).
9. E. M. Verbitskaya et al., Fis. Tekh. Poluprovod. **24** (1987) (8) 1388.
10. Yu. S. Tsyganov, JINR communication **P15-89-107**, Dubna (1989).
11. V. F. Kushniruk et al., JINR preprint **P13-96-36**, Dubna (1996).
12. W. Seibt, K. Sundsrtom and P. Tove, Nucl. Instr. and Meth. **113** (1973) 317.
13. J. von Borany, B.Schmidt, R.Groetzschel, "The application of high energy ion implantation for radiation detectors", submitted to Nucl. Instr. and Meth. **A**.