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The Current-voltage Characteristics Simulation of the Betavoltaic Power Supply

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In order to optimize betavoltaic power supply it was calculated the current-voltage characteristics when changing the depth of the upper *p*-layer and at changing doping levels structure areas. It is shown that an increase in the depth reduces the short-circuit current and thus reduces the open circuit voltage. It has been observed that the concentration of the lightly doped region more significantly influence on the current-voltage characteristics than the depth of the *p-n*-junction. The concentration of the n-region, equal to 10^{14} cm^{-3}, can be considered as during betavoltaic power supply design. It is shown that, by increasing the power supply activity the conversion efficiency of the structure increases, too.

Keywords: Betavoltaic effect, Beta power source, Betavoltaic battery, *p-i-n* diode, I-V characteristic simulation.

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1. INTRODUCTION

Betavoltaic power supplies were begun actively to explore in the 1950 s, one of the first power sources P. Rappaport described [1]. The main advantage of such sources compared to chemical sources is high energy consumption, long service life (determined by half-life of the isotope source) and reliability. All this leads to the conclusion that the creation of radiation-induced power supply and, as a particular problem, the betavoltaic effect investigation are very promising research direction.

Today in the world betavoltaic power sources based on different materials and radionuclide ^{63}Ni are being developed [2-7]. Beta Energy electron emitting by isotopes, ranges from 0 to 66.7 keV with the mean value – 17.1 keV, and the specific ^{63}Ni activity can reach 57 Ki/g [8]. In spite of the low energy density of the isotope ^{63}Ni, its above mentioned properties allow to combine the power supply at its base with capacitors and electrochemical batteries, which opens up new prospects for the use them in stand-alone power systems. Obviously, the computer simulation of the electrons absorbed energy, the process of charge transport and recombination allows, to determine the optimal values of the main structural and technological parameters such as the depth of the *p-n* junction, the substrate doping level, etc.

In order to optimize physical and topological structure betavoltaic power sources based on different materials the simulation program of voltage characteristics was developed. It is written based on Borland Delphi 7 language.

2. EXPERIMENTAL PROCEDURES

Creating effective radiation-induced power supply requires consideration of a number of factors that affect the process of the current formation. Simultaneous consideration of the absorption electrons energy the transfer of generated charge carriers and their recombination, is not possible without a computer simulation.

When considering different ways to describe the distribution for simulation energy of electrons the generation in a semiconductor structure it was accepted the analytical model of electron-hole pairs generation, proposed in [9].

The electron beam with the extension of the profile can be modeled by an analytical expression:

$$G(r) = G_0 \cdot F(x,y,z,E) \cdot h(z,E), \qquad (1)$$

where G_0 – the general generation rate given by:

$$G_0 = \frac{E \cdot I_b(1-k)}{qE_i}, \qquad (2)$$

where E – energy of electrons; I_b – electron beam current; q – electron charge; E_i – the energy required for the formation of electron-hole pairs; k – the proportion of electrons lost on backscatter.

The function takes into account the lateral distribution of the generation rate of electron-hole pairs, for example, for silicon it is described by:

$$F(x,y,z,E) = \frac{1{,}76}{2\pi\sigma R}\exp\left[-\frac{x^2+y^2}{\sigma^2}\right], \qquad (3)$$

where

$$\sigma^2 = 0{,}36d^2 + 0{,}11\frac{z^3}{R}, \qquad (4)$$

where d – diameter of the electron beam and R – the total depth of the electron path. The penetration depth of the electrons energy dependents on energy and can be described by the expression:

$$R = \frac{3{,}98 \cdot 10^{-2} \cdot E^{1{,}75}}{\rho}, \qquad (5)$$

where ρ – material density.

Function h (z, E) – describes the distribution depth of the electron-hole pair generation rate and can be approximated by normalized expression

$$\Lambda(\zeta) = 0,6 + 6,21 \cdot \zeta - 12,40 \cdot \zeta^2 + 5,69 \cdot \zeta^3, \quad (6)$$

where ζ – the depth normalized to the full electron penetrating depth $\zeta = z / R$ in area $0 < \zeta < R$.

Then it was calculated radiation-induced currents using transport equation and on the boundary of the space charge. The drift current in the space charge is calculated using the expression [10]:

$$J_{dr} = -q \int_0^{W_{SCR}} G(x) dx . \quad (7)$$

Then the total structure current, created by β-emission can be calculated:

$$J_R = J_{dr} + J_p + J_n , \quad (8)$$

The leakage current in theoretical calculations of two components: the diffusion of the quasi-neutral regions and the generation-recombination:

$$I_S = I_{dif} + I_{g-r} . \quad (9)$$

The efficiency of *p-i-n*-structure is calculated from the ratio

$$\eta = \frac{I_m U_m}{P_{in}} , \quad (10)$$

where P_{in} – incoming power emission.

3. RESULTS AND DISCUSSION

In this paper it is given the example of the silicon structure investigation with the following parameters: total thickness of 40 microns SiO_2 thickness of 20 nm, dopant concentration of the heavily doped layers is taken to be 10^{18} cm^{-3} concentration in the lightly doped *n*-type region varied from 10^{12} to 10^{16} cm^{-3}, lifetime in accordance with [11]. The area of the structure adopted for the calculation of 1 cm^2. As an initial structure for the simulation it was taken the structure shown in Fig. 1.

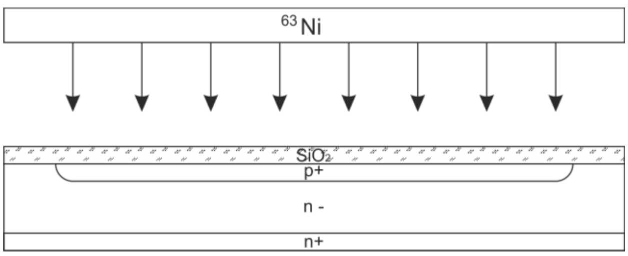

Fig. 1 – Silicon *p-i-n* structure

For the currents and voltages of betavoltaic power source simulation it is necessary to know and use in calculating the entire electrons spectrum, including the electron energy distribution. In work it was carried out the investigation with the use of the experimental spectrum distribution of the electron energy flux of the radiation source ^{63}Ni presented in [12].

Since the electrons flow from the ^{63}Ni radioisotope depends on the thickness of the sample, it is important to consider this point in the simulation. In [13] evaluated the maximum film thickness ^{63}Ni, with which the electron yield.

The most effective separation of charge carriers takes place in the space charge region (SCR) *p-n*-junction, so the bulk of the beta particles must stop in SCR rather than in the surface layer. With increasing depth from 0.1 to 0.5 mm the value of current is reduced, but not significantly, since at high enough lifetimes only redistribution of areas contribution occurs. A significant performance loss begins at a depth greater than 1 micron.

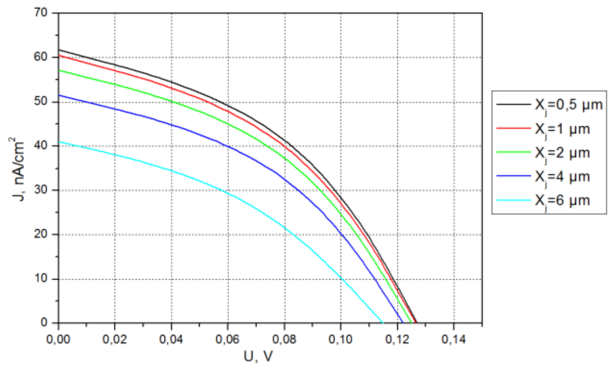

Fig. 2 – The dependence of the generated current in the structure vs voltage

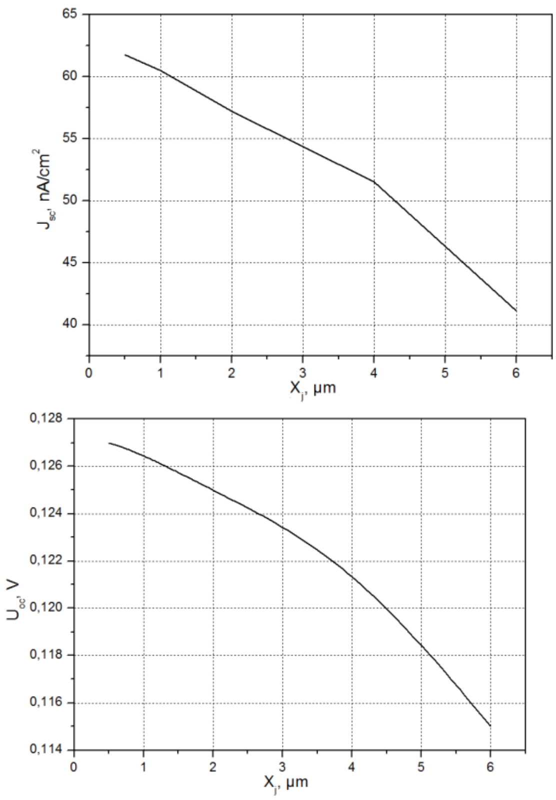

Fig. 3 – Dependence of the short-circuit current and open circuit voltage on the *p-n* junction depth

The depth of *p-n*-junction varied from 0.5 to 6 micrometers, the concentration in the *n*-layer is 10^{12} cm^{-3}, the ^{63}Ni radioisotope activity 2,7 mCi/cm^2.

Fig. 2 shows that the increase in the depth of the *p-n* junction reduces the short-circuit current and, therefore, the open circuit voltage. It is caused by the fact that the reduced contribution of current that is generated in the SCR due to its distance from the surface and thus decreases the number of generated charge carriers therein. However, increasing the *p*-region contribution due to its expansion and increase the number of carriers generated therein. At the same time, at a sufficiently high lifetime and a small *p*-layer thickness the number of carriers, which have reached the SCR increases.

The dependence of the current-voltage characteristics on the concentration in a weakly doped *n*-layer. In order to optimize the structure parameters it was investigated the influence of the doping level areas without changing the series resistance and spreading resistance. Influence of areas doping level depends on two parameters – change the width of the space charge region and changes in the characteristics of the semiconductor material, such as the lifetime and charge carriers mobility.

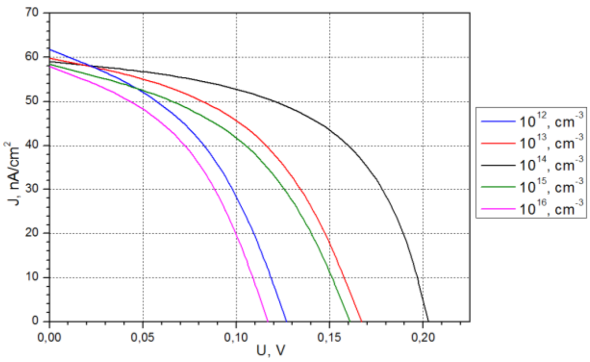

Fig. 4 – Dependence of the current generated in the structure vs voltage

The *p*-*n*-junction depth – 0.5 microns. The concentration in the n-layer was varied from 10^{12} to 10^{16} cm^{-3}, the radioisotope ^{63}Ni activity 2,7 mCi/cm^2.

Influence of the carrier concentration in the n-layer on the current-voltage characteristics is more important than the depth of the *p*-*n* junction. Despite the fact that the short circuit current is changed slightly, the open circuit voltage is changed significantly. It is caused by a change in the generation component of the reverse current, changing the width of the space charge region. At concentrations less than 10^{14} cm^{-3} the major contribution into the generation of reverse current component width SCR contributes and lifetime changes slightly, that leads to overall decrease in the current generation and as a result, the open circuit voltage increases. At concentrations higher than 10^{14} cm^{-3} the decrease of the lifetime makes a major contributor to a generation component and reverse current load voltage begins to decline significantly. Thus, for describing a number of concentration the value 10^{14} cm^{-3} can be considered optimal.

It was investigated the influence of the used radio isotype activity on the electrical characteristics. Fig. 6 shows the change in the current-voltage characteristics at different ^{63}Ni radionuclide activity.

The *p*-*n*-junction depth – 0.5 microns, the concentration in the *n*-layer of 10^{12} cm^{-3}, the activity of the radioisotope ^{63}Ni varied from 1 to 10 mCi/cm^2.

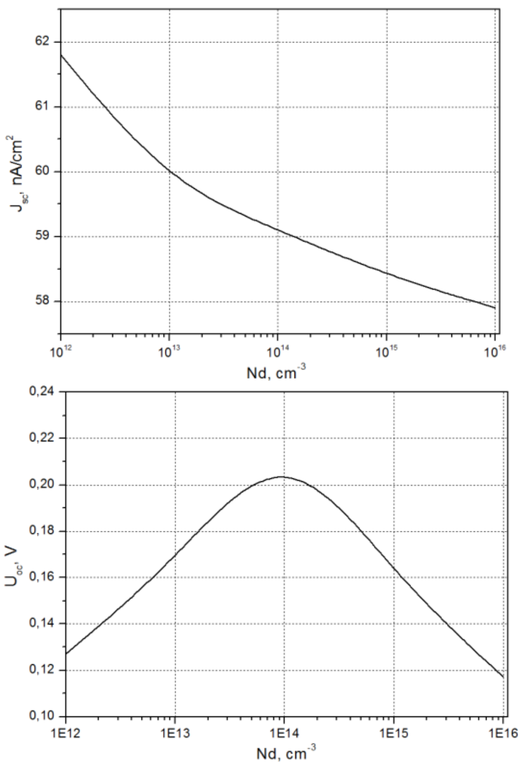

Fig. 5 – The dependence of short circuit current and open circuit voltage on the concentration of the lightly doped *n*-layer

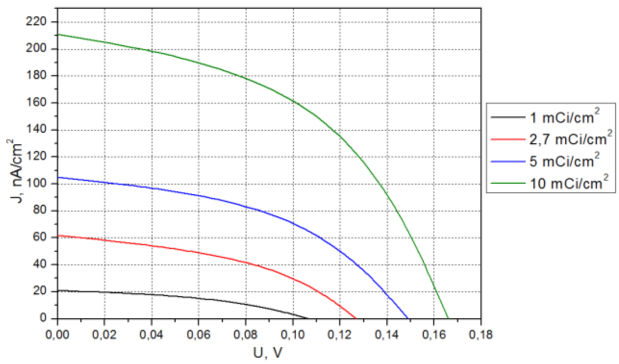

Fig. 6 – The dependence of the current generated in the structure of the voltage

Fig. 6 indicates that by increasing the activity of radionuclide ^{63}Ni the short circuit current significantly changed and, as a result, the open circuit voltage, too.

By increasing the source activity of 1 to 10 mCi/cm^2 the short circuit current linearly increases, and the open circuit voltage, too, accordingly, the efficiency of conversion. This is due to the increase in the ratio between short-circuit and reverse leakage current. By increasing the generation current caused by beta particles, the reverse current does not change, and it allows to make the following conclusion: by increasing the activity of radionuclide ^{63}Ni conversion efficiency will increase.

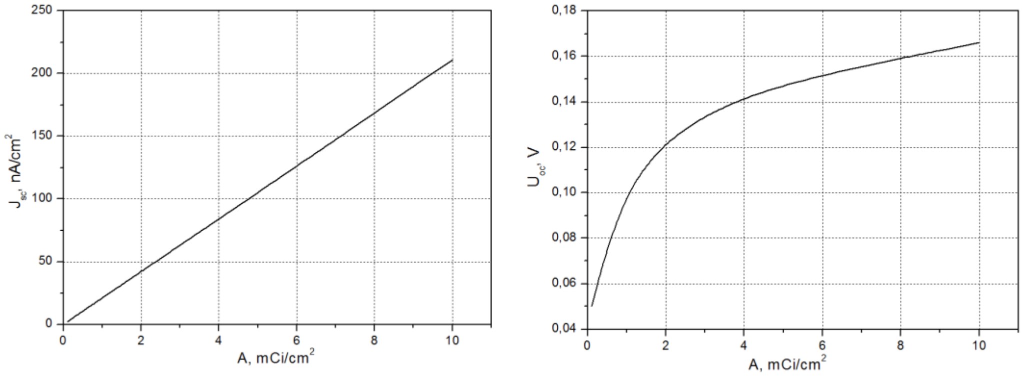

Fig. 7 – Dependence of the short-circuit current and open circuit voltage of ^{63}Ni radionuclide activity

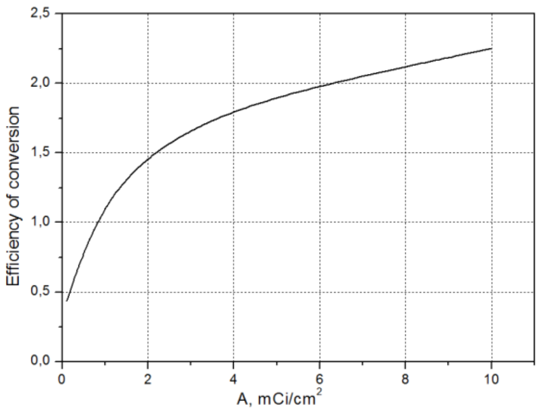

Fig. 8 – Dependence of the conversion efficiency of ^{63}Ni radionuclide activity

4. SUMMARY

In order to optimize the parameters of physical and topological structure of silicon betavoltaic power sources calculated the parameters of betavoltaic converter depending on changes in the upper p-layer depth, the doping level of *n*- layer and the ^{63}Ni radioisotope activity.

As a result of simulation features of betavoltaic converters it was detected: Increase in depth from 0.1 to 0.5 microns has practically no effect on the characteristics of the converter, and a noticeable reduction in performance begins with increasing depth greater than 1 micron. Influence of concentration on the current-voltage characteristics is more significantly than the depth of the junction, while the short circuit current is changed slightly, but the open circuit voltage significantly. For a number of concentrations the value of 10^{14} cm^{-3} can be considered optimal. Source activity increase leads to converter efficiency rise.

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