Simulation the Beta Power Sources Characteristics

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In this paper the simulation of silicon beta-stimulated power sources spectral sensitivity characteristics was carried out. It was analyzed the influence of the semiconductor material characteristics (the doping level, lifetime) and power supply design on the photosensitive structures characteristics in order to optimize them.

Keywords: Betavoltic effect of power beta source, Modeling the characteristics of the spectral sensitivity, Design optimization.

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1. INTRODUCTION

Beta-voltaic effect was discovered in the 60-70-s of the last century, but in recent years the interest in it has grown significantly due to the prospects of implementing the technology of microelectromechanical systems (MEMS). Energy sources advantages on the basis of radioisotopes are: long life (over 10 years depending on the isotope), low weight, small size, wide temperature range and high reliability. That is why the creation of radiation-stimulated energy sources and, as a particular problem, the beta-voltaic effect study seems the actual task [1].

Creating batteries with beta-^{63}Ni isotope is extremely promising area of research for several reasons. Firstly, the beta electron energy ranged from 0 to 66.7 keV with the average value 17.1 keV. These energies lie below the defect range, and can not lead to defects and to destruction of the crystal silicon structure. Thus, while the work unit time will be determined only by the time the beta source decay (for ^{63}Ni – 100 years). Secondly, even electrons with a maximum energy of 66.7 keV can not penetrate human skin layers and thereby cause significant harm. The number of carriers generated by one beta electron, ranges from 4 500 to 17 500 electron-hole pairs at energies of 17.1 and 66.7 keV, respectively. Third, despite the low energy density of ^{63}Ni (0.1-1 mW/cm^2), it can be used in microbatteries with a capacity < 200 nW/cm^3 [1].

Ways of improving the energy conversion efficiency were the selection of structures with higher band gap than that of silicon. For example, p-n junctions are used and based on GaN, GaAs and SiC, which will improve the structures electromotive force compared to silicon structures. Another way to increase efficiency is using silicon structures, which increase the p-n junction usable area [2-6].

Thus, the problem of simulation of radiation-stimulated current source for a structures types, defining the basic parameters affecting the effectiveness and efficiency of the source, as well as the most effective structures calculation are extremely important. [1].

The analysis carried out in [1] shows that on the basis of semiconducting materials requirements, the best option for structures betavoltic effects are silicon diodes for low-doped substrates with low surface layer.

Creating effective radiation-induced power supply source requires consideration of factors number that affect the current formation process. Simultaneous consideration of the electrons energy absorption, the transfer of charge carriers generated and their recombination, including recombination at the surface and boundaries of the layers requires computer modeling [7].

2. EXPERIMENTAL PROCEDURES

In order to optimize physical and topological structure of beta-silicon power supplies the program for spectral characteristics simulation was developed.

Simulation sensitivity silicon photosensitive structures simulation was performed by solving the basic system of equations: Poisson equation, the continuity and the transfer of electrons and holes equations [7].

In the numerical solution of the basic equations the original differential equation in partial derivatives are presented in the difference form.

Taking the boundary conditions at the fields edges and giving initial distribution of mobile charge carriers, it was obtained a nonlinear equations system. Thus, instead of differential equations, it is necessary to solve a nonlinear algebraic equations system.

If it is necessary, for the linear algebraic systems solution with matrices, containing some non-zero elements, matching has been used successfully [8, 9].

The program was developed using the language Borland Delphi 7 [10].

A large paper quantity are devoted to the electron range simulation [11-14]. Programs have been developed for calculating the electron ranges including Monte Carlo method [11]. The authors of [12-14] carried out simulation of energy release.

When considering different ways to describe the energy release distribution for the simulation electron generation in a semiconductor structure it is most convenient the analytical model for the electron-hole pairs generation, proposed in [15].

Electron beam with the profile extension was simulated analytical expression:

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

where G_0 – total generation rate, which is given by:

$$G_0 = \frac{E \cdot I_b (1 - k)}{q E_i}$$

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

Using the known parameters and the k value = 0,08 for silicon expression (2) can be rewritten as

$$G_0 = 1{,}6 \cdot 10^{18} \cdot E \cdot I_b$$

The function of the lateral velocity electron-hole pairs generation distribution for silicon is

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

where

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

where d – the electron beam diameter and R total depth electrons path.

The penetration depth depends on the energy and can be described by the expression:

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

where ρ – density of the material to silicon of 2.33 g/cm³.

Function $h(z, E)$ – gives the distribution depth for the electron-hole pairs generation rate and can be approximated by a normalized expression:

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

where ζ – depth, normalized to the total depth of electron penetration $\zeta = z / R$ in the range $0 < \zeta < R$.

The concentration electron-hole pairs distribution was calculated using the normalization to the total amount of generated pairs G_0.

The result is a electron-hole pairs distribution generation rate in the p-i-n structure.

For the semiconductor layers characteristics calculation database from Ioffe Institute was used [16]. To determine the sensitivity dependence it was set the energy range from 0 to 66.7 keV (electrons emission spectrum from ⁶³Ni), and in each monochromatic field of spectral range current was measured. Moreover, in order to analyze the physical processes occurring in the structure, and then optimize the structure is determined separately the radiation-induced currents generated by externally p- and n- regions and by space charge region [17]. It was set the 0.1 mW/cm² flux, corresponding to the range of the ⁶³Ni radiation power. As a result, the spectral sensitivity distribution was obtained in the units A/W. p-i-n-structure efficiency is calculated from the ratio [17]:

$$\eta = \frac{I_m U_m}{P_{in}},$$

where P_{in} – the power of the input radiation; I_m and U_m – are obtained from the condition of the maximum energy converter power.

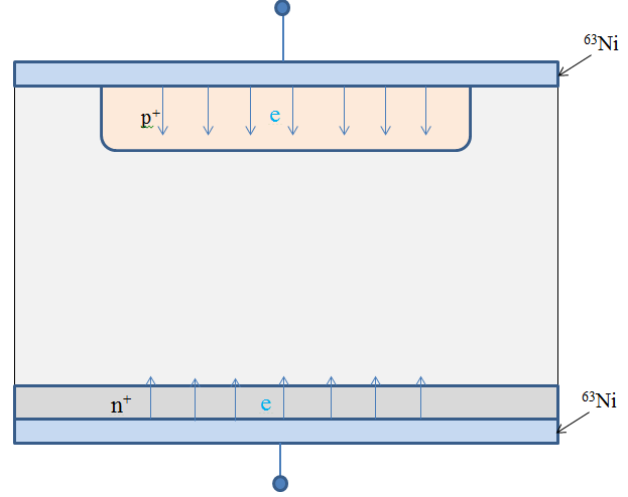The base structure for the simulation is shown in Fig. 1.

Fig. 1 – The base silicon p-i-n-structure chosen for simulation

The total semiconductor structure thickness is 40 microns. In the simulation it was assumed that the electrons emission from the ⁶³Ni occurs is uniformly per energies. It is clear that in fact it is not so, but if it is analyzed the structure efficiency in terms of *A/W*, it is not important, because it is considered a relative value. To separate the effective participation of the top and bottom ⁶³Ni contacts in the formation signal p-i-n-structures characteristics simulation was performed only with the top ⁶³Ni terminal contacts. The space charge region is reached only by high-energy electrons. However, the overall structure sensitivity in the *A/W* decreases, since it was shared in the calculation of the efficiency that total current is divided into more the power source. Therefore, when analyzing the various factors influence on the effectiveness of a separate structure appropriate to use the results in the *A/W* values, and the structures comparison with one or two contacts it must be considered radiation-induced currents.

3. RESULTS AND DISCUSSION

3.1 Influence of the *p*-region Electron Lifetime

Charge carriers mobility and lifetime influence is equal, and influence on the contribution of quasi-neutral regions in sensitivity. The less mobility and lifetime, the fewer the number of charge carriers reaches the space charge region, therefore, the quasi-neutral regions contribution is reduced. Charge carriers mobility and lifetime are reduced with increasing doping level, however, this varies the contact potential difference, and it will be changed the space charge region width. Therefore, to select only the lifetime change it will be changed the lifetime, without changing the doping level.

Fig. 2, 3 shows the change in structure sensitivity when changing the electron lifetime in p-type region to

the *p-n* junction 1 and 5 microns depth. It can be seen that the smaller the *p-n* junction depth, the less influence on the spectral sensitivity of the lifetime change. It is clear that the thinner layer of *p*-electrons a shorter distance must be passed, so the impact on the spectral characteristics of the lifetime is reduced. Any spectral characteristics changes occur only due to the top *p*-layer. The space charge region contribution and the *n*-region is not changed.
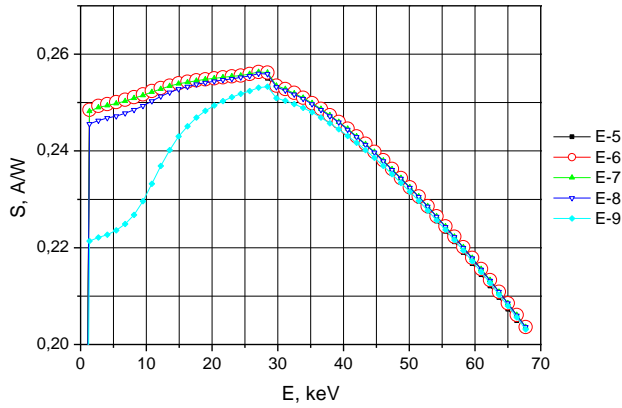

Fig. 2 – The dependence of the radiation induced power source spectral characteristics sensitivity on the electrons lifetime in the *p*-region ($\tau_n = 10^{-5} \div 10^{-9}$ s, $d = 1$ μm, $S = 10^4$ cm/s)

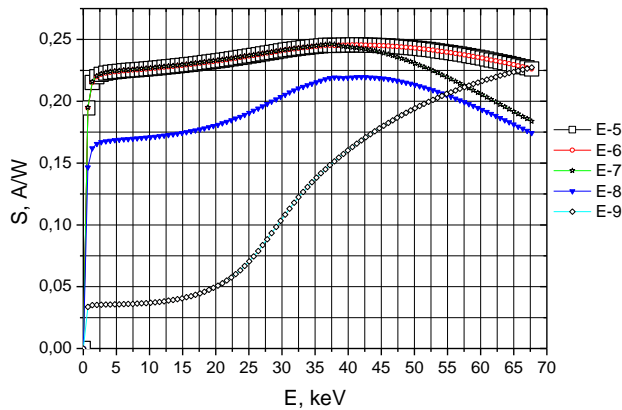**Fig. 3** – The dependence of the radiation induced power source the spectral sensitivity characteristics on the electrons lifetime in the *p*-region ($\tau_n = 10^{-5} \div 10^{-9}$ s, $d = 5$ μm, $S = 10^4$ cm/s)

At the same time, unlike the optical photodetector the changes occur in both the low and high energies. This is due to the fact that high-energy electrons form a electron-hole pairs substantial number on the whole electrons path.

3.2 The Holes Lifetime Influence in the *i*- and *n*- regions

The holes lifetime influence in the *i*- and *n*-regions is more significant, since *i*-region is substantially larger than the *p*-region. Figure 4 shows the effect the holes lifetime changes in the *i*-region or lightly doped *n*-region. When this change occurs solely by varying the contribution of the lightly doped *n*-region.
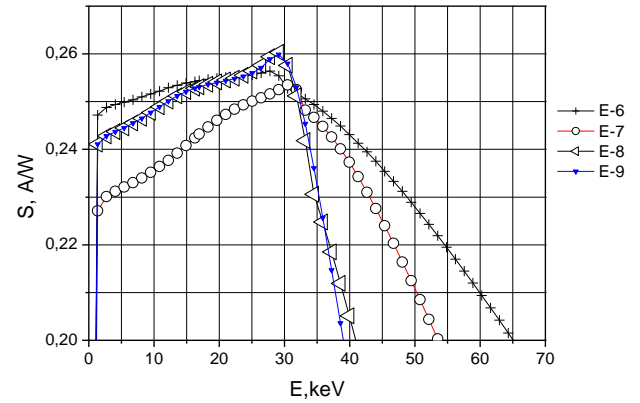

Fig. 4 – Dependence of the radiation induced power source spectral sensitivity characteristics on the holes lifetime in the *n*-region ($\tau_p = 10^{-6} \div 10^{-9}$ s, $d = 1$ μm)

A significant increase in the *p-n* junction depth reduces the life time influence. Firstly, because of the region dimensions decrease. Secondly, because it is reduced the distance to be traveled holes to take part in the radiation induced current formation.

The lifetime influence is also defined by the dopant concentration in the lightly doped *n*-region. The reason is that when the impurity concentration varies the space charge width, and therefore increases the size of the quasi-neutral regions.

Effect of the top *p*-layer thickness is due to several factors, and especially, the distribution of the incident radiation. When the electrons energy increases the range of electrons increases, and therefore expands the electron-hole pairs generation range. To participate in the current formation carriers must either be formed within the space charge region, or to reach the area of the quasi-neutral regions (electrons from the *p*-type region and holes from the *n*-region). The top *p*-layer effectiveness contribution is caused by some electrons fraction formed by emission to reach the space charge region. It is accordingly determined by the top layer thickness, i.e., the distance to the SCR, mobility and electron lifetime and surface recombination velocity.

For calculations, the following baseline characteristics of the structure:
  – doping level of the top *p*-layers – 10^{17} cm^{-3};
  – doping level of the lightly doped *n*-region 10^{14} cm^{-3};
  – doping level of the n^+-substrate 10^{18} cm^{-3};

In simulation the effect of the thickness of the upper *p*-layer it is taken the *p*-electron lifetime in *p*-layer – 10^{-6} s and electrons mobility in the *p*-layer – 700 cm^2·V·s^{-1} and the holes mobility in the *n*-layer – 450 cm^2·V·s^{-1} and the holes lifetime in the *n*-layer – 10^{-5} s in accordance with data [13]. Fig. 5 shows the effect of top *p*-layer structure thickness on the structure sensitivity characteristic with the contact ^{63}Ni, located at the *p*-layer side.

Figure 4 shows the increasing the top *p*-layer thickness reduces the sensitivity in the low energy region, at the same time in the field of high-energy sensitivity varies slightly. This is due to the fact that at low energies main electrons part is absorbed near the surface, and at the increase in the transition less of them depth
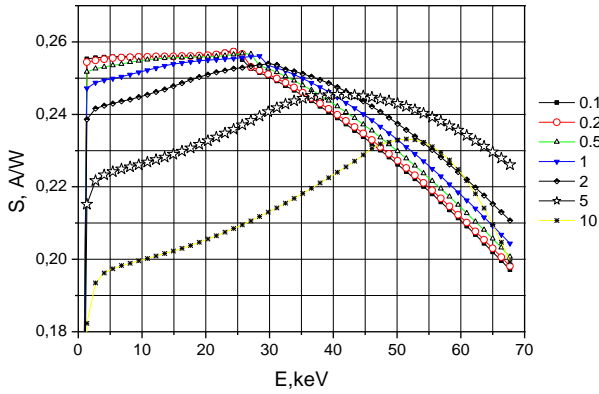
Fig. 5 – Influence of the top p-layer thickness on the spectral sensitivity characteristic structure (d from 0.1 to 10 microns), $\tau_n = 10^{-6}$ s, p-region doping level is 10^{17} cm^{-3}

comes to the space charge region. At high electron electron-hole pairs generation energies is more uniformly over the structure. With decreasing sensitivity at low energies it is simultaneously expanding the p-region sensitivity.

At the same time, the spectral characteristics of the space charge region contribution is reduced and shifted to higher energies.

Contribution into the n-region spectral sensitivity is shifted to higher energies.

By reducing the carrier lifetime the reduction in sensitivity at low energies is more noticeable because significantly fewer electrons reach the space charge region (Fig. 6).
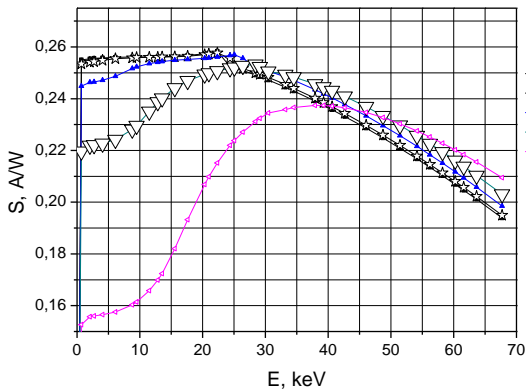

Fig. 6 – Influence of the top p-layer thickness on the spectral sensitivity characteristic structure. ($d \sim 0,1 \div 2$ microns, $\tau_p = 10^{-6}$ s). The doping level of the p-region – 10^{17} cm^{-3}

The addition of ^{63}Ni contact on the back side decreases the effect of the p-n junction depth. The reason is the reducing the p-region contribution is compensated by an n-region contribution increase.

In order to optimize the structure parameters it is interesting to consider the doping level influence of different areas. Here it is considered the doping level influence of the of the spectral response curve without changing the series resistance and spreading resistance. Doping areas level affected in two ways – change the space charge region width in the structure and the change in characteristics such as a semiconductor material lifetime and mobility with increasing doping level.

Since the effect of lifetime discussed previously, first consider the effect of changing the doping level without changing the lifetime and mobility. Reducing the doping level leads to the space charge region expansion in the lightly doped region direction.

In Figure 7 shows the change in the structure sensitivity when changing the doping level of the lightly doped region ($\tau_p = 10^{-5}$ s).
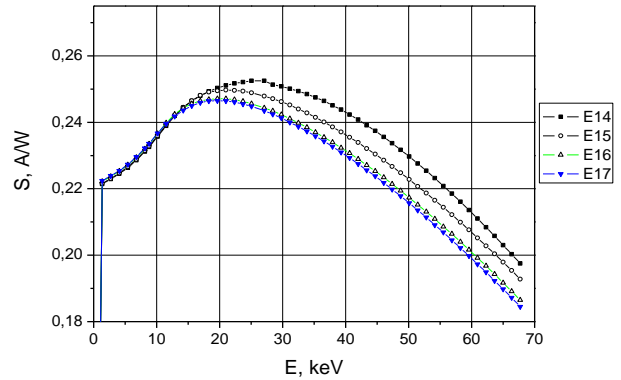

Fig. 7 – The doping level influence of the lightly doped region ($\tau_p = 10^{-5}$ s) on the spectral p-i-n structure sensitivity

With such a high lifetime the changing the spectral sensitivity is insignificant. At the same time with a decrease in the doping level it is increased the space charge region contribution associated with the expansion of the area. The contribution of the lightly doped n-region on the contrary decreases (Fig. 26) at such a high lifetime. It is caused by a decrease in the n-area size. The p-region contribution is not changed. Thus, there is a redistribution of the areas in the energy distribution of the sensitivity.

With a significant reduction of the lifetime contribution to 10^{-9} s n-region contribution is sharply reduced and the sensitivity depends almost exclusively on the space charge region.

The changes sensitivity dependence in the spectra p-i-n structures subject on the mobility changes and lifetime in accordance with [13]. However, the main changes are due to changes in the lightly doped n-region contribution.

The of the radiation-induced power source efficiency calculation performed according to the calculation method adopted for the solar energy converter [11].
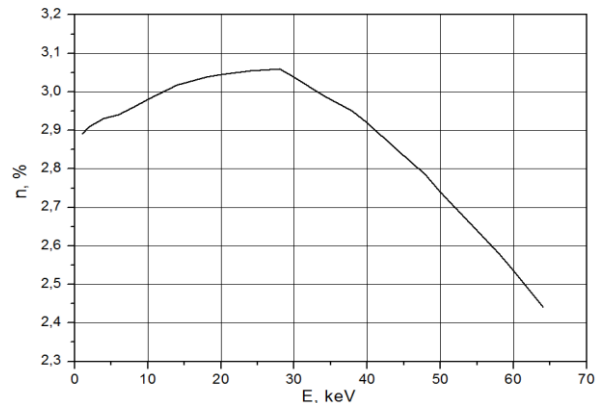

Fig. 8 – The radiation-induced power efficiency dependence on the electron energy. The p-layer thickness – 1 μm. ^{63}Ni metallization is arranged on the front side

Figures 8 show the radiation induced source efficiency dependence.

4. SUMMARY

1. It was carried out the lifetime impact simulation for mobile charge carriers in the radiation-induced power sources on their sensitivity dependence on the fast electrons energy.

2. In order to optimize the _p-i-n_ structures parameters it was calculated the parameters when changing the top layer depth and changing _p_-doping levels structure areas.

3. It is shown that at low doping lightly doped _n_-region the field support the maximum mobile carriers

collection generated by fast electrons.

4. It is shown that when the level of doping lightly doped _n_-region the structure sensitivity is less dependent on the lifetime.

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