Development and investigation of silicon converter beta radiation $^{63}\text{Ni}$ isotope

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Abstract. In this paper the results of the creation and researching characteristics of, experimental betavoltaic converters (BVC), based on silicon are discussed. It was presented the features of structural and technological performance of planar 2 D- structure of BVC. To study the parameters of the converter stream the beta particles of the radioisotope was simulated by $^{63}\text{Ni}$ electron flux from scanning electron microscope. It was investigated the dependence of the collecting electrons efficiency from the beam energy current-voltage characteristic was measured when irradiated by an electron beam, from which the value of the short-circuit current density equal to 126 nA / cm$^2$ and the value of the open circuit voltage of 150 mV were obtained. The maximum power density at 70 mV is 9.5 nW / cm$^2$, and the conversion efficiency is 2.1%. It was presented the results of experimental studies of the current-voltage characteristics of samples by irradiating a film $^{63}\text{Ni}$. The values of load voltage 111 mV and short circuit current density of 27 nA / cm$^2$ were obtained. Maximum power density was 1.52 nW / cm$^2$.

1. Introduction

Batteries that are based on using BVC with $^{63}\text{Ni}$ beta isotope, have a high energy density, long life with very small sizes, moreover, BVC does not require any additional maintenance during operation [1]. The creation of such batteries is extremely promising for use in devices special and household purpose [2, 3].

By the principle of operation to the BVC is similar to solar cells which convert photons into electric energy. The only difference is that the BVC work on the effect of the electron-hole pairs generation in the silicon bulk during the span not photons but beta particles. Subsequent separation of the generated current carriers in the semiconductor, as in the case of solar cells, is carried out by p-n junction or Schottky barrier.

Theoretically, the most effective material for the producing such batteries are semiconductors with a large band gap such as SiC, GaN, and C. The broadband materials have lower values of the induced current, but due to the induced voltage, these structures have a high rate of conversion into the electric...
power. Thus in [4, 5] BVC based on SiC, GaN were investigated, the conversion efficiency of these structures did not exceed 1.1%.

From a practical point of view the values of the diffusion length in available crystals of SiC, GaN and C are much smaller than the corresponding values in silicon. In addition, leakage currents that have a significant impact on the value of the induced voltage in silicon can reach values close to the theoretical. In structures based on SiC and GaN it is not observed such that this is not seen and it connected with higher concentration of structural defects in these crystals. Today, the technology of producing silicon structures has a quite high level, which makes it possible to produce large-area elements, consistent inclusion of which will raise the output voltage of the battery.

Energy conversion efficiency of beta decay on the silicon is currently quite low and does not exceed 0.5% [6, 7]. Low efficiency may be due to several reasons, the most studied presently include: charge carrier recombination, inelastic scattering of beta-particles, the absorption of the beta-particles in the layers where there is no generation of electron-hole pairs, etc.

The aim of this work is the development of constructive and technological methods for creating BVC structures with planar structure of the 2-D, as well as the further development of experimental methods for the study of such structures. The paper used as the BVC silicon p-i-n-structure irradiated by electrons flow, which imitated a radioisotope $^{63}$Ni with a specific activity of 10 Ci / g. The spectrum of electron irradiation was determined by scanning electron microscope.

Furthermore, it was also performed experimental investigation of characteristics 2D BVC structures were also investigated with the deposited $^{63}$Ni on film. $^{63}$N had the activity 2.7 mCi and external ionized current 3 nA. The experimental data obtained for 2D-structures can be used for creating 3D-structures that enable to considerably increase the area of the p-n junction and, hence, the efficiency of batteries based on BVC [8-10].

2. Technology for creating silicon beta radiation converter

The technology for manufacturing studied structures was developed taking into account the conducted computer simulations in [11]. As the initial substrate it was used a silicon wafer grown by floating zone melting with a resistivity of 5 Ohm · cm, thickness of 420 microns. Ohmic contact to the reverse side was carried out by diffusion of phosphorus (P), followed by speed up at a temperature (T) of 1000 °C for 45 min. A second ohmic contact was formed by ion doping of boron (B) with the energy of 60 keV and a dose of 500 µCi / cm$^2$. Formation of high-quality p-n junction with shallow depth was carried by ion implantation of boron out through a film of silicon oxide (SiO$_2$) thickness of 20 nm with a minimal energy of 10 keV and a dose of 10 µCi / cm$^2$. In forming the working area of the plate it was held getter annealing with slow cooling of about 1 °C / min [12]. Then, for p$^+$ regions it was produced ohmic contacts coated aluminum (Al) with thickness of 1 mm, heating the Al was at T = 475 °C, the reverse side is not metalized. Custom sample with the crystal working area of 1 cm$^2$ is shown in Figure 1.

Figure 1. Photo of betavoltaic element.
3. Results and discussion

For the semiconductor converter of beta energy particles parameters optimization into electrical current it is used electron beam scanning electron microscope (SEM) to simulate the beta radiation. This approach allows for a particular semiconductor structure to predict betavoltaic element parameters for any film thickness and activity of $^{63}$Ni film. For the method of measuring the induced current is used (IC) [13, 14]. In the method of IC focused electron beam SEM acts as a local source of nonequilibrium electron-hole pairs. The electric field inside the space charge region (SCR) separates the electron-hole pairs, which leads to the appearance of current in the external circuit. Current collected by the collector, is a detectable signal in the method of IC at this junction, which plays the role of a collector can be positioned both parallel and perpendicular to the incident beam. The value of IC quantity is generally determined by the geometry of the sample, as well as the spatial distribution of generation rates and recombination of electron-hole pairs.

For the calculation of induced current in the p-i-n diode caused by the emission of a radioactive isotope $^{63}$Ni from a film, it was used the approach proposed in [15, 16]. In these studies it was shown that induced by irradiation of the semiconductor structure current can be presented as

$$I_c = q \int \int \int_{-\infty}^{\infty} g(x, y, z) \Phi(x, y, z) dx dy dz$$

where $q$ - electron charge, $g(x, y, z)$ - function describing the electron-hole pairs generation and $\Phi(x, y, z)$ - the probability of collecting minority carriers, which is the current collected by the collector from a single charge, placed at the point $(x, y, z)$.

Since in this case the p-n junction area is much greater than its depth, SCR width and thickness of the film BVC $^{63}$Ni, the problem becomes one-dimensional, and the current can be calculated as:

$$I_c = q \int_0^\infty h(z) \Phi(z) dz$$

The function $h(z)$ can be calculated by Monte Carlo for the electron beam, and for the film thicknesses of radioactive nickel, as well as for any converter material.

In the present study we used a program developed in [17, 18]. Specific activity of $^{63}$Ni film was assumed to be 10 Ci / g (89 Ci / cm$^3$), and the film thickness was varied. When calculating the limiting element parameters the film thickness was 3 microns, as in further its energy radiation practically is not changed due to the absorption of energy in the film. The thickness of the protective coating of the diode is sufficiently small and energy loss in it can be ignored, and that the calculations it can be replaced by a silicon layer, in this layer the generation of charge carriers does not contribute to induced current.

The function $\Phi(z)$ depends only on the parameters of the semiconductor structure, and can be obtained [16] by solving an equation with the appropriate boundary conditions.

$$\Delta \Phi(z) - \Phi(z)/L^2(z) = 0$$

For example, a Schottky barrier boundary conditions: $\Phi(W) = 1$ and $\Phi \to 0$ for $z \to \infty$. For the p-n junction $\Phi(z) = 1$ on the borders of the SCR in p- and n-regions. It should also be noted that in the p- and n-regions in general, the value of the diffusion length $L$ is different, and you need to add as a boundary condition the recombination velocity on the surface.

Thus, to calculate the induced current it is necessary to know the depth of the p-n junction, the width of the SCR, values $L$ in p- and n-regions and the surface recombination velocity. In the paper, these parameters were determined by fitting the experimentally measured dependence of IC on the beam energy.
Figure 2 shows the efficiency of collecting electrons from the beam energy. The efficiency of collecting electrons was calculated by the formula:

\[
  f(E_b) = \frac{I_c \cdot E_i}{I_b \cdot E_b \cdot \eta},
\]

where \( I_c \) - measured induced current, \( E_i \) - the average energy of formation electron-hole pairs (\( E_i = 3.6 \text{ eV for Si} \)), \( I_b \) and \( E_b \) - current and the energy of the electron probe, respectively, \( \eta \) - the proportion of the beam energy absorbed by the sample (\( \eta \approx 0.9 \text{ for Si} \)).

As it is shown in Figure 2, it is already at an energy of 5 keV more than half of non-equilibrium carriers is collected.

![Figure 2. Dependence of the collection efficiency of the energy beam. Red- measured, black- calculated.](image)

Next it was calculated the probability of collecting \( \psi(z) \) and by using the function of generating \( h(z) \), the induced current was calculated. For a \(^{63}\)Ni film with thickness of 3 microns calculated induced current in the test structure was 126 nA / cm\(^2\).

Then the studied structure was placed in an electron microscope, and the beam current is chosen such that the induced current took the calculated value. Since the structure of the diffusion length was large enough, almost all generated non-equilibrium charge carriers reach the SCR and contribute to the current by irradiation as electron beam and beta particles. Therefore the choice of the beam energy in this case is not critical. At the same beam current it was measured by the current-voltage characteristics and structural parameters were determined for the energy converter of radiation from the \(^{63}\)Ni film into the electric current. The measured current-voltage characteristic of the electron beam irradiation is shown in Figure 3.
Figure 3. The current-voltage characteristic at an electron beam irradiation.

The following values were obtained after the measurements: a short-circuit current density \( J_{\text{sc}} = 126 \, \text{nA} / \text{cm}^2 \), the open circuit voltage \( V_{\text{oc}} = 0.15 \, \text{V} \) and a maximum power density \( P_{\text{max}} = 9.5 \, \text{nW} / \text{cm}^2 \). The value of the fill factor is 0.51, a low value of the fill factor is due to the low intensity of the beta radiation. The conversion efficiency under these conditions was 2.1 %.

Thus, if \(^{63}\text{Ni}\) films is applied on a produced structure (film thickness 3 microns), and wherein the leakage current remains at the same level the resulting BVC will have the obtained above parameters.

Investigation of beta radiation converter for irradiation it by film \(^{63}\text{Ni}\) radioisotope. Changes in the current-voltage characteristics of the structure was carried out on the installation of Agilent 1500B «Keysight» in a light-tight chamber. The results are shown in Figure 4.

To analyze the effectiveness of the structures obtained to use an external source of \(^{63}\text{Ni}\) beta particles of RITVETS company. Film source is a nickel foil area of 1 x 1 cm\(^2\) coated with a layer of \(^{63}\text{Ni}\), which is covered with a protective layer of Ni (thickness is about 0.2 microns). The activity of radioactive \(^{63}\text{Ni}\) layer is 2.7 mCi / cm\(^2\), the density of ionization current is 3 nA.

Figure 4. The current-voltage characteristic when irradiated radioisotope \(^{63}\text{Ni}\).

Under an actual irradiation by \(^{63}\text{Ni}\) radioisotope following values were obtained: short circuit current density \( J_{\text{sc}} = 27 \, \text{nA} / \text{cm}^2 \), the open circuit voltage \( V_{\text{oc}} = 0.111 \, \text{V} \). Low current density is due to the presence of the protective layer of Ni, which absorbs about 30% of energy. Maximum power
$P_{\text{max}}$ was 1.52 nW / cm$^2$ at a voltage of 76 mV. The conversion efficiency under these conditions can only be determined by theoretical calculation, it is about 1.68%.

4. Conclusions
This paper presents the technology of planar element betavoltaic converter production. For the beta radiation simulation of commercially available $^{63}$Ni radioisotope with large activity it was used the method of induced current. The structure effectively collects nonequilibrium charge carriers, e.g. at an energy of 5 keV more than half of electron-hole pairs is collected.

For a $^{63}$Ni film of 3 µm thickness calculated induced current density for the investigated structure was 126 nA / cm$^2$, the open circuit voltage $V_{\text{oc}} = 0.15$ V, maximum power density $P_{\text{max}} = 9.5$ nW / cm$^2$. At the same time the value of the fill factor is 0.51, a low level of fill factor is due to the low intensity of the beta radiation. The conversion efficiency under these conditions was 2.1%.

At irradiation by $^{63}$Ni radioisotope source following values were obtained: short-circuit current density $J_{\text{sc}} = 27$ nA / cm$^2$, the open circuit voltage was $V_{\text{oc}} = 0.111$ V, maximum power density $P_{\text{max}} = 1.52$ nW / cm$^2$ was obtained at a voltage 76 mV. BVC characteristics reduction compared with the theoretical ones and with data obtained by electron beam irradiation received by SEM, is due to losses in the film layers of non-radioactive nickel.

The experimental data can be used at producing a 3D-structure which allows high conversion efficiency.

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