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Optimization of Energy Conversion Efficiency Betavoltaic Element Based on Silicon

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It was developed the technology of manufacturing planar betavoltaic converter based on silicon, providing a higher rate of conversion of ionizing radiation into electrical energy by reducing reverse currents. The active region of silicon *p-i-n* structure is 1 cm², which is irradiated by the of radionuclide ^{63}Ni with the activity 2,7 mCi/cm². The results of experimental studies of C-V samples are presented. The values of the open-circuit voltage (V_{oc}) 0.111 V are presented and short circuit current density (J_{sc}) 27 nA/cm². The maximum density of output power (P_{max}) was 1.52 nW/cm².

Keywords: Betavoltaic effect betavoltaic battery, *p-i-n* diode, Gettering.

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1. INTRODUCTION

Modern electronic systems require increasing demand for power electrical and mechanical devices (MEMS). Traditional chemical power sources are not suitable for MEMS devices power supply because of their low power density and short life [1]. The need for low output power, durability, and without maintenance is inherent devices that are used in electronic space satellite equipment, sensors in remote locations (mines, far north, etc.), as well as in implantable medical devices.

Betavoltaic batteries are very promising sources of supply with long service life, which are suitable for powering various MEMS devices. Such batteries are consisted of two elements: the radioactive source of the electrons and the semiconductor structure, which generates a current influenced by beta radiation.

The ^{63}Ni radioisotope is acceptable source because of its pure beta radiation and long half-life (100 years). ^{63}Ni specific activity of 57 Ci/g, with the range of beta particles energy limited to energy 67 keV with maximum at 17.4 keV, wherein the power density is about 100 μW/Ci [2].

Theoretically, the most suitable materials for the betavoltaic batteries production are semiconductors with a large band gap such as SiC and GaN. However, the values of the minority carriers lifetime in the crystal is considerably lower than in silicon. Comparative evaluation based on SEM was carried out in [3], which showed that the cells based on Si ($P_{max} = 1.23 \cdot 10^{-8}$ W/cm²) don't much inferior to the elements based on SiC ($P_{max} = 1.515 \ 10^{-8}$ W/cm²). Since silicon is much cheaper than SiC and GaN, and the technology level of structures on base its well-developed, the question of the optimal material requires more detailed study.

One of the problems betavoltaic and solar cells based on silicon is the state of the *p-n* junction surface [4-6]. Surface charges, formed by uncontrolled impurities significantly increase the surface component of the reverse current [7]. Another problem is the high density of structural defects, which are formed in silicon during high temperature processing steps, which also lead to a significant increase in the reverse current [8].

In [9, 10] it was obtained experimental results with a ^{63}Ni radioisotope, but the short-circuit current (11 and 54 nA) and open-circuit voltage (0.8 and 82 mV) is far from theoretically possible. The reason for this it can be a great value of the reverse currents.

This work is focus on development of betavoltaic element production techniques that ensures reducing the influence of structural defects on its parameters and study the resulting structure.

One of the main processes taking place in the semiconductor when hit by electrons with energies 1-100 keV, is the ionization of atoms along the path of the electron. Fling in the *p-n*-junction the beta particle emitting by the radioisotope, slowing down, interacts with the atoms of the crystal lattice, resulting to the generation of electron-hole pairs. As a result, in the semiconductor it is formed a plurality of electron-hole pairs along the trajectory path of the electron. These electron-hole pairs in the depletion region and along the diffusion length in the region of the depletion region, are pulled by the electric field, creating a current in an external load. Efficiency of transformation of beta particles energy into electrical energy is in the range of a few percent.

Theoretically, excluding distribution by volume, the rate of electron-hole pairs generation in the semiconductor can be defined by the formula:

$$G_0 = \frac{A \cdot q \cdot E_0 (1 - p)}{E_i} \qquad (1)$$

where E_0 – electrons energy; A – Activity of the radioisotope; q – electron charge; E_i – the energy required for the formation of electron-hole pair (for silicon $E_i = 3.6$ eV); p – the fraction of electrons lost on backscatter. Total current patterns produced by beta radiation can be calculated:

$$J_L = J_{dr} + J_p + J_n \qquad (2)$$

Mobile charge carriers generated in the depletion region, form the current according to:

$$J_{dr} = -q\int_0^W G(x)dx \quad (3)$$

where W – the width of the depletion region.

The current densities at the boundaries of quasi-neutral region adjacenting to the space-charge region, are calculated using the transport equations for electrons and holes [11]:

$$J_n(x) = q\mu_n n(x)E + qD_n \frac{\partial n(x)}{\partial x}; \quad (4)$$

$$J_p(x) = q\mu_p p(x)E - qD_p \frac{\partial p(x)}{\partial x}, \quad (5)$$

where J_n and J_p – current density of electrons and holes, respectively, comprising a drift and diffusion components, A/cm^2; $n(x)$ and $p(x)$ – the concentration of electrons and holes at a given point of the semiconductor cm^{-3}; μ_n and μ_p – the mobility of electrons and holes, respectively, cm^2/Vs; D_n and D_p – diffusion coefficients of electrons and holes, respectively, cm^2/s; E – electric field intensity, V/cm.

The depth of beta particles penetration emitted by ^{63}Ni may be calculated by the formula Kanaya-Okayama:

$$R_{K-O} = \frac{0{,}0276 \cdot A \cdot E_0^{1{,}67}}{Z^{0{,}889} \cdot \rho}, \quad (6)$$

where $R_{K\text{-}O}$ is given in micrometers, A – average atomic weight of the sample, E_0 – eelectron energy in keV, Z – average atomic number of the sample, ρ – density g/cm^3.

Fig. 1 shows that particles with an average energy 17.3 keV penetrate into silicon to a depth of 4 μm, in order to achieve a higher energy conversion spatial charge region width must be no less than 4 microns.

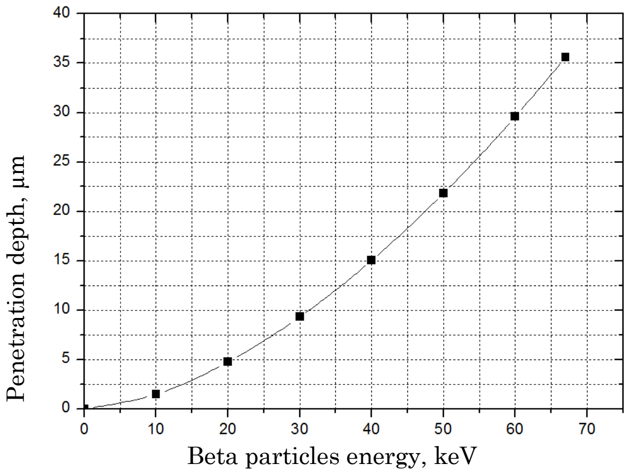

Fig. 1 The penetration depth of the beta particles in Si

Open-circuit voltage (V_{oc}) can be calculated by the known formula:

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_L}{J_0}+1\right), \quad (7)$$

where J_L – generated short-circuit current A/cm^2; J_0 – leakage current A/cm^2; k – the Boltzmann constant; T – temperature.

The leakage current in theoretical calculations consists of two components: the diffusion of the quasi-neutral regions and the generation-recombination part [11]:

$$J_0 = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} + \frac{qn_i W}{\tau}, \quad (8)$$

where n_i – own concentration of mobile charge carriers; n_{p0}, p_{n0} - equilibrium concentrations of minority carriers in the p- and n-regions, respectively; L_p and L_n – diffusion length of minority carriers; τ – minority carrier lifetime.

2. EXPERIMENTAL PROCEDURES

The investigated p-i-n structure is produced by standard techniques using the recommendations as presented in [12], the structure is shown in Fig. 2.

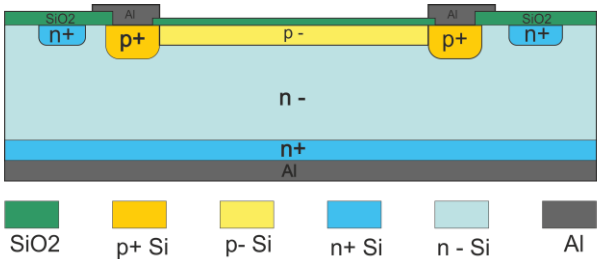

Fig. 2 – A typical p-i-n diodes structure

As the substrate it was used silicon wafers produced by floating zone melting method with a resistivity of 5 Ohm·cm, thickness of 420 microns. Floating zone melting method allows to obtain a substrate with a lower content of impurities O_2, C, Fe. The absence of undesirable impurities can reduce the rate of charge carriers recombination and increase the conversion efficiency. Ohmic contact to the reverse side was carried out by diffusion of phosphorus (P) c, followed by distillation at T = 1000 °C for 45 min. The second ohmic contact was formed by the B ion doping with implantation energy of 60 keV and a dose of 500 μCl/cm^2. The main problem was to create a high-quality p-n junction with shallow depth. Such p-n junction is needed to reduce losses in heavily doped p^+ region for the creation of such junction was formed thin SiO_2 film with 20 nm thickness, through this film it was carried out the ion boron (B) implantation of the workspace with minimal energy of 10 keV and a dose of 10 μCl/cm^2. To estimate the depth of the p-n junction in the work area it was used the program Sentaurus TCAD, after annealing the p-n junction depth less than 350 nm, the distribution profile is shown in Fig. 3.

When forming the working area plates were divided into two parts. In the first part regular annealing at T = 900 °C under N_2 was carried out, and the second one getter annealing with slow cooling of about 1 °C/min was held [13].

During the getter annealing undesirable impurities atoms diffuse through the crystal and accumulate in the damaged layer. Thus there is a work area cleaning of outside impurities that reduce the concentration of structural defects.

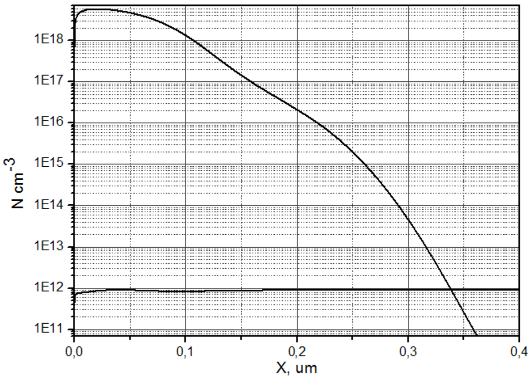

Fig. 3 – Impurity distribution profile in the betavoltaic element active zone

According to the calculations the depth of the *p-n* junction in the work area after annealing is less than 350 nm. Then for, a p^+ regions ohmic contacts were produced by Al deposition with 1 μm thickness, the Al heating was carried out at $T = 475$ °C, the reverse side is not metallized. Made samples with a working area of crystal 1 cm² is shown in Fig. 4.

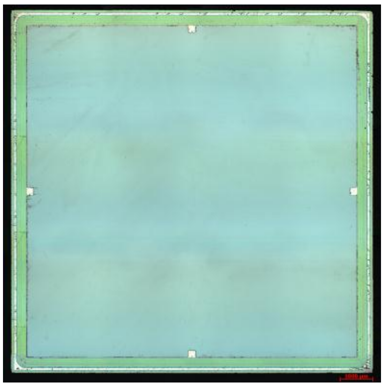

Fig. 4 – Photo of betavoltaic element

3. RESULTS AND DISCUSSION

The current-voltage characteristics of the structures were measured on installing Agilent 1500V company "Keysight" at room temperature (25 °C). To analyze the effectiveness of the structures obtained it was used an external source of ^{63}Ni beta particles. The source is a nickel foil area of 1 × 1 cm² coated with a ^{63}Ni layer, which is covered with a protective layer of Ni thickness of about 200 nm. The activity of radioactive ^{63}Ni layer is 2,7 mCi. Fig. 5 shows a comparison of current-voltage characteristics under the ^{63}Ni influence samples with and without gettering. Table 1 shows the parameters of the samples.

Table 1 – Parameters for betavoltaic components

	With gettering	Without gettering
J, nA/cm²(V = 30 V)	7,4	389,8
V_{oc}, mV	111	38
J_{sc}, nA/cm²	27	26
P_{max}, nW/cm²	1,52	0,33

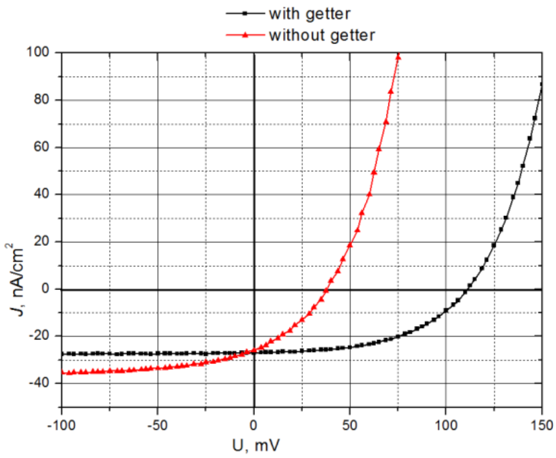

Fig. 5 – A comparison of current-voltage characteristics of samples with and without gettering

Because of the protective Ni layer it is impossible to pinpoint the incident power to the surface betavoltaic element, so a comparative evaluation of samples will be carried out for maximum output power. Fig. 6 shows the dependence of output power on the bias voltage for both sample types.

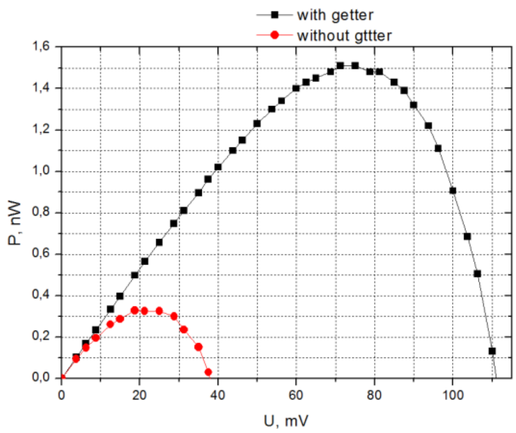

Fig. 6 – Comparison of output samples with and without gettering

Maximum output power for the sample without getting was 0,33 nW/cm², while the sample with gettering output the power is 1,52 nW/cm², which is 4.6 times higher. The sence of the following experiment was to study the conversion of the beta radiation energy at back side of the crystal. It would seem that the reverse side should not make any contribution to the transformation of energy, since the beta particles penetrate deep into the silicon is not more than 35 microns, and a maximum generation of electron-hole pairs takes place at a depth of 2-3 μm. However, in practice it was not the case, the ^{63}Ni source is set with the active surface up and fitted with the test sample. When measuring samples C-V in which no getter annealing it was not observed neither a power conversion C-V shift into region IV was not observed. And the samples that underwent getter annealing gave very comparable contribution to the transformation of energy in comparison with the irradiation of the crystal by the *p-n* junction.

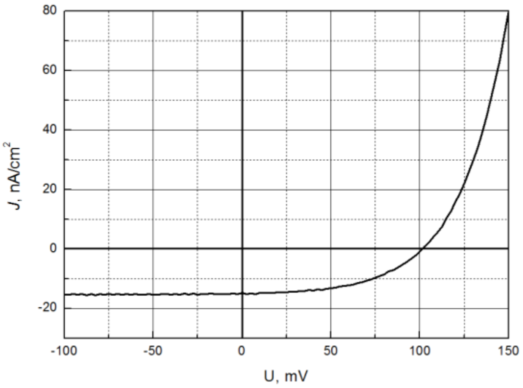

Fig. 8 – C-V irradiation from the reverse side of the samples with gettering

Short-circuit current is provided only by the diffusion component, it means that the lifetime of minority carriers is very high and amounts to more than $1·10^{-4}$ s, which also confirms the high gettering contribution. The value of short-circuit current was 14.8 nA/cm^2, and the value of the open circuit voltage was 0.1 V, the maximum output power was 0.76 nW/cm^2. It is known that radioisotopes radiation is isotropical, and this experiment shows that the use of gettering allows sequential assembly of the elements that will convert 95 % of the incident radiation from the radioisotope ^{63}Ni.

4. SUMMARY

Application gettering allows to reduce the structural defects concentration in the active regions betavoltaic elements and thereby reduce the level of reverse currents, which provides an increase in the conversion efficiency of beta radiation. It was measured valuesof the open circuit voltage (V_{oc}) 0.111 V and a short circuit current density (J_{sc}) 27 nA/cm^2. The maximum density of output power (P_{max}) was 1.52 nW/cm^2. It is shown that the efficiency of the samples using the gettering is 4.6 times greater than samples without gettering. The performance of this element will be improved based on the silicon planar technology (structure thickness 20 μm).

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