Characterization and Application of Nanomaterials (2018) Volume 1
doi:10.24294/can.v1i2.529

Efficiency beta batteries with direct energy conversion

Sergey V. Bulyarskiy[1], Ivan E. Abanin[2], Alexander V. Lakalin[1]

[1] *Institute of Nanotechnology of Microelectronics of the Russian Academy of Sciences, Moscow, Russia*

[2] *Scientific-Manufacturing Complex «Technological Centre» Moscow, Russia*

e-mail: bulyar2954@mail.ru

ABSTRACT

The properties of the beta batteries are compared, which are made on the basis of the different β-isotopes with beta decay. Tritium and Ni-63 make it possible to make β-sources of high activity, without harmful associated emissions, with low self-absorption, emitting high-energy β-electrons that penetrate deep into the semiconductor and generate a large number of electron-hole pairs. The efficiency of beta batteries needs to be analyzed based on the real energy distribution of β-electrons. It makes possible to obtain the real value of the energy absorbed inside the β-source, correctly estimate the amount of self-absorption of the β-electrons and part of the β-electrons there is a penetrate into the semiconductor, the number of electrons and holes that are generated in the semiconductor, and the magnitude of the idling voltage. Formulas for these quantities are calculated in this paper.

keywords: *isotopes; tritium; nickel-63; sources of beta radiation; self-absorption; surface activity; β-electrons; reflection coefficient; secondary electrons; idling voltage.*

1. Introduction

The sources of β-decay radiation contained a high specific energy density in the unit mass or volume of the substance[1]. Beta batteries with direct energy conversion attract scientists more often than other devices.

The isotopes used in power supply units (β-batteries) are: Ni-63, tritium, Sr-90 and Pm-147. They have a stock of energies from $3\cdot10^5$ to $2\cdot10^7$ W·h/kg. Therefore, it is reasonable to use them to fabricate batteries for long-term periods of use. For example, beta batteries can be developed with a service life more than 30 years based on the Ni-63 isotope[2,3]. Batteries based on direct energy conversion have an efficiency of about 1%. In this case, β-electrons generate electron-hole pairs in a semiconductor, which are separated by the electric field of a p–n-junction or a metal-semiconductor contact[4-6].

The nickel Ni-63 isotope has a half-life of 100 years. The low average energy of β-electrons (17.6 keV) does not create problems concerning radiation protection and is quite a lot lower than the semiconductor radiation-damage threshold, thus completely excluding p–n-junction degradation. Therefore, this isotope, despite its high cost, is rather widely used to fabricate β-batteries[2,3,7,8].

A disadvantage of structures based on this isotope is the low efficiency (not exceeding 1%) of β-batteries. This is a significant problem, which limits the use of beta batteries. An analysis of the scientific literature[1-8] shows that the structures with isotopes with shorter half-lives have an advantage. In this case, the number of decays per unit time (isotope activity) is larger and the current value proportional to the activity is higher. However, the efficiency of direct conversion of all the devices is rather low. It is evident that numerous factors affect the battery efficiency. Firstly, the source of emission: activity, energy of the emitted electrons, and their energy distribution. Secondly, design parameters: thickness of the isotope active layer, effects of self-absorption, structure and morphology of the layer, and the design features of the p–n-junction.

These factors are rather weakly elucidated in the scientific literature. This work is aimed at comparing the efficiency of the power supplies produced based on various sources of β-radiation and revealing the factors that reduce the efficiency of a device

2. Samples for studies

The power supplies that were studied in this work were composed of the source of β-radiation and specially prepared semiconductor convertor based on PIN-structure. Two types of beta sources were used. The first type of source was made of titanium foil, on the one of surfaces of which was located a layer of titanium ditrite - TiT_2. The second type of source was made from a nickel foil, which contained 20% of the Ni-63 isotope. The β-source sizes corresponded to the PIN-diode working surface. When the source was superimposed onto the diode, it contacted to the surface tightly enough practically without passing diffused light. A small air gap existed between the diode surface and the source, which did not play any significant role. The set of radiation sources of different activities was used by measurements. The properties of isotopes of beta radiation are given in Table 1.

Isotopes	**Half-life** $T_{0.5}$**, years**	**Average energy of the β-electrons (E_m), keV**	**Density (ρ), g/sm^3**	**Power emitted by a β-source with activity 1 Ci (P_k), µW/Ci**	**Isotope content in the material β-source, %**	**The activity on the surface of the β-source (As), mCi sm^{-2}**
Film of the TiT_2.	12.5	5.7	4.1	34	6	1.2-2.2
Foil of the Ni-63	100	17.8	8.9	100	17-20	5-27

Table 1. Properties of the isotopes

We used PIN-diodes with a 0.6 cm^2 working surface as convertors. The substrates of high quality monocrystalline silicon of the 100 KEF-4400 (111) brand (n-type silicon doped with phosphorous) were used as the initial material for the creation of PIN-diodes. Silicon ingots with a specific resistance of 1000 Ω·cm were grown using a floating zone remelting method. The density of stacking faults is not more than $5\cdot10^2$ cm^{-2}, the density of the dislocations is less than $1\cdot10^2$ cm^{-2} according to the technical specifications for the wafers of this bran.

Surface activity (As) was measured by a beta spectrometer directly on the finished samples.

It is known that the coefficient of converting β-radiation into the electrical current increases with a decrease in the reverse currents. Two technological operations were introduced in the PIN-diode technology, namely, an internal gettering and the creation of a guarding ring. The gettering was implemented by forming a strongly doped region with electron conductivity on the back side of a silicon wafer. This region was covered by layers of polysilicon and silicon nitride. Then, a gettering annealing was carried out at temperatures ranging from 700 to 1000°C. The reverse currents in the dark at 295 K and at a reverse bias voltage of 40 V was to 0.1-0.2 nA. A small reverse current took place thanks to the choice of high-quality silicon as the initial material and the introduction of the operations that were mentioned made it possible to reduce the current.

3. Experimental results

The dark current–voltage (I–V) characteristics at direct and reverse biases were measured for all the diodes by the standard method. Further, the sources of β-radiation of different activities were superimposed onto the diodes and the measurements of the I–V characteristics were repeated. In this case, the open-circuit voltage and short-circuit current were determined. The short-circuit current of the beta battery is shown in Figure 1. Parameters of beta batteries are shown in Table 2.

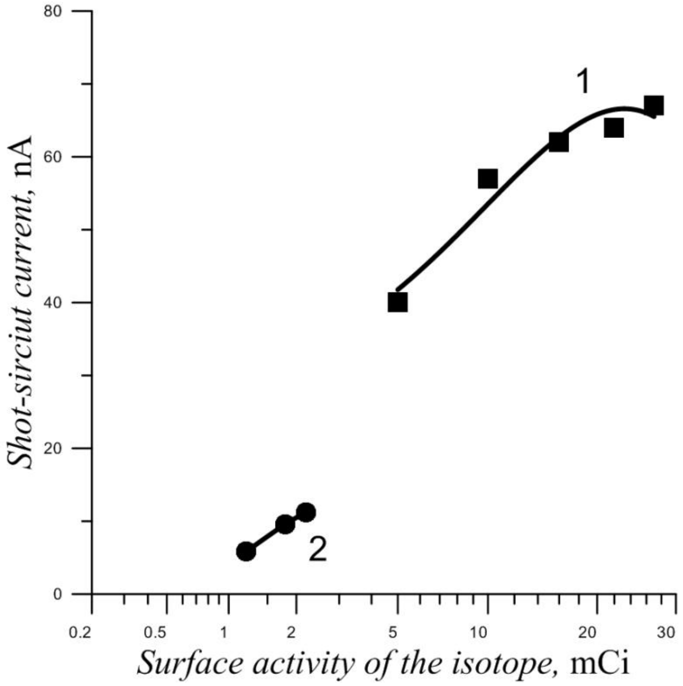

Figure 1: Dependence of the shot-circuit current from surface activity of the isotope, mCi: 1 – Ni-63; 2 – tritium.

Изотоп	A_s, mCi	P_{av}, nW	I_{cs}, nA	U_{xx}, mV	P, nW	η,%
H-3	1.2	43	5.8	58	0.22	0.53
	1.8	64	9.6	69	0.44	0.70
	2.2	79	11.2	72	0.54	0.65
Ni-63	5	535	40	105	2.81	0.53
	10	1070	57	112	4.3	0.4
	16	1170	62	117	4.94	0.29
	22	2350	64	119	5.1	0.22
	27	2780	67	120	5.8	0.21

Table 2. Parameters of beta batteries.

Note: A_s - surface activity of the β-source; P_{av} - power of the β-radiation of the β-source; I_{cs} - short-circuit current; U_{xx} - open-circuit voltage; P - the electrical power in the circuit is allocated to the load resistance of the optimum value; η - beta battery efficiency.

Power of the β-radiation of the β-source is calculated by formula:

$$P_{av} = P_k \cdot A_s \quad ,(1)$$

where P_k - power emitted by a substance with activity 1 Ci.

The electrical power in the circuit is allocated to the load resistance of the optimum value (P_{opt}) and is calculated by means of the load current-voltage characteristic, which is shown in Figure 2 by formula [9]:

$$P_{opt} = I_{\max} U_{\max} \quad ,(2)$$

$U_{\max}$ - voltage of the PIN-diode with the optimum load resistance of the electrical circuit. $I_{\max}$ - the diode current at the optimum load resistance of the electrical circuit.

The load characteristic (Figure 2, curve 2) was used to determine $U_{\max}$ and $I_{\max}$. The voltage $U_{\max}$ corresponds to the maximum of the load characteristic.

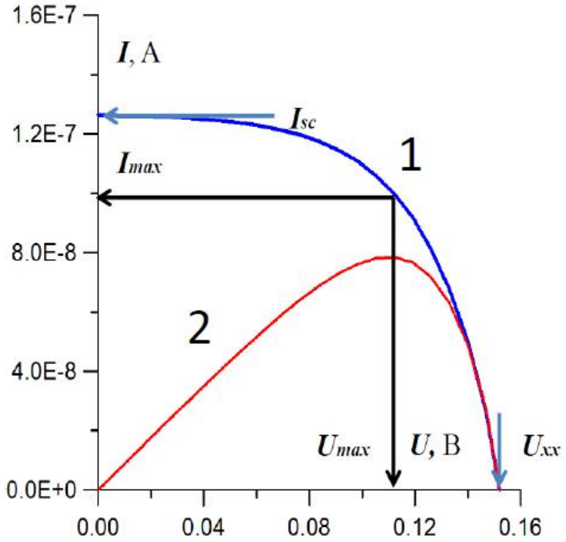

Figure 2: Electrical characteristics of the beta battery based on Ni-63.

1 – I–V- characteristic; 2 – the power, which is released on the load resistance, on the electrical voltage.

The current-voltage characteristic (I–V- characteristic) (Figure 2) makes it possible to calculate the fill factor (F_{ef}) of a semiconductor converter Eq. (2) [9]:

$$F_{ef} = \frac{I_{\max} U_{\max}}{I_{sc} U_{xx}} \quad .(3)$$

This value varied from 0.62 to 0.66 for the PIN-diodes used in this work. The beta battery efficiency is calculated by formula:

$$\eta = \frac{P_{opt}}{P_{av}} \quad .(4)$$

The open-circuit voltage was achieved maximum (120 mV) for the isotope Ni-63, while the short-circuit current was 67 nA. It's power achieved 5.8 nW (see **Table 2**). The isotope has undoubted advantages in comparison with tritium. Our result exceeds the achieved values by a factor of 1.5.

The experimental data for the beta battery with tritium and Ni-63 isotopes differ significantly. The experimental data for power sources with isotopes of tritium and Ni-63 differ significantly. The power of the Ni-63 isotope power sources exceeds the power of the same device with the tritium isotope by a factor of 3, with the same particle flux emitted from the source surface unit per unit time (surface activity As = 1 mCi). In addition, with increasing activity of the β-source, the power of the instrument with the isotope Ni-63 grows faster. This fenomen is associated with the fact that the Ni-63 isotope is characterized by a higher average energy of an electron emitted in β-decay. It is equal to E_{av} = 17.6 keV, while for tritium it is 5 keV. In order to form an electron-hole pair, an energy of is required in the case of silicon (E_g is the bandgap width of the semiconductor). The greater the energy of an electron emitted in β-decay the larger the number of electron-hole pairs it forms and the larger its quantum yield. The Table 2 shows a comparison between the quantum yields for Ni-63 and tritium isotopes.

4. Discussion of experimental results

4.1 Beta battery efficiency

The total efficiency of the beta battery is controlled by four main processes: self-absorption; the collection efficiency of electrons and holes which are generated in the space-charge region of the semiconductor part of the converter; secondary X-ray radiation, which occurs when electrons interact with matte and the semiconductor-structure efficiency [1,9]:

$$\eta = \eta_\beta \eta_c \eta_{e-h} \eta_s \text{ ,(5)}$$

where η_β is the fraction of β-electrons which reach the semiconductor converter surface; η_c is the fraction of β-electrons which arrive at the space-charge region and can contribute to the electric current; η_{e-h} is fraction of β-electrons that cause electron-hole pairs, η_s is the total efficiency of the diode which provides conversion.

4.2 Self-absorption of the β-source

In this section, we consider the first term of the Eq. (5) - η_β. The efficiency of beta batteries is related to the maximum flow that the source radioactive substance can emit from its surface (A_s). This quantity will be called surface activity. It is equal to the number of β-electrons that are emitted per unit time from a unit surface. It must be distinguished from the volumetric activity, which is declared in the passport of the β-radiation source. Volumetric activity is equal to the number of decays occurring in the entire volume of matter per unit time. This value can be determined on the basis of the parameters of the law of radioactive decay:

$$N = N_0 \exp(-\lambda t), \qquad (6)$$

where N_0 is the number of radionuclide atoms at the initial time (t = 0); λ is the decay constant, which is a property of the radionuclide.

The decay constant is related to the half-life ($T_{0.5}$), which is defined as the time interval during which half of the atoms of the radionuclide material there are decay - $T_{0.5} = \ln 2/\lambda$. This value is a reference and is known for all isotopes of radionuclides. Activity is a physical quantity that is equal to the number of decays per unit of time. It characterizes the decay rate, i.e. the number of decays per unit time in the entire volume of the source.

$$A = dN/dt = N_0 \ln 2/T_{0.5} \qquad (7)$$

In isotopes, the self-absorption phenomenon is pronounced, which means that far from all electrons are incident on the active-layer surface. Therefore, isotope-layer growth does not mean an increase in its surface activity. Let the initial activity of 1 cm^3 of a material be A_{0V}. This activity is calculated by the formula:

$$A_{v0} = \delta A/V, \qquad (8)$$

where V is the volume of the β-source; δ is a fraction of the atoms of the radioactive isotope in the β-source substance.

Electrons emitted during β-decay have energies of tens of keV. They lose their energy when they are scattered by a solid lattice. There are several scattering mechanisms among which of primary interest to us is scattering with the emission of secondary electrons which further contribute to the electric current of the power supply unit. For practical purposes, it is convenient to use a formula approximating the mentioned calculations performed by the Monte-Carlo method [10]:

$$h(\xi) = 0.60 + 6.21\xi - 12.04\xi^2 + 5.23\xi^3, \qquad \xi = \frac{z}{R(E)} \text{ ,(9)}$$

where z is the average depth of electron penetration into a material and R(E) is the maximum path length along the trajectory of an electron with energy E in a material with density ρ. To estimate this value, we use the formula [11]:

$$R(E) = \frac{0.0398}{\rho} E^{1.75} \qquad (10)$$

Function (10) means the probability of the detecting a particle with energy E at a certain depth.

The efficiency of beta batteries is related to the maximum flow that the source radioactive substance can emit from its surface. Then the activity of a material layer of thickness dz at the depth z from the surface is $A_z = A_{0V}Sdz$. This quantity is proportional to the number of electrons of any energy, which are generated in this layer.

The active-layer parameters are calculated as a rule using the average energies of β-electrons. Such an approach is not sufficiently accurate. In the present study, we perform numerical calculations using the experimental distributions of electrons emitted during the decay [12]. The electron energy during β-decay is known with a certain probability $W_c(E)$. We calculate this value by normalizing the experimental distribution to unity,

$$A_z \int_0^{E_{max}} f(E)dE = 1; \qquad W_c(E) = A_z f(E) \quad , \tag{11}$$

where $W_c(E)$ means the probability of detecting a β-electron in the energy range from E to E + dE. This value is shown in Figure 3 for Ni-63 isotopes.

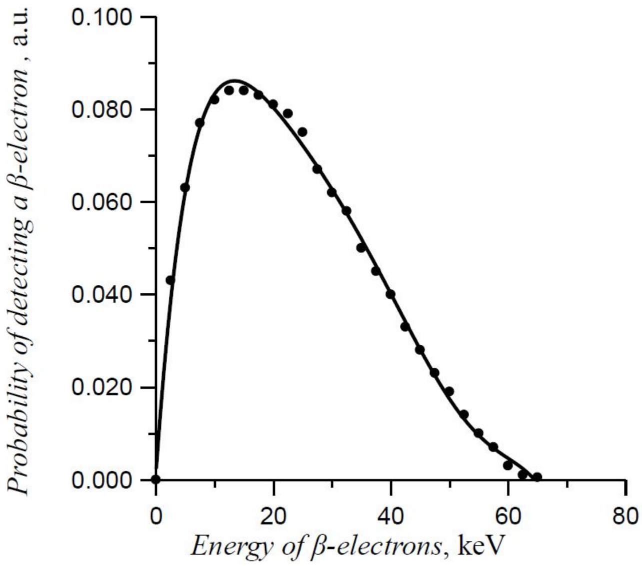

Figure 3: The probability of detecting a β-electron in the energy range from E to E + dE for the isotopes Ni-63 by Eq. (11).

The probability that an electron with energy E, generated at depth z will reach the surface is given by:

$$W_s(E) = W_c(E) h(z / R_c(E)) \quad . \tag{12}$$

This formula takes into account that half of all electrons have momentum directed toward the surface; however, two semiconductor converters are used. The structure is shaped as a sandwich with an emitter between the converters. The probability that an electron of any energy, generated at depth z will reach the surface is given by

$$W_s = \int_0^{E_{max}} W_c(E) h(z / R_c(E)) dE \quad . \tag{13}$$

Then the expression for the surface activity takes the form

$$A_s = A_{0V} S \int_0^d dz \int_0^{E_{max}} W_c(E) h(z / R_c(E)) dE \quad . \tag{14}$$

The total activity of the β-source (A) increases in proportion to its thickness d: $A = A_{0V}Sd$. The ratio of the surface activity Eq. (9) to the total activity is equal to the β-source efficiency factor η_β:

$$\eta_\beta = d^{-1} \int_0^d dz \int_0^{E_{max}} W_c(E) h(z / R_c(E)) dE \tag{15}$$

Power emitted by the β-source has a maximum at a certain thickness d_{opt} which is the optimal β-source thickness. Figure 4 shows the calculated Ni-63 and C-14 isotopes power emitted by the β-source of the isotope-layer thickness. The dependence, which is shown in Figure 4, is nonlinear. Therefore, the β-electrons are absorbed and at the optimum source thickness. So, efficiency factor η_β there is less than one at optimum thickness. It can be calculated using Ed. (15). The results of the calculation for all isotopes are shown in Table 3.

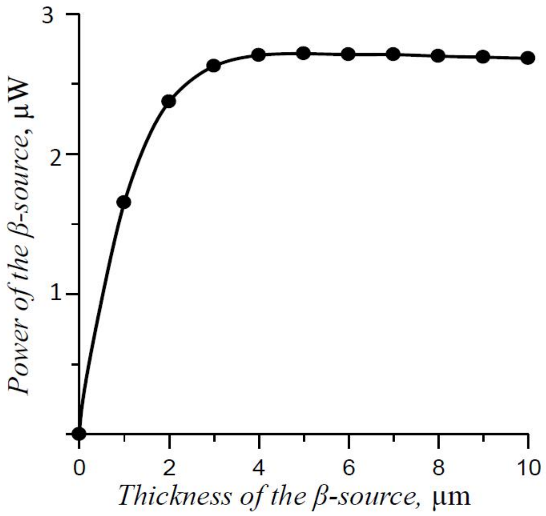

Figure 4: Radiation power of the β-sources based on isotopes Ni-63.

β - source material	Titanium ditrite	Ni-63
Optimal thickness d_{opt}, μm	0.35	1.5
Maximum surface activity, $A_{s\max}$, $mCi{\cdot}sm^{-2}$	18	24
The maximum power emitted by the β-source, P_{avmax}, μW	0.61	2.7
Efficiency factor η_β at optimum source thickness, %	70	75

Table 3. Optimal thickness of the β - source.

The optimal isotope Ni-63 layer thickness estimated in this study is on the order of 1.5 μm

4.3 Fraction of β-electrons which arrive at the space-charge region

A β-radiation source and a semiconductor converter of β-electron energy into electrical energy (PIN-diode) exist in close contact without a significant air gap. The physical boundary is between them, so the β-electrons emitted by the β-source are reflected from the outer boundary. The reflection coefficient (r_c) increases monotonically with increasing ordinal number of the target material. This coefficient can be estimated from the formula [13]:

$$r_c(Z) = 2^{-9/\sqrt{Z}} \quad ,(16)$$

Where: Z is the ordinal number of the element.

This formula is applied when the energy of the β-electron is E > 30 keV. If the inequality is not satisfied, then an additional error arises for β-electrons. The average electron energy of Ni-63 is 17.6 keV. Calculation by formula (16) contains an error. The coefficient of reflection of electrons with an energy of 5 keV (tritium) r_c = 0.22, and 17.6 keV (Ni-63) is r_c =0.2. Thus, for tritium, the error of the reflection coefficient is 10%, and for nickel the result 0.2 is accurate and it can be used in calculations. Now fraction of β-electrons which arrive at the space-charge region (η_c) is equal to η_c =1- r_c =0.8.

Losses on the reflection of the β-electrons, that have average energies and there is a move normally to the surface, do not determine the real losses with the required accuracy. The β-electrons exist from the β-source not only normally to the surface, but at any arbitrary angle. This dependence was calculated for an aluminum foil in [15] by the Monte Carlo method. The density of silicon is close to the density of aluminum, so these results can be used to analyze the reflection of the β-electrons from the surface of silicon. The results, which are shown in Figure 5 are approximated by the formula:

$$r_\beta(\varphi) = 0.121 + 2.48\cdot10^{-3}\varphi - 5.18\cdot10^{-5}\varphi^2 + 1.20\cdot10^{-6}\varphi^3 \quad .(17)$$

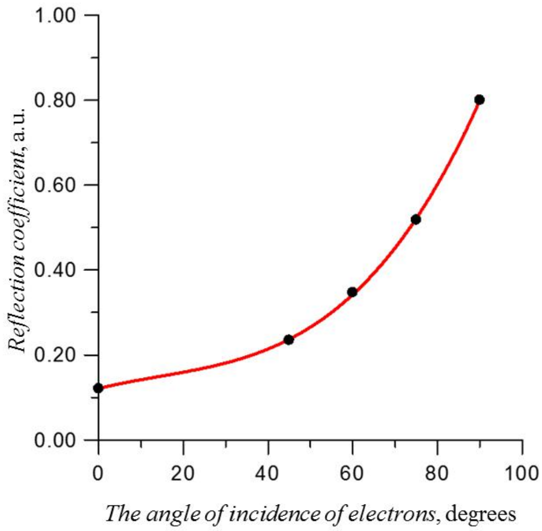

Figure 5: The coefficient of reflection of electrons from the surface of the PIN-structure at various angles of incidence.

The reflection coefficient was calculated by the mean value theorem by integrating Ed. (17) in the range from 0 to 90°. It is equal to 0.31 for silicon. The part of electrons that have passed through the surface of the silicon is 69%.

4.4 Fraction of β-electrons that cause the generation of electron-hole pairs in the PIN-structure η_{eh}

We calculated the fraction of β-electrons that penetrate the semiconductor in points B and C. These electrons have a lot of energy and create different phenomena in a solid state, when they lose their energy. For a systemization, the interactions are classified into two different types, namely elastic and inelastic interactions. Elastic Interactions is the case, then, no energy is transferred from the electron to the sample. As a result, the electron leaving the sample still has its original energy E_0. Such electrons contribute to the direct beam which contains the electrons that passes the sample in direction of the incident beam. Beta batteries have a thick semiconductor layer and these losses can be ignored. Elasticly scattered electrons will take part in the processes of inelastic interaction sooner or later. Therefore, the total cross section is the sum of the elastic (σ_{el}) and inelastic (σ_{inel}) cross sections. The ratio of these sections is determined by the empirical law [16,17]:

$$\frac{\sigma_{inel}}{\sigma_{el}} = \frac{18}{Z}$$

This law shows that the inelastic scattering cross-section for the silicon is larger than the elastic cross section. Electrons are scattered inelastically in 70% of cases.

The processes of inelastic scattered of electrons with matter lead to the following phenomena:

1. The energy of electrons is consumed by the electron-impact ionization of the atoms of matter into which the particle is introduced. This phenomenon produces electron-hole pairs that create a beta-voltaic effect.

2. The β-electrons in the field of the lattice nuclei of a substance results in the appearance of the different signals such plasmons, phonons, UV quanta or cathodoluminescence secondary X-ray radiation, which also reduces the energy of the particles.

3. The energy of electrons is consumed to form lattice defects of matter.

The electron energy of the isotopes used has a value from 2 to 150 keV. This value is small to form defects in the silicon of which the PIN-diode is made. Therefore, phenomenon 3 does not occur in our case. The energy of the β-electrons is small for the formation of any defects. Phenomenon 1 is useful, since it leads to the formation of electron-hole pairs and the appearance of a beta voltaic effect. Phenomenon 2 leads to energy loss, which is not desirable for the operation of beta batteries.

The loss of the energy of any β-electrons by inelastic scattering is determined by the energy of the β-electron and by the mechanism of these losses. The total value of these losses is determined by the Bethe-Bloch theory. In this value, the greatest contribution is made by the mechanisms that are associated with the formation of secondary electrons, plasmons, and X-rays.

The calculations performed in [18] show that in the β-electron energy region up to 100 eV 70% of their energy is expended on the formation of secondary electrons and 30% on the formation plasmons. At energies above 1 keV, the excitation energy of the inner shells of atoms predominates and exceeds the loss of plasmon formation by a factor of 4-6. Calculation of losses associated with secondary X-ray radiation is done in [19]. The coefficient of this losses r is only $\eta_\lambda = 0.2\%$. The results of [20-22] show that the excitation of the L-series will swell less than 10% of the energy. Leamy H.J. [23] believes that the main electron energy losses are due to the formation of secondary electron-hole pairs, and the other losses are 8%. One may assume that 60-80% of the electron energy is expended on the formation of secondary electrons.

4.5 Efficiency of the diode is provided conversion

High energy electrons are generated the electrons and holes in the i-region of the PIN-diode, which causes the current diffusion towards the surface. At diffusion, the electrons and holes recombine by non-radiative recombination centers in the bulk material. We will solve the continuity equation to obtain the theoretical value of the open circuit voltage under the assumptions [9]:

1. Because of the high doping level of the p- and n-regions, as compared to the i-base, the hole current flows through p-i-junction, and electronic current through n-i-junction. This assumption means that because the excess minor carriers do not penetrate the p- and n-regions, the recombination of electron-hole pairs can be neglected;

2. High level of carrier injection is realized in the i-region, then $n \gg n_i$, $p \gg n_i$. The voltage across the resistances of the p- and n-regions due to heavy doping is negligible. Full voltage across the p-i-n-diode is composed of the voltage drops across p-i-transition, n-i-transition and in i-region;

3 At high injection level, the lifetime of charge carriers in the i-region $\tau = \tau_\infty$ and does not depend on the charge carrier concentration (τ_∞ is the lifetime at high excitation level of the semiconductor). This assumption is valid for recombination of the charge carriers through the recombination centers;

4. In the i-region, the condition of the quasineutrality is true (n(x) = p(x)).

Under these assumptions, the equations for the current densities of electrons J_n and holes J_p and the continuity equation of i-region can be written as [9]:

$$J_p = e\mu_p pE - eD_p \frac{dp}{dx} \quad J_n = e\mu_n pE + eD_n \frac{dp}{dx} \tag{18}$$

$$-\frac{1}{e}\frac{dJ_p}{dx} - \frac{p-n_i}{\tau} + G(x) = 0 \quad \frac{1}{e}\frac{dJ_n}{dx} - \frac{p-n_i}{\tau} + G(x) = 0$$

where e is elementary charge; μ_n is mobility of the electrons; μ_p is mobility of holes; p is concentration of holes; F is electric field strength in i-region; D_p is diffusion coefficient of the holes; D_n is diffusion coefficient of the electrons; n_i is the intrinsic carrier concentration; G(x) is distribution function of the generated electrons and holes by i-region.

High-energy electrons, flying out of the isotope layer penetrate the semiconductor and generate secondary electrons, which cause the current. Each β-electron with energy (E) there are generates not one but multiple electron-hole pairs in interaction with the semiconductor material. Therefore, it is necessary to introduce the ratio β-electron energy to the energy of formation of electron-hole pairs in the material into a generation formula. The semiconductor layer parameters should be used for distribution of the generation function along space-charge region. The generation rate of secondary electrons at a depth x is determined by the electrons of all energies that are emitted from the β-source, so:

$$G(x) = A_s * \int_0^{E_{\max}} W_c(E) * \frac{E}{E_i} * h\left(\frac{x}{R_{ef}(E)}\right) dE$$,(19)

where $E_i = 2.596E_g + 0.714 = 3.62eV = 0.00362keV$ is energy of the formation of electron-hole pairs in silicon.

The density of silicon substituted into Eq. (10), which determines R(E). The Eq. (19) defines the number of electrons generated per second at a depth x (Fig.6). Dependency G(x) can be described by the empirical function in general

$$G(x) = g_1 \sum_{i=1}^{n} A_i \exp(-k_i x)$$,(20)

where g_1 is generation rate of electron-hole pairs by β-electrons; A_i and k_i are approximation constants of the generation rate determined by the Eq. (19).

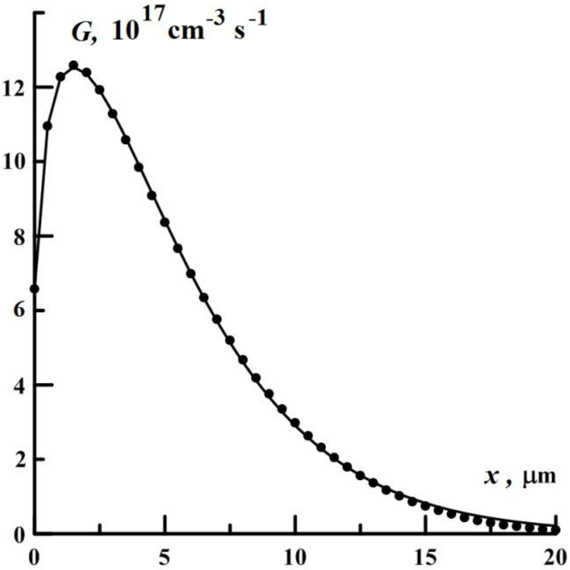

Figure 6: Distribution of high-energy electrons in the space-charge region of the PIN-diodes. Points is calculation by the Eq. (19); line is the approximation of calculation by three exponential terms by Eq. (20).

To calculate the open-circuit voltage it is necessary to solve the continuity equation Eq. (18). It is possible to formulate the problem in our case:

$$\begin{cases} \dfrac{d^2(p-n_i)}{dx^2} - \dfrac{p-n_i}{L_a^{\ 2}} + \dfrac{g_1}{D_a} \sum_{i=1}^{n} A_i \exp(-k_i x) = 0; \\ n = p; \\ \left.\dfrac{dp}{dx}\right|_{x=0} = -\dfrac{J}{2eD_p}; \\ \left.\dfrac{dp}{dx}\right|_{x=W} = \dfrac{J}{2eD_n}; \end{cases}$$ (21)

where $D_a = \dfrac{2k_B T \mu_p \mu_n}{e(\mu_p + \mu_n)}$ is ambipolar diffusion coefficient; e is the elementary charge; k_B is the Boltzmann constant; $D_{p(n)} = \dfrac{k_B T}{e} \mu_{p(n)}$ is diffusion coefficient; $L_a^{\ 2} = D_a \tau$ is ambipolar diffusion length; W is thickness of the i-region. A solution of Eq. (21) is a relationship:

$$p(x)=n_i+\frac{JL_a}{2e\,sh\left(\frac{W}{L_a}\right)}\left[\frac{ch\left(\frac{x}{L_a}\right)}{D_n}+\frac{ch\left(\frac{W-x}{L_a}\right)}{D_p}\right]+$$
$$+\frac{L_a}{sh\left(\frac{W}{L_a}\right)}\left[-\beta\,ch\left(\frac{x}{L_a}\right)+\alpha\,ch\left(\frac{W-x}{L_a}\right)\right]+$$
$$+\frac{g_1L_a^{\ 2}}{D_a}\sum_{i=1}^{n}\frac{A_i\exp(-k_ix)}{1-L_a^{\ 2}k_i^{\ 2}} \qquad (22)$$

Here we use the notations:

$$\begin{cases}\alpha=\dfrac{g_1L_a^{\ 2}}{D_a}\displaystyle\sum_{i=1}^{n}\dfrac{-k_iA_i}{1-L_a^{\ 2}k_i^{\ 2}};\\ \beta=\dfrac{g_1L_a^{\ 2}}{D_a}\displaystyle\sum_{i=1}^{n}\dfrac{-k_iA_i\exp(-k_iW)}{1-L_a^{\ 2}k_i^{\ 2}};\end{cases}\quad \begin{cases}\tilde{\alpha}=\dfrac{g_1L_a^{\ 2}}{D_a}\displaystyle\sum_{i=1}^{n}\dfrac{A_i}{1-L_a^{\ 2}k_i^{\ 2}};\\ \tilde{\beta}=\dfrac{g_1L_a^{\ 2}}{D_a}\displaystyle\sum_{i=1}^{n}\dfrac{A_i\exp(-k_iW)}{1-L_a^{\ 2}k_i^{\ 2}};\end{cases} \qquad (23)$$

We can calculate the idling voltage from the Ed. (22) and (23) it follows that:

$$U_{xx}=\frac{k_BT}{e}\ln\left(\frac{1}{n_i^2}\left(n_i+\frac{L_a}{sh\left(\frac{W}{L_a}\right)}\left[-\beta+\alpha\,ch\left(\frac{W}{L_a}\right)\right]+\tilde{\alpha}\right)\left(n_i+\frac{L_a}{sh\left(\frac{W}{L_a}\right)}\left[-\beta\,ch\left(\frac{W}{L_a}\right)+\alpha\right]+\tilde{\beta}\right)\right)+$$
$$+\frac{D_n-D_p}{\mu_p+\mu_n}\ln\left(\frac{n_i+\frac{L_a}{sh\left(\frac{W}{L_a}\right)}\left[-\beta+\alpha\,ch\left(\frac{W}{L_a}\right)\right]+\tilde{\alpha}}{n_i+\frac{L_a}{sh\left(\frac{W}{L_a}\right)}\left[-\beta\,ch\left(\frac{W}{L_a}\right)+\alpha\right]+\tilde{\beta}}\right) \qquad (24)$$

We can calculate the current of the PIN-structure only by numerical methods. We cat to get η_s after that by equation:

$$\eta_s=F_{ef}I_{sc}U_{xx}. \qquad (25)$$

However, if we do not know anything about the processes of generation and recombination in the PIN-diode, the properties of the recombination centers in it, the lifetimes of electrons and holes, we can’t to calculate the efficiency of a semiconductor converter.

5. Conclusions

The efficiency of the beta battery is dependent on a number of factors and is determined by the Ed. (4). The fraction of β-electrons, which reach the semiconductor converter surface η_β, is about 0.4. This is due to the fact that at the optimal thickness 80% of β-electrons pass into the radiation and half of them go back to the source. Some of the electrons are reflected from the surface of the semiconductor. This fraction which arrive the space-charge region and can contribute to the electric current is 0.7. The fraction of β-electrons that cause electron-hole pairs (η_{e-h}) is 0.6-0.8. The efficiency of the diode which provides conversion (η_s) is 0.66 in our case. The total efficiency is 0.12-0.16. The experimental value of the efficiency is 0.01. These values differ from each other and this is due to two factors: 1 - recombination in the active region of the diode; 2 - excess return current, which is not described by the classical Shockley-Read theory.

The number of secondary electrons that are generated by one β-electron and it can take part in the creation of an electric current is determined by the energy of the β-electron and the width of the forbidden band of the semiconductor.

$$N = \frac{E_{midl}}{2.8E_g + 0.5}$$

A great advantage of the isotope Ni-63 is the high energy of the electrons and the absence of harmful spurious emissions, such as gamma quants. Therefore, this isotope exceeds tritium and Pm-147. This β-source allows you to get the best electrical parameters of the batteries even with less activity of the source. Loss of energy in beta batteries should be analyzed and understand ways to increase the efficiency

References

1. Bower KE, Barbanel YA, Shreter YG, *et al*. Polymers, Phosphors, and Voltaics for Radioisotope Microbatteries. CRC Press, Boca Raton, London, New York, Washington. 2002; 472 p.
2. Reznev AA, Pustovalov AA, Maksimov EM, *et al*. Perspektivy sozdaniya miniatyurnogo istochnika toka na beta-voltaicheskom effekte s ispolzovaniem v kachestve aktivnogo elementa izotopa Ni-63. Nano- Mikrosist. Tekh. 2009; 3 (104): 14-16.
3. Chandrashekhar MVS, Thomas ChI, Li H, *et al*. Demonstration of a 4H SiC betavoltaic cell. Appl. Phys. Lett. 2006; 88: 033506-3.
4. Eiting CJ, Krishnamoorthy V, Romero E, *et al*. Proceedings of the 42nd Power Source Conference, Philadelphia, PA, June 12–15, 2006; 601-606.
5. Andreev VM, Kavetsky AG, Khvostikov VS, *et al*. Tritium-powered betacells based on $Al_xGa_{1-x}As$. Proceedings of the 28th IEEE Photovoltaic Specialists Conference, Anchorage, 2000; 1253-1256.
6. Rybicki GC. Silicon Carbide Radioisotope Batteries. NASA/CP-2001-210747/REV1, 2001; 199-233.
7. Guo H, Lal A. Nanopower Betavoltaic Microbatteries. Transducers, Solid-State Sensors, Actuators and Microsystems, 12th International Conference, Boston, 2003; 36-39.
8. Sun W, Kherani NP, *et al*. A Three-Dimensional Porous Silicon p-n Diode for Betavoltaics and Photovoltaics. Adv. Mater. 2005; 17: 1230-1233.
9. Sze SM. Physics of Semiconductor Devices. John Wiley and Sons (WIE), New York, Chichester, Brisbar, Toronto, Singapore, 1981; 868 p.
10. Everhart TE, Hoff P.H. Determination of kilovolt electron energy dissipation versus penetration distance in solid materials. J. Appl. Phys. 1971; 42: 5837-5846.
11. Ong VKS, Phua PC. Junction depth determination by reconstruction of the charge collection probability in a semiconductor device. Semicond. Sci. Technol. 2001; 16: 691-698.
12. Kolobashkin VM, Rubtsov PM, Aleksankin VG, Ruzhanskiy PA Beta-izluchenie produktov deleniya: Spravochnik. Atomizdat, Moscow, 1978; 472 p. (Beta-radiation of fission products: Handbook)
13. Arnal H, Verdier P, Vincensini P. Coefficient de retrodiffussion dans de gas d'electrons monocinetiques arrivant sur la cible sous une incindence oblique. Compt. Rend. Acad. Sci. 1969; 386: 1526-1536.
14. Remier L, Tollkamp C. Measuring the backscattering coefficient and secondary electron yield inside a SEM. Scanning. 1980; 3: 35-39.
15. Seltzer SM Transmission of Electrons through Foils. National Bureau of Standards. Washington, D.C. 20234. 1974.
16. Reimer L. Transmission Electron Microscopy, Physics of Image Formation, and Microanalysis. Springer, Berlin. 1989; 547 p.
17. Egerton RF. Electron Energy-Loss Spectroscopy in the Electron Microscope. Plenum Press, New York. 1996; 485 p.
18. Tung CJ, Ritchie RH, Ashley JC *et al*. Inelastic Interactions of Swift Electrons in Solids. Port Royal Hoad, Springfield, Virginia. 1976; 118 p.
19. Pucherov NN, Romanovsky SV, Chesnokova ND *et al*. Tablicy massovoy tormoznoy sposobnosti i probegov zaryazhennyh chastic s energiey 1-100 MeV. Kiev: "Naukova Dumka". 1975. 345 p. (Tables of the mass stopping power and ranges of charged particles with an energy of 1-100 MeV)
20. Egerton RF. Electron Energy-Loss Spectroscopy in the Electron Microscope, appendix B. Plenum Press, New York. 1986; 410 p.
21. Bartlett PL, Stelbovics AT. Calculation of electron-impact total-ionization cross sections. Phys. Rev. A 2002; 66: 012707-10.
22. Gryzinski M. Classical Theory of Atomic Collisions. I. Theory of Inelastic Collisions. Phys. Rev. 1965; 138: A336-A358.
23. Leamy HJ. Charge Collection Scanning Electron Microscopy J. Appl. Phys. 1982; 53: R51-R80.