Betavoltaic p⁻⁻n⁺-structure simulation

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Abstract. In order to increase the betavoltaic batteries efficiency output characteristics of the p⁻⁻n⁺ (n⁻⁻p⁺) - structures were simulated. Replacing the p⁺⁻n⁻-structures on the p⁻⁻n⁺ and n⁻⁻p⁺-structures enables the space-charge expansion to the crystal surface and thus to reduce the recombination loss in the heavy doped p⁺-layer and improve conversion of betavoltaic elements efficiency.

1. Introduction
Modern electronic systems more and more need power batteries for electrical and mechanical devices (MEMS). Traditional chemical power batteries are not suitable for power supplying MEMS devices due to their low power density and short lifetime [1]. The need for low output power, long lifetime and no need to repair inherent of devices that are used in electronic equipment, space satellites, sensors in remote locations (mines, far north, etc.), as well as in implantable medical devices.

Betavoltaic batteries are promising power sources with a long lifetime, which are suitable for a variety of low-power devices. Work of betavoltaic sources is based on the principle of converting the β-radiation emitted by the decay of a radioactive isotope, into electrical energy in the semiconductor body. The vast betavoltaic power supply consists of a beta-emitting material connected with p⁻⁻n⁺-junction [2-6].

Betavoltaic cells produce the power like photovoltaic devices and solar cells. One of the main processes taking place in the semiconductor when an electron contacts with it with energy 1-100 keV, is the ionization of atoms along the electron trajectory. As a result, in the semiconductor forming a great number of electron-hole pairs along the trajectory of high power electron. With a relatively low energy of the outer electron (up to 100 keV), knocking out electrons from the semiconductor atoms and the formation of pairs are the dominant processes, so the number of pairs is proportional to the energy of the outer electron. Under the action of the static electric field these pairs form the current having a value proportional to the product of the electrons flow and their energy.

2. Results and discussion
Optimizing the performance of radiation-stimulated power sources by selecting the doping level of the various regions and their sizes has limitations, so further improvement of device structures requires the selection of new betavoltaic element structures. Simulating of the formation of the power batteries output parameters allows to optimize the design of the device, without the need for expensive experiments. Simulation of the characteristics was carried out using a numerical solution of the basic system of equations given in [7, 8]. As the initial structure for simulation was taken p⁻⁻n⁺-structure shown in figure 1.
Previous simulation results obtained showed definite increase efficiency while reducing the depth of the p-n-junction, which is caused by the approach of the space charge region to the area with higher velocity of the generation radiation-stimulated of the mobile charge carriers [8]. Another way to increase the power efficiency can be changes in the level of doping regions so that the surface was light doped region, i.e. replacing p’ n-structure by p’ n’ structure. This achieves expansion space charge region not into the semiconductor but to the surface, that reduces recombination losses in heavy doped p’-layer.

Figure 2 shows the influence of the p’-n’-junction depth on the output parameters betavoltaic elements at different levels of doping the upper light doped p’-layer.

The released electric power increases with a decrease of the doping level in the light doped region and reducing the p-n-junction depth up to 1 micron, i.e., when approaching depletion region to the surface structure. When the impurity concentration in the p’-layer is $10^{15}$ cm$^{-3}$, the space charge region
reaches the surface structure with a thickness of a doped region light less than 1 micron. By reducing
the doping level less than $10^{12}$ cm$^{-3}$, the space charge region doesn’t reach the surface only at a
thickness more than 25 microns. The increase in the width of the depletion region at a concentration of
$10^{12}$ cm$^{-3}$ and a thickness more 25 microns causes to a significant decrease in efficiency compared to
the structures with a higher doping level. This is due to a significant increase of the space charge
region and, consequently, an increase of the current generation, which reduces the floating voltage,
and thus efficiency. It is interesting to consider how the structure various areas influence on the
generation current. Figure 3 shows the change of the different areas contribution at the doping level of
$10^{12}$ cm$^{-3}$.

![Figure 3](image)

**Figure 3.** Changing the different regions contribution in p-n$^+$-structure: a) the doping level of p-type
region $10^{12}$ cm$^{-3}$, b) the doping level of p-type region $10^{13}$ cm$^{-3}$.
(Source activity $^{63}$Ni – 2.7 mCi / cm$^2$).

At the light doped region thickness is 25 microns, when the space charge region does not reach the
surface the significant contribution to the electron stimulated current the p-type region electrons
contribute. By reducing the light doped region thickness, when the space charge region reaches the
surface the p-field electron current decreases to zero, the short circuit current is determined only by the
space-charge region current. With a further decrease in the p-type region thickness it is reduced space
charge region contribution, and simultaneously the total current is reduced. Then the contribution of
the depletion region continues to decline, but the area of charge carriers generation reaches the n-
region and the contribution of holes begins to increase.

By increasing the doping level of the p-region to $10^{13}$ cm$^{-3}$ the change in the areas contribution is
another trend (figure 3b). At the big thickness of the light doped region the main contribution to the
short-circuit current of the p-region electrons give and at light doped region thickness less than
10 microns the significant contribution depletion area provides.

Another problem to be considered is the type of conductivity of light doped p region or n-type. For
the p$^+$n-junction answer is obvious because at the required large depletion region the main contribution
comes from the space charge region and p$^+$-region electrons. The electrons mobility is higher, so
p$^+$n-structures are preferable. Simulation results presented in figure 4 show that the doping level of the
light doped region $10^{12}$ cm$^{-3}$ and the light doped region thickness less than 20 microns greater
efficiency is obtained for n$^+$-p$^+$-structures.
Figure 4. The thickness influence of the light doped region for p'-n' - and n'-p' structures on betavoltaic elements efficiency: a) the doping level of the light doped region - $10^{12}$ cm$^{-3}$, b) doping level of the light doped region - $10^{13}$ cm$^{-3}$ (Source activity 63Ni - 2.7 mCi / cm²).

It is caused by the fact that at small thickness of the light doped region, when the depletion region reaches the surface, the mobile carriers of quasi-neutral part in the light doped region do not contribute, and an additional contribution to the radiation-induced signal the mobile heavily doped region carriers provide. In the case of n'-p' structure these are electrons, which mobility is higher. By increasing the doping level to $10^{13}$ cm$^{-3}$, the efficiency is higher for p'-n' structure at light doped region thickness of more than 10 microns (figure 4b).

3. Conclusions
Usage as upper layer the light doped semiconductor (p-n' - and n-p' -structure) gives the possibility for extension of the space charge region to the direction of the surface and allows theoretically to increase the efficiency more than 1 %.

However, it requires manufacturing high quality surface structures to provide a low surface recombination velocity, i.e. the lifetime of mobile charge carriers close to the bulk one. At the doping level of the light doped region of $10^{12}$ cm$^{-3}$ and a small thickness of the upper i-layer (when the depletion region reaches the surface) the n'-p'-structure efficiency is higher than p'-n'-structure.

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