Betavoltaic device in *por-SiC/Si*

C-Nuclear Energy Converter

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Abstract. The miniature and low-power devices with long service life in hard operating conditions like the Carbon-14 beta-decay energy converters indeed as eternal resource for integrated MEMS and NEMS are considered. Authors discuss how to create the power supply for MEMS/NEMS devices, based on porous SiC/Si structure, which are tested to be used as the beta-decay energy converters of radioactive C-14 into electrical energy. This is based on the silicon carbide obtaining by self-organizing mono 3C-SiC endotaxy on the Si substrate. The new idea is the C-14 atoms including in molecules in the silicon carbide porous structure by this technology, which will increase the efficiency of the converter due to the greater intensity of electron-hole pairs generation rate in the space charge region. The synthesis of C-14 can be also performed by using the electronically controlled magneto-optic chamber.

1 Introduction

The development of energy-saving technologies, the functioning of the MEMS devices, the reliability of their operation for a long time in offline conditions led to the search of appropriate means of generating energy for them. Especially in the trends of microelectronics on the benchmark 30 micron size active microprocessor board that hosts all the necessary devices.

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Betavoltaic devices, also known as betavoltaic cells, are generators of electric current, in effect is the form of battery, which uses the energy from radionuclides emitting beta particles (electrons) [1]. A common source used is the hydrogen isotope, tritium, or Nickel-63.

From history it is well known that nuclear battery technology began in 1913, when Henry Moseley first demonstrated the beta cell [2]. And today the global market for active medical implants in 2016 amounted to 24.8 billions US dollars, and the capacity of the potential market of batteries in 2020 is estimated at $ 40 billions. The annual demand of Russian patients in pacemakers is about 60 thousands [3–5].

In this paper authors will discuss how to create the power source for MEMS/NEMS devices based on por-SiC/Si porous structure, which is tested to be used as the beta-decay energy converter of radioactive Carbon-14 into electrical energy [6–9]. This involves silicon carbide obtaining by self-organizing mono 3C-SiC endotaxy way on the Si substrate [10, 11]. The key interest in the present aspect has the systematic optimization of main parameters that affect the operational efficiency of the betavoltaic current source [12].

Energy converters of beta radiation are based on isotopes transformations reactions with half-lives of more than 100 years. Energy converters are designed to secure operational performance, allowing reinstallation on the objects with the corresponding lifetime. Analogues were brought out to the laboratory samples level for two years. The groundwork of this project is on the part of semiconductor technology: mastered growing por-SiC/Si heterostructures. The groundwork for the development of an energy source not specified. But there is information of methods and businesses with similar activities [12–17]. The use of the product will effectively solve the following problems: the provision of energy for autonomous systems and devices, MEMS devices, sensors in oil capital constructions as example, information systems ⚭ systems, including biosensors of medical direction and equipment.

1.1 Betavoltaics power source for pacemaker

There are a number of ways to use betavoltaics power sources in heart pacemakers [5]. The first way is to replace the lithium-ion battery in the pacemaker to betavoltaic source. The advantage of this method is compact because betavoltaic source is small in size and easy to fit into the pacemaker without changing the design. However, this method has some difficulties: modern betavoltaic sources can not provide sufficient power and stable DC current for simultaneous charging of the capacitor and the power drive circuit of the pacemaker.

The second method is the simultaneous use of a lithium-ion battery and betavoltaic source. Li-ion battery will power the control circuit and to charge the capacitors in the pulse generator, and betavoltaic source will be connected to the lithium-ion battery through the charge controller, and shall provide drip recharging the battery. Drip – charging a small current to compensate for self-discharge or discharging at low external load. Typically, this method of charging is used for lead-acid batteries to extend their lifespan, but can be used for lithium-ion batteries also. Because lithium-ion batteries are sensitive to overcharging, you need to implement drip charging through the charge controller. The pacemaker is a constant drip rechargeable lithium-ion battery will greatly increase its life cycle. The advantage of this method is the lack of necessary changes in the design of the pacemaker - you only need to slightly increase the body to fit two batteries and a charge controller. The downside is the increase in the size of a pacemaker, which may complicate implantation. However, given the size betavoltaic power supplies and charge controller, increasing the hull will be negligible. It is only necessary to make a small charge controller.

2 Model of the semiconductor betavoltaic Energy Converter device

Unlike most nuclear power sources, which use nuclear radiation to generate heat, which then is used to generate electricity (thermoelectric and thermionic sources), betavoltaics uses the non-thermal conversion process, converting electron-hole pairs produced by the ionization trail of beta particles traversing the semiconductor [12, 13, 18].

There are two competitive directions of the betavoltaic converters development: the accumulation of charges in the reactions of transformation of elements using supercapacitors; the charge separation in p-n junction of the solar battery analogue [13]; the combination of the two directions. In all cases, the main competitive advantage over other energy sources is the long life cycle of beta-converter. The disadvantage is due to low capacity and low efficiency, which is overcome technological way (the higher degree of enrichment of isotope using the developed nanoporous surfaces, reducing the leakage current of super capacitor and p-n junction, using a combination of several sources of beta-radiation flux; the system microcontroller, which controls the flow of the charge). The ratio 'price/performance' is determined by several factors: semiconductors heterostructures provide a price level conventional semiconductor discrete diodes or transistors, high power, the technology of nuclear fusion, the working fluid used in the operation of medical devices provide a level of price acceptable to the consumer, when there is no alternative. Planning design parameters and performances are following: Voltage range ~ 2 mV, Size of the device $\sim 10 \times 10 \times 0.3 \div 0.5$ mm, Mass of each structural element ≈ 0.17 g, Working current range 0.1 μA, Working temperature range $-50 \div 350^0$C.

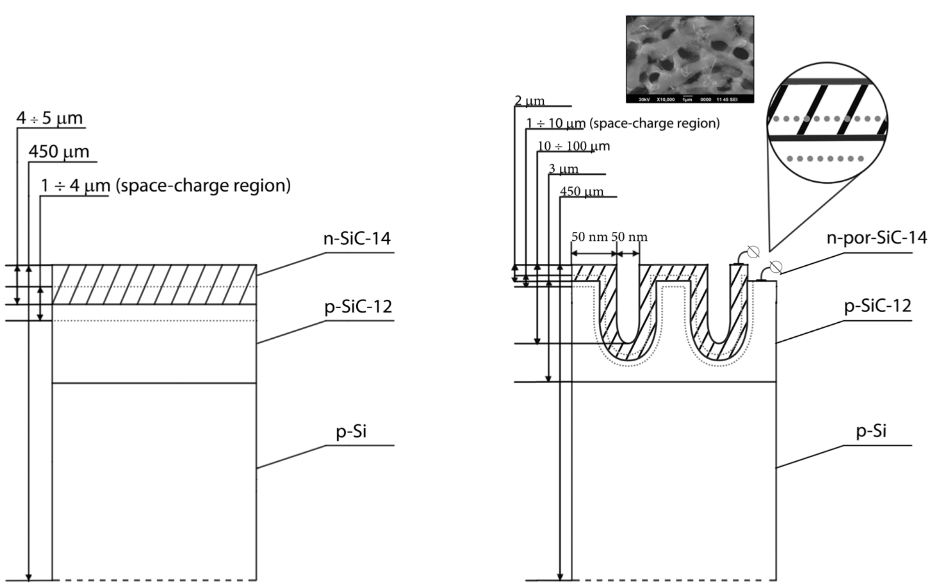

Figure 1. Two model structures variants [19].

The non-porous layer of n-type is determined by under the porous SiC, which is inevitably formed on the bottom of the pores and in fact is non-porous, i. e. p-n junction is the place to be in the right picture in Fig. 1 is still not in the porous layer. and indirectly associated with it and the space-charge region (SCR), between non-porous layers.

3 Carbon-14 choice of as the fuel

The data yield a conclusion on the promise of a new betavoltaic power supply source, namely, the nuclear battery based on Carbon-14, as the active substance would be more useful and less expensive [20]. Additional advantages of such power supply sources can be obtained in a silicon carbide structure based on the technology we developed [19]. Below let us consider the following comparison [20] with a technology that uses Nickel-63.

1. The production of C-14 in the dense ion plasma flow is much cheaper than the production of Ni-63 in Nickel target, due to the low cost of N-14.

2. Ion-plasma implantation C-14 on SiC substrate allows to reduce the crystal process and realize wide production on semiconductor converters on C-14.

3. At the same time, the production of Ni-63 by this technology is also possible, and the cost will be much reduced compared to traditional methods. Because of the greater mass of the ions, the equipment for ion-plasma sputtering with a seal of the flow of Nickel ions will be several times more expensive because of increased working installation area. At this stage, it is more sophisticated to produce C-14.

4. Specific activity of C-14 is different from the Ni-63 about in 10 times per unit volume, due to the huge difference in half-life times.

5. Self-absorption of Ni-63 is larger by approximately three times, which leads to the maximum limit optimal thickness of the layer to 4 microns, and for C-14 this thickness may be up to 60 microns which is better suited. The total quantity of the isotope C-14 may be an order of magnitude greater, therefore, guaranteed more power for the same size of power converters.

6. The specific power of Ni-63 per gram of the substance 5 times (due to more activity) exceeds the power density of C -14. But the maximum and average energies of electrons in the C-14 decay is in 2, and even 3, times more than in the Ni-63 decay.

7. The production cost of 12 *m*g C-14 will take approximately 8 hours, taking into account equipment depreciation, will cost about 170$.

Battery performance characteristics for automotive power applications can be described in terms of two parameters, specific power and specific energy. Specific power is related to the speed of vehicles and acceleration. Specific energy is related to range. Using these two variables, data are presented graphically for a number of commercially available battery systems and battery systems in development [21]. Both axes are logarithmic, which allows comparing performance of very different devices (for example, extremely high and extremely low power). The Ragone plot was first used to compare performance of batteries. It is suitable to compare any energy-storing devices [22].

4 Self-organizing mono 3C-SiC endotaxy technology

Authors present an original technology of manufacture and a model of the isotope energy converter based on the silicon carbide heterostructure, with Carbon-14 as fuel. The radionuclide C-14 is incorporated into the SiC molecule instead C-12 in the por-SiC phase in-por-SiC/SiC/Si heterostructure. Beta-radiation generates nonequilibrium charge carriers, separated by the internal field of p-n junction in the SiC-phase. The concept is based on the solid-phase transformation according to the Si-phase transformation diffusion model into the *SiC*-phase, which allows the buildup of *in*-por-*SiC* heterostructures [10, 11, 23, 24].

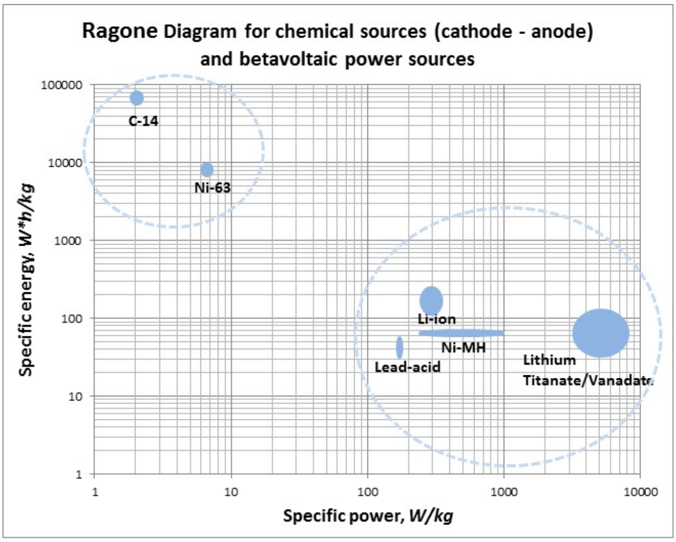

Figure 2. Ragone Diagram.

This is also possible to achieve by ion implantation of Carbon-14 into the silicon carbide phase [25–27]. The latter approach to the direct conversion can increase the effectiveness of betavoltaic energy converters.

To analyze concentration of Carbon atoms in SiC heterostructure, SIMS method was used. We provide one example (for the left picture case in Fig.1) to illustrate the generation of in SiC/Si heterostructure phase [28].

The method of secondary ion mass spectrometry (SIMS) [29–31] is used to analyze the composition of solid surfaces and thin substrates. The essence of the method is to irradiate the sample surface by a focused beam of ions (primary ions). When hitting the sample, the primary ions undergo multiple collisions, which are emitted from the sample atoms and clusters of atoms in the process of collisions, the latter spontaneously ionized (forming secondary ions). These secondary ions are collected in the secondary beam and analyzed.

The feature of the endotaxy process is the technological method of forming a p-n junction during SiC phase growth by diffusion mechanism. Homotransition is obtained by means of the previously entered extraneous impurities realloying [32]. This is illustrated on the Fig. 3 by the intersection of the concentration distributions of impurities: lines KDB_P and KDB_Ga at point **A** at the depth of 2.5 microns, and/or lines KDB_P and KDB_B at the point **B** of 7.5 μm depth.

The technology of the temperature sequence of phase transitions during solid diffusion allows for the appropriate controlling and stabilization along the way to grow up carbide contacts in the form of nanowhiskers and nanothreads [19].

4.1 Magneto optic synthesis chamber

The synthesis of Carbon-14 can be also performed by using the electronically controlled synthesis of nucleons in the 8-cyclic magneto-optic synthesis chamber [33–35]. Generation proton flux for

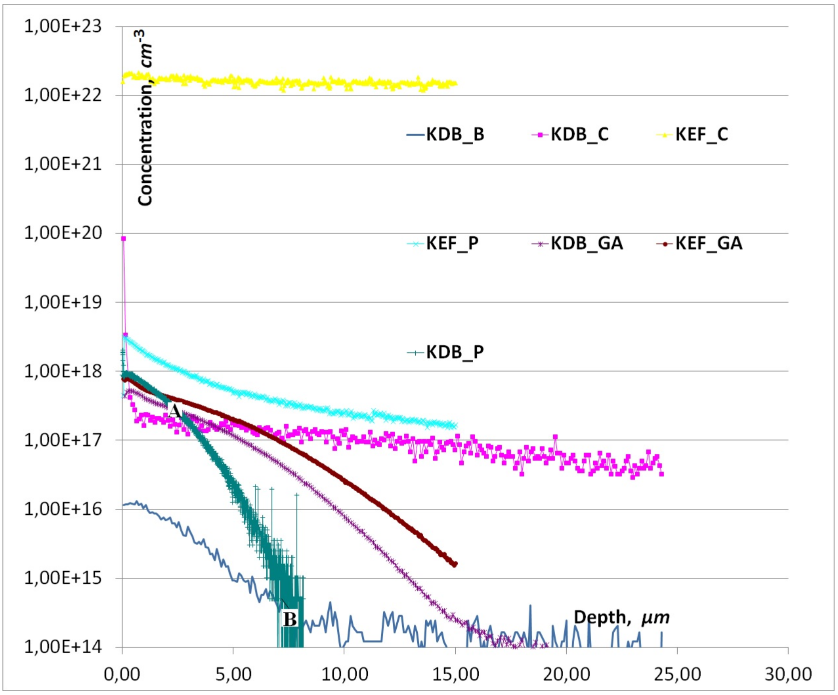

Figure 3. Diagram of concentrations dependencies on depth. The analyzed depth ranges from 5.3×10^{-8} to 24.3×10^{-6} m. The concentration of C-12 atoms (KDB_C curve), depending on the analyzed depth, ranges from 8.4×10^{19} to 3.2×10^{16} [20, 28].

the synthesis of neutrons by lithium ion target as a result of compaction of the primary flux of protons and sampling of parameters specify the density and average energy of the flow. Electronically controllable streams are formed in parameters repetition period T_{sl} and frequency discrete streams ω_{sl}. Generation dense proton flux for the synthesis of neutrons by lithium ion targets:

$$D + Li^6 \rightarrow Be^7 + n^0, \qquad D + Li^7 \rightarrow 2He^4 + n^0. \tag{1}$$

The synthesis reaction at the target dense nitrogen ions:

$$D + Li^7 \rightarrow C^4 + p^+. \tag{2}$$

The Device (see Fig. 4) consists of electronically controlled ion sources with magneto optic flux concentration with the ion energy of up to 50 keV, electronically controlled pulsed accelerator sections that form discrete ion flux with the ion energy from 200 to 600 keV, combined with an 8-cyclic magneto optic synthesis chamber and a controlled magneto-dynamic trap for generating dense neutron fluxes. The synthesis of C-14 by neutrons goes in a 4-cycle magneto optic chamber on the dense ion target. At the final stage, C-14 from the magneto optic storage is deposited on the SiC substrate. Multilayer formation of C-14 on the SiC substrate or on substrates from other materials is also possible.

The total energy of the incident particle and the target is above the Coulomb repulsion energy. Density n_i impinging stream for pulsed operation is equal to or above 10^{22} cm^{-3}. Retention time in

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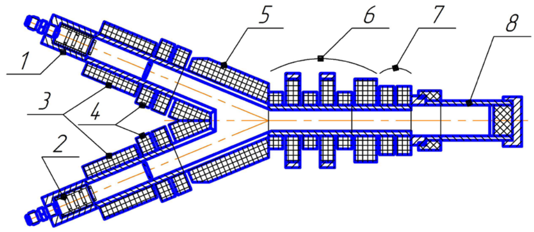

Figure 4. Magneto optic synthesis chamber. *1* – lithium deuteride LiD ionization, *2* – nitrogen N ionization, *3* – injector, *4* – magneto-optical drive-driver, *5* – accelerator-driver, *6* – magneto dynamic eight cyclic camera, *7* – magneto-optical drive-limiter, *8* – the C-14 drainage system. The density of neutron flux n=7.477E+18 cm^{-3}, the energy of neutrons in 1sr reaction (1): 2.72 E+6 MeV, the energy of neutrons is 2nd reaction (1): 12.0 E+6 MeV.

the magneto optical chamber with $\tau \geq 1$ s on one nuclear cycle. There is the ability to generate an 8-cycle synthesis of particles of different grades. Support deuterium-lithium reactions synthesis with a retention time in the system above the magneto optic c a single cycle is of 5 seconds.

4.2 Modeling estimates

As a basis for modeling and calculating of betavoltaic cell, working with the C-14 isotope, the model developed in [13] was chosen. The model is the simple structure of p-n junction in the cell, considered in cross section in Fig. 1 and takes into account such characteristics as: the generation rate, ionization loss energy, the electron-hole pairs formation, and the electron flux density. Betavoltaic cells based on standard silicon solar cells with bilateral coating with beta-radiation sources in the form of 63Ni isotope have been studied experimentally and by numerical simulation [13]. The optimal parameters of the cell, including its thickness, the doping level of the substrate, the depth of the p–n junction on its front side, and the p+ layer on the back side, as well as the activity of the source material, have been calculated in [13]. The limiting theoretical values of the open-circuit voltage (0.26 V), short-circuiting current (2.1 μA), the output power of the cell (0.39 μW), and the efficiency of the conversion of the radioactive energy onto the electric energy (4.8%) have been determined for a beta-source activity of 40 mCi. The results of numerical analysis have been compared with the experimental data in [13].

However, this model [13] does not account for some features of our battery and subsequently would be updated. In the simulation the Fig. 5 shows the comparison of the generation rate for C-14 and Ni-63 depending on the depth.

The Nickel-63 has larger generation rate, but C-14 electrons penetrate deeper. So the total rate of generation can be roughly the same, given the larger surface in the model isotope matrix with C-14 in the form of SiC-14 molecules in por-SiC/SiC/Si .

5 Summary

This development is intended for practical applications in MEMS and NEMS systems and sensors that require long-term autonomous operation. The suitability of C-14 as a source of beta-cells is proposed. Highlights the key parameters affecting the efficiency of beta-cells and conducted a qualitative analysis of the ways to increase the effectiveness of beta-source C-14 in the molecule SiC. Separately it is

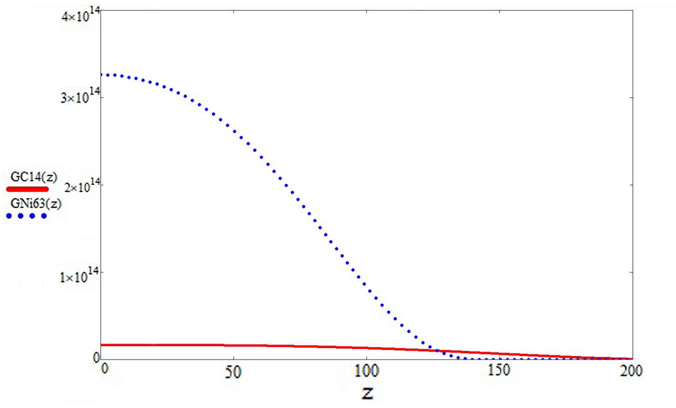

Figure 5. Generation rate comparison for C-14 and Ni-63. Notations for C-14 – solid red curve, Ni-63 – dot blue curve. Parameters: C-14 Specific activity 1.648×10^{11} Becquerel/gram. The energy at the one electron-hole pair of is 3.6 eV. The area of 4 cm^2 (as in [13]).

necessary to solve the problem of isotope enrichment C-14. We need to develop and conduct a series of experiments to verify the theoretical calculations and hypotheses.

The production of Carbon-14 at a cost lower than traditional production. The source of the neutron fluxes for the synthesis of radioactive isotopes for medical purposes. Modification device to vacuum ion-plasma deposition of Carbon-14 on the SiC substrate is developing still.

A method of implantation C-14 in molecule por-SiC is in step preparation heterostructures of p-n-transition. Technology has been developed and a mathematical model of the converter manufacturing: technological (route maps, physical parameters, tools) and design (assembly devices, housing, terminals, electrical insulation, recycling methods) documentation.

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