Optimization Design and Simulation of a betavoltaic nuclear battery based on Sr/Y-90 with MCNP/Geant4 codes

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Abstract
Betavoltaic battery is a device that converts the energy deposition due to the decay energy of beta emitting radioisotopes into electricity. In this paper, we have designed and simulated an optimized betavoltaic battery based on Sr/Y-90. Simulation is performed with multiple calculation codes. MCNP, Geant4 and Matlab computational codes are used to calculate the final output of the this battery. These codes are used for calculation of the deposited energy from beta particles and generated electron-hole pair in the semiconductor. Simulation results are compared with experimental results and prove to be accurate. Circular monocrystal silicon PIN diode with thicknesses of 500 micrometers in 0.5 cm radius and Sr/Y-90 radioisotope with 10 mCi activity is used in both simulation and experimental setup. As compared to experimental results, the findings indicate the high accuracy of the simulation.

Keywords: Sr/Y-90, Betavoltaic, Geant4, MCNP

Introduction
Nuclear batteries are long life energy sources which have attracted research interests in recent years. With the advancement of micro-electromechanical system (MEMS), small scale power sources have slowly become a bottleneck in MEMS applications. Because of their limitations in terms of volume, service lifetime, capacity to adjust to the environment etc., many types of miniaturized power source, such as solar cells and micro fuel cells, cannot fulfill the demands of MEMS devices for energy. Betavoltaic microbattery, with simple integration, stable yield performance, long service lifetime, high energy density, anti-jamming, and so on, has become one of the foremost critical types of the micro power source and is expected to end up as the finest choice of MEMS. [1] These types of nuclear batteries are categorized in the class of direct conversion nuclear batteries. In such cells the semiconductor structures with a p-n junction or Schottky barrier are used to convert energy deposition of radioactive decay into electric current.
Fabrication of effective betavoltaic battery requires thorough understanding of processes of charge carrier generation by deposited energy of beta rays inside a semiconductor device. [2]
The development of fabricated models would allow the calculation of output values of this batteries that can be achieved in devices fabricated of various semiconductor layers. However, in spite of a noticeable number of publications focused on this problem, the accuracy of estimation is unsatisfactory. For example, the published short circuit current values for Si-based semiconductors obtained by Zuo et al., 2013; Gorbatsevich et al., 2016, when normalized to the same source activity of 10 mCi/cm2, varied from 24.4 (Zuo et al., 2013) to 540 nA/cm2 (Gorbatsevich et al., 2016). The measurnment accuracy between the calculated and experimental values is not acceptable, the difference reaching up to 10 times.[3-5] In this paper we have designed and simulated a betavoltaic nuclear battery based on Sr/Y-90 radioisotope using MCNP/ GEANT4/ and MATLAB codes and compared the results with experiments. [6-8]

Materials and methods
Semiconductors, such as Si, GaAs, SiC, GaN, are mainly used for betavoltaic nuclear batteries. Si semiconductors are used in both experimental and theorical calculations. The theoretical energy conversion efficiency of the Si semiconductors, with a band gap of 1.12 eV, is between 20-29% due to its structure. [9]
To calculate the deposited energy of beta particles in silicon layer, we need to specify the spectrum of radioisotope source for use in the Monte Carlo method simulation. Sr/Y-90 radioisotope with activity of 10 mCi as the beta emitter source. Silicon PIN diode as the semiconductor are selected. The semiconductor is synthesized with impurity values of for both N and P layer. Sr/Y-90 is a betta emitter with approximately a half-life of 29.1 years and its spectrum is shown in Fig. 1.[10]

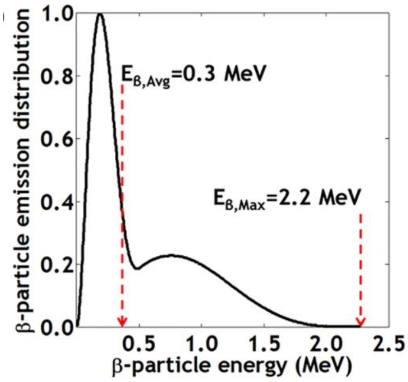

Fig 1. Normalized energy spectrum of β-particles emitted by the serial decay of Sr/Y90

After calculating the energy deposition of beta particles in the semiconductor, output parameters of semiconductor should be calculated. A circular area of silicon with a diameter of one centimeter and thickness of 500 um was selected and its thickness has been divided into several layers for the purpose of calculation, each with a thickness of δt. Sr-Y-90 source was placed on semiconductor. Also, in order to reduse noises and measure the outputs from cell, the output of the semiconductor is connected to a RLC low-pass filter and then connected to the oscilloscope. MATLAB is used to calculate the output of semiconductor simulation section. The simulation geometry, circuit setup and semiconductor used in this study shown in fig 2.

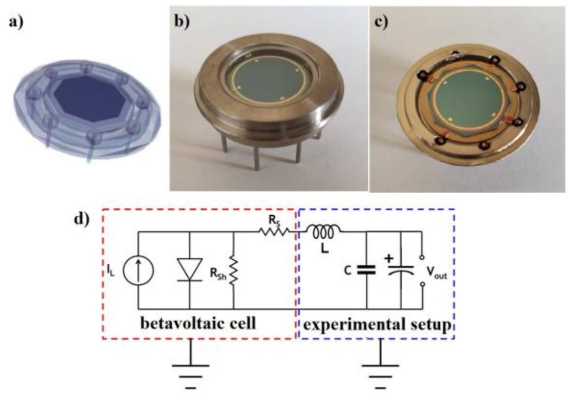

Fig 2. a) MCNP simulation scheme b) semiconductor with guard c) semiconductor without guard d) circuits configuration

Results and discussion

The calculated deposited energy in Si layer is ploted in Fig 3.

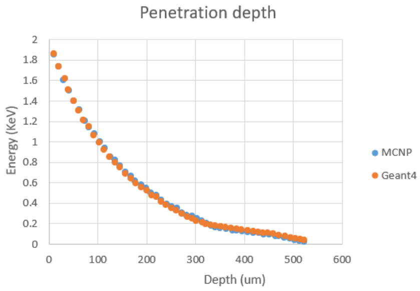

Fig 3. Deposited Energy in Si layer.

As one can see the maximum range of beta particles emitted from Sr/Y-90 is approximately 500 um in si layer.

The output of The open circuit voltage shown in Fig.4.

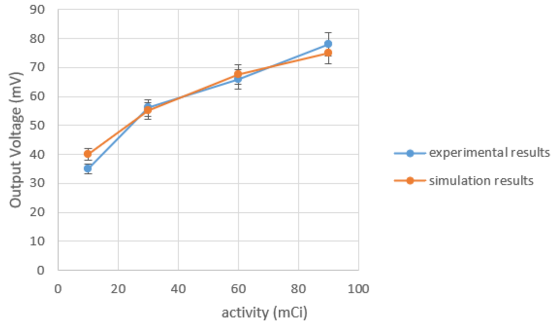

Fig 4. Open circuit voltage of experimental and simulation setups.

The short circuit current is illustrated in Fig.5.

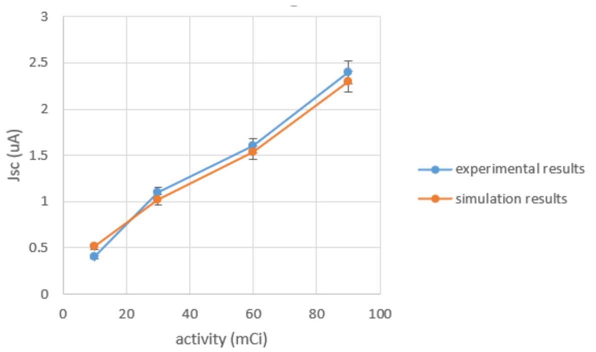

Fig 5. Open circuit voltage of experimental and simulation setups.

Conclusions

In summary, we designed, simulated, and fabricated a betavoltaic battery based on Sr/Y-90 radioisotope and Silicon semiconductor. We compared the simulation and experimental results and demonstrated the accuracy of the simulation results. A single cell of this battery can provide up to 35 mV voltage and 0.4 uA current. By increasing the activity of the beta emitter source we can reach up to 80 mV and 2.4 uA. In comparison to the output voltage, the current is more linear. This means if higher voltage is required, increasing the source activity can not provide the desired output.

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