Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, November 2-3, 2006

Betavoltaic Power Prediction by using a Monte Carlo Simulation

H.K. Jung [a], N.H. Lee [a], Y.S. Joo [a], C.W. Lee [a]
[a] Korea Atomic Energy Research Institute (KAERI), PO Box 105, Yusong, Daejon 305-600, Korea

1. Introduction

Semiconductor betavoltaic converters use energy from radioisotope sources to generate electricity for remote applications requiring a long life power. Radioisotope power sources can provide significant advantages of a high energy density and a longer life than chemical batteries. [1]

Micro-electromechanical Systems (MEMS) often require an on-board power source for a remote operation, especially in medical cases requiring an operation for more than 10 years.

The betavoltaic effect shown in Figure 1 is the generation of a potential due to a net positive charge flow of an electron-induced electron-hole production (EHP). When EHP diffuse into the depletion region of the semiconductor PN-junction, the electrical field of the depletion region sweeps them across the depletion region. Because the resulting current is from an n-type to a p-type semiconductor, the net power can be extracted. [2]

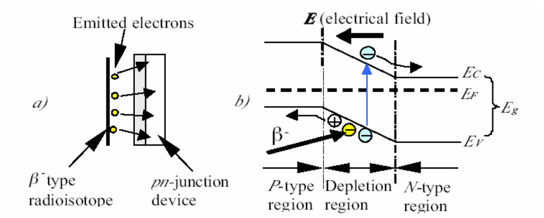

Figure 1. Betavoltaic effect a) Schematic diagram of the betavoltaic battery b) Potential diagram for a betavoltaic effect

Hence, the objective of this study is to provide the feasibility of nuclear sources (beta and alpha particles) for supplying a power to realistic MEMS devices.

2. Prediction of the betavoltaic performance

2.1 Design optimization of the radioisotope source

Selection of a radioisotope is a critical aspect in a betavoltaic conversion. In this study, Ni-63 is selected by considering its safety, lifetime, activity, and convenience of handling. The kinetic energies of the beta particles emitted from Ni-63 ranged from 0 to 66.7 keV, with an average of 17.6 keV. This energy makes it appropriate from the aspects of the damage concerns to silicon and an accidental exposure to the skin.

To determine the optimal layer thickness by considering the role of a self absorption, the Monte Carlo radiation transport code MCNP [3] was used to simulate the beta particle tracks. The beta spectrum of the Ni-63 radioisotope was obtained from Jung, et al [4]. The calculated beta flux is saturated when the thickness of the Ni-63 layer approaches 2.5 µm in Figure 2.

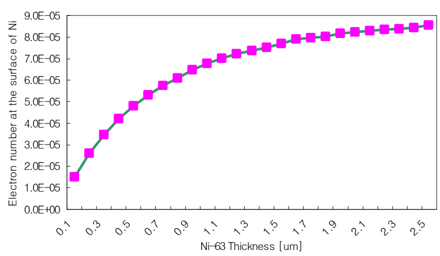

Figure 2. MCNP calculation of a self-absorption for Ni-63

2.2 Power prediction of the Silicon-based betavoltaic converter

The corresponding saturation power level is 1.0 µW at the contact area between the Ni-63 of 10 mCi and the Silicon of 1 cm^2 by a theoretical calculation. Practically, a betavoltaic device with a large thickness is not volume-efficient because all of the Ni-63 and Silicon is not engaged in a power generation. So the optimal thickness is about 1.5 μm for Ni-63.

The maximum theoretical current generated by a 10 mCi radioisotope activity can be calculated by assuming 3.2 eV for one Electron-Hole Pair generation in silicon.

$$I_{\max} = 10\,mCi \times (3.7\times 10^{10}\,dps) \times (17.6\,keV\ /\ 3.2\,eV) \times (1.6\times 10^{-19}\,C) = 3\times 10^{-7}\,A$$

An open circuit voltage (V_{oc}) can be calculated according to equation 1. [5]

$$V_{oc} = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) \qquad (1)$$

where n_i is the intrinsic carrier concentration, N_a and N_d are the acceptor and donor concentration respectively. For silicon, n_i =1X10^{10} cm^{-3}, N_a =5X10^{14} cm^{-3}, N_d =5X10^{18} cm^{-3} . We can obtain the results of V_{oc} =0.79 V.

To obtain the depletion length, equation 2 can be applied in this case.

$$X_p = \left[\frac{2\varepsilon V_{oc}}{e}\left(\frac{N_d}{N_a}\right)\left(\frac{1}{N_a + N_d}\right)\right]^{1/2} \qquad (2)$$

where ε is the permittivity of silicon. The calculated result of the depletion length is 1.4 μm. Therefore the optimal design of the silicon PN diode is described in Figure 3. This device can reach a maximum performance of a short circuit current of 0.3 μA and an open circuit voltage of 0.79 V, and the maximal output power is about 0.2 μW. When applying the fill factor of 81% to silicon [5], a maximum conversion efficiency of 16% can be obtained.

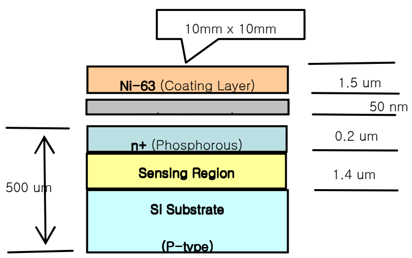

Figure 3. Design of the silicon betavoltaic device.

3. CONCLUSIONS

Ni-63 radioisotope was selected due to the mean energy of its radioactivity and an easy sealing of its beta-radiation. MCNP code was used with respect to the optimal design of the silicon diode and the electron energy usage of Ni-63 in order to predict the power capability of a Si-based betavoltaic cell. Betavoltaic power is expected to be applicable in the medical and military fields as a power source for MEMS device.

Acknowledgements

This work was supported as a part of nuclear basic research expansion program by the Korean Minister of Science and Technology.

References

1. Kenneth E. Bower, et al, Polymers, Phosphors, and Voltaics for Radioisotope Microbatteries, CRC Press, pp.441-455, 2002.
2. Hang Guo and Amit Lal, "Nanopower betavoltaic microbatteries", The 12th International Conference on Solid State Sensors, Actuators and Microsystems, Transducers '03, 2003.
3. Laurie Waters, Ed., MCNPX User's Manual, Version 2.5.0, LA-CP-05-0369, Los Alamos National Laboratory, April, 2005.
4. H.K. Jung, N.H. Lee, Y.S. Joo, Y.M. Cheong, "Betavoltaic Prediction using Ni-63 beta radioisotope and semiconductor ", presented at the Spring Conference of Korean Nuclear Society, Chuncheon, May 25-26, 2006.
5. C. Honsberg, W.A. Doolittle, M. Allen, C. Wang, "GaN Betavoltaic Energy Converters", presented at the 31st IEEE Photovoltaics Specialist Conference, Jan. 3-7, 2005.