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Design and simulation of betavoltaic battery using large-grain polysilicon

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HIGHLIGHTS

- Ni^{63} is employed as the pure beta radioisotope source.
- The planar p–n junction betavoltaic battery is based on large-grain polysilicon.
- The carriers transport model of large-grain polysilicon is used to determine the diffusion length of minority carrier.
- The average penetration depth was obtained by using the Monte Carlo Method.

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ABSTRACT

In this paper, we present the design and simulation of a p–n junction betavoltaic battery based on large-grain polysilicon. By the Monte Carlo simulation, the average penetration depth were obtained, according to which the optimal depletion region width was designed. The carriers transport model of large-grain polysilicon is used to determine the diffusion length of minority carrier. By optimizing the doping concentration, the maximum power conversion efficiency can be achieved to be 0.90% with a 10 mCi/cm^2 Ni-63 source radiation.

1. Introduction

With the rapid development of microsystems technology, there is an ever-increasing demand for micro-scale energy systems to power the majority of electrical and mechanical microdevices such as remote sensors and implantable medical chips (Guo et al., 2007). Because of the main disadvantages of fossil fuels and chemical batteries, such as periodic recharging or replacement of batteries, they may not always be feasible. Radioisotope-based energy conversion, which converts the power of nuclear radiation into electric power directly, is a promising way to meet many requirements for microsystems. The radioactive isotopes have the energy density of 10^2–10^4 times greater than fossil or chemical fuels, and have very long half-life from several tens of years to several hundreds of years without environmental impact (Ehrenberg et al., 1951). Semiconductor p–n junctions for conversion of nuclear-radiation into electricity were first suggested in the 1950s. One year later, Ehrenberg proposed the conception of "Betavoltaic Effect" for the first time (Deus, 2000). In 1954, Rappaport fabricated first betavoltaic battery based on silicon p–n junction, with a 30 mCi $^{90}Sr+^{90}Y$ source radiation, the maximum output power of this battery is 0.8 μW, and the conversion efficiency is 0.4%. However, a fast attenuation in performance of battery will happen due to the high-energy radiation damage in silicon (the average energy of beta particles from $^{90}Sr+^{90}Y$ radiation sources is about 0.7 MeV) (Guo et al., 2007). From then on, the betavoltaic isotope battery has attracted more and more research attention in increasing the energy conversion efficiency and lifetime. Table 1 shows the research advance in beta-voltaic isotope battery based on different semiconductor materials and isotope radiation sources in the past. It can be seen from Table 1 that almost all these studies for improving the energy conversion efficiency enable a dramatic increase in fabrication cost, especially in the use and fabrication of wide band-gap semiconductor (such as SiC and GaN).

Since the concept of betavoltaic direction conversion method is very similar to solar cells, the low-cost large-grain polysilicon materials which are used as main solar energy materials are

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Table 1
Research advance in betavoltaic isotope battery in the past.

Radiation source	Battery structure			Battery output parameter			Ref.
	activity (Ci)	material	I_{sc}(nA)	U_{oc}(V)	P(μW)	Efficiency (%)	
Tritium	Gas/678 Torr	a-Si:H	610/cm^2	0.43	0.129	1.2	(Guo and Lal, 2003)
Ni-63	0.001	Si	2.86	0.128	0.032	–	(Guo and Lal, 2003)
Tritium	gas	3D porous Si	18,000	0.016	–	0.22	(Sun et al., 2005)
P-33	0.23	SiC	565	2.04	0.58	0.56	(Eiting et al., 2006a, b)
Kr-85	1.2	SiC	–	1.8	–	0.75–1.15	(Eiting et al., 2006a, b)
Pm-147	0.008	Si	550	0.12	0.044	1.75	(Ehrenberg et al., 1951)
Ni-63	0.008	Si	23.3	0.463	0.00218	1.09	(Wang et al., 2010)
Ni-63	1.2×10^{-4}	SiC	25.57/cm^2	0.27	0.00408	1.01	(Kavetsky et al., 2002)
Ni-63	0.002	GaN	16/cm^2	1.62	–	1.13	(Cheng et al., 2011a, b)

considered naturally to use in the fabrication of betavoltaic batteries, the main reasons are as follows:

(1) The commercial, low-cost large-grain polysilicon can be obtained easily;
(2) The micro-fabrication technology is mature for the large-grain polysilicon;
(3) The electrical performance of large-grain polysilicon are close with single crystal silicon when the grain size of polysilicon is larger than 4 times size of film thickness.

Therefore, the betavoltaic batteries using large-grain polysilicon (the grain size is at least 4 times larger than the size of film thickness) are feasible. In this work we will focus on the design and simulation of a planar p–n junction betavoltaic battery based on large-grain polysilicon. For optimizing the design parameters, the short-circuit current density and open-circuit voltage will be simulated with a radiation source of 10 mCi Ni-63.

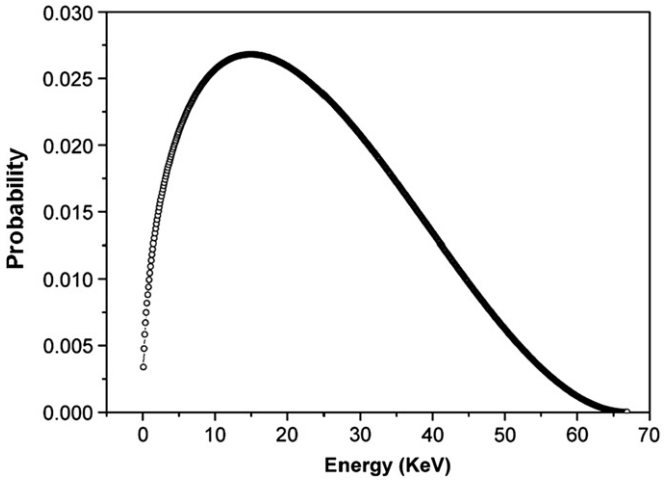

Fig. 1. Energy spectrum of beta particles from Ni-63.

2. Monte Carlo simulation for the electron trajectory

One of the key issues to design polysilicon betavoltaic battery is the junction depth. It is related to the penetration depth of beta particles in polysilicon. Taking lifetime, energy level and safety into account, Ni-63 seems to be the most suitable radioisotope source because of its pure beta particles radiation, long half-life (100 years) and low-energy radiation (maximum value of 66.7 keV).

To calculate the specific power of the beta flux reaching the surface of a Ni-63 containing material, one needs the distribution function of betas emitted probability per-unit-time in the decay of Ni-63 atoms over their energy (E), i.e., the beta spectrum. The theory of beta decay of nuclei describes the distribution of beta $W(E)dE$ as (Reid, 1984)

$$W(E)dE = C\cdot E^{'}\cdot(E'_m - E^{'})^2\cdot(E^{'2}-1)\cdot F(E,Z)dE, \quad (1)$$

where C is the constant incorporating the normalizing factors and parameters of the theory. E' and E'_m is given by

$$S_m = -\int_{E_1}^{E_0}\frac{dE}{(dE/d(\rho s))}, \quad (2)$$

$$l = S_m/50 \quad (3)$$

where m_0c^2 is the rest energy of beta particle, namely, 511.0 keV, and E_m is the maximum energy of beta particles. The factor $F(E, Z)$ can be represented as (Shimizu and Ding, 1992)

$$\cot\left(\frac{\theta}{2}\right) = \frac{2EP_0\sqrt{\xi_1}}{0.0144Z} \quad (4)$$

$$\phi = 2\pi\xi_2 \quad (5)$$

where Z is the atomic number of radiation source, $Z_{Ni}=28$; α is the fine-structure constant, namely, 1/137 (Shimizu and Ding, 1992). From the Eqs. (1)–(5), we can obtain the energy spectrum of beta particles from Ni-63 (see Fig. 1). In Fig. 1, the average kinetic energy of Ni-63 energy spectrum is 17.4 keV obtained by probability-weighted average for every power, and the maximum energy of Ni-63 energy spectrum is 66.9 keV.

A beta particle is essentially an electron that is emitted from the nucleus. The particle transport in a medium is a random process, following a statistical rule based on the movement status of all particles. In order to get more insight into the transport properties of beta particles in polysilicon, a simplified Monte Carlo (MC) approach suggested by Curgenven and Duncumb was used to simulate the beta particle trajectory in polysilicon. When beta particles travel in polysilicon, the energy loss is given by the well-known continuous loss approximation described by Bethe Formula (Shimizu and Ding, 1992),

$$\frac{dE}{d(\rho s)} = -\frac{785Z}{EA}\ln\left(\frac{1.166E}{J}\right), \quad (6)$$

where Z is the atomic number, E is the incident electron energy, ρ is the mass density, s is the distance along the electron trajectory, A is the atomic weight, and J is the mean ionization potential. From the Eq. (6), the total electron path length S_m is given by

$$S_m = -\int_{E_1}^{E_0}\frac{dE}{(dE/d(\rho s))}, \quad (7)$$

where E_0 is the initial energy of incident electron, and $E_1=1.03J$, suggested by Curgenven and Duncumb (Shimizu and Ding, 1992).

We use Monte Carlo method to demonstrate the statistical rule of motion electrons in a medium. When an electron with energy