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A methodology for efficiency optimization of betavoltaic cell design using an isotropic planar source having an energy dependent beta particle distribution

Sirichai Theirrattanakul, Mark Prelas*

Nuclear Science and Engineering Institute, University of Missouri, Columbia, MO 65211, USA

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ABSTRACT

Nuclear batteries based on silicon carbide betavoltaic cells have been studied extensively in the literature. This paper describes an analysis of design parameters, which can be applied to a variety of materials, but is specific to silicon carbide. In order to optimize the interface between a beta source and silicon carbide p-n junction, it is important to account for the specific isotope, angular distribution of the beta particles from the source, the energy distribution of the source as well as the geometrical aspects of the interface between the source and the transducer. In this work, both the angular distribution and energy distribution of the beta particles are modeled using a thin planar beta source (e.g., H-3, Ni-63, S-35, Pm-147, Sr-90, and Y-90) with GEANT4. Previous studies of betavoltaics with various source isotopes have shown that Monte Carlo based codes such as MCNPX, GEANT4 and Penelope generate similar results. GEANT4 is chosen because it has important strengths for the treatment of electron energies below one keV and it is widely available. The model demonstrates the effects of angular distribution, the maximum energy of the beta particle and energy distribution of the beta source on the betavoltaic and it is useful in determining the spatial profile of the power deposition in the cell.

1. Introduction

Optimization of betavoltaic cells is an important goal. A betavoltaic converts beta particle energy into an electric current from the production of electron-hole pairs as beta particles travel through the semiconductor material (Prelas et al., 2016, 2014a; Alam and Pierson, 2016; Liu et al., 2014; Kumar, 2016; Hong et al., 2014; Deus, 2000; Hang and Lal, 2003; Huang et al., 1998; Lu et al., 2011; Cheng et al., 2010; Shimizu and Ding, 1992; Rahastama and Waris, 2016; Zelenkov et al., 2015; Haiyang et al., 2011; Munson et al., 2015; Ulmen et al., 2009). These cells use a p-n junction structure as a transducer with materials such as Si, SiC, GaN, GaP and AlGaAs along with a radioisotope source typically located on the surface of the betavoltic (i.e., this geometrical arrangement is known as a surface source and is shown in Fig. 1 (Prelas et al., 2016)). When a beta particle transports through the depletion region of the p-n junction of the semiconductor material, it generates electron-hole pairs as it loses kinetic energy along its track in the material. The electron-hole pairs are then separated by the potential barrier that is created in the depletion region of the p-n junction. The main source of current production in the cell is from electron-hole production directly within the depletion region (Prelas et al., 2016, 2014a; Alam and Pierson, 2016). Other potential sources of current production comes from the diffusion of electron or holes created outside the depletion region into the potential barrier where the charge carriers are accelerated to the appropriate collector and by an energy recycling effect which will be described (Prelas et al., 2016).

In this study, the maximum practical efficiency for a betavoltaic nuclear battery (η_β) is determined for the limit of a thin planar source. This means that the thickness of layer 1 in Fig. 1 is thin enough so that the power absorbed by layer 1 (P_1) is inconsequential. As layer 1 becomes thicker, P_1 becomes greater and the cell efficiency drops due to self-absorption effects in the source material. Thus, the thin planar source approximation represents a maximum practical limit for the efficiency of a betavoltaic cell using a surface source interface based on the assumptions stated below. The methodology and concepts used in this study for determining a betavoltaic cell's maximum practical efficiency was adopted from reference (Prelas et al., 2016). The following parameters are considered:

- Maximum transport efficiency (η_d-defined as the faction of power deposited in the depletion region of the cell divided by the total power emitted from the beta source);

* Corresponding author.
E-mail address: prelasm@missouri.edu (M. Prelas).

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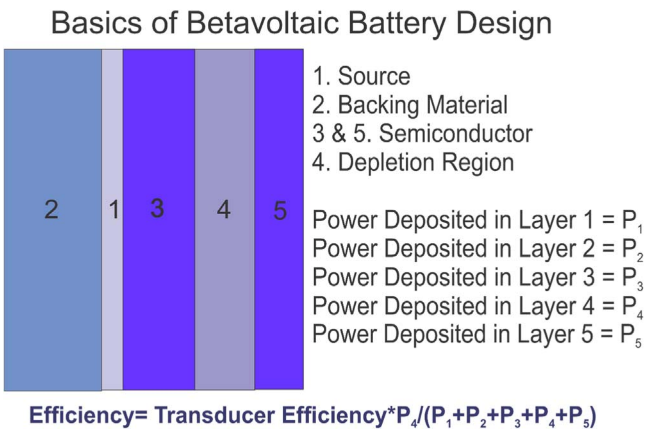

Fig. 1. Block diagram of a surface source interfaced to a betavoltaic cell. The efficiency of the betavoltaic can be analyzed simply in two parts. The first part is the efficiency of the transport of power from the source to the active region of the transducer. It is assumed that the betas generated by the source will be completely stopped by one of the layers. The second part is the transducer efficiency, which is a measure of how the power deposited in the active region of the transducer produces useful power output.

- The pair production efficiency (η_{pp}-defined as the amount of energy stored by the electron-hole pair (band-gap energy of the semiconductor) divided by the average energy needed to form an electron-hole pair (W value) which is also called the electron utilization efficiency $\eta_{ElectronUtilization}$ Prelas et al. (2016);
- The driving potential efficiency (η_{dp}– defined as the open circuit voltage divided by the band-gap energy (Prelas et al., 2016);
- The fill factor ($FF = \frac{JV}{J_{sc}V_{oc}}$: where J is the cell current, V is the cell voltage, J_{sc} is the short circuit current and V_{oc} is the cell open circuit voltage);
- The contribution of charge carriers created outside of the depletion region that diffuse to the potential barrier and are eventually collected. This contribution would contribute as a multiplication factor for the product of $\eta_{d*}\eta_{pp}$ – effectively a current multiplier;
- Another potential contribution to current is due to what this study calls an energy recycling effect (Prelas et al., 2016, 2014b). The effect is based on the principle that an electron-hole pair recombines outside of the potential barrier and a photon with an energy equal to the material's band-gap energy is produced. That photon is emitted isotropically and will then interact with the material (within the very short mean free path length of the photon in the material-λ_{ph}) to create another electron-hole pair. This process will perpetuate until an electron-hole pair forms within the depletion region or, the photon or a charge carrier is lost through some other process. This contribution would contribute as a multiplication factor for the product of $\eta_{d*}\eta_{pp}$ – effectively a current multiplier.

The products of the above factors lead to the betavoltaic efficiency as shown in Eq. (1) (Oh et al., 2012a). For demonstrating a methodology to calculate the parameters necessary to maximize the performance of a betavoltaic cell, a silicon carbide p-n junction is chosen as the example transducer. The maximum energy transport efficiency requires that the energy deposition in the depletion region be found from a source that has both an isotropic angular distribution and an energy distribution based on the radioisotope type. η_d depends upon the geometry, the energy spectrum, the average atomic number of the material that the source is embedded in, the thickness of the source, the geometrical interface to the SiC p-n junction, the location and the geometry of the depletion region of the SiC cell.

The contribution of charge carriers created outside of the depletion region that diffuse to the potential barrier is not considered in this study. The range of beta particles in the semiconductor (R) is typically much longer than the diffusion length (L_D) of charge carriers in the material. Because $R > L_D$, a large number of electron-hole pairs will be formed at a distance well beyond L_D from the potential barrier and thus should not contribute significantly to the current flow in the cell.

This study does not consider the energy recycling effect for the following reasons:

- it would be most effective for direct band-gap materials;
- the photon mean free path (λ_{ph}) is much shorter than the scale length of the cell (L_{cell}) which would require that numerous energy recycling events occur before an electron-hole pair forms in the depletion region;
- it would require that the surfaces of the cell be highly reflective in order to prohibit leakage of photons from the cell;
- it would require that the semiconductor material be virtually defect free in order to prohibit parasitic channels for energy loss.

The second term in Eq. (1), the pair production efficiency (η_{pp}), is material specific and is 0.42 for silicon carbide (Prelas et al., 2016, 2014b; Wrbanek et al., 2007).

The third term in Eq. (1), the diving potential efficiency (η_{dp}), is proportional to the open circuit voltage (V_{oc}) divided by the band-gap energy (E_g) (Prelas et al., 2016). Typically as band-gap energy increases the open circuit voltage increases. However, due to defects in typical wide band-gap materials, the optimal open circuit voltage is difficult to obtain. Thus a reasonable but conservative estimate for the driving potential efficiency of 0.5 is chosen (Prelas et al., 2016, 2014a; Oh et al., 2012a, 2012b).

The last term in Eq. (1) is the fill factor (FF), and this is typically between 0.7 and 0.8 for a high quality photovoltaic cell (Prelas et al., 2016).

Thus, the challenge of finding the transport efficiency, η_d, is fundamental to this study.

$$\eta_\beta = \eta_d \eta_{pp} \eta_{dp} FF \quad (1)$$

2. Beta source interface to SiC

The first step in the determination of η_d is to define the basic parameters of the source and how it is interfaced to the transducer. In this paper, a surface source, or thin planar source, is modeled. The specific of the surface source is that it is a uniform thin layer of radioisotope atoms placed on the surface of a semiconductor with a p-n junction (Fig. 1). This is called the planar source approximation, and it occurs when the thickness of the source layer (t_1) is much less than the range of the beta particles emitted by the source in the source material. This approximation assures that there will be little or no self-absorption in the source material (P_1 is essentially zero). Another important aspect of this study is that it considers the effects of beta energy spectra and beta energy specific to the various isotopes (e.g., H-3, Ni-63, S-35, Pm-147, Sr-90, and Y-90). It is well know that radiation damage becomes a serious issue for beta energies > 200 keV (Prelas et al., 2016). Nonetheless, it is still instructional to examine beta sources that have a maximum beta energy (E_{max}) > 200 keV (like Pm-147, Sr-90 and Y-90) to study how high energy betas affect the design of a betavoltaic cell. Another reason to consider high-energy beta sources is that the power density of a beta emitter increases as E_{max} becomes larger and increases as half-life ($t_{1/2}$) becomes shorter. E_{max} also plays a role in the dimensions of the layers in the cell design that impacts the cell's scale length. In other words, the overall dimensions of a betavoltaic cell decreases for a given power output if E_{max} is relatively large and/or $t_{1/2}$ is relatively short. If the planar source is large or near infinite, the energy loss at the edges of the cell will be inconsequential. Thus, the infinite planar source model is accurate under the condition where the source thickness is much less than the scale lengths associated with the source's surface.

Oh et. al. reported results (using MCNPX, GEANT4 and PENELOPE) from beta point sources with an angular and energy distribution acting