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Efficiency analysis of betavoltaic elements

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ABSTRACT

The conversion of energy of electrons produced by a radioactive β-source into electricity in a Si and SiC p—n junctions is modeled. The features of the generation function that describes the electron–hole pair production by an electron flux and the emergence of a "dead layer" are discussed. The collection efficiency Q that describes the rate of electron–hole pair production by incident beta particles, is calculated taking into account the presence of the dead layer. It is shown that in the case of high-grade Si p—n junctions, the collection efficiency of electron–hole pairs created by a high-energy electrons flux (such as, e.g., Pm-147 beta flux) is close or equal to unity in a wide range of electron energies. For SiC p–n junctions, Q is near unity only for electrons with relatively low energies of about 5 keV (produced, e.g., by a tritium source) and decreases rapidly with further increase of electron energy. The conditions, under which the influence of the dead layer on the collection efficiency is negligible, are determined. The open-circuit voltage is calculated for realistic values of the minority carriers' diffusion coefficients and lifetimes in Si and SiC p—n junctions, irradiated by a high-energy electrons flux. Our calculations allow to estimate the attainable efficiency of betavoltaic elements.

1. Introduction

Betavoltaic effect refers to conversion of energy from electrons generated in nuclear reactions into electricity in semiconductor p—n junctions. Long action periods (decades) and the ability to operate in a wide temperature range (from −50 to 150 °C) make betavoltaic effect attractive for a number of technological applications, such as communication devices, sensors in hard-to-reach areas, and implantable medical devices [1]. In particular, a battery for heart pacemakers based on the Si p—n junction and Pm-147 source of beta particles was produced [2]. Other popular beta-source and recipient are tritium and A_3B_5 semiconductors [3–5].

After the pioneering work of Ehrenberg et al. [6], betavoltaic conversion has been intensively investigated both experimentally [7–10] and theoretically [8,9]. Of particular importance in this respect is the efficiency of a betavoltaic cell, defined as the ratio of the power generated by the cell to the power delivered by the incident electrons. The first estimates of this parameter were performed in Refs. [2,10–12].

Betavoltaic and a more familiar photovoltaic effect are related and share several traits. In both cases, calculations of the limiting efficiency are made under the assumption that all electron–hole pairs produced by the incident beta particles or photons contribute to the betavoltaic or photovoltaic current. When viewed as a function of the band gap, E_g, the current generated by beta-particles decreases, whereas the open-circuit voltage grows with E_g. Because the latter effect dominates over the former, the overall betaconversion efficiency increases with E_g [2]. In the case of photovoltaics, in contrast, the photocurrent decrease with band gap is stronger, resulting in a maximum of photoconversion efficiency as a function of E_g [13].

In this research the attainable betavoltaic conversion efficiency is modeled using realistic values of minority carriers' lifetimes and diffusion coefficients to calculate the collection coefficient Q and open circuit voltage V_{OC}. The dominating recombination mechanisms were included in the formalism developed. The results were compared to the limiting photoconversion efficiency, which corresponds to the fundamental maximum of η.

For the betavoltaic cell we assume that the β source is in the form of a foil [2]. This allows considering the one-dimensional (slab) geometry for our theoretical analysis. The cross-section of the betavoltaics cell and β-source is shown schematically in Fig. 1. The beta electrons flux is directed toward p–n junction, which separates generated electron–hole pairs, are shown. The dead layer, where the scattering the beta-electrons can be neglected, is x_m thick, and is located close to the frontal surface of the sample and the β source.

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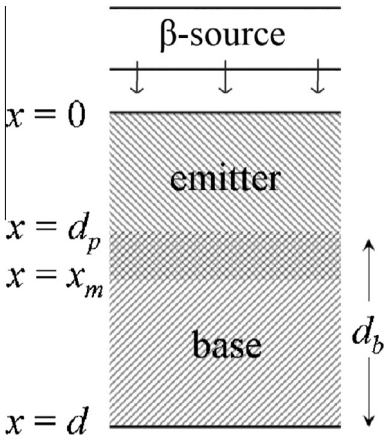

Fig. 1. Cross-section of the betavoltaic system with β-source adjacent to p–n junction. The emitter and the base are d_p and d_b thick, and p–n junction width $d = d_p + d_b$. The dead layer is x_m thick.

In the beta battery, each beta-electron produces a number of electron–hole pairs by dissipating its energy E in the semiconductor. Electron energy is in turn averaged with respect to the decay spectrum for each beta emitter [14]. Experimental spectra for tritium from [15] and promethium from [16] were used in beta-conversion efficiency calculation. Electron–hole pair generation function by a beta electron can be written as [17].

2. The collection efficiency analysis

Efficiency η of a betavoltaic converter can be written as a product of three terms [2]

$$\eta = \eta_\beta \eta_c \eta_s. \tag{1}$$

Here

$$\eta_\beta = N_\beta / N_0, \tag{2}$$

is the ratio of the beta-flux N_β, reaching the semiconductor surface, to the total flux N_0 emitted;

$$\eta_c = (1 - r)Q, \tag{3}$$

is the coupling efficiency, given by the product of absorption probability of a beta-particle (r is the coefficient of electron reflection from the semiconductor surface) and collection efficiency Q of electron–hole pairs; finally, the semiconductor efficiency is

$$\eta_s = qV_{OC}\mathrm{FF}/\varepsilon. \tag{4}$$

Here q is the elementary charge, V_{OC} is the open circuit voltage, FF is the fill factor of the current–voltage characteristics, $\varepsilon = (2.8E_g + 0.5)$ eV is the energy needed to create one electron–hole pair, and E_g is semiconductor band gap [18].

Previously, the maximal betavoltaic efficiency was obtained under an implicit assumption that each incident beta-particle produces electron–hole pairs, i.e., the collection efficiency $Q = 1$. To derive the collection efficiency Q, we initially also used the expression $g(x) \propto \exp(-\alpha x)$ for the generation function for electron–hole pairs created by beta-electron flux (see [8,11]), where α is the absorption coefficient, g is the generation rate of electron–hole pairs per unit volume, and x is the distance from the semiconductor front surface. This expression, however, is valid only outside of the dead layer when $x > x_m$, while $g(x)$ is assumed be zero at $x < x_m$ [19]. Sufficiently general expressions for Q in this approximation are given in [8,11], while the most general one is derived in [20]. It has the following form:

$$Q = Q_p + Q_n, \tag{5}$$

$$Q_p = \frac{\alpha L_p}{(\alpha L_p)^2 - 1} \cdot \frac{\alpha L_p + S_0 \frac{\tau_p}{L_p}\left(1 - e^{-\alpha d_p}\right)\cosh\left(\frac{d_p}{L_p}\right) - e^{-\alpha d_p}\sinh\left(\frac{d_p}{L_p}\right) - \alpha L_p e^{-\alpha d_p}}{S_0 \frac{\tau_p}{L_p}\sinh\left(\frac{d_p}{L_p}\right) + \cosh\left(\frac{d_p}{L_p}\right)}, \tag{6}$$

$$Q_n = \frac{\alpha L e^{-\alpha d_p}}{1 - (\alpha L)^2} \cdot \left\{ \frac{\left[S_d \cosh\left(\frac{d}{L}\right) + \frac{D}{L}\sinh\left(\frac{d}{L}\right)\right](1 + r_d e^{-2\alpha d}) + (\alpha D(1 - r_d) - S_d(1 + r_d))e^{-\alpha d}}{S_d \sinh\left(\frac{d}{L}\right) + \frac{D}{L}\cosh\left(\frac{d}{L}\right)} - \frac{-\alpha L S_d\left[\sinh\left(\frac{d}{L}\right) + \frac{D}{L}\cosh\left(\frac{d}{L}\right)\right](1 - r_d e^{-2\alpha d})}{S_d \sinh\left(\frac{d}{L}\right) + \frac{D}{L}\cosh\left(\frac{d}{L}\right)} \right\}. \tag{7}$$

Here, Q_p and Q_n are the collection coefficients of electron–hole pairs in the emitter and the base respectively, L_p is the diffusion length in the emitter, d_p is the thickness of the emitter, is the bulk lifetime in the emitter, r_d is the electron reflection coefficient from the back surface of the p—n junction, $L = (D\tau_b)^{1/2}$ is the diffusion length in the base, D and τ_b are the base diffusion coefficient and the bulk lifetime, respectively, d is the thickness of the base, S_0 is the effective surface recombination rate at the emitter surface, and S_d is the effective surface recombination rate at the back surface of the base.

In the case of a beta battery, each beta-electron dissipating its energy E in the semiconductor produces a number of electron–hole pairs. Electron energy is in turn averaged with respect to the decay spectrum in beta-conversion efficiency calculation. Electron–hole pair generation function by a beta electron can be written as [17]:

$$g(x) = -J(x)\frac{1}{\varepsilon}\frac{dE}{dx} = J(x)\frac{1}{\varepsilon}\frac{2\pi q^4 NZ}{E(x)}B[E(x)]. \tag{8}$$

Here $J(x)$ is the density of electrons flux, $(-\frac{dE}{dx})$ is the energy dissipation per unit path length, N is the number of absorber atoms per cm^3, Z is the atomic number of the absorber material, and $B(E)$ is the stopping number. The electron energy dissipation per unit path length can be calculated utilizing (8). The transcendent solution of (8) multiplied by the electron energy distribution function and integrated over the energy is fit well by the exponential generation function in the form $\frac{E_0}{\varepsilon}\alpha\exp(-\alpha x)$ [21].

The factor α in (5)–(7) describes the decay of excess concentration of electron–hole pairs generated by beta electrons. Comparing the averaged by decay energy left part of (8) to the exponential generation function, one can determine the α-value. This procedure yields $\alpha = 300\ \mathrm{cm}^{-1}$ for Pm-147/Si, $270\ \mathrm{cm}^{-1}$ for Pm-147/SiC, $3 \cdot 10^4\ \mathrm{cm}^{-1}$ for T/Si, and $1.5 \cdot 10^4\ \mathrm{cm}^{-1}$ for T/SiC.

The collection efficiency of a p—n junction based on high-quality silicon with Shockley–Read–Hall recombination lifetime $\tau_{SR} \approx 1$ ms can be calculated using (5)–(7). Due to the low currents in betavoltaic elements, the excess concentration of electron–hole pairs, Δp, is much smaller than the equilibrium majority charge carriers (holes) concentration in the base even for very long lifetimes. Considering the Shockley–Read–Hall lifetime τ_{SR} in the base, radiative recombination coefficient B_r, and Auger interband recombination coefficient C_{Auger}, the resultant bulk carrier lifetime τ_b can be written as

$$\tau_b = \left(\tau_{SR}^{-1} + B_r p_0 + C_{\mathrm{Auger}} p_0^2\right)^{-1}, \tag{9}$$

where p_0 is the equilibrium majority carriers' concentration in the base.

Fig. 2(a) shows the collection coefficient decrease with the increase in the effective surface recombination rate for silicon p—n junctions. In this case, the mean energy of Pm-147 electrons is 61.9 keV. The parameters used to calculate Si and SiC collection coefficients are given in Table 1. Absorption coefficient α is taken from (8), using the approach of [17]. For the above considered parameters, the collection coefficient depends very weakly on the