Development and Performance Optimization of SiC-Based Radiovoltaic Cells

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Abstract

To improve the total conversion efficiency and output power of radiation voltaic batteries, comprehensively considering the influence of depletion region width, diffusion length, and electrode structure on charge collection efficiency, total conversion efficiency, and output power, a 63Ni-SiC based PIN junction energy conversion device with relatively high total conversion efficiency and output power was successfully fabricated by optimizing the energy conversion device and electrode structure. The short-circuit current, open-circuit voltage, output power, and total conversion efficiency of the fabricated radiation voltaic battery reached 10.29 -13.43 nA/cm2, 1.32 -1.44 V, 11.66 -14.69 nW/cm2, and 2.24% -2.82%, respectively. Compared with the team' s previous work, the open-circuit voltage, fill factor (FF), and total conversion efficiency were increased by an average of 127.50%, 114.47%, and 512.10%, respectively, and the total conversion efficiency is higher than the results reported in literature (0.5% -1.99%). The results demonstrate that by adopting a PIN structure with a "concentration gradient I-layer" , optimizing the junction width and doping concentration, as well as optimizing the electrode material and structure, the total conversion efficiency and output power of radiation voltaic batteries can be significantly enhanced, providing important theoretical reference and experimental basis for the design and fabrication of radiation voltaic batteries.

Full Text

Fabrication and Performance Optimization of SiC-Based Betavoltaic Batteries

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Abstract

To enhance the overall conversion efficiency and output power of betavoltaic batteries, we comprehensively examined the influence of depletion region width, diffusion length, and electrode structure on charge collection efficiency, conversion efficiency, and output power. Through optimization of the energy conversion device and electrode architecture, we successfully fabricated 63Ni-SiC-based PIN junction converters exhibiting high overall conversion efficiency and output power. The fabricated devices achieved short-circuit currents of 10.29–13.43 nA/cm^2, open-circuit voltages of 1.32–1.44 V, output power densities of 11.66–14.69 nW/cm^2, and total conversion efficiencies of 2.24%–2.82%. Compared with our team' s previous work, the open-circuit voltage, fill factor, and overall conversion efficiency increased by an average of 127.50%, 114.47%, and 512.10%, respectively, while the overall conversion efficiency surpassed previously reported values (0.5%–1.99%). These results demonstrate that adopting a PIN structure with a "concentration gradient I-layer," optimizing junction width and doping concentration, and improving electrode materials and geometry can significantly enhance betavoltaic battery performance, providing important theoretical guidance and experimental validation for future device design and fabrication.

Keywords: Betavoltaic battery, SiC, 63Ni, Conversion efficiency, Output power, Ohmic contacts

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Betavoltaic nuclear batteries (hereinafter referred to as betavoltaic cells) have emerged as one of the most attractive micro-power sources for self-powered portable or embedded devices due to their long operational lifetime, high energy density, compact size, and strong interference resistance [1, 2]. These batteries consist primarily of a beta-emitting radioisotope and a semiconductor energy converter, generating electrical energy through the creation and collection of electron-hole pairs (EHPs) via beta irradiation. Among potential radioisotopes, 63Ni is particularly suitable due to its long half-life (approximately 100 years), moderate decay energy (average 17.4 keV, maximum 66.9 keV), and solid metallic form. For semiconductor selection, key considerations include radiation damage threshold, bandgap width, intrinsic carrier concentration, diffusion length, backscattering coefficient, and fabrication maturity. 4H-SiC has attracted significant attention for high-temperature, radiation-hardened, and high-performance power devices due to its superior radiation hardness and well-established processing technology [3]. Its wide bandgap, extremely low intrinsic carrier concentration, and low backscattering coefficient enable high conversion efficiency, open-circuit voltage, and output power, making it an excellent candidate for energy conversion devices.

Since Rappaport first demonstrated a betavoltaic cell based on 90Sr/90Y and a silicon p-n junction in 1954 [4], extensive experimental and theoretical research has been conducted. Abderrahmane et al. [5] highlighted that beta particle backscattering at the converter surface significantly affects conversion efficiency. Maximenko et al. [6] systematically investigated coupling efficiencies between 3H/63Ni and various semiconductors, identifying SiC as one of the optimal materials due to its low backscattering coefficient. Numerous studies [6–8] have shown that EHP recombination outside the depletion region substantially impacts collection and conversion efficiency. Zhao et al. [9] analyzed the effect of EHP recombination within the depletion region, finding that neglecting this phenomenon overestimates the conversion efficiency of SiC-based betavoltaic cells by a factor of 1.4. Sachenko et al. [10] employed classical drift-diffusion theory to study carrier collection efficiency, concluding that mismatch between EHP generation depth and diffusion length is the primary cause of low collection efficiency. Ohmic contact electrode fabrication processes and geometric structure influence current collection and transport in the external circuit, with low specific contact resistance and optimized geometry significantly improving battery performance [11–13].

Researchers have pursued various strategies to enhance conversion efficiency and output power, including adding metallic reflectors behind the radiation source to reduce directional energy loss [5], optimizing junction width and doping concentration to expand the depletion region and improve carrier collection efficiency [14–17], and inserting a "concentration gradient layer" in PN junctions to introduce additional electric fields that reduce radiation-induced carrier recombination losses [18, 19]. Currently, reported total conversion efficiencies for 63Ni-SiC-based cells range from 0.5% to 1.99% [20–24], with device conversion efficiencies of 3.7%–15.3% [3, 25] and output power densities of 2–8 nW/cm^2 [3, 20–25].

To improve the overall conversion efficiency and output power of betavoltaic cells, this work comprehensively considered the effects of depletion region width and diffusion length on EHP collection efficiency, overall conversion efficiency, and output power, fabricating 63Ni-SiC-based PIN junction converters. The results demonstrate that employing a PIN structure with a "concentration gradient I-layer," selecting optimal junction width and doping concentration, and optimizing electrode materials and structure yield betavoltaic cells with excellent overall conversion efficiency and output power.

1.1 Device Design

To minimize backscattering losses and enhance open-circuit voltage, we selected 4H-SiC as the converter material due to its low backscattering coefficient and extremely low intrinsic carrier concentration. Figure 1 [Figure 1: see original paper] illustrates the operating principle of betavoltaic cells: incident beta particles generate EHPs through ionization in the converter, which then drift, diffuse, and recombine under the built-in electric field, producing a radiation-induced current (Jβ) and forward current. These currents are ultimately transported through electrodes to the external circuit, completing the conversion of decay energy to electrical energy. The energy deposition profile of beta particles in the converter determines the EHP generation rate (G(x)), which directly affects battery performance. Using Monte Carlo simulations, we obtained the energy deposition distribution (Edep(x)) of beta particles from a 63Ni source along the incident direction in the converter. The 63Ni source used was a full-energy-spectrum source [26] with specific activity, abundance, and density of 2.1$×10^{11}$ Bq/g, 20%, and 8.9 g/cm^3, respectively. The EHP generation rate G(x) can be derived from the energy deposition distribution and source activity using Equation (1):

$$G(x) = A \cdot \frac{E_{dep}(x)}{\varepsilon} = G_0 \exp(-\alpha x) \quad (1)$$

where A is the source activity, x is the penetration depth of beta particles in the converter,   is the average ionization energy of SiC (7.78 eV) [16], and G_0 and α are the surface EHP generation rate and absorption coefficient, respectively, which depend on the source thickness t. EHPs generated within the depletion region can be fully collected (100% collection efficiency), while those generated outside must diffuse to the depletion region for collection. The collection efficiency CE(x) in this region is given by Equation (2):

$$CE(x) = 1 - \tanh\left(\frac{d(x)}{L}\right) \quad (2)$$

where d(x) represents the distance between the EHP generation location and the depletion region boundary (set to zero within the depletion region), and L is the minority carrier (electron or hole) diffusion length. The radiation-induced current density (Jβ) is then:

$$J_\beta = q \int_0^H G(x) \cdot CE(x)\, dx \quad (3)$$

where q is the electron charge and H is the converter thickness.

When the betavoltaic cell is short-circuited (applied bias V = 0 V), the forward current JF equals zero, and the output current J becomes the short-circuit current (JSC), which equals the radiation-induced current Jβ:

$$J_{SC} = J_\beta - J_F = J_\beta \quad (4)$$

From the Shockley equation [27], the open-circuit voltage (VOC) is expressed as:

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{J_{SC}}{J_0} + 1\right) \quad (5)$$

where k is the Boltzmann constant (1.38$\times 10^{-23}$ J/K) and T is the temperature (300 K in this work). J_0 is the reverse saturation current, which is positively correlated with intrinsic carrier concentration and inversely correlated with doping concentration [14, 28]. Thus, reducing J_0 is key to increasing VOC. The maximum output power (Pout) is:

$$P_{out} = J_{SC} V_{OC} FF \quad (6)$$

where FF is the fill factor, defined as VmJm/VOCJSC, with Vm obtained by solving d(V·J)/dV = 0 and Jm derived from Equation (5). The total conversion efficiency is tot = Pout/(A·E·q), which is proportional to output power, where E is the average energy of beta particles from 63Ni (17.4 keV).

According to drift-diffusion theory, minority carriers within the depletion region and within one diffusion length from its edge can be effectively collected. This region is defined as the effective charge collection region (ECR) with length H_{ECR} = (Wd + Ln + Lp). To expand H_{ECR}, we employed a PIN structure with a "concentration gradient I-layer," which generates an additional electric field compared to conventional PN junctions, increasing the effective collection length to H_{ECR} = (Wd + Ln + 2Lp + Lp1) and thereby reducing EHP recombination losses and enhancing collection efficiency [19]. Here, Wd, Ln, Lp, and Lp1 represent the depletion width, electron diffusion length in the P-region, and hole diffusion lengths in the I- and N-regions, respectively.

As shown in Figure 2 Figure 2: see original paper-(b), Wd, Ln, and Lp decrease with increasing doping concentration. Lower doping concentrations favor larger Wd, Ln, and Lp, thereby improving EHP collection efficiency and short-circuit current JSC. Therefore, reducing doping concentration to increase depletion width and diffusion length—matching the beta particle range with the effective charge collection region in the converter—is crucial for enhancing output power and total conversion efficiency.

Figure 3 Figure 3: see original paper reveals that JSC increases with decreasing ND (I-region doping concentration) but shows little sensitivity to NA (P-region doping concentration). This occurs because Ln varies much more significantly with ND than Lp does with NA (see Figure 2(b)), and reducing ND substantially increases H_{ECR}, thereby enhancing charge collection efficiency and JSC. Figure 3(b) shows that VOC increases with both NA and ND due to reduced reverse saturation current density (J_0) at higher doping concentrations (see Figure 2(c)). Figure 3(c) illustrates the relationship between Pout and doping concentration, showing that Pout initially increases with NA before saturating, while exhibiting an inverse correlation with ND. Consequently, heavy doping in the P-region and light doping in the I-region significantly improve Pout and total conversion efficiency.

In summary, betavoltaic cell design for enhanced performance should satisfy three criteria: (1) select semiconductor materials with low backscattering coefficients and extremely low intrinsic carrier concentrations (e.g., 4H-SiC); (2) employ a PIN structure with a "concentration gradient I-layer" to reduce EHP recombination losses and improve collection efficiency; and (3) utilize heavy P-region doping and light I-region doping to boost output power and conversion efficiency. Based on current SiC low-doping process capabilities, we set the I-layer doping concentration to ND = 10^{14} cm^{-3}. Heavy doping concentrations for the P^+ and N^+ regions were set to NA = 10^{19} cm^{-3} and Nd = 2×10^{18} cm^{-3}, respectively, to ensure good ohmic contacts. Given that 63Ni beta particles penetrate 10.2 m in SiC converters [19] and that the depletion width is 5.65 m with Ln and Lp of 11.06 m and 11.44 m, respectively, at P^+ and I-region doping concentrations of 10^{19} and 10^{14} cm^{-3}, we set the P^+ layer and I-layer thicknesses to 0.2 m and 10 m to align the beta particle range with the effective charge collection region, with the depletion region primarily residing in the I-region requiring the P^+ layer to be as thin as possible.

1.2 Electrode Design

Ohmic contact electrode material selection and geometry significantly affect current collection and transport in the external circuit, with low specific contact resistance and optimized structures markedly improving battery performance [11–13].

Table 1 summarizes experimental conditions and parameters for ohmic contact formation on N-type and P-type SiC. N-type SiC typically employs Ni-based metallization systems annealed in nitrogen at high temperature, achieving high-quality ohmic contacts with specific contact resistance below 10^{-5} $\Omega\cdot cm^2$ [29]. P-type SiC ohmic contacts are more challenging, requiring high-work-function metal systems, increased doping concentrations, rapid annealing, and protective layers. Table 1 shows comparable specific contact resistances for Ni/Ti/Al/W and Ni/Ti/Al/Ni P-type electrodes. Our previous work [13] fabricated both electrode types using identical annealing processes, revealing that Ni/Ti/Al/W exhibited lower specific contact resistance (3.35×10^{-5} $\Omega\cdot cm^2$) than Ni/Ti/Al/Ni (2.73×10^{-4} $\Omega\cdot cm^2$). Additionally, using chemically stable W as a capping layer effectively mitigates surface oxidation issues with Ni. Therefore, this work selected Ni/Ti/Al/W (50/30/90/50 nm) for P-type ohmic contacts. To further reduce contact resistance, we chose Ti/Ni as the primary N-type ohmic contact material, capped with inert Au to prevent oxidation, forming stable Ti/Ni/Au (80/110/100 nm) contacts.

To enhance surface current transport efficiency, the N-type electrode (back contact) employs a full-coverage structure. Since the P-type electrode faces the radiation source, excessive area coverage and thickness cause beta particle energy loss; therefore, a grid structure consisting of wide busbars and narrow finger electrodes was adopted, as shown in Figure 4 [Figure 4: see original paper]. The finger electrodes collect current, which is then transported to the external load through busbars. Electrode grid density determines collection efficiency and resistance, but excessive grid lines significantly increase beta particle shading losses, reducing radiation-induced current. Therefore, balancing collection efficiency, resistance, and shading losses requires optimizing grid width and spacing.

Power losses associated with surface electrodes in betavoltaic cells include diffusion layer resistance loss (rd), busbar resistance loss (rb), finger resistance loss (rf), finger contact resistance loss (cf), and grid shading loss (s). The total power loss rate is expressed by the modified Equation (7) [12]:

$$\eta = \eta_{rd}+\eta_{rb}+\eta_{rf}+\eta_{cf}+\eta_{s} = \frac{J_m H^2 \rho_{\square}}{12V_m}+\frac{J_m L L_a}{3w_b h_b V_m}+\frac{J_m H L^2 \rho_p}{12 w_f h_f V_m}+\frac{J_m H \rho_c}{V_m}\left(\frac{(H+w_f)\cdot w_b+(H+w_f)\cdot(w_b+2}{L_a \cdot L}\right.$$

where , p, c, wb, wf, hb, hf, and La are 4.2×10^{6} Ω, 0.0187 Ω· m, 3350 Ω· m^2, 100 m, 30 m, 220 nm, 220 nm, and 0.3 cm, respectively [13, 35]. From Equations (3)-(5), Jm and Vm were determined to be 22.18 nA/cm^2 and 2.18 V. e represents the beta particle energy loss rate caused by the 220 nm-thick full-coverage P-type electrode, calculated via Monte Carlo simulation as 28.92%. Table 2 lists relevant parameters for grid electrode design.

Figure 5 [Figure 5: see original paper] shows the relationship between total power loss rate and finger length L and spacing H. As L increases, decreases, indicating that the number of busbars should be minimized for a given cell area. Additionally, decreases with increasing H. When L = 3000 m and H > 500 m, falls below 2%, with the rate of change diminishing toward zero. Thus, increasing H and L appropriately reduces total power loss.

2.1 Device Fabrication and Performance Testing

The fabrication process for betavoltaic converters primarily includes epitaxy, photolithography, etching, passivation, electrode preparation, and annealing, as detailed in Figure 6 [Figure 6: see original paper] with corresponding material parameters. Following the optimization criteria from Section 1.1, we used 350 m-thick N-type SiC substrates with a doping concentration of 2×10^{18} cm^{-3}. A 10 m-thick N-type lightly doped intrinsic layer (I-layer) with ND = 1×10^{14} cm^{-3} was grown via chemical vapor deposition (CVD), followed by a 0.2 m P^+ layer doped at NA = 1×10^{19} cm^{-3}. Inductively coupled plasma (ICP) etching created 50 m-wide isolation trenches, yielding individual devices measuring 0.4 cm × 0.4 cm. Passivation employed dry oxidation with subsequent annealing in N_2 to reduce surface leakage current. Based on Section 1.2 optimization criteria, four P-type electrode variants (#1-#4) with different geometries were fabricated via secondary photolithography and magnetron sputtering of Ni/Ti/Al/W (50/30/90/50 nm), with geometric parameters listed in Table 3 . Full-coverage Ti/Ni/Au (80/110/100 nm) back contacts were deposited by magnetron sputtering, followed by annealing at 950°C in nitrogen for 5 minutes to form stable ohmic contacts.

Test cells were placed in the vacuum chamber of a Cascode SUMMIT200 probe station (Figure 7 Figure 7: see original paper), with 63Ni source sheets positioned on the cell surface. I-V characteristics were measured using a Keysight B1500A semiconductor analyzer after evacuation. Figure 7(b) shows the test configuration, with the 63Ni source above the sample and probes contacting the electrodes. The 63Ni source activity was approximately 1.85$×10^{8}$ Bq/cm^2 (5 mCi/cm^2) with ~20% abundance.

2.2 Results and Discussion

Figure 8 Figure 8: see original paper and (b) present the measured J-V curves for samples #1-#4 under source and dark conditions, respectively. Reverse saturation current density J_0 was extracted by fitting the forward-bias dark J-V curves using $\ln J = qV/nkT + \ln J_0$ [40], where n is the ideality factor. The JSC increased from 10.29 nA/cm^2 to 13.43 nA/cm^2 as finger spacing H increased, primarily because reduced electrode density lowered beta particle shading losses, increasing energy deposition and EHP generation in the converter. This trend aligns with the decreasing total power loss rate with increasing H shown in Figure 5.

Further analysis yielded FF, J_0, Pout, tot, and relative loss rates, summarized in Table 3. VOC ranged from 1.32-1.44 V, FF from 0.79-0.83, Pout from 11.66-14.69 nW/cm^2, and tot from 2.24%-2.82%. Both Pout and tot increased with H, consistent with JSC behavior, as reduced shading losses increased deposited power. Compared with our previous work [36], VOC, FF, and tot improved by an average of 127.50%, 114.47%, and 512.10%, respectively. These improvements stem from: (1) optimized P-type ohmic contact materials (from Ti/Al/Au (50/100/100 nm) to Ni/Ti/Al/W (50/30/90/50 nm)), annealing conditions (1050°C/3 min to 950°C/5 min), and sparser grid electrode structures that reduced shading losses; (2) overall process improvements in epitaxy, passivation, and ohmic contacts that dramatically reduced reverse saturation current J_0 by 4-13 orders of magnitude, significantly boosting VOC and overall performance.

The total conversion efficiency also exceeds previously reported values (tot: 0.5%-1.99% [20-24]). For PIN structures [20, 23], this improvement primarily results from reducing the I-layer doping concentration from 1$×10^{\{15\}-3×10}${15}$ cm^{-3} to 1$×10^{14}$ cm^{-3}, which enhanced charge collection efficiency. Additionally, increasing the I-layer thickness from 3.5–4 m to 10 m may have improved matching between the beta particle range and the effective charge collection region.

Normalized to cell #1's output power density, relative loss rates increase with H, consistent with theoretical predictions (Figure 5), confirming that appropriately increasing electrode spacing reduces total power loss and enhances conversion efficiency and output power.

3 Conclusion

By comprehensively considering backscattering effects, depletion region width, diffusion length, and electrode structure, we designed and fabricated high-performance 63Ni-SiC-based PIN junction betavoltaic cells. Under optimized conditions, the devices achieved short-circuit currents of 10.29–13.43 nA/cm^2, open-circuit voltages of 1.32–1.44 V, output power densities of 11.66–14.69 nW/cm^2, and total conversion efficiencies of 2.24%–2.82%. Compared with our previous work, VOC, FF, and tot improved by an average of 127.50%, 114.47%, and 512.10%, respectively, surpassing reported literature values. Short-circuit current, output power, and total conversion efficiency increased with finger electrode spacing. These results validate that optimizing converter design and electrode structure effectively enhances betavoltaic cell performance, providing crucial theoretical guidance and experimental foundations for future development.

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Author Contributions

Hou-Jun He: conceptualization, theoretical calculations, experimental fabrication, testing, data analysis, manuscript drafting. Yun-Cheng Han: overall supervision, manuscript review and revision. Xiao-Yu Wang: manuscript review, editing, and revision. Lei Ren: manuscript editing and revision. Xiang-Dong Meng: manuscript revision. Ming-Jie Zheng: guidance, revision, and supervision.

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Note: Figure translations are in progress. See original paper for figures.