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Evaluation of a betavoltaic energy converter supporting scalable modular structure

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Distinct from conventional energy-harvesting (EH) technologies, such as the use of photovoltaic, piezoelectric, and thermoelectric effects, betavoltaic energy conversion can consistently generate uniform electric power, independent of environmental variations, and provide a constant output of high DC voltage, even under conditions of ultra-low-power EH. It can also dramatically reduce the energy loss incurred in the processes of voltage boosting and regulation. This study realized betavoltaic cells comprised of p-i-n junctions based on silicon carbide, fabricated through a customized semiconductor recipe, and a Ni foil plated with a Ni-63 radioisotope. The betavoltaic energy converter (BEC) includes an array of 16 parallel-connected betavoltaic cells. Experimental results demonstrate that the series and parallel connections of two BECs result in an open-circuit voltage V_{oc} of 3.06 V with a short-circuit current I_{sc} of 48.5 nA, and a V_{oc} of 1.50 V with an I_{sc} of 92.6 nA, respectively. The capacitor charging efficiency in terms of the current generated from the two series-connected BECs was measured to be approximately 90.7%.

KEYWORDS
beta ray, betavoltaic cell, betavoltaic device, betavoltaic energy conversion, energy harvesting

1 | INTRODUCTION

Numerous studies have attempted to improve the reliability of energy-harvesting (EH) systems through various approaches, such as low-power circuit designs for power management [1], maximum power point tracking [2,3], and multi-input EH [4], to compensate for performance inconsistencies and maximize the throughput of harvested energy. However, the high dependency of energy generation on environmental changes and low-level output voltages under poor EH conditions with conventional energy sources, such as light [5], vibration [6], temperature variation [3], and radio frequency (RF) signals [7], which result in low conversion efficiency into available electric energy, have remained as critical limitations to current EH systems [8].

Analogous to the operation of a photovoltaic effect converting the kinetic energy of photons from a light source, such as the sun, into electric energy in a doped semiconductor, the betavoltaic effect utilizes beta particles, rather than photons, from a beta-ray emitting radioisotope [9–13]. Each high-energy beta particle can contribute numerous electron-hole pairs (EHPs), whereas a low-energy photon generates only a single EHP. When EHPs diffuse into the depletion region of a p-n junction or Schottky junction, the native electrostatic potential separates the EHPs before they recombine, resulting in a current flowing from an n-type to a p-type semiconductor [14,15].

TABLE 1 Characteristics of beta-ray emitting radioisotopes

Radioisotope	Half-life (years)	Average energy of beta particles (keV)	Maximum energy of beta particles (keV)
Y-90	0.007	933.6	2,280.1
Pm-147	2.62	224.6	61.93
Kr-85	10.76	250.7	687.4
H-3	12.32	5.69	18.59
Sr-90	28.79	195.8	546.2
Ni-63	100.2	17.42	66.94

In this study, we implemented a betavoltaic energy converter (BEC) by employing Ni-63 as a beta-ray irradiator and a custom-designed p-i-n semiconductor based on four-hexagonal SiC (4H-SiC). Compared to the other candidates for beta-ray-emitting radioisotopes listed in Table 1 [11,16], Ni-63 was chosen as the most suitable radioisotope source for designing a BEC based on its long half-life and soft irradiation energy below the maximum threshold for inflicting radiation damage on a p-i-n junction of SiC, which was reported to be 248.5 keV [11,17].

The constant electron emission from Ni-63, which has a half-life of 100.2 years, guarantees stable EH conditions irrespective of environmental changes, even under conditions of significantly low and high temperatures, where the performances and lifetimes of conventional chemical batteries substantially degrade [18]. The wide bandgap energy of 4H-SiC, approximately 3.23 eV at room temperature of 300 K [19], which is approximately three times wider than that of Si at 1.12 eV, provides a high DC output voltage, enabling direct delivery of electric power to application systems without additional power management processes for voltage boosting and regulation. Therefore, the BEC can potentially be applied as a battery for application systems without the use of energy-storage devices.

This paper presents the implementation of a betavoltaic cell with a size of 4×4 mm^2 as a component for a BEC, which is comprised of a p-i-n junction semiconductor based on SiC and an Ni foil made from stable isotopes of Ni plated with the Ni-63 radioisotope. A single BEC containing an array of 16 betavoltaic cells in parallel achieves an open-circuit voltage V_{oc} and short-circuit current I_{sc} of approximately 1.6 V and 49 nA, respectively. Based on a modular interface, the maximum output of V_{oc} and I_{sc} can be easily enhanced through series and parallel connections of BECs.

The remainder of this paper is organized as follows. Section 2 describes the implementation processes of the proposed BEC, experimental results are presented in Section 3, and conclusions are provided in Section 4.

2 | IMPLEMENTATION OF BETAVOLTAIC ENERGY CONVERTER

2.1 | Modeling of betavoltaic energy conversion

Figure 1 presents an equivalent circuit model of a betavoltaic energy conversion, where I_β is a current generated by betavoltaic energy conversion and I_{diode} is a p-n junction diode current. The output current I_{out} can be presented as

$$I_{\text{out}} = I_\beta - I_{\text{diode}} - I_{\text{sh}}, \tag{1}$$

$$= I_\beta - I_o\left\{\exp\left(\frac{q(V_{\text{load}} + I_{\text{out}}R_{\text{se}})}{nkT}\right) - 1\right\} - \frac{V_{\text{load}} + I_{\text{out}}R_{\text{se}}}{R_{\text{sh}}}, \tag{2}$$

where R_{se} is a series resistance, R_{sh} is a shunt resistance, I_o is a reverse-bias saturation current related to a diode leakage current, q is the electron charge, k is the Boltzmann constant, T is the absolute temperature, and n is an ideality factor that defines how closely the current characteristics match those of an ideal diode, where $n = 1$ for an ideal diode. Under the ideal conditions for a BEC, the series resistance R_{se} and shunt resistance R_{sh} are zero and infinity, respectively. Additionally, V_{oc} and I_{sc} can be derived when I_{out} and V_{load} are both zero. V_{oc}, which is proportional to the value of R_{sh}, can be increased by a semiconductor with wider bandgap energy and a higher doping concentration [11].

2.2 | Implementation process for a BEC

Because a unit cell of a BEC only generates power at a nanowatt scale [20,21], the core problems in securing the availability of a system are how to efficiently increase and gather generated energy in a usable form. This paper presents a simple and feasible approach to solving these problems by adopting an array of betavoltaic cells supporting a scalable modular structure. While the output electric power

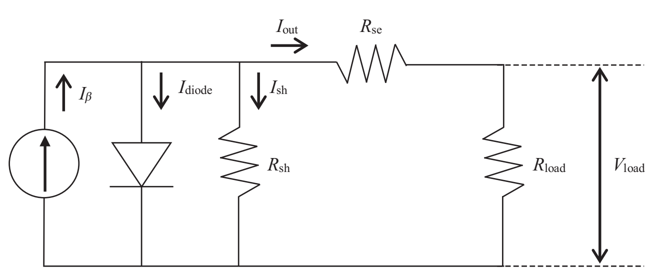

FIGURE 1 Equivalent circuit model of a betavoltaic energy conversion

of the BEC can be scaled up by increasing the circuit-die size of individual betavoltaic cells, excessive expansion of the die size leads to increased defects in circuits and yield loss as a result of process variations in 4H-SiC fabrication. Therefore, in this study, the proposed BEC was implemented by connecting of 16 betavoltaic cells with a die size of 4×4 mm^2 in parallel. Each betavoltaic cell consists of two layers, where the p-i-n junction, beta-ray absorber, and Ni foil plated with Ni-63, and the beta-ray irradiator are placed on the lower and upper layers, respectively. The location of the irradiator on the absorber was fixed by applying an epoxy to the edge of a betavoltaic cell.

Figure 2A illustrates each layer of the absorber fabricated on the highly doped N$^+$-type 4H-SiC substrate layer with measured sheet resistances of 0.015–0.025 ohm·cm, followed by the epitaxial growth of the N-type layer as a buffer layer, low-doped N$^-$-type layer indicating the i-type layer, and highly doped P$^+$-type layer. The p-i-n diode structure enables the extension of the depletion region across the intrinsic region, resulting in an increase in its volume, where EHPs can be generated by beta particles, and improvement of the betavoltaic energy conversion efficiency for a given thickness of the absorber. The required thickness of the SiC to cover the penetration depth by the average beta particle emission energy of approximately 17 keV from Ni-63 was reported to be approximately 4 μm [22]. The thickness of the i-type layer, which acts as an absorption layer, was set to a sufficient value in terms of the penetration depths of beta particles considering variations in emission energy. The photomask presented in Figure 2B was created from three pattern layers to pattern and etch the isolations, contacts, and metals. By applying the photomask, SiC-metal ohmic contacts were formed from a customized semiconductor fabrication recipe and process controls, which are briefly described in Table 2.

The beta-ray irradiator was fabricated by forming a micrometer-thick Ni-63 thin film on the Ni foil by adopting an electroplating procedure [23–25]. As presented in Table 3, the electroplating solution for small-scale Ni-63 electroplating was manufactured by mixing Ni-63 nickel chloride ($^{63}NiCl_2$), boric acid (H_3BO_3), sodium chloride (NaCl), and saccharin, then adding 0.5% Tween 20 to prevent the generation of bubbles in the solution during processing. The temperature, current density, and acidity of the electroplating bath were maintained at 40°C, 15 mA/cm^2, and pH 4, respectively.

Figure 3A presents the complete BEC containing an array of 16 parallel-connected betavoltaic cells, where each

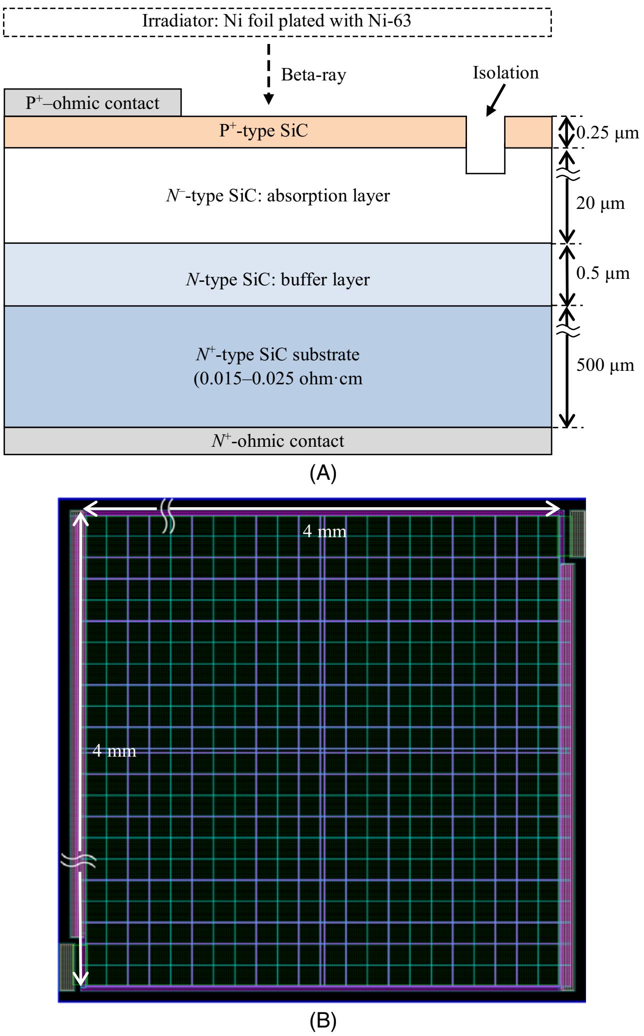

FIGURE 2 (A) Structural diagram of the absorber and (B) photomask layout of the absorber

TABLE 2 Procedure for forming SiC-metal ohmic contacts

N-type ohmic contact	P-type ohmic contact
1) NiVa sputtering deposition	1) Ti/Al sputtering deposition
2) Annealing at 1,000°C for 3 min to form silicide	2) Annealing at 1,000°C for 2 min to form silicide
3) Ti/Ag deposition after RF etching to remove Va from the surface	3) Al deposition after RF etching the surface

TABLE 3 Composition and conditions of electroplating solution

Composition				
$^{63}NiCl_2$	H_3BO_3	NaCl	Saccharin	Tween 20
0.05 M*	0.4 M	0.7 M	0.00829 M	0.5%
Condition				
Temperature	**Current density**	**Cathode**	**Anode**	**pH**
40°C	15 mA/cm^2	Ni foil	Pt-coated Ti mesh	4.0

*1 mol/L = 1 M.

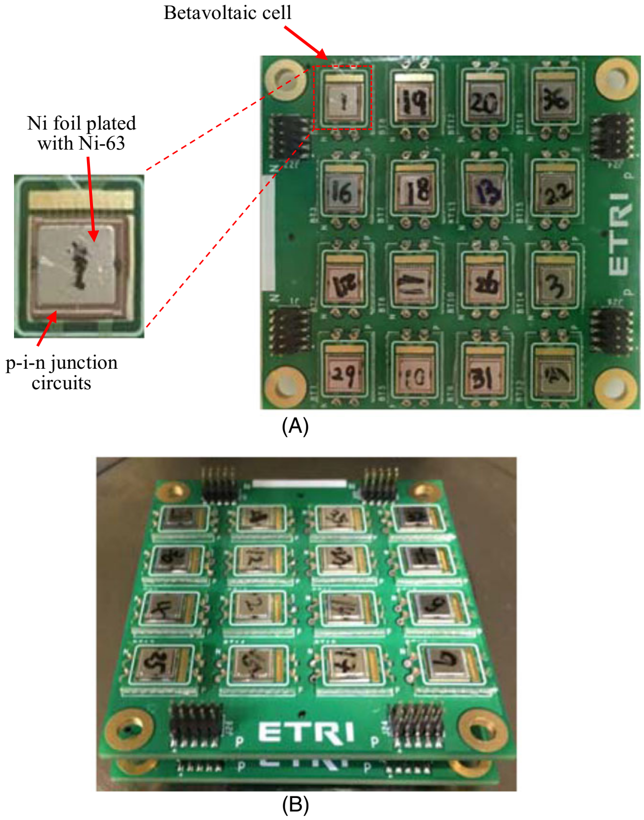

FIGURE 3 (A) Betavoltaic energy converter (BEC) containing an array of 16 parallel-connected betavoltaic cells and (B) stacked BECs with modular interfaces

betavoltaic cell is attached to the printed circuit board (PCB) via wire bonding. As shown in Figure 3B, the modular interface of the BEC provides a simple method to increase the output voltage and current by the series and parallel connections of BECs.

The SiC device process, including absorber fabrication and arrangement of the absorbers, was separated from irradiator fabrication, which handles the beta particle source. Following the implementation of an array of parallel-connected absorbers on the PCB, the irradiators were added in the final step of the production process.

3 | MEASUREMENT RESULTS

Figure 4 presents the average measured dark current-voltage (I-V) curve and 36 I-V curves with different irradiators for the absorber. The dark I-V curve verifies the normal operation of the absorber with an average leakage current of approximately 36.2 pA and turn-on voltage of approximately 1.8 V. Because the average beta-ray emission energy of 17.4 keV of Ni-63 is higher than the bandgap energy of 3.3 eV of 4H-SiC, the beta rays from the irradiator induce EHPs in the absorber. When the EHPs diffuse into the depletion region of the p-i-n junction, the electrical field of the depletion region sweeps the EHPs across the depletion region, creating a current, as shown by the curves with the irradiators.

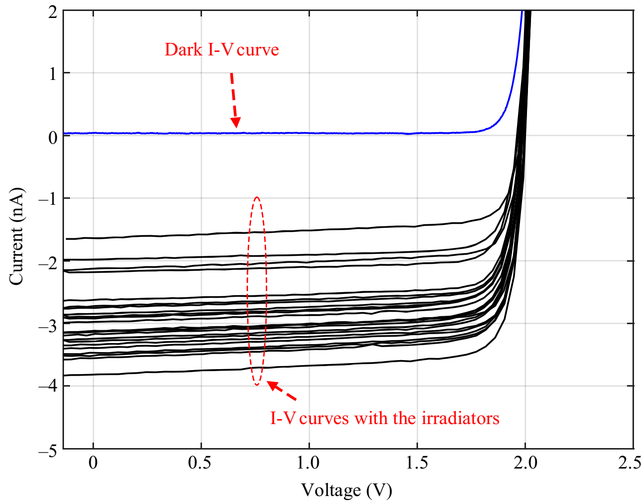

FIGURE 4 Measured dark I-V curve and I-V curves with the irradiators for the absorber

The values of V_{oc} and I_{sc} of the betavoltaic cells vary with the strength of the beta-rays from the irradiators. Figure 5 presents the measured V_{oc} and I_{sc} values over the counts per second (CPS) of the beta particles for 36 beta cells, which were evaluated by a CoMo 170 detector [26]. CPS is a measurement unit for measuring the strength of a radioisotope source and is generally utilized to track the number of particles encountered on the surface of a corresponding object. The CPS values were measured while maintaining a constant distance of 20 cm from each fabricated irradiator without an absorber and I_{sc} was determined based on the measurement of the I-V curve characteristics

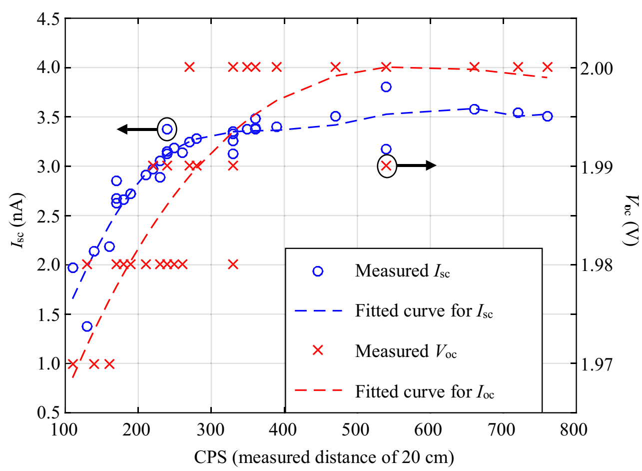

FIGURE 5 I_{sc} and V_{oc} over counts per second of beta particles for 36 beta cells

of the betavoltaic cells, which are comprised of the corresponding irradiator and absorber. As shown by the fitted curves, V_{oc} and I_{sc} increase to approximately 2 V and 3.5 nA, respectively, with an increase in the values of the CPS. As determined intrinsically by the bandgap energy of 4H-SiC, V_{oc} varies within a voltage range of approximately ±0.03 V. Additionally, I_{sc} is saturated at approximately 3.5 nA at CPS values greater than approximately 350. The saturation of I_{sc} in terms of the increase in CPS is expected to occur based on the limited size of the absorber surface for the given thicknesses of the absorber and irradiator. A larger surface area for the entry of beta particles into the absorber results in greater energy deposition and higher power generation for the betavoltaic cells [27].

Table 4 lists the EH performances of betavoltaic cells from previous studies employing SiC and Ni-63 in terms of V_{oc}, I_{sc}, and current density I_D. As indicated in the table, the cells developed in this study contribute to significant increases in V_{oc}, I_{sc}, and I_D of approximately 103.1%, 498.0%, and 13.5%, respectively.

Figure 6 presents the I-V curves of the BEC, as well as series and parallel connections of two BECs. Based on the stacking interface of the BEC shown in Figure 3B, V_{oc} and I_{sc} increase linearly with an increase in the number of combined BECs, with the connection direction determining whether the BECs are linked in series or parallel.

The 32 betavoltaic cells with the highest I_{sc} values were selected and divided into two groups of 16 betavoltaic cells to create equal current sums of approximately 49 nA for two BECs. The measured V_{oc} values of the two BECs were approximately 1.57 V and 1.55 V, which correspond to the lowest V_{oc} values among the V_{oc} values of the betavoltaic cells in each BEC, where voltage losses were incurred by the connections and path resistances on the PCB. The series and parallel connections of the two BECs resulted in a V_{oc} of 3.06 V with an I_{sc} of 48.5 nA and V_{oc} of 1.05 V with an I_{sc} of 92.6 nA, respectively. Therefore, the power summation efficiencies of the series and parallel connections were approximately 97.1% and 90.9%, respectively. Additionally, the summation efficiencies of the series connection for V_{oc} and parallel connection for I_{sc} were approximately 98.1% and 94.5%, respectively.

Figure 7 presents the evaluation board utilized to charge a capacitor based on the energy generated by the series-connected BECs. After 600 s of charging by the BECs, the capacitor voltage was measured as approximately 2.4 V, where the size of the tantalum capacitor was 10 µF. When the voltage-rise time τ_{cap} reached V_{EH} in the given capacitor C_{EH} with the supplied current, I_{EH} was approximated as follows:

$$I_{EH} = \Delta I \cong \frac{dQ}{dt} = C_{EH}\frac{dV}{dt} \cong C_{EH}\frac{\Delta V}{\Delta t} = C_{EH}\frac{V_{EH}}{\tau_{cap}} \quad (3)$$

$$\tau_{cap} \cong C_{EH}\frac{V_{EH}}{I_{EH}} \quad (4)$$

τ_{cap} was calculated to be approximately 544.2 s, where V_{EH} was 2.4 V, C_{EH} was 10 µF, and I_{EH} was 44.1 nA, which was approximated as the mean current between the voltages of 0 V and 2.4 V for the series-connected BECs shown in Figure 6. The series-connected BECs achieved a capacitor charging efficiency of 544.2 s/600 s × 100% = 90.7%. Our experiments verified that the harvested

TABLE 4 Performance comparison of betavoltaic cells

Work	Size (mm^2)	V_{oc} (V)	I_{sc} (nA)	I_D (nA/cm^2)
[20]	2 × 2	0.98	0.510	12.75
[21]	0.5 × 0.5	0.72	0.042	16.80
This work	4 × 4	1.99	3.050	19.06

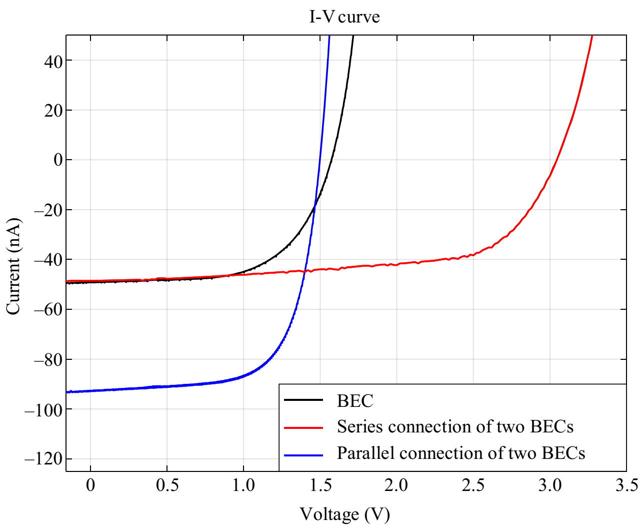

FIGURE 6 Measured I-V curves of the betavoltaic energy converter (BEC), and series and parallel connections of two BECs

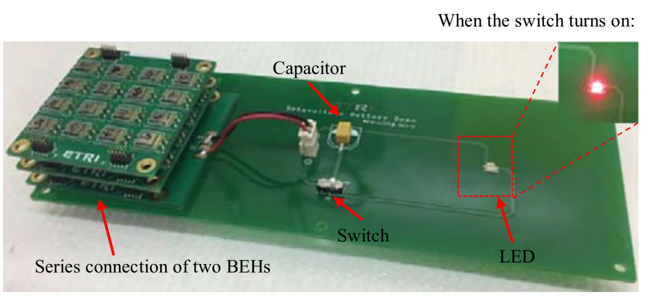

FIGURE 7 Evaluation board for experiments on charging a capacitor with the energy generated from the betavoltaic energy converters

energy from the BEC can be stored in an energy-storage device, resulting in a high available voltage for turning on the LED, without any additional power-management devices.

4 | CONCLUSION

This paper presented the implementation processes and performance analyses of an energy harvester based on betavoltaic energy conversion. A BEC was implemented as an array of 16 betavoltaic cells comprised of a fabricated SiC p-i-n junction semiconductor and Ni foil plated with Ni-63, acting as absorber and irradiator of beta rays, respectively. Experimental results demonstrated that output voltage and current can be effectively increased through the simple connection of individual betavoltaic cells. They also demonstrated that the harvested energy can be stored in a capacitor with a high DC voltage without additional power-management devices.

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