

Optimization of C-14 betavoltaic cells based on p-i-n structure

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HIGHLIGHTS

- The performance of betavoltaic battery with C-14 beta-emitting source was investigated for the p-i-n junction.
- The optimal i-layer thickness was found to be 22, 27, and 20 μm for C-14 betavoltaic with B-Ga₂O₃, GaAs, and GaN.
- The maximum output power density of the p-n junction battery were 21.13, 8.09, and 16.89 $\mu\text{W}\cdot\text{cm}^{-2}$, respectively.
- The conversion efficiency of the p-i-n junction betavoltaic batteries improved by 0.50%, 1.48%, and 1.06%.

ABSTRACT

This research investigated the optimization of performance and the impact of intrinsic (i) layer thickness in betavoltaic batteries that utilize C-14 radioactive sources combined with B-Ga₂O₃, GaAs, and GaN semiconductors in p-i-n junction configurations. Using Monte Carlo simulations and numerical analysis, the study optimized the doping concentrations and thickness of the i-layer. The findings indicated that, compared to the p-n betavoltaic batteries exposed to the same beta emitting source, p-i-n betavoltaic batteries exhibit better performance. The optimal i-layer thickness was found to be 22, 27, and 20 μm for C-14 betavoltaic with B-Ga₂O₃, GaAs, and GaN semiconductor, respectively. With this optimized i-layer thickness, the maximum power density (P_m) increased by 0.50%, 1.50%, and 1.14% for B-Ga₂O₃, GaAs, and GaN, respectively respect to p-n junction structure. Additionally, the conversion efficiency of the p-i-n junction betavoltaic batteries improved by 0.50%, 1.48%, and 1.06% compared to their p-n junction counterparts with the same materials. This work offers valuable guidance for the optimal design of p-i-n betavoltaic batteries and enhancing maximum power density for various applications.

KEYWORDS

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1 Introduction

The relentless advancement of low-power electronic systems, particularly for applications in micro-electromechanical systems (MEMS), remote sensors, and medical implants, has created a critical and growing demand for autonomous, long-lasting, and compact power sources (Rahastama et al., 2021; Summerer and Stephenson, 2011; Chen et al., 2025). Among the different energy harvesting methods, betavoltaic energy conversion stands out as a promising option. Betavoltaic batteries utilize the decay energy from beta-emitting radioisotopes to generate electron-hole pairs (EHPs) within a semiconductor, providing high energy density and the potential for uninterrupted operation over many years, unaffected by environmental factors like darkness or extreme temperature (Oh et al., 2012).

The heart of a betavoltaic cell is its semiconductor junction, where the energy conversion take place. Early

devices used simple p-n junctions, but their performance is inherently limited for this purpose. In a typical p-n junction, the depletion region-the critical area where generated EHPs are separated by the built-in electric field to generate current-is quite narrow. However, high-energy beta particles penetrate deep into the semiconductor, depositing their energy over a significant depth, often several microns. In a p-n junction, many EHPs form outside this narrow depletion region, in the neutral bulk material. These carriers have a high chance of recombining before reaching the junction, leading to significant energy loss and low efficiency in collecting charge carriers.

To enhance the performance of a betavoltaic battery, certain fabrication and design challenges must be overcome. Loss of beta energy from backscattering and self-absorption was reduced by adjusting the junction thickness, source thickness, and increasing depletion width (Naseem et al., 2023). In this regard there are some re-

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cent researches that could enhance the betavoltaic devices performance. For instance, some researchers have been enhanced performance compared to the C-14 pristine betavoltaic cell by develop a dye-sensitized betavoltaic cell, composed of nano-sized quantum dots, and ruthenium-based dye sensitized TiO_2 as electrodes. In this cell, emitted beta radiations are absorbed by the dye rather than TiO_2 (Hwang et al., 2020; Kim et al., 2024). Hong Soo Kim et al., demonstrated a perovskite based betavoltaic cell incorporating form a midinium lead iodide (FAPbI_3) and C-14 nanoparticles, achieving an unprecedented energy conversion efficiency of 10.79%. Their device features enhanced charge generation, with each incident betaparticle initiating electron avalanche multiplication (Kim et al., 2026a).

Also, utilizing chlorine-based dual additives with perovskite film and radioactive isotopes of C-14 nanoparticle/quantum dot ($^{14}\text{CNP/CQD}$) electrodes, was enhanced the phase stability and power conversion ecieney (PCE) of the betavoltaic device (Kim et al., 2025).

One way to overcome the critical limitation of collecting charge carriers is using p-i-n junction structure. By placing a thick intrinsic (i) semiconductor layer between the p-type and n-type layers, the device is engineered to maximize the depletion region width (Yoon et al., 2020; Oh et al., 2012). In an ideal p-i-n junction, the entire i-layer is fully depleted, creating a large, and uniform electric field throughout its entire thickness. This design offers two key advantages for betavoltaic cells: 1) The thick i-layer is designed to match the penetration depth of the beta particles, ensuring that a larger proportion of the radioactive decay energy is absorbed directly within the active depletion region. 2) EHPs generated in this extended depletion region are immediately separated by the strong electric field, sweeping electrons and holes to their respective contacts. This drift-driven collection process is much faster and more efficient than the diffusion-based collection in the neutral regions of a p-n junction, thereby reducing recombination losses. With this advantageous of p-i-n junction, numerous studies have been conducted to access the electrical performance of this structure in betavoltaic batteries, concluding that growth of a high quality i-layer is important for improving the P_m in Betavoltaic cell (Yoon et al., 2020). For example, Shitong He et al. found that, compared to a Si/p-n betavoltaic battery exposed to the same Ni-63 source at 290 K, the Si/p-i-n betavoltaic battery demonstrated notable performance improvements, including the short-circuit current density (J_{sc}) and maximum power density (P_m) increased by 13.59% and 12.16%, respectively (He et al., 2025).

Kim et al. investigated p-i-n structured GaN nuclear batteries using technology computer-aided design (TCAD) simulations alongside electron beam irradiation experiments, focusing on the function of the i-layer in p-i-n junction nuclear batteries. They achieved an actual conversion efficiency of 4.58% for 17 keV electrons. Their findings revealed that the incorporating an i-GaN layer and the optimizing parameters such as i-layer thickness are crucial for enhancing the power performance of betavoltaic cells (Kim et al., 2021). Hogan et al. modified a transmis-

sion electron microscope to simulate the effects of Pm-147 radiation on p-i-n structured GaN transducers. Under an average particle energy of 62 keV from Pm-147, the device produced an output power of $2.45 \mu\text{W.cm}^{-2}$ and a conversion efficiency of 0.79% (Hogan et al., 2020). Further optimization of the GaN transducer structure with a Pm-147 source showed that a 5- μm -thick i-layer broadened the energy collection region, thereby improving both conversion efficiency and power output (Zhang et al., 2025a).

Although the theoretical benefits of the p-i-n design are well recognized, the advancement of high-performance C-14-based betavoltaic cells has been limited by insufficient comprehensive optimization. This study addresses this issue through an extensive numerical analysis aimed at calculating, enhancing, and optimizing the electrical parameters of a p-i-n junction betavoltaic cell powered by a C-14 source. Our evaluation offers vital insights into the balance among between open-circuit voltage, short-circuit current density, and overall conversion efficiency, clearly demonstrating the superiority of the optimized p-i-n design compared to a traditional p-n junction. The obtained results not only clarify the fundamental limitations of C-14 betavoltaic technology but also provide a practical design framework for developing high-performance, long-lasting betavoltaic micro batteries.

2 Materials and Methods

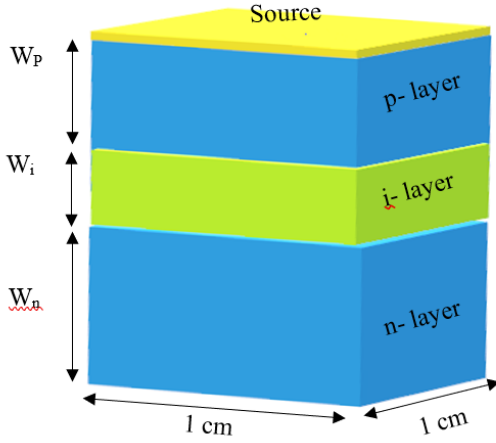
2.1 Device Structure and Material Properties

A p-i-n junction design was chosen for all semiconductors materials to maximize the width of the depletion region and improve the efficiency of charge carrier collection. The general device structure, illustrated in Fig. 1, consists of: p-type layer, i-layer, and n-type layer. The thicknesses of the p-layer, i-layer, and n-layer were denoted as W_p , W_i , and W_n , respectively.

The beta source was placed on the p-side because the built-in electric field in the depletion region is from the n-side toward the p-side; thus, minority carriers (electrons) generated in the p-region are efficiently swept across the junction. Also, beta particles from low-energy isotopes such as C-14 have a short penetration depth, so placing the source on the p-side ensures that carrier generation occurs in close proximity to the depletion region where the electric field assists in carrier separation. The heavily doped p-layer reduces surface recombination velocity and acts as a passivation layer. In contrast, n-layer irradiation would require minority carriers (holes) to diffuse through the entire thick n-base -where no electric field exists- before reaching the junction, leading to significant recombination losses. Even if the n-layer thickness is reduced to minimize this diffusion path, the series resistance would increase substantially and degrade the device performance. Therefore, p-layer irradiation is the optimal and universally adopted configuration in betavoltaic devices.

Table 1: : Properties of used Semiconductors (Zheng et al., 2022; Dong et al., 2010; Gachovska and Hudgins, 2024; Levinshtein et al., 2001; Okur et al., 2012; Kotecha et al., 2019; Lyle et al., 2021; Carey IV et al., 2017; Zhang et al., 2025b).

Parameter	B-Ga ₂ O ₃	GaAs	GaN
Density (g.cm ⁻³)	5.88	5.32	6.15
Bandgap (E_g) (eV)	4.80	1.42	3.40
Dielectric Constant (ϵ_r)	10.00	12.90	8.90
Electron Mobility (μ_n) (cm ² .V ⁻¹ .s ⁻¹)	1.50E02	8.50E03	1.00E03
Hole Mobility (μ_p) (cm ² .V ⁻¹ .s ⁻¹)	15.00	4.00E02	3.00E01
Avg. EHP Creation Energy (E_{pair}) (eV)	15.60	4.80	8.90
Sn, and Sp are the surface recombination velocity of carriers ($\mu\text{m.s}^{-1}$)	1.80E11	1.00E11	2.20E11

**Figure 1:** Schematic view of p-i-n structure of betavoltaic battery.

This research utilized a numerical simulation approach to model and evaluate the performance of betavoltaic cells made from three semiconductor materials: Gallium Oxide (B-Ga₂O₃), Gallium Arsenide (GaAs), and Gallium Nitride (GaN). These materials were chosen due to their previously demonstrated high power density and conversion efficiency based on p-n junction, as reported in an earlier study (Mohammadi, 2026). For Ga₂O₃, the -polymorph (B-Ga₂O₃) was selected because it is currently the only phase that can be fabricated into thick layers of 20-25 μm required for this study. It should also be noted that practical p-n junction formation on Ga₂O₃ requires heterojunction architectures using other p-type semiconductors (e.g., NiO, Cu₂O, or p-GaN), as achieving stable p-type doping in GaO remains challenging. This consideration, while beyond the scope of the present simulation study, is important for experimental realization. The physical properties of these semiconductors were listed in Table 1. The methodology involved two main stages: (1) simulating the transport of beta particles emitted from a C-14 source and the subsequent generation of EHPs within the semiconductor, and (2) modeling the electrical behavior and charge collection in the p-i-n junction device structure to determine key performance metrics.

In this work, the radioisotope of C-14 was used as the beta emitting source for the betavoltaic battery, characterized by a maximum beta energy (E_{max}) of 156 keV, an average energy (E_{avg}) of 49.7 keV, and a long half-life of about 5,730 years. The C-14 beta source was modeled

as a thin layer with an optimized thickness of 60 μm positioned at the top of the device. The continuous C-14 beta spectrum was discretized into 200 energy bins with an average resolution of 0.78 keV, based on ICRU Report 56 data (on Radiological Units, 1957).

2.2 Beta Particle Transport and EHP Generation

The interaction of the C-14 beta particles with the semiconductor materials was simulated using the Monte Carlo method, carried out through the MCNPX 2.6 code (Pelowitz, 2008). An optimized C-14 source thickness of as 60 μm was specified in the MCNP input file, and the energy deposition of 10⁶ beta particles was calculated as a function of depth within each semiconductor material (with a relative error below 1%), based on the details provided in the previous report (Mohammadi, 2026). Importantly, the Monte Carlo simulations explicitly accounted for self-absorption effects within the source layer, including energy loss and angular scattering of beta particles as they traveled through the 60 μm -thick C-14 material. Consequently, the beta energy spectrum incident on the semiconductor was the self-absorption-modified spectrum rather than the intrinsic C-14 spectrum. Beta particles were emitted from the source with an isotropic angular distribution, which was sampled uniformly in both polar and azimuthal angles for each simulated particle. It should be noted that all calculated values were per 1 Ci activity, which is standard in comparative betavoltaic performance studies. The depth-dependent EHP generation rate, $G(x) = G_0 e^{-\alpha x}$, was then fitted to resulting data, where x represents the depth within the semiconductor. The fitted absorption coefficient α was obtained as 0.19 μm^{-1} for B-Ga₂O₃, 0.16 μm^{-1} for GaAs, and 0.19 μm^{-1} for GaN ($R^2 = 0.99$).

2.3 Electrical parameters

The electrical parameters of the p-i-n junction structure were assessed using the formula given in Table 2 (Dong et al., 2010). Referring to the suggestions in other literature research, the minimum junction depth (x_j) of 0.05 μm was chosen for the calculation model in this work (Zheng et al., 2022). This thickness ensuring direct comparability with established models and is the effective range of low-energy beta particles to maximize carrier collection and minimize recombination.

Table 2: The electrical parameters for p-i-n junction.

Parameter	Formula	Input data
		k =Boltzmann's constant q = Electron charge T =300 K N_a =Acceptor concentration N_d =Donor concentration
Minority electron diffusion length in the p-type region (L_n) (μm)	Eq. (1)	-
Minority hole diffusion length in the n-type region (L_n) (μm)	Eq. (2)	-
Average ionization energy (E_{ehp}) (eV)	$2.8E_g + 0.5$	-
Short-Circuit Current Density (J_{sc}) ($\mu\text{A.cm}^{-2}$)	Eq. (3)	x_j = p-layer thickness (0.05 mm) n_i = Intrinsic carrier concentration h = n-layer thickness
Leakage current density (J_0) ($\mu\text{A.cm}^{-2}$)	Eq. (4)	-
open-circuit voltage (V_{OC}) (V)	Eq. (5)	-
Filling factor (FF)	Eq. (6)	-
Maximum output power density (P_m) ($\mu\text{W.cm}^{-2}$)	$FF \times V_{OC} \times J_{sc}$	-
Energy conversion efficiency (η)	$\frac{P_m}{P_{in}}$	-

Table 3: Comparison between outputs of p-n junction and p-i-n junction for $N_a = 1.00E18 \text{ cm}^{-3}$, $N_d = 1.00E14 \text{ cm}^{-3}$, and p-layer thickness of 0.05 mm.

Junction	$J_{sc} (\mu\text{A.cm}^{-2})$		$J_0 (\mu\text{A.cm}^{-2})$		V_{OC} (V)		Width of depletion region (μm)		FF (%)		$P_m (\mu\text{W.cm}^{-2})$		η (%)	
	p-n	p-i-n	p-n	p-i-n	p-n	p-i-n	p-n	p-i-n	p-n	p-i-n	p-n	p-i-n	p-n	p-i-n
B-Ga ₂ O ₃	5.45	5.47	5.60E-68	5.61E-68	3.98	3.97	7.10	10.00	96.11	96.10	20.91	20.97	7.18	7.20
GaAs	1.58	1.59E01	9.31E-12	9.13E-12	6.09E-01	6.09E-01	4.08	10.00	82.90	82.95	7.97	8.06	2.71	2.74
GaN	7.08	7.12	5.54E-44	5.54E-44	2.51	2.51	5.50	10.00	94.30	94.30	16.70	16.80	5.68	5.71

All simulations in this work were performed at a fixed temperature of 300 K, corresponding to standard room temperature operation. This temperature was selected as it represents the most relevant operating condition for typical betavoltaic applications, such as implantable medical devices and remote sensors, where the device is expected to function in ambient thermal environments. Furthermore, for the low-activity C-14 source considered here, the self-heating effect is negligible due to the microwatt-level power density, ensuring that the device temperature remains essentially at ambient conditions. Therefore, temperature-dependent parameters-such as bandgap energy, carrier mobility, and intrinsic carrier concentration-were not incorporated into the present model. It is evident that for higher-activity sources or operation in extreme temperature environments, thermal effects could become significant, and a temperature-dependent model would be necessary. This is identified as a valuable extension for future investigations.

It should be noted that thermal effects were not considered in this simulation model. This exclusion is justified by the relatively low decay power density of the selected radioisotope, which typically yields a temperature rise of less than a few degrees Celsius above ambient under standard operating conditions, particularly when considering practical device packaging and heat dissipation through the surrounding environment. Moreover, the primary objective of this work is to establish a fundamental electrical performance baseline, and incorporating temperature-dependent parameters such as carrier mobility, bandgap narrowing, and intrinsic carrier concentration would introduce additional complexities that could obscure the core transport mechanisms under investigation. Nevertheless, we acknowledge that for high-activity sources or extended

operational lifetimes, thermal accumulation may become non-negligible. Therefore, a more comprehensive model coupling thermal and electrical effects is identified as a valuable direction for future studies.

3 Results and discussion

3.1 Comparison between p-n and p-i-n junction outputs

To preliminarily investigate the effect of the p-i-n junction, a comparison was made between the outputs of a p-n junction from the previous study and the results for the p-i-n structure (Mohammadi, 2026). The parameters of N_a , N_d , and p-layer thickness were chosen from optimal values obtained in the prior study (Mohammadi, 2026). For p-i-n junction, the addition of an i-layer was set 10 for comparison, which effectively increased the depletion width. As indicated in Table 3, the relevant parameters show improvement compared to the corresponding p-n configuration. Specifically, the conversion efficiency increased by 2.76%, 1.11%, and 0.53% for B-Ga₂O₃, GaAs, and GaN, respectively. This initial analysis confirms that the p-i-n junction outperforms the p-n junction.

The main results, focusing on the short-circuit current density (J_{sc}) and the maximum output power (P_m), are presented and discussed here.

3.2 Short-Circuit Current Density analysis in p-i-n junction

Figure 2 presents the relationship between the short-circuit current density, J_{sc} , and the acceptor doping concentration, N_a , in the p-type layer for different fixed thicknesses of the i-layer. A clear trend is seen across all three

semiconductors: J_{sc} exhibits a significant decrease as N_a increases beyond approximately 10^{17} cm^{-3} . This occurs because higher doping reduces the minority carrier diffusion length in the p-type region. Higher doping concentrations increase impurity scattering and recombination centers, severely limiting the distance that electrons (the minority carriers in the p-layer) can diffuse before recombining. Consequently, fewer electrons generated in the p-layer can reach the depletion region to contribute to the photocurrent, causing a drop in overall J_{sc} . This result highlights the importance of optimizing the doping level in the quasi-neutral regions, not just the i-layer, to reduce losses related to carrier diffusion.

Comparing three materials, GaAs consistently shows the highest J_{sc} values, followed by GaN and then B-Ga₂O₃. For instance, at $N_a = 1.00E16 \text{ cm}^{-3}$ and i-layer thickness of $12 \mu\text{m}$, the J_{sc} value was 5.48, 15.97, and $7.14 \mu\text{A.cm}^{-2}$, for B-Ga₂O₃, GaAs, and GaN, respectively. This order is mainly due to two factors: 1) EHP Creation Energy (E_{pair}): GaAs has the lowest E_{pair} (4.8 eV), meaning each incoming beta particle generates more electron-hole pairs compared to GaN (8.9 eV) and B-Ga₂O₃ (15.6 eV). 2) Carrier Mobility: GaAs's exceptionally high electron mobility enables more efficient charge transport and collection, further increasing its current output.

3.3 Maximum output power analysis in p-i-n junction

The effect of p-type doping concentration (N_a) on the maximum output power density (P_m), was studied while keeping the n-type doping fixed (N_d). As illustrated in Fig. 3, increased steadily with before saturating at approximately $1.00E18 \text{ cm}^{-3}$. This rise is attributed to the enhancement of the built-in potential, which directly enhance the open-circuit voltage (V_{OC}) and fill factor (FF). The saturation happens when the built-in potential reaches its maximum. It is noted that while higher can slightly reduce the short-circuit current due to a shorter minority carrier diffusion length in the p-type emitter, this effect is minor in the p-i-n structure, where charge collection mainly occurs by drift within the thick i-layer. In fact, is less critical here since most current is generated in the i-layer, making device performance more sensitive to V_{OC} and FF rather than small diffusion current losses in the neutral p-region. Looking at the results, the calculated P_m for three semiconductors at an acceptor doping of $N_a = 1.00E18 \text{ cm}^{-3}$ and an i-layer thickness of $12 \mu\text{m}$ reveals a clear ranking: B-Ga₂O₃ has the highest P_m ($21.28 \mu\text{W.cm}^{-2}$), followed by GaN ($16.85 \mu\text{W.cm}^{-2}$), and then GaAs ($8.06 \mu\text{W.cm}^{-2}$). This may seem surprising initially, given GaAs's better EHP creation energy and carrier mobility. However, a deeper analysis reveals that this outcome stems from the specific operating conditions and the fundamental trade-offs among key performance factors.

The superiority of B-Ga₂O₃ in this configuration can be attributed to its very high open-circuit voltage ($V_{OC}=4.04 \text{ V}$), which results from its ultra-wide bandgap of 4.8 eV. Since P_m is the product of J_{sc} , V_{OC} , and FF, a

high V_{OC} can offset a lower J_{sc} .

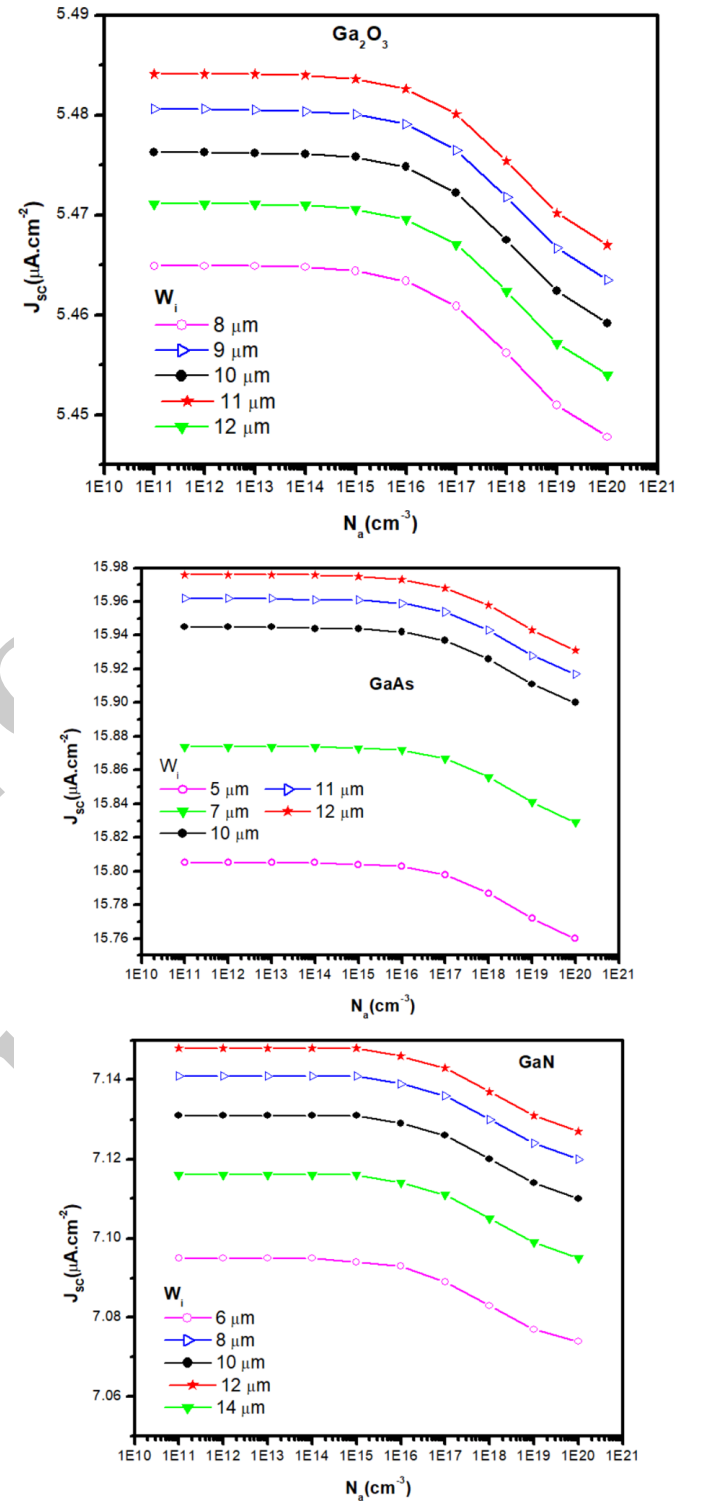


Figure 2: Effect of N_a on J_{sc} for different i-layer thickness. $N_d = 1.00E14 \text{ cm}^{-3}$, and thickness of p-layer is $0.05 \mu\text{m}$.

This finding does not contradict expectations but rather demonstrates an important design principle: there is no single “best” material for betavoltaic cells; instead, the best material depends on the specific constraints. When device architecture (such as a very thick i-layer) or operating conditions limit the current, a wide-bandgap semiconductor like B-Ga₂O₃ can be a better choice due to

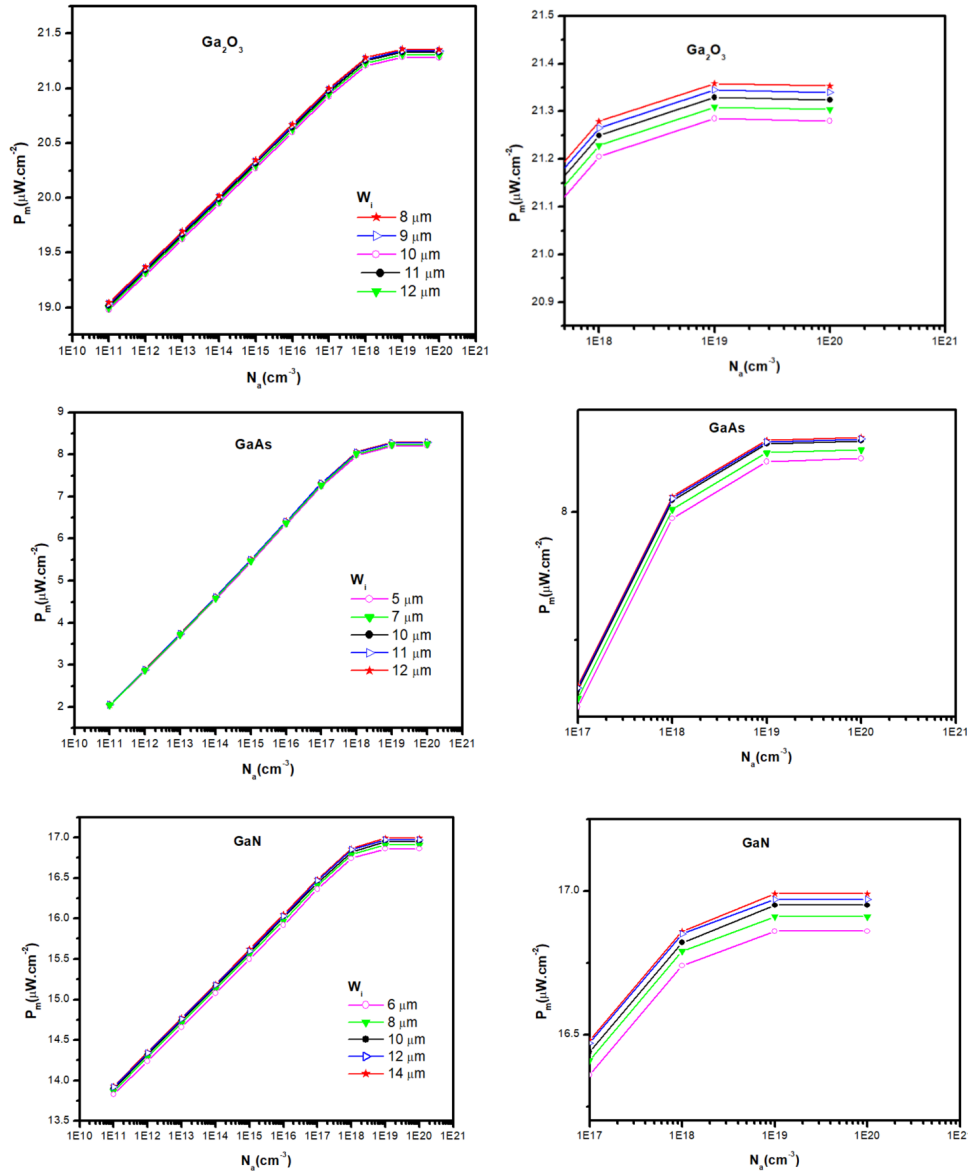


Figure 3: Effect of N_a on P_m for different W_i value (Left figure) and zoom of it (Right figure) with $N_d = 1.00\text{E}14 \text{ cm}^{-3}$.

its high-voltage operation. This insight is vital for designing betavoltaic cells aimed at maximizing power density from a low-current sources, highlighting a unique role where ultra-wide bandgap semiconductors like B- Ga_2O_3 can outperform traditional semiconductors like GaAs.

3.4 Optimization of the i-layer thickness

The most important design factor for the p-i-n betavoltaic cell is the thickness of the i-layer (W_i). Figure 4 shows how both the J_{sc} and P_m change with W_i , using optimized doping concentrations of $N_a = 1.00\text{E}18 \text{ cm}^{-3}$, and $N_d = 1.00\text{E}14 \text{ cm}^{-3}$.

The results demonstrate a clear and predictable relationship: initially, both J_{sc} and P_m increase steadily as W_i grows. When W_i is small, the depletion region is thinner than the average penetration depth of the beta particles, causing much of the high-energy radiation to pass through the i-layer without depositing energy. Many EHPs are in-

stead generated in the neutral n-type substrate, where recombination rates are high. As W_i increases, more beta particle energy is absorbed within the depletion region. The strong electric field there enables quick and efficient carrier collection through drift, leading to a sharp increase in J_{sc} , and consequently P_m . However, this upward trend does not continue indefinitely. At a certain W_i , both J_{sc} and P_m reached their peak values. This saturation point corresponds roughly to the maximum penetration depth of the most beta particles. Beyond this thickness, nearly all the source energy is absorbed, so increasing W_i further does not generate more carriers and may even have slight negative effects. A thicker i-layer can reduce the built-in electric field, potentially slowing carrier drift, and any defects in the intrinsic bulk become more impactful. Therefore, exceeding the saturation thickness offers no performance benefit and may be economically and technologically unfavorable.

The saturation thickness depends on material, linked

to its density and stopping power. Semiconductor like B-Ga₂O₃ and GaN, which have higher atomic numbers and densities, exhibited the shortest saturation thicknesses, about 22 μm and 20 μm , respectively, effectively stopping the beta particles over shorter distances. In contrast, GaAs, with a lower density, requires a thicker i-layer (around 27 μm) to fully absorb the incident radiation.

3.5 Optimized design for p-i-n junction of C-14 Betavoltaic Cells

Table 4 provides a summary of the overall performance metrics at the optimized i-layer thickness and doping levels.

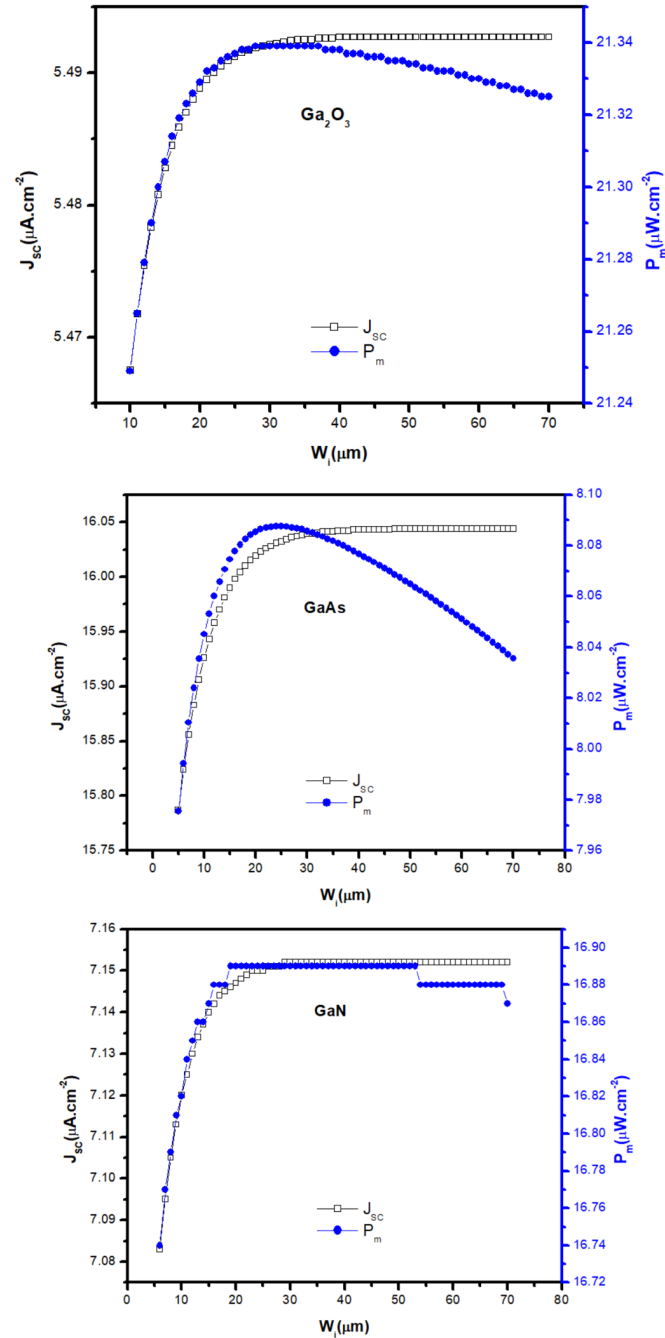


Figure 4: Effect of i-layer thickness (W_i) on J_{sc} and P_m with $N_d = 1.00E14 \text{ cm}^{-3}$ and $N_a = 1.00E18 \text{ cm}^{-3}$.

Table 4: Optimized performance parameters for p-i-n junction of C-14 Betavoltaic Cells.

Parameter	B-Ga ₂ O ₃	GaAs	GaN
$N_a \text{ (cm}^{-3}\text{)}$	1.00E18	1.00E18	1.00E18
$N_d \text{ (cm}^{-3}\text{)}$	1.00E14	1.00E14	1.00E14
p-layer thickness (μm)	0.05	0.05	0.05
Optimal i-layer thickness (μm)	22	27	20
$J_{sc} \text{ (}\mu\text{A.cm}^{-2}\text{)}$	5.49	16.04	7.15
$V_{oc} \text{ (V)}$	4.04	0.61	2.51
$P_m \text{ (}\mu\text{W.cm}^{-2}\text{)}$	21.13	8.09	16.89
Conversion efficiency (%)	7.26	2.75	5.74

Compared to p-n betavoltaic batteries irradiated by the same source, the p-i-n betavoltaic batteries show better performance, with P_m increases of 0.50%, 1.50%, and 1.14% for B-Ga₂O₃, GaAs, and GaN, respectively. Correspondingly, the conversion efficiency of the p-i-n junction betavoltaic batteries improved by 0.50%, 1.48%, and 1.06% over p-n junction with B-Ga₂O₃, GaAs, and GaN, respectively.

The analysis indicates that the adding an i-layer to C-14-based GaN, GaAs, and B-Ga₂O₃ betavoltaic cells yields a modest performance gain of about 1%, in P_m , which is significantly less than the 12.16% improvement observed in a ⁶³Ni-Si p-i-n junction (He et al., 2025). This difference is not due to design flaw but stems from the fundamental physics of beta particle interactions and charge collection in these materials. The limited advantage of the p-i-n structure for C-14 can be explained by two primary reasons: 1) The i-layer primary role is to extend the depletion region, increasing the volume where the electric field can efficiently collect charge carriers through drift. The success of this approach depends entirely on the penetration depth of beta particles. For Ni-63 (with $E_{avg} \approx 17 \text{ keV}$), the average penetration depth in silicon is several micrometers. In a typical p-n junction, the depletion region is narrow (usually less than 1 μm), capturing only a portion of the generated EHPs, with many lost to recombination in neutral regions. Adding an i-layer to form a p-i-n structure significantly expands the depletion width, capturing a much larger fraction of the generated carriers and leading to a substantial 12% increase in P_m . While, for C-14 (with $E_{avg} \approx 49 \text{ keV}$) despite the higher maximum energy, the continuous energy spectrum leads to a very shallow penetration depth (around 1-2 μm in gallium-based semiconductors) due to their higher atomic number and density compared to silicon (2.33 g.cm^{-3}). The depletion region in a standard p-n junctions of these materials is already wide enough to collect most of the EHPs generated by C-14. Therefore, adding a thick i-layer provides diminishing returns, as few additional carriers are generated beyond the reach of the original p-n junction's electric field. The roughly 1% improvement likely results from slight reductions in recombination near the depletion region edges rather than a fundamental increase in the collected carriers. 2) Wide bandgap semiconductors like B-Ga₂O₃, GaAs, and GaN have an exponentially lower intrinsic concentrations (n_i), which naturally leads to wider depletion regions in a p-n junctions compared to silicon at similar doping levels. This means the baseline col-

lection efficiency is already high in these materials. In other words, the high values of indicate that even when some carriers are produced in neutral regions, the effect of non-radiative recombination on the diffusion length is less significant compared to narrow-bandgap semiconductors such as silicon. This means the disadvantage of relying on diffusion for carrier collection is smaller, which reduce the advantage of moving entirely to a drift-based collection method.

Importantly, this study identifies a specific saturation thickness for i-layer, providing a key design guideline to prevent excessive use of materials and complexity while maintaining performance.

4 Conclusions

This study theoretically examined the performance of p-i-n junction betavoltaic cells using a C-14 beta source was investigated. The key discovery was identifying a specific saturation thickness for i-layer in each semiconductor material (GaAs, GaN, and B-Ga₂O₃). At this saturation thickness, both the short-circuit current density, J_{sc} , and maximum output power, P_m , reach a plateau, indicating the fundamental limit for energy absorption from the C-14 beta spectrum. Increasing the i-layer thickness beyond this point does not improve performance, establishing an important design guideline to avoid unnecessary material consumption and added complexity. The optimal i-layer thickness was found to be 22, 27, and 20 μm for C-14 betavoltaic with B-Ga₂O₃, GaAs, and GaN semiconductor, respectively. Given the obtained results, the maximum output power density of the p-n junction battery for B-Ga₂O₃, GaAs, and GaN were 21.18, 8.09, and 16.89, respectively. In addition, the associated conversion efficiency was 7.27%, 2.75%, and 5.74% for these semiconductors, respectively. Compared to the previously reported p-n junction, the p-i-n junction betavoltaic batteries demonstrated higher maximum power density and energy conversion efficiency, making this structure a promising design for efficient betavoltaic batteries. However, the improvement was not remarkable for C-14 betavoltaic battery respect to ⁶³Ni sources.

This result provides an important design insight that for high atomic number (high- Z) semiconductors and low-penetration beta sources like C-14, efforts to optimize performance should focus less on increasing the i-layer thickness and more on other parameters, such as surface passivation, contact engineering, and source specific activity, where greater performance improvements are likely achievable. Overall, these results provide design considerations for achieving a high efficiency betavoltaic cells.

The key insight from this work is not merely that an optimal i-layer thickness exists -which is well established- but rather that for high- Z , wide-bandgap semiconductors coupled with high-average-energy beta sources (C-14, 49.7 keV), the marginal benefit of adding an i-layer is fundamentally limited to $< 2\%$. This stands in stark contrast to low- Z semiconductors (Si) with low-energy beta sources (Ni-63, 17 keV), where gains exceed 12%. This finding provides a decision framework: p-i-n struc-

tures are strongly recommended for low- Z /low- E_β combinations but offer only marginal gains for high- Z /high- E_β combinations, where efforts should instead focus on surface passivation, contact engineering, and source specific activity. This study focuses on optimized thickness of i-layer. But the other parameters such as surface passivation, contact engineering, source geometry, or heterojunction designs must be evaluated in future works.

It should be noted that the real-world effects such as radiation-induced defects, contact resistance, interface recombination, and long-term material degradation should be considered in Betavoltaic batteries evaluations, potentially overestimating achievable device performance.

Among the factors limiting long-term betavoltaic performance, radiation-induced defects warrant particular consideration. The primary damage mechanism in the semiconductor absorber is the degradation of carrier collection efficiency due to increased recombination in the neutral region and depletion region. This manifests as a gradual reduction in short-circuit current and maximum output power over the battery's operational lifetime (Kim et al., 2026b; Kaloni et al., 2025). However, given the relatively low beta energy of C-14 and its long half-life (5730 years), the damage accumulation rate is slow. For practical device lifetimes (decades), these effects are expected to be modest compared to the isotope's decay, though they should be considered for long-term reliability predictions.

Appendix A. Formula of Table 2

$$\sqrt{\frac{kT}{q} \frac{9400}{1 + \left(\frac{N_a}{10^{17}}\right)^{0.5}} \left(\frac{1.3 \times 10^9}{N_a}\right)^{0.9}} \quad (1)$$

$$\sqrt{\frac{kT}{q} \frac{1}{2.5 \times 10^{-3} + 4 \times 10^{-21} \times N_d} \left(\frac{4 \times 10^9}{N_d}\right)^{0.92}} \quad (2)$$

$$\begin{aligned} & \frac{q}{E_{ehp}} \frac{G_0 L_n}{\alpha^2 L_n^2 - 1} \times \\ & \left[\frac{\frac{S_n L_n}{D_n} + \alpha L_n - e^{-\alpha x_j} \left(\frac{S_n L_n}{D_n} \cosh\left(\frac{x_j}{L_n}\right) + \sinh\left(\frac{x_j}{L_n}\right) \right)}{\frac{S_n L_n}{D_n} \sinh\left(\frac{x_j}{L_n}\right) + \cosh\left(\frac{x_j}{L_n}\right)} \right. \\ & \left. - \alpha L_n e^{-\alpha x_j} \right. \\ & + \frac{q}{E_{ehp}} \frac{G_0 L_p}{\alpha^2 L_p^2 - 1} e^{-\alpha(x_j+W)} \times \\ & \left[\alpha L_p - \frac{\frac{S_p L_p}{D_p} \left(\cosh\left(\frac{h}{L_p}\right) - e^{-\alpha h} \right) + \sinh\left(\frac{h}{L_p}\right) + \alpha L_p e^{-\alpha h}}{\frac{S_p L_p}{D_p} \sinh\left(\frac{h}{L_p}\right) + \cosh\left(\frac{h}{L_p}\right)} \right] \\ & + \frac{G_0}{\alpha} e^{-\alpha x_j} (1 - e^{-\alpha W}) \frac{q}{E_{ehp}} \end{aligned} \quad (3)$$

$$q \frac{n_i^2}{N_a} \frac{D_n}{L_n} \left[\frac{\frac{D_n}{L_n} \sinh \frac{h}{L_n} + S_n \cosh \frac{x_j}{L_n}}{\frac{D_n}{L_n} \cosh \frac{x_j}{L_n} + S_n \sinh \frac{x_j}{L_n}} \right] \quad (4)$$

$$+ q \frac{n_i^2}{N_d} \frac{D_p}{L_p} \left[\frac{\frac{D_p}{L_p} \sinh \frac{h}{L_p} + S_p \cosh \frac{h}{L_p}}{\frac{D_p}{L_p} \cosh \frac{h}{L_p} + S_p \sinh \frac{h}{L_p}} \right] \quad (5)$$

$$\frac{kT}{q} \ln \left(\frac{J_{sc}}{J_0} + 1 \right) \quad (6)$$

$$\frac{\frac{qV_{OC}}{kT} - \ln \left(\frac{qV_{OC}}{kT} + 0.72 \right)}{\frac{qV_{OC}}{kT} + 1}$$

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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