Self-Powered Betavoltaic Cell Design for Enabling Long-Term Power in Space*

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***Abstract*— In this work, GaN-based PIN betavoltaic cells were fabricated and experimentally evaluated under electron beam irradiation. The devices were fabricated on GaN-on-sapphire templates, using both fully and partially anode-covered layouts to examine the effect of anode coverage on power conversion efficiency. The devices were characterized under dark and 17 keV electron beam irradiation, corresponding to the average energy of Ni-63 beta decay. Monte Carlo simulations were conducted to evaluate the energy absorption and penetration depth of incident electrons within the GaN layers. In our results, the fully anode-covered structure exhibited the highest performance, achieving power conversion efficiency of 4.75%, which is the highest reported value for GaN-based betavoltaic cells under equivalent irradiation conditions.**

Keywords—betavoltaic cell, GaN, PIN junction, monte carlo simulation, e-beam irradiation

I. Introduction

Betavoltaic (BV) cells are nuclear micro-power devices that directly convert the kinetic energy of β-particles emitted from radioactive isotopes into electrical energy using semiconductor junctions. BV cells operate independently of external illumination and exhibit excellent long-term stability, rendering them highly suitable for autonomous power applications in extreme or inaccessible environments, such as space exploration, implantable medical systems, and remote sensing platforms.

Gallium nitride (GaN) is considered a promising semiconductor material for BV cells due to its inherent material properties. As a wide bandgap semiconductor ($E_g \approx$ 3.4 eV), GaN offers a higher theoretical open-circuit voltage (V_{OC}) and power conversion efficiency (PCE) compared to conventional semiconductors. In addition, GaN exhibits excellent radiation hardness, which suppresses material degradation under prolonged β-particle irradiation and ensures long-term operational stability of the device.

The basic operation mechanism of a BV cell is analogous in principle to that of photovoltaic cells: incident beta particles induce impact ionization within the semiconductor junction, generating multiple electron–hole pairs (EHPs). These carriers are then separated by the built-in electric field of a p–n, p–i–n, or Schottky junction and collected at the respective electrodes, thereby producing electric power.

To achieve high PCE, it is essential that the majority of EHPs generated by incident β-particles are created within the depletion region, where they can be effectively separated and collected by the built-in electric field. Since β-particles have limited penetration depth, the alignment of the depletion region with the energy deposition profile is critical. Therefore, the optimization of both the width and position of the depletion region plays a key role in enhancing carrier collection efficiency. If EHPs are generated outside the depletion region, significant recombination losses can occur before collection.

II. Experiments and simulation

A. *Fabrication of GaN PIN junction*

The GaN-based epitaxial structure used in this study was grown on a sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The structure consisted of a PIN diode configuration, where the top p-type GaN layer had a doping concentration of 7×10^{17} cm^{-3} and a thickness of 300 nm. The intrinsic (i-type or UID) GaN layer, which served as the depletion region, was 3 μm thick with a low doping concentration of 5×10^{16} cm^{-3}. The bottom n^{++}-type GaN layer was 1.2 μm thick and heavily doped to 5×10^{18} cm^{-3}. We fabricated GaN-based BV cells with two different anode configurations: one with a fully covered anode and the other with a partially covered anode (Fig. 1). By comparing the electrical characteristics of these devices, the influence of anode coverage on overall device performance was systematically investigated.

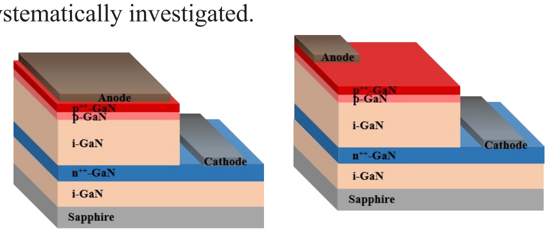

Figure 1. Schematic of the device structure : fully covered anode (left) partially covered anode (right)

B. *Monte carlo simulation*

To evaluate the interaction between incident β-particles and the device structures, Monte Carlo simulations were carried out using the GEANT4. The simulation was performed for both anode configurations—fully and partially covered—by irradiating electrons onto the device surface. The electron energies were set to 5 keV, 17 keV, and 30 keV, corresponding to representative values within the β-decay energy spectrum of Ni-63. For each case, the penetration range of electrons, defined as the depth at which 99.9% of incident electrons come to rest, was calculated. Additionally, the energy absorbed in each layer of the device structure was quantitatively extracted to determine the spatial distribution of energy deposition.

TABLE 1. Structure with fully covered anode

	Range		Mean Energy Deposit (keV/incident electron)						
Energy (keV)	Mean Range	dR	Au	Ni	Pd	p^{++}-GaN	p-GaN	i-GaN	SUM
5	0.15	0.05	3.22	0.13	0.00	0.00			3.350
17	1.35	0.05	1.74	0.58	0.31	0.20	5.20	4.13	12.157
30	3.85	0.05	0.97	0.34	0.19	0.12	3.93	17.33	22.880

TABLE 2. Structure with partially covered anode

	Range		Mean Energy Deposit (keV/incident electron)				
Energy (keV)	Mean Range	dR	p^{++}-GaN	p-GaN	i-GaN	n^{++}-GaN	SUM
5	0.15	0.05	0.33	3.78			4.110
17	1.45	0.05	0.10	5.59	8.09		13.780
30	3.95	0.1	0.00	3.07	21.02	0.00	24.090

III. Results

To evaluate the electrical characteristics of the BV cells, electron beam irradiation was performed using a scanning electron microscope (SEM) equipped with a nanoprobe workstation. From the measured I–V characteristics of the BV cells, key performance parameters—including open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), fill factor (FF), and PCE—were extracted.

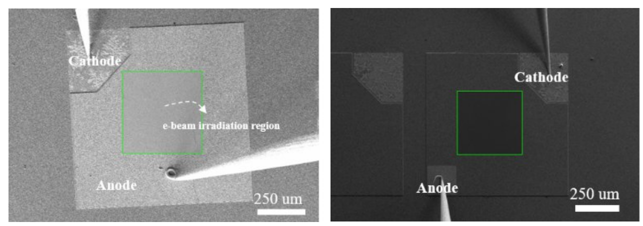

Figure 2. Measurement of SEM image of the fabricated BV cells : fully covered anode (left) partially covered anode (right)

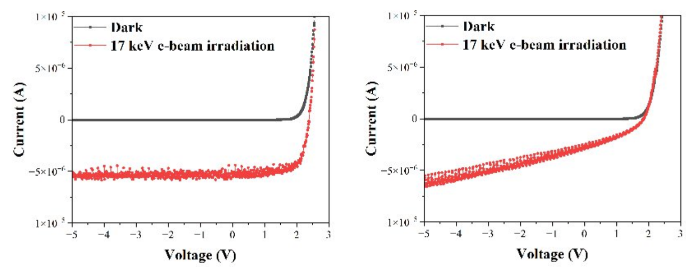

Figure 3. Characteristics of BV cell under dark and 17 kV e-beam irradiation : fully covered anode (left) partially covered anode (right)

TABLE 3. Extraction of key performance parameter

	V_{in}	I_{in}	P_{in}	I_{SC}	V_{OC}	$P_{max,out}$	FF	PCE
fully	17 kV	9.2 nA	156.4 uW	4.95 uA	2.44 V	7.428 uW	0.615	4.75 %
partially				3.24 uA	2.3 V	3.064 uW	0.41	1.96 %

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