Modeling, design, fabrication and experimentation of a GaN-based, 63Ni betavoltaic battery

C Munson, Q. Gaimard, Kamel Merghem, S. Sundaram, J. Rogers, Jacques Sanoit (de), P Voss, A. Ramdane, Jean-Paul Salvestrini, A. Ougazzaden

To cite this version:


HAL Id: cea-01765048
https://hal-cea.archives-ouvertes.fr/cea-01765048
Submitted on 10 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Modeling, design, fabrication and experimentation of a GaN-based, $^{63}$Ni betavoltaic battery

C E Munson IV$^{1,2}$, Q Gaimard$^3$, K Merghem$^3$, S Sundaram$^1$, D J Rogers$^1$, J de Sanoit$^3$, P L Voss$^{1,2}$, A Ramdane$^1$, J P Salvestrini$^{1,2}$, and A Ougazzaden$^{1,2}$

1 Georgia Tech Lorraine and CNRS, UMI GT-CNRS 2958, 2 rue Marconi, 57070 Metz, France
2 Georgia Institute of Technology, School of ECE, 777 Atlantic Drive NW, Atlanta, GA 30332, United States of America
3 CNRS, C2N, Route de Nozay, 91460, Marcoussis, France
4 Nanovation, 8 route de Chevreuse, Chateaufort, 78117, France
5 CEA, LIST, DRT / DM2I / LCD, Batiment 451, 91191 Gif sur Yvette, France

E-mail: abdallah.ougazzaden@georgiatech-metz.fr

Abstract

GaN is a durable, radiation hard and wide-bandgap semiconductor material, making it ideal for usage with betavoltaic batteries. This paper describes the design, fabrication and experimental testing of 1 cm$^2$ GaN-based betavoltaic batteries (that achieve an output power of 2.23 nW) along with a full model that accurately simulates the device performance which is the highest to date (to the best of our knowledge) for GaN-based devices with a $^{63}$Ni source.

Keywords: betavoltaic, battery, GaN, $^{63}$Ni

1. Introduction

Numerous fields require long-life power sources on the micro- or milliwatt scale. Although lithium-ion batteries currently respond to many of the requirements, the technology only has a functional lifespan on the order of a few years and such batteries require frequent recharging. When replacement/recharging is excessively expensive or impractical (such as in pacemakers, undersea sensing electronics and space applications), however, another option is required and betavoltaic batteries (which convert beta particle energy into electricity by means of radiation-resistant p-n junctions) have long been considered an attractive option in that they do not need recharging and they have a lifespan in excess of a few decades. Unfortunately, however, practical fabrication of betavoltaics with adequate power outputs has proven difficult up till now.

Tritium ($^3$H), $^{63}$Ni and $^{147}$Pm are the most common radionuclei considered for use as sources in betavoltaic batteries. They offer (respectively) average beta particle energies of 5.6, 17.4 and 224.1 keV and half-lives of 12.3, 100 and 2.6 years [1]. The relatively low beta particle energies released from $^3$H and $^{63}$Ni, in particular, make them more suitable for use in consumer-grade batteries than $^{147}$Pm since the beta particles can be selectively blocked by only a few micrometers of shielding and they can thus be safely and easily packaged. Amongst these two radionuclei, $^{63}$Ni has a superior half-life, which makes it a better choice as a long-term energy source and it is, therefore, the source considered in this paper.

Previous studies on the conversion of $^{63}$Ni beta particle energy into electricity by means of GaN-based p-n junctions reported output powers from 23 pW to 0.57 nW [2–5]. Note that, in practice, the power output is typically lower than theoretical expectations, which are often above 2 nW [6]. Similar experiments with silicon and SiC based devices using $^{60}$Ni achieved output powers of around 15.4 pW [7] and 0.34 nW [8], though some silicon designs approached 9 nW [9].

In this paper, a new state-of-the-art betavoltaic consisting of a p-GaN / i-GaN / n-GaN PIN structure on top of which a thin
63Ni layer is deposited, is fabricated and tested. Preliminary modeling for such a structure was introduced in a previous paper published by our group, along with a series and shunt resistance (SSR) model [10]. Similarly, there has also been MCNP-based simulations created to estimate the performance of 147Pm sandwiched between p–n junction GaN layers [11].

In this paper, more refined versions of these models (for the 63Ni betavoltaic absorption and electrical circuit) used to design the betavoltaic GaN PIN device along with its fabrication process, and the device performance, are presented. The establishment of a reusable betavoltaic cell test platform which was developed to conform with radiation safety norms is also reported.

2. Model

In the following, a 63Ni absorption model is developed which takes into account both self-absorption and beta particle trajectory incidence angle. The SSR model for the PIN structure, (developed in previous work [10]) is also outlined.

2.1. 63Ni absorption model

Monte Carlo (MC) simulations [1] were used to estimate the beta particle energy deposited into the GaN based on a fixed surface area (1 cm$^2$) of 63Ni. The increase in activity and emitted power with 63Ni thickness, was investigated in order to take into account the interplay of self-absorption, incidence angle and beta particle energy. A thickness range of 0 to 4000 nm was used for 63Ni so that saturation effects could be studied for both thick and thin layers. The simulation results yield the proportion of emitted beta particle energy that makes it into the GaN material (denoted as $N(y,d,e,\theta)$, in nm). These are then be combined to form an overall 63Ni model. This model considers reflectance from the device surface and all angles of incidence (equation 1), for an energy emittance profile mimicking that of 63Ni (equation 2). It is also valid for various 63Ni thicknesses as chosen by equation 3:

$$\alpha_\theta = \sum_{\theta=0}^{\pi} N(y,d,e,\theta) \times (1 - R_\theta) \times \Delta \theta$$  \hspace{1cm} (1)

$$\alpha_e = \sum_{e=5}^{60} \alpha_\theta(y,d,e) \times Pr(E = e) \times \Delta e$$  \hspace{1cm} (2)

$$\alpha_T(y,t) = \sum_{d=0}^{t} \alpha_e(y,d) \times \Delta d$$  \hspace{1cm} (3)

where $R_\theta$ is the percent reflectance at a given angle $\theta$, $Pr(E = e)$ is the probability of an electron being emitted from 63Ni at the given energy $e$ (eV), $y$ is the y-coordinate of depth into the device (nm) and $t$ is the total 63Ni thickness (nm). Equation 4 provides an estimation for the total amount of energy $P_{nm}$ emitted from a 1 cm$^2 \times 1$ nm volume of 63Ni, not considering self-absorption (which is taken into account in the simulation data, N):

$$P_{nm} \approx \rho \times \frac{A}{10^7} \times E_{avg} \times q \left( \frac{W}{cm^2 \times nm} \right)$$  \hspace{1cm} (4)

where $\rho$ is the density of 63Ni (8.91 g cm$^3$) and $A$ is the specific activity of 63Ni per gram ($2.2 \times 10^{12}$ Bq/g) [4], $E_{avg}$ is the average energy released from 63Ni (17 keV) and $q$ is the electron charge.

The results of these simulations, for a p-GaN / i-GaN / n-GaN PIN structure of 270 nm, 200 nm and 1 $\mu$m, respectively, can be seen in figure 1, where we show the absorption profiles of beta particles in GaN for various 63Ni thicknesses. For very thin layers of 63Ni the GaN absorption is more pronounced, while for thick 63Ni layers the profile smoothes out to a more impeded, exponential absorption curve. This is possibly due to self-absorption as the 63Ni source becomes thicker.

Finally, figure 2 shows that the power absorbed in the GaN material saturates towards 2.85 $\mu$W cm$^{-2}$ as the 63Ni thickness increases. Assuming an unlimited device size, the optimal 63Ni thickness is infinitely thin, since this would result in the least amount of self-absorption. It can be estimated that the optimal 63Ni thickness (for a 1 cm$^2$ sized device) is around 1500 nm of 63Ni, since the absorbed power quickly begins to saturate after this point. These results match well with results published in literature, which demonstrate a similar saturation towards 2.85 $\mu$W cm$^{-2}$ with increasing 63Ni thickness [12].
2.2. Device model and series–shunt resistance model

The device modeling software used for this paper was Silvaco, although any device modeling software could be used. The SSR models were used in order to take into account the non-ideal behavior of the PIN diode and contacts, which consider both recombination effects and defects introduced by the device, as well as imperfections due to contacts. Taking into account these series and shunt resistances, which can be determined experimentally or estimated based on similar devices, the current and voltage of the PIN diode can be rewritten as:

\[ V = I_d \times R_s + \left( 1 + \frac{R_s}{R_{sh}} \right) \times V_d \]  
\[ I = I_d + \frac{V_d}{R_{sh}} \]

where \( R_s \) is the total series resistance, \( R_{sh} \) the total shunt resistance, and \( I_d \) and \( V_d \) are, respectively, the current and voltage obtained using a Silvaco simulation of the ideal PIN structure.

3. Design, material growth, processing and packaging

3.1. Device design

The device design was governed by the total amount of \(^{63}\text{Ni}\) activity available. A device consisted of a p-GaN/i-GaN/n-GaN PIN structure on top of which a thin \(^{63}\text{Ni}\) layer was placed. As it has been seen before, the optimal \(^{63}\text{Ni}\) thickness, for a 1 cm\(^2\) sized device, is around 1500 nm. This thickness corresponds to around 1.2 GBq of activity after electrodeposition (see subsection material growth). This means that six devices with 1 cm\(^2\) in size could be realized. This number of devices is reasonable knowing that the final mounting of the devices will be done in a sealed glovebox leading to a non-negligible risk of having failed devices at the end (see subsection packaging).

Considering a realistic p-type doping of \(5 \times 10^{17} \text{ cm}^{-3}\) and an unintentional intrinsic doping of \(1 \times 10^{17} \text{ cm}^{-3}\), which are the doping levels we were able to achieve with our equipment during this experiment, this would result in an electric field that spanned around 200–300 nm of the intrinsic region. Taking this into account, figure 3(a) shows the chosen device design which includes a 40 nm current spreading layer on top of the device (20 nm of gold and 20 nm of palladium) to form the p-contact. This is followed by a 270 nm thick p-GaN region and a 200 nm thick i-GaN region. The rest of the device consists of 1 \(\mu\)m thick n-type GaN. Figure 3(b) shows a sketch of the device after electrical contact processing. The current spreading layer allows for better carrier collection even if the lower electron energies (less than 5 keV) are almost entirely absorbed within it (see figure 4). The p-GaN layer absorbs electron energies around 8 keV, whereas the intrinsic GaN region absorbs electron energies around the \(^{63}\text{Ni}\) emission peak (14 keV). Finally, most electrons having energies above 22 keV are absorbed in the n-GaN region and substrate.

\[ PCE(\%) = \eta_\nu \times \eta_{bp} \times \eta_i \times \eta_{be} \]

where \( \eta_\nu \) is the amount of energy that is not backscattered from the surface of the device (MC simulations indicate that 29% of the beta particle energy should be backscattered), \( \eta_{bp} \) is the amount of energy that is transmitted through the spreading layer (9% of the beta particle energy is absorbed in the metallic spreading layer, again based on MC simulation), \( \eta_i \) is the amount of electron energy falling within the
i-GaN region, 12% of the beta particle energy is absorbed in the i-GaN region, again based on MC simulation as seen in figure 1) and $\eta_{be}$ is the maximum betavoltaic current efficiency for GaN [13] which is 27%. This leads to a highest possible PCE of around 2.09%.

3.2. Material growth

3.2.1. GaN epitaxy. All the PIN structures were grown at 1030 °C using a T-shaped MOVPE reactor under a pressure of 100 Torr and a V/III ratio of 8000. Trimethylgallium and ammonia were used as precursors for gallium and nitrogen, respectively. SiH4 and CP2Mg were used as n-type and p-type dopants, respectively. The growths were performed on 2° sapphire wafers, starting with 1.8 µm thick buffer of intrinsic GaN. The PIN structures were structurally and morphologically characterized with high resolution x-ray diffraction, scanning electron microscope (SEM) and atomic force microscope. The dopant concentrations and their profiles were characterized by Hall effect measurements and secondary ion mass spectroscopy (SIMS) analysis, respectively.

3.2.2. $^{63}Ni$ deposition. $^{63}Ni$ was synthesized using neutron and gamma ray bombardment of a $^{62}Ni$ target followed by an acid dissolution and radiochemical separation in order to obtain $^{63}NiCl_2$ radioactive salt. A modified Watts bath was then prepared using $^{63}NiCl_2$, H2O, Na2SO4 and H3BO3. The $^{63}Ni$ material was then electrodeposited onto the two sides of a piece of copper foil approximately 1 cm2 in surface area with 140 µm thick copper foil, which absorbed all energy that was emitted away from the devices, and using a Pt anode (see figure 5). The deposition yield was approximately 80% leading to 2.4 GBq of activity deposited on the two facets of the copper foil for each source. Assuming a 17 keV average beta particle energy, this equates to approximately 6.545 µW of energy emitted (i.e. 3.27 µW emitted from each side of the source).

3.3. Device processing

Three metallic patterns were defined by lift-off using contact photolithography. A thin spreading bilayer of palladium and gold (20 nm / 20 nm) was first deposited as a p-contact on the GaN p-type top layer, over an area of 8 × 8 mm2. A contact pad, made of palladium and gold bilayer (20 nm / 200 nm), was subsequently deposited on the side of this spreading layer to allow for wire bonding. The mesa was then dry etched, to a depth of 1 µm, so as to reach the n-type layer. This step was achieved using BCl3/Cl2/N2 inductively coupled plasma reactive-ion etching (RIE), through a SiO2 mask. The n-contact consisted of titanium / aluminum / gold (10 nm / 30 nm / 300 nm) deposition. To ensure good ohmic contacts, the diodes were subsequently rapid thermal annealed under N2 atmosphere. A photograph of a fabricated device is shown in figure 6(a). The final steps involved dicing the diodes, mounting on specific holders and wire bonding (see figure 6(b)).

4. Results

A total of nine 1 × 1 cm2, GaN-based PIN devices and three $^{63}Ni$ sources were fabricated. Hall measurements revealed p-type and n-type doping levels of around $1 × 10^{17}$ cm$^{-3}$ and $5 × 10^{18}$ cm$^{-3}$, respectively. SIMS revealed the doping depth profiles to have relatively abrupt steps at the interfaces. The PIN devices exhibited a turn-on voltage of around 3.5V and a leakage current on the order of 3–70 µA under a bias voltage of −5V (this current was relatively high because of the comparatively large size of the device). A typical I–V plot of these devices is shown in figure 8.
4.1 Electron beam simulation

Before experimenting with actual $^{63}$Ni, some preliminary experiments were performed in an SEM using an 80 $\mu$W beam power and a 17 keV accelerating voltage (so as to simulate the typical $^{63}$Ni beta particle energy). Figure 7 shows both the dark and electron beam IV measurements for two of the devices, which are typical of the devices having high and medium current leakage, respectively. For both of them, the short-circuit electron beam induced currents (EBIC) are similar and approximately equal to 3.5–4 $\mu$A, whereas the open circuit voltages ($V_{oc}$) are quite different and equal to 150 mV and 1 V for the devices having high and medium current leakage, respectively. The inset depicts a typical EBIC image recorded during these experiments, showing a very uniform carrier collection efficiency and thus beta-current generation throughout the entire device. Since the EBIC signal is proportional to the generated current, the EBIC images did not vary significantly between the different devices.

Finally, Figure 8 shows the collected current under 80 $\mu$W of irradiation, both through the current spreading layer and directly on the p-GaN field.

Figure 7. (a) Schematic and photographs of (b) open and (c) closed testing box, with turnkey screw mechanism for varying the betavoltaic to $^{63}$Ni source distance.

Figure 8. Typical I–V plot of the fabricated PIN devices.

Figure 9. Dark and electron beam exposed IV measurements for two of the devices recorded with a 17 keV beam energy and an 80 $\mu$W power. Inset: typical EBIC image, showing consistent current generation throughout the device.

Figure 10. $e$-beam generated current under 80 $\mu$W of irradiation, both through the current spreading layer and directly on the p-GaN field.

4.1 Electron beam simulation

Before experimenting with actual $^{63}$Ni, some preliminary experiments were performed in an SEM using an 80 $\mu$W beam power and a 17 keV accelerating voltage (so as to simulate the typical $^{63}$Ni beta particle energy). Figure 9 shows both the dark and electron beam IV measurements for two of the devices, which are typical of the devices having high and medium current leakage, respectively. For both of them, the short-circuit electron beam induced currents (EBIC) are similar and approximately equal to 3.5–4 $\mu$A, whereas the open circuit voltages ($V_{oc}$) are quite different and equal to 150 mV and 1 V for the devices having high and medium current leakage, respectively. The inset depicts a typical EBIC image recorded during these experiments, showing a very uniform carrier collection efficiency and thus beta-current generation throughout the entire device. Since the EBIC signal is proportional to the generated current, the EBIC images did not vary significantly between the different devices.

Finally, Figure 10 shows the collected current under 80 $\mu$W of $e$-beam irradiation, both through the metallic current spreading contact layer (green line) and directly on the p-GaN field (without any metallization, blue line). The difference between the two curves can be attributed to the absorption of the impinging electrons in the metallic current spreading contact layer or backscattering at a higher amount, which leads to less generated electron-hole pairs in the PIN junction. Thus, the beam current losses in the metallic layer lead to a decrease by around 21% of both the short circuit current and open circuit voltage.
4.2. $^{63}$Ni experimental data

Among the nine fabricated devices, two were damaged during the mounting in the testing boxes. Among the seven devices that were left, two of them were placed closer to the $^{63}$Ni source (around 0.5 mm gap) and the other five were placed at around 5 mm from the $^{63}$Ni source (wire bonding prevented closer positioning). Table 1 summarizes the results obtained for the different devices in terms of short circuit current ($I_{sc}$) and $V_{oc}$. For all of the devices, the results weakly depended on the box in which the PIN device, and thus $^{63}$Ni source, was mounted. It is clear that both the distance to the $^{63}$Ni source and the current leakage value affected the performance of the device. As seen in the previous subsection, $I_{sc}$ is only slightly lower for the high leakage current devices (average $I_{sc}$ of 1.15 ± 0.2 nA) than for the medium leakage current devices (average $I_{sc}$ of 1.4 ± 0.2 nA), whereas, a one order of magnitude lower $V_{oc}$ was expected (see figure 11).

Additionally, the $I_{sc}$ for devices placed closer to the $^{63}$Ni source (3.05 ± 0.1 nA) is much higher than that obtained for devices positioned 4 mm (9 times) further away. The beta particles counted versus absorber thickness (air in this case), can be estimated by $N(x) = N_0 \times e^{(-\mu_B x \rho)}$ where $N_0$ is the initial beta particles counted (at zero absorber thickness), $\mu_B$ is the beta absorption coefficient (which is 2071.16 cm$^2$ g$^{-1}$ for air) and $\rho$ is the density of the absorber (1.205 × 10$^{-3}$ g cm$^{-3}$ for air). This predicts losses of 12 and 68%, respectively, for gaps of 0.5 and 4.5 mm. Accordingly, an $I_{sc}$ of 3.05 nA for a device placed 0.5 mm from the source should drop to 0.98 nA for a device 4.5 mm away from the source. This is in very good agreement with the measured value of 1.15 ± 0.2 nA.

Particularly noteworthy are the two devices with medium leakage current, which had an $I_{sc}$ of 1.4 ± 0.2 nA, a $V_{oc}$ of 0.79 ± 0.01 V and a fill factor (FF) of 47% (see figure 11), corresponding to a generated power ($P = V_{oc} \times I_{sc} \times FF$) of 0.52 ± 0.08 nW and leading to a PCE of 0.016%. As shown in table 2, the generated power can be easily doubled by connecting the two devices in series (i.e. placing them on either side of the $^{63}$Ni source). This leads to a device with a generated power of 1.04 ± 0.1 nW with the same PCE. Furthermore, if the two devices in series are placed closer to the source this leads to an $I_{sc}$ of 3 nA, and the generated power and PCE can be increased to 2.23 nW and 0.034% , respectively.

4.3. Model comparison

The model prepared in section 2 can now be used to compare the predicted device performance with these experimental values. The series device described at the end of the previous subsection (in which devices are positioned in proximity to each side of the $^{63}$Ni source) was adopted for modeling. Figure 12 shows both the experimental and simulated (both ideal and SSR models) dark current-voltage curves for this device. The SSR model, with 7 Ω and 910 MΩ as series and shunt resistance, the $I_{sc}$ of 3.05 nA for a device placed 0.5 mm from the source should drop to 0.98 nA for a device 4.5 mm away from the source. This is in very good agreement with the measured value of 1.15 ± 0.2 nA.

Particularly noteworthy are the two devices with medium leakage current, which had an $I_{sc}$ of 1.4 ± 0.2 nA, a $V_{oc}$ of 0.79 ± 0.01 V and a fill factor (FF) of 47% (see figure 11), corresponding to a generated power ($P = V_{oc} \times I_{sc} \times FF$) of 0.52 ± 0.08 nW and leading to a PCE of 0.016%. As shown in table 2, the generated power can be easily doubled by connecting the two devices in series (i.e. placing them on either side of the $^{63}$Ni source). This leads to a device with a generated power of 1.04 ± 0.1 nW with the same PCE. Furthermore, if the two devices in series are placed closer to the source this leads to an $I_{sc}$ of 3 nA, and the generated power and PCE can be increased to 2.23 nW and 0.034% , respectively.

4.3. Model comparison

The model prepared in section 2 can now be used to compare the predicted device performance with these experimental values. The series device described at the end of the previous subsection (in which devices are positioned in proximity to each side of the $^{63}$Ni source) was adopted for modeling. Figure 12 shows both the experimental and simulated (both ideal and SSR models) dark current-voltage curves for this device. The SSR model, with 7 Ω and 910 MΩ as series and shunt resistance,
Experimental results, which shows a 9.9 \( \mu \text{W cm}^{-2} \) decrease of both \( V_{oc} \) and FF. This is rather close to the experimental results, with only a minor variation in the \( V_{oc} \) and FF. This model was also combined with the device and SSR models, and gave a very good fit with the experimental data.

Table 3. Betavoltaic device performance under a 6.545 \( \mu \text{W} \) \( ^{63}\text{Ni} \) source and two 1 cm\(^2 \) PIN devices mounted in series.

<table>
<thead>
<tr>
<th>( ^{63}\text{Ni} ) model</th>
<th>Ideal device</th>
<th>SSR model</th>
<th>Exp. data</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{oc} ) (nA)</td>
<td>3.03</td>
<td>3.03</td>
<td>3</td>
</tr>
<tr>
<td>( V_{oc} ) (V)</td>
<td>5.6</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>FF (%)</td>
<td>90.9</td>
<td>53.6</td>
<td>46.9</td>
</tr>
<tr>
<td>( P ) (nW)</td>
<td>15.42</td>
<td>2.76</td>
<td>2.23</td>
</tr>
<tr>
<td>( P_{oc} ) (( \mu \text{W cm}^{-2} ))</td>
<td>68.45</td>
<td>12.25</td>
<td>9.9</td>
</tr>
<tr>
<td>PCE (%)</td>
<td>0.23</td>
<td>0.042</td>
<td>0.034</td>
</tr>
</tbody>
</table>

respectively, and an ideality of 3.6, fits the experimental results well. Similarly, figure 13 shows the IV curves under \( ^{63}\text{Ni} \) irradiation in order to highlight the betacurrents. The green dashed curve is based on the experimental results under \( ^{63}\text{Ni} \) irradiation (6.545 \( \mu \text{W} \) total). The solid blue line shows the SSR model predictions, and the dashed gray line shows the results directly from the ideal. Again, the SSR is in very good agreement with the experimental results, with only a minor variation in the \( V_{oc} \) expectations (though still within 0.1 V).

Table 3 shows these results more quantitatively. The ideal device model predicts a generated power of 68.45 \( \mu \text{W cm}^{-2} \) with a 6.545 \( \mu \text{W} \) \( ^{63}\text{Ni} \) input. After adding the SSR model, we can see that this drops to 12.25 \( \mu \text{W cm}^{-2} \), due to a large decrease of both \( V_{oc} \) and FF. This is rather close to the experimental results, (which shows 9.9 \( \mu \text{W cm}^{-2} \)), the difference being mostly due to the smaller FF.

5. Conclusion

This paper described the design, fabrication and experimental testing of 1 cm\(^2 \) GaN/\( ^{63}\text{Ni} \) based betavoltaic batteries and a versatile testing box which allowed for reusability and tuning of the device/source distance. The optimal devices constructed in these experiments achieved an output power of 0.52 nW, which could likely be extended to 1.04 nW if the boxes are run as-designed in series configuration. We additionally feel a simple reduction of the sample/source gap should allow 2.23 nW output, however. It was proposed that the efficiency of the experimental device was limited predominantly due to the relatively thick p-GaN region (270 nm) and current spreading layers (40 nm), combined with a relatively thin i-GaN region (200 nm) having excessive residual doping. These issues can be improved in the future by optimizing the active layer thicknesses, replacing the i-GaN with dilute BGaN alloy (which allows a several order of magnitude in resistivity [14, 15]), and decreasing the thickness of the current spreading layer down to 20 nm or using interdigitated electrodes.

The paper also presented the development of a \( ^{63}\text{Ni} \) betavoltaic simulation model that can be quickly and easily generated with standard Monte Carlo simulation software (such as CASINO) but can still provide high-quality and accurate results that match well with literature. This model was also combined with the device and SSR models, and gave a very good fit with the experimental data.

Acknowledgments

This work was supported by the Agence Nationale de la Recherche of France as part of the BATGAN project (ANR-11-BS09-0038).

ORCID IDs

J P Salvestrini 🌟 https://orcid.org/0000-0002-0482-1178

References


