A theoretical model of a Sr-90 nuclear battery

C. Davis* [a)1]
McMaster University, 1280 Main Street West, Hamilton, Canada.

(Dated: **30 November 2016**)

In this paper a theoretical nuclear battery based upon a GaN Schotty diode is analyzed with a Sr-90 source. This theoretical battery was calculated to produce 20.61 nW from a 1 cm^2 1 mCi source. The fill factor of the theortical device was calculated to be 0.5782 and the efficiency is 1.72%.The theoretical power of this battery shows an increase in power compared to the same device using a Ni-63 source of the same parameters. It is discussed that the use of Sr-90 as a radioisotope for a nuclear battery is not practical with current technology due to radiation damage and inability to create GaN semiconductors with a low dopant concentration and increased depletion region widths.

Keywords: Nuclear Battery, Betavoltaic, Sr-90, GaN Shottky Barrier

I. INTRODUCTION

The nuclear battery was a technology studied in the early 1950's and 1960's, its use was for applications that require a long battery life such as medical implants[1]. In the 1970's the emergence of lithium batteries put a damper on the research of nuclear batteries due to the increased efficiency, and lower cost. Today there has been a re-emergence of the technology with better manufacturing techniques for semiconductors as well as radiation resistance materials.

The design of a nuclear battery is analagous to that of a solar cell. Incident radiation in a semiconductor causes electron hole pairs in a material that drift into a depletion region where a built in electric field moves the charge carriers. The charge is collected in an anode and cathode on the device and current is produced. In solar cell operation the radiation is photon's, in a nuclear battery the incidentradiation is typically charged particles such as a β particle (electron) or a α particle (helium nucleus).These charged particles are created from a radioactive source and are used to create electron hole pairs in the semiconductor device. In the early development of the nuclear battery, alphavoltaics and betavoltaics were used with a silicon based P-N junction device. The resultant nuclear batteries were of low efficiency and the α particles caused damage to the silicon crystal structure and further reduced the efficiency of the devices[2].

The recent increase in research in nuclear batteries has been with betavoltaics in particular. Some common radioactive isotopes used in betavoltaic devices are Ni-63 with a half-life of 101.6± 1.97 years[3] and H-3 (Tritium) with a half-life of 12.3 years[4].These isotopes have are ideal for a betavoltaic due to their long half-lives and that they are purely β emitters. A particular limitation to these isotopes is the low energy decay of the β particles, Ni-63 has a max decay energy of 66.98 KeV[5] and H-3 has a max decay energy of 18.6 KeV[6]. A lower decay energy results in a lower power betavoltaic,it is suggested that a higher energy β emitter is investigated such as Sr-90.

In this article a theoretical nuclear battery based upon a GaN, Schotty based Sr-90 betavoltaic is proposed.Strontium-90 is a beta emitter with a max β decay energy of 0.546 MeV[7]. It also has a half life of 28.8 years[7]. Strontium-90 is also purely a β emitter, which is favourable from a radiation hazard standpoint.The chosen betavoltaic design is based upon a Schottky barrier GaN based battery due to the high radiation resitance of metal (Schottky barrier) and GaN large radiation resistance[8].

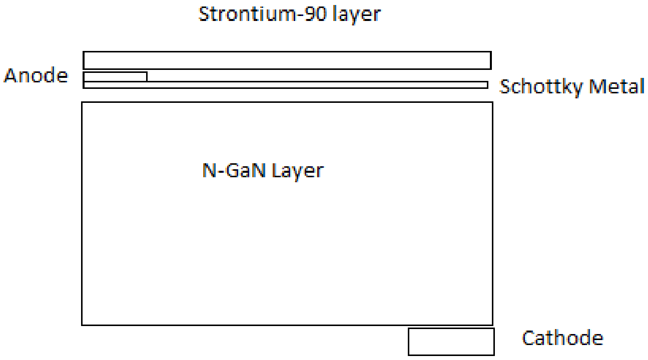

FIG. 1. Theoretical Schottky GaN based Betavoltaic

II. EXPERIMENTAL PROCEDURE

The theoretical betavoltaic will use a thin layer of Schottky metal placed upon a N-GaN epilayer, with electrodes placed upon Schottky layer and N-GaN layer refer to Fig. 1. To determine the performance of the device, various parameters were calculated using MatLab.

A. β particle range in GaN

To determine the optimal depletion width of the GaN based Schottky betavoltaic the range of electrons in the GaN must be determined. To determine the β range the Katz-Penfold range equation was used. The equation is as follows[9]

$$R_{max} = \frac{0.412}{\rho} E_{\beta}^{1.265-0.0954(E_{\beta})}; 0.01 \leq E_{\beta} \leq 2.5 MeV \quad (1)$$

Where ρ is the density of the material (GaN) and E_{β} is the kinetic energy of the incident β particle.The range was calculated for a distribution of energies from $E_{\beta} = 0$ to $E_{\beta} = 0.546$ MeV

The penetration depth was also calculated at the average energy beta decay $\overline{E_{\beta}}$ 0.196 MeV. The depth was found to be 66 μm, which can be taken as an approximate target for the depletion width.The entire spectra of β range is from 0-300 μm, to make a GaN semiconductor with a depletion region in the 100's of μm requires a very low charge carrier concentration that can not yet be manufactured.

Determining the depletion width will factor into determining the power characteristics of the betavoltaic and the efficiency. The depletion region width for a schottky barrier diode can be determined by[10]

$$W = \sqrt{\frac{2\epsilon_s \phi_i}{qN_D}} = \sqrt{\frac{2\epsilon_s(\phi_b - kTln(N_C/N_D))}{qN_D}} \quad (2)$$

Where

ϵ_s	dielectric constant of GaN
ϕ_i	build in potential
N_D	doping concentration
N_C	conduction band density of states of GaN
ϕ_b	Schottky barrier height
k	Boltzmanns constant
T	absolute temperature

Inspecting Fig. 3 it can be seen that for a depletion width equal to the range of the average β (66μm) a doping concentration approximately 9.3E10 electrons cm^{-3} is required. For an optimal design, a wider depletion region increases the betavoltaics efficiency, so the dopant concentration will be taken to be 1x10^9 cm^{-3} corresponding to a depletion region width of 85 μm for increased beta absorption and efficiency.

B. Calculating device power

The short circuit current was calculated for this betavoltaic which is a sum of the depletion region current I_o and the substrate region current I_N. The equation used is[10]

$$I_s = I_D + I_N = \lambda\phi\frac{E_{avg}}{Epair}(\alpha_1 + \alpha_2) \quad (3)$$

Where

λ	metal penetration coefficient
ϕ	activity of the radioisotope
q	electron charge
E_{avg}	average energy of radioisotope
E_{pair}	energy required to create electron hole pairs
α_1 α_2	current contribution factors from depletion and epilayer regions

α_1=1-exp(-$\frac{w_d}{L_a}$)

$\alpha_2 = \frac{L_p L_a}{L_a^2 - L_p^2}[(\coth\frac{L-w_d}{L_p}$-$\frac{L_p}{L_a}$)exp(-$\frac{w_d}{L_a}$)-$\frac{exp(-L/L_a)}{sinh((L-w_d)/L_p)}]$

L_a	stopping range of β particles
L_p	diffusion length of minority carriers
L	n-type epilayer thickness

The open circuit voltage was then calculated using the formula[10]

$$V_{oc} = \frac{nkT}{q} ln(\frac{I_{sc}}{I_o} + 1) \quad (4)$$

n	ideal factor
I_o	reverse saturation current

Calculating the open circuit voltage requires the reverse saturation current to be known. To determine the reverse saturation current the following equation was used[10]

$$I_o = SA^*T^2 exp(-\frac{q\phi_b}{kT}) \quad (5)$$

Where

S	cross section area of device
A*	effective Richardson constant
ϕ_b	Schottky barrier height

The current for these devices in operation is given by[10]

$$I = I_{sc} - I_o(exp(\frac{qV}{nkT}) - 1) \quad (6)$$

To determine performance factors of the battery such as power, fill factor and efficiency, it is required to determine the max power. This was calculated numerically using matlab by using

$$\frac{\partial(IV)}{\partial V} = 0 \quad (7)$$

The max power was found and as a metric of evaluation the filling factor and efficiency of the device were calculated by the following equations

The filling factor (FF) is

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (8)$$

$$\eta = \frac{V_m I_m}{q\phi\overline{E_{\beta}}} \quad (9)$$

TABLE I. Calculation Parameters

Parameter	Value	Reference
ϵ_s	9	11
N_D	$1x10^9 cm^{-3}$	-
N_C	$2.23x10^{18} cm^{-3}$	11
ϕ_b	0.95 eV	11
k	$1.38064852x10^{-23} \frac{J}{K}$	-
T	300 K	
λ	1	-
ϕ	1mCi	-
E_{avg}	0.196 MeV	7
E_{pair}	10.17 eV[12]	
L_a	66	- μm
L_p	1.5	13 μm
L	100	- μm
S	$1cm^2$	-
$A*$	$26.4A/K^2cm^2$	11
n	2.9[12]	

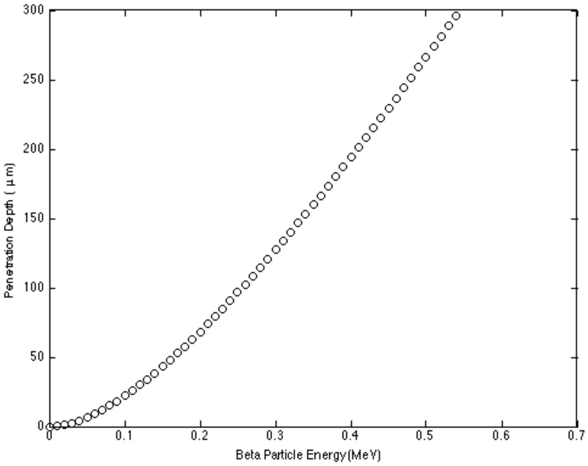

FIG. 2. Beta Penetration Depth

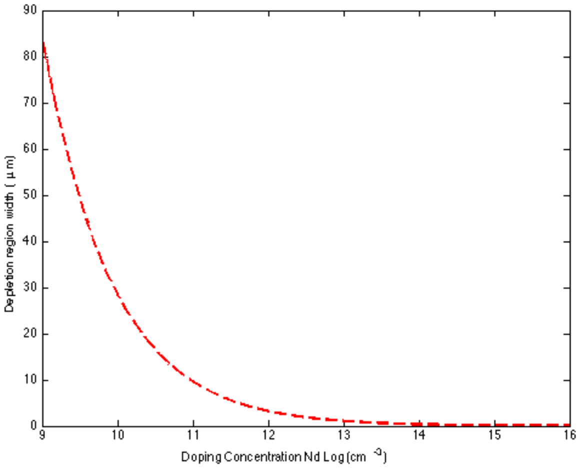

FIG. 3. Depletion Width

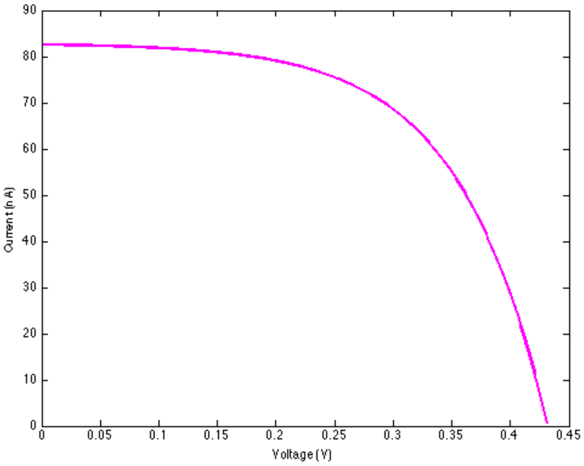

FIG. 4. I-V Curve

III. RESULTS AND DISCUSSION

Calculations using the parameters specified in Table I yielded a Schottky barrier width of 85 μm, corresponding to a N-type doping carrier concentration in the GaN of 1x10^9 cm^{-3}. The short ciruit current I_{sc} was calculated to be 82.57 nA and the open circuit voltage was determined to be V_{oc} 0.4316V. The max power was determined to be 20.61 nW at a operating voltage of 0.31 V and current of 66.48 nA. The filling factor was determined to be 0.5782 and the efficiency of the device is 1.79% see Fig. 4. A similar GaN Schottky barrier device using Ni-63 of 1 mCi radioactivity determined a theoretical power of 4.2nW[14]. This shows that there is a potentially to create higher power betavoltaics using Sr-90 as the source.

There are critcal limitations, however in this theoretical analysis there were some factors ignored that will effect the operation of the device. In practice due to manufacturing limitations there is no current way of growing a GaN layer with a dopant density of 1x10^9 cm^{-3}. Currently the typically found values of the dopant concentration is 1x10^{15} cm^{-3}, there are proposed methods that can potentially reduce the carrier concentration to1x10^{13} cm^{-3}[14].However, at these dopant concentrations, the depletion region widths are 0.1 and 1 μm respectively. This will yield a max power of 0.3849 nW maximum. As well as a fill factor of 0.4349 and efficiency of .0334%. The manufacturing limitation of GaN makes it an impractical candidate for a betavoltaic using Sr-90. Further more in this analysis it was ignored that GaN decays to Y-90 another β emitter with a β_{max} of 2.28 MeV. The β energies would be too large to be absorbed by the proposed nuclear battery.

The theoretical battery analyzed has another large limitation in practice, the radiation resistance of GaN is limited to a damage threshold of 440 KeV[15]. As a result, in practice the Sr-90 would damage the GaN and will reduce the power out put and efficency of the device over time. Other semiconductors such as silicon have even lower thresholds for radiation damages (220 KeV)[15]. A final consideration is the radiation emitted from the proposed battery. Due to the high energy Y-90 β, shielding is likely required, when shielding high energy β particles bremsstralung (braking radiation) can occur and cause highly penetrating x-rays to be emitted.

Due to manufacturing limitations and radiation resistance limits of current semiconductors it is not recommended that Sr-90 be used as a radioactive isotope for nuclear microbatteries. There if materials were designed sufficiently radioactively 'hard' and were able to be made with a sufficient depletion region width, Sr-90 is a good potential isotope. It could provide more power than the commonly used Ni-63 microbattery and has a sufficiently long life with a $T_{1/2}$ of 28.8 years.

Further research to advance the nuclear battery will include the increasing the radiation resistance of semiconductor materials and for the Schottky GaN betavoltaic, an increase in power and efficiency can be achieved if manufacturing methods can reduce the dopant density in the material.

CONCLUSION

It has been demonstrated that a GaN Schottky battery using Sr-90 and a radioisotope can produce a power of 20.61 nW. This power is achieved at an operating voltage of 0.31 V and 66.48 nA, resulting in a fill factor of 0.5782 and efficiency of 1.79%. However, Sr-90 is not recommended currently as a radioisotope for beta voltaics. For Sr-90 to be a practical source for betavoltaics, semiconductors with sufficient radiation hardness and battery design with sufficient depletion widths must be created. GaN Schottky betavoltaics provide larger amounts of radiation resistance compared to other betavoltaic designs such as P-N silicon batteries, but due manufacturing limitations cannot achieve a sufficient depletion region width. Future research to increase the performance of betavoltaic devices should look into increasing the radiation resistance of the devices so higher energy radioisotopes such as Sr-90 can be used, as well as increasing ability to create larger depletion region widths in radiation resistant semiconductors.

REFERENCES

[1] W.E. Matheson, Engineering in Medicine 401 (1975).

[2] S. Bailey, D. Wilt, S. Castro, C. Cress, and R. Raffaelle, Conference Record of the Thirty-First IEEE Photovoltaic Specialists Conference, 2005.

[3] R. Collé and B. Zimmerman, Applied Radiation and Isotopes 47, 677 (1996).

[4] L. Lucas and M. Unterweger, Journal of Research of the National Institute of Standards and Technology 105, 541 (2000).

[5] H.W. Wilson, Physical Review 79, 1032 (1950).

[6] F.T. Porter, Physical Review 115, 450 (1959).

[7] Nucleide.org. Strontium-90 data sheet

[8] Y. Liu, R. Hu, Y. Yang, G. Wang, S. Luo, and N. Liu, Applied Radiation and Isotopes 70, 438 (2012).

[9] L. Katz and A.S. Penfold, Reviews of Modern Physics 24, 28 (1952).

[10] G. Lutz, Semiconductor Radiation Detectors: Device Physics (Springer, Berlin, 1999).

[11] Levinshtein M. E., S.L. Rumyantsev, and M. Shur, Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, SiC, SiGe (Wiley, New York, 2001).

[12] Z. Cheng, H. San, Y. Li, and X. Chen, 2010 IEEE 5th International Conference on Nano/Micro Engineered and Molecular Systems (2010).

[13] Z. Bandić, P. Bridger, E. Piquette, and T. Mcgill, Solid-State Electronics 44, 221 (2000).

[14] H. San, S. Yao, X. Wang, Z. Cheng, and X. Chen, Applied Radiation and Isotopes 80, 17 (2013).

[15] S.J. Pearton, F. Ren, E. Patrick, M.E. Law, and A.Y. Polyakov, ECS J. Solid State Sci. Technol. ECS Journal of Solid State Science and Technology 5, (2015).