

Conceptual Design of GaN Betavoltaic Battery using in Cardiac Pacemaker

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Abstract

Pacemaker is an electronic biomedical device which stimulates and regulates or amplify the human heartbeat by delivering weak electrical pulses to the cardiac muscle at regular intervals when its natural regulating mechanisms break down.

The purpose of the present work is to introduce a kind of low power Betavoltaic battery using in nuclear powered cardiac pacemakers which have higher efficiency than those available with previous devices.

In this design, two p-n diode structures from GaN semiconductor were used to collect the charge from a layer of ⁶³Ni as a source which is centered between the two p-n junctions. MCNP simulation results have been used to determine the amount of electron current from interaction of beta particles in p-n junctions.

Calculation results indicate that the short circuit current, open circuit voltage and efficiency of a single device are 1.1 $\mu\text{A}/\text{cm}^2$, 2.7 volt and 25%, respectively. Also, it's concluded that with suitable arrangement of these single devices, one could construct a battery with required current, voltage and power for this application.

Keywords: Betavoltaic battery, Cardiac pacemaker

1. Introduction

The batteries with stable current and voltage and long life have wide application in medicine, oil and mining industries and space equipment in which the replacement of batteries is highly inconvenient also often place sensors in dangerous or hard-to-reach locations and recharging have a high cost, moreover require light and so small power source. One of the ideas to reach this aim is conversion of nuclear energy to electrical energy.

The developments in design and implementation of power source in adjacent to advance electronic circuitry is an important aspect in optimization of pacemakers. For instance, many implant patients continue to outlive their batteries which require costly and risky replacement surgery. So such device needs to have high energy density power source and maintain a stable current and voltage for a long period of time to avoid frequent replacements. In addition, the size is also an important consideration for implantable batteries. Nuclear powered Batteries are divided to two main groups depending on conversion process; thermoelectric and Betavoltaic that Betavoltaic batteries are being nominated as a suitable one for these applications.

Electrical energy of a nuclear battery is produced from radioactive materials decaying by a suitable energy conversion process. Theoretically, any kind of radiation (alpha, beta and low energy gamma/X-rays) can all be used to produce electricity. For a long-lived semiconductor-based device, however, only the beta-emitting

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radioisotopes are suitable because semiconducting materials are very susceptible to the point-defect damage caused by alpha particles, and there are no known low-energy gamma/X-ray emitting isotopes that has a long enough half-life to satisfy the device life time requirement. But in practice, it has been used both beta and alpha emitter radioisotopes to manufacture the nuclear batteries[1,2].

In Betavoltaic devices, a semiconductor is used as p-n junction. When a charged particle passes through a depletion region in p-n junction, the overall significant effect is the production of many electron-hole pairs along the track. Presence of the fixed charges on either side of the junction, cause the depletion region acts as a charged capacitor. Electrons and holes formed within the depletion region will drift under the influence of the corresponding electric field created by p and n layers of the p-n junction. Upon switching in an external load, an electrical current passes in the circuit, depending on the intensity of ionizing radiation, without any extra power supply.

It is desire that the depletion region width to be large enough so most of the beta particles to be absorbed in depletion region. Therefore at least it needs to have a thin dopant in one side.

1.1 Beta emitter sources

There are several beta emitter radioisotopes with half lives more than one year. The suitable and practical radioisotope selection plays a critical part in multiple aspects of the design of a Betavoltaic converter. The output power demand concerning its application is the first factor in source isotope selection. The other factors affecting the performance of a Betavoltaic device are expected life time of device according to its application, specific activity, reliability (e.g. in pacemaker application), radiation damage, dimensions, toxicity of radioactive materials, gamma and bremsstrahlung radiation, manufacturing cost, availability of radioisotope, purity of source and required shielding.

1.2 Suitable Semiconductors

Currently used semiconductors in this application consist of Si, Ge, Ga and their compounds. By using a Wide Band Gap semiconductor such as silicon compounds like SiC and a-Si:H or Nitride compounds like GaN and AlGaN, the maximum bond energy/minimal atomic displacement probability and so higher efficiency is achieved while still maintaining a conductive material. Furthermore, maximum radiation energy of beta particles shouldn't be higher than threshold energy for Radiation Damage of semiconductor.

In addition, the penetration depth is a function of the material density; a denser material requires collection over shorter distances. Therefore it needs thicker one for less dense material to absorb the incident radiation. For example, Si which has approximately half the density of GaN will require twice its thickness.

2. material and methods

The MCNP Monte Carlo code has been used to determine the amount of radioisotope radiation flux in different region of material and calculate the number of desired interactions.

The number of electron-hole pairs generated from an energetic beta particle per volume and time, in a semiconductor is as follows [3,4].

$$G = k \lambda n E_{avg} / \epsilon \quad (1)$$

Where ε is the radiation ionization energy, E_{avg} is the average energy of the energetic particle. k is the fraction of beta particles that participate in the creation of electron-hole pairs which can be obtained by using Monte Carlo Calculation. λ is the decay constant and n is the concentration of radioactive material. The current of beta particles (I_β) can be calculated by

$$I_\beta = qGtS \quad (2)$$

Where q is the electronic charge, t is the thickness and S is the cross sectional area of device. It is assumed that all of the electron-holes generated in the depletion region are collected and the collection probability for outside is determined by their distance from the depletion region.

The ideal electrical circuit model for Betavoltaic device consists of a current source and an ideal diode as illustrated in figure 1.

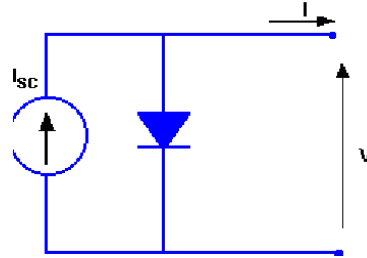


Figure 1. Ideal circuit model of Betavoltaic device

The power of the Betavoltaic converter depends on the volume of the radioisotope used, the amount of beta radiation energy deposited in it and the thickness of absorbing semiconductor material. Also, efficiency can be expressed as [3,4]:

$$\eta = P_{out}/P_{tot} \times 100\% \quad (3)$$

Where P_{out} is the maximum available power of the device which obtains from multiplication of short circuit current, open circuit voltage and Fill Factor (FF), P_{tot} is determined from multiplying specific power available from source (Watt/Ci) and amount of radiative material ($Ci^{-1}cm^{-2}$).

2.1 Components of a Betavoltaic converter

A Betavoltaic device consists of a semiconductor as a p-n junction and a beta emitter isotope. In the isotope selection, what already practically was used is limited to ^{147}Pm , $^{90}Sr/Y$, ^{63}Ni , 3H (Tritium). Properties of these sources have been presented in table 1 [2, 3, 4, 5, 6]. ^{90}Sr was one of the first radioactive elements used in a Betavoltaic device. Also it is good choice for higher power applications. Tritium has a wide application in medicine, but its low half life limits its applicability. Half life of ^{147}Pm is low and has also gamma radiation, However its beta particle energy is higher than ^{63}Ni and tritium energy. ^{63}Ni is another pure beta emitting radioactive isotope that has a lower decay energy, higher half life, lower activity and power density, and It can be readily plated to the semiconductor surface[2].

Table 1. Pure Beta particle emitters

Radioactive Source	Half-Life (year)	Specific Activity (GBq/g)	Maximum Decay Energy	Average Decay Energy	Specific Power μ Watt/Ci
Tritium, ^3H	12.3	357000	18.6 keV	5.7 keV	33.7
^{63}Ni	100	2190	67 keV	17 keV	100
^{147}Pm	2.6	36260	230 keV	73 keV	367
$^{90}\text{Sr/Y}$	28.6	5050	546 keV	196 keV	
	41.52		2.283 MeV	935 keV	

Reviewing the properties were represented in Table 1, it seems that ^{63}Ni is the appropriate isotope as for required power (in this application about some microwatt) and half-life. Its maximum energy is below the radiation damage threshold for most semiconductors and also it is a pure beta emitter and needs simple shielding considerations.

In semiconductor selection, there are various options like SiC and GaN. The GaN has been chosen in comparison with SiC, due to its high resistant to the creation of defects and radiation damage. Therefore have a stable voltage. Also it is very hard, mechanically stable material with large heat capacity. In addition in this work, battery parameters were optimized for different layers thickness.

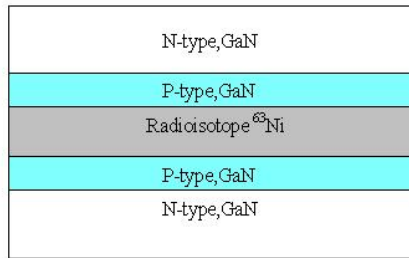
3. Simulation of GaN Betavoltaic device

3.1 Calculation of the electron-hole generation rate using Monte Carlo

Method

In this part, for calculating the electron-hole generation rate, it needs to determine the flux and spatial distribution of emitted beta particles in semiconductor.

Studied geometry is depicted in figure 2. In this structure, device comprises a central radioisotope as a layer of ^{63}Ni , surrounded by two p-n junctions from GaN semiconductor. Arranging the semiconductors and radioactive source layers in aspect of adjacent p or n region with source can make two similar structure with small difference in current and voltage. In accordance with simulation results, having a p-type region adjacent to source is more efficient.

**Figure 2. Structure of GaN Betavoltaic device**

Source has been selected from a layer of ^{63}Ni with $1.5 \mu\text{m}$ thickness and overall device cross section of 1cm^2 . The lower limit of radioisotope thickness is determined by required power depending on application and production technology and the upper limit by self-absorption of emitted particles (commonly between 0.1 to $5 \mu\text{m}$) [7,8]. Practically, because the beta particles emitted from ^{63}Ni have very short ranges, there exists a saturation thickness for the ^{63}Ni layer and for the GaN layer. Thicknesses that are greater than these saturation values will not produce additional electrical power. Evolution of the available power as a function of the Ni-63 layer thickness and the GaN layers thickness, for the above configuration is shown in Figure 3.

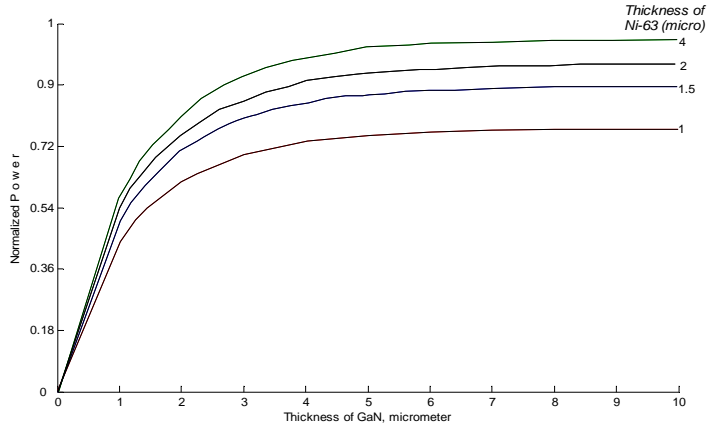


Figure 3. Available power to a GaN radioisotope converter as a function of the Ni-63 layer thickness and the GaN layers thickness

The amount of impurity in each semiconductor-junction stratum is important in depletion region width and open circuit voltage determination. It should be compromised in amount of impurity selection, between this and carrier diffusion length. To achieve high energy-conversion efficiency, the minority carrier diffusion length is required to be bigger than maximum beta particles range [9] and to achieve higher voltage the leakage current of pn-junction (which is dependent on amount of impurity) is required to be small. Figure 4 shows diffusion length and voltage versus impurity concentration [10].

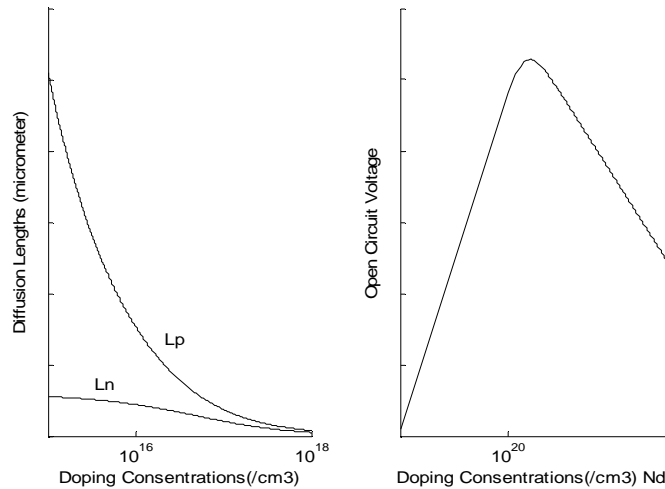


Figure 4. Diffusion length and open circuit voltage versus impurity concentration

3.2 Calculation of Recombination and Charge Collection

Net produced current in the device is obtained according to generation-recombination and charge collection probability in all regions. So recombination of the significant part of the generated electron-hole in outside the depletion region must be involved in calculation. Because of the dependency of recombination velocity to position and charge carrier concentration, exact calculation of recombination current is very complex [11]. Principally, there are three recombination mechanisms as Auger, SHR, and Radiative [5,11,12] and the total recombination rate is presented with the following relation;

$$\frac{1}{\tau} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{shr}} + \frac{1}{\tau_{aug}} \quad (5)$$

Electron-hole collection probability is the generated carrier collection probability, if they reach to depletion region. It depends on distance from the place of producing carrier to depletion region, recombination mechanisms and also carrier diffusion length. This value is determined 100 percent for generated carrier into depletion region and for n and p region obtain with following relation [2];

$$CE = 1 - \tanh\left(\frac{W}{L}\right) \quad (6)$$

Where W is distance from depletion region and L minority carrier diffusion length. For this calculation, it needs to split the geometry to several spatial meshes to calculate the carrier collection probability as a function of location.

4. Results

Simulated Betavoltaic device parameters for ^{63}Ni source have been presented in table 2. Obtained yield for modeled device shows that this device have a higher efficiency in comparison to other similar batteries, especially thermoelectric batteries (~15% maximum efficiency).

In addition, the obtained results for presented Betavoltaic device where compared with two kind of lithium batteries [13].

Table 2. Simulation results of GaN Betavoltaic with ^{63}Ni source

	Optimum thickness μm	Jsc $\mu\text{A}/\text{cm}^2$	Voc (Volt)	Energy Content mW-hr/mg	Efficiency η	Life Time (Year)
GaN P-type region N-type region ^{63}Ni	1 3 1.5 (~ 1.3 mg)	1.1	2.7	204.55 (4 years)	25%	>30
Lithium/Iodine	1 mgr	6.1	2.5	0.5		5-10
Lithium-Ion	1 mgr	3.79	2.5	0.3		5-10

5. Conclusion

The results show that Betavoltaic batteries be useful in low-power applications, such as cardiac pacemaker, especially due to more safety. Range of beta particles emitted form using radioisotope is very short which require minimal shielding and are unable to penetrate human skin. Also it will be a suitable replacement for the thermoelectric device which have lower efficiency and also Lithium ones which have lower energy content and longevity, higher weight and dimension with the same order of power and voltage.

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