Geometrical Optimization of GaN Betavoltaic Microbattery

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Abstract: - In this manuscript three geometrical structures have been considered for a GaN Betavoltaic Microbattery and geometrical optimization has been performed for the preferred structure via Monte Carlo simulation. The approach takes into account the optimization of the structure due to minimize the effects of self-absorption in source and maximize the contact area magnification. Results indicate that the cylindrical array of beta cells have the best performance.

Key-Words: - Betavoltaic, Microbattery, Geometrical Optimization, GaN

1 Introduction

Microbatteries are essential for portable electronics, cellular phones and MEMs devices to be miniaturized. Also the batteries with stable current and voltage as well as long life have wide application in medicine, oil and mining industries and space equipment. In other word, everywhere such as dangerous or hard-to-reach locations which the replacement of batteries is highly inconvenient and recharging have a high cost nuclear batteries are the best choice. Also they are highly reliable, safe and can be processed and operated in conditions where other batteries would fail.

A solid state microbattery is required in these applications because of the need for processibility and functionality under special conditions. These are the proper power sources that can be made small enough to embed into MEMS devices and wireless micro sensors. Most conventional batteries will fail in these applications because of degassing and degradation of organic content inside of the battery.

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 radioisotopes are suitable because semiconductor 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.

A Betavoltaic device consists of a semiconductor as a p-n junction and a beta emitter isotope as source. 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's the objective of this study, first to determine the more efficient geometrical structure for the Betavoltaic, second to optimize its parameters in order to achieve minimum self-absorption in source and maximum contact area magnification. The optimization has been done via Monte Carlo simulation with the utilization MCNP code.

In order to assess the influence of geometrical source parameter such as radius, height and the spacing between cells in a structure calculation has been done for a unit cell from 1cm2 area of device.

2 Material and Methods

In semiconductor selection as a p-n junction, the Si is one of the famous and applicable materials in solid state devices but III/V semiconductors have several advantages over silicon. They are direct and wide band-gap material, and enable precise fabrication by surface micromachining, due to the ability to epitaxially grow very thin layers with abrupt transitions from one material to the next. Therefore, these materials are at the forefront of next generation of Betavoltaics as we considered them. Hence, the GaN has been chosen in comparison with

others, such as SiC, due to its high resistant to the creation of defects and radiation damage so it will have a stable voltage. Also it is very hard, mechanically stable material with large heat capacity [1].
In addition, Ni-63 is the appropriate isotope as for required power, in low power application. 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 [1].
In what follows GaN and Ni-63 has been considered as the best selection of material and source respectively for low power application.

2.1 Geometrical structure

In accordance with our previous study on Betavoltaic, as discussed in Ref. [1], the best configuration for planar embodiment which is depicted in figure 1, comprises a central radioisotope as a layer of Ni-63, surrounded by two p-n junctions from GaN semiconductor.

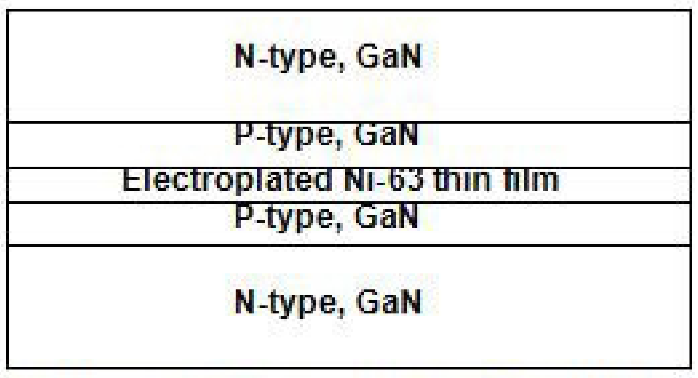

Fig. 1 Structure of Planar GaN Betavoltaic device

When the radioactive material is disposed in a long, narrow volume in a semiconductor, there is a much greater probability that a beta particle produced by a decay event will enter the junction region between p-n layers and induce a current flow.
Moreover, it should be noted that the current of a particular device is related, at least in part, to the surface area of the junction available to collect electrons quickly after the decay event. The greater the area of junction provided in a particular volume of radioactive material, the greater the induced current [2].
Power density of the device can be optimized by altering the geometrical parameters and configuration, modifying the structure and choosing the suitable material and source. So in addition to planar structure, two other configurations were considered for the purpose of increasing the probability of current generation per decay. These are shown in figure 2.

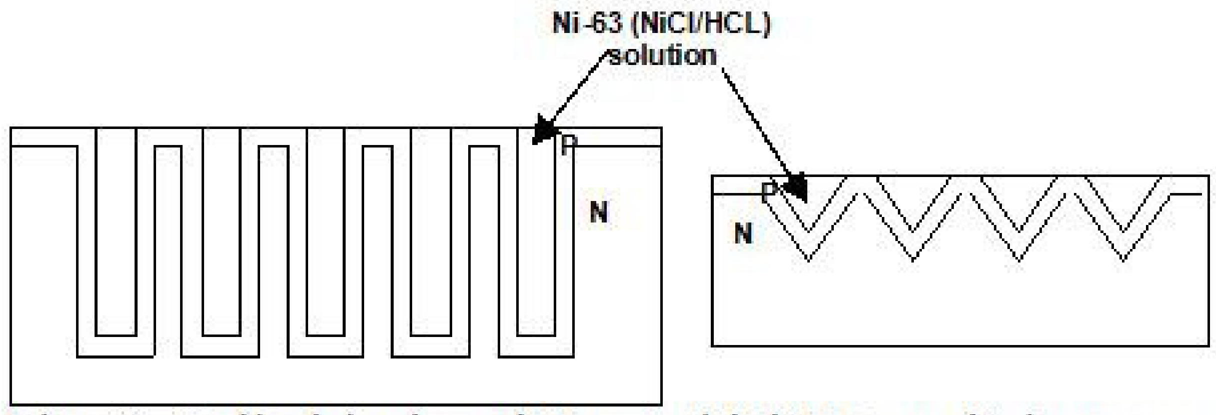

Fig. 2 Cylindrical and Pyramidal Betavoltaic array structure

3 Simulation and Calculation

3.1 Comparison of Various Structures

The simulation results show that: 1) cylindrical array is more efficient than the others in the power density, due to more area magnification and less self absorption, 2) the power density increases with increasing the diameter to height ratio, 3) because of more self-absorption in source, the pyramidal array is not as good as cylindrical array, although, area magnification causes slightly higher power in comparison with planar. Results for various structures by using the same source activity are presented in table 1.

Table 1

Comparison of various Betavoltaic micro battery structure results with the same source activity of about $100mCi/cm^2$

	Isc ($\mu A/cm^2$)	Power Density ($\mu Watt/cm^2$)
Planar	0.4347	1.189
Pyramidal	0.658	1.507
Cylindrical	1.455	3.923

Based on the above results, the cylindrical model has been chosen for geometrical optimizing.

3.2 Cylindrical Array Optimization

There are two main parameters in designing a cylindrical array of beta cells; dimension of each cell, comprise diameter and height and the space between cells, thereby number of cells per area can be determined.
So as to optimize a single cell, optimum diameter and height were considered. According to previous notes, increasing the diameter to height ratio causes the higher power density and current. Hence, it was explored for the best value. The generated current and power density are calculated for different value of these two parameters. In this case, the optimal

parameters are based on the assumption that source activity to be constant. The results presented in table 2 are for a cylindrical array of 440 cells.

Table 2

Optimization of a single cell dimension

Height to Diameter Ratio (HDR)	Isc (nA)	Power Density (nWatt/0.7mm^2)
25	0.4707	1.2703
200	1.3615	3.6717
300	1.3987	3.7649
500	1.6158	4.3440
1150	2.1632	5.8065
(More than 1mm thick) 1200	2.1835	5.8599

Results show that by increasing the contact area between source and p-n junction, the generated power increases. But there are some limitations in increasing the height. The lateral dimensions should be in the mm range, and the thickness in the range of micrometers. This is due to the fact that micro systems like MEMS components are generally less than 1cm2 in area and less than 1 mm thick. So the 5th trial was chosen as the best one.

To optimize the array, it should be determined the optimum spacing between cells. Therefore the n-type region thickness has been altered. Range of Ni-63 beta particle with average energy of 17 keV in GaN is about 1.136µm and the range of particles with maximum energy of 67 keV is about 16.2µm. Hence, if it is desirable to investigate each cell performance individually, the space should be chosen higher than the maximum beta's range, (i.e. more than 32.4µm, 16.2x2). Thereby first, calculation has been done for 40µm spacing with about 17µm n-type region thickness for collecting all particles in each cell. If this space to be less than the range of beta particles, it will enter into adjacent cell and should be considered there, but collection probability of these particles is low. The results of altering the n-type region thickness shown in table 3 are for a cylindrical array of 440 cells with the radius of 0.75µm and 300µm height.

Table 3

Optimization of device dimension

Thickness of each Cell µm	Isc (nA)	Power (nWatt)
5	0.9471	2.5388
6	0.9831	2.6362
7	0.9829	2.6356
8	1.0251	2.7499
14	1.1125	2.9944
16.2	1.1533	3.1053
17	1.3615	3.7649
40	1.3615	3.7649

It is shown that the thickness less than half of beta's maximum range in GaN is not efficient. But for thickness more than this space there are not significant changes. According to results in table III the optimum thickness is about 17 µm.

Accordingly, it seems that the optimum width and the depth of the micro cells are 0.8342 (diameter of cylinder) and 970 µm respectively and Space between cells will be 17 µm. If the cross section of device to be 1cm2 there will be about 344569 cells in a single device and total current and power density will be 1.69µA and 4.537µWatt respectively. Finally, a practical model has been proposed in table IV which its source density is about 56.32mCi/cm2, if it is possible to use the source in solid state radioactive but in practice liquid solutions such as ^{63}NiCl/HCl is common for this case [3]. So the concentration of radioisotope (activity of liquid) will affect output power. In presented results of table 4 liquid activity is about 10mCi/µl and 302500 cells is used for source density of about 1mCi/cm^2.

Table 4

Practical and optimum model for GaN Betavoltaic device

Device/cell Parameters µm	Source Density mCi/cm^2	Isc (µA/cm^2)	Power Density (µWatt/cm^2)
Source Dimension: Radius 0.5 Height 450	56.32	0.857	2.293
Device Parameters: Height 500 302500 cells (Array; 550x550)	1	0.01627	0.04188

Equivalent electronic circuit of this device consists of parallel current sources. By using the series of these devices and also with increasing the liquid activity can be produced higher current and power according to application.

4 Conclusion

It is concluded from the results that in semiconductor base micro devices, the geometrical parameters play a special role. Obtained yield for modeled devices indicates that cylindrical array of Betavoltaic cells compare to others has better performance and power density increases with higher height to diameter ratio.
Also, the results show Betavoltaic batteries can be useful in low-power applications, such as implantable medical devices and MEMs, 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.

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