

GaN BETAVOLTAIC ENERGY CONVERTERS

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ABSTRACT

Semiconductor betavoltaic converters use energy from radioisotope sources to generate electricity for remote applications requiring power for 5-50 years. To be competitive with thermoelectric devices, they must achieve an efficiency above 20% [1]. This paper presents the design rules and efficiency calculations for such high efficiency GaN betavoltaic converters, and experimentally demonstrates the radiation tolerance of GaN.

DIRECT RADIOISOTOPE CONVERTERS

Radioisotope power conversion, in which the energy from the decay of radioisotopes is used as a power source, allows powering of applications which are unsuited to power sources such as photovoltaics or generators or to batteries. These applications are typically remote, not accessible to any external energy source (including sunlight), and often must last between 5 to 50 years. They include not only space, but also small power sources for biomedical uses. Radioisotope thermal generators (RTGs) are often used to convert the energy from the radioisotope by, converting it to heat, and then converting the heat to electricity via either a thermoelectric device, or thermophotovoltaics (TPV). Alternately, the radioisotope may be directly converted into electricity via betavoltaics, in which the energy from a beta particle creates electron holes pairs which are collected and used to generate power. similar to a solar cell.

While devices converting radioisotope sources via the photovoltaic effect have existed since they were proposed by Rappaport in 1954 [2], two key issues have hindered their more widespread use. The first of these is that typical power densities are relatively low, due to the low incident particle fluxes from radioisotope sources which emit beta particles [3]. A second key issue is that in previous devices extensive degradation of performance in relatively short times was due to degradation of the lattice structure in crystalline cells or displacement of hydrogen in amorphous silicon cells. The radiation damage further has hindered the ability to achieve higher power devices in that higher power radioisotope sources cause the material to degrade more rapidly. Therefore, most solid-state nuclear-based energy sources used thermoelectric approach. However,

the use of wide-band gap materials, particularly GaN-based materials, allows both high efficiency (greater than the 15% from thermoelectric converters) and radiation tolerance.

BETA PARTICLE RADIOISOTOPE SOURCES

The isotope selection plays a critical part in multiple aspects of the design of the betavoltaic converter. Factors affecting the performance of a betavoltaic device include; the type of particles emitted from the source and from subsequent decay events; the energy spectrum of the emitted particles, which in conjunction with the type of particle determine how far they penetrate into a given material (thus impacting both device design, radiation damage, power of the betavoltaic converter and safety); the half-life of the isotope (which determines the lifetime of the betavoltaic device); and the specific activity (the number of decay events per second per mass or volume) of the source, which, in conjunction with the energy of the particles determines the available power. Theoretically, radioisotopes emitting alpha particles, beta particles 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 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. Given these constraints, suitable beta-emitting isotopes include ³H, ⁶³Ni, and ⁹⁰Sr/⁹⁰Y, which are compared in Table 1. ⁹⁰Sr/⁹⁰Y is good choice for higher power applications if the semiconductor has sufficient radiation resistance to its high energy particles and if the converter is properly shielded. Tritium is extensively used in biological applications, and but its low half life limits its applicability. ⁶³Ni has a lower energy decay, a higher half life, lower activity and power density, and it can be readily be incorporated into a semiconductor device as the nickel can be plated to the semiconductor surface. Due to the ease of including ⁶³Ni in a conventional semiconductor process and its low energies, ⁶³Ni is used as the radioisotope in the remainder of the calculations.

Table 1: Radioisotope sources for a betavoltaic converter.

Element	Particle	Half Life	Activity (GBq/g)	Decay energy max	Decay Energy average
Tritium, ³ H	Beta	12.3 years	357,000	18.6 keV	5.7 keV
⁶³ Ni	Beta	100 years	2,190	67 keV	17 keV
⁹⁰ Sr/ ⁹⁰ Y	Beta	28.6 years	5,050	546 keV 2.283 keV	196 keV 935 keV

DESIGN OF BETAVOLTAIC CONVERTERS

The key difference between a betavoltaic device and a photovoltaic device is the electron generation mechanisms and the importance of radiation resistance. In a betavoltaic device, a single particle from the radioisotope generates a large number of electron-hole pairs, and the spatial distribution of these electrons is different than those from a solar spectrum. The penetration depth of the incident radiation, rather than the absorption depth, determines the distance over which the generated electrons need to be collected. As the penetration depth is a function of the density of the material and the energy of the beta particle, a denser material or a lower energy radioisotope source will require collection over shorter distances. In addition, since the energy of the particle emitted from the radioisotope is substantially larger than the band gap of the device, higher band gaps give higher efficiencies as well as being more radiation tolerant. However, the band gap typically cannot be made arbitrarily high, as such high band gaps have poor conductivities, making it difficult to collect carriers. A final difference between a betavoltaic and photovoltaic device is that the optical considerations (ie low reflection, etc) do not apply. Instead, large surface area with contact between the radioisotope and the semiconductor is required for high power devices.

In order to determine the efficiency of a GaN/⁶³Ni betavoltaic converter, several parameters are calculated: (1) the power available to the betavoltaic converter from the radioisotope; (2) the number of electron hole pairs generated and the collection efficiency of the electron hole pairs (which depends on the penetration depth); and (3) the open circuit voltage, FF, and efficiency from the above parameters. Additionally, the efficiency dependence on the radiation must be determined.

Radioisotope power and penetration depth

The power available to a betavoltaic converter depends on the volume of the radioisotope used, on the amount of energy from the isotope deposited in the volume of the isotope itself, and on the thickness of the absorbing semiconductor material. Because the beta particles emitted from ⁶³Ni have very short ranges, there exists a saturation thickness for the ⁶³Ni layer and for the GaN layer. Thicknesses that are greater than these saturation values will not produce additional electrical power. To determine the saturation thicknesses and the corresponding power level that can be produced by such a device, we have used the Monte Carlo radiation transport code MCNP to simulate beta particle tracks [4]. The beta spectrum of ⁶³Ni used in the MCNP simulation was obtained from Cross et al [5]. The results for a 1 cm x 1 cm area device are shown in Figure 1. The power level saturates when the thicknesses of the ⁶³Ni layer and the GaN layer approach 3 μm and 6 μm, respectively, and the corresponding saturation power level is 2.85 μW for a contact area between the ⁶³Ni and the GaN of 1 cm². Practically, a device having large thicknesses is not very volume-efficient because much of the ⁶³Ni and GaN is not engaged in power generation. The optimum thickness should be about 1.5 μm for

⁶³Ni and 4 μm for GaN, in which case the available power in the GaN is 2.15 μW. This uses less than ½ the volume of the radioisotope (and hence ½ the cost), but produces 75% of the power. Since the penetration of the radiation depends on the density of the material, less dense materials such as silicon (which has approximately one-half the density of GaN), will require twice the thickness to absorb the incident radiation.

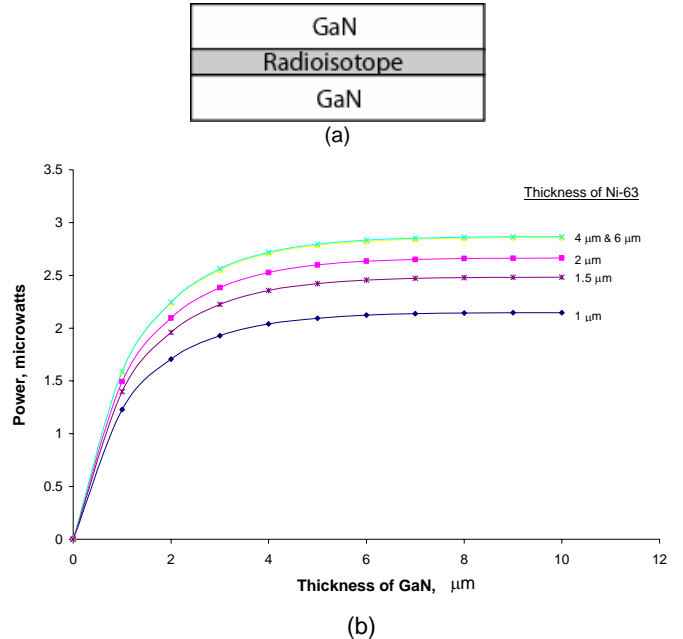


Figure 1: (a) Radioisotope configuration used for modeling the energy deposited in the GaN. (b) Power available to a GaN radio isotope converter as a function of the thickness of the Ni-63 layer and the thickness of the GaN layers for the configuration in (a).

Generation and collection

The next step in the calculation of betavoltaic efficiency is to determine the number of electron hole pairs generated and collected. The minority carrier concentration (for holes) is calculated by $p = G\tau$, where τ is the minority carrier lifetime and G is the generation rate given by:

$$G = \frac{N(1-f)E}{E_{ehp}}$$

where N is the number of high energy decays per second incident on the device, f is the backscatter coefficient (negligible for most materials but is slightly angle dependent), E is the beta particle energy, and E_{ehp} is the average energy that it takes to generate an electron. For generation of carriers by radioisotopes, the average energy to generate an electron hole pair, E_{ehp} , is 3.64 for silicon and is about 3 times the band gap for all measured materials. The maximum current can be found by assuming unity collection efficiency, which gives for of GaN on a 1 cm² surface area and 4 μm of ⁶³Ni, the current density $J_{collected} = 5 \mu A/cm^2$.

The actual current collected depends on the penetration depth and on the betavoltaic device configuration. The collection efficiency is calculated similarly to photovoltaic devices. An electron generated inside the depletion region has a collection probability of unity, while the collection probability for electrons generated outside the depletion region is determined by the distance from the depletion region and the minority carrier diffusion length according to the equation:

$$CE = 1 - \tanh(W/L)$$

where W is the distance from a pn junction and L is the diffusion length. The thickness, W , is determined by the penetration of radiation into the material.

The open circuit voltage of the device can be estimated by the equation:

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{np}{n_i^2}\right)$$

where n_i is the intrinsic carrier concentration (which for GaN is $4.6 \times 10^{-11} \text{ cm}^{-3}$) and np is the product of the number of generated electron hole pairs and the majority carrier concentration, giving for GaN $V_{oc} = 2.3 \text{ V}$. For Si, the intrinsic carrier concentration is $1 \times 10^{10} \text{ cm}^{-3}$, and $\tau = 1 \text{ msec}$ and $E_G = 1.1 \text{ eV}$, giving an open circuit voltage of 0.54 V . This voltage is lower than that for a Si solar cell with a similar lifetime due to the lower number of generated electrons. For $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$, with a band gap of 5.8 eV and $n_i = 7.4 \times 10^{-31} \text{ cm}^{-3}$ and $\tau = 1 \text{ nsec}$, $V_{oc} = 4.9 \text{ V}$. The FF is obtained based on the open circuit voltage. Using these parameters, the efficiency of Si, GaN and $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ betavoltaic devices are shown in Table 2. Importantly, the efficiencies of both the GaN and AlGaN are substantially higher than those from the efficiencies of other radioisotope sources.

Table 2: Si, GaN, and $\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$ betavoltaic devices.

Material	V_{oc} (V)	$I_{collected}$ (μA)	FF	Efficiency
Si	0.54	3.2	81	13.7%
GaN	2.3	1.1	94	25.4%
$\text{Al}_{0.7}\text{Ga}_{0.3}\text{N}$	4.9	0.6	97	27.4%

RADIATION RESISTANCE OF GaN

The aspects which determine the radiation resistance are a combination of the energy emitted by the radioisotope source and the bond strength of the semiconductor material. To create a defect, enough radiated energy must be absorbed to break the atomic bonds in the material and then allow the atoms broken out of the lattice to diffuse away from their original location. The probability of lattice damage, both from a thresholding as well as accumulation point of view, is decreased as the semiconductor chemical bond strength in the material increases [2]. By using a wide bandgap semiconductor such as GaN or AlGaN, the maximum bond energy/minimal atomic displacement probability is achieved while still maintaining a conductive material. For example, using AlGaN with up to ~70% Al content gives a band gap of ~5.8 eV which is 6 times more resistant to the creation of defects than Si.

In addition to the high bond strength, the high density of the III-Nitride materials results in very low impurity/defect diffusivities. In the wide bandgap semiconductors, the diffusion of impurities is highly retarded, making substitutional doping of these semiconductors impossible. Due to this low diffusivity, any atomic bonds broken by the high-energy electrons, can not diffuse far from their original location. Thus, the likelihood of the displaced atom diffusing back into its own lattice location is high. This inherent self-annealing ability is a hallmark of radiation tolerant materials. Further, high radiation tolerance for the nitride material system is expected due to the lower atomic number. One mechanism for atomic displacement occurring in materials is due to interactions of the high energy impinging electrons with core lattice electrons, and these interactions increase as the atomic number of the atoms in the crystal increase. For example, InP has shown improved radiation tolerance over InAs due the fewer electrons that can interact with the high energy particle [6]. Thus, it is expected and confirmed experimentally [7] that InN will have superior radiation tolerance.

Recent studies of radiation damage in III-Nitrides indicate a superior ability to postpone defect formation until very high doses and/or energies are used. A general summation of several radiation studies (for example [8,9,10]) indicates effectively no radiation damage for electron energies less than ~ 0.1 MeV while energies above this range can lead to both shallow and deep energy level defect formation as well as degradation in mobility and major changes in carrier concentrations. There are further reports which indicate material improvement under electron injection in the tens of keV range. This improvement in diffusion length through "electron beam annealing" has been reported for n-type GaN [11] but is most noticeable for p-type GaN where it is reported that a threefold improvement in minority carrier diffusion length has been observed [12].

To examine the feasibility of using higher energy sources and the radiation damage induced by such sources, a set of silicon solar cells and a GaN n-type sample were exposed to radiation in a ^{60}Co source at a hot cell laboratory in the Neely Nuclear Research Center at Georgia Tech. Although ^{60}Co is a gamma source, Compton scattering produces electrons equivalent to approximately 200 keV for comparison purposes. It should be noted that neither sample had been prepared with the goal of inherent radiation hardness. Doses of 10 Mrad and 100 Mrad were investigated. For the silicon solar cells, the effect of the radiation on the lifetime of a solar cell can be calculated by analyzing the change in open circuit voltage of the devices. Assuming that the base region of the solar cell dominates, then the change in V_{oc} allows calculation of the change in diffusion length, and gives a reduction by a factor of 1.7 in the diffusion length after the 10 Mrad dose, and a factor of 7.2 after the 100 Mrad dose. In term of minority carrier lifetimes, these correspond to a reduction in the minority carrier lifetime by a factor of 3 and 52 respectively.

The design and issues of a radiation hard GaN betavoltaic device is substantially different than that of a sili-

con betavoltaic device. In a silicon betavoltaic device, the diffusion length remains longer than the depth at which electrons are generated, but the degradation in lifetime causes a substantial change in the open circuit voltage. However, in a GaN device, there are several factors driving higher efficiency. First, the voltage of the GaN betavoltaic device is higher due to the higher band gap of GaN compared to Si. Since the change in voltage is proportional to the change in diffusion length, even as the same change in minority carrier lifetime gives a lower percentage change in V_{oc} .

Table 3: Before and after measurements of parameters of silicon solar cells.

Before Radiation			
	V_{oc} (mV)	J_{sc} mA/cm ²	Eff (%)
Device #1	620	34.4	13.6
Device #2	619	34.4	13.8
Device #3	628	34.5	10.6
After 10 Mrad			
	V_{oc} (mV)	J_{sc} mA/cm ²	Eff (%)
Device #1	606	33.4	12.7
Device #2	605	33.5	14.7
Device #3	612	32.8	7.9
After 100 Mrad			
	V_{oc} (mV)	J_{sc} mA/cm ²	Eff (%)
Device #1	569	29.6	10.9
Device #2	571	29.6	12.2
Device #3	576	29.6	7.69

Second, the reduced damage coefficients of GaN compared even to GaAs [13] mean that degradation is not so severe as in silicon. The photoluminescence (PL) measurements in Fig 2 shows that after a dose of 100 Mrad, the PL peak decreases by a factor of about 3. The increase in photoluminescence after the 10 Mrad dose is explained by an increase in the doping as shown in Table 4. Taking the final doping into account, the minority carrier lifetime decreases by a factor of 5. Hence these results demonstrate the radiation tolerance of GaN, as the lifetime decreased by a factor of 5 for the high energy sources, while the lifetime of silicon decreased by a factor of 50 or more. A change in the lifetime of 5 corresponds to a change in V_{oc} of (V_{oc} of GaN = 2.63 eV) of 1.6%, compared to the degradation in the silicon voltage of 25%. The PL peaks do not provide enough data points to extrapolate accurate damage coefficients, but using published damage coefficients for the saturation current [13], gives a maximum degradation in the voltage by 10%.

Table 4: Hall measurements of the irradiated GaN.

	Before radiation	10M rad	100M rad
Concentration (cm ⁻³)	1.4E19	3.8E19	2.5~3.9E19
Mobility (cm ² /V.s)	64	26	25~40
Receptivity (Ω.cm)	6.95E-3	6.16E-3	6.20E-3

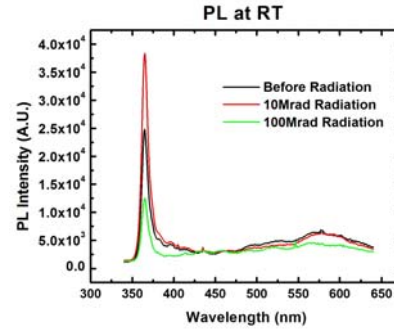


Figure 2: Room temperature photoluminescence data for a GaN sample irradiated using a Cobalt-60 source.

CONCLUSIONS

The use of GaN for a betavoltaic converter with a ⁶³Ni source allows stable radioisotope converter with efficiencies of 25%. These efficiencies are higher than those presently available with thermoelectric converters (~15%), thus making radioisotope conversion a promising new application for "photovoltaic" devices.

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