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Betavoltaics

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Betavoltaic devices are semiconductor energy conversion structures which are coupled with beta radiation sources. These devices are in many respects similar to solar cells and convert radiation directly into electrical energy. Beta radiation (high energy electrons) originates from nuclear reactions occurring in radio isotopes, other types of radiation which can originate from radio isotope decay are alpha radiation (particles that are helium nuclei consisting of two protons and two neutrons) and gamma radiation (high frequency electromagnetic radiation similar in form to radio waves or visible light). Both alpha and beta radiation are easily stopped by a few millimeters of air or a layer of dead skin while gamma rays can penetrate through the entire body. The amount of radiation exposure is determine by the total dose that the human body receives, when we compare the radiation sources we find that the most dangerous radiation is alpha radiation which has a significantly higher effective dose than either beta or gamma radiation. Beta radiation is the safest radiation source from two perspectives, effective dose as well as penetration depth. The safety of beta sources allows them to be employed in high volume applications such as smoke detectors and exit signs. Examples of beta radiation sources are Nickel 63 (Ni^{63}), Tritium (H^3) and Promethium (Pm^{147}). Betavoltaic devices find potential utilization in systems which require small amounts of power (.01-100 micro watts), and operate in a small foot print (less than $10^{-2}cm^{-2}$) for long time periods (2-25years). **Figure 1** shows a schematic view of a betavotaic device. In this realization the isotope is integrated into the device package as a solid foil (gaseous sources can also be used). The package is an important part of the beta voltaic design as it must position the isotope within a few thousand's of an inch of the semiconductor as well as provide the necessary shielding and physical durability.

Betavoltaic devices have a surprisingly long history with a commercial device the *Betacell* produced in the early 70's. The *Betacell* had an overall efficiency of 2.3% and over 100 people received heart pacemakers powered by *Betacell.* At that time of Betacell manufacture the majority of low power applications required power levels that were too high for the *Betacell* to produce. With the continuing development of nanotechnology the power requirements for electronics have significantly dropped together with the size of individual devices and circuits.

Betavoltaics now find a technology landscape in which the surface to volume ratio of the analog and digital devices and circuits has increased dramatically. In this environment betavoltaics are increasingly becoming a competitive micro power option.

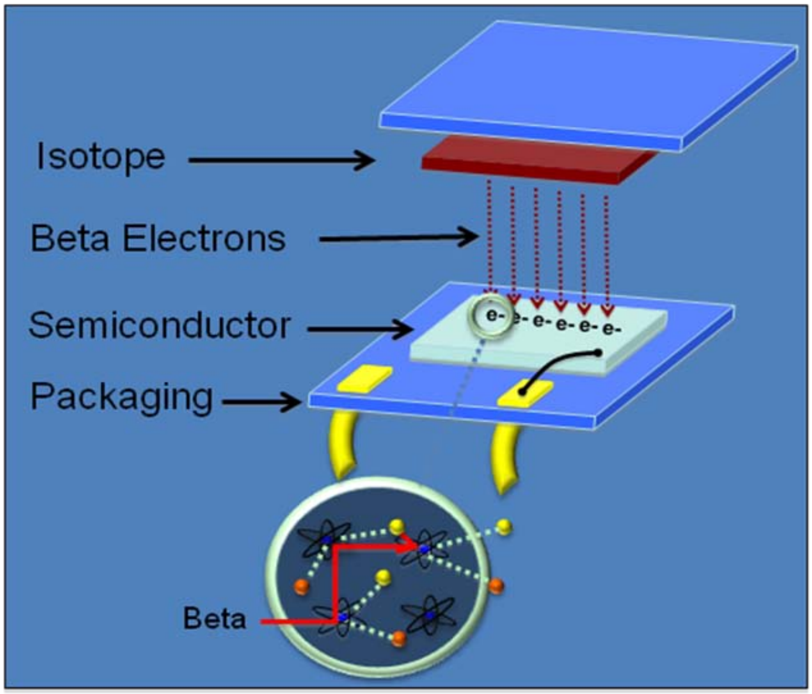

Fig1. Schematic of Betavoltaic device

Theory of radiation cell operation

The beta voltaic energy conversion process begins with the emission of high energy electrons from the radioisotope. The loss of the electron from the isotope would normally cause the radioisotope to acquire a positive charge. However, the radio isotope is connected to ground potential through the package as shown in **Fig. 1**. The connection to ground provides a path for electrons to flow to the isotope maintaining charge neutrality.

Betavoltaic devices use semiconductor PN junctions or metal Schottky junctions to collect charge. **Figure 2** illustrates some of the physical process which occurs during beta voltaic energy conversion in a pn semiconductor junction. The high energy beta electron (10keV-200keV in energy) is incident on the semiconductor. The high energy electron transfers its energy to the semiconductor via several sequential interactions. The first interactions produce plasmons (quanta of charge oscillations) and secondary electrons with lower energies.

Subsequent interactions produce acoustic and optical phonons (quanta of crystal vibrations) as well as electron-hole pairs shown in the diagram as open and closed circles.

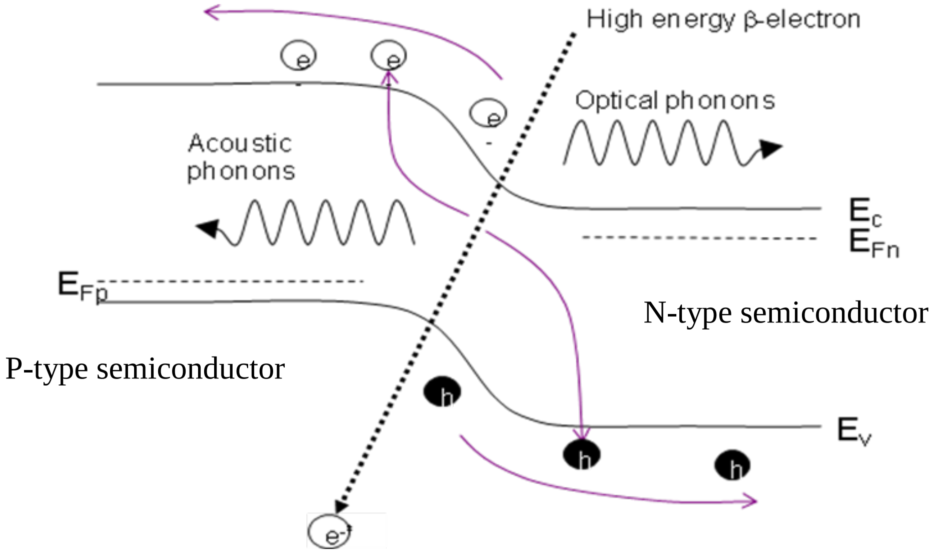

Fig2 Illustration of beta charge generation and collection in a pn semiconductor junction

The effects of this energy cascade are described by the heuristic parameter E_{e-h} the mean electron-hole pair creation energy. The mean electron-hole pair creation energy is the average energy required to produce one electron hole pair. Using the mean electron hole pair creation energy it is possible to calculate the current flow out of the battery under short circuit condition (battery terminals connected together) this is referred to as the short circuit current . The short circuit current produced from a beta device is given by following relationship

$$(1) \quad I_{sc}/A = J_{gen} = (J_{\beta} * E_{mean\ \beta} * (1-\eta))/\ E_{e-h}$$

where A is the device area J_{gen} is the net generated electron current density , J_{β} the net flux of beta electrons from the radiation source $E_{mean\ \beta}$ the mean beta electron energy generated by the beta source, E_{e-h} the mean electron-hole pair creation energy, (which is 5.5eV for SiC), and η which is the backscattering yield, (percent of beta electrons backscattered at the semiconductor/air interface). For example electrons with energy of 5.68KeV (the mean electron energy for Tritium) will produce ~1000 electron hole pairs in SiC if the backscatter yield (η) is 0%. For a flux of high energy electrons equal to 5nA/cm^2 a short circuit current density of 5uA/cm^2 will ensue. This equation assumes 100% carrier collection efficiency of the beta's generated in the semiconductor. A battery is defined by two parameters the short circuit current density (previously discussed) and the open circuit voltage (batteries terminals not connected). The the open circuit voltage can be calculated from the short circuit current using well known semiconductor device equations (also valid for solar cells). The open circuit voltage is given as

$$(2) \quad V_{oc} = nV_T\ln(J_{gen}/J_{ss})$$

Where V_{oc} is the circuit voltage, n the ideality factor, V_T the thermal voltage =25.9mV at T=300K, J_{gen} the current generated by the radioactive source and J_{ss} is the reverse saturation current of the diode used in the cell. The ideality factor (n) is a measure of the quality of the semiconductor junction, the constant has a value between one. (high quality junction) and two (leaky junction). Reverse saturation current is the "leakage current" that flows internally inside the battery when the battery terminals are not connected. This leakage current can be affected by imperfections in the semiconductor material (such as electron traps or material dislocations) which will increase J_{ss} and therefore reduce V_{oc}. The open circuit voltage is determined by the electronic bandgap of the semiconductor forming the PN junction (in addition to J_{ss} as previously mentioned). **Fig. 3** shows the plot of the betavoltaic IV curve the open circuit voltage (V_{oc}), short circuit current (I_{sc}) and the maximum power point ($I_{mp}V_{mp}$) are indicated in the plot. The slope of the curve at the maximum power point is equal to the load resistance at maximum power.

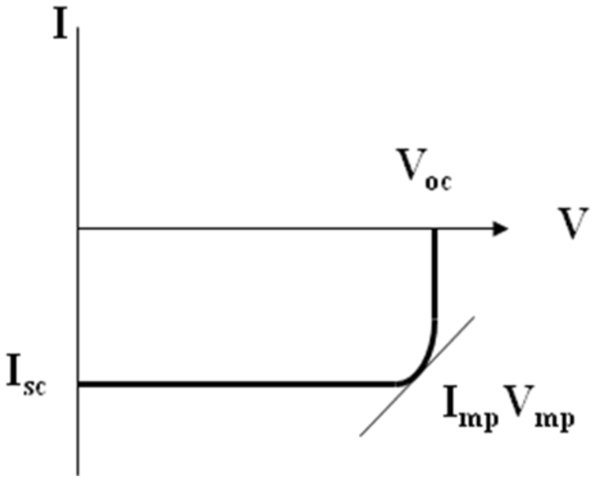

Fig 3 IV plot of beta voltaic device

Application of wide bandgap semiconductors to Betavoltaics

Several semiconductor materials, such as Silicon (Si), Silicon Carbide (SiC), Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Nitride (GaN) may be used to form the charge separation junction. Wide bangap semiconductors materials produce betavoltaic batteries with the highest theorectical efficiencies. Semiconductor theory predicts that if a large bandgap semiconductor is used to form the pn junction the reverse saturation current will be very low. Restated, the "apparent" resistance which appears across the output of the device will be very high. This apparent resistance is referred to as the shunt resistance of the battery. Betavoltaic devices operate at very low output currents, it is therefore important that the shunt resistance is very high limiting the internal battery losses and increasing the battery efficiency. Si, the semiconductor industry workhorse, cannot realize sufficiently high open circuit voltages or power conversion efficiencies to be an optimal alternative for beta-voltaic batteries. **Figure 4** compares the theoretical limit efficiencies of various semiconductor materials when excited by Promethium. The mean electron-hole pair creation energy $E_{e\text{-}h}$ is similar for most of the material systems which implies that the short circuit current density for all the materials will be approximately the same. However the larger bandgap materials produce higher open circuit voltages which directly translate into devices with greater conversion efficiencies. **Figure 4** does not account for backscattering loses or defects in the material which could limit charge detection.

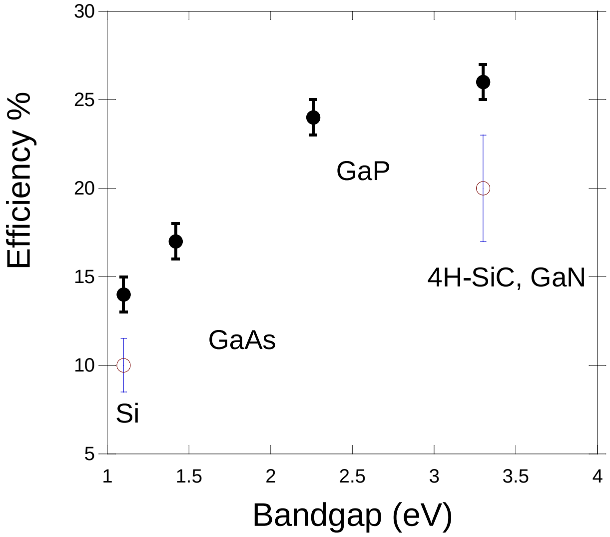

Fig4. Betavoltaic efficiency versus semiconductor bandgap. The closed circles are the calculated efficiency of the device as a function of bandgap using the approach of [2] . The open circles are measured values for betavoltaic devices. For the Si device Pm^{147} is used as the radioisotope. For the SiC device the data is take with N^{63} as the radio isotope

Betavoltaic sources

There are several candidate radioisotopes which can be inserted as a power source for beta-voltaic batteries. Of these sources, Nickle-63 (Ni^{63}), Tritium (H^3), and Promethium (Pm^{147}) have been used in experimental (and in the case of Promethium production) devices. The energy spectra and absorption characteristics of beta sources are fully defined by the mean energy of the beta source and the maximum energy of the beta source. The other important attributes of the radiation source are the isotope half live and the isotope activity (which directly translates into beta flux). **Table 1** compares the attributes of the popular beta sources. If the energy of a beta electron is known we can calculate the penetration depth of the electron in a material of density ρ using the following relationship

$$(3) \quad R=4E^{1.75}/100\rho$$

Where R is the range in um, ρ is the density of the absorbing material in $g/cm^3$and E is the energy of the electron in keV. For a given source the penetration depth determines how much radiation will be absorbed in the charge separating semiconductor as well as how much radiation is “self absorbed” by the source. The amount of useable energy is limited to the number of high energy electrons which are able to escape from the surface of the source. Due to the high absorbance of the beta source only electrons from a very thin layer of radioisotope are extracted. In order to maximize source efficiency it is necessary to form the isotope with a large surface to volume ratio. In the choice of betavoltaic sources it is desirable to use sources with the highest mean energy; such isotopes will produce greater numbers of electron hole pairs for the same activity. However, the down side is that the higher electron energies can produce radiation damage in the semiconductor which ultimately limits the lifetime of the device. Also, at electron energies > than 100keV the production of X-rays (Bremsstrahlung radiation) becomes likely increasing the shielding requirements of the package. Careful engineering is required to implement the optimal isotope for a specific application.

	E_{max} (keV)	E_{mean} (keV)	Activity (Gbq/mg)	Half Life (Years)
Ni^{63}	67	17	.37	92
H^{3}	18.6	5.685	37	12.32
Pm^{147}	230	73	15	2.62

Table 1 Betavoltaic radioisotope source characteristics

Applications of Betavoltaic powered systems

Betavoltaic batteries can deliver cost effective continuous power in the range of 10nW to .1uW. The energy density of Betavoltaic batteries is in the range of 3- 200 W-hr-cm^{-3} (depending on the isotope and details of the design) which compares to 250-360 mW-hr-cm^{-3} typical for Li batteries. The half lives of the important radioisotopes (see Table 1) can be as long as 92 years or as short as 2.6 years. Therefore, Betavoltics find the greatest utility when there is need for a remote stand alone application (where battery change out is difficult), which is coupled with a need for long life. Further, electronics often needs to operate in harsh environments where the temperature extremes exclude the use of conventional Li batteries. In another type of systems implementation Betavoltaic batteries can be used to “trickle charge” thin film Li batteries (which are able to withstand harsh environments) or ultra capacitors in order to be able to provide relatively large amounts of energy over a short period of time. This system topology can be used for applications which operate principally in the standby mode such as anti-tamper circuits. Anti-tamper circuits need to have a small amount of continuous power to maintain security vigilance but a relatively large amount of power to actuate alarms should there be a security breach.

Sensor networks are a ubiquitous class of applications which are remote in nature. The intelligent microprocessors which are at the heart of these networks are being developed using techniques which significantly reduce the operating energy requirements[4]. Currently, digital circuits can idle at .36uW of power and produce a 24 bit data packet every 3 seconds from a

1.8uW power source. Low power analog circuits are able to do 40 measurements a second from the same 1.8uW power source. It is anticipated that both digital and analog circuits will continue to become more energy efficient. Medical applications represent systems that are poised to take advantage of the aforementioned low energy circuits as well as new developments in MEMS (Micro Electronic Machining). Low power (1 to 100μW) medical applications included implantable sensors (i.e. glucose monitors) or pacemakers[4].

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Key Words

Betavoltaic, radioisotopes, nuclear battery, silicon carbide, wide bandgap, micro power

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