RADIOVOLTAICS: HIGH-EFFICIENCY CONVERSION OF IONIZING RADIATION DIRECTLY TO ELECTRICAL POWER

D. Coso[1], J. Segal[2], J. Hasi[2], C. Kenney[2], S. Chu[3], S. Yee[4], A. Majumdar[1]
[1]Department of Mechanical Engineering, Stanford University, Stanford, CA, USA
[2]SLAC National Accelerator Laboratory, Menlo Park, CA, USA
[3]Departments of Physics and Molecular & Cellular Physiology, Stanford University, Stanford, CA, USA
[4]Department of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT

Radiovoltaic devices can directly convert high-energy β−electron or α-particle emissions from radioisotopes to electrical power through the generation and separation of electron hole pairs in semiconductors. By carefully matching length scales involved in the physics of absorbing high-energy electrons in semiconductors and the diffusion lengths of electrons and holes, it is possible to increase the power conversion efficiency. This paper demonstrates a distinct increase in conversion efficiency in p-i-n diodes compared to pn diodes.

KEYWORDS

Nuclear decay; Direct energy conversion; Semiconductor device design.

INTRODUCTION

The ability to store energy and convert it into electrical power has wide applications. While a majority of current work focuses on batteries, the energy densities of current Li-ion ones are typically 0.3-0.4 kWh/kg and about 1 kWh/l. Liquid hydrocarbon fuels have energy densities of 10-12 kWh/kg and 9-10 kWh/l, and are widely used for power generation through various engines and fuel cells. Finally, radioisotopes such as ^{90}Sr have power densities on the order of 1 kW/l, with a half life of about 30 years, resulting in volumetric energy densities ~10^5 kWh/l. Given the enormous energy densities and long lifetime of radioisotopes, it has long been desired to develop power generators from radioisotope decays.

Radioisotope Thermoelectric Generators (RTGs) convert the heat generated from a high-energy particle emitted during radioactive decay to electricity via semiconductor-based thermoelectric generators or heat engines. Widely used in space missions, the state-of-the-art RTGs have power levels < 5kW and peak efficiencies < 8%.[1] Note that because of the thermodynamic (or Carnot) penalty of heat engines, it is unlikely that the efficiency could be further improved. Hence, there have been several attempts to directly convert the energy from high-energy particles, especially α and β particles, to electrical power without a heat engine, but rather through electron-hole excitation in *p-n* junctions formed in semiconductor devices.

Betavoltaic devices[2,3] were first developed by Paul Rappaport[4,5] at RCA in 1953, which used an alloy containing ^{90}Sr to a *p-n* semiconductor diode to create a conversion devices with an efficiency of 0.2% capable of generating 0.8 μW. Between 1967 and 1974 Donald W. Douglas Laboratories further developed this technology, which ultimately resulted in the invention of the Betacel powered by ^{147}Pm with conversion efficiency of 4% and produced nearly 400 μW. In 2002, a β-voltaic was created at the University of Wisconsin with a power output of 0.069 nW and a conversion efficiency ~1%[6,7]. An efficiency of 4.94% with a power output of 99.85 nW was achieved by Nanjing University of Aeronautics and Astronautics in 2012 by using a silicon p-n semiconductor powered by Ni-63[8]. In 2006, Betabatt created a similar device but this device also suffered from rapid device degradation[9]. Recently, Widetronix created a 6% efficient device using Ni-63 as the power source generating 10nW-1μW[10]. In 2008, City Labs produced a H-3 β-voltaic known as the nano-tritium battery with a conversion efficiency of 7.5% generating 840 nW[11]. In 2010, this became the first β-voltaic to receive a general license allowing it to be sold to the general public.

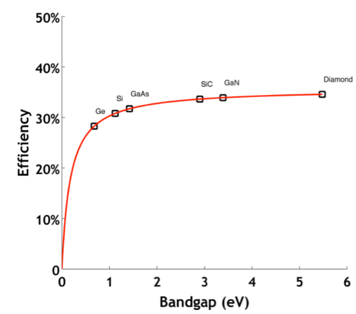

Fig. 1 Maximum efficiency as a function of bandgap for various semiconductors.

While the demonstrated efficiency limit has so far been 8%[12,13] and 11.2%, there is no fundamental reason why it cannot be higher. Based on the correlation between the ionization energy and bandgap[14], the theoretical limit of the conversion efficiency can be predicted, and is shown in Fig. 1. For Si, the maximum efficiency is about 30%, whereas the maximum possible efficiency is about 35%. Clearly, there is significant room for improvement.

DEVICE DESIGN

There are two important sets of length scales involved in direct conversion of high-energy β-electrons to electrical power in semiconductor devices:

1. *Semiconductor*: The diffusion length (L_{diff}) of minority carriers in a semiconductor, which for an indirect gap semiconductor such as Si, L_{diff} ~ 1 mm for electrons and

holes doping < 10^{15} cm^{-3} and drops below 10 μm for doping > 10^{18} cm^{-3}.

2. *Primary Electrons*: The penetration depth of the β-electrons. If the material is a metal, L_{abs} ~100 nm, whereas if it is a semiconductor, it could be ~10 μm. The size (L_{rad}) of the region over which the incident primary electrons create secondary and tertiary electrons in the semiconductor, which then produce electron-hole (*e-h*) pair excitations in the semiconductor. This is given by empirical relations[15]

$$x(\mu m)(depth) = \frac{0.1E_p^{1.5}}{\rho};\ y(\mu m)(width) = \frac{0.077E_p^{1.5}}{\rho}$$

where E_p is the energy of the incident primary electron (in keV) and ρ is the material density (g/cm^3). For 100 keV primary electrons impinging on Si, L_{rad} ~ 50 μm.

These length scales suggest that to achieve high efficiency, one needs to adopt the device design shown in Fig. 2, which is different from a *pn* junction that has so far been used by previous studies.

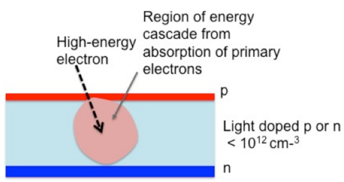

Fig. 2 Design of an ideal device with a large region of lightly-doped semiconductor sandwiched with highly doped p and n layers, which act as contacts. The lightly-doped or intrinsic region allows for high diffusion lengths as well as some carrier drift based on the built in electric field to separate electrons and holes.

RESULTS

Figure 3 shows some preliminary results of current-voltage curves from the *p-i-n* diode in response to an incident electron beam at 30 keV energy and at different currents. The power conversion efficiency of both *p-i-n* diodes (Fig. 2) and *pn* diodes in response to incident

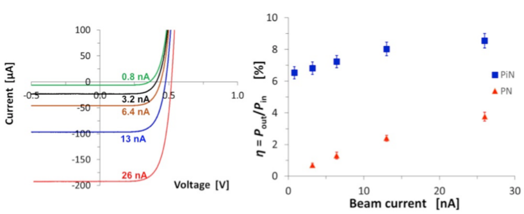

Fig. 3 (Left) Current-voltage curves from an off-the-shelf p-i-n diode with a 285μm-thick lightly doped i-layer sandwiched between a 1.7 μm-thick p contact and a 5 μm-thick n contact. (Right) Power conversion efficiency of p-i-n diode and pn diode. The pn diode had a 300 μm-thick n layer and 1.7 μm-thick p contact The data clearly shows that a p-i-n diode is 2-4 times more efficient than the pn diode. The electron beam was injected through the top p-contact in both cases.

electrons at 30 kV are also shown. It is clear that the *p-i-n* diodes are 2-4 times more efficient than the *pn* junction suggesting that careful attention to matching various length scales involved in the physics could help increase the power conversion efficiency.

CONCLUSIONS

This paper shows that by careful attention to matching length scales involved in the physics of absorbing high-energy electrons in semiconductors and the diffusion lengths of electrons and holes, it is possible to increase the power conversion efficiency.

REFERENCES

1. Yang, J. & Caillat, T. "Thermoelectric materials for space and automotive power generation," *MRS Bull.* **31,** 224–229 (2006).
2. Prelas, M.A., et al., *A review of nuclear batteries.* Progress in Nuclear Energy, 2014. **75**(0): p. 117-148.
3. Shripad T. Revankar, T.A., *Adavances in Betavoltaic Power Sources.* Energy Power Sources, 2014. **1**(6): p. 8
4. Rappaport, P., *The Electron-Voltaic Effect in p-n Junctions Induced by Beta-Particle Bombardment.* Physical Review, 1954. **93**(1): p. 246-247
5. W. Ehrenberg, C.S.L., R. West, *The electron voltaic effect.* Proc. Phys. Soc, 1951. **64**(424).
6. Blanchard J. Henederson, L.A.A., *A nuclear microbattery for MEMS devices.* US Dept of Energy, 2002. **DE-FG07-99ID13781**: p. 1-10
7. Gao, H., et al., *Demonstration, radiation tolerance and design on a betavoltaic micropower.* Energy, 2013. **51**(0): p. 116-122
8. Tang, X., et al., *Optimization design and analysis of Si-63Ni betavoltaic battery.* Science China Technological Sciences, 2012. **55**(4): p. 990-996.
9. Sun, W., et al., *A Three-Dimensional Porous Silicon p–n Diode for Betavoltaics and Photovoltaics.* Advanced Materials, 2005. **17**(10): p. 1230-1233.
10. Chandrashekhar, M.V.S., et al., *Demonstration of a 4H SiC betavoltaic cell.* Applied Physics Letters, 2006. **88**(3): p. 033506.
11. T. Adams, S.T.R., P. Cabauy, L.C. Olsen, *Status of betavoltaic power sources for nano and micro power applications.* Proc. 45th Power Sources Conference 2012.
12. L.C. Olsen, P. Cabauy, B.J. Elkind, "Betavoltaic power sources," *Physics Today* **65**, 35-38 (2012).
13. MVS Chandrashekhar, *Demonstration of a 4H SiC Betavoltaic Cell*, PhD Thesis, Cornell University (2007).
14. C.A. Klein, "Bandgap dependence and related features of radiation ionization energies in semiconductors," *J. Appl. Phys.* **39**, 2029 (1968).
15. P.J. Potts, *Handbook of silicate rock analysis*, p. 336 (1987)