



LAZARUS RADIOISOTOPE GENERATOR

Executive summary

Study

Principal Investigator: Vittorio G. Palmieri (Progetti e Campioni Srls)

Activity summary:

Radioisotope generators provide electrical power for spacecrafts by converting the energy released by the decay of radioisotope fuel into electricity. Non-thermal converters (voltaic devices) make use of the photoelectric effect much in the same way a solar cell does. They are much easier to miniaturize for future chip-sized deep space probes, however performance quickly degrades due to radiation damage. The Lazarus effect has been shown to greatly reduce radiation damage in semiconductor detectors operated at cryogenic temperatures and passive radiative cooling could be easily provided in space. We have investigated the performances of state-of-the-art silicon radiation detectors operated at cryogenic temperatures as alpha and beta voltaic devices (power generation). The initial efficiency as well as the radiation hardness increase significantly when compared to room temperature operation and can exceed that of diamond devices. Radiation damage at room temperature prior to launch does not seem to prevent successful operation in space at cryogenic temperatures. However, suitable strategies to further extend the observed good performances over longer periods of time are still required. The use of the same techniques of defect engineering successfully applied in silicon radiation detectors could be envisaged. This as well as modifying the semiconductor junction topology to maximize electric fields. Moreover, using silicon as semiconductor could allow integrating control electronics in a monolithic approach.

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Introduction

Radioisotope generators provide electrical power for spacecrafts by converting the energy released by the decay of radioisotope fuel into electricity. The most common type is represented by Radioisotope Thermoelectric Generators (RTGs), using ^{238}Pu fuel and thermoelectrics to convert heat into electricity. Since they have no moving parts that can fail or wear out, RTGs are extremely reliable; however, the typical energy conversion efficiency is just about 5% [NASA (2013)]. Moreover, they are difficult to miniaturize because of the need for a hot mass.

Non-thermal converters (Voltaic devices) make use of the photoelectric effect much in the same way a solar cell does. However, instead of having incoming photons creating individual electron-hole pairs in the depleted region of a semiconductor junction, high-energy particles (typically a few keV for beta or a few MeV for alpha particles) produce each hundreds of thousands or millions of pairs at the same time. Theoretical efficiency can be several times that of thermal converters and they are easy to miniaturize in chip format, however they are rarely used because performance quickly degrades due to radiation damage [Spencer (2019)].

The Lazarus effect has been shown to greatly reduce radiation damage effects in semiconductor detectors when operated at cryogenic temperatures. Silicon devices, cooled at liquid nitrogen temperature, outperformed diamond and other high band gap materials by orders of magnitude in terms of maximum radiation dose in High Energy Physics (HEP) experiments [New Scientist (1998)].

An Alpha or Beta Voltaic silicon radioisotope generator could operate in space at the required low temperature just radiating energy towards the deep space, not requiring any active cooling. Moreover, using silicon as semiconductor for the generator allows integrating control electronics in a monolithic approach [Snoeys (2013)]. This could be particularly suited for future chip-sized deep space probes. Because of short penetration range, Alpha Voltaic silicon devices could also make use of thin substrates (30 μm), which could allow folding a large surface within a small volume at launch.

While for any Voltaic device the radioisotope layer must be directly exposed to the semiconductor junction to maximize energy input, the junction substrate does not need to be directly exposed to deep space for the radiative cooling to take place. Any interposed material having high thermal conductivity could be used to transfer heat to a suitable surface facing deep space, which should still have high emissivity. Silicon itself has high thermal conductivity (same as copper) at 90 K and carbon composites, having excellent mechanical properties, feature even higher values. Moreover, the use of selective coatings could help in regulating the temperature device at the desired level even in presence of star light [Chen (2016)].

Agreements with both the Department of Physics of the University of Naples "Federico II" (DIPFIS) and the Institute of Applied Sciences and Intelligent Systems of the National Research Council of Italy have been signed to perform the experiments with radioactive sources and to design and manufacture optimized silicon devices. SINTEF of Norway has been chosen as supplier of commercial pad silicon radiation detectors.

A full-time employee has been hired by Progetti e Campioni to work exclusively at this study.

Conclusions

This study shows that silicon pad diode radiation detectors can be successfully operated as both Alpha and Beta Voltaic devices with high energy radioisotopes when operated at cryogenic temperatures.

The 11.4% efficiency value measured at 80 K with a SINTEF p-on-n silicon pad radiation detector operated in PV mode under alpha particle illumination is unprecedented for any Alpha Voltaic device, independent of the semiconductor of choice.

To our knowledge the best efficiency achieved so far and documented in the scientific literature is still almost three times lower [Bormashov (2015)]:

	Unit	Liu (2018)	This Work	Bormashov (2015)
Material	-	Diamond	Si p-on-n #1 (80K)	Diamond
Isotope	-	²⁴¹ Am	²⁴¹ Am	²³⁸ Pu
Activity	μCi/cm ²	8.9	144	2'100
V _{oc}	V	1.13	0.85	1.85
I _{sc}	nA/cm ²	3	140	2'470
	nA	0.05	35	37'000
P _{max}	nW/cm ²	2.0	100	24'000
	nW	0.03	25	36'000
η _{total}	%	0.8	11.4	3.6
FF	-	0.52	0.85	0.52

Moreover, the 3.6% value for the diamond Schottky device of Bormashov (2015) was measured with a much stronger alpha source (15 times the activity of the one we used). Since V_{oc} increases with I_{sc}, which in turn is related to the incoming particle flux, the stronger the source the higher is the efficiency. Therefore, we expect an even higher efficiency for our device, if the source activity would be increased. In fact, Liu 2018 reports a 0.8% efficiency for a similar diamond Schottky diode, but with a source 16 times weaker than ours.

In terms of efficiency reduction because of radiation damage, still at 80 K, the p-on-n diodes shows a residual efficiency after an irradiation fluence of 5E+11 part/cm² of about 0.5%. Also, this value is unprecedented for silicon Voltaic devices, which are not usually measured with alpha particles due to the very rapid degradation of their efficiency at room temperature (also observed in our study). Comparison of this value with those reported for diamond devices is difficult because of the difference in alpha particle source activity, but a residual efficiency of about 1.8% after 2E+12 part/cm² has been reported with a source 15 times stronger than ours [Bormashov (2015)].

For what concerns the SINTEF p-on-n silicon pad radiation detector operated in PV mode under beta particle illumination, even if we cannot compare its efficiency because the Monte Carlo simulation has not yet been performed, we can consider that a fully stabilized P_{max} of 6 nW corresponds to about 24 nW cm⁻² when considering the diode surface of 5x5 mm². This, for the 4 mCi cm⁻² 90Sr source we use, leads to a power-activity ratio of 6 nW mCi⁻¹. This value is one order of magnitude better than the typical figure for state-of-the-art silicon beta voltaic devices using ⁶³Ni radioisotope [Krasnov (2019)].

It is worth mentioning that, while commercial Beta Voltaic devices using semiconductor diodes at room temperature exist, they only make use of short living or very expensive radioisotopes like ⁶³Ni

and ^3H . This because the low energy electrons emitted prevent radiation damage in the semiconductor lattice (for example silicon has a radiation damage energy threshold of about 200 keV). At least for applications in space where cooling is not an issue, a Beta Voltaic Lazarus Radioisotope Generator could therefore allow using cheaper ^{90}Sr for the first time. In fact, ^{90}Sr has a high product yield in the fission of both ^{235}U and ^{239}Pu and is thus available in large quantities at a relatively low price if extracted from spent nuclear fuel. ^{90}Sr has been routinely used by the Soviets for RTGs [Efremov (1979)].

Finally, the radio current measurements under reverse bias show that as the fluence increases, there is a strong dependence of the collected charge (which in turn produces the measured current) on the reverse bias voltage: with just a few Volts the current increases by almost 50%. This is in line with what had been observed previously in the context of HEP experiments related to the Lazarus effect [Palmieri 1998 bis]. Suitable strategies to increase the devices' operating voltage could be therefore considered to further improve the previous results.

During this study, we have designed and built several additions to instruments and experimental apparatus that allow us to investigate the radiation damage of semiconductor devices at cryogenic temperatures. Our group has further expanded knowledge in these measurement techniques. In addition, we have performed simulations with tools, which have been adapted to the specific requirements of this study.

While our investigations appear to be in line with previous studies at room temperature, the investigation at low temperatures substantially expanded and improved the level of results and their range of application, opening the way to novel technological developments.

Recommendations

Based on the detailed results and successful conclusions of this study the following recommendations are suggested for a possible early technology development.

Simpler diode structures without guard rings for reverse bias operation should be manufactured and measured both with n-type and p-type silicon. These could take advantage of the manufacturing technology developed for solar cells and should feature low thickness (50 μm or less) substrates in the case of Alpha Voltaic devices [Schuster (2017)].

In the case of ^{90}Sr Beta Voltaic devices, individual diode chips could be stacked with interleaved thin radioisotope layers in between to further increase the efficiency [Dixon (2016)]. Dedicated experiments will have to be performed to establish the optimal thickness of each individual diode, based on the charge collection length at the temperature of choice.

Defect engineering has proven successful in decreasing radiation damage in silicon radiation detectors irradiated with high energy charged particles and should be investigated to further improve the radiation hardness of both Alpha and Beta Voltaic Lazarus Radioisotope Generators. In particular, the introduction of a controlled amount of oxygen within the silicon bulk has been successfully tested [Li (2001)] and could be combined with the manufacturing process implemented by ISASI in the fabrication of their devices.

High intensity ^{90}Sr radioactive sources should be employed to confirm the long-term efficiency stabilization observed in this study, in a reasonable time frame. These strong sources will have to be operated remotely in a dedicated facility and a suitable cryostat will have to be designed and built, if not already available at the facility of choice.

Additionally, our study supports the development and use of a variety of technologies relying on the methods and principles here explored.

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