

On the Possibility to Use Energy Harvesting on Beta Radiation in Nuclear Environments

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Abstract—This paper presents experimental results showing that the energy contained in beta radiation can be harvested by using diodes. A single BPW34 photodiode generates around 12 pA dc, so enough to power integrated analog blocks.

Index Terms—energy harvesting, ionizing radiation

I. INTRODUCTION

Most nuclear technologies require remote monitoring with energy-independent systems for the safety of humans and environment. Remote monitoring is already proposed by the industry [1], [2]. The autonomy in energy can be achieved by means of energy harvesting, as demonstrated in [3] for dry-cask storage of nuclear waste. However, the energy sources that are usually harvested—light, heat, mechanical vibrations, radio-frequency waves—are not always available or reliable in nuclear applications. Therefore, no universal energy harvesting solution can be built to operate in nuclear environments.

Yet, the sole energy source that is permanently present in the close environment comes from the application itself: ionizing radiation emitted by the nuclear material [4]. For this reason, a solution to perform Energy Harvesting on ionizing Radiation (EnHaRa) is proposed.

This paper presents the feasibility analysis carried out to use energy harvesting on beta radiation, a specific type of ionizing radiation. The physical phenomena on which the β -rays harvesting relies are described in section II. The complete methodology used to perform the feasibility analysis is presented in section III, whereas the main results are presented in section IV and discussed in section V. The contributions are summarized and the perspectives are provided in section VI.

II. MAIN PRINCIPLES OF BETA RAYS HARVESTING

Beta radiation is light charged particles, i.e., electrons (β^-) or positrons (β^+). Positrons are antimatter particles that annihilate with matter electrons, generating two 511 keV photons after having slowed down in matter. Electrons are particles that interact with the matter they are traversing, mainly by electromagnetic processes: excitation and ionization most likely at low energy. At high energy (a few tens of megaelectronvolts or higher), electrons can also interact with the Coulomb field of the atomic nuclei, leading to the emission

of photons which are often in the X-ray range. This process is called braking radiation or bremsstrahlung [5].

In the case of β -rays of a few megaelectronvolts, the dominant energy transfer mechanisms to be considered are thus ionization and excitation. Ionization leads to the creation of electron-positive ion pairs, whereas excitation followed by de-excitation of the atoms is responsible for the emission of photons which can be absorbed in the material by photoelectric effect, leading to the creation of electron-hole pairs. The total energy transferred from the incident radiation to the material can be estimated by the Bethe-Bloch equation [5], [6] giving the deposited energy per unit path inside the material absorber:

$$-\frac{dE}{dx} = \frac{2\pi\rho ZNz^2e^4}{Am_e v^2} \left\{ \ln \left[\frac{2m_e v^2 W_m}{I^2(1-\beta^2)} \right] - 2\beta^2 - \delta - U \right\}, \quad (1)$$

where the constant N is the Avogadro number, e and m_e are the charge and the rest mass of the electron. This formula shows the dependence on the radiation properties (charge ze and velocity $v = \beta c$) as well as on the nature of the material (atomic number Z , atomic weight A , density ρ , mean excitation energy of the atoms of the material I) and on the maximum transferable energy from the incident radiation to atomic electrons W_m . Correction terms, δ for the density-effect and U for the shell correction, are also included in (1). The energy transfer can also be estimated by using databases such as ESTAR [7]. In any case, because of these electromagnetic processes, β -rays cease a part of their energy to the material they are traversing.

In a semiconductor device, excitation and ionization lead to the creation of electron-hole pairs along the paths of the β -rays passing through the device, as expressed by the generation rates of excess carriers in the continuity equations [6]:

$$\frac{\partial n}{\partial t} = \frac{1}{e} \nabla \cdot \vec{J}_e + G_e - U_e \quad (2)$$

and

$$\frac{\partial p}{\partial t} = -\frac{1}{e} \nabla \cdot \vec{J}_h + G_h - U_h, \quad (3)$$

where \vec{J} is the current density (e for electrons and h for holes), G is the generation rate caused by external influences, U is the recombination rate, n and p are the concentration

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in electrons and holes, respectively. This phenomenon results in accumulation effects, such as Total Ionizing Dose (TID) and displacement damage, or transient events, e.g., Single-Event Transients (SETs) [8], [9]. Even though such effects are generally damaging for semiconductors (accelerated aging), they are used by radiation sensors for detection [6], [10].

To go further in the idea of turning a damaging effect into a positive feature, collecting the electron-hole pairs generated by the passage of β -rays through a semiconductor device to harvest energy is the updated aged concept [11], [12] proposed in this paper. The novelty is that the internal electric field of a pn or a pin junction will be used to separate holes and electrons before recombination. This generates a transient current that can be harvested to power an integrated circuit, such as a node of a wireless sensor network (WSN), which can be used to monitor remotely nuclear environments.

III. FEASIBILITY ANALYSIS: METHODOLOGY

The proof that harvesting energy from beta radiation is possible has been carried out by experiments. To do so, the following methodology has been introduced:

- the creation of an experimental apparatus allowing to measure currents of the order of magnitude of those generated by exposure of diodes to β -rays;
- the choice of diodes tested as possible harvesters;
- the assessment on the risk of interference and the implementation of countermeasures;
- the elaboration of a measurement process that ensures maximum repeatability;
- the estimation of the accuracy on measurements.

A. Description of the experimental apparatus

When diodes are exposed to beta radiation, the generation of a current is expected. As the main objective of this work is to allow energy harvesting from low currents, it is necessary to avoid wasting energy as well as additional processes that would be required prior to the β -rays harvesting process, such as charging an external capacitor. Therefore, no external bias voltage is applied on the diodes in the experiments.

Consequently, only the internal electric field can separate holes from electrons before recombination. In this case, the intensity of the generated current is low because the electric charges are not accelerated by an external electric field [13]. Therefore, an instrument that can measure current intensities with sufficient sensitivity and speed is necessary. Such an instrument is called an electrometer, and the B2985A from Keysight has been chosen as it can measure current as low as 0.01 fA and electric charge of 1 fC at maximum 20 000 sample/s [14].

The diode under test (DUT) is placed at a specific distance and aligned with the radiation source beam thanks to a specific method, which is currently in a patenting process [15]. Then the DUT and the radiation source are placed in a Faraday cage and connected to the electrometer by means of a triaxial cable (Fig. 1).

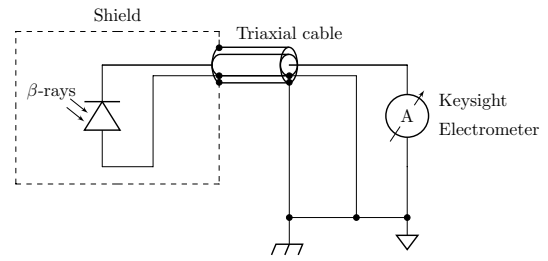


Fig. 1. Schematic of the experimental apparatus used to measure the currents generated by diodes irradiated by β -rays.

B. Choice of diodes tested as possible harvesters

Two types of commercial diodes have been tested as possible harvesters: BPW34 pin photodiodes (PD), and red LEDs.

BPW34 pin photodiodes have been chosen because they have already been successfully used for γ -rays detection without bias voltage [16], [17], as pin junctions have a wider depletion region than pn junctions to collect the generated electric charges.

LEDs are interesting candidates because they can operate as photodiodes when enlightened by an electromagnetic wave, hence the possibility that they can operate as current generator when irradiated with beta particles. They are also cheaper than actual photodiodes.

C. Risk assessment on interference

The measurements involved in these experiments require additional cautions to avoid interference, which can originate from:

- 1) the photoelectric effect caused by visible light on the diode under test, as the device is photosensitive;
- 2) the influence of the electrical grid, as the expected current intensities are in the range of femtoampere to picoampere.

The former phenomenon can be prevented by placing the DUT into the dark. The latter is mitigated by shielding, i.e., the aforementioned Faraday cage.

In addition, any interference that would remain on the measurements can be filtered by post-processing. Regarding the influence of the electrical grid (50 Hz in Europe), the proposed method consists in calculating the Fast Fourier Transform (FFT) of the raw signal, canceling the 50 Hz component, and then computing the inverse FFT (IFFT), as depicted in Fig. 2. Data processing is based on the NumPy library [18].

D. Description of the measurement process

The established measurement process has to take the experimental constraints into account. One of the major constraints

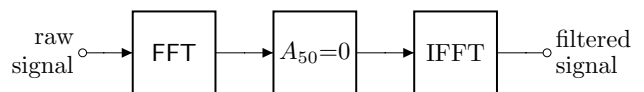


Fig. 2. Data processing used to filter the 50 Hz interferer induced by the electrical grid into the raw signal.

comes from the impossibility to switch on and off the radiation source. This requires to place or remove the source on or from the setup anytime the radiation conditions are modified. Another constraint is the possible aging of the diodes due to TID and displacement damage. As the effects of the aging on the harvesting capabilities are not considered in this study, a new diode sample is used after each measurements campaign.

The measurement process used in these experiments is the following:

- 1) perform the calibration of the electrometer, including the instrument warm-up;
- 2) run multiple or continuous acquisitions to measure the diode's dark current in the absence of radiation;
- 3) place the beta radiation source;
- 4) run several or continuous acquisitions to measure the possible effects of β -rays on the diode's dark current;
- 5) remove the radiation source from the test bench.

Steps 2 to 5 can be repeated any times than necessary to obtain the desired statistical accuracy.

E. Estimation of the accuracy on measurements

Measurements are affected by errors due to the precision of the electrometer, which can be estimated. The total error on a measurement performed by the electrometer can be expressed as

$$\varepsilon_{\text{meas}} = \varepsilon_{\text{meas}|\text{range}} + \varepsilon_{\text{meas}|\text{apert.}}, \quad (4)$$

where $\varepsilon_{\text{meas}|\text{range}}$ is the error on the measurement due to the chosen range and $\varepsilon_{\text{meas}|\text{apert.}}$ is the error due to the selected aperture. The range is defined as the maximum of the interval of values that can be measured, whereas the aperture is the observation time necessary for the instrument to get a data point. $\varepsilon_{\text{meas}|\text{range}}$ consists of a systematic offset, $\varepsilon_{\text{offset}|\text{range}}$, and an error on reading that is proportional (coefficient $\alpha_{\text{read}|\text{range}}$) to the read value x_{read} , hence

$$\varepsilon_{\text{meas}|\text{range}} = \varepsilon_{\text{offset}|\text{range}} + \alpha_{\text{read}|\text{range}} x_{\text{read}}. \quad (5)$$

$\varepsilon_{\text{meas}|\text{apert.}}$ is an error proportional (coefficient $\alpha_{\text{range}|\text{apert.}}$) to the chosen range x_{range} that can be expressed as

$$\varepsilon_{\text{meas}|\text{apert.}} = \alpha_{\text{range}|\text{apert.}} x_{\text{range}}. \quad (6)$$

The total error can therefore be computed by combining (4), (5) and (6):

$$\varepsilon_{\text{meas}} = \varepsilon_{\text{offset}|\text{range}} + \alpha_{\text{read}|\text{range}} x_{\text{read}} + \alpha_{\text{range}|\text{apert.}} x_{\text{range}}. \quad (7)$$

The systematic error $\varepsilon_{\text{offset}|\text{range}}$ as well as the proportional coefficients $\alpha_{\text{read}|\text{range}}$ and $\alpha_{\text{range}|\text{apert.}}$ are tabulated in [14].

IV. EXPERIMENTAL RESULTS

Three parameters may have an effect on the measurements: (1) the temperature, (2) the distance between DUTs and radiation source, and (3) the beta radiation source. The first results of this study are performed at room temperature (lab). As beta particles interact throughout their path in the matter and so lose energy, the tested diodes have been placed as

close as possible from the radiation source output, at a few millimeters. This way, only a negligible amount of the beta kinetic energy is lost in the air before the DUT is hit. Finally, beta rays are produced by ^{90}Sr , hence ranging from 0 MeV to 2.283 MeV. The source activity is around 150 MBq, but the counting rate at the output of the collimator is around 1500 counts per second on a 28 mm² circular surface.

When comparing the real-time measurements of diodes' dark currents, two trends can be observed. Exposure to β -rays appears to have a negligible effect on red LEDs, either on dc or ac magnitudes, i.e., a difference of a few tens of femtoamperes (Table I). In contrast, the increase in dc current is on average 12 pA in the case of BPW34 *pin* photodiode, which is significant. An increase in the peak-to-peak amplitude of roughly 800 fA is also observed, which is due to bursts of currents of approximately 1 pA peak-to-peak amplitude and a few tens or hundreds of milliseconds of duration (Fig. 3). These bursts are not observed when the radiation source is removed. The results shown in Table I have been obtained by averaging five runs of 1 s on one sample of each type of diode, for each condition (normal operation or beta radiation exposure).

Errors on measurements due to the electrometer have been computed with (7) and are presented in Table II. As no effect has been noticed during beta irradiation, and as the dark current is very low in the case of red LEDs, the relative error is found to be very high. This is not meaningful because the currents measured in the experiments are close to the sensitivity of the electrometer. In the case of BPW34 photodiodes, the relative error is below 2%, which is acceptable. The curve of the dark current of PD exposed to β -rays (Fig. 3) is presented with the upper and lower limits due to the error interval in Fig. 4 (ac only).

V. DISCUSSION

A clear increase in the BPW34 *pin* photodiode's dark current is observed when exposed to β -rays, even though no bias voltage is applied. Around 12 pA is obtained with a single photodiode, but could be raised if several PDs are connected

TABLE I
MEASUREMENTS OF DIODES' DARK CURRENTS: INCREASE IN CURRENT INDUCED BY EXPOSURE TO BETA RADIATION

Electrical Characteristics	Diode Under Test	
	Red LED	BPW34 PD
$I_{\text{dc},\beta}$ (pA)	0.085	12.084
$I_{\text{ac},\beta}$ (pA)	0.036	0.802

TABLE II
ESTIMATION OF THE TOTAL ERRORS DUE TO THE ELECTROMETER ON THE DIODE'S DARK CURRENT MEASUREMENT

Error on Dark Current	Diode Under Test	
	Red LED	BPW34 PD
$\varepsilon_{\text{no rad.}}$ (%)	N/A	1.3
ε_{β} (%)	17.8	1.9

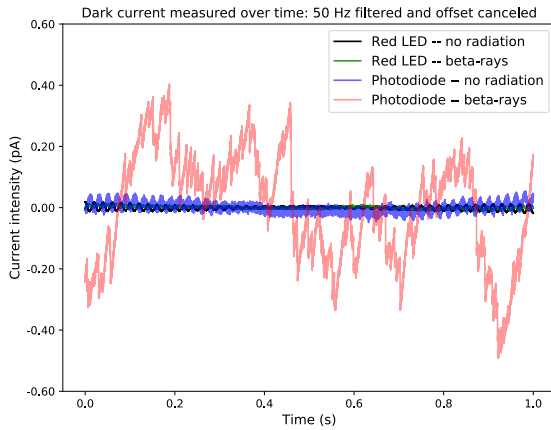


Fig. 3. Evolution of diodes' dark current over time in normal or beta radiation operation. All signals' 50 Hz components have been filtered (FFT method); all dc offsets canceled for easier comparison of ac behavior.

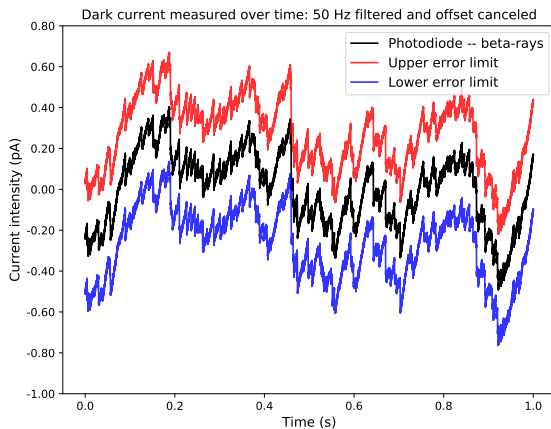


Fig. 4. Error interval for the ac dark current of the BPW34 photodiode exposed to beta radiation shown in Fig. 3.

in parallel and irradiated. This is enough to power integrated circuits designed to operate with picowatts [19], [20]. The results obtained in this preliminary study are encouraging for the use of BPW34 photodiodes to harvest energy from beta radiation and the error estimated on the measurements proves a high confidence level in our experimental approach.

Red LEDs, on the other hand, do not show any significant effect on the current recorded during irradiation by β -rays. This tends to indicate that this type of diode is not a good candidate for harvesting beta radiation, taking into account that their sensitive area is quite smaller compared to photodiodes.

VI. CONCLUSION

The experimental results presented in this paper demonstrated that harvesting energy from beta radiation is possible by using BPW34 *pin* photodiodes. Currents of the order of tens of picoamperes were observed as harvested dc current. Such

intensities are sufficient to power integrated analog blocks designed in current transistor technologies. For example, parts of the circuit of a node of a wireless sensor network used to monitor a nuclear environment.

Perspectives for further development of this concept include the study of different types of photodiodes as well as the study of the harvesting capabilities versus the aging induced by radiation damage.

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