Application of Transimpedance Amplifiers in PIN Photodiode Dosimetry

L. Spahić, S. Ilić, M. Anđelković, A. J. Palma, G. S. Ristić

Abstract - This paper analyzes the properties of commercial silicon PIN photodiodes BPW34 as direct γ-radiation sensors. Sample is formed by four photodiodes connected in parallel and polarized reversely. Current to voltage conversion and amplification is performed using a prototype circuit with a low noise transimpedance (TIA) operational amplifier with input current range of 1 nA – 3.3 µA. The voltage characteristic from the amplifier circuit and induced current characteristic is measured by source measuring unit (SMU) Keithley 2636A for the same irradiation dose rates. Sample is irradiated for 140 s using a ^{60}Co γ-ray source. Obtained results have shown very good linearity between amplification circuit output voltage and induced photocurrent measured with SMU Keithley 2636A for dose rates ranging from 2.5 Gy/h to 11 Gy/h. Using voltage to current conversion formula, amplification of circuit input current is calculated and compared to induced photocurrent measured with SMU. These results show amplification circuit current error offset. Also, non-linearity results are shown for photocurrent under 1 nA. Due to offset error, but good linearity response, an output voltage vs. radiation dose calibration curve is given.

I. Introduction

In dosimetry applications, there is a requirement for a high precision measurements of very low photocurrents, generated by ionizing radiation in the range of a few pA to a few µA, proportional to ionizing radiation exposure. It is challenging to measure such low level current, so a certain techniques and special design has to be applied to achieve high precision and linearity. Such measurements are mostly performed by converting the generated photocurrent into proportionally adequate voltage.

The main element for current to voltage conversion is transimpedance (TIA) operational amplifier because of its high input impedance, high gain accuracy, good linearity and low noise. For the purpose of experimental research, a prototype of a current to voltage conversion and amplification electronic circuit is developed. In theory the electronic circuit should be able to convert input current in range of 1 nA to 3.3 µA. Output voltage, proportional to input current, in range of mV and V can be used for further processing and acquisition, calculation of absorbed radiation dose etc. Also, as gamma radiation detector, a commercial silicon PIN photodiodes BPW34 are used.

The aim of this research is to test precision and linearity between radiation-induced photocurrent and output voltage. Also, the results from the proposed solution have been compared with those obtained with a source measuring unit (SMU) Keithley 2636A.

L. Spahić, S. Ilić, and G. S. Ristić are with the Applied Physics Laboratory, University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia.
E-mail: luka.spahic@elfak.rs
M. Anđelković is with the IHP – Leibniz-Institut für innovative Mikroelektronik, Frankfurt Oder, Germany.
E-mail: andjelkovic@ihp-microelectronics.com
A. J. Palma is with the University of Granada, Granada, Spain.
E-mail: ajpalma@ugr.es

II. The Concept of Photocurrent Amplification Circuit Based on TIA

As presented in the Fig. 1, a block diagram of the designed electronic circuit consists of input preamplifier, instrumentation amplifier, voltage regulator and block for dual power supplying.

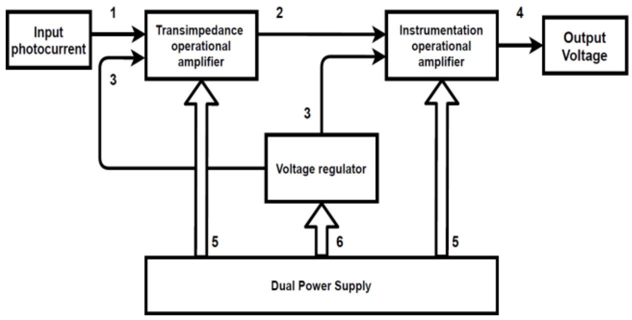

Fig. 1. Transimpedance amplifier circuit block diagram design.

A signal from a current source is connected to the input (1). That signal is the current that needs to be converted to voltage and proportionally amplified. Current is supplied to the inverting input of the TIA operational amplifier.

A reference voltage (3) from the voltage regulator is applied to the non-inverting input of both TIA and instrumentational operational amplifier. Transimpedance operational amplifier output (2) is further connected to the inverting input of the instrumentation amplifier. The reference voltage at the non-inverting input of the operational amplifiers is a good solution from the aspect of gain stability, instead of using the zero reference point (common ground). The applied voltage from the voltage regulator to the non-inverting input of the transimpedance amplifier is subtracted in the instrumentation amplifier, which ensures the preservation of the useful signal. The power supply of the entire electronic circuit is external and dual. This type of power supply was chosen under recommendation by the amplifier manufacturers used in this paper. The voltage supplied to the non-inverting inputs of the amplifier (3) is significantly lower than the supply voltage, so it is reduced by voltage regulator, at the input of which (6) a positive voltage of dual supply is applied. A stable voltage of smaller amplitude than the positive voltage of dual supply is obtained at its output (3).

The request for choice of the transimpedance amplifier component are small polarization input current, small voltage offset and large open loop gain [1, 2]. Based on these features, a Burr-Brown operational amplifier from Texas Instruments OPA129U in an SMD enclosure was selected. The output voltage, for input current, is calculated according to the following equation:

$$V_{OUT} = 4.8 \times 10^{6} I_{INPUT} + 0.015 \ \ \text{[V]} \tag{1}$$

The Eq. 1 will be used later for calculation of converted current and comparison to the measured photocurrent. The transimpedance amplifier circuit PCB design is shown in Fig. 2.

Fig. 2. Amplification circuit PCB design. [3]

III. Experiment setup

Four reverse-biased commercial PIN photodiodes BPW34 are connected in parallel (to obtain higher irradiation area) and irradiated for 140 s using a ^{60}Co γ-source at the Vinča Institute of Nuclear Sciences, Belgrade, Serbia. The irradiation dose rates were 11, 7.5, 5, 2.5, and 1 Gy/h, at reverse-bias voltages 15 V, 30 V, and 45 V. The experiment setup block diagram is presented in Fig. 3.

The photodiode common anode is connected to an electro-mechanical relay controlled by microcontroller (MCU). The relay pins are over two BNC connectors connected to an amplification circuit (pin 0) and to two-channel SMU (pin 1). Timer programed MCU controls relay that switches from position 0, after 70 s, to position 1. With such configuration we measure TIA amplification output voltage and the direct photocurrent from PIN diodes for the same dose rate. The coaxial cable length from PIN diodes to SMU and to amplification circuit is almost the same, to maintain the same measurements condition.

To sustain good noise immunity, the photodiode was soldered on a small printed circuit board and wrapped with light-proof tape.

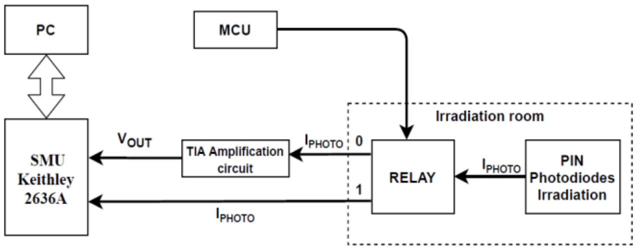

Fig. 3. Experiment setup block diagram.

SMU is connected to a PC and controlled by compatible program written in C#. Timer inside MCU is started at the same time as SMU begins its measurement. After 20 s, the gamma irradiation of photodiodes begins. It is important to see the voltage response when irradiation begins.

Next 70 s, relay is in position 0, and SMU is measures amplification circuit output voltage. After 70 s, MCU toggles relay to position 1, and SMU measures a direct photocurrent from irradiated PIN photodiodes.

IV. Experiment results and discussion

The first step of the experiment was to set γ-irradiation dose of 11 Gy/h (3.1 mGy/s) for 70 s each, for 15 V applied reverse polarization. Output voltage and current response are presented in Fig. 4 and 5. In parallel to voltage response photocurrent characteristic is given. It can be seen that the voltage and current time responses coincide. The curves straightening during irradiation is similar. This first result confirms voltage response linearity.

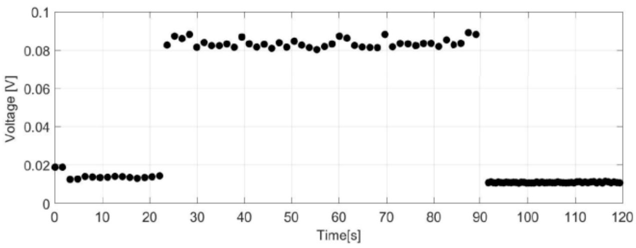

Fig. 4. Output voltage profile at irradiation dose rate of 3.1 mGy/s for 15 V reverse polarization.

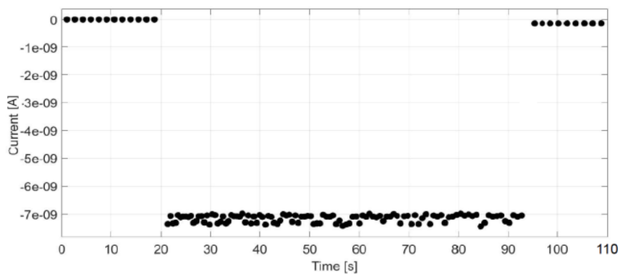

Fig. 5. Induced photocurrent profile at irradiation dose rate of 3.1 mGy/s for 15 V reverse polarization.

Next, for the same γ-irradiation dose rate of 11 Gy/h the reverse photodiode polarization is changed to 30 V. It is expected that output voltage or induced photocurrent changes should not occur.

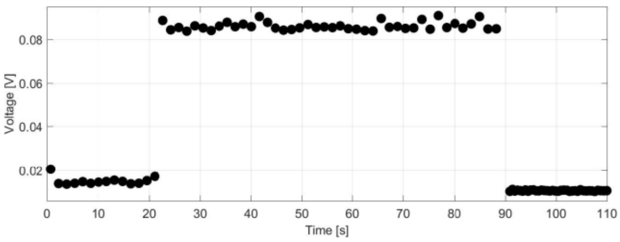

Fig. 6. Output voltage profile at irradiation dose rate of 3.1 mGy/s for 30 V reverse polarization.

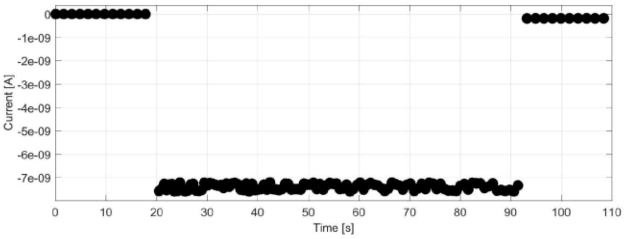

Fig. 7. Induced photocurrent profile at irradiation dose rate of 3.1 mGy/s for 30 V reverse polarization.

According to results in Fig. 6 and 7, it is shown that a reverse voltage increase does not significantly affect the output voltage neither the photocurrent. This is concluded by comparison of Fig. 4 and 6, and Fig. 5 and 7. This is due to weak dependence of depletion area width on reverse voltage, mostly defined by width of intrinsic silicon region in PIN structure. By that evidence, further analysis are done for 15 V reverse voltage.

Graph in Fig. 8 and 9 shows set irradiation dose of 7.5 Gy/h (2.1 mGy/s) for 70 s each, for 15 V applied reverse photodiode polarization.

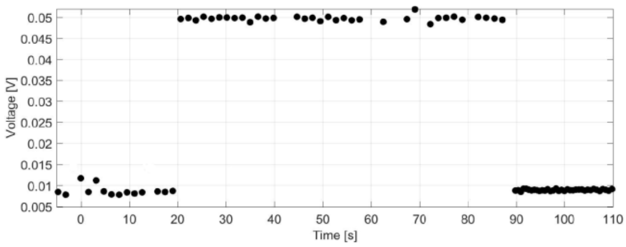

Fig. 8. Output voltage profile at irradiation dose rate of 2.1 mGy/s for 15 V reverse polarization.

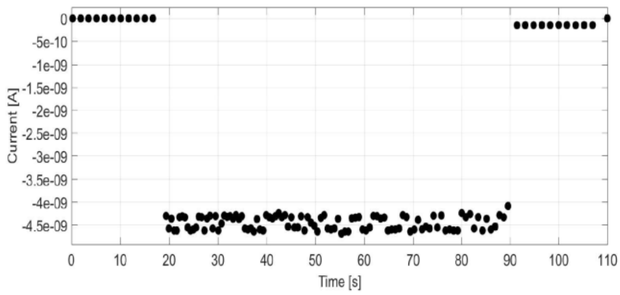

Fig. 9. Induced photocurrent profile at irradiation dose rate of 2.1 mGy/s for 15 V reverse polarization.

Figs. 8 and 9 presents results for output voltage and induced photocurrent. Solid output voltage linearity response due the lower γ-irradiation is presented. A result shows that, when irradiation dose is changed, the voltage output changes, but the curve stay flat as shown on previous results, which proofs good linearity response. Further irradiation is done for doses 5 Gy/h and 2.5 Gy/h for 70 s each, for 15 V applied inverse photodiode polarization. The results for these radiation doses also has good linearity response.

Output voltage offset, as presented on previous graphs is around 15 mV at zero input current. Considering that amplification circuit is designed for minimum 1 nA input current, instability and non-linearity happens for current lower than 1 nA. This can be seen in Fig. 10, where for 1 Gy/h and 15 V applied reverse polarization input photocurrent is around 0.55 nA.

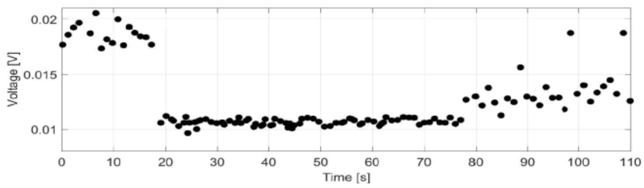

Fig. 10. Output voltage profile at irradiation dose rate of 0.28 mGy/s for 15 V reverse polarization.

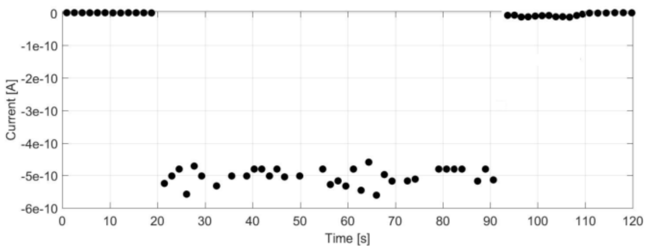

Fig. 11. Induced photocurrent profile at irradiation dose rate of 0.28 mGy/s for 15 V reverse polarization.

Fig. 10 shows output voltage for currents below 1 nA. Due to amplification circuit design, input current range is 1 nA – 3.3 μA. Any out of range input current, will result in non-linearity and amplification circuit instability. Also, it can be seen in Fig. 10, that the near end of the measurement the measured points are scattered. That situation did not happened on previous results where current was above 1 nA. The linear voltage response exists only for currents above 1 nA, with applied irradiation dose rates lager than 1 Gy/h. Changes in the voltage polarization did not affect the output voltage response.

Further, using SMU Keithley 2636A, the precision and accuracy of amplification circuit was tested. From Eq. 1 and using voltage output results, the converted input current has been calculated. Calculation example is done for voltage output values when photodiodes are irradiated at 11 Gy/h dose rate (Fig. 4). The amplification circuit input current, based on output voltage results, is calculated and shown on Fig. 12.

By comparing results from Fig. 5 (photocurrent measured by SMU) and Fig. 12 (amplification circuit input current), a current offset can be noticed. Instead of getting expected calculated current value around 7.35 nA, measured by SMU, the calculated current equals to a value of 13.5 nA measured by amplification circuit. The expected value was 7.35 nA, but actual was 13.5 nA. Difference between those two values represent the unwanted offset.

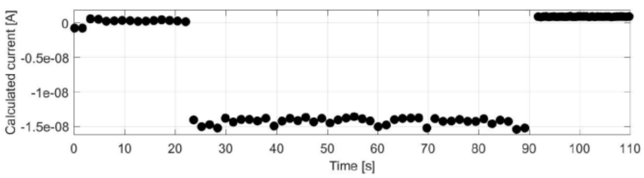

Fig. 12. Calculated current using Eq. 1 for output voltage results presented in Fig. 4.

However, linearity is achieved, but high precision and accuracy did not meet expected criteria. Also, according to results presented above, for output voltage graph where linearity was confirmed, a calibration curve for output voltage vs. applied irradiation dose rate was given.

Fig. 13 shows logarithmic scale of the relation between the dose rate and the induced photocurrent converted to voltage. Because of non-linearity the accurate dose rate measurement should be above 2 Gy/h.

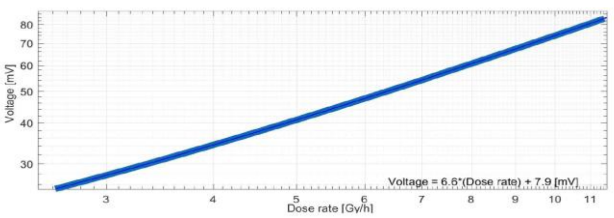

Fig. 13. Output voltage versus dose rate

III. Conclusion

General explanation of TIA amplification circuit design and PIN photodiodes as γ-radiation sensors has been shown. Obtained results show good linearity response for input current above 1 nA, and irradiation dose rate above 1 Gy/h. With measured output voltage, photocurrent and calculated current results, it has been concluded that high precision and accuracy did not meet the highest expected criteria. However, that high precision and accuracy can be achieved for higher values of input current. The value of input photocurrent has to be over 10 nA. Higher induced current could be achieved with other photodiodes having a higher output current value when irradiated or by extending current capabilities by more diodes connected in parallel.

Due to good linearity, a linear calibration curve, voltage vs. irradiation dose rate was presented. The curve can be used for determining irradiation dose in range from 2.5 – 11 Gy/h. Future work should continue on improving a accuracy of an amplification circuit and usage of other photodiodes variant with output photocurrent above 10 nA.

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