X-ray detection using MOS and PIN diodes biased in the constant reverse current or voltage modes

Marcelo L. da Conceição
LSI/PSI/EPUSP
University of São Paulo
São Paulo, Brazil
marceloete.af@gmail.com

Marcos N. Watanabe
LSI/PSI/EPUSP
University of São Paulo
São Paulo, Brazil
marcosnwatanabe@usp.br
ORCID: 0000-0003-0879-8451

Sebastião G. dos Santos Filho
LSI/PSI/EPUSP
University of São Paulo
São Paulo, Brazil
sgsantos@usp.br
ORCID: 0000-0002-0324-5703

2022 6th International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT) | 978-1-6654-7168-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/INSCIT55544.2022.9913753

Abstract*— This article discusses X-ray detection using MOS and PIN diodes biased in the modes of constant reverse current or voltage, aiming at radiological protection and as pixels for direct digital imaging radiography applications. MOS diodes operating with stationary width of the depletion region at a constant reverse current are proposed for X-ray detection using an Al/SiO_2(2.20 nm)/Si-P structure fabricated on 10 Ω.cm substrates. A miniature X-ray system (Mini X model from Amptek) was used to illuminate the diodes, at 2 cm away, inside of an aluminum chamber to protect against the X-ray radiation. As a result, the MOS diodes showed good voltage response as function of the bias voltage of the X-ray tube for flux varying from 0 to around 500 mSv/h. In this case, the MOS voltage response increased from 0 to 0.25 mV for the X-ray bias voltage varying from 0 to 40 kV at a filament current of 50 µA. X-ray detection in a constant reverse voltage mode for the MOS diode was unfeasible due to poor current response superimposed to the background electrical noise. On the other hand, unlike the MOS diode, the PIN diode showed good current response in the constant reverse voltage mode as function of the bias voltage of the X-ray tube for flux varying from 0 to around 500 mSv/h. It was noteworthy that the PIN current response increased proportionally with the bias voltage from and 0 to 40 nA at a reverse biasing of -5 V, which are similar to the results reported in the literature for PIN diodes.

Keywords*— *X-ray detection, MOS diode, PIN diode.

I. INTRODUCTION

In direct X-ray detectors the energy transported by the radiation is converted into electrical charges that is recognized electronically. PIN and MOS diodes produced by conventional semiconductor fabrication, provide cost-effective measurements for detection of all forms of ionizing radiation including extreme UV, soft X-rays, and hard X-rays [1,2]. This form of detection operates via photoionization, a process where ionizing radiation strikes an atom and releases electron-hole pairs in the semiconductor and are collected to detect the X-rays [3].

PIN and MOS cells can be used as pixels for direct digital imaging radiography, which is an emerging application that uses X-ray detectors to transfer images directly to the computers. Digital radiography market size in 2019, is $2.01 billion and is projected to reach revenue of $2.82 billion by 2025. [2, 3].

It is worth of note that the MOS (metal-oxide-semiconductor) cell is a possible candidate for direct digital detectors applications because it has several important characteristics such as [4]: I) it can be used on the same silicon substrate employed for the current integrated circuits with doping level around $1x10^{15}cm^{-3}$, II) it is a low cost technology, III) its fabricating process is very simple and IV) its IxV (current x voltage) characteristic is reproducible. In addition, a recent work has shown improved performance by using scintillator materials to convert x-rays to visible light and improve the sensitivity [2].

For X-ray detection, electrical noise in MOS and PIN diodes originates from the discrete nature of electric charge and with ordinary electronic amplification and shielding, shot noise dominates other noise sources for photocurrent exceeding about 5pA [5, 6].

The X-ray detection in the constant voltage mode is useful in many applications in which only the intensity of the radiation is of interest, rather than sensing any changes in or information about the incident energy distribution of the radiation. It is averaged out many of the fluctuations in the intervals between individual radiation interactions and the average current can be written as the product of the interaction rate (r) and the charge per interaction (Q) [7], which in turn is given by the product of the elementary charge ($q = 1.6x10^{-19}$ C) and the ratio between the average energy deposited per event (E) and the average energy required to produce a unit charge pair (E_{elp}) (e.g., electron-hole pair in semiconductors) [7].

In this work, MOS and PIN diodes were investigated for direct X-ray detection in the constant reverse voltage or current modes. In addition, a new approach using a constant reverse current mode was demonstrated to be efficient for MOS diodes to detect X-ray with different intensities.

II. EXPERIMENTAL

A. *Measurement set up for X-ray illumination of the MOS and PIN diodes*

A miniature X-ray system (Mini X model from Amptek) [8] was used to illuminate the diodes, located at 2 cm away, with flux around 500 mSv/h for X-ray tube voltage and current of 40kV and 100 µA, respectively, at a cone angle of 120°. The X-ray system includes an Ag X-ray tube (λ = 22.1 keV), a beryllium window, a brass safety plug, the power supply, the control electronics and the USB communications to the computer. The high voltage power supply ranging from 10 to 40kV produces a bias voltage between the Ag target (which is grounded) and the filament for current in the range of 5 to 100 µA.

Constant reverse voltage biasing in the range of 0 to 5V and constant reverse current in the range of 0 to 200 nA were applied to the MOS and PIN diodes with the aid of a National Instruments PXIe-4145 source measure unit in order to extract the temporal current response for constant voltage biasing and the temporal voltage response for constant current biasing, in both cases, after turning on different intensities of X-ray illumination on the surface area of the diodes inside of a grounded box, as shown in Fig. 1, to avoid external electrical interference and X-ray leakage. In addition, IxV curves were also extracted. The 4145 unit was programmed to apply voltage to the PIN and MOS diodes from 1 V to -1 V and from 0 to 5 V, respectively, both with voltage step of 0.1 V.

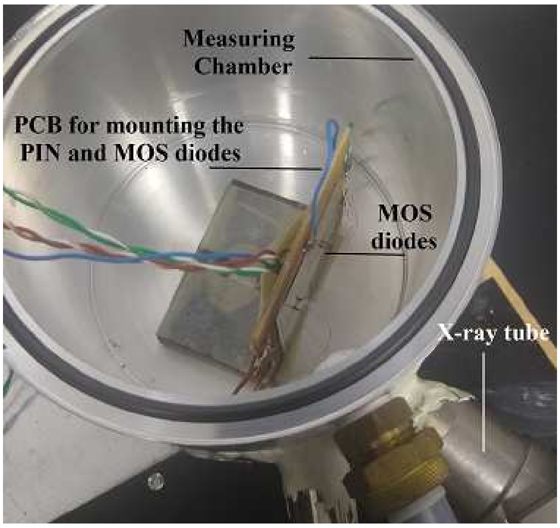

Fig. 1. Experimental setup for X-ray illumination of the MOS and PIN diodes and electrical measurements.

B. MOS diode fabrication

Si-p substrates (100), resistivity of 10 Ω.cm, 3 inches in diameter were used. They were chemically cleaned using a modified RCA cleaning [9] as follows: I) $16H_2O + 7H_2O_2(37\%) + 1NH_4OH(38\%)$, II) $4H_2O + 1HCl(38\%)$, both at 90°C for 15 min. At the beginning of the cleaning and after each bath of the modified RCA, the silicon wafers were rinsed in deionized water (DI) for 5 min. Following, the wafers were dipped in diluted hydrofluoric acid ($80H_2O$: $1HF(49\%)$) for 100 s at room temperature. Finally, the silicon wafers were rinsed in DI water for 3 min.

The gate dielectrics were grown by rapid thermal oxidation (RTO) at 850ºC for 100 s in an ultra-pure mixture of nitrogen and oxygen using a gas flux of $5N_2+1O_2$ in order to obtain a dielectric thickness of 2.20 nm, as measured by a Autoel IV ellipsometer at a wavelength of 632 nm and confirmed with the aid of a Transmission Electron Microscope (TEM) with an error below 5%.

Aluminum was deposited by physical vapor deposition (PVD: Edwards vacuum coater auto 306) for the obtention of the gate material and back contact. Lithography was used to define the gate geometry of the MOS diodes. The aluminum was chemically defined in a bath of $175H_3PO_4 + 70H_2O + 15HNO_3$ at a temperature of 40ºC.

Figure 2a and 2b show the top view and profile of the MOS diodes with square area of 3.24 cm^2. In the same silicon substrate were fabricated the gate metal with width (W) of 50μm and spacing among the lines (S) of 50μm [4]. The total area is also the effective area for X-ray detection since the 200nm aluminum layer does not block the X-ray as reported in the literature [2]. The effective area of the MOS diode was chosen ten orders of magnitude higher compared to the PIN diode in order to investigate the feasibility of achieving higher sensitivity for X-ray detection.

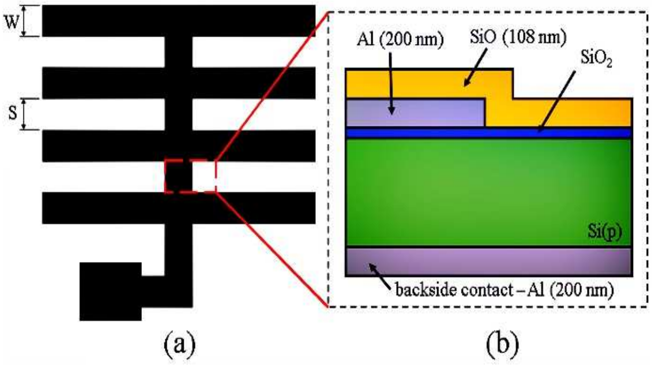

Fig. 2. MOS diode: (a) top view and (b) profile view.

C. PIN diode characteristics

Silicon PIN diodes (BPW34 from Vishay Semiconductors) with large radiant sensitive area (A=7.5 mm^2), wide cone angle of $\theta = \pm 65^o$, fast response times (~100ns) and small junction capacitance (10-60pF) were employed for X-ray detection [10, 11].

III. Results and discussions

A. X-ray detection using MOS diode

After positioning the diode at 2 cm from the Ag X-ray tube, as shown in Fig. 1, constant reverse voltage in the range of 0 to -5V and constant reverse current in the range of 0 to 200 nA were applied to the MOS diodes for the X-ray high voltage ranging from 10 to 40kV at filament currents of 50 and 100 μA. X-ray detection in the constant reverse voltage mode was unfeasible due to the poor current response superimposed to the background electrical noise as illustrated in Fig. 3, which can be attributed to a rapid accommodation of the depletion region width to the electron-hole pairs generated by the X-ray ionizing flux in the range of 0 to 500 mSv/h.

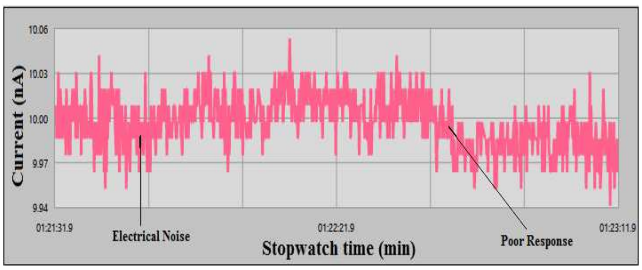

Fig. 3. *MOS current response in the constante voltage mode (-1 V) for the X-ray tube biased to 40 kV and filament current of* 100 μA (~ 500 mSv/h)

On the other hand, X-ray detection in the constant reverse current mode was feasible in the mV range (100 μA – 1 mV) as illustrated in Fig. 4.

As already mentioned, the X-ray flux was varied in the range of 0 to ~ 500 mSv/h. The percentage of electron energy that is transformed into X-rays increases with the increase of the high voltage between the Ag target (which is grounded) and the filament. The wavelength λ of the characteristic X-rays of each element decreases with increasing atomic number and is 0.05610 nm for Ag (22.1 keV). When we increase the current of the filament, there is an increase in temperature of the cathode filament, releasing a greater number of electrons. In this way, more electrons will be accelerated towards the anode and there will be an increase in the intensity of the generated radiation, without meaning an improvement in quality of this same radiation. That is, it is possible to increase the intensity without increasing the energy of the irradiated photons.

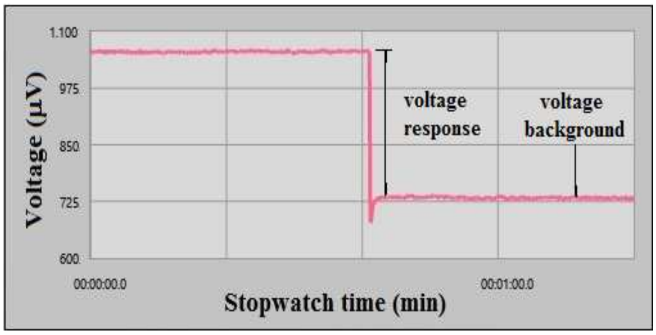

Fig. 4. *MOS voltage response in the constant current mode (200 nA) for the X-ray tube biased to 40 kV and filament current of* 100 μA (~ 500 mSv/h)

Fig. 5 shows the MOS voltage response as a function of the bias voltage of the X-ray tube for filament current of 50 μA. It is noteworthy that the voltage response increases proportionally with the bias voltage higher than ~ 15 kV. This is due to the increase in the energy percentage of the electrons that will subsequently promote the generation of X-rays as the bias voltage of the X-ray tube increases. In this case of constant reverse current, the width of the depletion region of the MOS diode remains almost constant and the voltage response is a consequence of the generated charge from electron-hole pairs that can be described [7] as the average standard deviation (σ_Q) of the in time charge changes in the depletion region ($\Delta V \approx \sigma_Q/C_D$, where C_D is the depletion capacitance).

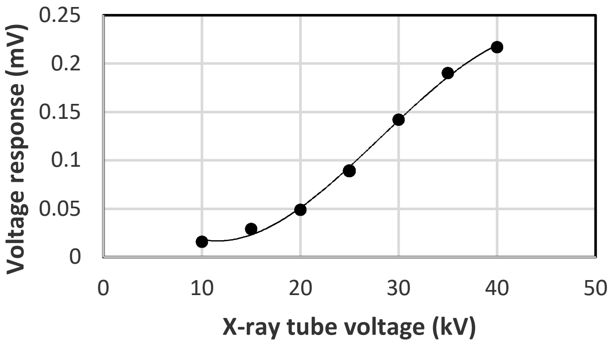

Fig. 5. *MOS voltage response in the constant current mode (200 nA) as a function of the X-ray tube voltage for filament current of* 50 μA.

On the other hand, the increase of the filament current to 100 μA leads to a voltage response that increases the downward concave feature for voltages above 30 kV. This is possibly due to a more limited generation of electron-hole pairs in the depletion region of the MOS diode whose width is ~ 1 μm, which is about ten times lower compared to the width of the intrinsic layer of the PIN diode (~ 10 μm).

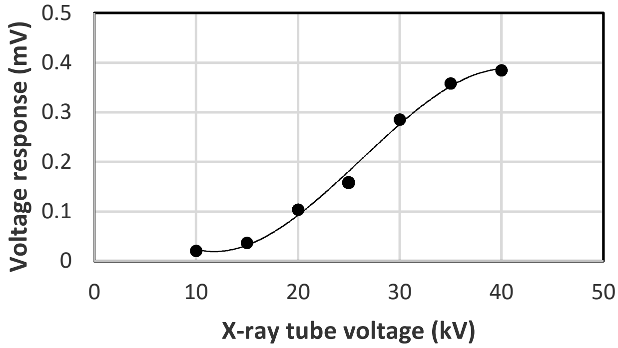

Fig. 6. *MOS voltage response in the constant current mode (200 nA) as a function of the X-ray tube voltage for filament current of* 100 μA.

B. *X-ray detection using PIN diode*

After positioning the diode at 2 cm from the Ag X-ray tube, as shown in Fig. 1, constant reverse voltage in the range of 0 to -5V and constant reverse current in the range of 0 to 200 nA were applied to the PIN diodes for the X-ray high voltage ranging from 10 to 40kV at filament currents of 50 and 100 μA. Fig. 7 illustrates the current response for the X-ray tube biased to 40 kV and filament current of 100 μA.

X-ray detection in the constant reverse current mode was unstable in the range of 0 to 200 nA with an increase of the electrical noise because the PIN diode was operating with the intrinsic region not completely depleted.

Fig. 8 shows the PIN current response as a function of the bias voltage of the X-ray tube for filament current of 50 μA. It is noteworthy that the current response increases with the bias voltage with a downward concave tendency for voltages above 30 kV. This is possibly due to a more limited energy percentage of the electrons for voltages above 30 kV since the filament current is 50 μA.

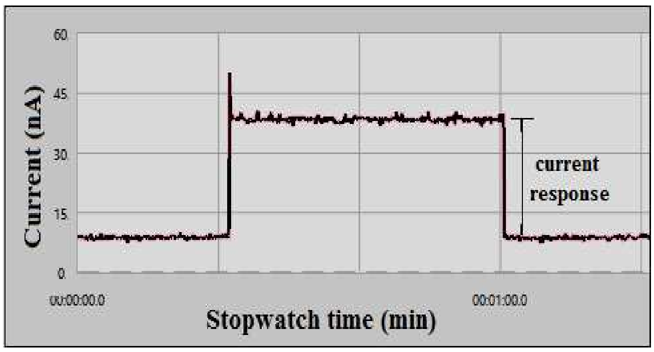

Fig. 7. *PIN current response in the constant voltage mode (-5V) for the X-ray tube biased to 40 kV and filament current of* 100 μA (~ 500 mSv/h)

After increasing the filament current to 100 µA, the downward concave tendency is much less pronounced and the current response starts to increase proportionally with bias voltage in the range of ~15 kV and 40 kV as observed in Fig. 9, which are similar results compared with that reported in the literature for PIN diodes [3, 12, 13]. This effect can be understood as an increase in temperature of the cathode filament, releasing a greater number of electrons and there will be an increase in the intensity of the generated radiation with an increase of the proportional relation between the current response and the bias voltage.

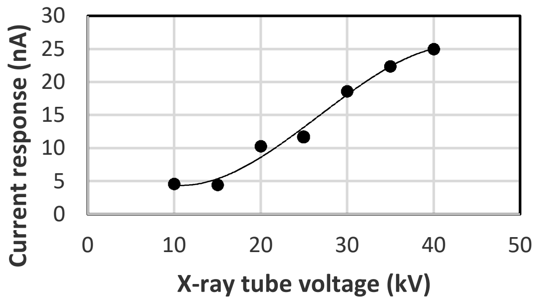

Fig. 8. *PIN current response in the constant voltage mode (-5 V) as a function of the X-ray tube voltage for a filament current of* 50 µA.

Thus, MOS and PIN diodes are sensitive to X-ray detection with flux up to 500 mSv/h. The reported maximum limits are in mSv/h range for some cases of radiotherapy and medical diagnostic applications as recommended by the National Nuclear Energy Commission from Brazil [14].

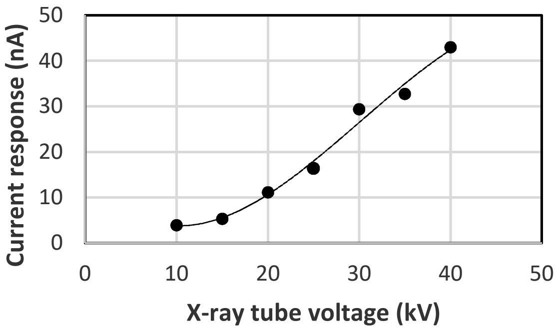

Fig. 9. *PIN current response in the constant voltage mode (-5 V) as a function of the X-ray tube voltage for a filament current of* 100 µA.

The PIN current response in the constant voltage mode and the MOS voltage response in the constant current mode are both governed by the generated charge in the depletion region, characterized by many individual events overlapped in time, which makes possible to take the average current response due to the generated charge in time [7] or the average voltage associated to the standard deviation of the produced charge [7] along a stationary depletion width of the MOS diode as proposed in this work. Thus, the ratio between the PIN current response and the MOS voltage response is approximately constant per unit of area for each intensity at a given X-ray energy. As a result, MOS or PIN diodes can be used for X-ray detection with similar sensitivities obtained from the ratio between voltage or current response and the corresponding basis line, respectively.

IV. Conclusions

X-ray detection using MOS and PIN diodes biased in the modes of constant reverse current or voltage was shown.

The MOS diodes showed voltage response only in the constant reverse current mode as function of the bias voltage of the X-ray tube for flux varying from 0 to around 500 mSv/h. The voltage response increased from 0 to 0.25 mV for the X-ray bias voltage varying from 0 to 40 kV at an X-ray current of 50 µA. On the other hand, unlike the MOS diode, the best PIN performance was the current response as a function of the bias voltage of the X-ray tube and it was noteworthy that the current response increases proportionally with the bias voltage of the X-ray tube for filament current of 100 µA. This was interpreted as the increase in the number of incident electrons that will subsequently promote the generation of X-rays as the bias voltage of the X-ray tube increases.

In addition, the new approach of the MOS diode operating with a stationary depletion width at a constant current proved to be sensitive to X-ray radiation flux in the range of 0 to ~500 mSv/h, as in the case of the PIN diode operating at a constant voltage. The National Nuclear Energy Commission, a brazilian regulatory body, reported dose limits in mSv/h range for some cases of radiotherapy and medical diagnostic applications, which is compatible with the range for MOS and PIN X-ray detectors as shown in this work.

References

[1] A. Datta, Z. Zhong, S.A. Motakef, “A new generation of direct X-ray detectors for medical and synchrotron imaging applications,” Sci. Rep. vol.10, pp.20097, 2020.

[2] M. Hoheisel, “Review of medical imaging with emphasis on X-ray detectors,” Nucl. Instrum. Methods Phys. Res. vol. A563, pp. 215–224, 2006.

[3] F. J. Ramírez-Jiménez, “X-Ray Spectroscopy with PIN diodes,” AIP Conference Proceedings, vol. 857, pp. 121, 2006.

[4] M. N. Watanabe, W. Chiappim, V. Christiano and S. G. d. S. Filho, “MOS solar cells for indoor LED energy harvesting: influence of the grating geometry and the thickness of the gate dielectrics,” *2019 34th Symposium on Microelectronics Technology and Devices (SBMicro)*, 2019, pp. 1-4, doi: 10.1109/SBMicro.2019.8919375.

[5] J. D. Spear, “Shot noise in x-ray measurements with *p-i-n* diodes,” Review of Scientific Instruments, vol. 76, pp. 076101, 2005.

[6] A.van der Ziel, Noise in solid state devices and circuits, 1st ed., New York: Wiley-Interscience, 1986.

[7] G. F. Knoll, Radiation Detection and Measurement, 3rd ed., New York: John Willey & Sons., 2000, pp. 65–119.

[8] AMPTEK Inc, available in the web site: http://www.amptek .com/

[9] K. Reinhardt and W. Kern. Handbook of Silicon Wafer Cleaning Technology. 2nd ed. Norvich, NY: William Andrew, 2008.

[10] BPW34 (https://www.mouser.com) Vishay Semiconductors.

[11] The PIN diode circuit designers’handbook. Watertown: Microsemi Corporation, 1998.

[12] R.L. Owen, J.M. Holton, C. Schulze-Briesea, E.F. Garman, “Determination of X-ray flux using silicon pin diodes,” J. Synchrotron Rad., vol. 16, pp. 143–151, 2009.

[13] C, Romeim A, D. Fulvio, C, A. Traino, R. Ciolini, F. d'Errico, “Characterization of a low-cost PIN photodiode for dosimetry in diagnostic radiology,” Physica Medica, vol. 31, pp. 112-116, 2015.

[14] Diretrizes Básicas de Proteção Radiológica. Resolução CNEN 164/14, 27/04/2014. [Norma CNEN NN 3.01.].