Ionizing radiation effects in a rectifier circuit

A C V Bôas¹, M A Guazzelli¹, R C Giacomini¹ and N H Medina²

¹ Departamento de Física, Centro Universitário FEI, São Bernardo do Campo, Brazil.
² Instituto de Física da Universidade de São Paulo, São Paulo, Brazil.

E-mail: ¹ alexiscvb.fei@gmail.com

Abstract. This work aims to study the effects of ionizing radiation on a half-wave rectifier circuit. The diodes of the circuit, rectifier and Zener, were exposed to X-rays of 10 keV of effective energy. The characteristic curves of both diodes were evaluated before and after being subjected to cumulative total ionizing dose (TID) effects. The accumulation of charges in the dielectric structures of the diodes alter their individual functionalities, but the changes verified in the rectification were irrelevant. In this study, three irradiation methods were used to correlate the physical mechanisms responsible for the effects caused by radiation with variations in the electrical parameters of the devices and the efficiency of the rectifier circuit.

1. Introduction

In the mid-19th century, little was known about semiconductors and devices made with these materials. There were, however, some empirical work, as was the case with the invention of the solid-state rectifier, presented by F. Braun, in 1874 [1]. This rectifier was made with PbS crystal, welded with a metal wire (contact tip diode). This diode showed to be very unstable and it was temporarily abandoned until it was necessary to resume it, since the valve diodes were not attending the demand for high-frequency usage. The beginning of the 20th century in turn was fundamental for microelectronics, since there was a huge progress in theoretical Physics, with the development of quantum mechanics [2]. Semiconductor devices generally are separated into two categories: majority-carrier devices and minority-carrier devices. Field-effect transistors (FET's) and Schottky barrier diodes are the primary representatives of the majority-carrier device category. Most other semiconductor devices including bipolar transistors, solar cells, diodes, rectifiers, and silicon-controlled devices are in the categories of the minority carrier devices [3]. On the other hand, the damage provoked in the electronic devices by the effects of exposure to ionizing radiation is basically defined by three main mechanisms: 1) the accumulation of charges in the dielectric structures and semiconductor interfaces defined by Total Ionizing Dose (TID); 2) the incidence of high energy linear transfer (LET) ionizing particles in a sensitive region of the circuit or device defined by Single Event Effect (SEE); 3) the interaction between an incident particle and the crystalline lattice of the material, damaging its crystalline structure, known as Displacement Damage (DD) [4]. The device chosen to analyze the radiation effects was a diode because, due to its sensitivity to radiation and the quantities required in today's circuitry, have received considerable attention to determine the effects of radiation on their electrical properties. This attention has included exposure to various radiation environments, with measurements of electrical characteristics before, after, and/or during the irradiation processes. Results of these investigations have shown permanent changes in the diode characteristics, including increases in forward-voltage drop and reverse current and decreases in reverse-recovery time [3]. There are several applications for the diodes, they can be part of logic gates (AND/OR), they can comprise gyros circuits, stapler circuits, voltage multipliers, protection circuits of any kind, led displays.
However, they are primarily important for application as voltage rectifiers [5]. Although, all rectifier circuits need diodes, it can come in many topologies, such as half-wave rectifier, full-wave rectifier, central bypass rectifier [5]. This work aims to study the effects of ionizing radiation on a half-wave rectifier circuit. A typical application of the rectifier circuit is the cellphone charger, which converts the AC voltage of the power outlet into a continuous 5 V. Nevertheless, the most impressive application could be considered the use as rectifier for the various rectifying voltage circuits required by a satellite in space [2, 5]. Due to the great variety and importance of the applications, the rectifier circuit was chosen to be studied in this work. The effects of radiation, and its variations are considered individual changes of a particular component, and it may modify the functionality of the circuit, for example the rectification of the signal [1, 4].

1.1. Half-wave rectifier circuit
The half-wave rectifier circuit has the function of transforming an alternating voltage supply into a direct voltage signal. In the circuit of Figure 1, capacitor C1 and a Zener diode are used for output voltage regulation [6]. This circuit operates with the interaction between the diodes. The junction diode (DR) has the function of eliminating all the negative part of the incoming signal. The Zener diode (DZ) limits the output voltage, working in the avalanche region and bringing a certain stability and precision to the circuit output. This circuit is simple to analyze and robust to external interference, allowing a study of the individual behavior of each diode [5, 6]. In addition, it is possible to verify how much the alterations of each characteristic parameter of the diodes can affect the circuit behavior. Figure 1 shows the half-wave rectifier circuit used in this work. Figure 2 presents the input and output signals from the numeric circuit simulation (SPICE).

![Figure 1. Half-wave rectifier circuit scheme.](image1)

![Figure 2. Circuit response simulation.](image2)

2. Methodology
The circuit exposure to ionizing radiation was carried out at the Laboratory of Ionizing Radiation Effects (LERI – Laboratório de Efeitos da Radiação Ionizante) at Centro Universitário FEI, using a Shimadzu XRD-6100 diffractometer. The diodes were de-encapsulated in FEI Materials Laboratory and characterized through a PXI-NI platform [2]. The set-up programming was done in LabView to operate in conjunction with the PXI-NI platform. The modules work varying voltage and measure point to point the current on the diode. The device was under test (DUT) placed perpendicular to the X-ray beam. Both diodes were de-encapsulated with chemical processes to avoid the X-ray absorption by the epoxy cover.

2.1. Three methods of irradiation
In order to understand the behavior of the rectifier circuit after the irradiation of the two diodes, which have different functions in the circuit, three different test methodologies were performed. In the first method, both diodes were subjected to accumulated TID of about 3.5 krad (100 rad = 1 Gy), performed in two irradiation procedures with a time interval of one week between them, using a dose rate of 3.2 rad(Si)/min. In the second method, five irradiation steps were performed with a 24 hour time interval between them, in this method both diodes were exposed at a dose rate of 566 rad(Si)/min, totaling an
accumulated dose of 250 krad. In the third method, only the junction diode was exposed to eight irradiation steps with a time interval of 10 minutes between them, at a dose rate of 1204 rad(Si)/min, totaling a total dose of 96 krad. Table 1 shows the summary of the three methods.

| METHOD | 1º | 2º | 3º |
|--------|----|----|----|
| DOSE RATE (rad(Si)/min) | (3.2±0.2) | (566±30) | (1204±60) |
| TOTAL DOSE (krad) | (3.49±0.17) | (250±12) | (96±5) |

The DUTs were characterized before and after each irradiation method, in order to establish some correlation between the effects of the radiation of each device individually and the general effect caused in the signal of the rectifier circuit. To study the behavior of the rectifier circuit, several combinations were made using the diodes DR and DZ that underwent the effects of different TIDs through the three methods of irradiation posed in this study.

3. Results and Discussion

Only one representative characteristic Iₜ versus V curve for each method will be presented as a way of exemplifying the results. In Figures 3 and 4 the junction diode (DR) and Zener diode (DZ) characteristic curves after the first method are shown. Figure 5 and 6 shows the DR and DZ diode characteristic curves after the second method and in Figure 7 the DR diode characteristic curve after the third method is shown.
Table 2. Rectified Voltages in the three applied methods

| METHOD   | DIODE      | RECTIFIED VOLTAGE (± 2%) |
|----------|------------|--------------------------|
| FIRST    | DR0/DZ0    | 5.90 V                   |
| SECOND   | DR1/DZ     | 5.95 V                   |
| SECOND   | DR2/DZ     | 6.06 V                   |
| SECOND   | DR/DZ1     | 5.93 V                   |
| SECOND   | DR/DZ2     | 5.94 V                   |
| SECOND   | DR1/DZ1    | 5.92 V                   |
| SECOND   | DR1/DZ2    | 5.91 V                   |
| SECOND   | DR2/DZ2    | 5.94 V                   |
| THIRD    | DR3/DZ     | 6.10 V                   |
| THIRD    | DR3/DZ1    | 5.95 V                   |
| THIRD    | DR3/DZ2    | 5.96 V                   |

The results indicate the junction diodes with the first irradiation method present the higher variation in its characteristic curve parameters, as shown in Figure 3, while the Zener diode with all other irradiation procedures fluctuated very little. In order to obtain the various rectifying voltages of the circuit, several tests were performed, with several irradiated diode combinations. Table 2 shows the rectified voltage for each of these circuit configuration, where DR represents the rectifier diode and DZ the Zener diode, the number after the diode type represents the order in which it was irradiated. For example, DR2 was irradiated after DR1, but both belong to the second applied method. When only DR or DZ is used it means that a non-irradiated diode was used. The rectified reference voltage measured is 5.90 V.

4. Conclusion
Considering a rectifying voltage, without irradiation, of 5.9 V and observing the characterization of eleven diode combinations in the rectified circuit, the rectified voltages are very close to the reference value, the lower voltage was obtained using the first method and was about 5.9 V and the highest voltage was about 6.10 V obtained with the third irradiation method. The mean rectifier voltage after all irradiation procedures is (5.96 ±0.02) V, indicating the rectifier circuit is tolerant to radiation taking into account the X-ray doses the diodes were submitted. Even with the effect of the accumulated radiation (TID), the junction region, modified by the entrapment of charges, and the variation of the work function (φ) of the semiconductor, there were small variations in the rectified voltage, due to the fact that it is the Zener diode that dictates the rectifying voltage in the circuit, and for all irradiation methods the Zener diode suffered little variation in its functionality.

5. References
[1] Swart J 2009 Semicondutores – Fundamentos, técnicas e aplicações Editora da Unicamp (São Paulo: Campinas)
[2] Cirne K H 2011 Estudo e fabricação de MOSFET’s robustos à radiação para aplicações espaciais de circuitos integrados Dissertação de Mestrado (Centro Universitário da FEI)
[3] C L Hanks and D J Hamman 1971 Radiation effects design handbook (Washington D.C.)
[4] Johnston A 2010 Reliability and radiation Effects in Compound Semiconductors World Scientific Publishing Co. Pte. Ltd (California: Institute of Technology)
[5] Boylestad R and Nashelsky L 2012 Electronic Devices and Circuit Theory Pearson 11th ed
[6] Sedra A S and Smith K C 2004 Microelectronics Circuits Pearson 5th ed (New York/Oxford)

Acknowledgments
This work was supported by Centro Universitário FEI; FAPESP Proc. No. 2017/18181-2; CNPq, FINEP Proc. No. 01.12.0224.00; INCT-FNA Proc. No. 464898/2014-5.