GAMMA-RAY IRRADIATION TESTS OF CMOS SENSORS USED IN IMAGING TECHNIQUES

by

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Technologically-enhanced electronic image sensors are used in various fields as diagnostic techniques in medicine or space applications. In the latter case the devices can be exposed to intense radiation fluxes over time which may impair the functioning of the same equipment.
In this paper we report the results of gamma-ray irradiation tests on CMOS image sensors simulating the space radiation over a long time period.
Gamma-ray irradiation tests were carried out by means of IGS-3 gamma irradiation facility of Palermo University, based on ^{60}Co sources with different activities. To reduce the dose rate and realize a narrow gamma-ray beam, a lead-collimation system was purposely built. It permits to have dose rate values less than 10 mGy/s and to irradiate CMOS Image Sensors during operation. The total ionizing dose to CMOS image sensors was monitored *in-situ*, during irradiation, up to 1000 Gy and images were acquired every 25 Gy.
At the end of the tests, the sensors continued to operate despite a background noise and some pixels were completely saturated. These effects, however, involve isolated pixels and therefore, should not affect the image quality.

Key words: imaging technique, CMOS image sensor, gamma irradiation

INTRODUCTION

Technologically-enhanced electronic image sensors are used in various radiation-sensitive fields and equipments like accelerator based facilities, nuclear power plants, solar system exploration and telecommunications satellites, high altitude flight (avionics), high energy physics experiments, medical diagnostic imaging and therapy, industrial imaging, and so on.

The devices can be exposed to intense radiation over time, which may impair the functioning of the same equipments. It is very important to test the electronic devices simulating the radiation conditions to which may be subjected over a long time period. Effects of radiation may widely change depending on the particular operating principle of the considered electronic device.

Despite the complexity of the interaction processes and their dependence on the properties of the incident particles and of the target materials, two are the basic radiation damage mechanisms affecting semiconductor devices: ionization damage (ID) and/or displacement damage (DD) [1]. ID takes place when energy deposited in semiconductor or insulating layers (mainly SiO_2) produces charge carriers (electron-hole pairs) which diffuse or drift to other locations where they may get trapped, leading to unintended concentrations of charge and parasitic fields. This kind of damage is the primary effect of an exposure to X-rays, γ-rays, and charged particles and it affects mainly devices based on surface conduction (*e. g.*, MOSFET) [2].

Displacement Damage occurs when incident radiation moves atoms from their lattice site and the resulting defects modify the electronic properties of the crystal. This is the primary mechanism of device degradation for high energy neutron irradiation, although a certain amount of atomic displacement may be determined by charged particles (including Compton secondary electrons). DD mainly affects devices based on bulk conduction (*e. g.*, BJT, diodes, JFET) [3].

Effects of radiation in semiconductor devices can be included in one of two broad classes: total ion-

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izing dose (TID) and single event (SE) effects. TID effects are due to the progressive build-up of trapped charge in insulating layers or at the Si/SiO interface (as a consequence of ionization phenomena) or to defects in the bulk of the devices (originating from accumulation of displacement events). TID uniformly affects the whole device, because it results from the effect of several particles randomly hitting the device and also is usually related to long term response of devices [4]. SE effects are due to charge deposition induced by a single particle that crosses a sensitive device region and the damage may result in a destruction of the electronic component. SE effects occur stochastically and only a tiny part of the device, corresponding to the position of the particle strike, is affected [5].

Previous studies on non-volatile memories demonstrated the effectiveness of *in-situ* biasing and monitoring of complex integrated circuits in order to collect useful data about their effective radiation tolerance [6-8].

In this work, CMOS image sensors (CIS) based on metal oxide semiconductor (MOS) technology, which are widely used for consumer electronics integrated circuits manufacturing, are taken into consideration. The CIS is a 640 480 pixels matrix industrial test vehicle, purposely designed for the technological development of new pixel solutions. The single pixel has a 4 um 4 um active area and is of the 4-T type. The CIS is interfaced through a USB camera board, provided with PC frame-grabbing software.

Gamma-ray irradiation tests were carried out by means of the IGS-3 gamma irradiation facility of Palermo University [9]. To reduce dose-rate and realize a narrow gamma-ray beam, a lead-collimation system was purposely built. It allows to have dose rate values less than 10 mGy/s and to irradiate only the CIS to test the electronic characteristics degradation under irradiation, without appreciable damage of the camera board circuits.

MATERIALS AND METHODS

The CIS devices are supplied by TowerJazz Ltd. (Israel), a company specialized in design, development and manufacture of CIS for X-ray Imaging.

Gamma-ray irradiation tests were performed at IGS-3 irradiation facility of Palermo University, an experimental gamma irradiator, with ^{60}Co sources, designed for general purpose scientific applications. It can be charged to achieve an overall activity up to about 100 TBq. The complex consists of a concrete shielding, irradiation control, and safety systems [10].

The IGS-3 cell type irradiation system, with a panoramic irradiation cavity (fig. 1) is designed to contain 12 cylindrical ^{60}Co sources. The source driving system consists of 12 tubes of stainless steel, each of which can accommodate a doubly-encapsulated stainless steel cylindrical ^{60}Co source, 110 mm in height and 6.3 mm diameter. The pipes are driven into or out of the lead shielding through an electro-mechanic source-holder system. In the inner position it can irradiate small volumes (up to about 0.5 liters) at high dose rate. Larger volumes at lower dose-rate can be irradiated outside the cavity.

Figure 1. The IGS-3 gamma irradiator

The complex is located inside a concrete shielding, and all the systems for irradiation control and safety monitoring are placed in an external protected room. A thick iron door equivalent to 5 mm of lead separates the cell from the rest of the laboratory. A ventilation system provides for the air exchange within the cell.

At this time, the irradiation facility is equipped with a total $8.9 \cdot 10^{12}$ Bq, composed of twelve ^{60}Co gamma-ray sources of different activity: 6 sources of $1.17 \cdot 10^{11}$ Bq each, 3 sources of $3.2 \cdot 10^{11}$ Bq each and 3 sources of $1.65 \cdot 10^{12}$ Bq each. The source disposition on the workplace and related isodose profiles are shown in fig. 2. The facility is fully equipped with dosimeters to ensure safe operation and certified irradiation levels.

To reduce the dose-rate and to realize a narrow gamma-ray beam hitting only the sensor and shielding the camera board, a lead-collimation system (see fig. 3) was purposely realized. Its main characteristics are:
– inner wall of the lead shield at 25 cm from the center of the sources,
– thickness of the lead shield: 8 cm,

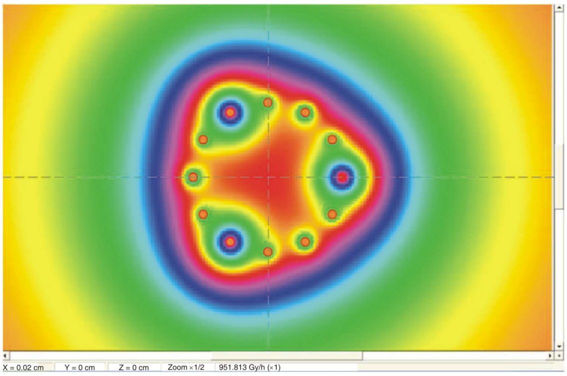

Figure 2. Source configuration and isodose profile on the work-plane (colours scale is not representative of the dose rate values)

Figure 3. The lead collimation system

– diameter of collimation hole: 30 mm, and
– height of collimation hole: 80 mm.

To verify the attenuation level at the inner side of the shield, remote measurements of dose and dose-rate were performed using PTW UNIDOS electrometers connected via shielded cables (about 30 meters) to some suitable ionization chambers with various sensitive volumes. Among them, ionization chambers mainly used are: TM23361-0561, sensitive volume 30 cm^3; TM30015-0011, 1 cm^3; and TM30013-3256, 0.6 cm^3. The electrometers measure both the ionization current (dose rate) and the charge (integrated dose).

Figure 4 shows the measuring points selected on the inner side of the collimation system and fig. 5 shows the plot of corresponding measured dose-rate values. This confirms us the attenuation of the shielding system (with a reduction factor of about 100) and the collimation of the beam. A further test on the uniformity of the shielding attenuation for protecting the electronic circuits board was also performed: we placed a glass plate behind the shield to verify both the collimation and the shielding uniformity real effect.

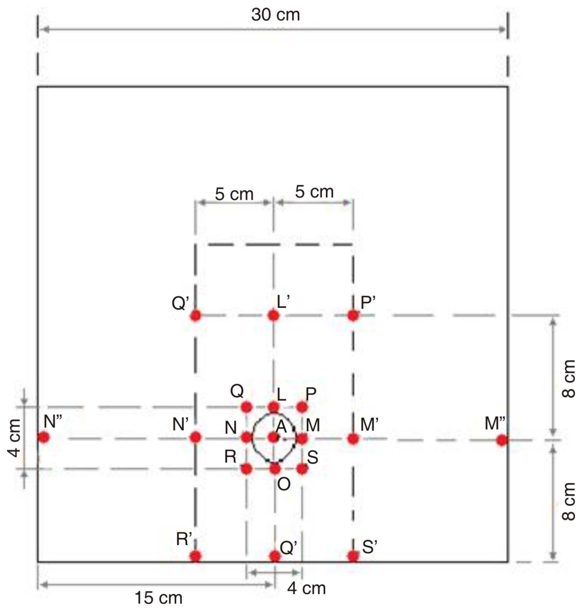

Figure 4. Measuring points on the inner side of the shield to verify its attenuation level

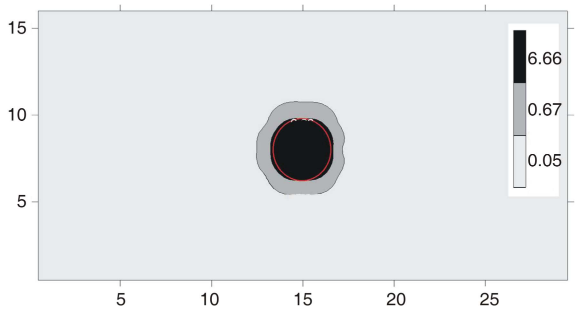

Figure 5. Plot of dose rate values in the measuring points (in mGys^{-1})

The results of irradiation are shown in fig. 6. A comparison of figs. 5 and 6 highlighted the good collimation and uniformity obtained with the lead-collimation system.

To carry out the irradiation test, the electronic board is placed so that the collimated beam is centred on the sensor, with the active area facing the sources (fig. 7). The irradiation has been realized with the camera board operating in video mode, so obtaining a very realistic test condition. Control instrumentation and a PC were located outside the shielding, in the pre-chamber where a very low dose-rate environmental conditions are realized. The PC was interfaced to the camera through a 3 m USB cable, connected to the LAN and remotely controlled using the software TeamViewer^{TM}. The test was performed following the rules contained in ESCC Basic Specifications No. 22900 [10].

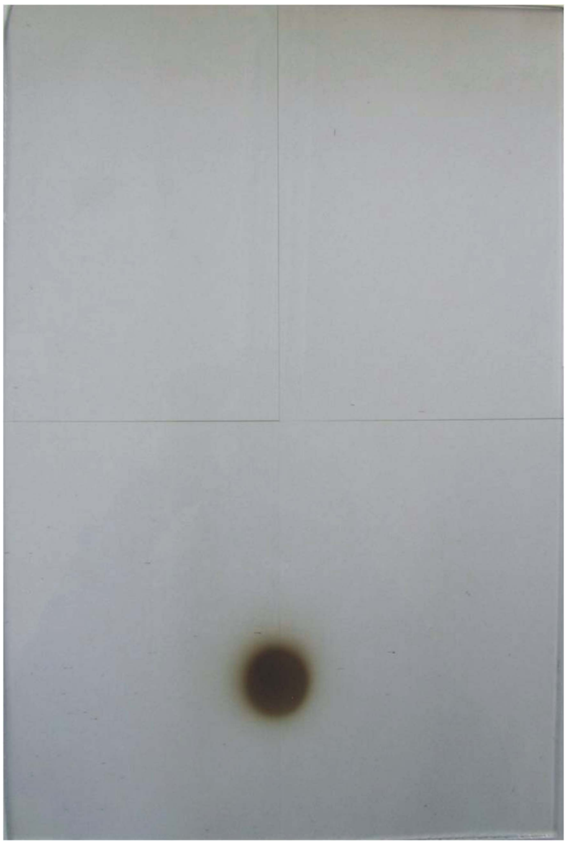

Figure 6. Experimental exposure of a glass plate placed behind the shield

Figure 7. Photograph of the board placed inside the shield

RESULTS AND DISCUSSION

With the above experimental set-up, the active-mode TID response of the CIS was monitored *in-situ*, during irradiation, up to 100 Gy, and images were acquired every 25 Gy.

The images acquired at the beginning, at different stages during the irradiation, and end of the test, have been analyzed to evaluate the effects of the radiation on several devices. A qualitative analysis of the images at the end of irradiation, compared to the starting ones, shows damage related to weak background noise. The brightness of many pixels is more than the expected value, and some even are completely saturated. These effects, however, involve isolated pixels and therefore should not affect the image quality, since it can be filtered by using pre-processing software so that these pixels can be labeled as "not-operating". The images acquired during irradiation, instead, have a noise level more persistent and extended, with many more pixels in saturation (displayed in white). This is due to the interaction of gamma photons with the photosensitive elements of the sensors and, of course, these effects should not be taken into consideration for real applications. In fact, when the ^{60}Co sources are removed, the level of noise is drastically reduced. Figure 8 reports an image taken during irradiation, evidencing the effects not only as saturated intensity pixels, but also as secondary particle (electrons) tracks. Fig-

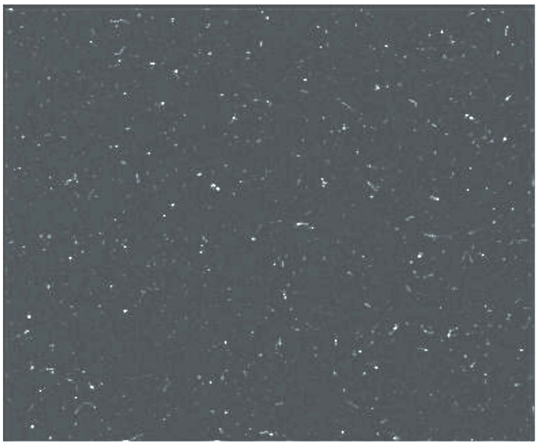

Figure 8 . Acquired image from the CMOS camera, in dark conditions, during irradiation. Primary (single white pixels) and secondary electrons interactions (tracks) are clearly evidenced at short exposure times

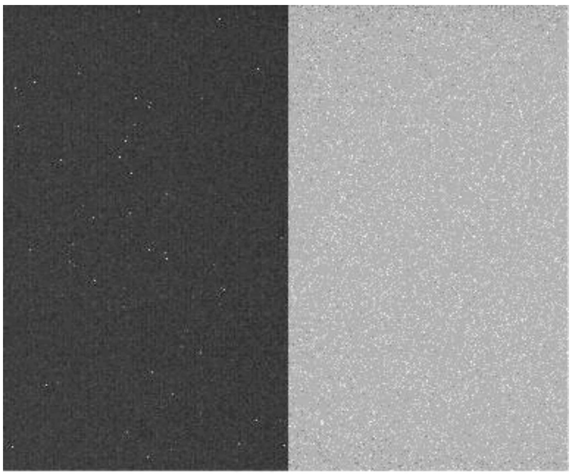

Figure 9. Comparison between the dark image of the new CIS (left) and the dark image after 300 Gy dose (right). Main degradation, at this dose level, is due to dark current noise increasing

ure 9 shows a post-irradiation comparison between the dark image of a new CIS (left) and the dark image after 300 Gy dose (right). Main degradation, at this dose level, is due to dark current noise increasing.

CONCLUSIONS

At the end of the tests, the images produced by the sensors have been verified and highlighted a background noise. The brightness of many pixels resulted higher than the expected value, and some pixels were completely saturated.

These effects, however, involve isolated pixels and therefore, in principle, should not affect the image quality because the digital image could be filtered by a pre-processing software. However, the use of these sensors in space applications, as in medical imaging diagnostics, must be done carefully because of likely artifacts due to high TID. The images acquired during irradiation show a widespread and persistent noise, with many pixels in saturation. Although it is not realistic the use of such sensors in high dose-rate environmental conditions, it must be taken into account that many pixels can be influenced by irradiation interaction with device sensitive regions.

AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by C. Pace and S. Rizzo, experiments were carried out by S. G. Cappello, A. Parlato, and E. Tomarchio, data analysis was performed by C. Pace and E. Tomarchio. All authors analysed and discussed the results. The manuscript was written by C. Pace, S. Rizzo, and E. Tomarchio. The figures were prepared by A. Parlato and C. Pace.

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ТЕСТИРАЊЕ CMOS СЕНЗОРА КОЈИ СЕ КОРИСТЕ У ИМИЦИНГ ТЕХНИКАМА ОЗРАЧИВАЊЕМ ГАМА ЗРАЦИМА

Технолошки побољшани електронски сензори слика користе се у разним областима као што су дијагностичке методе у медицини, или свемирске примене. У овом другом случају уређаји могу бити изложени јаком зрачењу током времена што може довести до поремећаја у раду опреме. У овом раду приказујемо резултате тестова озрачивања CMOS сензора гама зрачењем симулирајући зрачење у свемиру у току дугог временског периода. Тестови озрачивања спроведени су средствима IGS-3 постројења Универзитета у Палерму, који су засновани на изворима ^{60}Co различитих активности. Како би се смањила јачина дозе и остварио узак сноп гама зрака, направљен је посебан колиматорски систем од олова који дозвољава јачину дозе мању од 10 mGy/s и озрачивање само сензора слике током теста. Укупна јонизујућа доза CMOS сензора праћена је *in situ* до вредности од 1000 Gy, а слике су прибављане на сваких 25 Gy. На крају теста, сензори су наставили да раде без обзира на позадински шум и потпуну засићеност неких пиксела. Ови ефекти, међутим, обухватају изоловане пикселе и стога немају утицај на квалитет слике.

Кључне речи: имицинг техника, CMOS сензор слике, гама озрачивање