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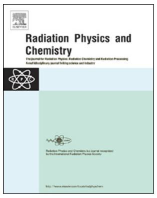

E.D.R.A., the Argentine facility to simulate radiation damage in space

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ABSTRACT

E.D.R.A. (Ensayos de Daño por Radiación y Ambiente/Test of Radiation and Environmental Damage) is a system composed of a beam line and a vacuum chamber installed at Tandar (a 20 MV Van de Graaff tandem accelerator). It has been designed to analyze devices' behaviour under simulated space conditions. The facility features: large irradiation area with uniform beam current, controlled target temperature in a range from LN_2 to 300 °C, good target connectivity by multiple BNC and DB25 feedthrough connectors for *in situ* measurements and control during sample irradiations, and capability of irradiation under very low fluxes. Using this last feature, it is possible to measure space solar cells under proton irradiation to study Total Non Ionizing Dose (TNID), or semiconductor devices under operation to assess their response to Total Ionizing Dose (TID) or Single Event Phenomena (SEP) effects. Multiple sample studies are easily made by using remotely controlled rotary target holders, and a solar simulator illumination source is also available at the facility. The beam current and its uniformity can be assessed and monitored by a system of multiple, electron suppressed, Faraday cups. For SEP measurements, PIN diodes particle detectors are used.

1. Introduction

In space, electronic components (including solar cells) are subject to an extremely hostile environment. Physical factors, such as mechanical shocks and pressure changes during launching operations, temperature cycling, high vacuum and electrostatic stresses, can affect their working performance. Also, the presence of a strong radiation field due to cosmic rays and particles trapped by the Earth's magnetic field, have significant effects in electronic devices, reducing eventually their in-orbit lifetime (Alurralde et al., 2013).

The main consequence of the exposure to space environment is the accumulation of damage in the semiconductor lattices (produced mainly by protons and electrons). This effect can be accounted by the so called Total Ionizing Dose (TID) and the Total Non-Ionizing Dose (TNID). Another mechanism worth to be considered is the occurrence of Single Event Phenomena (SEP), produced typically by high energy particles that could deposit (directly or indirectly) huge amounts of energy in the electronic system, especially nearby sensitive zones of semiconductor devices. This processes is typical, for example, of spallation reactions in matter produced by high energy cosmic rays (Velazco et al., 2007).

To study those phenomena and their effects on electronic devices, it is necessary to emulate the space environment in a laboratory. High vacuum, controlled temperature and solar illumination can be easily achieved, while radiation dose can be emulated by equivalent doses produced, for example, by a particle accelerator.

In order to fulfill those requirements, we developed an irradiation facility at the Tandar Van de Graaff tandem accelerator (Fig. 1), belonging to the Argentine National Atomic Energy Commission (CNEA). In the following sections, we describe the main characteristics of the experimental setup, and some of the experiments done using the facility (Alurralde et al., 2007, 2013).

2. The facility

The beam line E.D.R.A. (Ensayos de Daño por Radiación y Ambiente/Test of Radiation and Environmental Damage) (Fig. 1) is installed at CNEA's 20 MV Tandem Van de Graaff Heavy ion Accelerator (Tandar). The layout of the machine is vertical with the ion source at the top. The vacuum level in the acceleration column is 10^{-7} mbar. A

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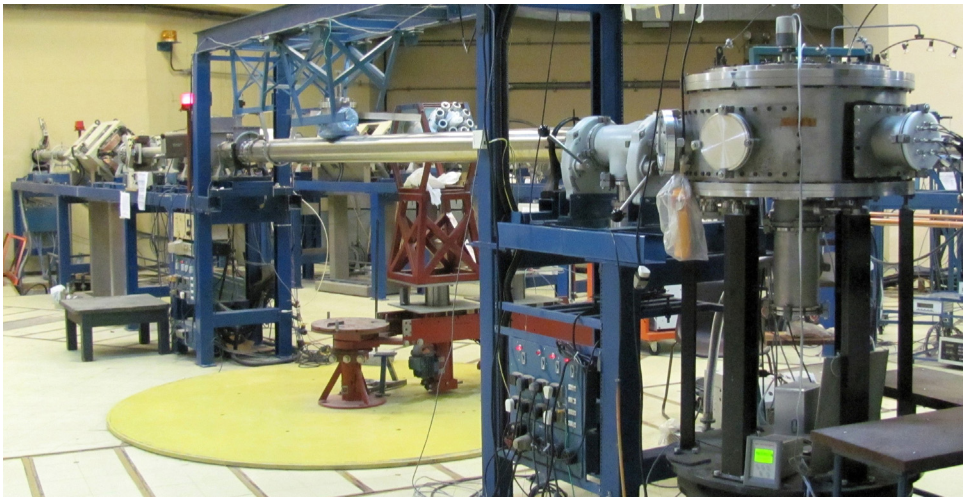

Fig. 1. Irradiation line and chamber installed in one of the Tandar accelerator beam lines.

Table 1
Some heavy ions and energies available at the Tandar accelerator.

Ions	$^{12}C_6$	$^{16}O_8$	$^{19}F_9$	$^{48}Ti_{22}$	$^{58}Ni_{28}$	$^{79}Br_{35}$	$^{127}I_{53}$	$^{197}Au_{79}$
Energy beam (MeV)	25	30	75	90	120	140	150	170

wide range of beam species is available, from protons with energies up to 15 MeV to diverse heavy ion species and energies (Table 1).

Once the beam reaches the bottom of the column, an analyzer magnet deflects it by 90°. This magnet can be rotated in order to deliver the beam to the different experimental lines.

A pneumatic gate valve comes between the Tandar accelerator and our 10 cm diameter beam line (Fig. 2), where vacuum is maintained at 10^{-7} mbar by using two ionic pumps and a titanium sublimation pump. Right after the valve, a quadrupole triplet and a pair of magnetic steerers inject and focus the beam along the axis of the beam tube.

A rotating disc with 16 foil holders (one empty and the others with foils of different materials and thickness) is used for modifying the beam properties, such as degrading its energy, reducing its intensity or spreading the particle beam. The beam tube is thereafter enlarged (from 10 to 15 cm diameter) in order to allow a larger irradiation area.

Two 6" manual pendulum gate valves divide the line, and its vacuum system, from the irradiation chamber. Between both valves, a turbomolecular pump and a dual stage rotary mechanical pump are connected. This set of valves allows a practical and safe operation and opening the chamber without losing the high vacuum in the beam line or damaging the turbomolecular pump.

Finally, at the end of the beam line, a large irradiation chamber is installed. Directly under the chamber, a mechanical pump is connected, used to reach a preliminary vacuum level of 10^{-3} mbar. In order to reach a working vacuum level of 10^{-6} mbar, the pumps between pendulum valves are used. The vacuum level at this zone is monitored during operation.

Recently, new upgrades have been made in the chamber: motor drivers for the internal rings, new wiring for experiments and a set of magnetically suppressed Faraday cups, which allow us to determine the beam's uniformity at the target position. A detailed description of the irradiation chamber is given below.

2.1. *The irradiation chamber*

The irradiation chamber, made of stainless steel, is a 25 mm thick cylinder with a 680 mm inner diameter and a height of 340 mm. The base is a 25 mm thick circular plate supporting the concentric rotating rings system. The lid can be lifted and displaced laterally by an electric hoist.

Five ISO-160 flanges have been mounted on its side and ten CF-6 flanges have been equally distributed between the base and the chamber lid (Fig. 3a). Three of the side flanges are used as electrical feedthroughs (using DB25 and BNC connectors). Another flange, installed at about − 120°, holds a 150 mm Borosilicate viewport: this 6.5 mm thick window was designed and placed in such a way that an external solar simulator can be placed next to the window and illuminate the center of the chamber. Thus, it is possible to illuminate solar cells and optoelectronic devices during irradiation or *in situ* tests.

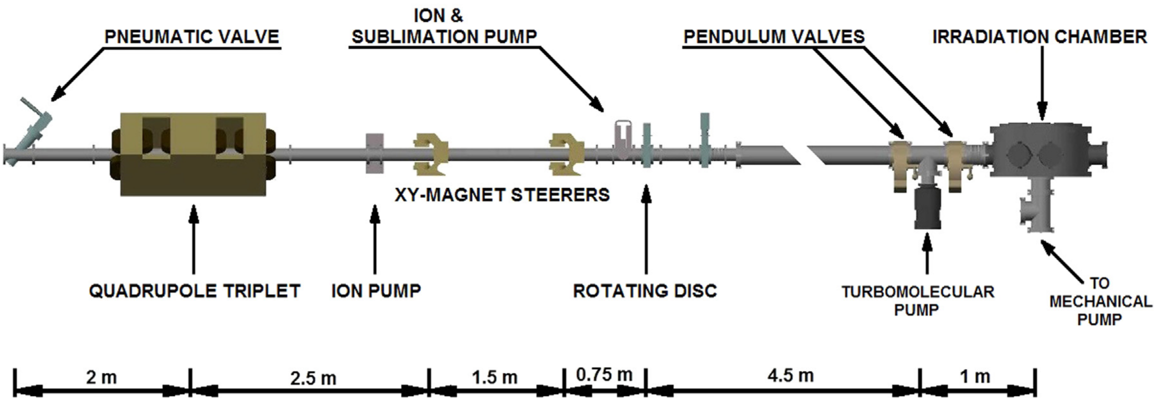

Fig. 2. A schematic view of the E.D.R.A. beam line.

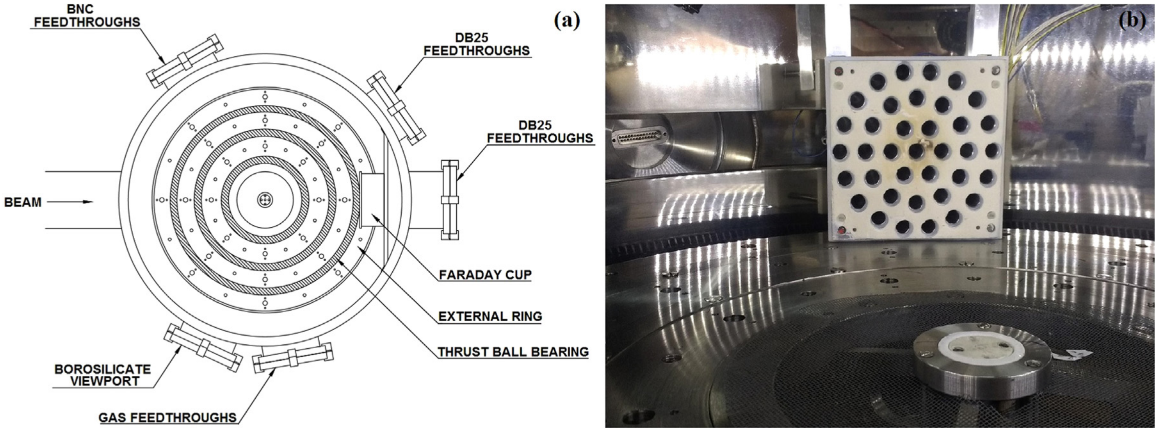

Fig. 3. (a) Irradiation chamber (top view). Electrical connections and gears are not shown. (b) Faraday cup array.

The fifth flange has a gas feedthrough, allowing us to test and measure devices under controlled temperature conditions. By using a PID controller, temperature can be kept constant or be varied (ramps or cycles). The temperature in up to 8 different points of the sample can be registered by eight-channel 16 bit data loggers. Accuracy in temperature measurements is better than 1 °C using Pt-100 sensors. Two sample holders with controlled temperature are available, made with different materials, sizes and capacities. The first one is an 80 mm × 160 mm aluminium plate containing resistor heater elements. This plate is thermally connected to a cooling copper plate with circulation of refrigeration fluid (water, air or LN_2 can be used). This holder works in a temperature range of − 150 °C and + 150 °C, and is installed fixed in the center of the irradiation chamber facing towards the beam. The second one, 80 mm × 80 mm, is made entirely of copper containing resistor heater elements. The cooling system consists in a labyrinth-shaped inner cavity machined inside a copper block, connected to the gas feedthrough. Ten flexible copper braids welded to the blocks carry the heat from the holder plate to the cooling block. This design presents thermal impedance large enough to allow stabilization in a range of temperatures between − 100 °C and + 100 °C. In addition, the sample holder can be rotated from + 90° to − 20° with respect to the beam incidence (Tamasi et al., 2009).

In the base of the chamber there are three concentric rings which can be rotated from the outside without breaking the vacuum or altering the setup of the beam optics. A smooth, low-friction movement has been achieved by using thrust ball bearings. Also, a 23 mm diameter rod is located at the center of the chamber for specimen support. The rod has two degrees of freedom: rotation and vertical translation.

Each ring has tapped through-holes interleaved, as shown in Fig. 3, allowing the user to install multiple sample or detectors holders. In order to control remotely each ring position, stepper motors and gears were installed. By using a software, an accuracy of about 0.25° per step has been achieved. The central rod can be rotated with an accuracy of 3° and displaced vertically 0.1 mm per step.

At the end of the chamber, a 37 Faraday cup (FC) array was designed and constructed to measure beam current (Fig. 3b). As a consequence, beam intensity and uniformity can be known. Each cup consists of a 70 mm long and 10 mm inner diameter aluminium cylinder, electrically connected to a multiplexer system through the DB25 feedthroughs. A couple of neodymium magnets are installed in every cup to suppress the secondary electrons (Schmidt and Wetzig, 2013). Current measurements are recorded with a Keithley 6517A electrometer connected to the multiplexer system, used to choose the FC to measure. At present, only 9 central FC are connected to the multiplexer and used for beam characterization and dosimetry. Another multiplexer will be available in the future in order to allow measuring the 37 FCs.

Observation and illumination of the chamber interior is possible using a CCD camera mounted on the inner side of the chamber. The camera is placed just above the beam entry port, pointing towards the Faraday cups. It has infrared LEDs, allowing the observation of the target even under irradiation.

3. Beam characterization and dosimetry

Experiments with various particles, energies and current intensities have been performed using the facility. To characterize and monitor an intense beam, the array of FCs can be used. For SEP experiments very weak beam intensities are used, below the FC sensitivity. For these studies silicon PIN photodiode detectors are employed, with conventional pulse counting electronic.

3.1. Faraday cups

For beam current intensity higher than a few nA the FCs can be used for dosimetry. A simple procedure is used for adjusting the beam optics elements to guide the beam and to hit the center of the irradiation chamber. This is first done using an empty foil holder in the rotating disc and observing the beam spot produced on a phosphor paint applied on the front surface of the FC's front plate. Once the beam is collected by the center cup, the rotating disc is adjusted to set the dispersing aluminium foil required for get a uniform beam at the target. The overall beam uniformity achieved with this technique is better than 10% over the whole target area (Ochoa et al., 2017).

The current in the central FC and eight surrounding cups is measured for a definite period of time. A geometric factor is calculated, obtaining a relationship between measurements on each cup. Once the sample is set at the center position, the indication from one or more lateral cups is used for dosimetry during the irradiation.

3.2. Pin diode

As fluxes decrease to a hundred particles/(cm^2.s), handling the beam becomes very difficult. Thus, experiments are carried out with a stable and manageable current, while a tantalum (Ta) filter (covered by a copper foil) limits flux by allowing particles to pass only through the holes. Three different filters with different numbers of holes and hole diameters were made. The copper foil is used as a dispersive foil to spread the beam uniformly over the sample area.

Within this values of intensity, beam characterization and dosimetry are performed with a set of PIN photodiodes (Fig. 4). The silicon diodes have a sensitive area of 5 mm^2, and their signals are preamplified, shaped/amplified, discriminated and counted using conventional NIM electronic modules. An arrangement of 5 diodes is used for those experiments. Four diodes are fixed around the device under test (DUT)

Fig. 4. Schematic setup for SEP experiments (a) Shutter closed for beam characterization, (b) Shutter open for DUT irradiation.

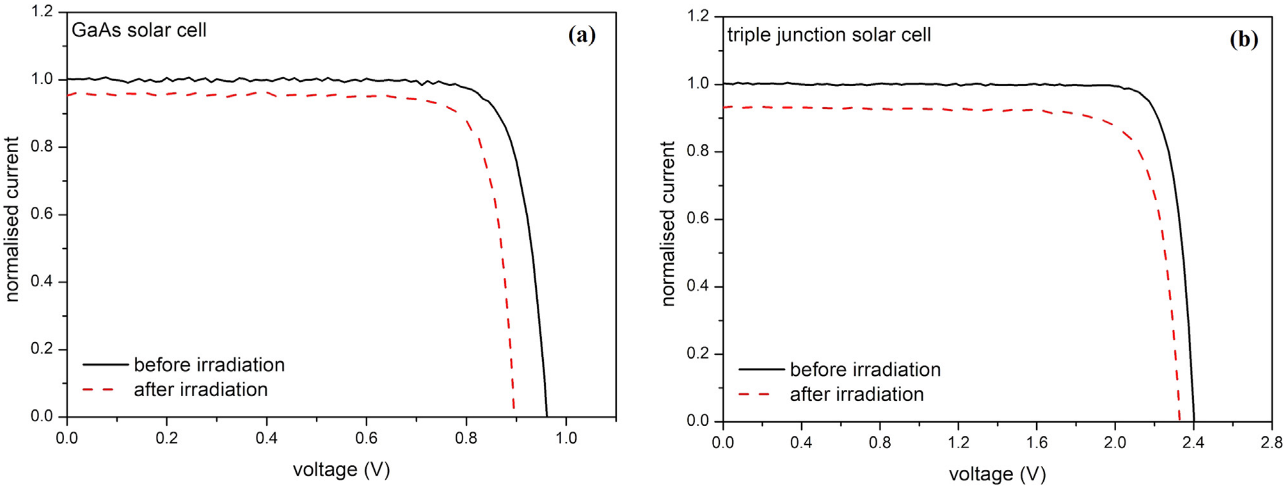

Fig. 5. Normalized I-V curve for (a) GaAs homojunction solar cells, (b) multijunction solar cell irradiated with a 10 MeV proton beam and a fluence of 2.93x 10^{11} p/cm^2 and 3.76x 10^{11} p/cm^2 respectively.

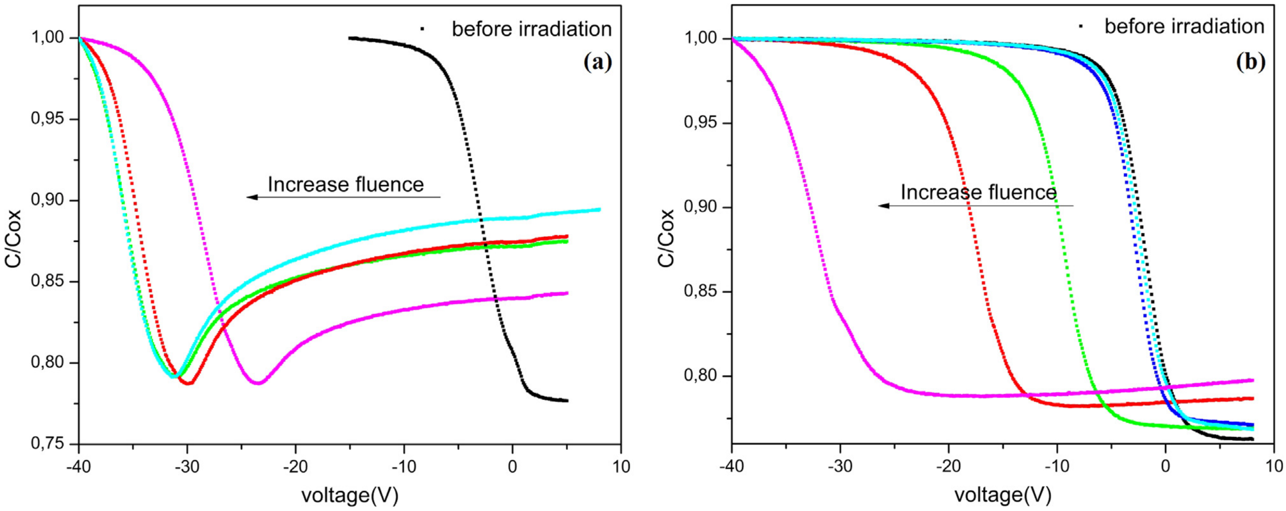

Fig. 6. Normalized C-V curves at 1 MHz for MOS capacitors irradiated with (a) 25 MeV ^{16}O ions and (b) 10 MeV protons.

and the last one is mounted in a mobile beam shutter, which can be placed in front of the DUT (Ibarra et al., 2014).

The rotating disc is set to a position corresponding to the Ta-Cu filter with the attenuation factor selected for the experiment. The ion beam passes through the holes and the copper foil and reaches the irradiation chamber. When the shutter is closed, the number of particles/(cm^2.s) can be calculated from the number of detector counts using the PIN diode area and the irradiation time for normalization. Then, the shutter is opened and the ion beam hit the DUT. Dose can be measured using the fixed detectors total recorded count.

4. The experiments

Since 2004, several experiments were performed at the E.D.R.A. facility. Due to the versatility of the beam line and the irradiation chamber, a large number of experimental conditions could be achieved.

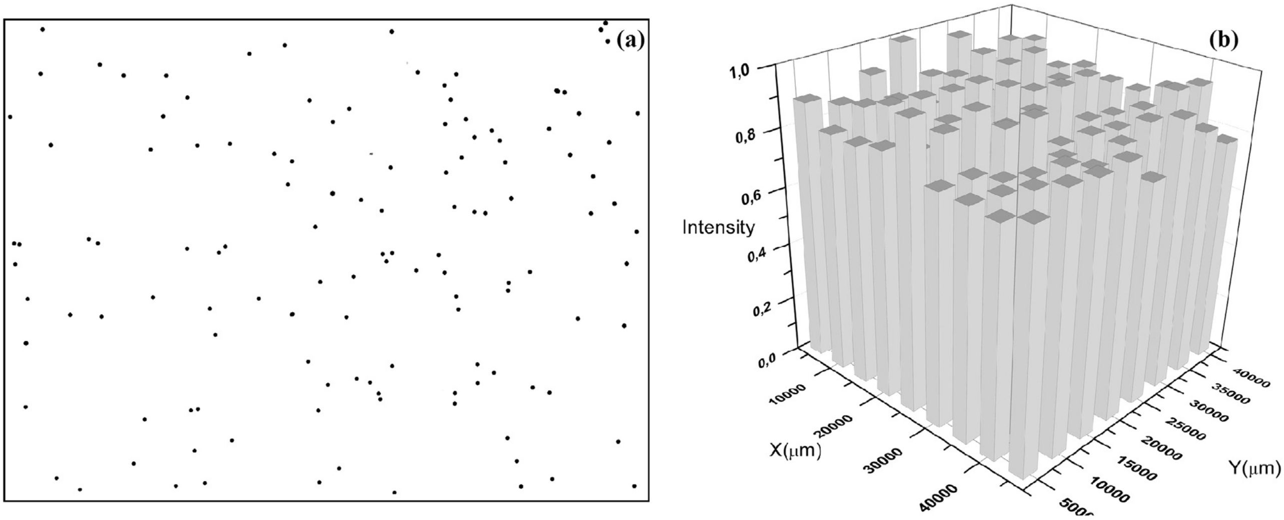

Fig. 7. (a) Optical micrograph of polymer irradiated. (b) Tracks intensity (count number) observed in a 50 × 50 mm^2 polymer foil irradiated with Ta-Cu filter and an 83 MeV ^{127}I beam.

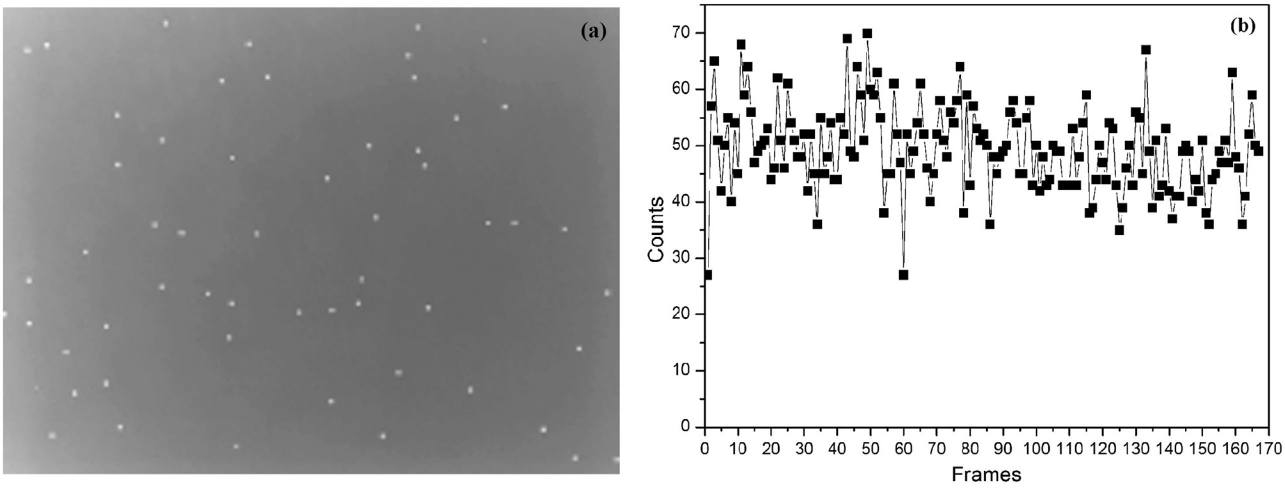

Fig. 8. (a) Sensor response for protons, (b) Number of detected particles in 170 frames of a webcam irradiated with Ta-Cu filter and a fluence of 1 x 10^7 p/cm^2 using an 8 MeV proton beam.

Diverse studies, from radiation damage test for space qualification of electronic devices, to studies of new electronic components and materials were carried out (Sondon et al., 2009; Alurralde et al., 2013; Yaccuzzi et al., 2015; Saint Martin et al., 2017; Ochoa et al., 2017; Garcia et al., 2017).

Commercial, triple junctions solar cells, as well as numerous experimental solar cells and coarse solar sensors have been irradiated with a 10 MeV proton beam (Alurralde et al., 2008; Tamasi et al., 2009). Also, environmental tests on silicon sensors and studies of radiation damage in new resistive memories were performed (Ghenzi et al., 2014).

To illustrate these capabilities, some examples of experiments done at the facility and their results are described below.

4.1. Total non ionizing dose experiments

One example is the study of the gradual degradation of devices performance produced by displacement damage in a set of homojunctions GaAs solar cells and multijunction solar cells (Ochoa et al., 2017). The devices were mounted on a holder in one of the concentric rings of the chamber. The I-V (Current-Voltage) curves were measured *ex situ* before and after irradiation using a TS-Space Close Match solar simulator at $T = 28\,^{\circ}$C with 1.367 kW/m^2 (equivalent to AM0 spectrum). The irradiance was set using AM0 calibrated GaInP and GaAs isotype cells to adjust the spectral intervals 300–700 nm and 700–900 nm respectively. Finally, an AM0 calibrated GaInP/GaAs/Ge triple junction cell was used to verify the proper simulator calibration.

In addition, the solar cells were measured *in situ* before and after each dose during the irradiation experiment using a Sciencetech solar simulator with AM0 filter coupled to the irradiation chamber through a borosilicate window and using a source measure unit (SMU) Keithley 2602A with four wire configuration (Fig. 5). All I-V curves are presented under standard conditions (1 sun AM0, 28 °C) after temperature and irradiance corrections using as reference the measurements performed with TS-Space simulator.

4.2. Total ionizing dose experiments

Another application of the facility has been the study of the cumulative effects induced by an exposure to protons and electrons present in the space environment, the so called TID effects. One experiment of this kind was performed with MOS capacitors irradiated with 25 MeV ^{16}O ions with 4 accumulated fluences (from 1 x 10^{10} to 2 x 10^{11} p/cm^2) and 10 MeV protons with 5 accumulated fluences (from 6 x 10^8 to 2 x

10^{11} p/cm^2) (Ibarra et al., 2015). *In situ* characterization was performed by means of C-V (Capacitance-Voltage) measurements during irradiation experiments and from the curves obtained the characteristic parameters were estimated (Fig. 6).

4.3. Single event phenomena effects

As the Ta filters were made at CNEA (Ibarra et al., 2012), several experiments were performed in order to test the filter attenuation factors and the uniformity of the ion beam at the irradiation chamber. Special insulator polymer foils Lexan™ were used as nuclear track detector (NTD). The ion beam produces molecular structure modifications (nuclear tracks) in the polymer due to the high energy density, deposited through electronic and nuclear interactions (Portu et al., 2011).

The NTD were irradiated with several heavy ions species and a beam intensity chosen in order to produce an average track density of 1 x 10^6 p/cm^2. The detectors were chemically etched and then observed in an optical microscope equipped with a digital acquisition system. Tracks in the micrographs were counted and the coordinates (x, y) of each track were recorded (Fig. 7a). The track distribution was studied applying spatial statistics to the data obtained from the micrographs. Free, R software environment for statistical computing and graphics was used with this aim (R Development Core Team, 2011). The analysis concluded that tracks are randomly distributed with 99.95% confidence, so the beam uniformity was verified.

Also, in order to test the capabilities of the filter system we irradiated a webcam sensor with an 8 MeV proton beam and Ta-Cu filter. A 100-second film was recorded in using the three Ta-cu filters. To analyze the result, the films were separated into frames (Fig. 8). Statistical analysis was performed and a random and uniform distribution of illuminated pixels was verified.

5. Conclusions

E.D.R.A. is an irradiation facility designed to study device's behaviour under simulated space conditions. Using this system, it is possible to measure space solar cells under proton irradiation to study Total Non Ionizing Dose, or electronic devices under operation to assess their response to Total Ionizing Dose or Single Event Phenomena effects.

The capabilities and the flexible design of the chamber were described. This versatility allows performing qualification tests on devices (thermovacuum, thermocycled, radiation damage tests). Also, research radiation experiments are carried out in devices of various kinds and geometries, using the motorized rings and rotating disc.

To illustrate the capabilities, several experiments were described. In order to study the degradation produced in the spatial environment, III-V solar cells were irradiated with a 10 MeV proton beam. To study the accumulation of damage, capacitors were irradiated with 25 MeV ^{16}O ions and 10 MeV protons. Finally, to show the ability to perform ultra-low flux experiments (*e.g.,* SEP), a webcam was irradiated with 8 MeV protons.

One goal of this line is to provide support to the Argentine National Commission for Space Activities (CONAE) studying the response to space radiation of electronic devices for space application. On the other hand the DES continues carrying out research tasks and studying the radiation damage in solar cells, always seeking novel aspects.

EDRA flexibility allows studying the behaviour of several different devices and materials under development at DES and other research institutes, universities or companies.

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