SIRAD: an irradiation facility at the LNL Tandem accelerator for radiation damage studies on semiconductor detectors and electronic devices and systems

J. Wyss\textsuperscript{a}, D. Bisello\textsuperscript{b,\*}, D. Pantano\textsuperscript{b}

\textsuperscript{a}Facoltà di Ingegneria dell’Università di Cassino, Cassino, INFN Sezione di Pisa, Pisa, Italy
\textsuperscript{b}Dipartimento di Fisica, dell’Università di Padova, INFN Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy

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Abstract

This article describes the essential features of the SIRAD facility of the INFN Laboratori Nazionali di Legnaro. This facility, located at the 15 MV Tandem accelerator, is dedicated to radiation damage studies (bulk damage, total dose and Single Event Effects) induced by protons and heavy ions on semiconductor detectors, electronic devices and systems. SIRAD is at present routinely used by groups involved in detector development for elementary particle physics, in electronic device physics and in space applications. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The study of the effects of the radiation—natural and artificial—on semiconductor devices is an important and lively field of scientific and technological research inspite of 50 years of history. Tolerance to radiation is an important issue in many applications of electronic devices and sensors: nuclear plants, space research, telecommunication, avionics, medical imaging, high energy physics. In particular, the interest is quickly growing in this latter field due to the huge radiation levels expected for the experiments at the new accelerators.

Radiation damage of a semiconductor device occurs when there is a deposition of energy in the form of atomic displacement and/or ionization. In both cases the effects can be cumulative—bulk damage and total dose effects—or instantaneous—Single Event Effects (SEE).

The tolerance to bulk damage and total dose effects is usually measured by irradiating the particular item under study with a standard particle beam or electromagnetic wave, or by extrapolating from measurements with different particle beams at fixed energies the damage induced by a radiation with a continuous energy spectrum and various components.
The sensitivity of a device to SEE is generally determined by measuring the rate of occurrence of the particular effect under study as a function of the energy deposited, typically by irradiating the device with ions of different LET.

Both these aspects can be addressed by the SIRAD irradiation facility which will be described in the following (Table 1).

2. The facility

The SIRAD irradiation facility is located at the INFN Legnaro 15 MV Tandem accelerator that can deliver proton and ion beams up to Au. After passing through the analyzing and switching magnets, the beam is injected into the +70° line of the heavily shielded Experimental Hall n. 1. The essential elements of the SIRAD line, shown schematically in Fig. 1 are:

(1) a system of adjustable horizontal and vertical slits,
(2) a quadrupole doublet for focusing the beam down to millimetric spots,
(3) an electric rastering system for irradiating extended targets,
(4) a diagnostic chamber with a wire beam profiling monitor (BPM) and an extractable Faraday cup (FC70),
(5) an irradiation chamber including a battery of small Faraday cups and a battery of silicon diodes with pulse counting electronics.

The essential beam optics elements are shown schematically in Fig. 2, the longitudinal beam profile is that of a 130 MeV $^{28}$Si beam with charge $Q = 9$ focused down to millimetric size on the target plane. Beam line calculations are based on the TRANSPORT [1] package.

2.1. Protons

The cross section of a typical focused proton beam in the SIRAD line has Gaussian shape with a RMS of a few mm. In order to irradiate large target areas (e.g. large or numerous samples) the beam can be rattled uniformly by means of vertical and horizontal deflection plates 1 m long, with 5 cm gaps, and with linearly ramped voltages (non linearity < 2% over 85% of $V_{pp}$, $V_{max} = \pm 15$ kV) at slightly different frequencies ($v_x = 625$ Hz, $v_y = 612$ Hz) (Fig. 3).

The rastering system permits an uniform irradiation over a fiducial area of 5 cm x 5 cm on the target plane positioned 7.5 m downstream. The uniformity measured by a battery of nine small Faraday cups (see Section 5.2) is better than a few percent (Figs. 4 and 5).

The maximum proton currents routinely available (20 – 25 nA) are limited by the activation of the beam line. With such values uniform fluences up to $10^{14}$ p cm$^{-2}$ over the full fiducial area can be achieved in about 5 h.

2.2. Ions

The maximum rigidity of the +70° line, about 1.5 T m, allows the injection of almost all ions available at Legnaro (see Table 2). The values reported for the different ion species refer to the most probable charge state using two foil strippers. The LET is calculated for a silicon target.

To reach the low ion fluxes required for SEE studies the standard recipe involves adjusting the fields in the switching magnet quadrupole doublet and the SIRAD quadrupole doublet. Typically both switching quadrupoles are set to zero, while

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Radiation effects studied at SIRAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy transfer</td>
<td>Protons</td>
</tr>
<tr>
<td>Displacement</td>
<td>Bulk damage</td>
</tr>
<tr>
<td>Ionization</td>
<td>Surface damage</td>
</tr>
</tbody>
</table>

The rastering system was constructed by IBA, Ion Beam Applications, Louvain-la-Neuve, Belgium.

In Table 2 the potential is taken to be 15 MV and the injection energy is taken to be 150 keV. Actually the injection energy presently available is 180 keV.

Switching doublet (quad1,quad2) and the SIRAD doublet (quad3,quad4) where the number corresponds to the natural succession encountered by an ion. Quad2 and quad3 have positive polarity; i.e. they focus in the horizontal plane and defocus in the vertical plane, while quad1 and quad4 are negative.
the SIRAD quadrupoles are both set to about 50% of their maximum value of 12.8 T/m. With such settings the beam is focused about 10 m before the target plane (Fig. 6). At this point the distribution and intensity of the ion flux on the target plane can be controlled by:

1. adjusting the machine collimators (the source),
2. adjusting the SIRAD collimators,
3. changing the fields of the SIRAD quadrupoles (fine adjustments),
4. inserting a third stripper outside the Tandem just before the analyzing magnet thereby changing charge distribution of the ion beam.

3. Beam diagnostics and current monitors

Beam diagnostics is performed by a system of wires and a Faraday cup, both extractable, positioned in a diagnostic chamber located 80 cm upstream of the target plane. On-line monitoring of the beam current and uniformity on the target is provided by a system of small Faraday cups or silicon diodes located in its proximity. In ion irradiations visual inspection of the beam profile can be performed on a quartz window positioned at the end of the irradiation chamber.
3.1. Wires

The transverse beam profile and the rastering uniformity can be measured by an extractable grid [2] of 50 μm XY wires placed 80 cm upstream of the sample holder. The beam profile is directly obtained from the current distribution in the wire system: 4 the two wire planes orthogonal to the beam define separately the horizontal and vertical profile of the beam. Each plane consists of 39 gold plated tungsten–rhenium wires (50 μm diameter) evenly distributed over 5 cm. With no rastering, the wire spacing allows beam spot adjustments to millimetric sizes.

The wire system is crucial for quick beam diagnostics such as beam centering and adjustments to the rastering profile obtained by changing the voltage on the rastering plates. It takes advantage of two mechanisms;

1) the impinging primary ion is stopped in a wire thereby depositing its charge (except protons),

2) extraction of secondary electrons produced by primary ion striking the wires. Although secondary electron production by protons is not copious, the typical proton currents used at SIRAD are high enough for the wire system to be sensitive allowing for diagnostics.

3.2. Faraday cups

An extractable Faraday cup (FC70) can be inserted just behind the wire system for beam positioning and precision measurement of its current. The cup, made of a gold plated copper cylinder 43 mm long and plugged by a tantalum cone, is complete with a stainless steel electron suppressor with a 15 mm central hole.

The system of nine independent small Faraday cups, arranged in a square formation, 3-by-3, positioned 10 cm behind the target plane matching with the fiducial area, monitors the current during irradiation. Each of these cups is a 12 cm deep aluminum square tube 15 mm wide plugged by a tantalum target 2 mm thick; the nine tubes are electrically isolated from one another and from a tantalum electron suppressor plate 2 mm thick.

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4 The current is not an absolute measurement of the beam current unless the secondary electrons are suppressed.
Fig. 4. Current uniformity. The current density versus the voltage on the deflector plates. For the specific ion and energy, the corner cups are not illuminated for voltages below 4.5 kV. For higher voltages the cups are uniformly illuminated. The curve is a power law fit to the central cup currents. The currents drop with the expected dependence on voltage (area).

Table 2
Surface LETs and range in silicon for typical ions at Tandem energies

<table>
<thead>
<tr>
<th>Ion</th>
<th>Kin (MeV)</th>
<th>Surface LET (MeV cm²/mg)</th>
<th>Range (μm)</th>
<th>Probability</th>
<th>Rigidity T m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>30.15</td>
<td>0.015</td>
<td>5000</td>
<td>1</td>
<td>0.80</td>
</tr>
<tr>
<td>³⁷Li</td>
<td>60.15</td>
<td>0.35</td>
<td>435</td>
<td>0.94</td>
<td>1</td>
</tr>
<tr>
<td>¹²C</td>
<td>101.4</td>
<td>1.4</td>
<td>191</td>
<td>0.35</td>
<td>0.8</td>
</tr>
<tr>
<td>¹⁶O</td>
<td>116.4</td>
<td>2.9</td>
<td>122</td>
<td>0.30</td>
<td>0.9</td>
</tr>
<tr>
<td>¹⁹F</td>
<td>131.4</td>
<td>3.6</td>
<td>113</td>
<td>0.21</td>
<td>0.9</td>
</tr>
<tr>
<td>²⁸Si</td>
<td>168.9</td>
<td>8.5</td>
<td>70</td>
<td>0.13</td>
<td>0.9</td>
</tr>
<tr>
<td>³⁵Cl</td>
<td>183.9</td>
<td>12.4</td>
<td>57</td>
<td>0.11</td>
<td>1</td>
</tr>
<tr>
<td>⁵⁸Ni</td>
<td>247.7</td>
<td>26.5</td>
<td>41</td>
<td>0.069</td>
<td>1.02</td>
</tr>
<tr>
<td>⁶³Cu</td>
<td>247.7</td>
<td>28</td>
<td>38</td>
<td>0.067</td>
<td>1.06</td>
</tr>
<tr>
<td>⁷⁹Br</td>
<td>258.9</td>
<td>38</td>
<td>35</td>
<td>0.055</td>
<td>1.14</td>
</tr>
<tr>
<td>¹⁰⁷Ag</td>
<td>296.4</td>
<td>53</td>
<td>33</td>
<td>0.044</td>
<td>1.22</td>
</tr>
<tr>
<td>¹²⁷I</td>
<td>296.4</td>
<td>59</td>
<td>30</td>
<td>0.040</td>
<td>1.33</td>
</tr>
<tr>
<td>¹⁹⁷Au</td>
<td>333.9</td>
<td>80</td>
<td>28</td>
<td>0.032</td>
<td>1.54</td>
</tr>
</tbody>
</table>
with 9 square holes (6 mm-by-6 mm) that define the sensitive areas.

The current [integrated charge] values which directly give the particle flux [fluence] are measured as voltage drops on 100 MOhm resistors by HP34401A multimeters which permit a sensitivity of 10 pA. A current preamplifier stage can increase the sensitivity to 100 fA with a RMS noise of 25 fA.

3.3. Counting diodes

For single event effect studies, the particle flux must be on one hand low enough to distinguish the effects caused by the impacts of single ions and on the other hand high enough to observe a significant number of single effects in a reasonable amount of time.

In most practical cases, the necessary flux remains below the sensitivity of the Faraday cups. Therefore, ion fluxes lower than a few $10^5$ ions/cm$^2$/s are monitored by a battery of silicon diode detectors with sensitive areas of 0.16 cm$^2$ and pulse counting electronics.\footnote{The present diodes are PNN$^+$ structures with multiguards designed by N. Bacchetta, INFN-Padova, and processed by Micron Semiconductor Ltd., Lancing, Sussex BN15 8UN, UK.} In the present design the diodes are distributed at the vertices of a square 4 cm across located immediately upstream of the target plane. The typical non-uniformity over these upstream diodes is smooth enough to allow a good estimate of the flux at the position of the DUT, device under test (Fig. 7).

Another group of 4 diodes, packed into a 1 cm-by-1 cm$^2$, can exchange positions with the DUT. This mobile group of diodes is used during the beam setup to check the estimate of flux on the DUT obtained from the 4 detectors upstream.

Both the diode groups are read-out simultaneously by an electronic module in which signals are preamplified, shaped and discriminated. The threshold corresponds to an energy loss of 4 MeV in silicon and the chain is linear up to 500 MeV (Figs. 8 and 9). The shaping time of the order of 5 $\mu$s allows a maximum rate of 200 kHz. Therefore, the fluxes routinely obtained are limited to less than about $3 \times 10^5$ ions cm$^{-2}$ s$^{-1}$ to keep...
pile-up effects from affecting the flux measurements. The counting electronics will be soon upgraded (threshold to 1 MeV and rate to 500 kHz) to be able to handle higher rates necessary for the lightest ions with small LET.

Nevertheless silicon diodes suffer severe damage when exposed to heavy ions; in particular the charge collected for a given bias voltage decreases. Therefore, the charge distribution of the pulses is continuously monitored during the duration of an irradiation session to make sure the charge collected per impact remains above the threshold of the pulse counting electronics. The diodes used have a multiguard structure that allows one to raise the bias voltages (up to 500 V) to help the maintenance of full counting efficiency as long as possible (e.g. throughout a typical 48 h run).

### 4. The irradiation chamber and the sample holder

Irradiations, both with protons and heavy ions, are performed in vacuum, to take advantage of the full beam energy. The vacuum, which must be better than $8 \times 10^{-9}$ mbar for the beam to be delivered, is obtained with a VARIAN molecular pump (Turbo-V 550) and monitored with a Penning probe.

The irradiation chamber was designed to permit further improvements, as the possibility to irradiate samples kept at liquid nitrogen temperature.
As a consequence its volume is big (130 l), this value being further increased by the presence of the diagnostic chamber (25 l). The time required to attain the desired pressure value in such a volume is about 450 with clean samples under test. A substantial reduction is expected soon by operating re-entries with N₂.

A multiple sample holder (bayonet system), 30 cm long and 10 cm wide, allows for the irradiation of different samples without breaking the vacuum. The vertical position of the sample holder can be varied with continuity through a controlled step motor. The sample holder is inserted into the irradiation chamber through a circular flange of diameter 160 mm. An adjacent lateral circular flange of diameter 160 mm contains BNC feed-throughs (16 at present) for connecting signal and/or control cables to the mounted samples.

5. Beam operations

Proton beams are routinely delivered by the Tandem. The time required to get the beam centered in our extractable Faraday cup is usually less than 15'. Some caution must be used in varying the proton energy by changing the Tandem voltage to take into account the conditioning time required to increase the voltage, typical of electrostatic machines.

With heavy ions the time to get the desired intensity and uniformity on the target can be up to 30' since low intensity and defocused ion beams are not routinely required to the Tandem operators.

In general, the stability during a shift is such that the machine settings for a certain beam are reproducible and previous beam conditions can be re-obtained in few minutes.

More time is needed when various ion species are required by the experiment. An ion species is changed in about 1 h. This includes changing the source and the Tandem optics to extract the new beam and making the final adjustments to the beam in the SIRAD line (focusing, defocusing). Also, for a given ion species, changes in energy can be obtained by varying the Tandem voltage and/or the charge state of a given species. If only the charge state is changed the total time to deliver the new energy beam is about 30'. This includes extracting the beam and final adjustments. This time is comparable to the pump-down time of the irradiation chamber. A valve, recently installed between the diagnostic chamber and the irradiation chamber, allows preparing the beam during pump-down.

6. The activity

Irradiations started in Fall 1997 with proton and in Spring 1999 with ion beams. The present activity at SIRAD can be broadly grouped into two classes:

(1) Proton irradiation of silicon diodes and detectors, for use in HEP, with the purpose of optimizing their tolerance to the very harsh radiation levels expected at the next generation experiments [3]. Studies are performed on the roles played by substrate resistivity and impurity concentration [4–7], the layout of multiguard structures on diodes fabricated by various producers, and different fabrication technologies in achieving radiation tolerance. Tests are also made of full size detectors developed by the CMS [8] and CDF [9] collaborations for the experimentation at the future Large Hadron Collider (LHC) and at the Tevatron.

(2) Heavy ion irradiation of electronic devices and systems to induce SEE, such as latchups in analog and digital devices, logic upsets in digital components, burn-outs in power devices, and total dose effects. The SEE studies are of great importance for assessing the radiation tolerance of present commercial CMOS and bipolar devices for their application in HEP experiments and space environment. This activity is performed within the CMS [10] and PAMELA [11] experiments, the CERN based TOLRAD collaboration [12], the Italian joint MURST/INFN R&DI program Electronics and particle detectors for space research and contracts with industries.
The studies of Single Event Burn-out Effects induced on power diodes [13] are sponsored by industrial partners. Present studies on total dose effects include measurements of radiation induced leakage current and soft breakdown in gate oxides in MOS capacitors [14,15].

7. Conclusions

The SIRAD facility, constructed in 1996, was originally intended for proton irradiations. Since then the heavy-ion program has grown quickly. The facility is flexible and competitive and there is room for further improvements.

It is currently used by a large number of experiments thanks to a shift budget of \(\approx 20\) days/year.

Nevertheless the maximum rigidity of the line is about 1.5 T m, as the line is at 70\(^\circ\), and this makes difficult to inject ions with very high LETs and obtain tenuous currents of ions with the lowest LETs. We are planning to move the SIRAD facility to 50\(^\circ\) beam line which also allows us to inject ions from the ALPI post-accelerator [16].

Of course SIRAD can only make a global characterisation of the sensitivity to SEE of the device under test. To obtain a spatial characterisation at the micron level or better we are planning, following an idea developed at the SANDIA Laboratory [17], the insertion of an electron microscope to collect and measure the electrons emitted by the ions hitting the device. In this way the behaviour of the device may be correlated with the impact point.

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References