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LNL irradiation facilities for radiation damage studies on electronic devices

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Summary. — In this paper we will review the wide range of irradiation facilities installed at the INFN Legnaro National Laboratories and routinely used for radiation damage studies on silicon detectors, electronic components and systems. The SIRAD irradiation facility, dedicated to Single Event Effect (SEE) and bulk damage studies, is installed at the 14 MV Tandem XTU accelerator and can deliver ion beams from H up to Au in the energy range from 28 MeV to 300 MeV. An Ion Electron Emission Microscope, also installed at SIRAD, allows SEE testing with micrometric sensitivity. For total dose tests, two facilities are presently available: an X-rays source and a ^{60}Co γ-ray source. The 7 MV Van de Graaff CN accelerator provides ^{1}H beams in the energy range 2–7 MeV and currents up to few μA for both total dose and bulk damage studies. At this facility, very high dose rates (up to $\sim$100 krad/s (SiO_2)) can be achieved. Finally, also neutron beams are available, produced at the CN accelerator, by the reaction d + Be $\Rightarrow$ n + B.

PACS `61.82.Fk` – Radiation effects on semiconductors.
PACS `61.80.Jh` – Ion irradiation effects.
PACS `61.80.Cb` – X-ray effects.

1. – Introduction

Radiation is ubiquitous and may affect living beings, as well as materials. Tolerance to radiation is an important issue in many applications of electronic devices and sensors: physics at the accelerators, space research, telecommunication, avionics, nuclear plants, fusion reactor projects, medical imaging. In particular, ground-based commercial electronics is becoming more and more susceptible to radiation effects induced by atmospheric neutrons (created in the air-showers initiated by very high energy galactic cosmic rays interacting with the atomic nuclei of the upper atmosphere) due to technology trends in electronics towards smaller structures. Electronics designed to work in harsh environments has to be validated, *i.e.* its reliability has to be checked for the radiation doses foreseen in the actual environment. This is usually carried out with ground tests with particle accelerators or photons sources.

2. – Radiation effects

When a particle strikes a microelectronics device, it can transfer energy to the medium both by atomic displacement and/or by ionization, giving rise to different kinds of macroscopic damages: Single Event Effects (SEE), Total Dose Effects (TID), Total Displacement Damage (TDD).

SEE is the damage induced by the passage of a single energetic ionizing particle which releases enough ionization in a sensitive volume to induce a device/system malfunction; it is therefore a threshold effect. TDD is the cumulative damage caused by the displacement of crystal atoms by the interaction of the incident particles with the nuclei of the lattice atoms. TID is the performance degradation of irradiated devices due to the accumulation of charge in oxide layers and at the Si-SiO_2 interface in microelectronic circuits exposed to ionizing radiation.

Depending on the radiation environment, one or more of the previously described effects may affect the operation of the electronic devices and systems.

3. – LNL irradiation facilities

The INFN Legnaro National Laboratories (LNL) located close to Padova (Italy) are a well-known center for validation of electronics operating in radiation harsh environments. Here a large number of tools are present to test microelectronics devices and systems, as well as silicon detectors, concerning the different types of radiation effects previously described. Also studies of material modifications induced by high dose irradiations can be performed.

3˙1. *The SIRAD irradiation facility.* – Both Single Event Effects (SEE) and bulk damage studies are routinely performed at the LNL SIRAD irradiation facility (fig. 1) [1, 2]. Irradiations at SIRAD started in 1997 with protons (bulk damage) and in 1999 with ion beams (SEE). The SIRAD irradiation facility is serviced by the Tandem-XTU accelerator with a maximum operating voltage of 15 MV. Table I reports the characteristics of the ion beams available at SIRAD with the typical Tandem setting of 14 MV [1, 2].

Depending on the type of test, the SIRAD beam line can operate both at high and low ion fluxes, $\phi \geq 5 \times 10^8\,\text{cm}^{-2}\text{s}^{-1}$ and $\phi \leq 5 \times 10^5\,\text{cm}^{-2}\text{s}^{-1}$, respectively. For high-flux operations the beam diagnostics is performed by a set of Faraday cups. For SEE studies the ion flux on the target plane is typically in the range 10^2–$10^4\,\text{cm}^{-2}\text{s}^{-1}$, far below the sensitivity of the Faraday cups. Silicon diodes are then used with pulse shaping and counting electronics to directly measure the ion flux.

3˙2. *The Ion Electron Emission Microscope.* – An Ion Electron Emission Microscope (IEEM) [4, 5] was installed in 2004 at the end of SIRAD to include micrometric SEE characterizations. In the IEEM technique the impact positions of individual heavy ions are reconstructed, over a circular area of 180 μm diameter, with a resolution of few micrometers, by imaging the secondary electrons emitted by the impacted surface. Any ion-induced SEE signal in the DUT is time-correlated to the ion impact positions reconstructed by the IEEM. This information is then used to build a micrometric map of

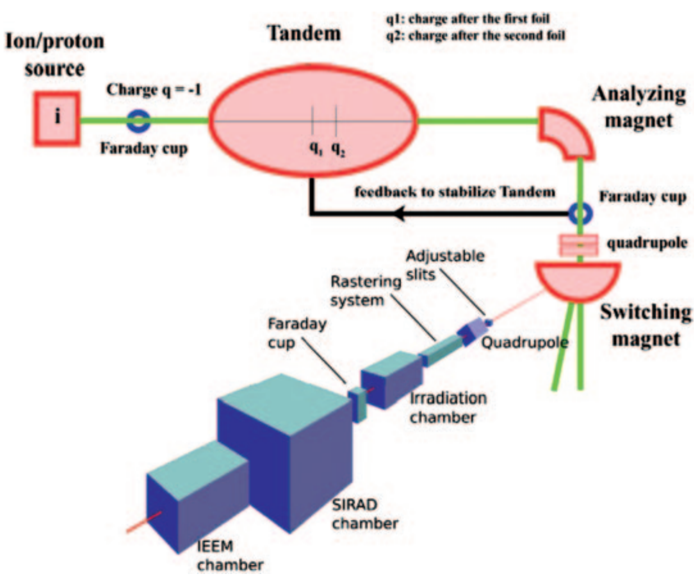

Fig. 1. – Schematic view of the SIRAD beamline at the Tandem accelerator.

Table I. – *Characteristics of the typical ion beams available at SIRAD from Tandem and ALPI accelerators. Surface LET and range are calculated in Si using SRIM* [3].

Ion	E_{Tandem} (MeV)	Q_1	Q_2	LET_{Tandem} (MeV cm^2/mg)	R_{Tandem} (μm)	E_{ALPI} (MeV)	LET_{ALPI} (MeV cm^2/mg)	R_{ALPI} (μm)
^{1}H	28	1	1	0.02	4390			
^{7}Li	56	3	3	0.37	378			
^{11}B	80	4	5	1.01	195			
^{12}C	94	5	6	1.49	171			
^{16}O	108	6	7	2.84	109			
^{19}F	122	7	8	3.87	99.3			
^{28}Si	157	8	11	8.59	61.5	542	3.9	373
^{32}S	171	9	12	10.1	54.4	591	5.2	311
^{35}Cl	171	9	12	12.5	49.1	591	6.2	268
^{48}Ti	196	10	14	19.8	39.3	686	10.9	188
^{51}V	196	10	14	21.4	37.1	686	12.2	171
^{58}Ni	220	11	16	28.4	33.7	780	17.3	147
^{63}Cu	220	11	16	30.5	33.3	780	19.1	135
^{74}Ge	231	11	17	35.1	31.8	826	23.8	121
^{79}Br	241	11	18	38.6	31.3	871	28.1	112
^{107}Ag	266	12	20	54.7	27.6	966	49.4	83
^{127}I	276	12	21	61.8	27.9	1011	61.8	77
^{197}Au	301	13	23	81.3	27.3	1185	92.4	69

the DUT sensitivity to SEE. The IEEM has been successfully used to perform Single Event Upset (SEU) and Ion-Beam–Induced Charge Collection studies on electronic devices [6-8]. More recently, this technique has been used to investigate the origin of supply current spikes in NAND Flash memories when irradiated with heavy ions [9].

3·3. *The ALPI post-accelerator*. – At present, the SIRAD capability to perform SEE studies of electronic devices with thick superficial layers of metallizations/oxides or by backside irradiation, is limited by the particle range of the ions accelerated by the Tandem (see table I). In particular, the heaviest ions (Ag, I, Au) have a range lower than 40 μm, which is the limit requested by the European Space Agency (ESA).

The linear superconducting ALPI post-accelerator [10], is used to give an energy boost to the ions already accelerated by the Tandem or by the PIAVE injector [11]. The high-energy ALPI ions would have the proper range in Silicon (table I).

4. – Total dose studies

For total dose tests, two facilities are presently available: an X-ray Irradiation System and a ^{60}Co γ-ray source.

The RP-149 Semiconductor Irradiation System from Seifert is equipped with a standard tube for X-ray diffraction analysis: maximum power 3000 W, maximum voltage 60 kV, tungsten anode. The tube is located inside a shielding cabinet and it can be moved with an accuracy of 30 μm along the x-, y- (motorized) and z- (manual) axis for accurate positioning on the DUT [12]. A dose rate up to 2 krad(Si)/s can be reached. The ^{60}Co Irradiation Facility is a Panoramic Gammabeam model 150 produced by Nordion Ltd (Canada). The energies of the emitted γ photons are 1.165 MeV and 1.332 MeV. It is a point source for $d > 10$ cm ($d = 10$–300 cm). At $d = 20$ cm the dose rate is 1.425 rad/s (5.10 krad/h) [13, 14].

4·1. *The CN accelerator*. – The CN accelerator is a Van de Graaff accelerator with a maximum terminal working voltage of 7 MV. The ion beams available are $^1H^+$, $^2H^+$, $^3He^+$, $^3He^{++}$, $^4He^+$, $^4He^{++}$ pulsed and continuous. The terminal voltage can be varied from about 1.0 to 6.1 MV. The beam current is $\leq 5\,\mu$A (depending on the channel, and limited mainly by radioprotection reasons) on a spot size of 2–3 mm^2. The beam used for irradiations is serviced by a sample holder which allows to vary the sample temperature from $-10\,^\circ$C to room temperature. Proton beams with these features can be used for both total dose and bulk damage studies. Very high dose rates (up to $\sim$100 krad/s (SiO_2)) can be easily achieved. In addition, the shielding of the laboratory infrastructure allows the irradiation of Be- and Li-based targets with high-current proton beams to produce well characterized fast-neutrons beams. Neutron beams produced in the reaction $\mathrm{d} + \mathrm{Be} \Rightarrow \mathrm{n} + \mathrm{B}$ have a flux which peaks in the forward direction and has a main bump at $E = 3.2$ MeV with a long energy tail up to 11 MeV [15].

4·2. *Other accelerators*. – Irradiations can be also performed at the AN 2000 and at the ion implanter. The AN2000 is a Van de Graaff accelerator with a maximum terminal working voltage of 2.5 MV. The available accelerated ions are ^{1}H, ^{4}He single charged. The beam is continuous. The energy range is 0.25–2.2 MeV. The beam current is few μA (max) on a spot size of 2–3 mm^2. For low energy irradiations, an ion implanter (Danfysik 1090) is also available. The ion energy is in the range E_{ion}: 40–200 keV (Proton range 0.4–1.8 μm in Si); the current density is $J_{beam} \geq 2\,\mu$A/cm^2 over a maximum rastered area of 20×20 cm^2.

5. – Future perspectives

The future installation at LNL of a variable energy (35–70 MeV), high current (500 μA) proton cyclotron will open the possibility of high-flux neutron facilities to perform various research activities. In particular, we foresee the construction of a neutron irradiation facility [16] to study neutron-induced SEE, which are cause of growing concern for commercial electronics. The proposed neutron-SEE facility will offer three tools [17]:

1) an intense atmospheric-like neutron beam;

2) a source of quasi mono-energetic neutrons (QMN) with a controllable energy peak;

3) a direct protons line with variable energy in the 20–70 MeV interval.

6. – Conclusions

We have reviewed the different types of irradiation facilities for radiation damage studies on microelectronic devices and systems and on semiconductor detectors which are presently operating at LNL. These include facilities for bulk damage, SEE (even with micrometric capabilities) and total dose studies. A future facility is foreseen, which will provide intense neutron fluxes and which would integrate the present LNL testing capabilities.

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