Modern Silicon Sensor Devices and their use in HEP, space and medical applications

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INTRODUCTION

The aim of these lectures is to give to the audience a general overview on Silicon Detectors mainly from an experimental point of view: the focus will be mainly on possible application, assembling and testing procedure, facility description etc., while links will be provided for more detailed description of semiconductors theory description.

Due to the amplitude of this field only few topics and examples will be described in more detail, while many other relevant topics will be skipped completely.

Feel free to contact me anytime for questions or suggestions: benedetto.diruzza@unifg.it

NOTE:
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Lecture 1:
Introduction to silicon sensors.
General (tentative) classification: Strips sensors, Hybrid and Monolithic (MAPS) pixel sensors, SiPM, LGAD, others.
Overview of applications in HEP and space missions.
MAPS assembling procedure: the ALPIDE chip and the Alice ITS2 construction.
Trends for Monolithic Active Pixel Detector: studies for large area bent sensors.

Lecture 2:
Overview on the effects of radiation on silicon detectors and electronic devices:
Total Ionizing Dose (TID), Displaced Damage (DD), Single Event Effects (SEE).
Monitoring the radiation dose effects on silicon devices
The Trento proton and x-ray Irradiation Facilities and their use.
X-ray dose delivered measurement for silicon devices.
Procedures for dose evaluation and radiation hardness characterization of devices:
Useful software tools (SPENVIS, TRIM, SpekPy).

Lecture 3:
Overview on the use of radiations for cancer treatment.
Dose measurement for medical application. Beam monitoring and beam Quality Assurance (QA) devices.
Flash irradiation.
Ion therapy facilities: the CNAO and the Trento Proton Therapy Center.
Examples of HEP technologies for to medical applications:
the iMPACT project and the FOOT Experiment.
Lecture 2
References C
Suggested web reference for lecture 2

Serena Mattiazzo: SIRAD School 2019, Legnaro (Padova)
Introduction to Radiation Damage: Physics and Basic Concepts
https://drive.google.com/drive/folders/1y7AEdYsyhxjE3IfwhDP5h-Dn4tizXpvl

Jeffery Wyss: SIRAD School 2009, Legnaro (Padova)
Introduction to radiation damage: concepts, physical quantities, radiation environments
https://sirad.pd.infn.it/scuola_legnaro_2009/Presentazioni_Web/01_ScuolaLNL2009_Wyss.ppt

SiPM Radiation: Quantifying Light for Nuclear, Space and Medical Instruments under Harsh Radiation Conditions
CERN 2022
https://indico.cern.ch/event/1093102/timetable/?view=standard_numbered

Radiation Environment and its effects in EEE components and hardness assurance for space applications. CERN - ESA - SSC WORKSHOP
CERN 2017
https://indico.cern.ch/event/635099
References D
Suggested web reference for lecture 2

RD50/Michael Moll page
NIEL tables
https://rd50.web.cern.ch/NIEL/default.html

CERN x-ray irradiation facility
https://espace.cern.ch/project-xrayese/_layouts/15/start.aspx#

CERN Irradiation facility database
https://irradiation-facilities.web.cern.ch/index.php

RADNEXT: H2020 INFRAIA-02-2020 infrastructure project
https://radnext.web.cern.ch

SPENVIS Software pakage
https://www.spenvis.oma.be
Recap about the effect of irradiation on silicon devices (1)

Particle interactions with silicon sensors:

· Non-ionizing energy loss
  Particles (neutrons, pions, protons, ions, even electrons) can displace atoms from their usual lattice sites and produce “bulk” damage effects, also called displaced damage (DD).

· Ionizing energy loss
  Ionizing radiation, such as x-rays, gammas, and all charged particles create free charge in materials, which affects properties and performance. This effect is called Total Ionizing Dose (TID) damage.

· Single Event Effect
  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 (threshold effect).
Recap about the effect of irradiation on silicon devices (2)

### Radiation: Microscopic effects → macroscopic effects

<table>
<thead>
<tr>
<th>micro-effect</th>
<th>macro-effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small $\Delta E_{\text{ionization}}$ deposited uniformly and delivered over a long time.</strong></td>
<td>charged particles</td>
</tr>
<tr>
<td><strong>Sudden large $\Delta E_{\text{ionization}}$ deposited in the 'wrong place at the wrong time'.</strong></td>
<td>heavy charged particles (protons, ions)</td>
</tr>
<tr>
<td><strong>Accumulation of small $\Delta E$ transfers to atomic nuclei (Coulomb, nuclear interactions).</strong></td>
<td>protons, neutrons, high energy electrons</td>
</tr>
<tr>
<td><strong>Sudden high $\Delta E$ transfer to a single nucleus at the 'wrong place and time'.</strong></td>
<td>Energetic heavy particles (protons, neutrons, energetic ions)</td>
</tr>
</tbody>
</table>

Slide from J. Wyss
Recap about the effect of irradiation on silicon devices (2)

**Source**
- What kind is it (natural, reactor, accelerator)
- Activity
- **Luminosity** of accelerator

**Radiation Field**
- Where are you with respect to the source
- Exposure: what are you exposed to (types of particle at your location)
  - Flux
  - Fluence

**Exposed material**
- What are you made of (silicon, oxide, etc)
- Dose, dose rate
- **Stopping power** of particles (LET, NIEL)
- Various effects (cumulative, sudden)

Slide from S. Mattiazzo
Recap about the the effect of irradiation on silicon devices (2)

Radiation damage quantities (2)

- **Flux** \( (\phi) \) is the number of particles per unit of area and per unit of time
  
  \[
  \phi = \text{particles}/(\text{Area} \times \text{Time})
  \]

  Measurement Unit: particles/(cm\(^2 \times s\))

- **Fluence** \( (\Phi) \) is the number of particles per unit of area (time integral of the flux)
  
  \[
  \Phi = \int \phi \cdot dt = \text{particles/Area}
  \]

  Measurement Unit: particles/cm\(^2\)

Slide from
S. Mattiazzo
Recap about the effect of irradiation on silicon devices (2)

**Radiation damage quantities (3)**

- **Dose** ($D$) is the energy deposited by radiation per unit of mass

- **Absorbed Dose**: is the energy delivered to irradiated matter per unit mass by ionizing radiation
  - $1 \text{ rad} = 100 \text{ erg/g}$
  - $1 \text{ Gray (Gy)} = 1 \text{ J/kg}$
  - $1 \text{ Gy} = 100 \text{ rad}$
  - $1 \text{ rad} = 0.01 \text{ Gy}$

- **Displacement Damage Dose**
  - The fraction of the total energy absorption (per unit of mass) that results in damage to the lattice structure of solids through displacement of atoms

- **Dose equivalent**
  - It refers to a quantity applied to biological effects. It includes scaling factors to account for the more severe effects of certain kinds of radiation

Slide from S. Mattiazzo
Recap about the effect of irradiation on silicon devices (2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Radioactivity</th>
<th>Absorbed Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Rate of radiation emission (transformation or disintegration)</td>
<td>Energy delivered by radiation per unit of mass of irradiated material</td>
</tr>
<tr>
<td><strong>Common Unit</strong></td>
<td><strong>Curie (Ci)</strong></td>
<td><strong>Rad</strong></td>
</tr>
<tr>
<td><strong>Symbol</strong></td>
<td>1 Ci = 37 GBq (a large amount)</td>
<td>1 rad = 100 erg/g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 rad = 0.01 Gy</td>
</tr>
<tr>
<td><strong>International Units</strong></td>
<td><strong>Bequerel (Bq)</strong></td>
<td><strong>Gray (Gy)</strong></td>
</tr>
<tr>
<td><strong>(SI) symbol</strong></td>
<td>1 Bq = 1 event of disintegration per second (a very small amount)</td>
<td>1 Gy = 1 J/kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Gy = 100 rad</td>
</tr>
</tbody>
</table>

Slide from S. Mattiazzo
Recap about the the effect of irradiation on silicon devices (2)

Dose for particles

Dose \( \text{(energy/mass)} = \text{proportionality} \times \text{fluence} \times \text{factor} \)

Total Ionising DOSE (TID) = \( \frac{\text{energy to ionisation}}{\text{mass}} = \text{LET} \times \Phi \)

Displacement Damage DOSE (DDD) = \( \frac{\text{energy to displacements}}{\text{mass}} = \text{NIEL} \times \Phi \)

- Typically Linear Energy Transfer (LET) and Non Ionizing Energy Loss (NIEL) expressed in MeV-cm\(^2\)/mg
- Energy deposited in a block of matter:
  - energy to ionization = LET(energy-length\(^2\)/mass) \times \text{fluence} \times \text{mass}
  - energy to displacements = NIEL(energy-length\(^2\)/mass) \times \text{fluence} \times \text{mass}
TID

Slide from Marc Poizat:
https://indico.cern.ch/event/635099/contributions/2570674/attachments/1456398/2248961/Radiation_Effects_and_RHA_ESA_Course_9-10_May_2017_TID_MP_FINAL.pdf

**Radiation Units**

TID: Deposited energy 1 Gray = 1 J/kg (International System Unit)

- Commonly used unit: **rad** (Radiation Absorbed Dose)
- 1 Gy = 100 rad

\[ \Delta E = \Delta E_{\text{ionization}} + \Delta E_{\text{displacement}} \]

Energy to create one electron-hole pair:
- In SiO\textsubscript{2}: \( \sim 17 \text{ eV} \rightarrow \sim 7.8 \times 10^{12} \text{ e-/h pair per rad.cm}^3 \)
- In Si: 3.6 eV \( \rightarrow \) 4 \( \times 10^{13} \text{ e-/h pair per rad.cm}^3 \)

DD: Energy to create displacement damage
- In Si: 21 eV
Radiation Damage in Silicon Detectors

- The two types of radiation damage to detector materials:
  - **TID** ("surface damage") due to ionization energy loss and trapping of charges in oxide layers and interfaces. It affects:
    - interstrip capacitance (noise factor), breakdown behavior
  - **DDD** ("bulk damage") due to non-ionizing energy loss and build up of crystal defects. It leads to:
    - changes in effective doping concentration (higher depletion voltage)
    - Increase of leakage current (increase of shot noise, thermal runaway!)
    - Increase of charge carrier trapping and hence loss of collected charge.
Displacement damage in Silicon
for neutrons, protons, pions and electrons

A. Vasilescu & G. Lindstroem

From: https://rd50.web.cern.ch/NIEL/NIEL-all.pdf
Depletion Voltage

- Depletion voltage is the bias voltage required to get rid of free carriers in the bulk of the detector.

- The expected evolution depends on the dose (Hamburg Model):

- Before type inversion the depletion voltage decreases due to the reduction in the amount of free carriers

- After type inversion, depletion voltage steadily increases.

Sensor can operate while the Bias Voltage is below the Breaking Voltage

Depletion Voltage study – Signal Vs. Bias

- Plot charge for different bias voltages

- Define depletion voltage, $V_d$, as voltage that collects 95% of the charge at the plateau

- Depletion Voltage as a function of integrated luminosity
  
  3rd order polynomial fit around the inversion point
  
  Linear fit to extrapolate to the future
Depletion Voltage Projections L00-L0

**Prediction for L00**

- L00 ladders
  - Bias-Scan data (average)
  - Extrapolation for ladders
- Sensor breakdown
- Power Supply limit

**Prediction for SVX-L0**

- SVX-L0 ladders
  - Bias-Scan data (average)
  - Extrapolation for ladders
  - Extrapolation from average
- Sensor breakdown
- Power Supply limit

06/11/2011  TIPP 2011  Benedetto Di Ruzza
Not only the sensors are in a radiation environment.

Main components:
- **Silicon Readout Controller (SRC)**: “brain” of the system
- **Fiber Interface Board (FIB)**: control signals and optical readout
- **Portcard**: chip commands and optical transmitters (DOIMs)
Dark current and Beneficial annealing effect

Figure 6. Dark current increases with integrated luminosity with a slope which is proportional to the SiPM area. Deviation from the linear behaviour is due to the recovery time in absence of beam and variation in instantaneous luminosity. The evolution of the dark current in 2017 is shown.

First results from the CMS SiPM-based hadronic endcap calorimeter
DOI: 10.1088/1742-6596/1162/1/012009
Dark current and Beneficial annealing effect

Figure 3. Radiation effects on VELO. Left plot shows the measured leakage current at $-8^\circ$C as function of the luminosity. Each blue line corresponds to a single sensor, the green curve is the mean current value excluding those sensors with initial high currents, and the pink band corresponds to predicted currents. The effective depletion voltage (EDV) for different sensors is shown in left plot. Blue dots corresponds to sensors with initially lower leakage currents, and black to sensors with high leakage current at the beginning.
Facilities for Radiation Hardness characterization

Neutron irradiation for Displacement Damage Studies on Silicon Devices
- The Triga Mark II reactor in Lubiana (Slovenia)
- The Frascati Neutron Generator: a multipurpose facility for physics and engineering (Italy)

Proton Irradiation for Displacement Damage Studies on Silicon Devices
- The Trento Proton Therapy Center (TPTC)
- TPTC Experimental Area
- Experimental area beam parameters
  Irradiation configurations:
  - Small area, high proton intensity irradiation: direct irradiation configuration.
  - Large area, medium/low proton intensity irradiation: double ring configuration.
  - SEE rates studies

X ray irradiation of for TID studies
- The TIFPA-INFN x-ray irradiation laboratory
- Tungsten emission spectrum X-ray penetration in silicon
- FBK SiPM x-ray irradiation campaign

Conclusions on radiation hardness characterization
The TRIGA MARK II reactor in Lubiana, Slovenia

In-core irradiation columns

https://doi.org/10.1016/j.apradiso.2017.09.022
The Frascati Neutron Generator (FNG), Italy: A multipurpose facility for physics and engineering

Deuterons are accelerated by means of an electrostatic accelerator up to 300 kV and 1 mA current is delivered onto a Titanium target, loaded with Deuterium or Tritium, where D-D or D-T fusion reactions (namely \( D+T \rightarrow n+^4He+17.6 \text{ MeV} \) and \( D+D \rightarrow n+^3He+3.27 \text{ MeV} \)) take place.

Description: DOI 10.1088/1742-6596/1021/1/012004
Contact person: Salvatore Fiore (salvatore.fiore@enea.it)

FNG is included in the RADNEXT H2020 program: https://radnext.web.cern.ch
The Trento Proton Therapy Center (TPTC)

https://protonterapia.provincia.tn.it/eng/?/switchlanguage/to/protonterapia_eng
The Experimental Area

Two Experimental beamlines for in-air irradiation

Beam distribution line

Patch-panel for remote control room – cave cables connection (ethernet, BNC, SHV, serial, USB)

Operated by TIFPA-INFN
www.tifpa.infn.it
Beam parameters

The TPTC accelerator and beam distribution system was realized and is operated by the Ion Beam Accelerator Company (IBA, [https://www.iba-worldwide.com](https://www.iba-worldwide.com)).

The proton accelerator is a IBA Proteus 235 cyclotron working at 106 MHz.

Beam current:
- Dark current mode: from ~200 p/s up to ~200 kp/s (mainly for tracking experiments)
- High current mode: From ~0.1nA up to 320 nA

The proton energy at the cyclotron exit is 230 MeV, this energy can be lowered down until 70 MeV using a passive degrader.

The beam delivered in the experimental area has a **gaussian transverse intensity profile** with sigma and peak value depending on the beam energy.

(See REF1 for details)

<table>
<thead>
<tr>
<th>Energy(*)</th>
<th>Average sigma (gaussian profile)</th>
<th>Flux(**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[MeV]</td>
<td>[mm]</td>
<td>[p/s]</td>
</tr>
<tr>
<td>70.2</td>
<td>6.92</td>
<td>3.8x10^6</td>
</tr>
<tr>
<td>100.0</td>
<td>5.68</td>
<td>1.2x10^7</td>
</tr>
<tr>
<td>142.9</td>
<td>4.56</td>
<td>3.6x10^7</td>
</tr>
<tr>
<td>169.4</td>
<td>4.00</td>
<td>7.4x10^7</td>
</tr>
<tr>
<td>202.4</td>
<td>3.48</td>
<td>1.4x10^8</td>
</tr>
<tr>
<td>228.2</td>
<td>2.73</td>
<td>2.3x10^8</td>
</tr>
</tbody>
</table>

(*) Nominal energy at the beamline window
(**) Nominal flux evaluated for 1 nA current

(*** Due to beam transportation losses only ~10% of this nominal current is available in the experimental area)
Irradiation Configurations

**Small target area** and **high beam intensity**: **direct beam irradiation** configuration. Irradiation performed with non uniform intensity beam. The gaussian profile of the beam can be tuned changing the beam energy.

**Large target area** and **medium/low beam intensity**: **double ring** configuration. Two set up available:
- small dual ring ==> circumference of ~3 cm radius with flat intensity profile medium beam intensity
- large dual ring ==> circumference of ~8 cm radius with flat intensity profile low beam intensity

Due to **administrative restrictions**, in the experimental cave can be delivered a maximum amount of charge **equal to 0.5 mC every day.** With this limitation **only around ~4*10^{12} protons** can be delivered on the target in **one irradiation day.**
Direct beam irradiation configuration

In a direct proton beam irradiation the maximum amount of beam can be delivered on the target but the beam transverse intensity distribution is not uniform but gaussian. The gaussian's sigma can be tuned from 2.73 mm up to 6.92 mm decreasing the beam energy from 228MeV down to 70MeV. Decreasing the beam energy also the beam intensity decreases: this happen because the beam energy is lowered in a passive way adding stopping material in the beam path after the cyclotron beam exit.

For a **100MeV Proton beam** with a 5.68 mm Gaussian sigma profile, the fraction $F$ of the total beam with gaussian intensity profile delivered inside a radius $r$ circumference can be evaluated as follow:

$$F = 1 - e^{-0.5 \times (r/\sigma)^2}$$

Considering $r=2.5$ and 3.0 mm:

- $r_{\text{red}}$ 2.50 mm $\implies F = 0.095$
- $r_{\text{blue}}$ 3.00 mm $\implies F = 0.133$
Direct beam irradiation configuration

With a 100 MeV proton beam, with the 0.5mC administrative limitation, a total amount of $4.32 \times 10^{12}$ protons can be delivered on the target in one irradiation day.

In this condition, the **average fluence** inside a radius $r$ circumference is:

100 MeV Energy is a good trade-off between beam intensity (increasing with energy) and beam spreading (decreasing with energy).

Even if **the beam fluence is not uniform** and the area considered is small, these configuration are interesting for SiPM and single pixels prototypes irradiation studies.
Case application: Direct beam irradiation on FBK SiPM

Direct beam irradiation on FBK SiPM:

in this type of irradiation the Detector Under Test (DUT) precise alignment with the beam axis is crucial
Dual Ring configuration

First foil

incoming proton beam (gaussian profile, 148MeV)

beampipe

Dual ring

scattered proton beam (flat profile, ~140 MeV)

Target area

Monitor drift chamber

Small dual ring intensity profile

Fluence in one irradiation day: ~5.0 * 10^11 p/cm^2

(See REF2 for details)
Dual Ring configuration

The dual ring set-up can be assembled in two configurations:
- small dual ring ==> circumference of ~3 cm radius with flat intensity profile
- large dual ring ==> circumference of ~8 cm radius with flat intensity profile

The intensity peak is different in the two configurations.
(See REF2 for details)

This configuration is commonly used for large area irradiation on cells culture or radiation damage studies on electronic devices and silicon sensors.
Case application: Dual Ring used for FBK SiPM Irradiation

- Small dual ring configuration used.
- On target proton energy lowered to 70 MeV using additional degrader (solid water).
- Additional Dark Box (by FBK) with remote controlled window for SiPM characterizations between irradiation steps.

See Stefano Merzi talk in this Workshop for detailed results: https://indico.cern.ch/event/1093102/contributions/4802136
Case application: SEEs studies on large area electronic devices

On October 2021, for the first time, the **small dual-ring set-up** was used also for **Single Event Upset rate** measurement.

The HERMES-SP collaboration ([https://www.hermes-sp.eu](https://www.hermes-sp.eu)) equipped a special daisy-wheel remotely controlled with commercial electronic boards to be tested on the spokes.

Each board was powered on and irradiated, meanwhile a controller located in the center of the wheel was checking the status of the board. In this way was possible to measure the number of board failures for each fluence step for every board.

The daisy-wheel set-up allowed to test in short time 8 different boards without entering in the irradiation cave.
Final considerations on proton irradiation and references

- Since the TPTC is a medical facility the beam in the experimental area is available only at the end of medical treatment, that is from ~19.30 up to 22:30 Mon-Fri, 8-13 on Sat.
- For high dose irradiation the 0.5 mC/day administrative limit can force to split the operations in multiple days.
- In order to allow precision DUT measurement inside the experimental cave, also the electromagnetic background characterization was performed.

**Proton beam characterization REF1:**
*Proton beam characterization in the experimental room of the Trento Proton Therapy facility*
F. Tommasino et al., 2017; DOI:10.1016/j.nima.2017.06.017

**Dual ring description REF2:**
*A new facility for proton radiobiology at the Trento proton therapy centre: Design and implementation*

**Experimental cave electromagnetic background characterization:**
*Experimental Assessment of the Electromagnetic Background Noise in the Trento Proton Therapy Center*
B. Di Ruzza et al, DOI: 10.1109/ICECET52533.2021.9698549
https://ieeexplore.ieee.org/document/9698549
The TIFPA-INFN x-ray irradiation Laboratory

INTRODUCTION

The TIFPA-INFN center is equipped with a x-ray tungsten irradiation station optimized for medical/biophysical irradiation: 195kV, 5mA current, 3mm Al filter and PTW Farmer Chamber Dose measurement system. After a filter replacement, the station was used for SiPM TID studies at 40kV and 20mA current. The x-ray spectrum of the new tube configuration was checked using simulations realized with the SpekPy toolkit and doserate measurement.

The ratio diode doserate (both SiO2 and Si dose) / Farmer Chamber doserate was evaluated performing PTW Farmer Chamber dose measurements in the Padova INFN x-ray irradiation station.

Using this configuration a 10Mrad irradiation was successfully performed in 3 working days in Trento (using only the Farmer Chamber for dose measurement) performing also SiPM characterizations at different irradiation dose levels.
The TIFPA-INFN x-ray irradiation Laboratory

X-Ray cabinet

PTW Farmer Chamber with SiPM

Tube detail

PTW Electrometer

TIFPA-INFN: www.tifpa.infn.it
UniTN Biological Department: https://www.cibio.unitn.it

https://www.ptwdosimetry.com/en/
X-Ray spectrum emission

a) Ideal Bremsstrahlung spectrum for a tungsten anode (tube voltage 90 kV)

b) An Actual spectrum at the beam exit port with characteristic X rays (anode angle: 20°, inherent filtration: 1 mm Be)

c) The spectrum Filtered with an equivalent of 2.5 mm Al
Tungsten emission spectrum simulation (SpekPy*)

195 kV, 10mA, 0.18mm Al filter

Example of x-ray spectrum with W anode at 195kV, 10mA current, 0.18mm Al filter, 30 cmFSD

L lines

K lines

1st half-value-layer= 0.1120 mm Mean Energy: 49.45 keV

(*) https://doi.org/10.1016/j.ejmp.2020.04.026
Tungsten emission spectrum simulation (SpekPy*)

SiPM Radiation Field simulation with the SpekPy* software toolkit:

Considered tube configuration:
tungsten anode, 0.8mm Be window;
40kV anode tension, 20mA current, 0.180 mm Al filter,
20 cm FSD target position.

(*) https://doi.org/10.1016/j.ejmp.2020.04.026
X-ray in silicon

Total Attenuation With Coherent Scattering of Photons in Silicon

Data from NIST: [https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients](https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients)
Fraction of Absorbed Energy in Silicon

Photon Energy [MeV]

W L lines

W K lines

Evaluated from NIST data: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients
The TIFPA-INFN x-ray irradiation Laboratory

- Tube voltage: 30, 40 e 50 kV
- Tube current: 10-30 mA
- Filter: 0.180 mm Al
- Target distance: 20 FSD

Dose Instrument used:
- Calibrated PTW Farmer Chamber
The TIFPA-INFN x-ray irradiation dose measurement

For x-ray irradiation on silicon devices the dose measurement system is performed with calibrated diodes described in this CERN link:

https://espace.cern.ch/project-xrayese/_layouts/15/start.aspx#/Calibration/Forms/AllItems.aspx

In the Trento x-ray laboratory, in order to use the available PTW Farmer Chamber dose measurement system, a preliminary comparison Farmer chamber vs calibrated diode read-out were performed in the Padova INFN x-ray station using exactly the planned SiPM radiation field. In this way was evaluated the read-out ratio farmer chamber dose/Si dose.
Case application: FBK SiPM Irradiations

Overview of the irradiation set-up

SiPM online characterization system (FBK)

Farmer chamber and SiPM support (FBK)

X Rays beam

For results see:
DOI: 10.1016/j.nima.2022.167502
Lesson learned: a proton medical facility and a general purpose x-ray irradiation cabinet can be successfully used for silicon sensors radiation hardness characterization.

For this irradiation work I want to thanks:
Anna Rita Altamura, Fabio Acerbi, Stefano Merzi (FBK),
Federico Faccio (CERN), Riccardo Campana (INAF),
Devis Pantano, Simona Mattiazzo, Jeff Wyss (INFN Padova),
I. Rashevskaya, G. Battistoni, E.Scifoni (TIFPA-INFN)
F. Tommasino (UniTN)
Usefull software tools
Particle fluence evaluation in Space
SPENVIS:
particle fluence evaluation and spectrum evaluation

International Space Station (ISS)

Orbit Parameters:
370-460 km altitude, 51.6 deg. inclination

https://www.spenvis.oma.be
SPENVIS: particle fluence evaluation and spectrum evaluation

International Space Station

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370-460 km altitude, 51.6 deg. inclination

https://www.spenvis.oma.be
SPENVIS: 
particle fluence evaluation and spectrum evaluation

International Space Station
Orbit Parameters:
370-460 km altitude, 51.6 deg. inclination

Displacement damage in Silicon, induced by protons and electrons for this orbit can be evaluated for a 5 years mission using the Vasilescu & G. Lindstroem radiation damage evaluation tables (RD50 collaboration):

Proton spectrum: D/95MeV mb = 1.60E+13  (proton energy range: 0.1MeV – 300 MeV)
Electron spectrum: D/95MeV mb = 1.03E+11  (electron energy range: 0.04MeV – 7 MeV)

https://www.spenvis.oma.be
5 years LEO Polar mission
5 years LEO Polar mission

30 days proton flux

Orbit parameters:
507 km circular orbit radius
97 degree inclination

Protons:
Trapped radiation models

Proton model: AP-8
Model version: solar minimum
Threshold flux for exposure (/cm^2/s): 0.01

Model developed by: NSSDC
5 years LEO Polar mission

Orbit parameters:
507 km rcircular orbit radius
97 degree inclination

Protons:
Trapped radiation models
5 years LEO Polar mission

30 days electron flux

Orbit parameters:
- 507 km circular orbit radius
- 97 degree inclination

Electrons:
Trapped radiation models
5 years LEO Polar mission

Orbit parameters:
507 km rcircular orbit radius
97 degree inclination

Electrons:
Trapped radiation models
SRIM:
ions ranges and ionization evaluation for elements and compounds

5 MeV protons in silicon

http://www.srim.org/SRIM/SRIMLEGL.htm
SRIM:
ions ranges evaluation for elements and compounds

70 MeV protons in water

230 MeV protons in water

http://www.srim.org/SRIM/SRIMLEGL.htm
X-ray tube structure
SpekPy:

195 kV, 10mA, 0.18mm Al filter

Example of x-ray spectrum with W anode at 195kV, 10mA current, 0.18mm Al filter, 30 cm FSD

L lines

K lines

1st half-value-layer = 0.1120 mm  Mean Energy: 49.45 keV

Tungsten emission spectrum simulation (SpekPy*)

SiPM Radiation Field simulation with the SpekPy* software toolkit:

Considered tube configuration:
tungsten anode, 0.8mm Be window;
40kV anode tension, 20mA current, 0.180 mm Al filter, 20 cm FSD target position.

(*) https://doi.org/10.1016/j.ejmp.2020.04.026
End part 2

Thanks for you attention!

comments, questions ... suggestions ?

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Back-up slides
ICHEP 2020 Conference: Benedetto Di Ruzza
*Proton and x-ray irradiation of silicon devices at the TIFPA-INFN facilities in Trento (Italy)*
slides: https://indico.cern.ch/event/868940/contributions/3815732
proceeding: DOI: 10.22323/1.390.0685; https://pos.sissa.it/390/685

16th "Trento" Workshop on Advanced Silicon Radiation Detectors 2021: Benedetto Di Ruzza
*Ionizing and Non-Ionizing Energy Loss irradiation studies with 70-230 MeV protons at the Trento Proton Therapy Center*
slides: https://indico.cern.ch/event/983068/contributions/4223200

WEBLINKS
• Trento Institute for Fundamental Physics and Applications (TIFPA):
  https://www.tifpa.infn.it/about-tifpa

• TIFPA Activity Reports:
  https://www.tifpa.infn.it/contacts/downloads

• Bruno Kessler Foundation (FBK):
  https://www.fbk.eu/en
WEB References

TIFPA-INFN:  www.tifpa.infn.it
APSS:  https://protonterapia.provincia.tn.it/eng
Physics UniTN:  https://www.physics.unitn.it/en
Biology UniTN:  https://www.cibio.unitn.it
IBA:  https://iba-worldwide.com

Trento Proton Therapy Center:
Experimental Area info and Beam Time applications:
http://www.tifpa.infn.it/sc-init/med-tech/p-beam-research

TIFPA Activity Reports:
https://www.tifpa.infn.it/contacts/downloads

Experimental area beam characterization:
REF1 – Proton beam characterization in the experimental room of the Trento Proton Therapy facility
DOI: http://dx.doi.org/10.1016/j.nima.2017.06.017

REF2 – A new facility for proton radiobiology at the Trento proton therapy centre: Design and implementation
DOI: https://doi.org/10.1016/j.ejmp.2019.02.001
Proton induced displacement damage in Silicon

A. Vasielescu & G. Lindstroem
The TIFPA-INFN x-ray irradiation Laboratory

silicon density: 2.330 g/cm³

Fraction of Absorbed Energy

layer thickness (micron)

Photon Energy [MeV]
Cabinet Xstrahl RS225

**X-Ray Tube Output Limits**
- **Voltage**: Up to 220kV
- **Current**: 1.0mA to 30mA
- **Power**: 3000W (broad focus for designated stability)

**X-Ray Cabinet Dimensions**
- **Height**: 2010mm
- **Width**: 1105mm
- **Depth**: 960mm
- **Weight**: 1100kg

**Lead Shielded Irradiation Chamber Dimensions**
- **Height**: 650mm
- **Width**: 570mm
- **Depth**: 600mm

Shielding of cabinet to ≤ 2µSv/hour at 5 cm from any accessible surfaces as per IRR99 guidelines.

In this set-up configuration the x-ray uniform spot is a circumference of 4.5 cm radius and can be used for sensors or electronic circuits TID characterization studies requiring total dose of the order of 1-50 Mrad.
R-X support plane

- $r=6$ cm
- $r=9$ cm
- $r=12$ cm
Tungsten emission spectrum

Example of x-ray spectrum with W anode at 195kV, 10mA current, 2.0mm Al filter, 30 cm FSD
SiPM Radiation Field simulation with the the SpekPy* software toolkit:

Considered tube configuration:
tungsten anode, 0.8mm Be window;
40kV anode tension, 20mA current, 0.180 mm Al filter, 20 cm FSD target position.

(*) https://doi.org/10.1016/j.ejmp.2020.04.026

In order to use the PTW Farmer Chamber dose measurement system, preliminary comparison framer chamber vs calibrated diode read-out were performed in the Padova INFN x-ray station using exactly the planed SiPM radiation field. In this way was evaluated the read-out ratio farmer chamber dose/Si dose .
Diode - Farmer Chamber doserate comparison at the Padova x-ray irradiation laboratory

Ratio Diode Doserate/PTW Doserate

\[
\text{SiO}_2 = 7.72 \pm 0.04 \quad \text{Si} = 13.79 \pm 0.07
\]

Residuals Ratio Diode Doserate/PTW Doserate

![Graph showing residuals ratio of diode doserate to PTW doserate against tube current in mA.](image-url)
Slide from Marc Poizat: 
https://indico.cern.ch/event/635099/contributions/2570674/attachments/1456398/2248961/Radiation_Effects_and_RHA_ESA_Course_9-10_May_2017_TID_MP_FINAL.pdf
INTRODUCTION

Lecture 1 26/9, 2 - 5 pm: Introduction to silicon sensors – Use of silicon sensors as imaging and tracking devices in HEP, space mission and medical applications

Lecture 2 27/9, 2 - 5 pm: Silicon Sensors radiation hardness characterization

Lecture 3 28/9, 2 - 4 pm: Medical application of photons and charged particles for cancer treatment – Facilities for radiation therapy – Dose measurement devices