Ion Electron Emission Microscope

A new way to perform Single Event Effect devices characterization
The SIRAD IEEM Project

What’s about?
► We are building a new instrument dedicated to study the *radiation induced Single Events Effect* on electronic devices.
► The aim is to have a facility capable to perform a micrometric characterization of devices respect their sensitivity to SEE. This means to be able to get a map (x,y) that illustrates the SEE sensitivity of the device with resolution equal or better than 1µm.

What we’re going to see:
► What SEE are and what means perform SEE microscopy.
► The usual way to do SEE microscopy: micro-beam technique.
► A novel way: IEEM microscopy.
► The SIRAD IEEM microscopy project solutions & performances.
► Conclusions and some hints for future users.
A *single incident particle* may produce directly or indirectly enough energy in the form of ionization to cause a single macroscopic (anomalous) effect in a polarized device.

**SEE effects** are *induced* in a live electronic device if the *ionization* induced in the *sensitive volume* of the device by a primary ionizing particle or by secondary particles or by a recoiling nucleus is higher than some characteristic *SEE threshold value*.

**Some kind of SEE:**

**SEU** (Single event upset): data corruption; data stored in register cells are altered by induced charge.

**SEL** (single event latchup): potentially destructive inherent p-n-p-n in CMOS.
What is SEE Microscopy:
► See Microscopy will allow a micrometric SEE sensitivity characterization of the device instead of a global one.
► The goal is to get a map of the device respect to its sensitivity to SEE.

SEE Microscopy allows to:
► Take data to test and validate theoretical models.
► Diagnose problems unpredictable by simulations.
► Test and certificate the performances of a specific device for radioactive environments.
► Analyze the performance of different kinds of construction technology and/or topology.
SEE Microscopy techniques

**Microbeam:**
Use a *micro-focused beam* to scan the entire device with µm resolution watching at each point for eventual SEE.

![Diagram of Microbeam](image)

**IEEM Technique:**
Use a *broad beam* on the device and recognize each single ion impact with µm resolution; correlate it with eventual SEE.

![Diagram of IEEM Technique](image)

- **Nuclear Microprobe:**
  - Focusing (e.g. triplet) and scanning system

- **Microfocused beam**
  - $(X_{beam}, Y_{beam})$

- **Rastering pattern**

- **Analysis of signal**

- **Target**

- **2D electron detector at focal plane of electron optics**

- **Secondary electrons**

- **Electron optics**

- **Broad ion beam**

- **Coating**

- **Analysis of signal**
Microbeam vs. IEEM microscopy

Micro-beam facilities
In the nuclear microprobe technique a micro-focused beam spot is systematically moved with micro-precision across a device to build up a sensitivity map. Lateral resolution: 0.3(best) ÷ 1 µm.

IEEM technique (B.L.Doyle, SANDIA, 1999)
Instead of micro-focusing the beam, one uses a broad beam and then reconstructs the impact point for each impinging ions! Lateral resolution: 0.6 ÷ 1 µm.

Not focusing needed! → Easy to couple to any kind of accelerator: the microscope is completely independent from the accelerator machine! Possible off line use (α sources)

But, higher LET ions are required to simulate space radiation environment

High energy & Heavy ions
Cyclotrons, Linacs
High magnetic rigidity
Poor energy resolution
Difficult to focus!
**Base physics process:**
Impinging ions on target generate a ionization column where electrons are stripped from original bounds. Some of this $e^{-}$ escape the surface energy barrier before recombine and generate an electrons yield (few eV average energy) leaving the target. *Detecting the coordinates of outcoming $e^{-}$ bunch allows to know the impinging ion position!*

**Detection – imaging electrons:**
To detect the $e^{-}$ bunch an electronic microscope is used. The first stage of this device has a potential of some kV respect to the target, allowing it to collect the escaping electrons. After collecting them it acts on electrons exactly as an optical one acts on photons: it return a magnified (some 100×) image of the source. So, at the focal plane of the electronic microscope, we have an enlarge image of the impinging point.
Detection - from electron to photons:
On the focal plane a bi-dimensional electrons multiplier (micro channel plate, MCP) amplifies the (few) incoming electrons by a factor $\sim 10^7$. A fast phosphor then converts multiplied electrons into a light spot, allowing to redirect the light signal outside the beamline vacuum chamber to allow easier detection (SIRAD original schematic).

Detection – from photons to position:
At this point, it remains nothing more to get the light spot position and the job is done: the light spot position represent the original impinging ion position on the target!

How to do this? – Conventional imaging techniques doesn’t fit our needs.
SIRAD IEEM: Schematic summary

- Ions beam
- Secondary electrons
- Photons
- Position Sensitive Detector (PSD)
- Fast (P47) Phosphor layer to convert e\(^-\) to γ
- All this stuff is off-axis respect to the beam!

- High e\(^-\) yield coating
- High electric field (~15kV)
- Target
- PEEM Microscope (160÷1600× magnifying factor)
- Large area (ø 4cm) 2D electrons multiplier (MCP)
- Optical system
- DAQ
- X
- Y
- T
- PC

~ 1÷100 e\(^-\), depending on material & ion

High electric field (~15kV), depending on material & ion
**Microscope:**
A commercial PEEM is used as electronic microscope with variable magnifying factor (160× typical).

**Sensor:**
A MCP with a fast phosphor converts electrons to photons, which are then bridged via an optical system to an external Position Sensitive Detector.
Why a PEEM configuration?
A complete PEEM setup had realized to test & develop the sensor for the IEEM. No matter from where electron come, ions or $\gamma$: sensing problems and solutions are exactly the same! At present we are working to install the microscope onto the beamline.

Old experimental setup

- UV Lamp
- STAIB PEEM Microscope
- Laminar flow supports to reduce vibrations
- Turbo pump (Vacuum of about $10^{-6}$ needed)
- Ion pump for vibration-free operation
IEEM efficiency vs. resolution with ions:

0.2µm resolution with γ in standard PEEM mode to reach maximum efficiency.

Factor 3 worst from γ to ions!

A maximum resolution of about 0.6µm is expected in IEEM mode.

IEEM efficiency vs. resolution with ions:

Expected IEEM Resolution

A maximum resolution of about 0.6µm is expected in IEEM mode.
Expected IEEM efficiency

**Global IEEM efficiency:**
- PEEM transmission eff. (30%)
- MCP detection eff. (50%)
- Sensing chain eff. (>99%)
- Secondary electrons Yield

Yield = LET * a * Z^{(b-2)}

An efficiency better than 98% is expected for ions with \(Z>15\) (P) and gold coating!

But \(Z > 9\) (F) would be sufficient with C-Doped coating!

Yield = \(\text{LET} \times a \times Z^{(b-2)}\)

<table>
<thead>
<tr>
<th>Material</th>
<th>(a) (A/eV)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gold</td>
<td>0.16</td>
<td>1.59</td>
</tr>
<tr>
<td>aluminum</td>
<td>0.44</td>
<td>1.53</td>
</tr>
</tbody>
</table>

\(\text{LET}\) is the Linear Energy Transfer, which is a measure of the energy lost by the ion in traversing the material. The yield is a function of the atomic number \(Z\) of the material and the parameters \(a\) and \(b\).
### Available ions at SIRAD

<table>
<thead>
<tr>
<th>Ion</th>
<th>E (Mev)</th>
<th>Range in Si (µm)</th>
<th>LET⁰ in Si (Mev×cm²/mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹H</td>
<td>28.7</td>
<td>4390</td>
<td>0.02</td>
</tr>
<tr>
<td>⁷Li</td>
<td>56.18</td>
<td>378</td>
<td>0.37</td>
</tr>
<tr>
<td>¹¹B</td>
<td>80.68</td>
<td>196</td>
<td>1.01</td>
</tr>
<tr>
<td>¹²C</td>
<td>94.68</td>
<td>171</td>
<td>1.49</td>
</tr>
<tr>
<td>¹⁶O</td>
<td>108.68</td>
<td>109</td>
<td>2.85</td>
</tr>
<tr>
<td>¹⁹F</td>
<td>122.68</td>
<td>99.3</td>
<td>3.67</td>
</tr>
<tr>
<td>²⁸Si</td>
<td>157.68</td>
<td>61.5</td>
<td>8.59</td>
</tr>
<tr>
<td>³²S</td>
<td>171.68</td>
<td>54.4</td>
<td>10.1</td>
</tr>
<tr>
<td>³⁵Cl</td>
<td>171.68</td>
<td>49.1</td>
<td>12.5</td>
</tr>
<tr>
<td>⁴⁸Ti</td>
<td>196.18</td>
<td>39.3</td>
<td>19.8</td>
</tr>
<tr>
<td>⁵¹V</td>
<td>196.18</td>
<td>37.1</td>
<td>21.4</td>
</tr>
<tr>
<td>⁵⁸Ni</td>
<td>220.68</td>
<td>33.7</td>
<td>28.4</td>
</tr>
<tr>
<td>⁶³Cu</td>
<td>220.68</td>
<td>33.0</td>
<td>30.5</td>
</tr>
<tr>
<td>⁷⁴Ge</td>
<td>231.18</td>
<td>31.8</td>
<td>35.5</td>
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<tr>
<td>⁷⁹Br</td>
<td>241.68</td>
<td>31.3</td>
<td>38.6</td>
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<tr>
<td>¹⁰⁷Ag</td>
<td>266.18</td>
<td>27.6</td>
<td>54.7</td>
</tr>
<tr>
<td>¹²⁷I</td>
<td>276.68</td>
<td>27.9</td>
<td>61.8</td>
</tr>
<tr>
<td>¹⁹⁷Au</td>
<td>275.68</td>
<td>23.4</td>
<td>81.7</td>
</tr>
</tbody>
</table>

- Ion species from ¹H (23-30 MeV) up to ¹⁹⁷Au (1.4 MeV/amu)
- **LET** from 0.02 MeV×cm²/mg (¹H) up to 81.7 MeV×cm²/mg (¹⁹⁷Au)
SIRAD way: PSD sensing system

Features:
- Handles rates up to $4 \times 10^4$ Hz
- Resolution better than 400 lp
- CCD camera coupled for fine focusing
- Complete PC control & data readout

45° mirror
Anular MCP and phosphor
High aperture (F/ 1.4) lens
Image intensifier
Secondary optical path
Position Sensitive Detector

Piero Giubilato - IEEM Microscope, SIRAD Workshop, Legnaro 02/04/2004
For every point we know:
- \((x,y)\) of photons spot impact
- Time of each impact
- Emitted energy (pseudo scale)

**PEEM image** using a CCD camera. The target is a 40µm step copper TEM grid about 10µm thick. Field of view is 250µm.
Images with PSD sensing system

The cross is a free substrate area in a uniform field of gold (by sputtering, 450 nm thickness).

A similar cross acquired via the PSD sensing system. Note: a detail of about 2µm is discerned.
SIRAD way: Double digital sensor

Features:
- Handles rates up to $3.7 \times 10^4$ Hz
- Resolution better than 1000 lp!
- Can handle **multiple hits** on a frame!
- **Hotspots** & non-uniformity handling.
- No image intensifier needed!

14*14µm 1024 square pixel Linear CCD

45° mirror

High aperture (F/1.4) lens

Anular MCP and phosphor

Double achromat separated by Beamsplitter

Cylindrical lenses
Linear CCD sensor performances

**Resolution over 40*40mm² area**

This data show how this new approach to IEEM imaging will allow to exploit the future development of high-resolution microscopes and/or MCP stages.

Piero Giubilato - *IEEM Microscope, SIRAD Workshop*, Legnaro 02/04/2004
SIRAD IEEM: workflow summary

Device under test

Impact DB

#1 $X_1, Y_1 \quad t_1$
#2 $X_2, Y_2 \quad t_2$
#3 $X_3, Y_3 \quad t_3$
#4 $X_4, Y_4 \quad t_4$
...
...
#n $X_n, Y_n \quad t_n$

Single SEE Position

Device control setup and status analysis (user provided)

Beam

IEEM

Output

Data req.

MAP
IEEM test: SDRAM SEU mapping

10^4 Bits in fov

Effective SEE resolution

SDRAM DAQ

IEEM DAQ

Database

<table>
<thead>
<tr>
<th></th>
<th>X1, Y1</th>
<th>R1, C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>X1, Y1</td>
<td>R1, C1</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>N</td>
<td>Xn, Yn</td>
<td>Rn, Cn</td>
</tr>
</tbody>
</table>

Post Processing

IEEM Map

Piero Giubilato - IEEM Microscope, SIRAD Workshop, Legnaro 02/04/2004
**IEEM: the ion microscope be able to:**

- Resolution better than 1\(\mu\)m (up to 0.6 \(\mu\)m) on the device with a FOV of 250\(\mu\)m and full efficiency. Higher resolution if no 100% efficiency needed.
- Events rate handling up to 40 kHz.
- Precise timestamp (32 bit) system to allow easy event triggering.
- Some others others (???) state of the art features!

**Interested users, mind that:**

- Sample must be coated to provide electron emission.
- Device under test must be completely remote controlled.
- Sample should have a clean (no edges) layout (HV field).
- Can’t have any magnets or stray electric field around sample.
- You must provide a trigger for interesting event.

[http://sirad.pd.infn.it/pagineieem/](http://sirad.pd.infn.it/pagineieem/)