Radiation tests analysis

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Introduction and motivations

Devices and experimental set-up for the irradiation campaign

Radiation-matter interaction simulations
  - SRIM/TRIM simulation results
  - Energy loss predictions for the devices under study

Proton irradiation experimental results and discussion
  - Threshold voltage shifts in irradiated RADFETs
  - Floating gate errors in irradiated NAND Flash memories

Conclusions
**Introduction and motivations**

- The purpose is to **evaluate the shielding potential of different aluminum structures** with respect to the **space radiation** environment, through a set of **simulations and experiments**

- **High-energy protons** were chosen for this assessment
  - Protons are the **most abundant particles in space** and they are extremely relevant for the Low Earth Orbit (LEO) environment
  - Protons are the **most penetrating particles**, having the longest range for charged particles at a given energy, due to the low rate of ionization
  - Protons can also generate **secondary effects through nuclear reactions**, which are less frequent with heavier particles
Experimental devices

- Two radiation sensitive devices were used to assess the modifications induced in the proton beam by five aluminum shields.

1. RADiation Field Effect Transistors (RADFET): TY1004 manufactured by Tyndall
   - Two identical p-channel MOSFETs (M1 and M2) with a gate oxide thickness of 400 nm and an aspect ratio W/L of 300 μm/50 μm. M1 and M2 have individual gate and drain terminals, the source and bulk are shorted.
   - $V_{th\,\text{shift}}$ (due to charge trapped in oxides) is proportional to ionizing dose.

2. NAND Flash memories: 29F64G08CBAAAWP manufactured by Micron Technology
   - Example of a chip that can be used in a satellite and be subject to radiation-induced degradation: number of errors in memory cells depends on dose.
For the RADFETs, a dedicated set-up was developed for the on-line and off-line measurement of the threshold voltage ($V_{th}$)

A custom test board and control software were used to characterize the RADFET in terms of $V_{th}$ with a portable semiconductor parameter analyzer (Agilent U2722A)
For the **NAND Flash memories**, custom hardware and software were developed for the on-line and off-line read-out of the floating gate array.

An **FPGA control motherboard** connected to a dedicated daughterboard, including a socket with the device under test, was used.
Irradiations

- Irradiations were carried out at the TANDEM accelerator at the INFN Laboratori Nazionali di Legnaro (LNL) with a 2cm x 2cm 24.76-MeV proton beam in a vacuum chamber

- Overall, 8 RADFETs and 8 NAND Flash memories were used for these experiments

- One RADFET and one NAND Flash memory were irradiated without any shielding and measured online during the irradiation for calibration purposes

- Then for each shielding configuration, a), b), c), d), e), no shield, one RADFET and one NAND Flash were irradiated and read offline after exposure, once the activation levels allowed us to handle them (about 24 hours)
Radiation-matter interaction simulations were performed to evaluate proton transport through the shields and the layers above the active regions of the monitoring devices.

- Stopping and Range of Ions in Matter (SRIM) and Transport of Ions in Matter (TRIM) Monte Carlo codes were used to study:
  - Proton energy loss
  - Proton ranges
  - Proton Linear Energy Transfer (LET) across the different layers

**TRIM simulation of** $10^5$ **24.76-MeV protons impinging on an aluminum-epoxy-silicon stack (mimicking one of the thickest shield b) and the packaged NAND Flash memory)**
Radiation-matter simulation results (1/2)

- The **loss of range** method was used to determine the energy after each layer.
- **Proton energies** are reported at the boundaries between different layers.

| Shield type | Proton initial E [MeV] | Proton E after shield [MeV] | Proton E @ RADFET sensitive area [MeV] | Proton E after package | Proton E in NAND sensitive area [MeV] | Proton LET @ RADFET sensitive area [MeV cm$^2$/mg] | Proton LET @ NAND sensitive area [MeV cm$^2$/mg] |
|-------------|-------------------------|------------------------------|----------------------------------------|------------------------|----------------------------------------|------------------------------------------------|--|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| a)          | 24.76                   | 23.2                         | 23.15                                  | 20.8                   | 20.75                                  | 1.81·10$^{-2}$                                   | 1.98·10$^{-2}$ | b)          | 24.76                   | 13.7                    | 13.65                                  | 9.7                         | 9.65                    | 2.74·10$^{-2}$                                   | 3.58·10$^{-2}$ | c)          | 24.76                   | 18                      | 17.95                                  | 14.9                         | 14.85                    | 2.21·10$^{-2}$                                   | 2.56·10$^{-2}$ | d)          | 24.76                   | 17.1                    | 17.05                                  | 13.9                         | 13.85                    | 2.3·10$^{-2}$                                   | 2.71·10$^{-2}$ | e)          | 24.76                   | 13.9                    | 13.85                                  | 9.9                          | 9.84                     | 2.71·10$^{-2}$                                   | 3.53·10$^{-2}$ | No shield | 24.76                   | -                       | 24.7                    | 22.5                         | 22.45                      | 1.72·10$^{-2}$                                   | 1.85·10$^{-2}$ |
Radiation-matter simulation results (2/2)

- Dose rates at the devices sensitive volumes based on simulation results

<table>
<thead>
<tr>
<th>Shield type</th>
<th>Dose rate [rad/s] for $2 \cdot 10^8$ cm$^{-2}$ s$^{-1}$ proton flux @ RADFET</th>
<th>Dose rate [rad/s] for $2 \cdot 10^8$ cm$^{-2}$ s$^{-1}$ proton flux @ NAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>57.92</td>
<td>63.23</td>
</tr>
<tr>
<td>b)</td>
<td>87.68</td>
<td>114.56</td>
</tr>
<tr>
<td>c)</td>
<td>70.72</td>
<td>81.92</td>
</tr>
<tr>
<td>d)</td>
<td>73.60</td>
<td>86.59</td>
</tr>
<tr>
<td>e)</td>
<td>86.59</td>
<td>112.83</td>
</tr>
<tr>
<td>No shield</td>
<td>55.07</td>
<td>59.33</td>
</tr>
</tbody>
</table>

- Based on these values, the radiation experimental conditions were chosen (e.g. proton fluences) and the results consequently analyzed
Overall, 49 irradiation runs with 24.76-MeV protons were performed

- Flux \( \sim 10^8 \text{ p/cm}^2/\text{s} \)
- Fluences \( 10^9 - 10^{10} \text{ p/cm}^2 \) depending on the device under test

- Runs 1-26: RADFET calibration
- Runs 27-42: NAND Flash memory calibration
- Runs 43-48: measurement of RADFET and NAND Flash memories with different shielding configurations
- Run 49: double check of RADFET calibration
The threshold voltage ($V_{th}$) was measured online during exposure as a function of radiation dose.

$V_{th}$ is perfectly reproducible for the two MOSFETs in the RADFET.

The $V_{th}$ variation in the post-radiation annealing phase was characterized.

The $V_{th}$ decreases versus time, due to positive charge trapping recombination/neutralization in the RADFET gate oxide layer.
The number of Floating Gate (FG) errors was measured online during exposure as a function of radiation dose.

Number of errors increases versus dose due to loss of charge from memory cells and, to a smaller extent, positive charge trapping in the oxides.

Errors in FG cells for memories programmed with solid pattern ‘33’ ‘55’ before proton irradiation.
RADFETs irradiated with different shields (1/2)

- $V_{th}$ shifts were measured in the RADFETs irradiated behind the different shields.
  - Measurements were performed at a given time after irradiation in all RADFETs, to avoid different annealing times.

$V_{th}$ shifts in MOSFET 1
RADFETs irradiated with different shields (2/2)

- RADFET threshold voltage shifts as a function of dose (calculated with SRIM simulations), for the different shielding conditions and compared with the RADFET calibration curve
- The correlation between the dose received in the different shielding configuration and the $V_{th}$ shifts expected from the calibration curve is reasonable, with only one outlier
The number of FG errors were measured in NAND Flash memories irradiated behind the different shields.
- Number of FG errors as a function of dose (calculated with SRIM simulations), for the different shielding conditions, compared with the NAND Flash calibration curve.

- The data show a good correlation between the dose received in the different shielding configurations and the number of floating gate errors expected from the calibration curve.
Discussion of irradiation results

- The data are scattered around the calibration line, and there is no systematic trend detected, meaning that the geometry of the aluminum shield has little impact on the shielding effectiveness (at least in the tested range of thicknesses and geometries)
  - The various shields behave as Aluminium layers with an equivalent thickness given by the sum of the thicknesses crossed by the proton beam in the actual shield

- Possible sources of variability that may have contributed to data scattering
  - Monitor-to-monitor variability (each shield was tested with a different device)
  - Differences in thickness and density in nominally identical shields
Conclusions

- The **shielding potential of different aluminum shields with respect to proton radiation** was evaluated through a set of simulations and experiments.

- Two types of radiation-sensitive devices were chosen:
  - RADFETs (radiation monitors)
  - NAND Flash memories (commercial devices that can suffer from radiation effects)

- **Radiation-matter interaction Monte Carlo simulations** were performed to evaluate proton transport through the shields and the layers above the active regions of the monitoring devices.

- Based on simulation results, an **ad-hoc irradiation campaign was performed with 24.76-MeV protons**.

- For both types of radiation monitoring devices, the **geometry of the aluminum shield has little impact on the shielding effectiveness**:
  - The various shields behave as aluminum layers with an equivalent thickness given by the sum of the thicknesses crossed by the proton beam in the actual shield.
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