Radiation tests analysis

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Outline

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- 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**

a) Simple panel (thickness 0.5 mm)

b) Simple panel (thickness 2 mm)

c) Multilayer panel (eq. thickness 1.4 mm)

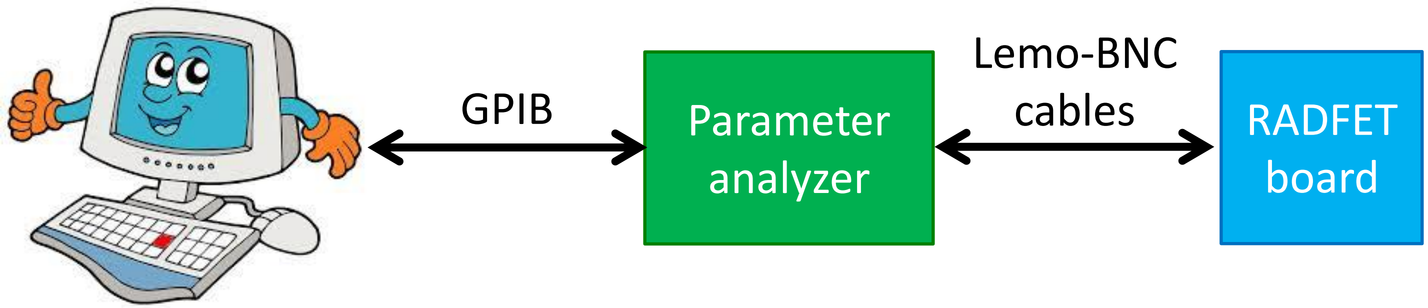
d) Corrugated panel 1 (eq. thickness 1.495 mm)

e) Corrugated panel 2 (eq. thickness 1.99 mm)

- **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} shift** (due to charge trapped in oxides) is **proportional to ionizing dose**
- **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**

RADFET experimental set-up

- 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)



GPIB

Parameter analyzer

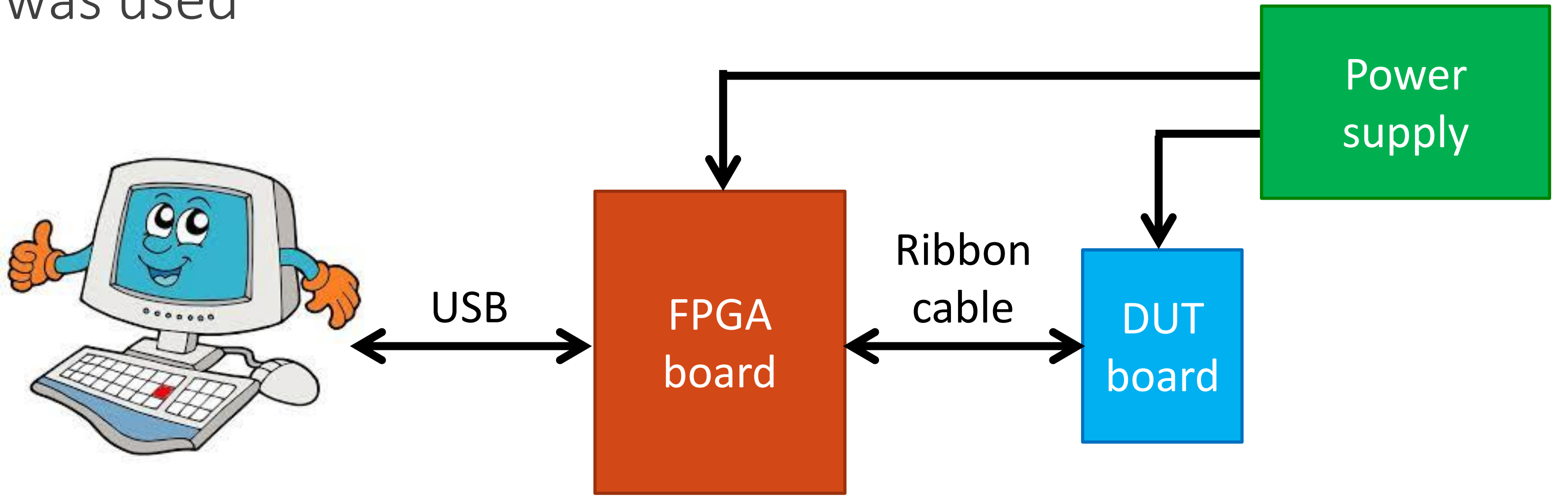
Lemo-BNC cables

RADFET board

RADFET experimental set-up

NAND Flash memory experimental set-up

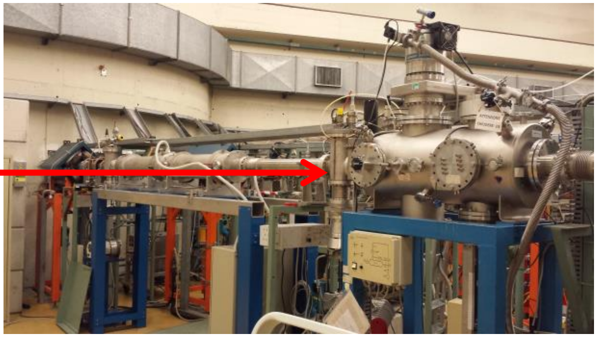
- For the **NAND Flash memories**, custom hardware and software were developed for the on-line and off-line read-out of the floating gate array
- An **FPGA control motherboard** connected to a dedicated daughterboard, including a socket with the device under test, was used

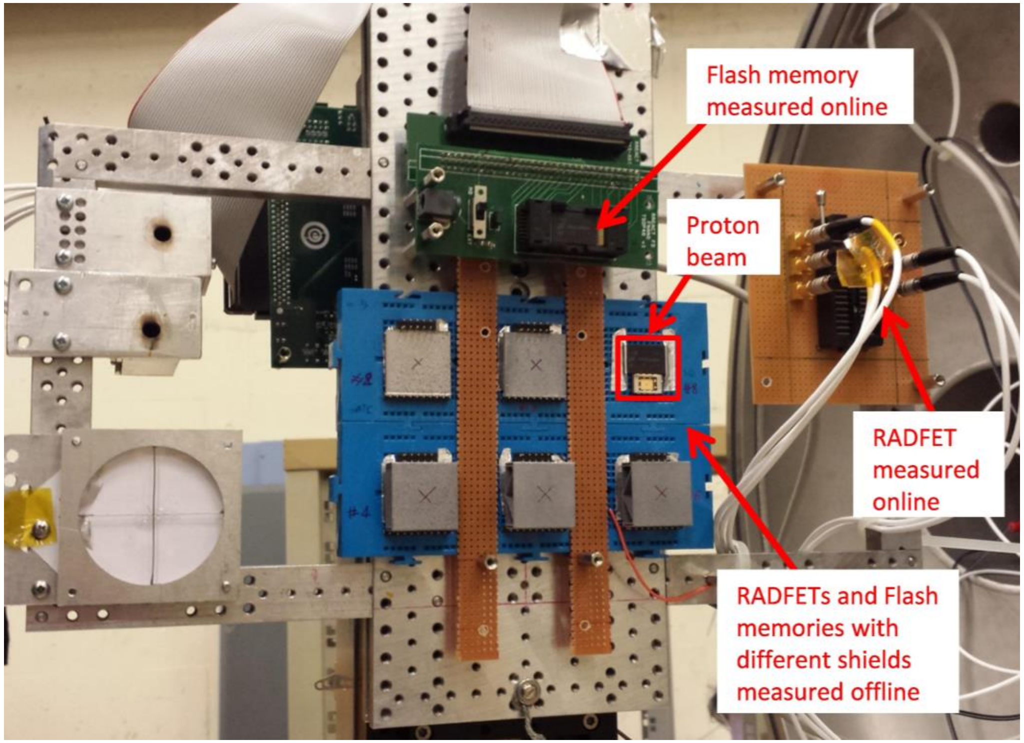


NAND Flash memory experimental set-up

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



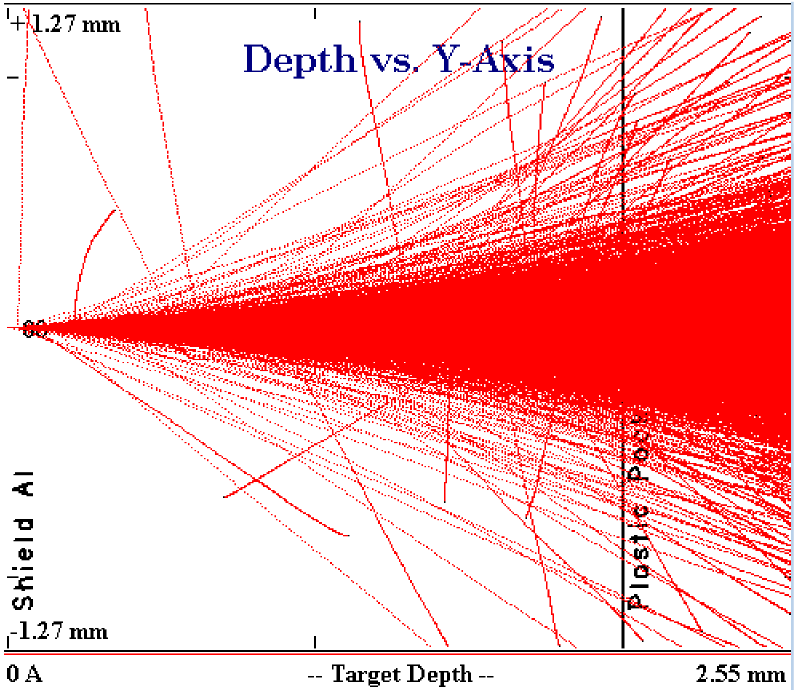


- **One RADFET and one NAND Flash memory were irradiated without any shielding and measured online** during the irradiation for **calibration** purposes
- Then **for each shielding configuration, a), b), c), d), e), no shield, one RADFET and one NAND Flash were irradiated and read offline after exposure**, once the activation levels allowed us to handle them (about 24 hours)

Radiation-matter interaction simulations

- 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 NAND package [MeV]	Proton E in NAND sensitive area [MeV]	Proton LET @ RADFET sensitive area [MeV cm²/mg]	Proton LET @ NAND sensitive area [MeV cm²/mg]
a)	24.76	23.2	23.15	20.8	20.75	**$1.81 \cdot 10^{-2}$**	**$1.98 \cdot 10^{-2}$**
b)	24.76	13.7	13.65	9.7	9.65	**$2.74 \cdot 10^{-2}$**	**$3.58 \cdot 10^{-2}$**
c)	24.76	18	17.95	14.9	14.85	**$2.21 \cdot 10^{-2}$**	**$2.56 \cdot 10^{-2}$**
d)	24.76	17.1	17.05	13.9	13.85	**$2.3 \cdot 10^{-2}$**	**$2.71 \cdot 10^{-2}$**
e)	24.76	13.9	13.85	9.9	9.84	**$2.71 \cdot 10^{-2}$**	**$3.53 \cdot 10^{-2}$**
No shield	24.76	-	24.7	22.5	22.45	**$1.72 \cdot 10^{-2}$**	**$1.85 \cdot 10^{-2}$**

Radiation-matter simulation results (2/2)

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

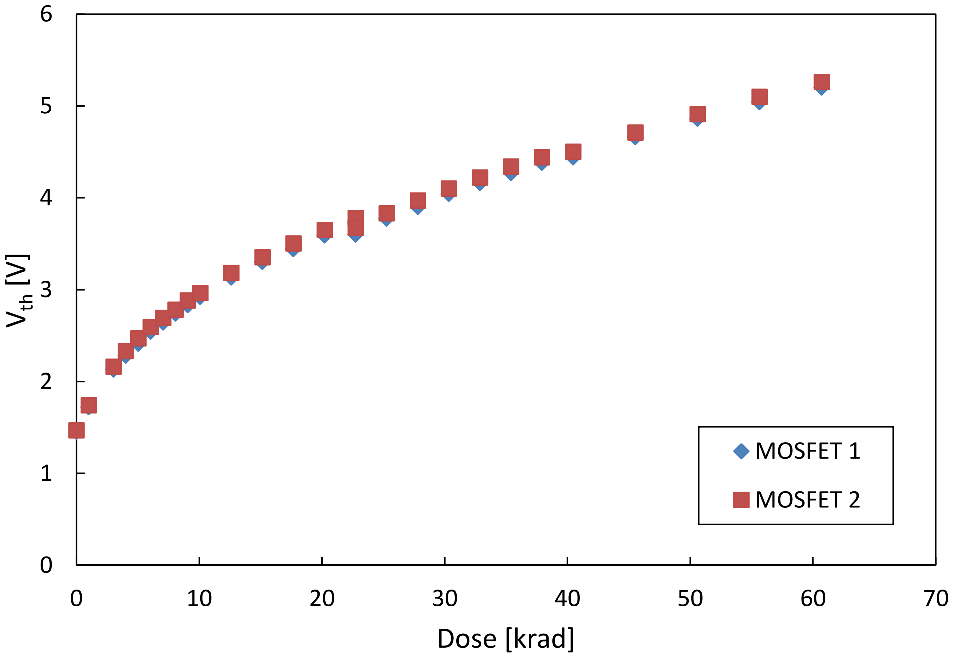
Shield type	Dose rate [rad/s] for $2 \cdot 10^8$ cm^{-2} s^{-1} proton flux @ RADFET	Dose rate [rad/s] for $2 \cdot 10^8$ cm^{-2} s^{-1} proton flux @ NAND
a)	57.92	63.23
b)	87.68	114.56
c)	70.72	81.92
d)	73.60	86.59
e)	86.59	112.83
No shield	55.07	59.33

- Based on these values, the radiation experimental conditions were chosen (e.g. proton fluences) and the results consequently analyzed

Irradiation runs details

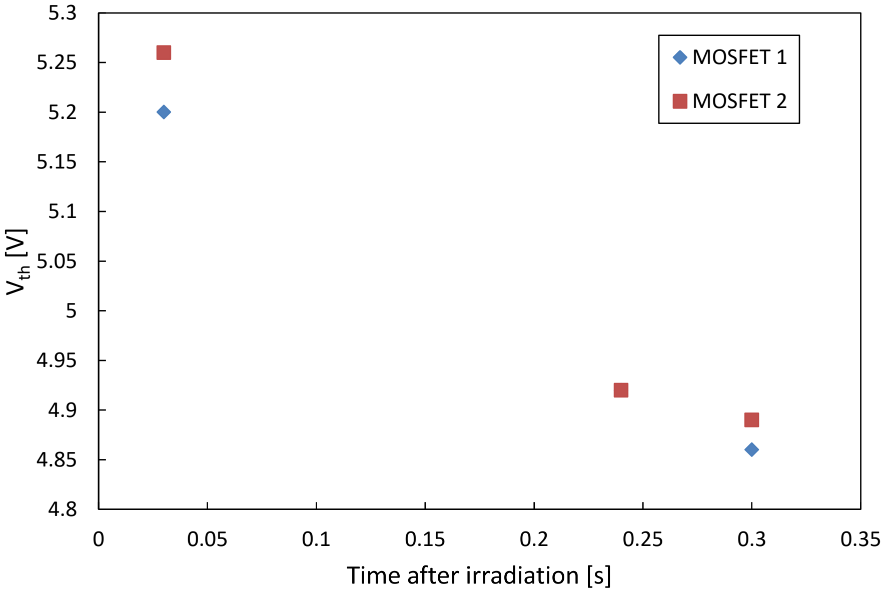
- Overall, 49 irradiation runs with 24.76-MeV protons were performed
  - Flux ~ 10^8 p/cm^2/s
  - Fluences 10^9 – 10^{10} p/cm^2 depending on the device under test
- Runs 1-26: RADFET calibration
- Runs 27-42: NAND Flash memory calibration
- Runs 43-48: measurement of RADFET and NAND Flash memories with different shielding configurations
- Run 49: double check of RADFET calibration

RADFET calibration

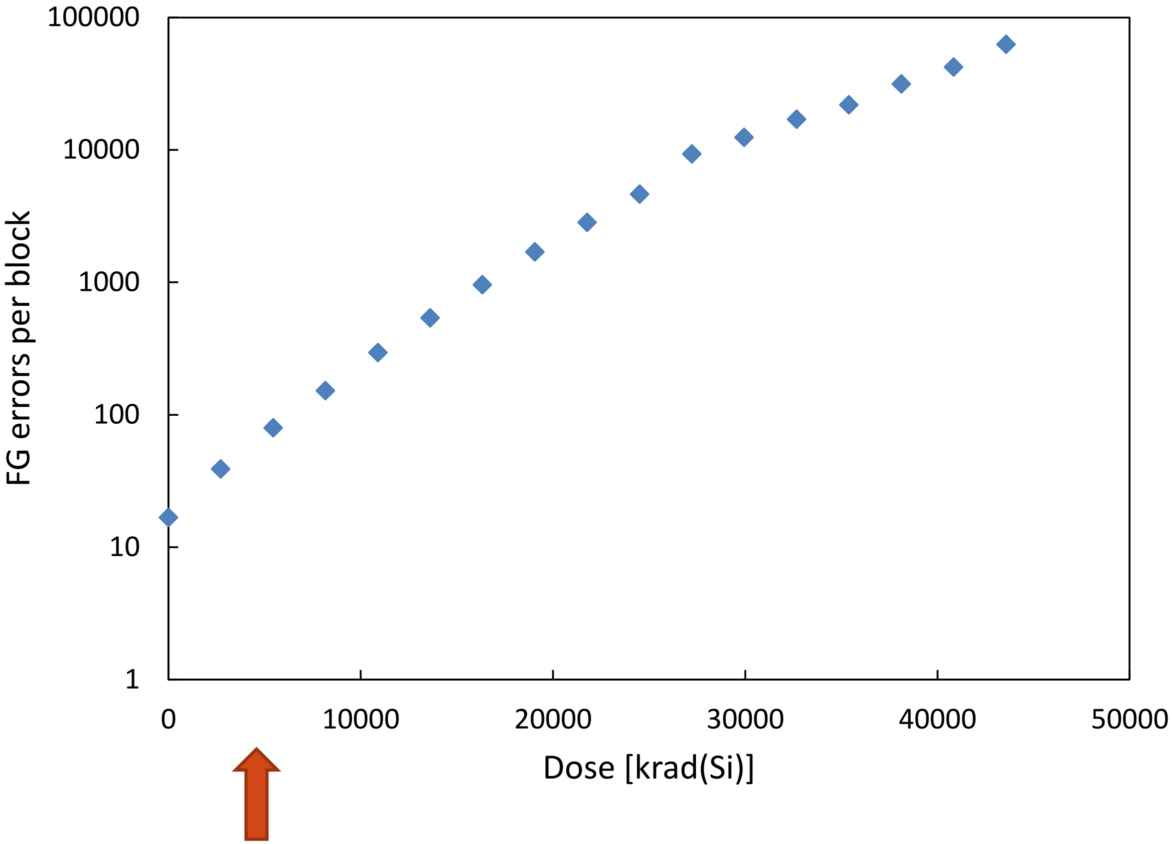


- The **threshold voltage (V_{th})** was measured online during exposure **as a function of radiation dose**
- V_{th} is perfectly reproducible for the two MOSFETs in the RADFET

- 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



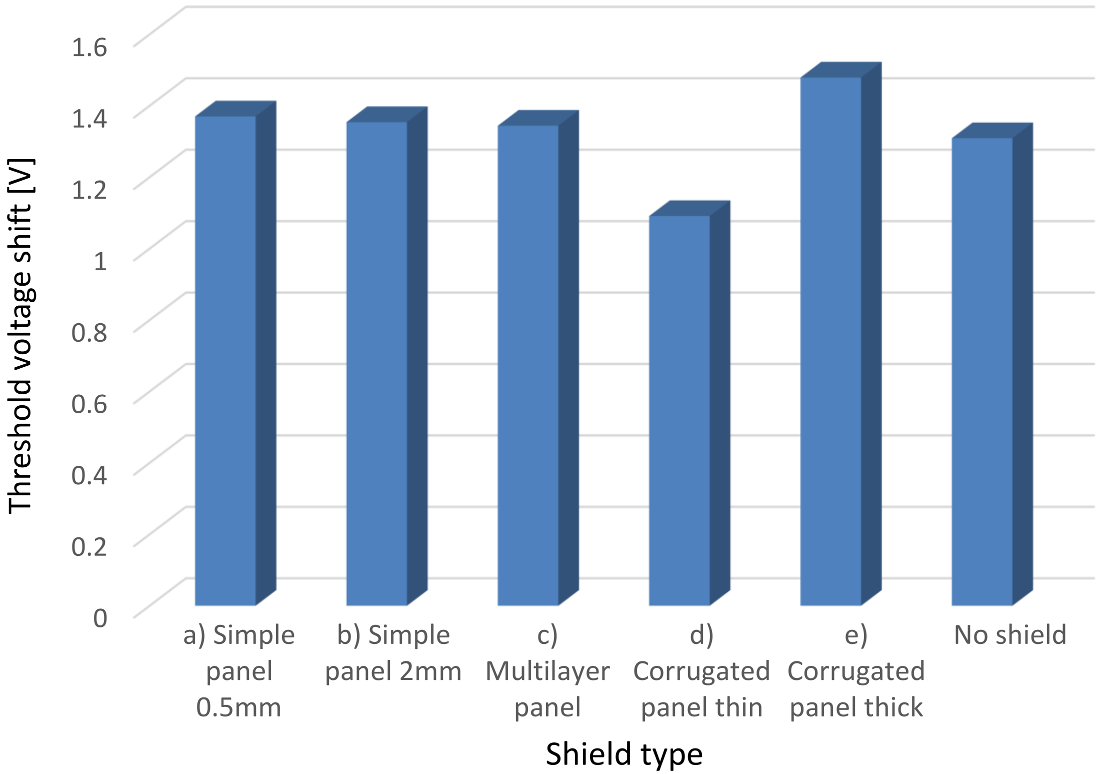
NAND Flash memory calibration



Errors in FG cells for memories programmed with solid pattern '33' '55' before proton irradiation

- 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

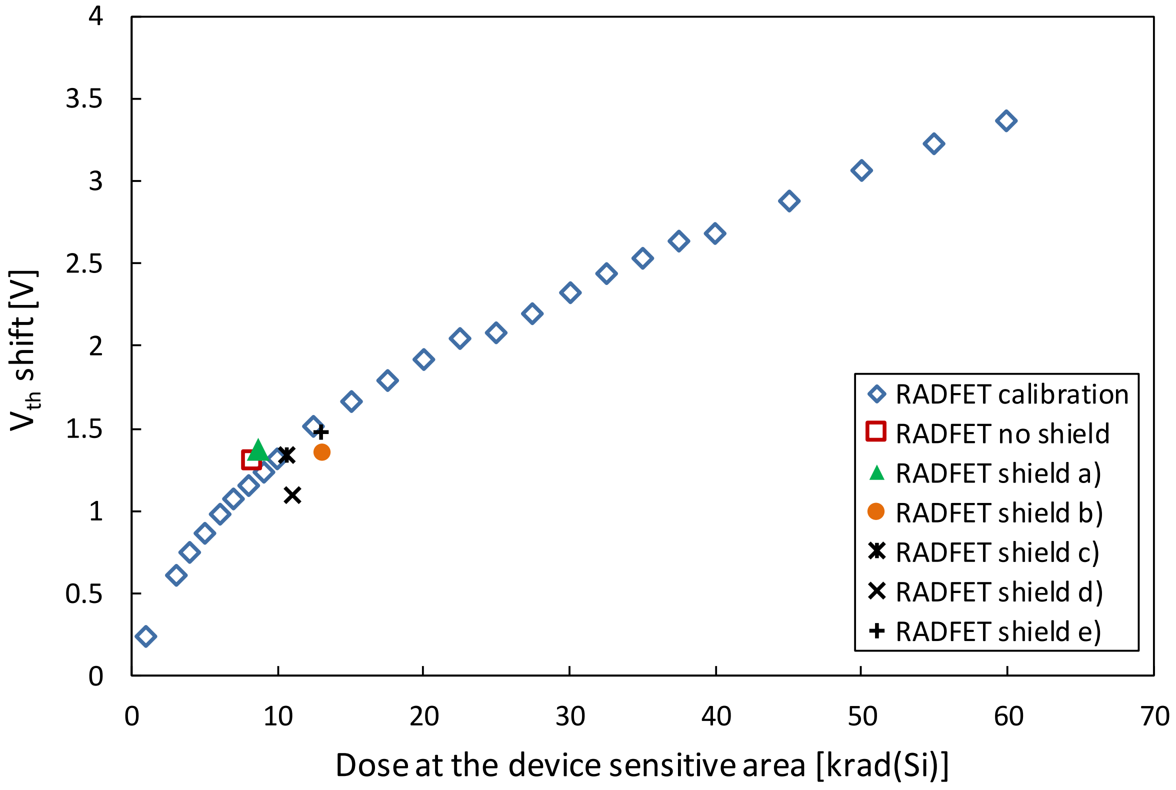
RADFETs irradiated with different shields (1/2)



V_{th} shifts in MOSFET 1

- 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

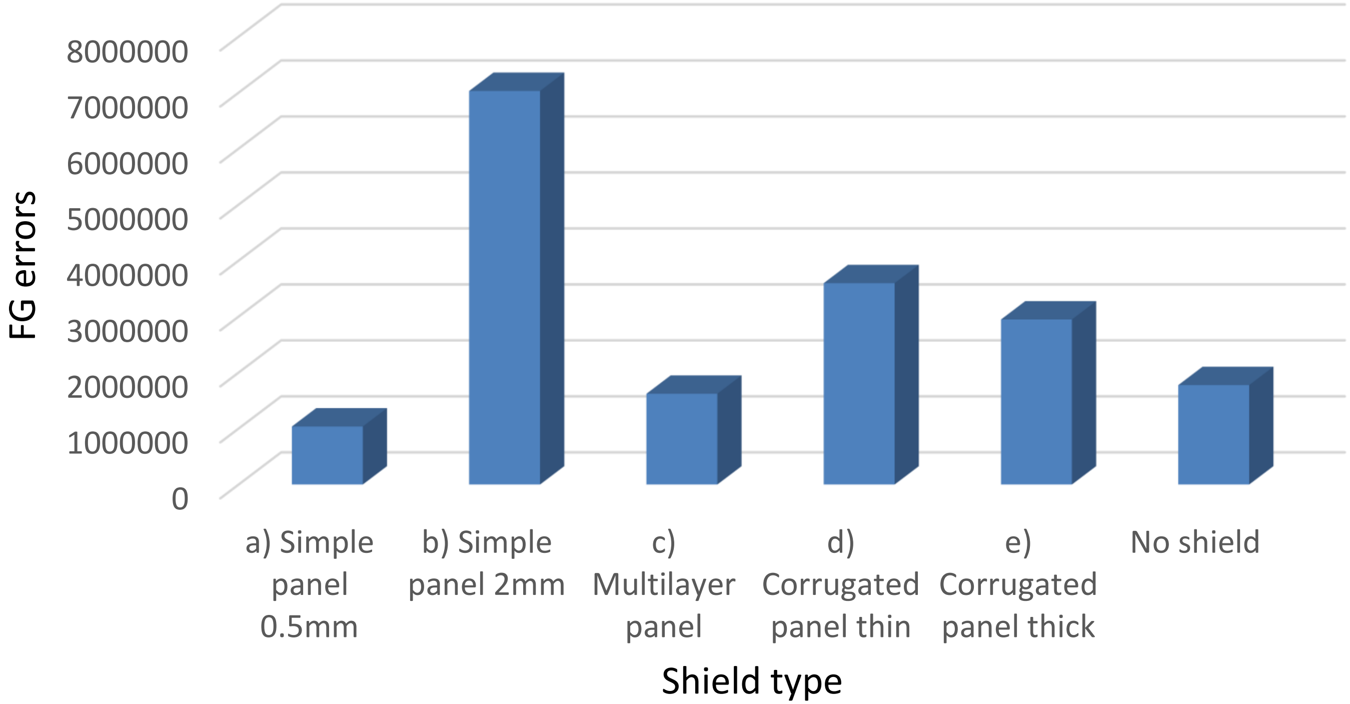
RADFETs irradiated with different shields (2/2)



V_{th} shifts in MOSFET 1

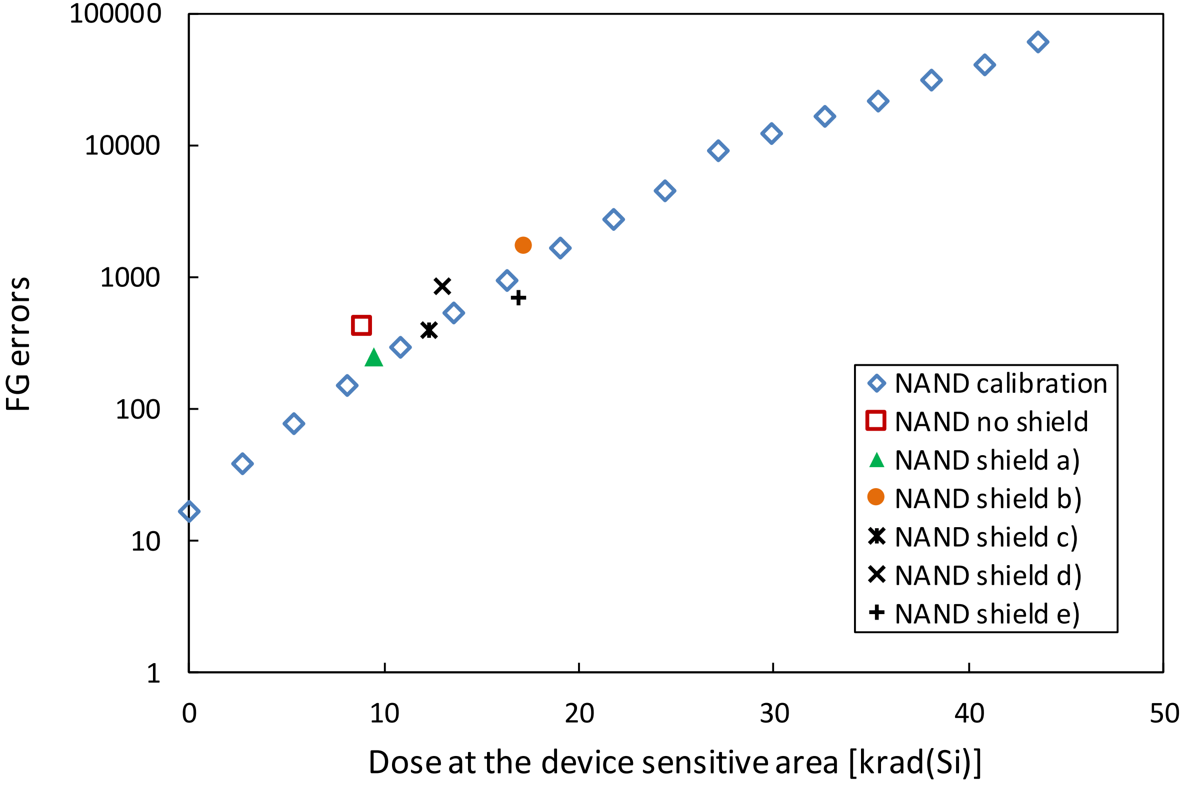
- RADFET threshold voltage shifts as a function of dose (calculated with SRIM simulations), for the different shielding conditions and compared with the RADFET calibration curve
- The correlation between the dose received in the different shielding configuration and the V_{th} shifts expected from the calibration curve is reasonable, with only one outlier

NAND Flash irradiated with different shields (1/2)



- The number of FG errors were measured in NAND Flash memories irradiated behind the different shields

NAND Flash irradiated with different shields (2/2)



- 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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