X-Ray Fault Injection in non-volatile memories of Power Off Devices

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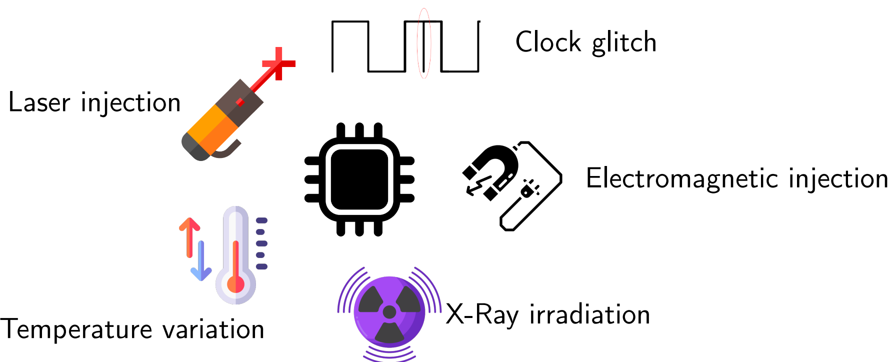
Introduction

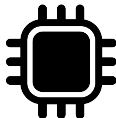
Fault Attack

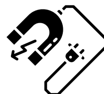
Disturbing the device to modify its behavior to obtain information or disable internal protection mechanisms



Introduction

Laser injection





Electromagnetic injection

Benefits

High time and spatial accuracy

Limitations

The device must be powered $\Rightarrow$ some countermeasures exist

Advantages

X-Ray can have an effect in non-volatile memories of power off devices

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1. Flash memory, floating gate transistor and X-ray effects
   - Flash Memory and floating gate transistor
   - X-Ray effects on floating gate transistor
2. Experiments
3. Results
4. Conclusion

Overview

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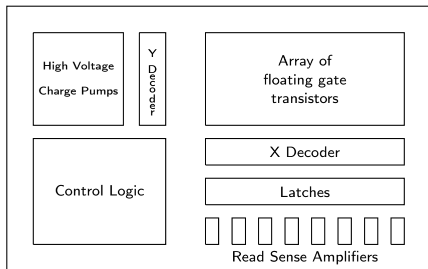
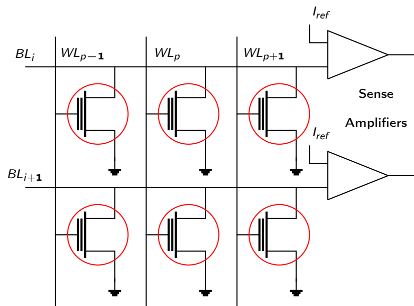
Usual organization of Flash memories

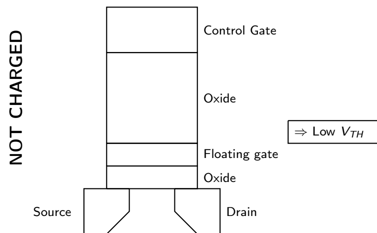


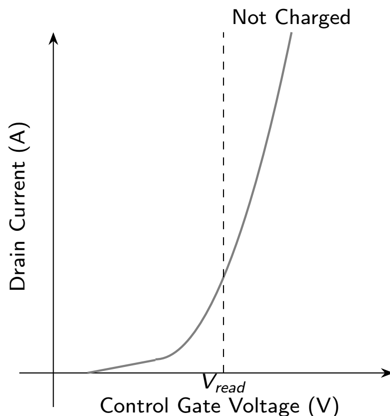


Floating gate transistors

S. Skorobogatov, 'Optical Fault Masking Attacks', in 2010 Workshop on Fault Diagnosis and Tolerance in Cryptography, Santa Barbara, CA, TBD: IEEE, Aug. 2010, pp. 23–29

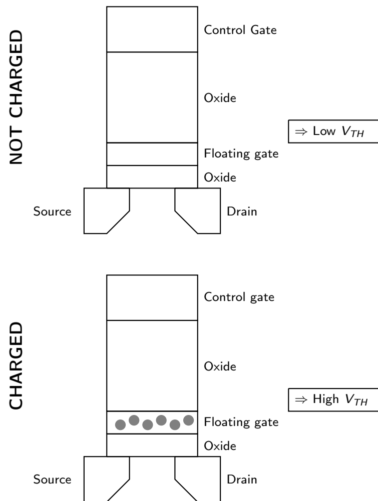
Floating gate transistor

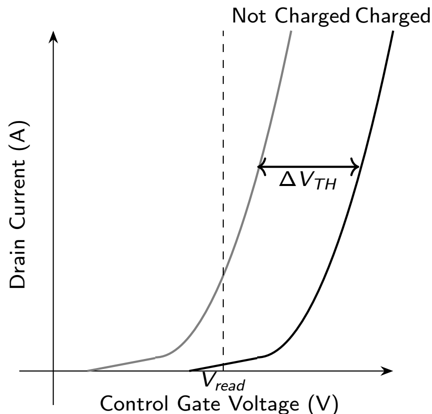




S. Gerardin et al., 'Radiation Effects in Flash Memories', IEEE Trans. Nucl. Sci., vol. 60, no. 3, pp. 1953–1969, Jun. 2013

Floating gate transistor





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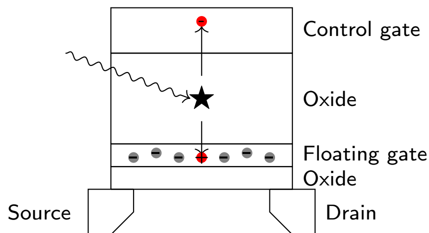
TID mecanisms in floating gate transistor



Effect 1

- e^+/h^- pair created by radiation is separated by the electric field
- one of them escapes through the control gate
- the other one is injected into the floating gate

⇒ recombination with stored charges

⇒ decrease of the charge

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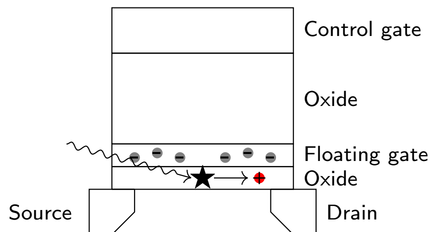

Effect 2

- the charge can be trapped in the oxide
- Phenomenon is not significant because of the thinness of the oxides

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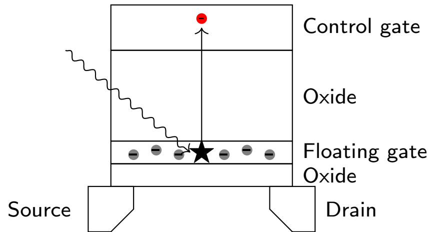
TID mecanisms in floating gate transistor



Effect 3: *photoemission*

- charges stored in the floating gate get enough energy from the radiation to escape from the potential well

$\Rightarrow$ decrease of the stored charge

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TID mecanisms in floating gate transistor

3 different effects:

- electron-hole pair generation in the oxide
- charge trapping in the oxide
- **photoemission**

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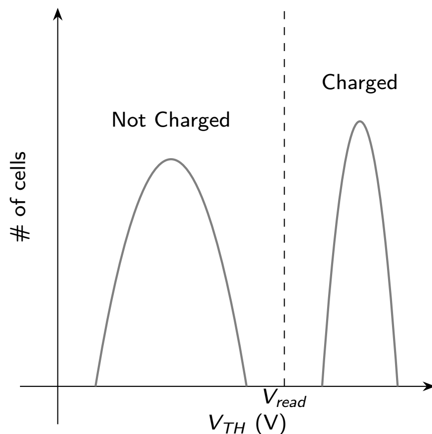
Influence of ionizing radiation on the threshold voltage distribution



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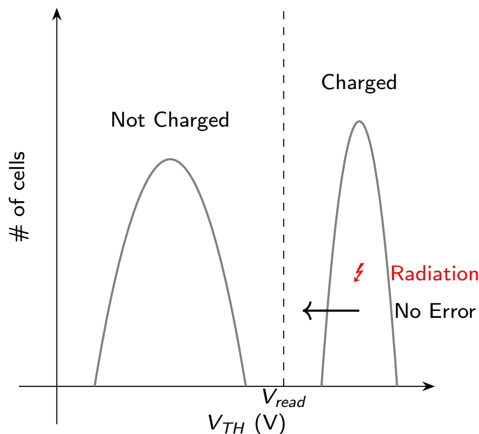

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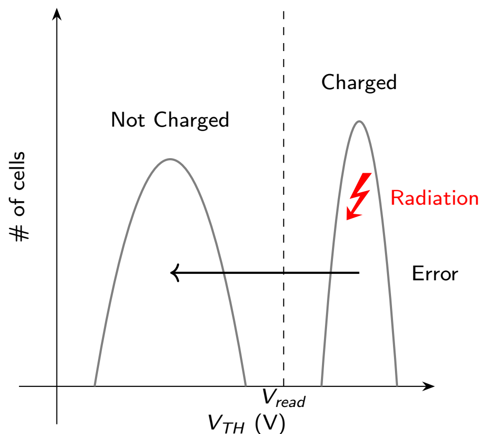

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2 Experiments
- X-Ray setup
- Targets
- Protocol

3 Results

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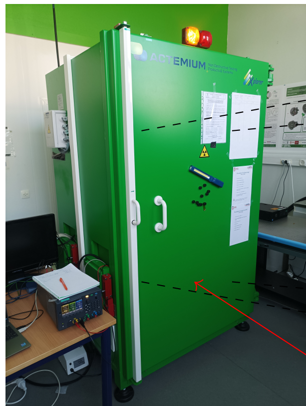
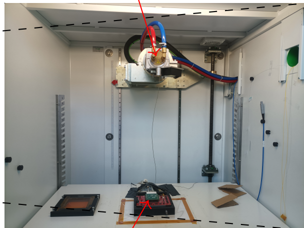
X-Ray irradiator





X-Ray Source

Target

Lead enclosure

Settings

- Tungsten (W) anode
- Source : 100kV and 45mA ⇒ photons with 40keV energy

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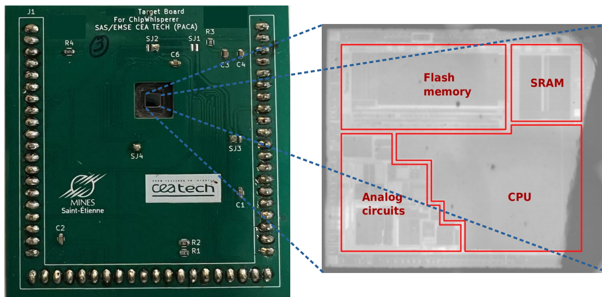
Targets



Targets settings

- 32-bit microcontroller with ARM Cortex-M3 core
- 128 kB of Flash memory (erase state : `0xFFFFFFFF`)
- 2048 bitlines and 512 wordlines
- security bits preventing from reading memory if activated

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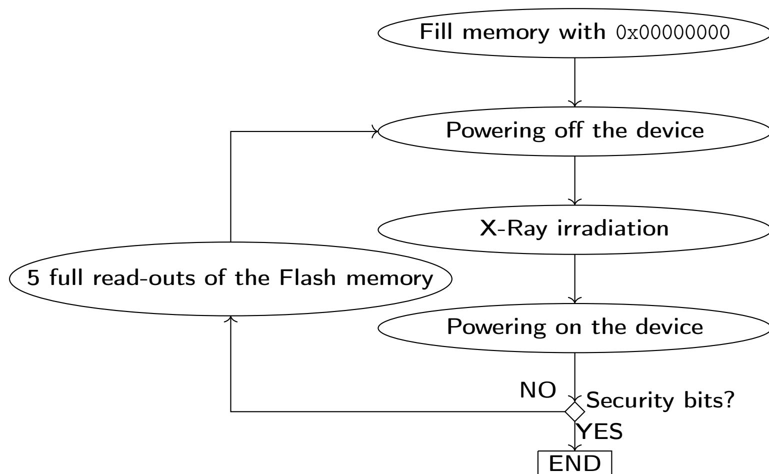
Protocol



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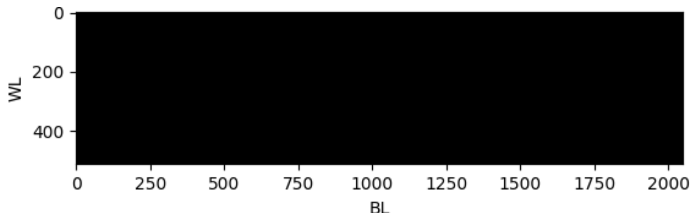
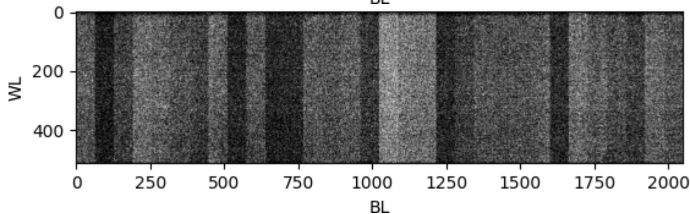
Bitsets in Flash memory

Color	Bit Value	Faulty	FGMOS state
White	1	Yes	Discharged
Black	0	No	Charged

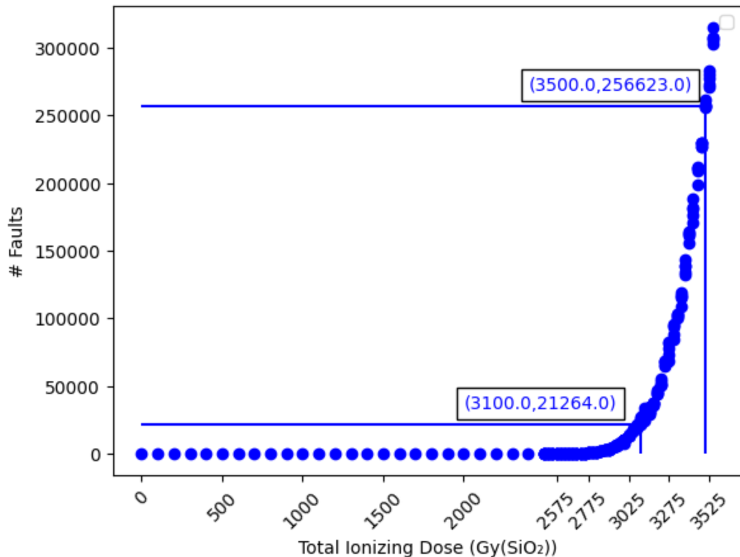
Before irradiation:



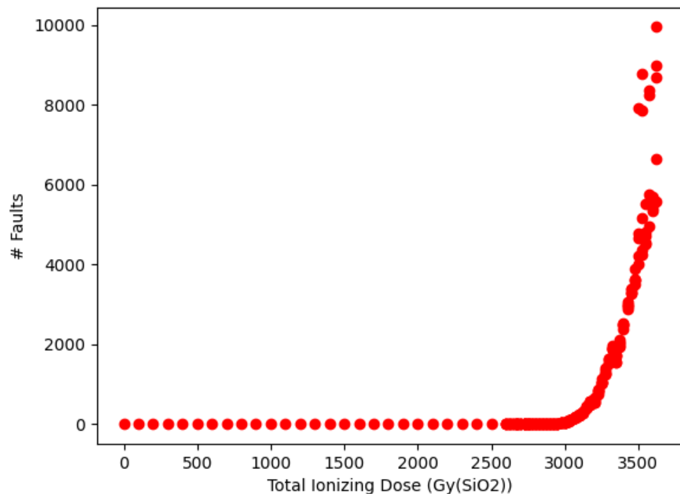
After irradiation:



Faults in Flash memory



Faults in EEPROM memory



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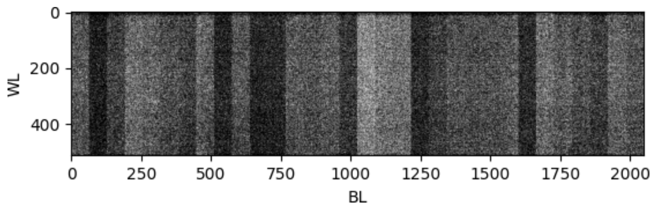
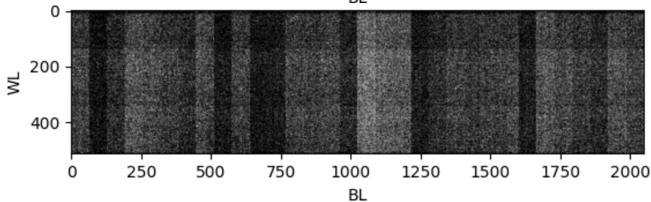
Time and thermal recovery

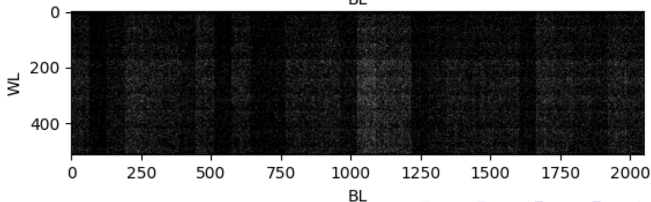
After irradiation:



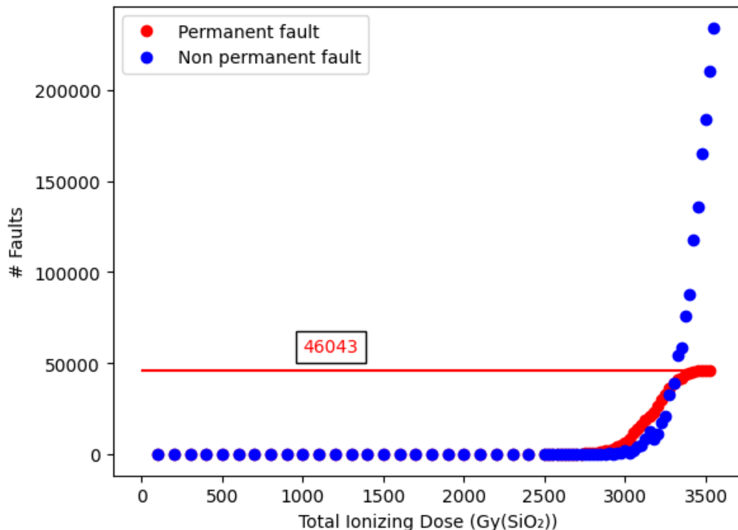
After time recovery:
7 days @ room temperature



After thermal recovery:
2h @ 150°C



Permanent VS non-permanent faults



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Conclusion

- X-Ray can have an effect on non-volatile memories of power off devices
- Exponential dependance between the total ionizing dose and the number of faults
- Thermal recuperation is possible for the non-permanent faults
- Permanent faults are due to the discharge of the floating gate transistors

Thank you for listening. Do you have any questions?

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