BITFLIP 2025

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Ph.D. in microelectronics

Fault Injection Attacks on Unpowered Devices

MINES Saint-Étienne
Une école de l'IMT

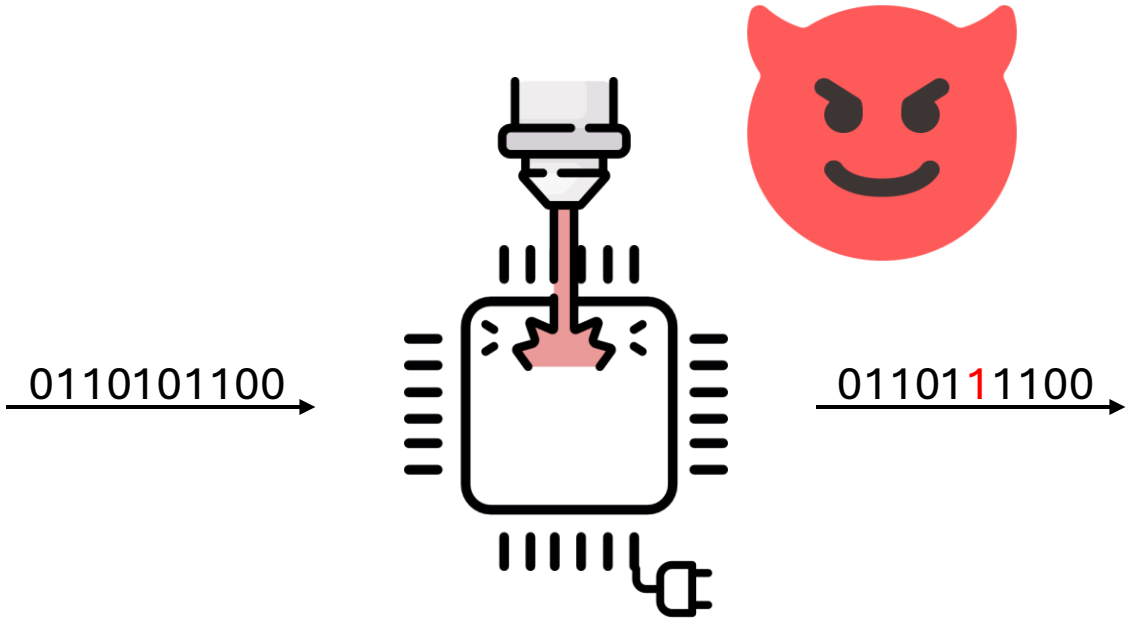
50 years 1976-2026

Laboratoire Hubert Curien
UMR ▪ CNRS ▪ 5516 ▪ Saint-Étienne

Context

State of the art

Almost all the attacks performed on powered devices



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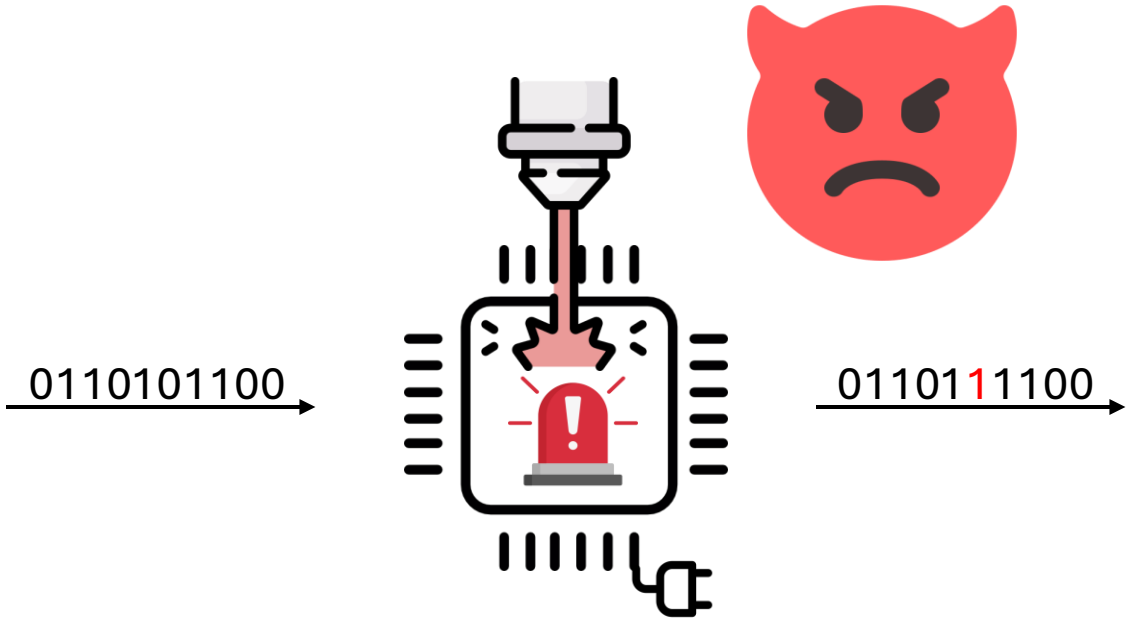
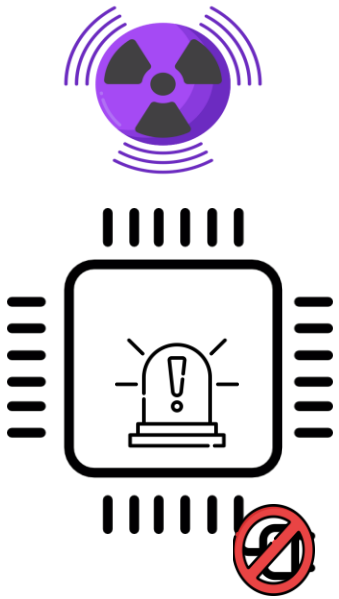


Context

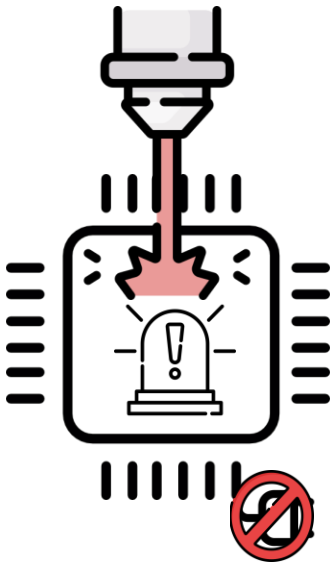
State of the art

Almost all the attacks performed on powered devices

X-Ray



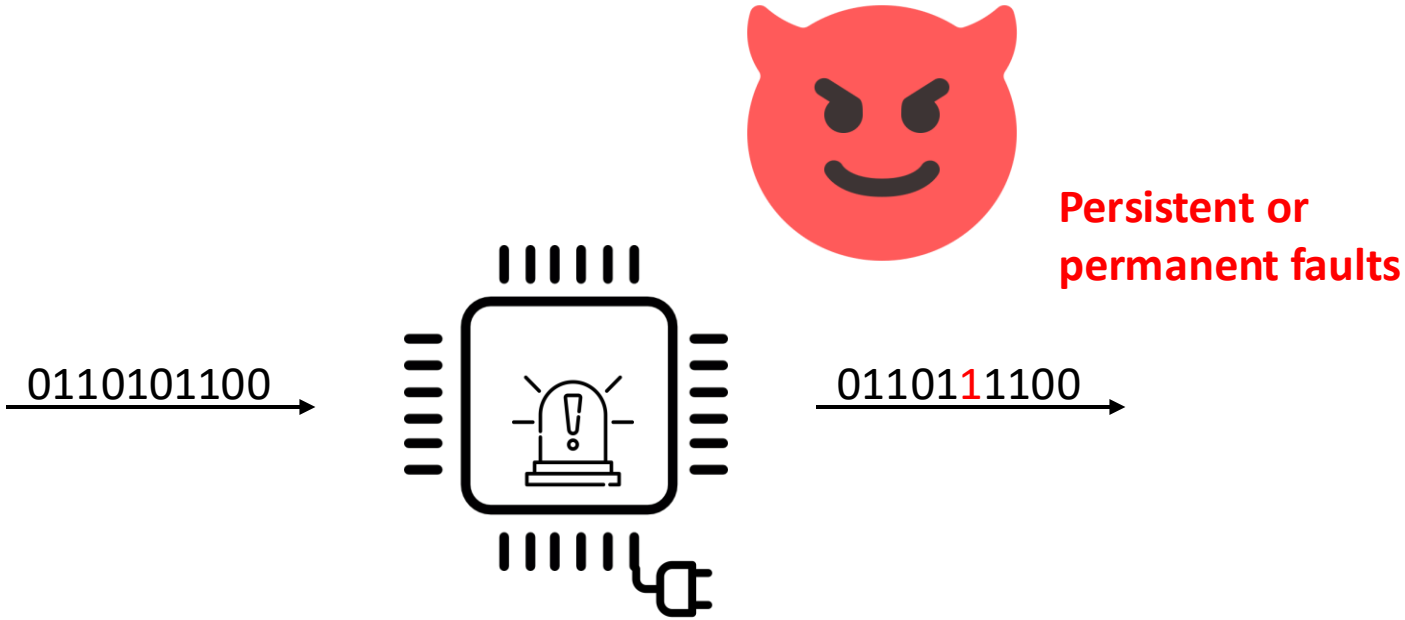
Laser



Context

State of the art

Almost all the attacks performed on powered devices



Context

Problem

How to bypass the sensors?

Solution

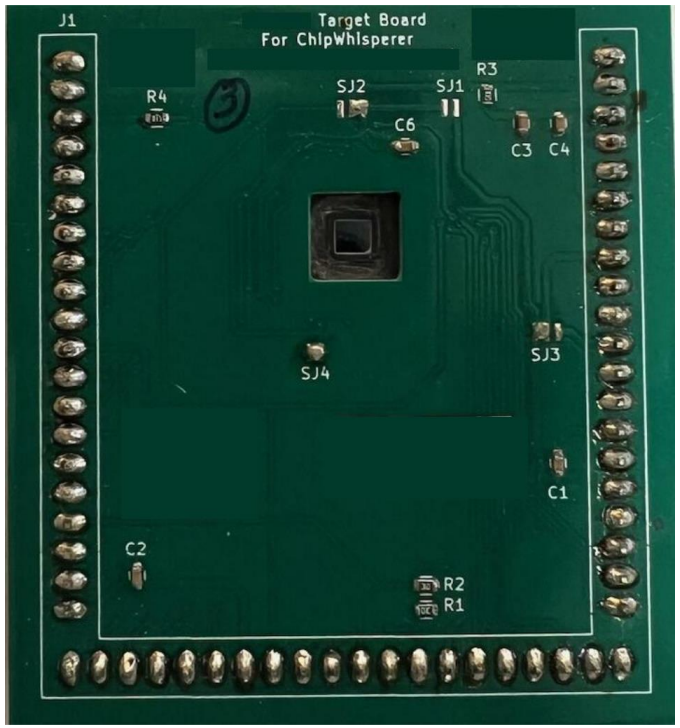
Attack unpowered devices

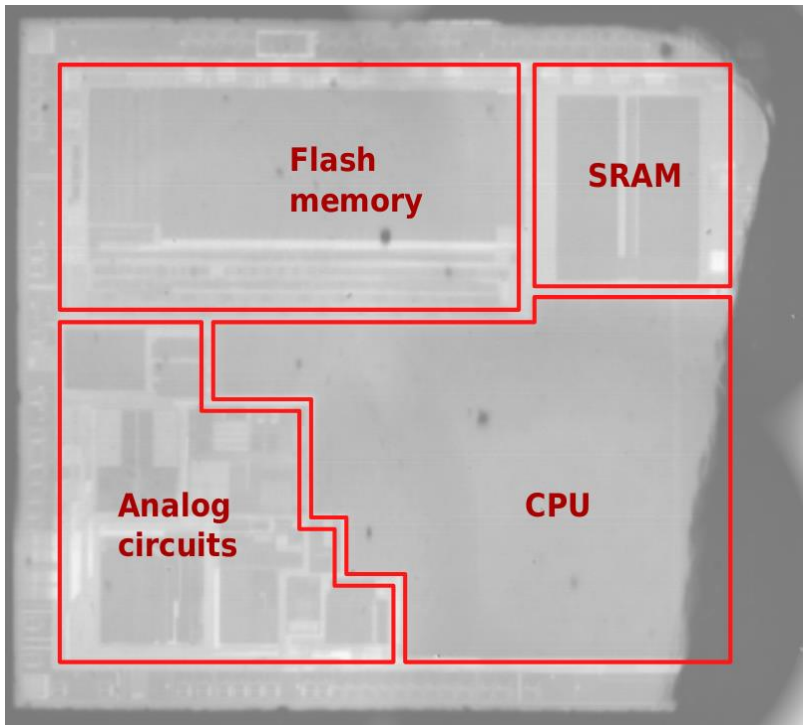
- No detection possible
- No synchronization required

Ideas

- Break the sensors
- Corrupt stored information: Non-Volatile Memories (Flash)

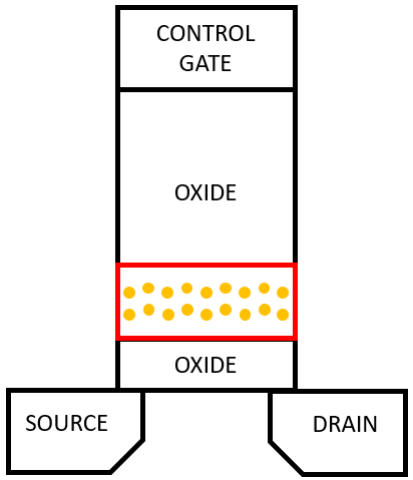
Hardware target



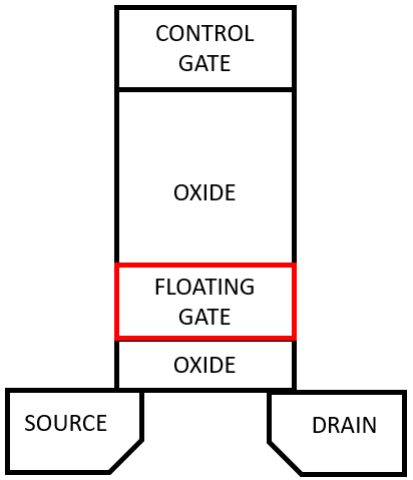


- STM32F1 open on the backside (32-bit microcontroller)
- 128 kB of Flash memory (128 pages of 1 kB)

Floating gate transistors in Flash memories



Charged cell

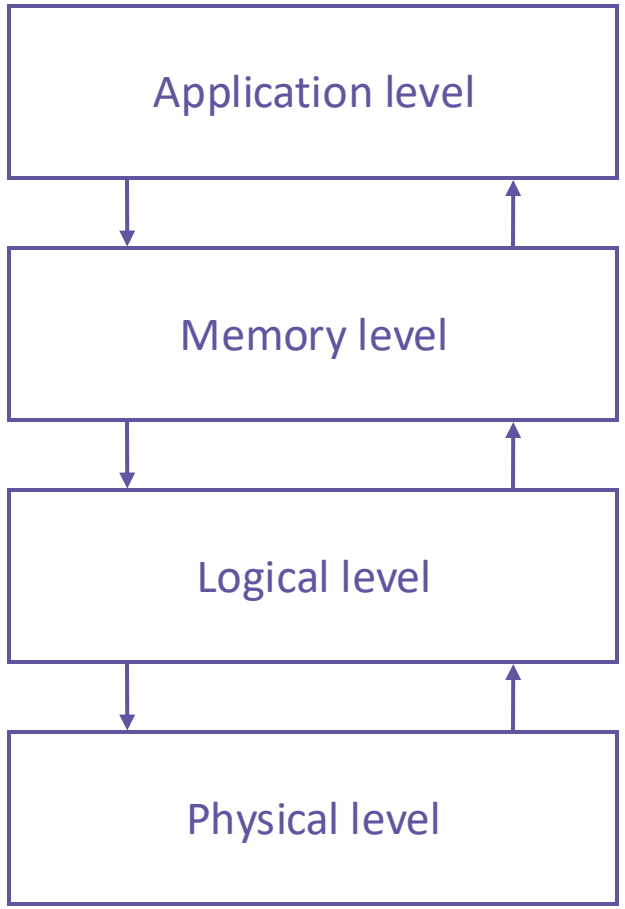


Discharged cell

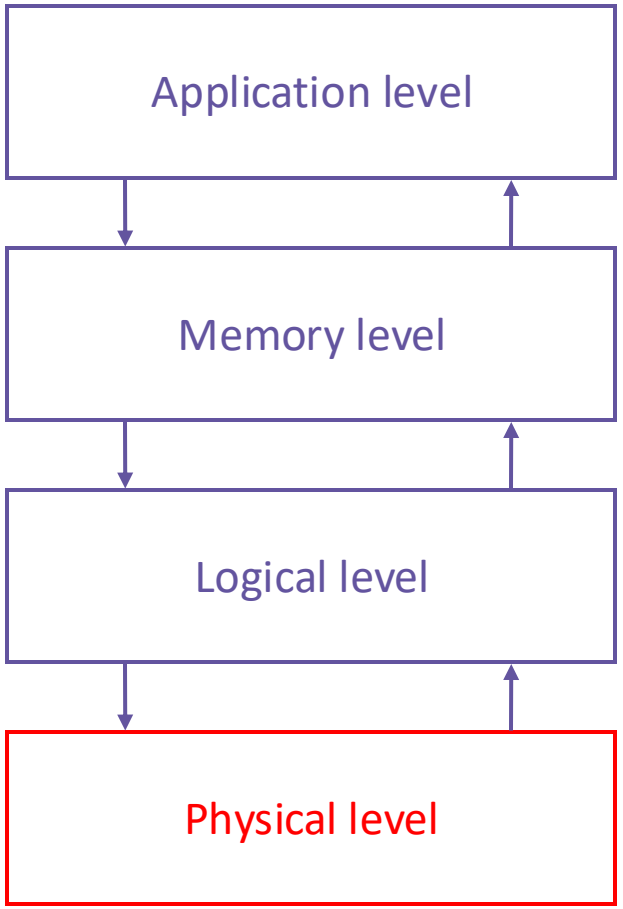
Convention:

- Charged = '0'
- Discharged = '1'

Abstraction levels

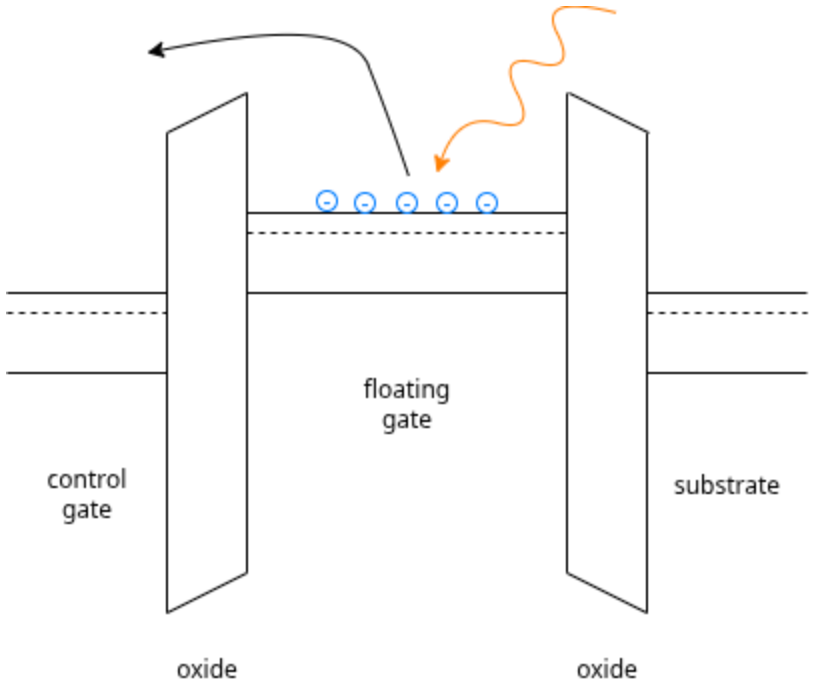


Abstraction levels



X-Ray Fault Injection

Total Ionizing Dose effect on FGmos[1]



Photoemission effect

Three different mechanims:

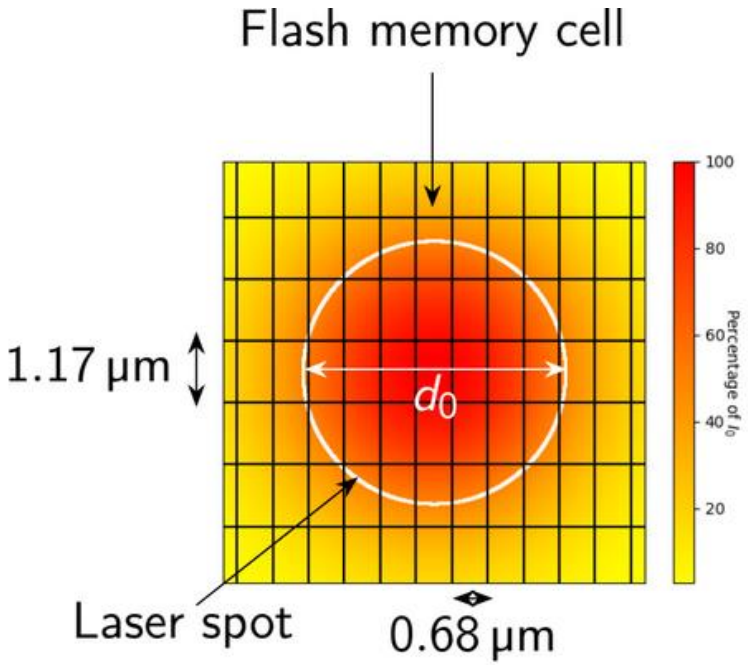
- Electron/hole pair generation in the oxides
- Charge trapping in the oxides
- Photoemission

[1]Gerardin et al., "Radiation Effects in Flash Memories", IEEE Transactions on Nuclear Sciences 2013

Laser Fault Injection

Temperature effect on FGmos

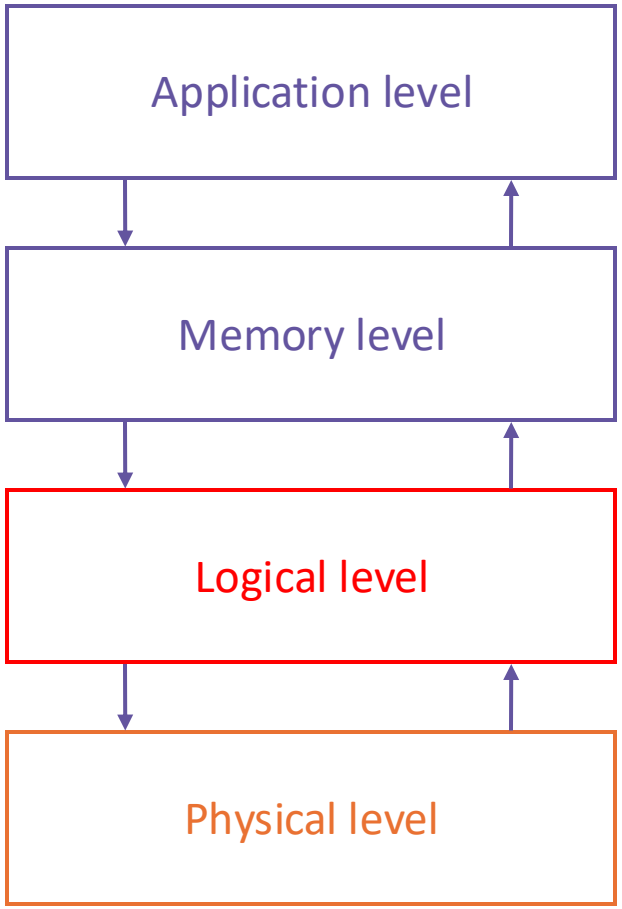
- Laser beam energy → Temperature increase → Floating gate discharge[2]



Heatmap induced by the laser exposition (d_0=5µm)

[2]Sands, "Pulsed laser heating and melting", Heat Transfer: IntechOpen 2011

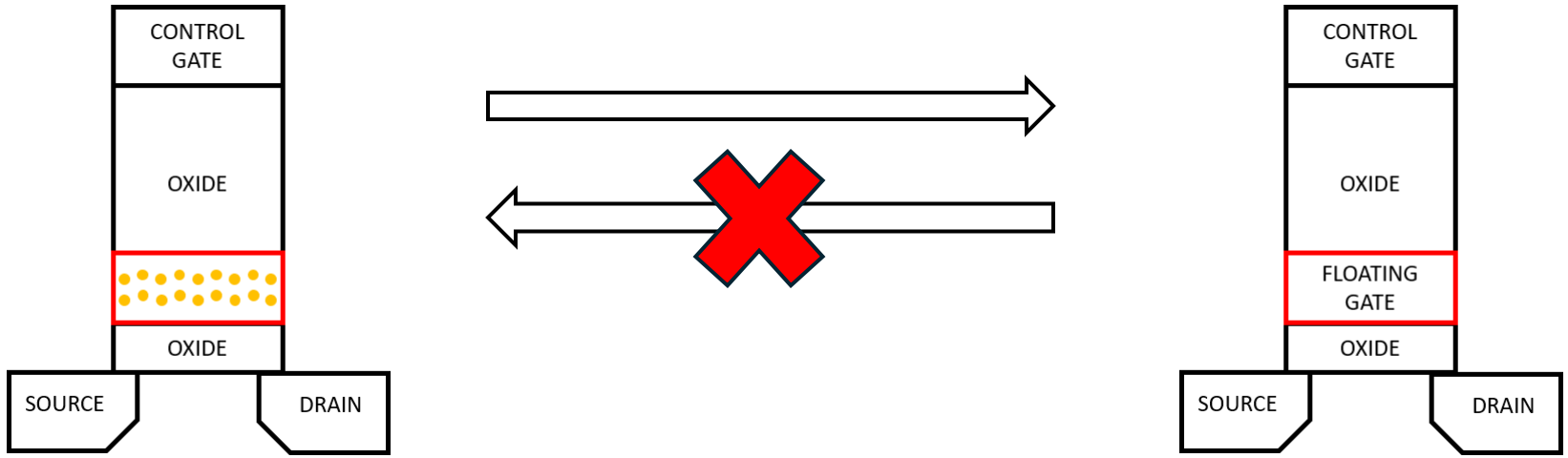
Abstraction levels



Floating gate transistors discharge by photoemission or heating

Abstraction levels : Logical level

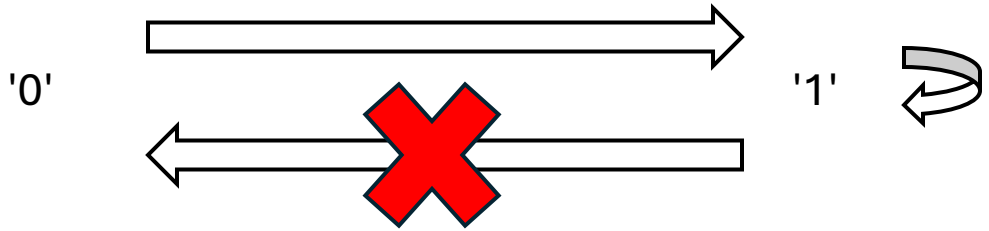
- From the physical level:



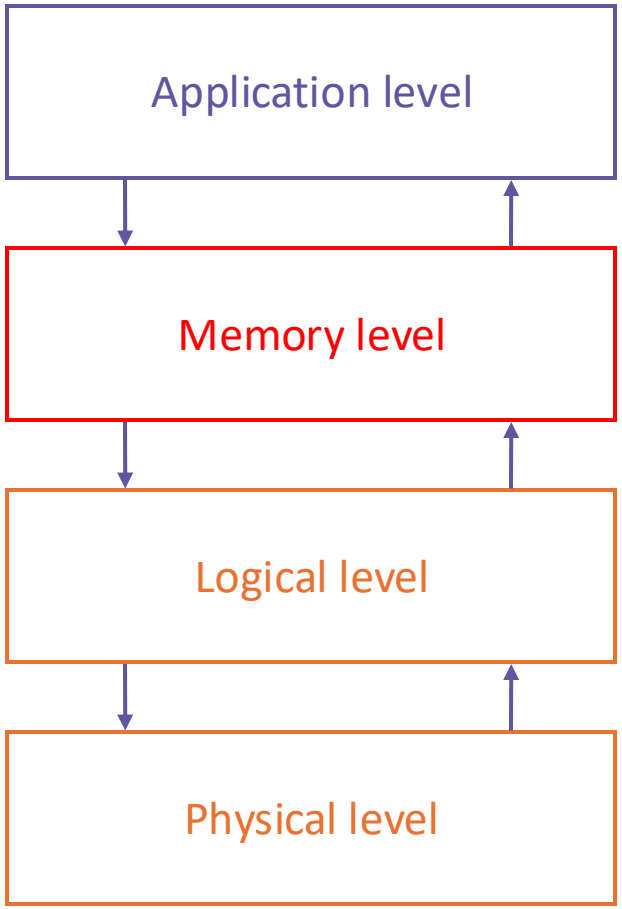
Charged cell

Discharged cell

- To the logical level:



Abstraction levels



Bitsets ('0'→ '1')

Floating gate transistors discharge by photoemission or heating

X-Ray Fault Injection

Experimental setup

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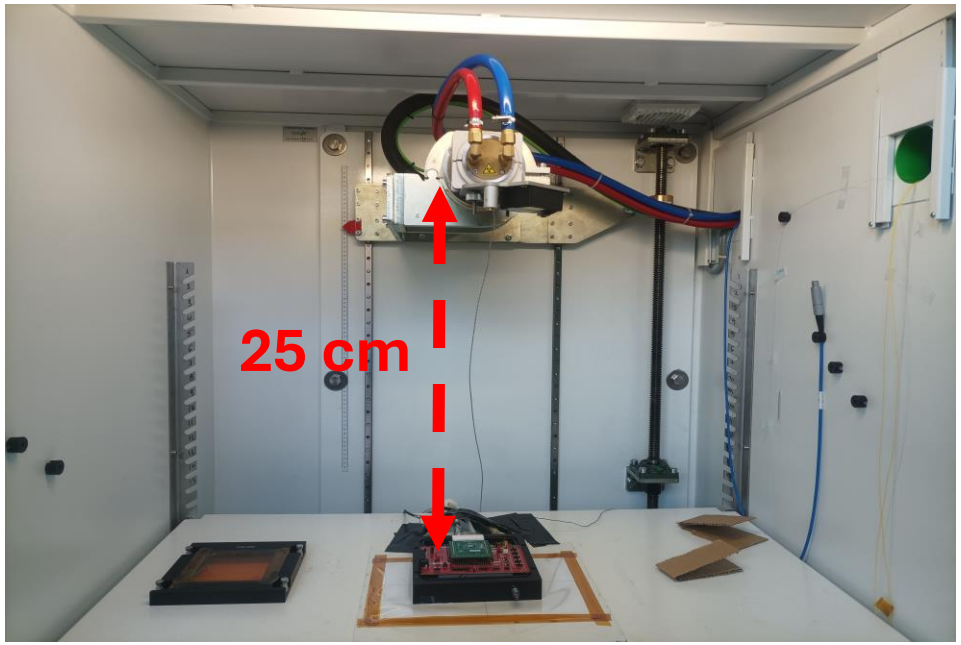
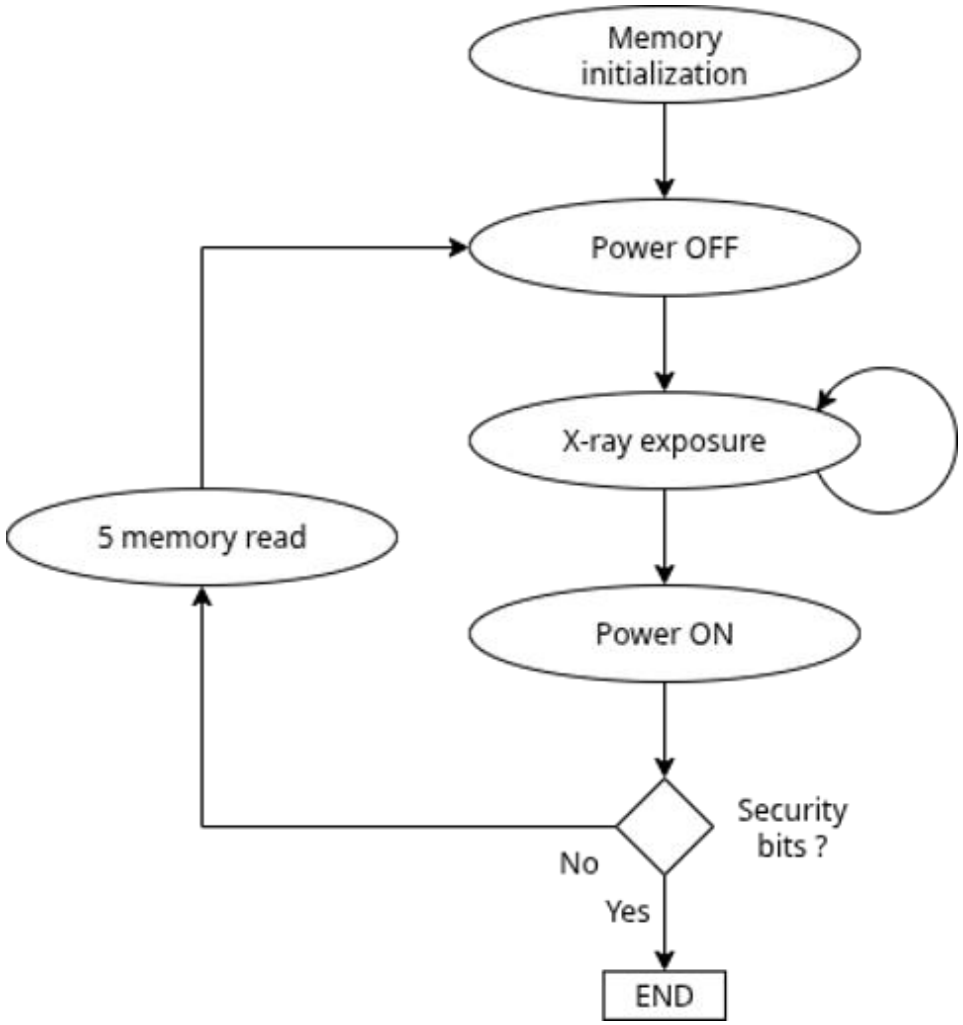


⚠ **The entire target is irradiated !**

X-Ray Fault Injection

Results



X-Ray Fault Injection

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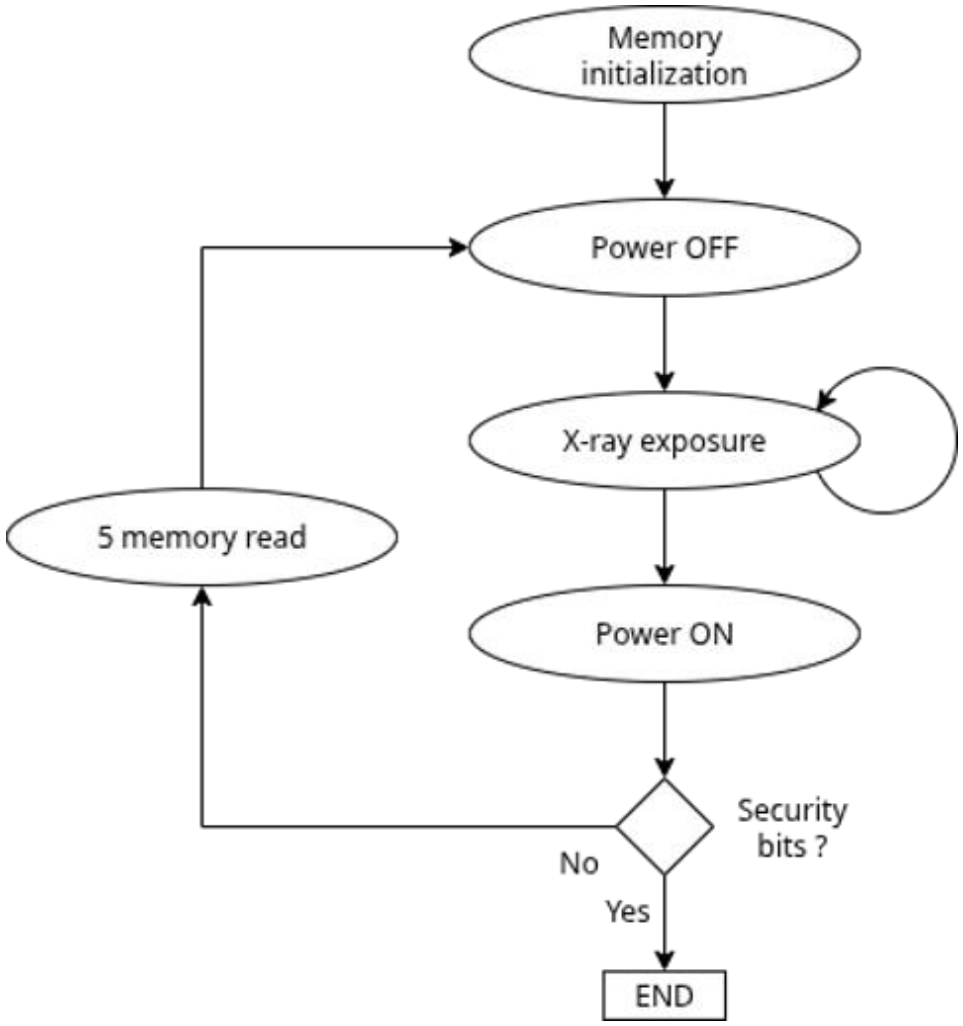

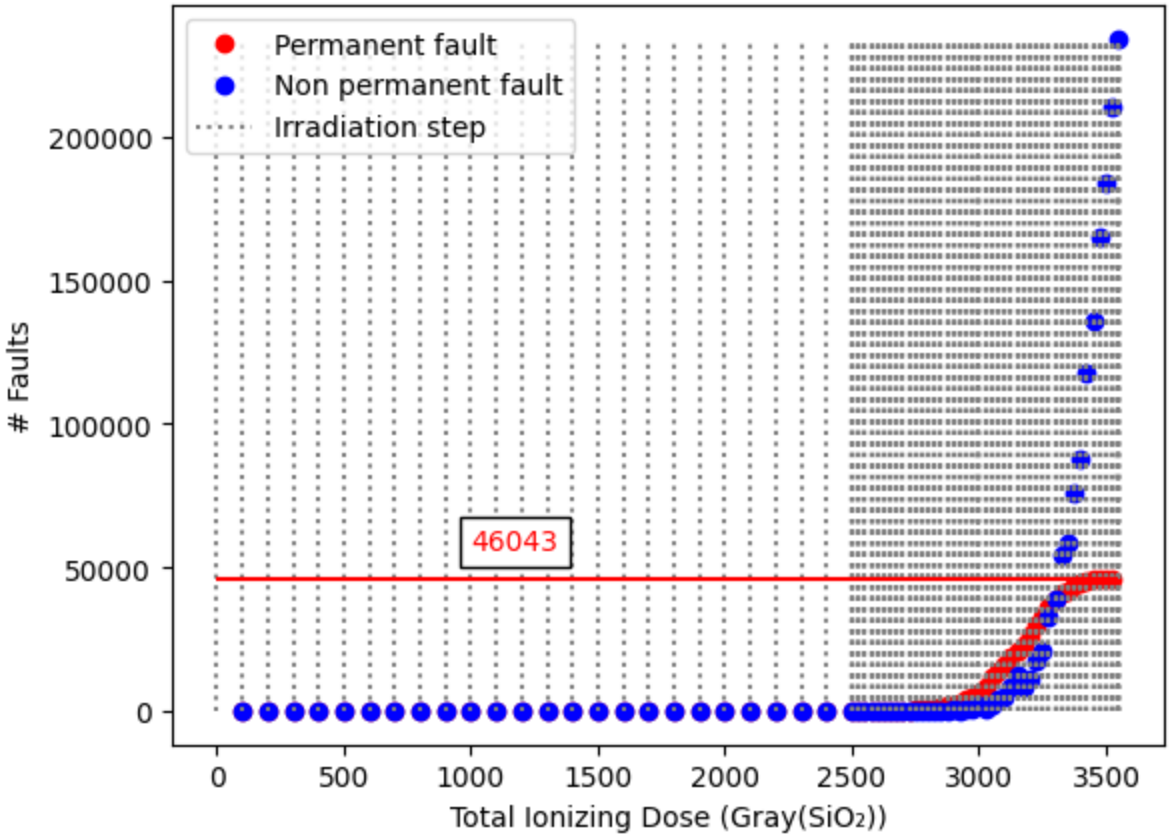

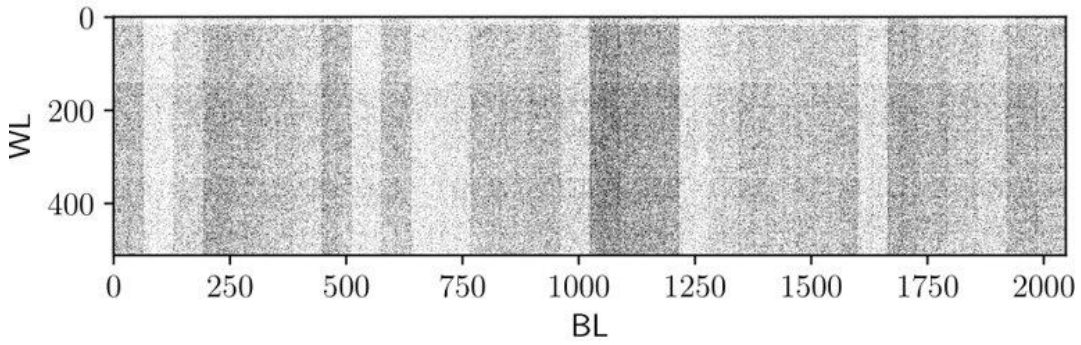

X-Ray Fault Injection

Synthesis

Fault mechanism
• Floating gate transistors discharge by photoemission

X-Ray Fault Injection

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Limitations

- Faults injected but not localized, therefore non exploitable

X-Ray Fault Injection

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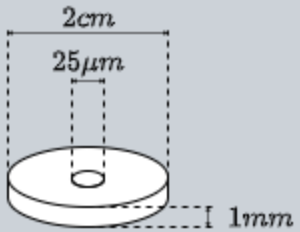
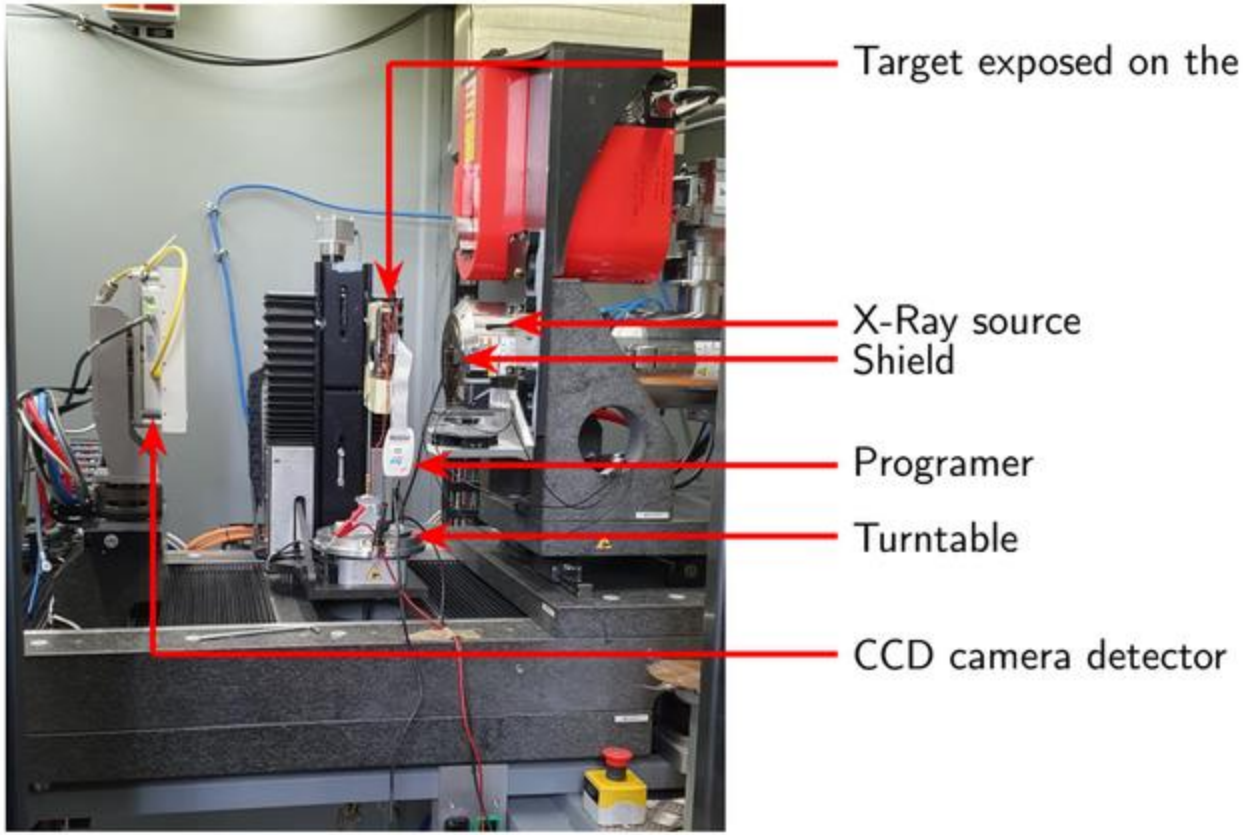
Design of a focalization shield

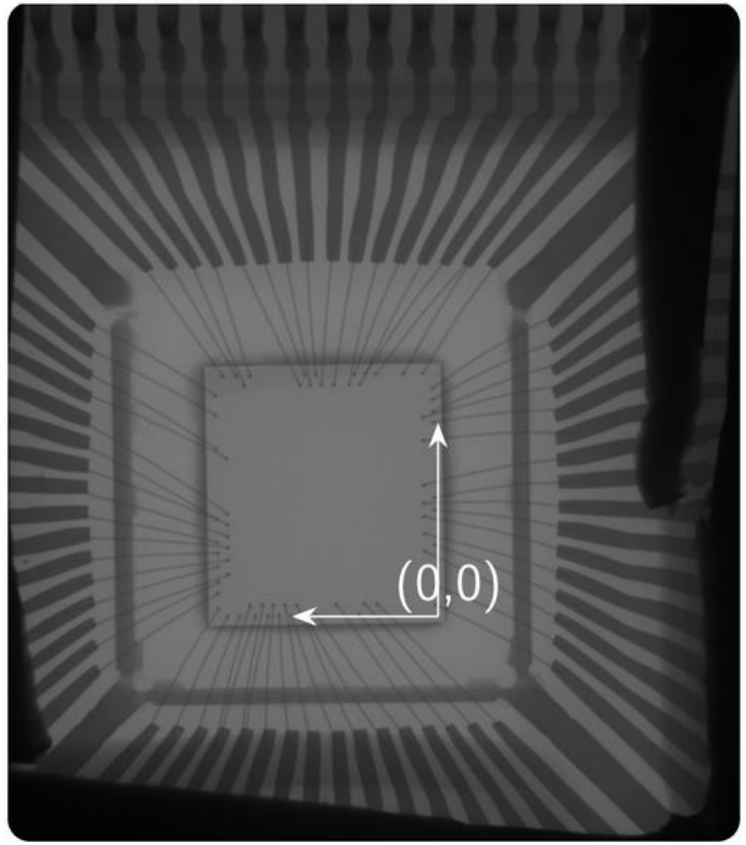
- Tungsten (W)



X-Ray Fault Injection

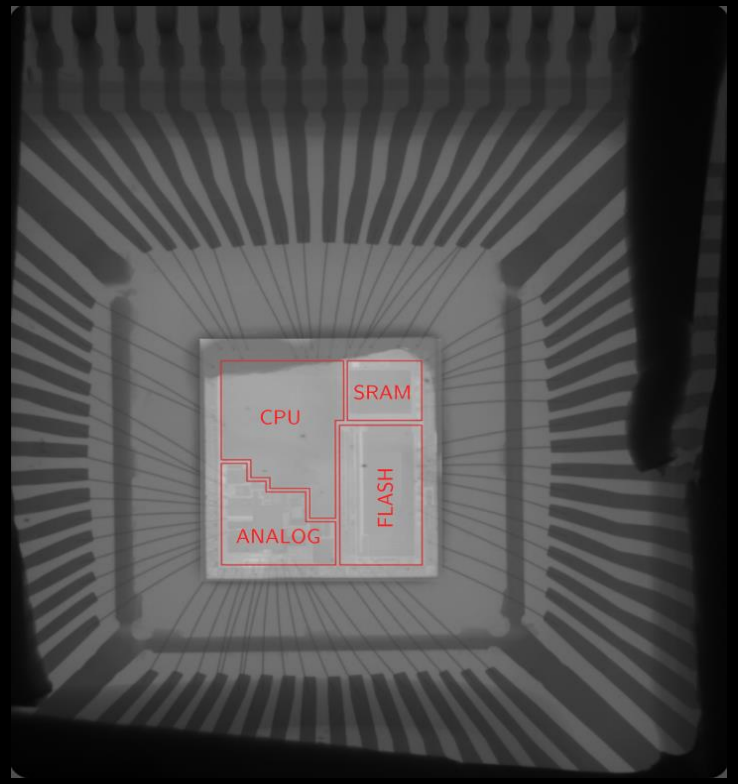
Experimental setup

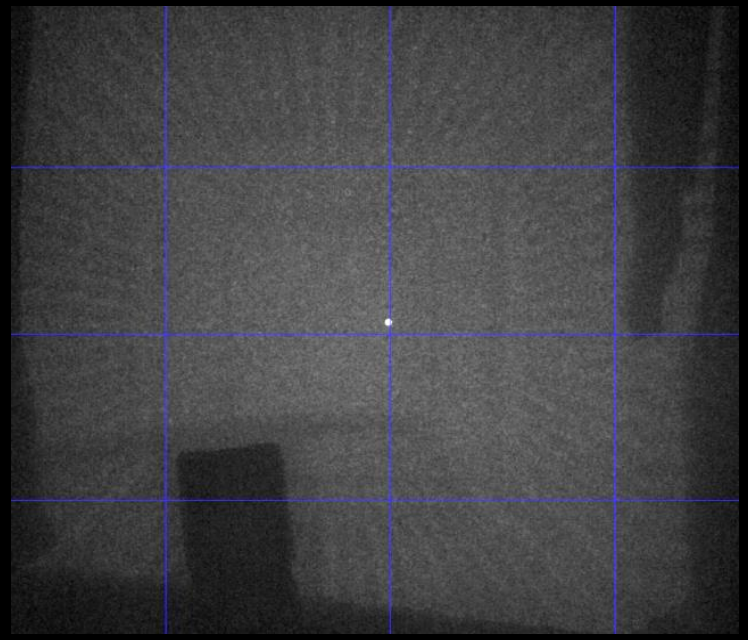




X-Ray Fault Injection

Obtained pictures



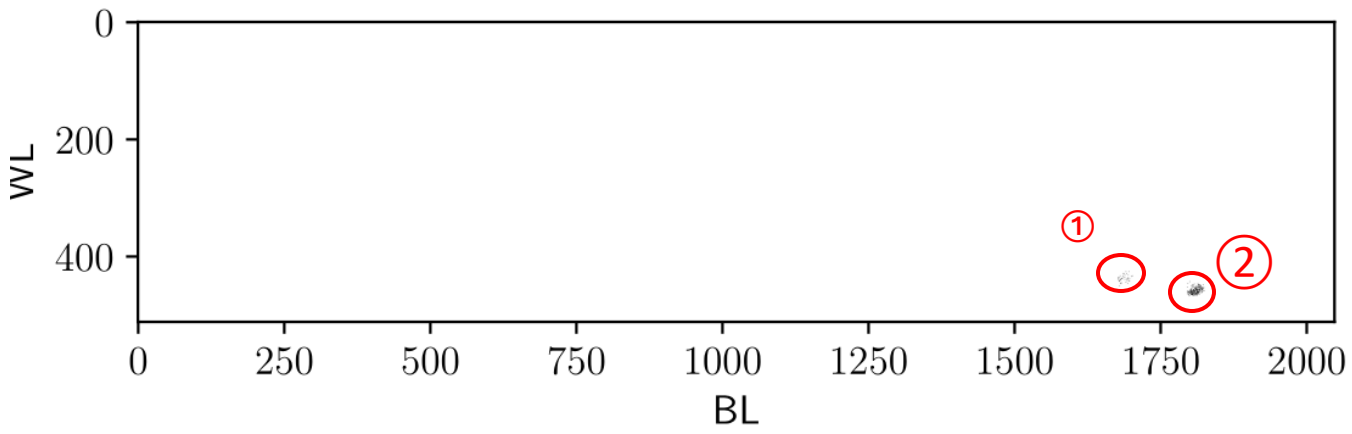


X-Ray Fault Injection

Results

2 different positions:

- Position ① : (0.6 mm,1.1 mm) ⇒ 1h of irradiation
- Position ② : (0.6 mm,1.2 mm) ⇒ 2h15 of irradiation



Results

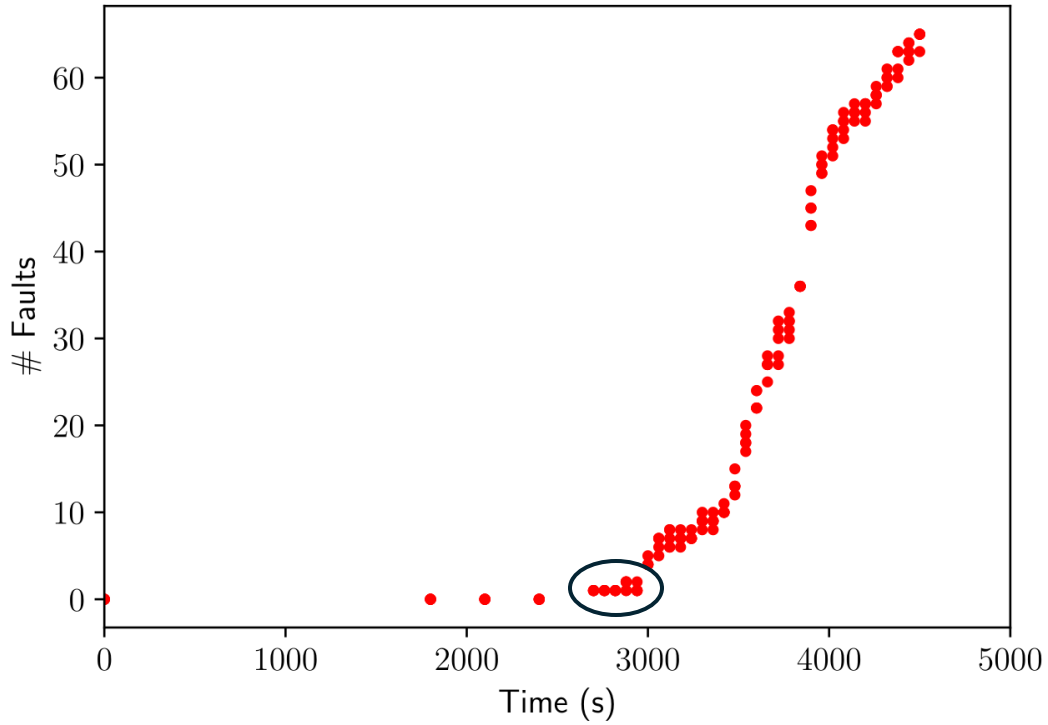
- Position ①: ≃ 70 localized faults
- Position ②: ≃ 300 localized faults

X-Ray Fault Injection

Results

Position ①:

- (0.6 mm,1.1 mm) ⇒ 1h of irradiation ⇒ ≃ 70 localized faults

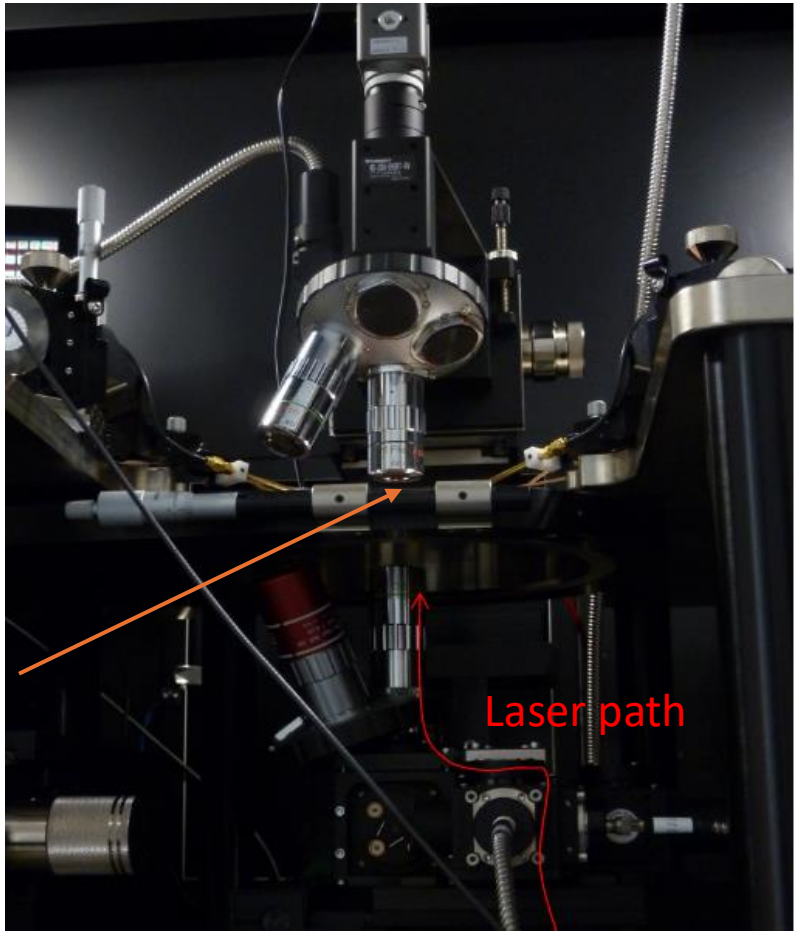


Results

Only few faulty bits for a given exposure time!

Laser Fault Injection

Experimental setup



- 1,064 nm laser source (near-IR)
- 5 µm spot with a x20 magnifying lens
- Backside view with an IR camera
- Same setup as usual powered LFI

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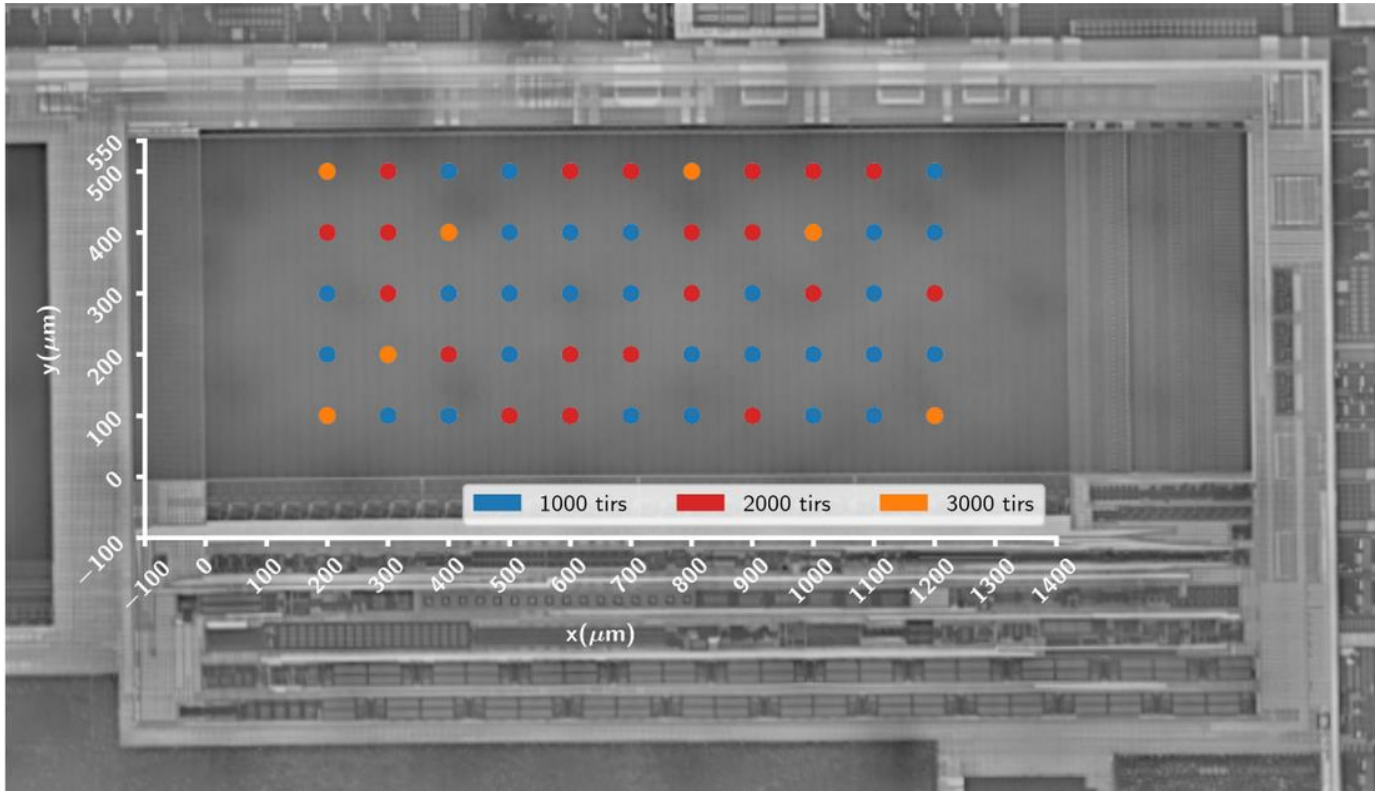
European Cyber Week

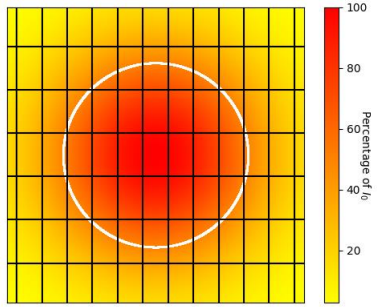
Laser Fault Injection

Results

- Memory initialized to 0x00000000 before laser exposure



- Reverse engineering of the Flash memory mapping possible



- Single bit faults in 33%
- 2.2 faulty bits on average

Laser Fault Injection

Abstraction levels : Memory level

Code corruption (ARMv7 ISA)

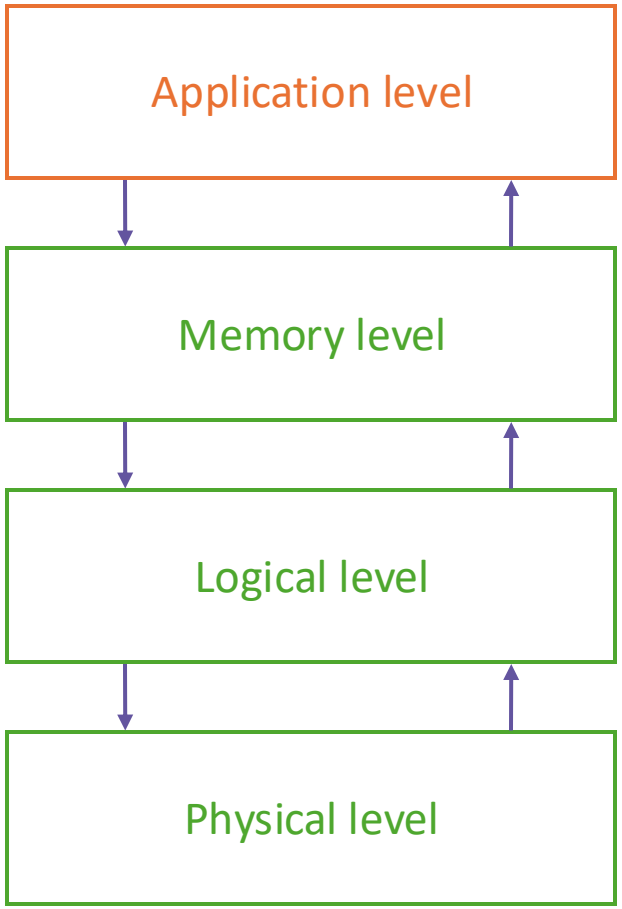
31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Generic MOVW																															
1	1	1	1	0	i	1	0	0	1	0	0	imm4				0	imm3			Rd				imm8							
MOVW,R0,0																															
1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOVW,R0,4																															
1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
MOVW,R1,0																															
1	1	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MOVT,R0,0																															
1	1	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Example of possible corruptions on a MOVW instruction[3]

- Also possible to corrupt permanent data

[3]Colombier et al., "Laser-induced Single-bit Faults in Flash Memory: Instructions Corruption on a 32-bit Microcontroller", IEEE HOST 2019

Abstraction levels



Code or data corruption

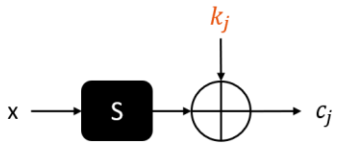
Bitsets ('0'→ '1')

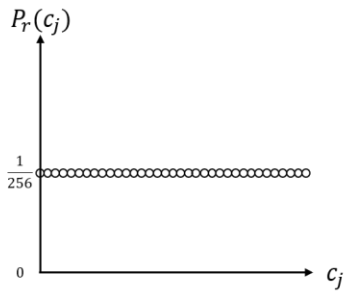
Floating gate transistors discharge by photoemission or heating

Laser Fault Injection

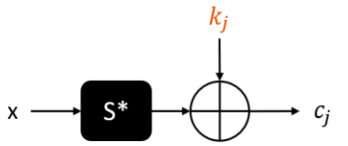
Abstraction levels : Application level

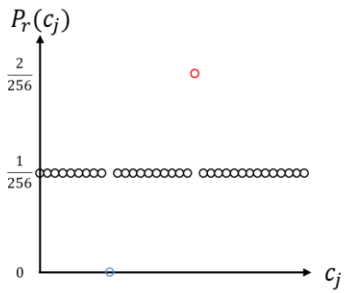
- Persistent Fault Analysis[4] (PFA)
- Persistent fault injection on the S-Box (AES, DES, ASCON,…)
- Statistical study on the bytes of the ciphertexts





Without fault





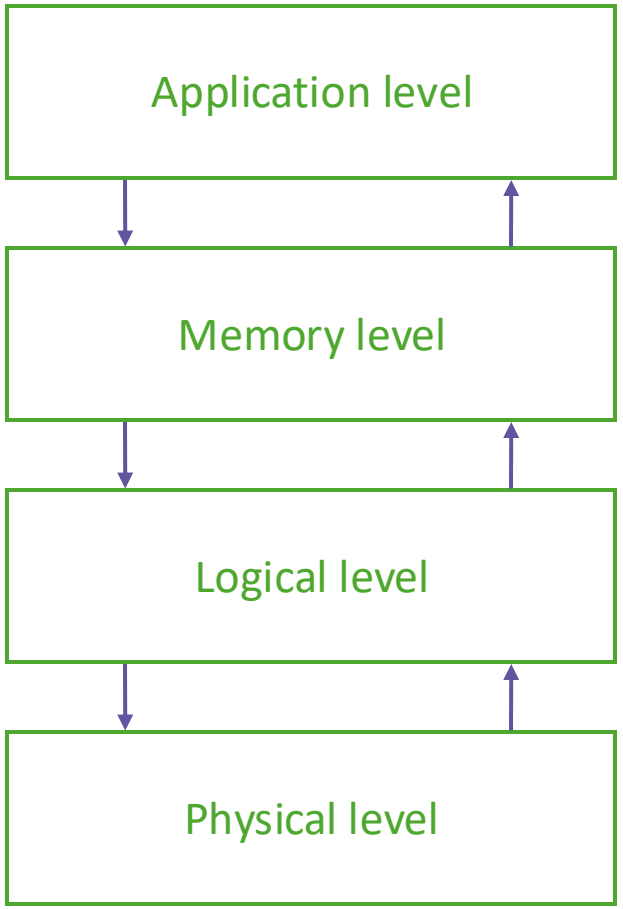
With one faulty byte

Successful PFA

First experimental realization of the PFA on unpowered devices

[4]Zhang et al., "Persistent Fault Analysis on Block Ciphers", TCHES 2018

Abstraction levels



PFA on AES

Code or data corruption

Bitsets ('0'→ '1')

Floating gate transistors discharge by photoemission or heating

Conclusion

Unpowered devices

- Reality of the threat of these attacks
- Hardware sensors not effective
- No synchronization required

X-Ray Fault Injection

- Possibility of focusing fault injection using a tungsten mask with a thickness of 1 mm
- Fault injection on powered and unpowered devices
- Attack scenarios become feasible

Grandamme et al., "X-Ray Fault Injection in Non-Volatile Memories of Power OFF Devices", IEEE PAINE 2023
Grandamme et al., "X-Ray Fault Injection Localization with a Shield on Powered and Unpowered Devices", IEEE PAINE 2025

Laser Fault Injection

- New fault model from the physical level up to the application level
- Validation of a PFA-type attack scenario

Grandamme et al., "Switching Off your Device Does Not Protect Against Fault Attacks", TCHES 2024

Thank you for your attention !

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- MITIX (ANR-20-CE39-0012)
- FAMAS.