Study of a Thermal Annealing Approach for Very High Total Dose Environments

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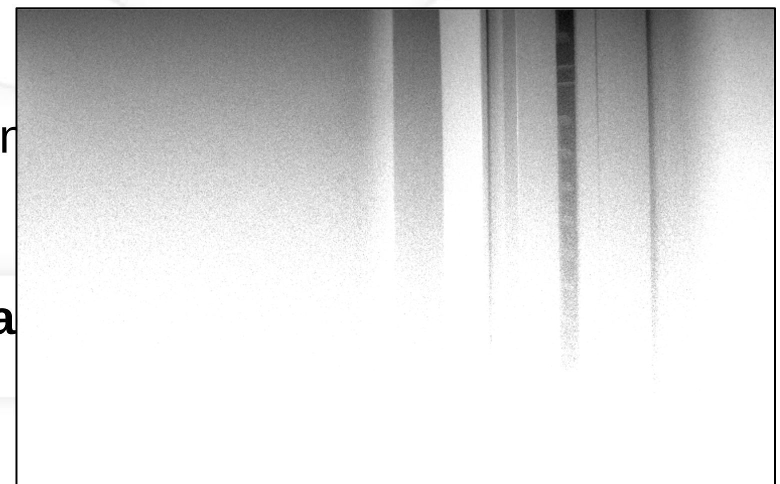
1. Context

Issue

Environment : **Civil Nuclear Power** (Power plant) and **Space**

→ **Cameras** : deploying solar panels, observation, monitoring, ...



→ **Re** ... or

→ Fra ... **a**

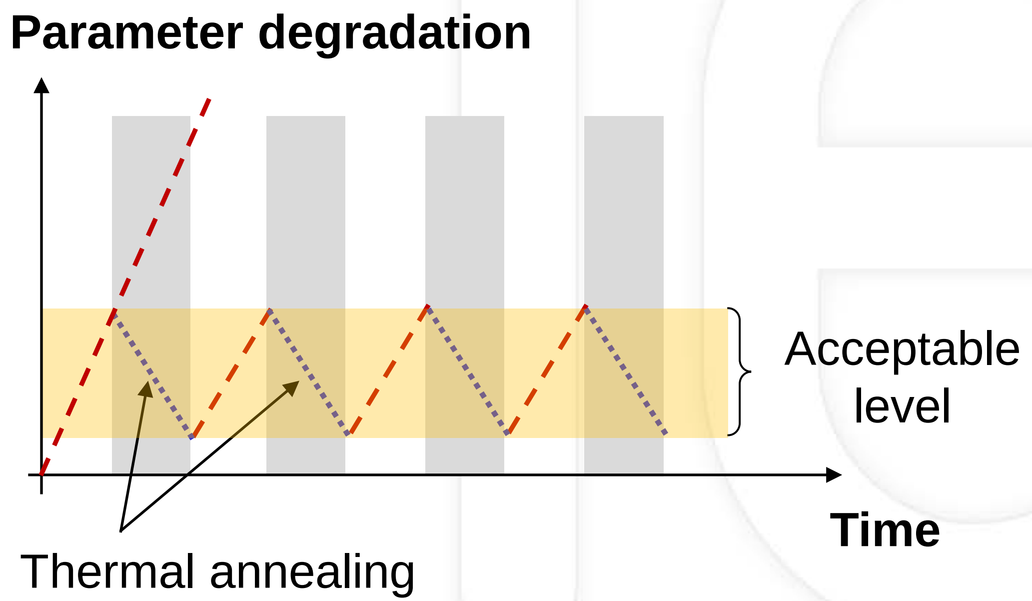
→ **Human access/repair impossible** : high doses, in flight, ...

Limited lifetime

How to extend lifetime of CMOS APS image sensor in harsh environment until 300 krad then 1Mrad and more ?

Main objective : <u>extend CMOS APS image sensor lifetime in harsh environment</u>

- Develop **thermal annealing method**[1]
  → Heat to recover initial parameters
- Apply this method at regular time to recover frame



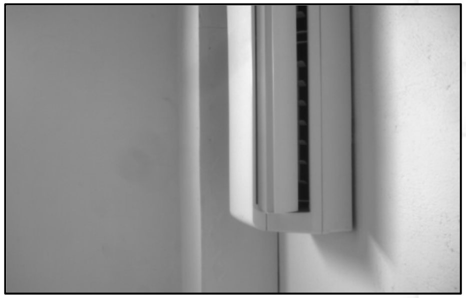
<u>Define fundamental parameters :</u>
Bias, temperature, annealing duration

[1] F. Roig, L. Dusseau, J. Boch, et al., « A Thermal Annealing Approach to Extend Metal Oxide Semiconductor Devices Lifetime Exposed to Very High Dose Levels », IEEE RADECS, Sept 2012, Biarritz (France).

1. Context

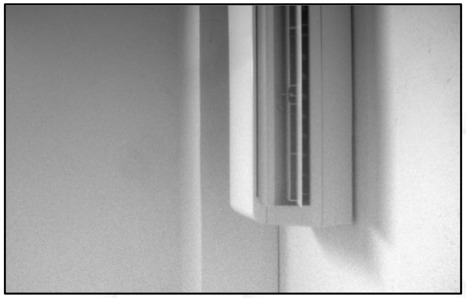
Radiation-induced effects on image sensor

Typical X-Rays degradation

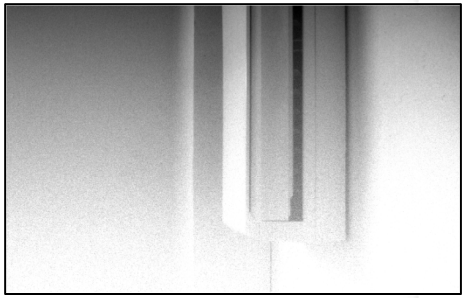


Before irradiation

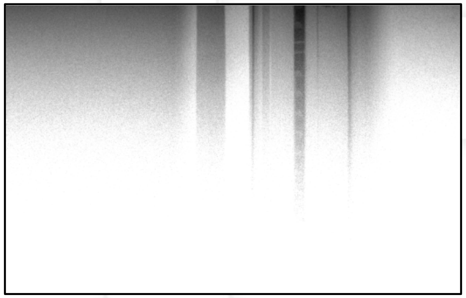
Time →



After 250 krad



After 325 krad



After 625 krad

Hot pixel = *pixel with high dark current*

Main effects on CMOS APS

- Increase of dark current

→ Increase of « hot pixels »

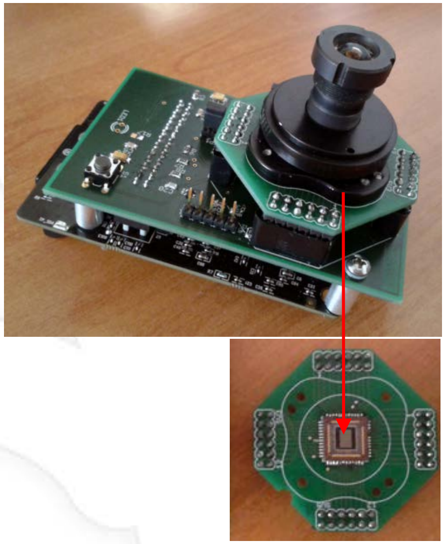
- Random Telegraph Signals noise

- Reduced of responsivity

Dark current :

- Leakage current in the absence of light

Image sensor principle
Architecture



- **CMOS** image sensor : pixel matrix
- **Active-Pixel Sensor (APS)** : photo-detector + active amplifier
- **Pixel** : place of conversion photons → electrons by photoelectric effect

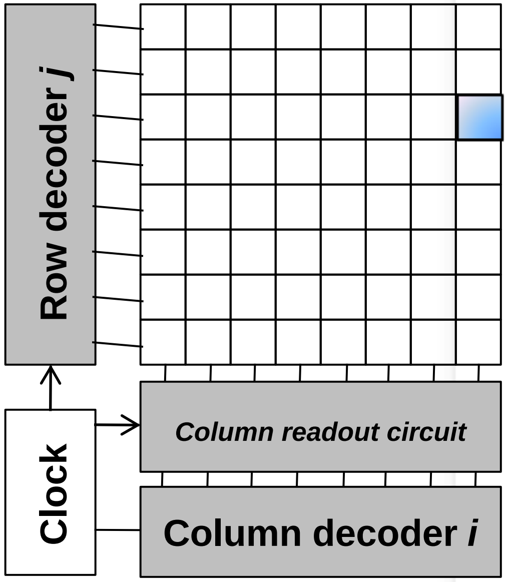


Image sensor architecture

« Pinned-PhotoDiode 4T APS »

1st Test of Thermal annealing

Experiments

→ Irradiation with 22 krad step

→ Condition tests : all pins grounded

→ Continuous thermal annealing at High Temp.

→ Condition tests : all pins grounded

: 01h00 – 200°C
: 02h30 – 200°C
: 03h30 – 200°C
: 06h30 – 200°C
: 71h30 – 25°C

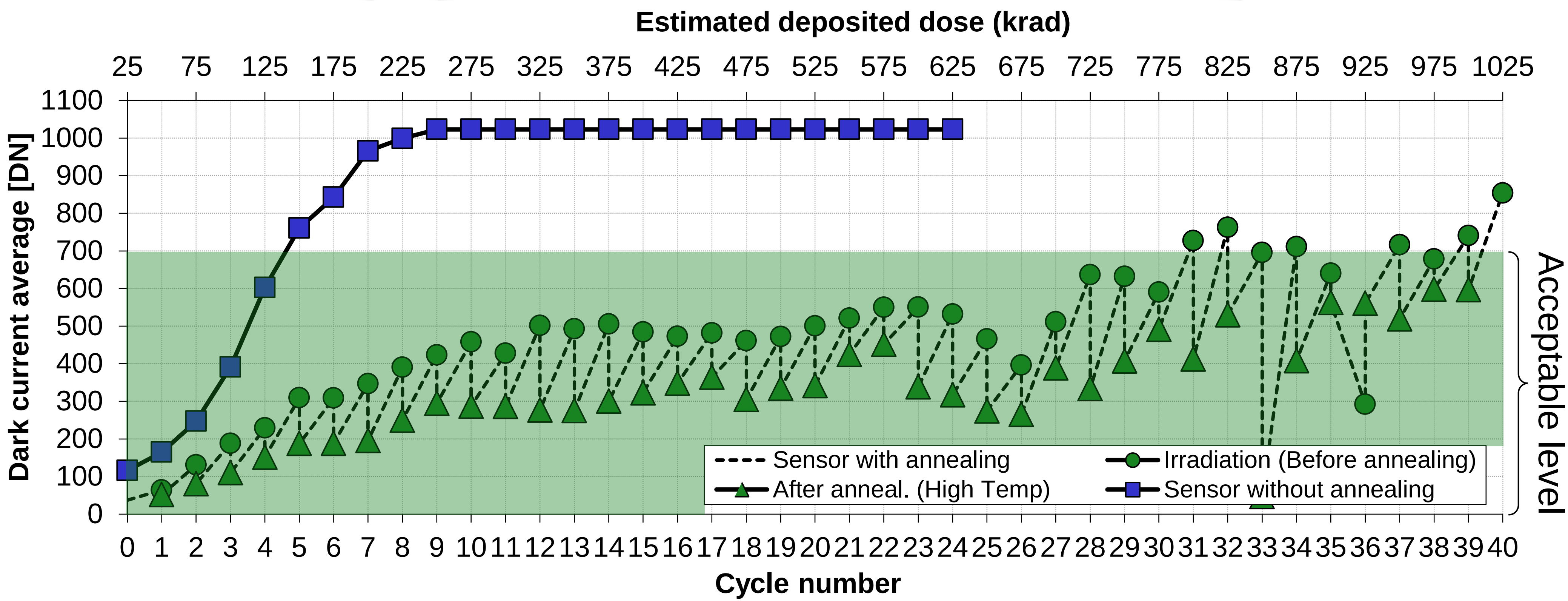
High temperature (> 150°C : several minutes) allows to recover **faster** than low temperature (<150°C : several hours)

Reliability in time

X- Rays Experiments

→ Sensor A **without annealing** :
- Irradiation by 25 krad step
- All pins grounded

→ Sensor B **with annealing** (175C/30 minutes) :
- Irradiation by 25 krad step
- All pins grounded



At 175ºC/30min : 40 irradiation and annealing cycles and **1 Mrad !!**

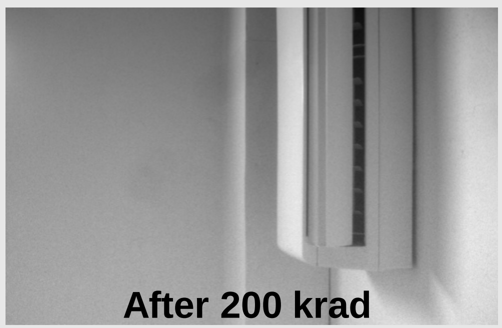
[2] S. Dhombres, A. Michez , J. Boch, *and al.*, « *Study of a thermal annealing approach for very high total dose environments* », IEEE Trans. Nucl. Sci., Dec 2014

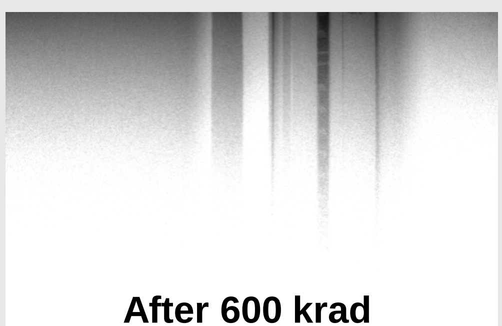
Reliability in time

Experiments

Sensor A – without annealing

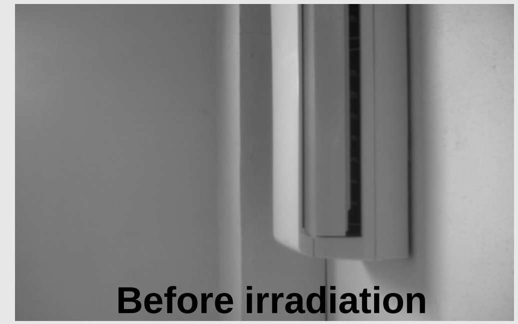

Before irradiation


After 200 krad

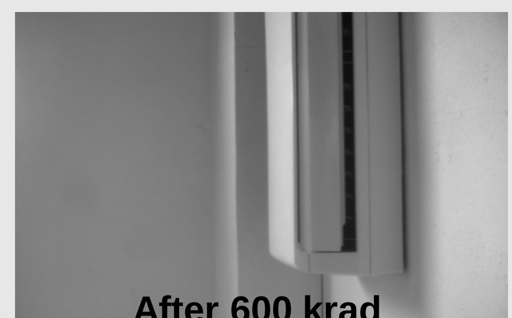

After 600 krad

Unusable

Sensor B – with annealing


Before irradiation


After 200 krad


After 600 krad

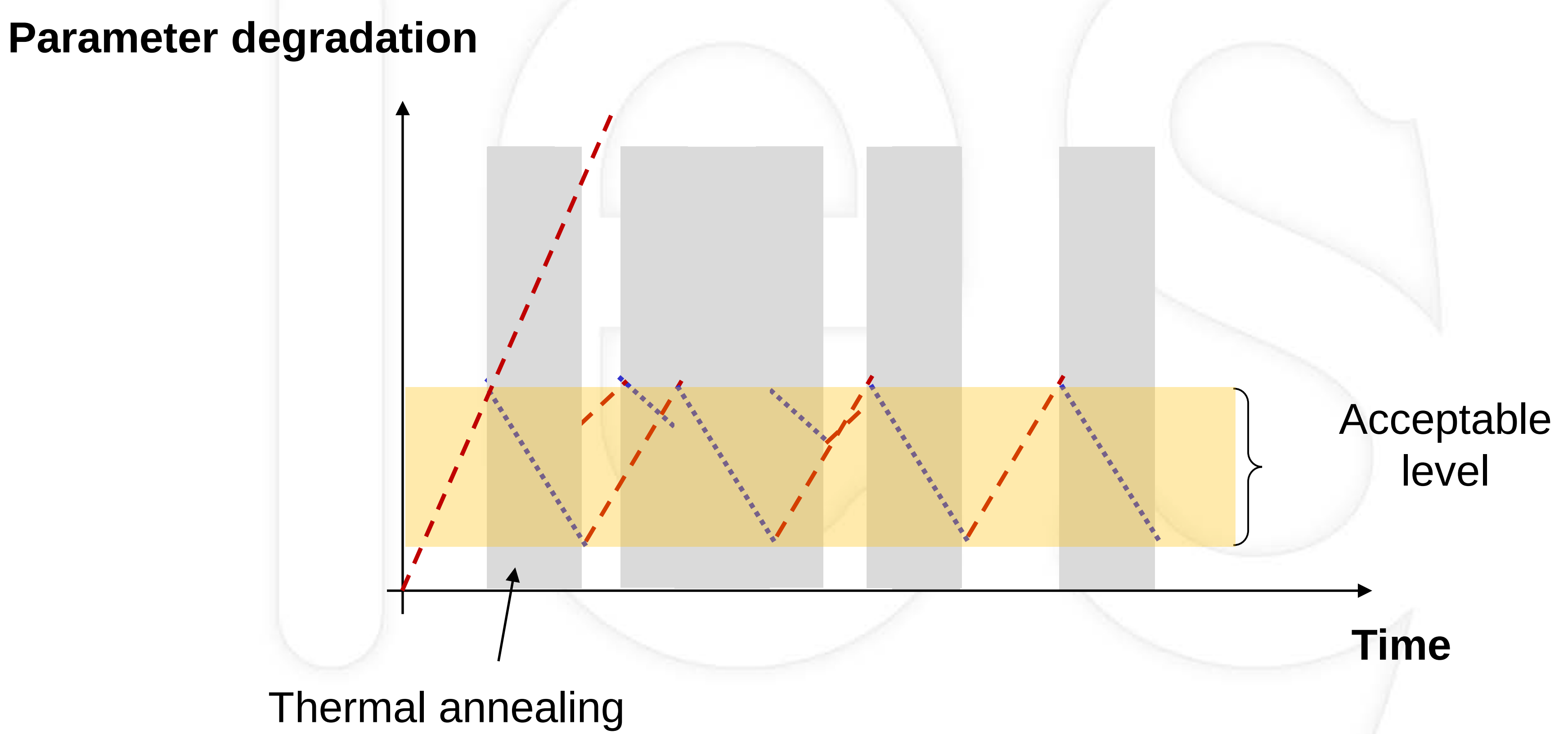
Usable

Keys Parameters of Thermal Annealing

X- Rays Experiments

To keep an acceptable level:

- Increase of Temperature
- Increase of Thermal Annealing Duration
- Decrease of Dose Step



Thermal annealing protocol

IRF130 power MOSFETs

→ Annealing is also sensitive to electric field

→ CMOS APS image sensor = complex component

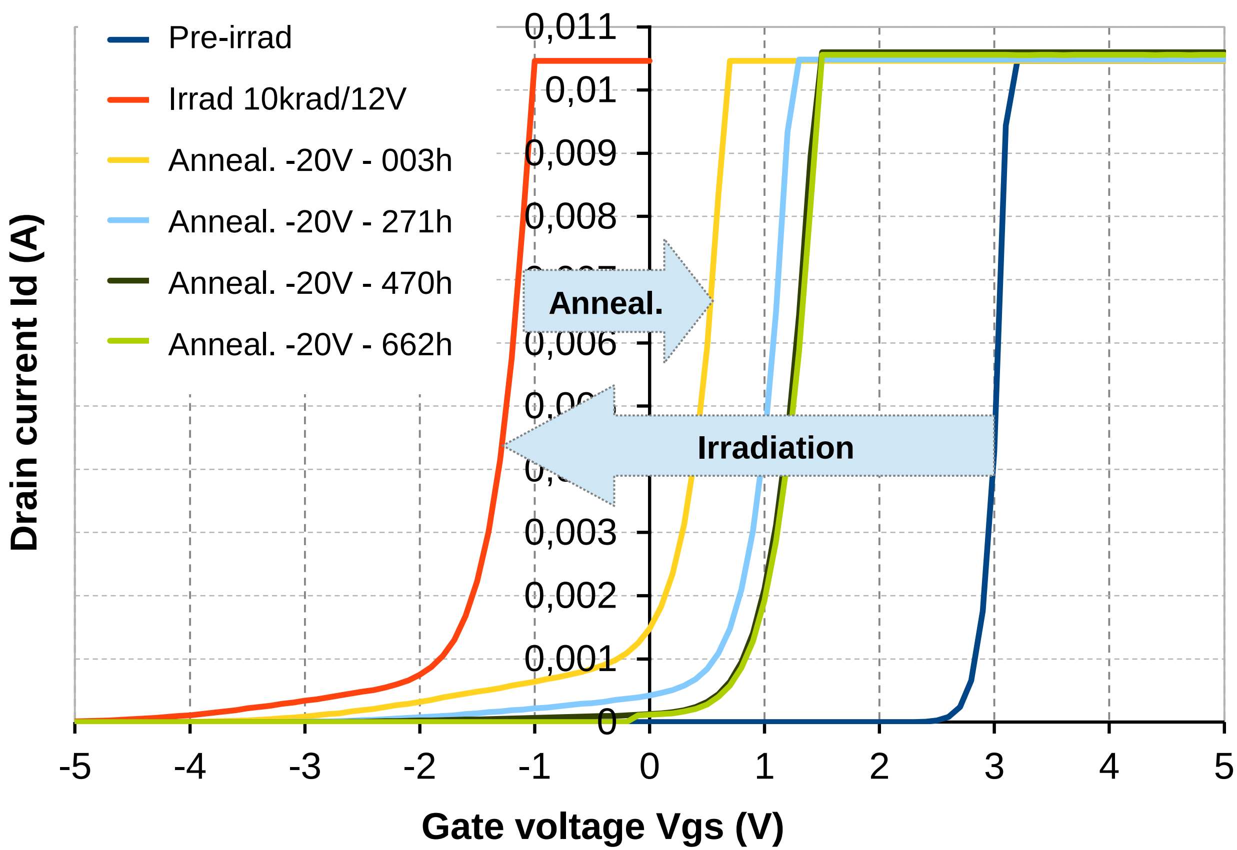
→ Tested on IRF130 N-power MOSFET and vertical structure.

Method development and
Better understanding of mechanisms

Thermal annealing protocol

Negative bias during thermal annealing

Negative bias during annealing



Dose rate : 108,1 rad/s

Bias during irradiation 10 krad : +12V

Bias during annealing at 100°C : -20V

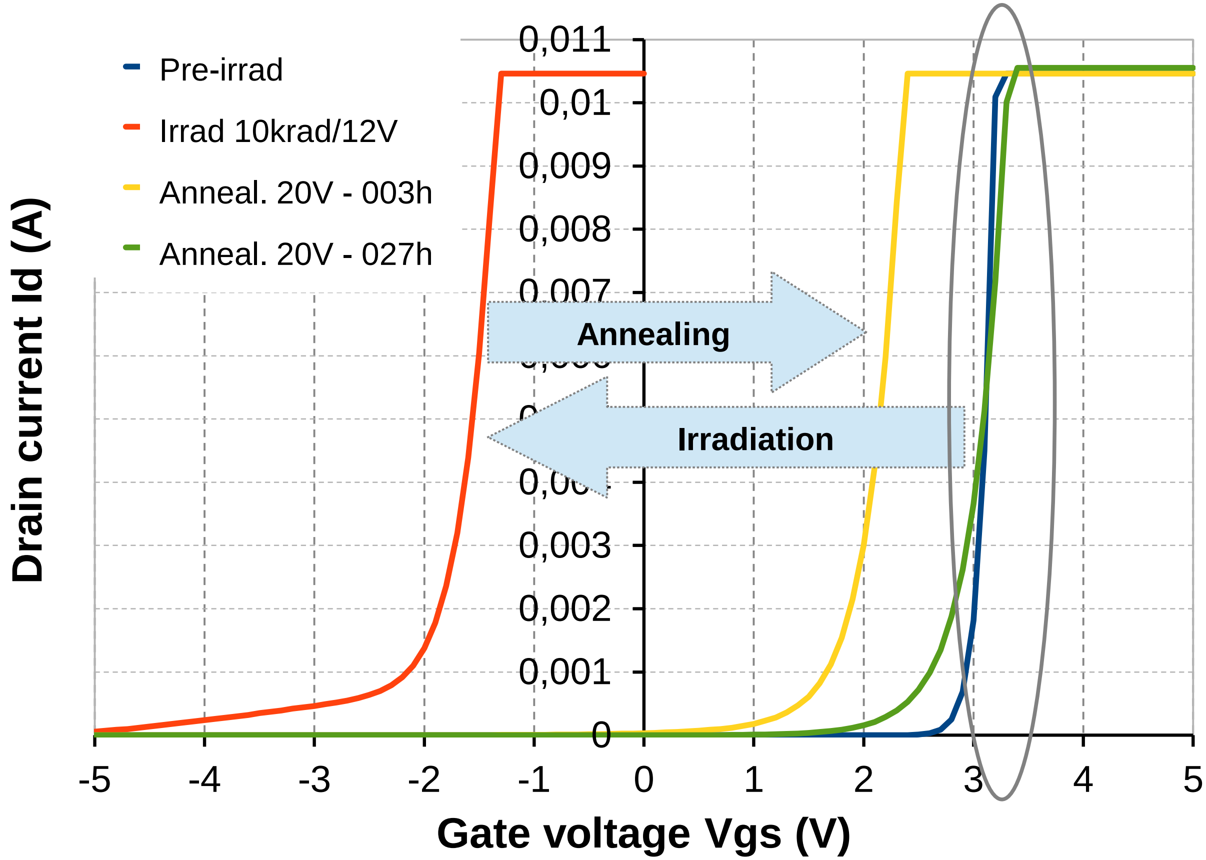
Incomplete recovery

Saturation recovery

Thermal annealing protocol

Positive bias during thermal annealing

Positive bias during annealing



Dose rate : 108,1 rad/s

Bias during irradiation 10 krad : +12V

Bias during annealing 100°C : +20V

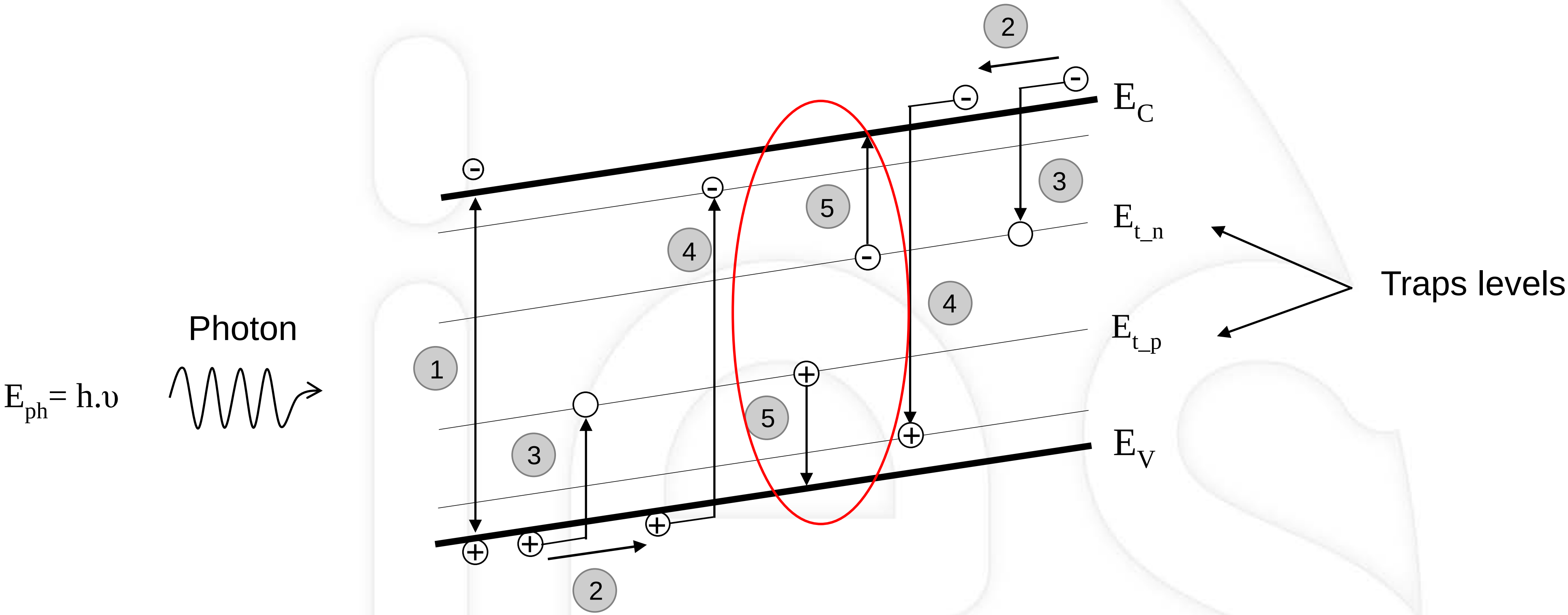
*Complete recovery after **27h***

For 0V, -20V bias → recovery > 1000h !

Bias/Duration effects

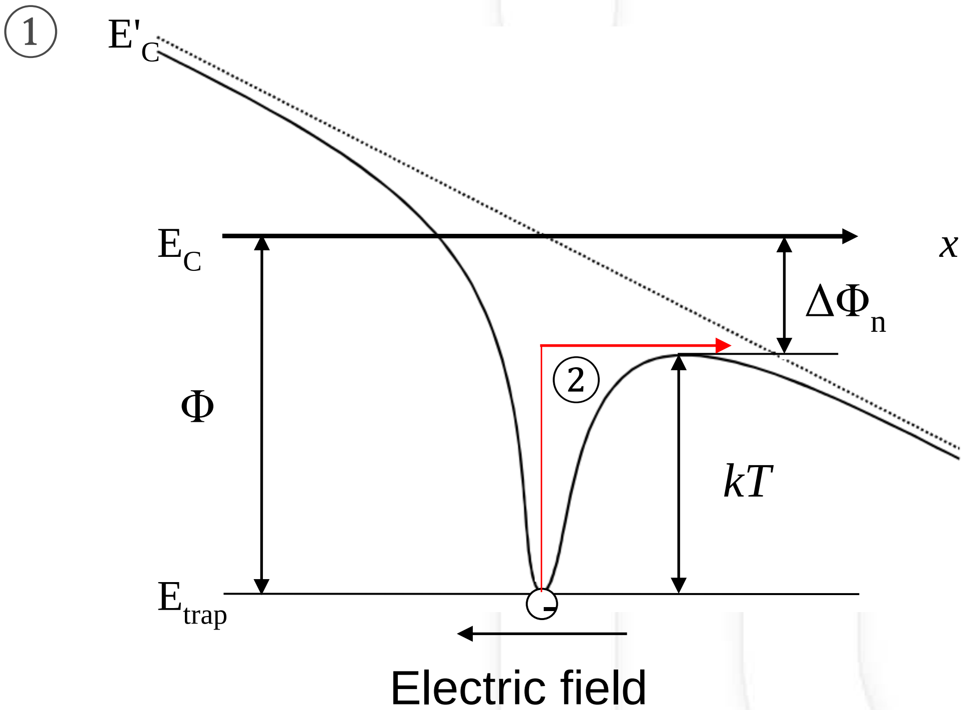
Trapping/Detrapping

Temperature effect



1. Radiation-induced electron-hole pairs generation
2. Carriers drift-diffusion in their respective allowed band
3. Free carriers trapping
4. Recombination of trapped carriers by free carriers of opposite type
5. Thermal reemission of trapped carriers to their respective allowed band

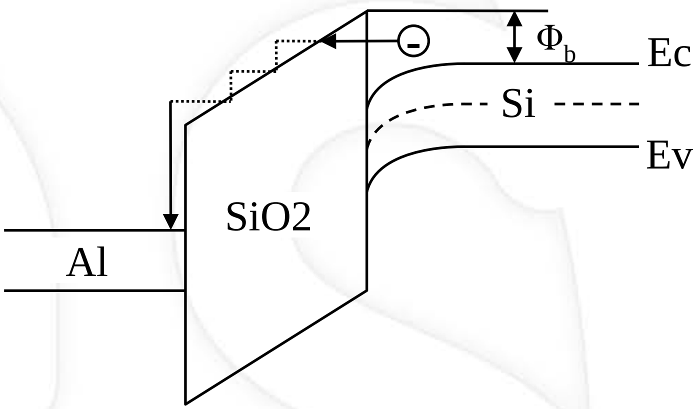
Poole-Frenkel effect



1 Electric field curves conduction band

2 Barrier potential lowering for electrons

Tunneling effect



1 Electric field curves conduction band

2 Apparent thinning barrier potential lowering for electrons

Conclusion / Perspectives

Conclusion

→ *Heating image sensor allows to :*

- recover degraded electrical parameters (dark current)
- keep an usable frame after 1Mrad and more.

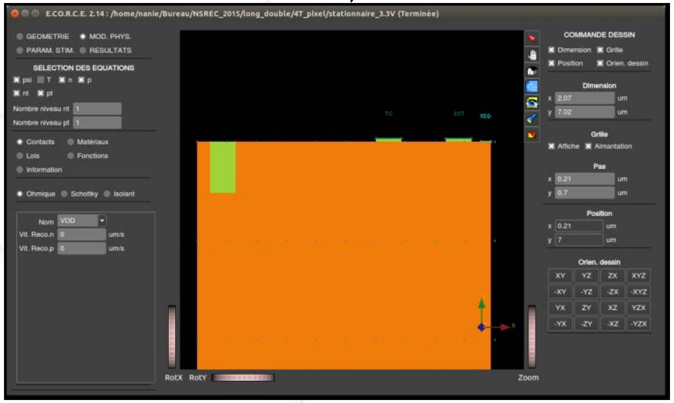
→ *40 irradiations/annealing cycles were supported at high temperature : reliability in time*

→ *No premature breakdown observed due to thermal cycles if temperature < 150°C*

Perspectives

→ *On going :*

- Understanding of physical mechanisms with TCAD ECORCE (Pixel modeling in 2D).
- Law extraction depending of thermal annealing duration and temperature



Thank you for your attention

Any questions ?

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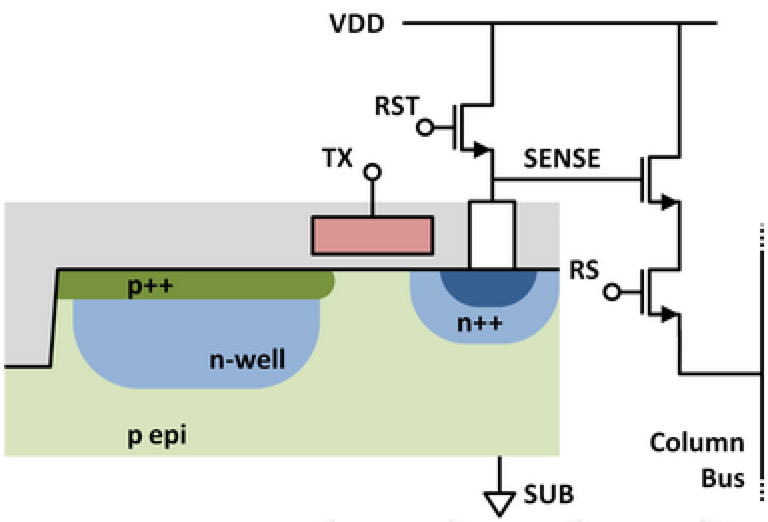
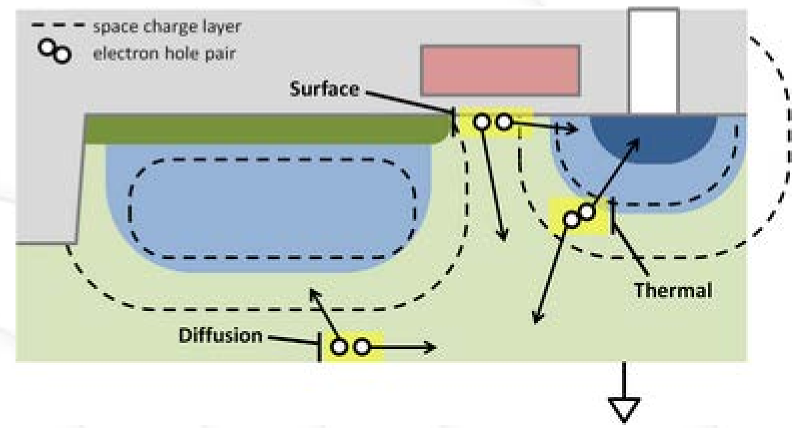
Systheia WE CAN SEE IT

Dark current mechanisms

Origin





- Measurement in complete dark **without illumination.**
- Dark count = an electron is generated and pixel electronic considers it as an incident photon

4 main mechanisms :

- Surface generation from trap states at the Si-SiO2 interface
- Trap-assisted thermal generation of charge in the space charge layer
- The diffusion current due to thermal generation of charge in the bulk
- Crosstalk between neighboring pixels during charge collection, storage, and possibly readout