Radiation Hardening of Digital Color CMOS Camera-on-a-Chip Building Blocks for Grad Total Ionizing Dose Environments

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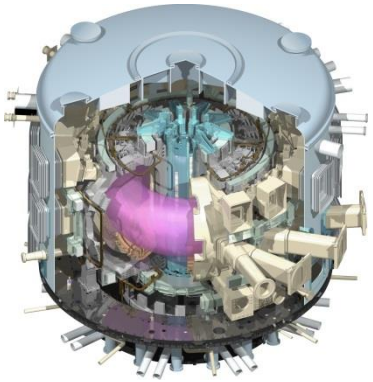
Radiation Effects on Optoelectronic Detectors, 16th September 2016, Toulouse

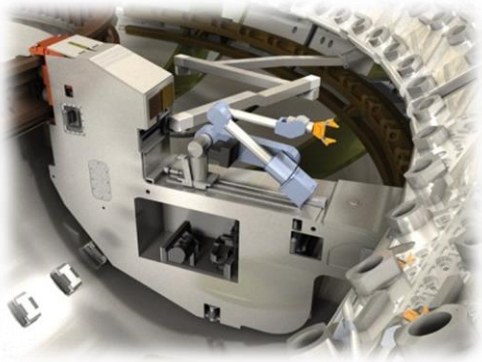
Context and Motivations

- **ITER remote handling operations require imaging systems**
  - Compact, lightweight and low power/voltage
  - Radiation hard (failure TID **>> 1MGy(SiO_2)**(>>**100 Mrad**))

    Gamma radiation only *(plasma OFF)*
  - Color and high definition (≥ 1Mpix)



- **Tube camera, not suitable because of**
  - Size, cabling, voltage, resolution and reliability
- **Existing solid-state image sensor based camera**
  - **Limited** by their radiation **hardness: ≤100 kGy**



Dedicated development required

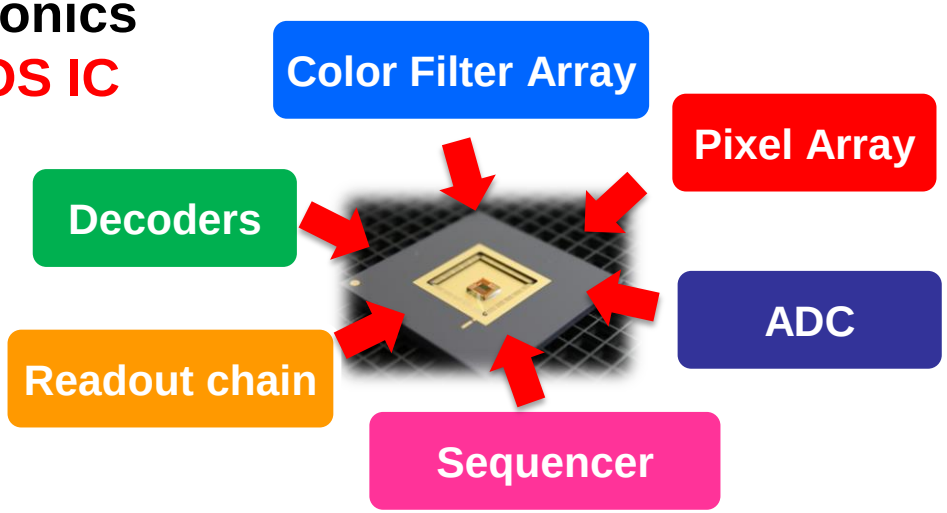
Rad-Hard CIS State of the art (MGy range)

- **What can be found in literature:**
  - A few dark current measurements on STAR250 **A**ctive **P**ixel **S**ensor (**APS**) up to 1MGy *(Bogaerts et al. 2003)* (***old non-CIS process***)
  - A few dark current measurements up to 2 MGy on CMOS APS developed for Electron Microscopy based on standard (**non-CIS**) CMOS process *(Contarato et al. 2012)*
- **What is missing:**
  - No result ever published on **CIS processes** in the MGy range
  - An **image** captured with an **APS/CIS** exposed to 1MGy (=100Mrad) or more has **never been published**
  - No data on the TID effects on **opto-electrical performances** of **APS/CIS** in the MGy range

Camera Radiation Hardening Strategy

- **Integrate all the required electronics on a single Rad Hard (RH) CMOS IC**

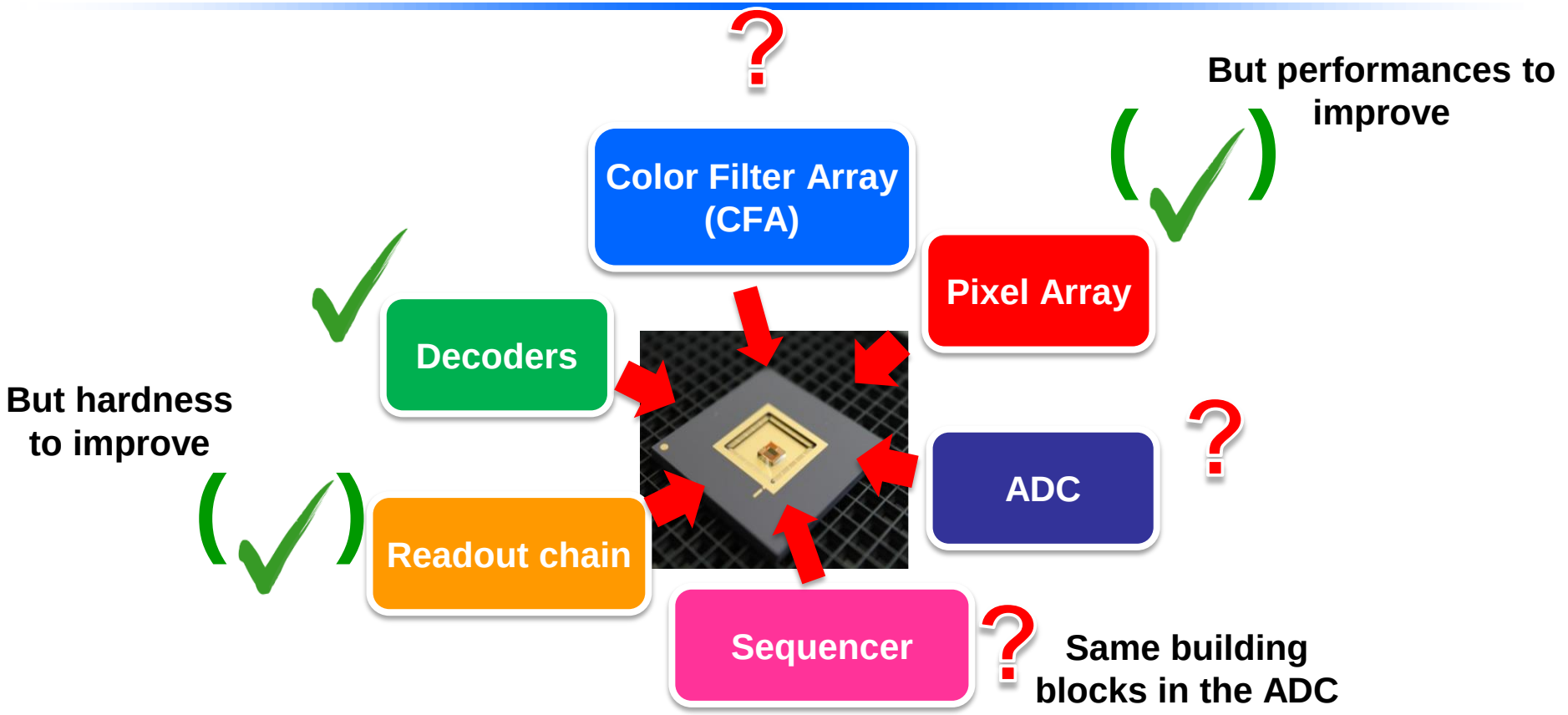
RH Camera-on-a-Chip (this work)



  - No need for additional MGy RH electronics
  - Very compact
  - Complete control of the radiation hardness

- **Associated RH developments**
  - Rad-Hard **optical system** (led by *Univ. Saint-Etienne)*
  - Rad-Hard LED based **illumination system** (led by CEA)

Feasibility of a CMOS based Multi-MGy Rad-Hard Color Camera-on-a-Chip?



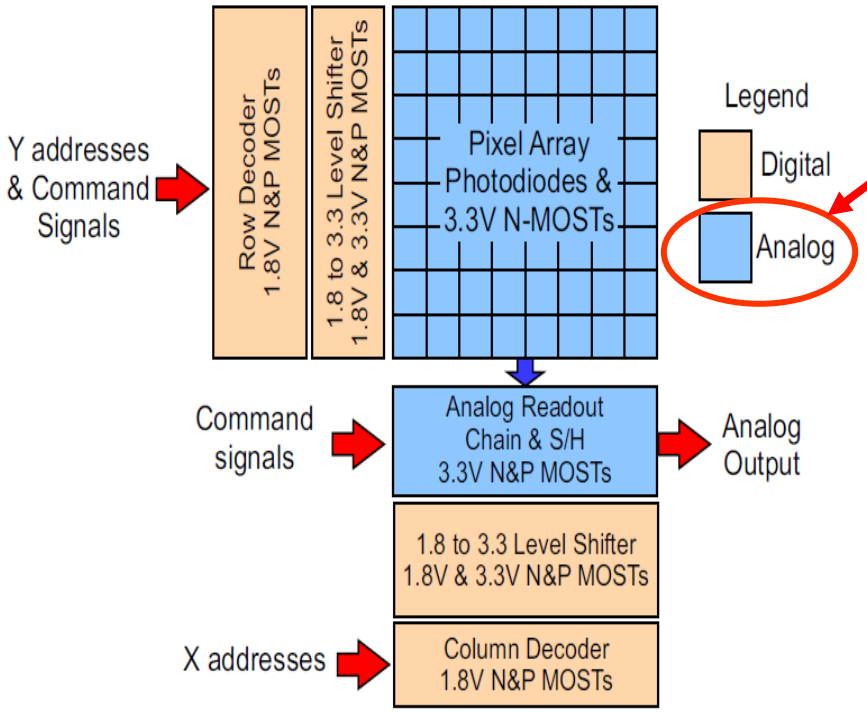
- **Goal of this work:**
  - Demonstrate that CMOS Image Sensor (CIS) can withstand a TID of 1MGy or more
  - Explore original mitigation techniques to **improve the image sensor performances**
  - Analyze MGy radiation effects on **CFA** and on a basic imager **ADC**

- **Presentazione della srategia con i due sensori**

- **RAD HARD**
- **FUSEV**

Experimental Details:
CIS overview & Irradiation Details

128x128 10µm pitch pixels



FULL ELT DESIGN (N&P MOSTs)

Most sensitive part: 3.3V analog circuits

180 nm commercial CIS technology

Irradiation details:

- 10keV X-rays
- CIS biased (se
- Room temperature
- Dose rate: 180kGy/h
- Dose values in Gy(SiO

(^{60}Co ©-ray in the paper)

GND in the paper

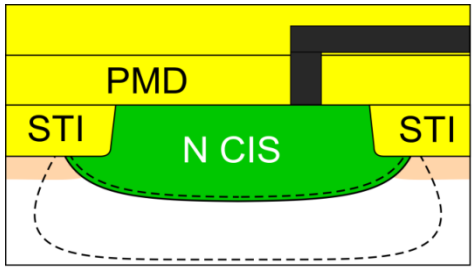
18kGy/h in the paper

- Pure 1.8V digital and I/O pads: IMEC-ESA Rad-Hard DARE Library
- 3.3V Analog/Mixed signal circuits and pixels ← Rad-Hard by ISAE

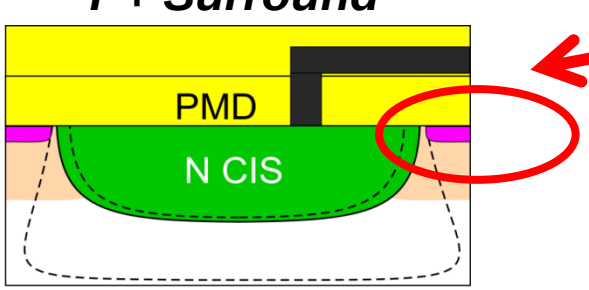
CMOS Image Sensor (CIS) Design : photodiode radiation hardening

- **Four 3T photodiode designs have been studied:**

Standard Photodiode

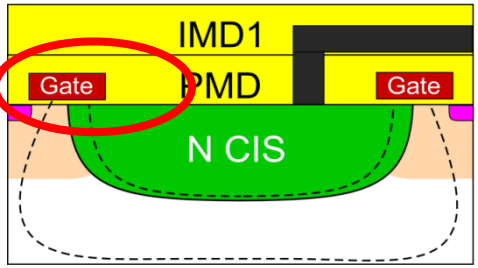


P+ Surround



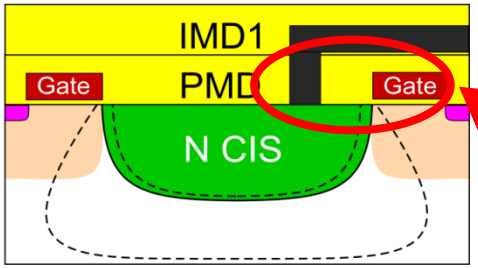
- **Most Promising Designs for High Dose :**

Proposed Improvement: Gate Overlap Design



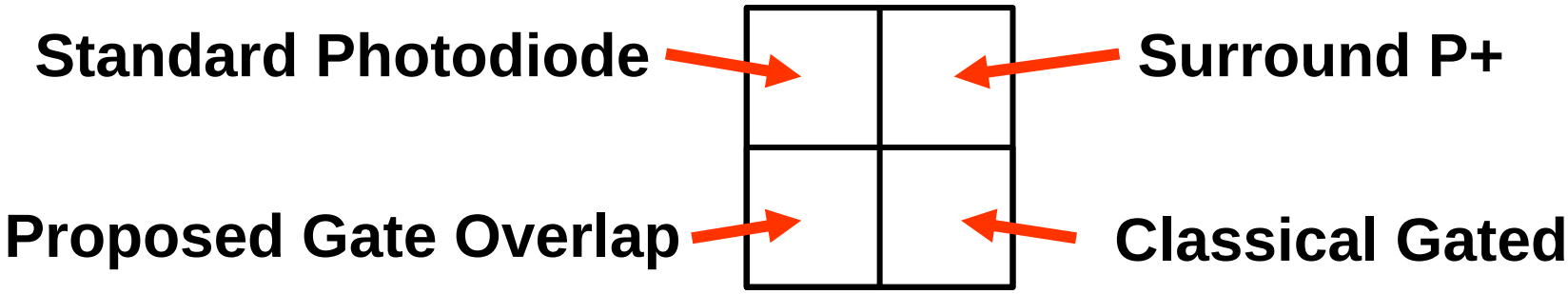
Gate with voluntary N-overlap (≈0.3 µm)

Classical Gated Diode (gate aligned N implant)



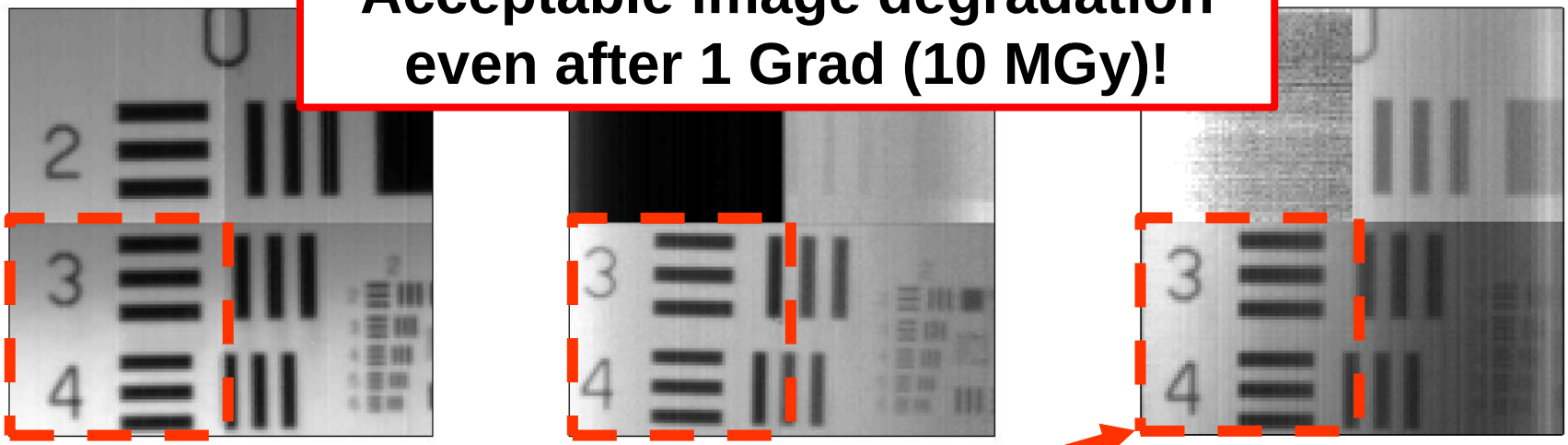
Gate (N-aligned)

Post Irradiation Results: Raw Images (no image correction)



Before Irradiation @4 MGy (400 Mrad) @10 MGy (1 Grad)

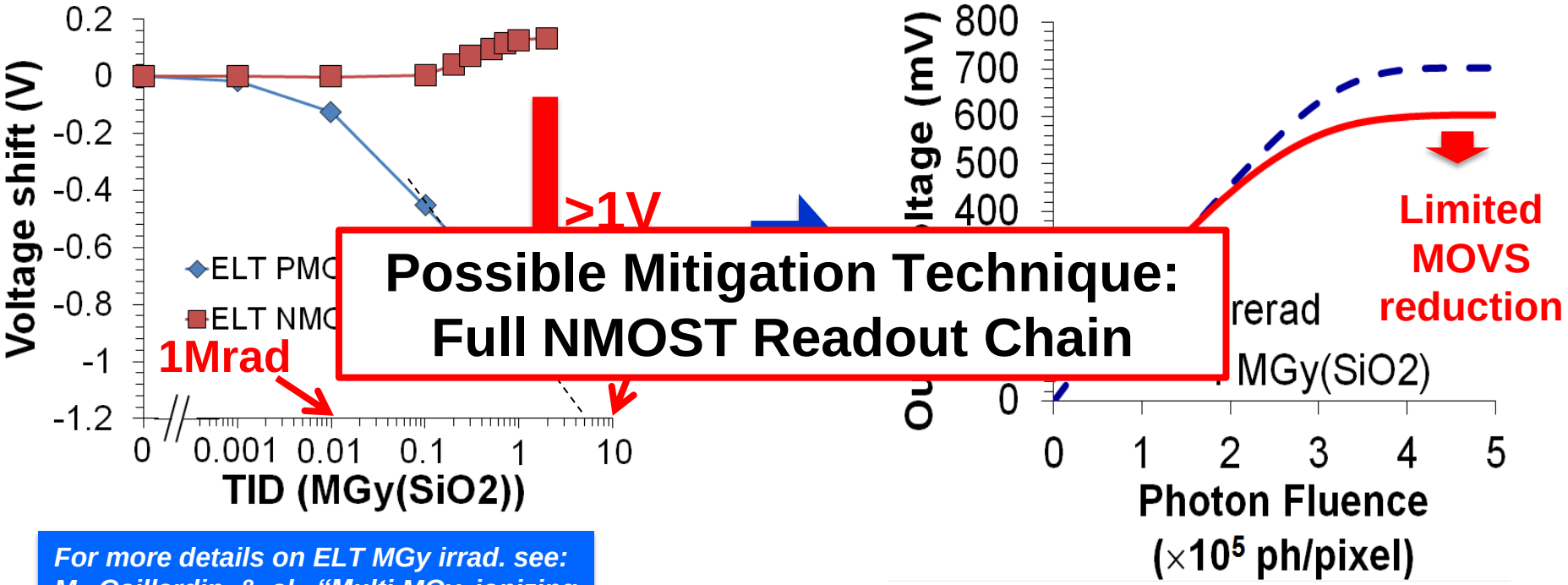
Acceptable image degradation even after 1 Grad (10 MGy)!



Main Radiation Effects:
3.3V ELT PMOST Threshold Voltage Shift

- Very limited 3.3V NMOST ELT degradation (<200mV ΔV_{th})
- Large (& surprising) 3.3V PMOST ELT ΔV_{th} (>1V!)
  - Compensated by decreasing PMOST current source bias voltage

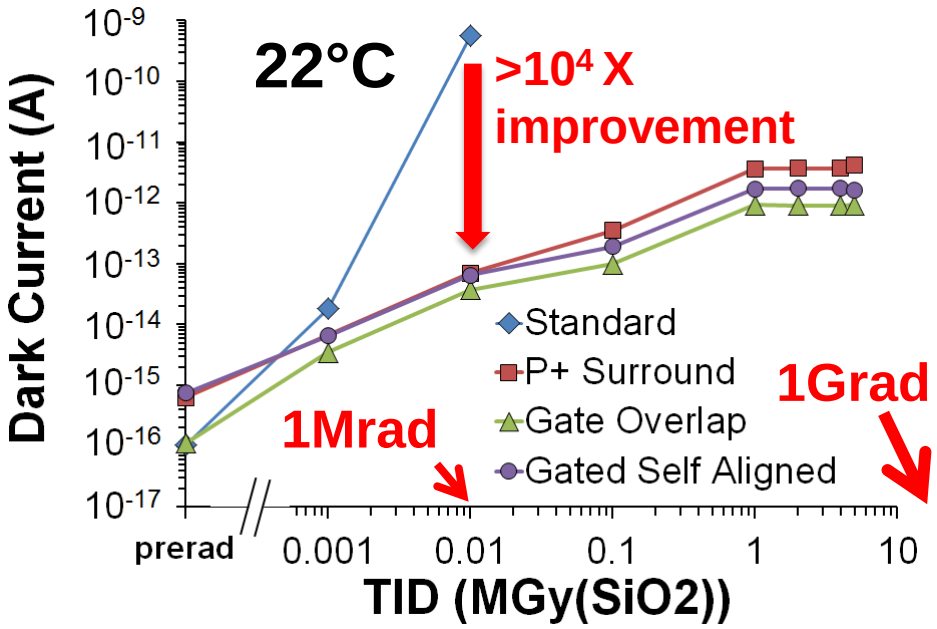
➡ Limited Maximum Output Voltage Swing (MOVS) decrease



For more details on ELT MGy irrad. see: M. Gaillardin & al. "Multi-MGy ionizing dose effects in CMOS devices: from micron to decananometer technologies"

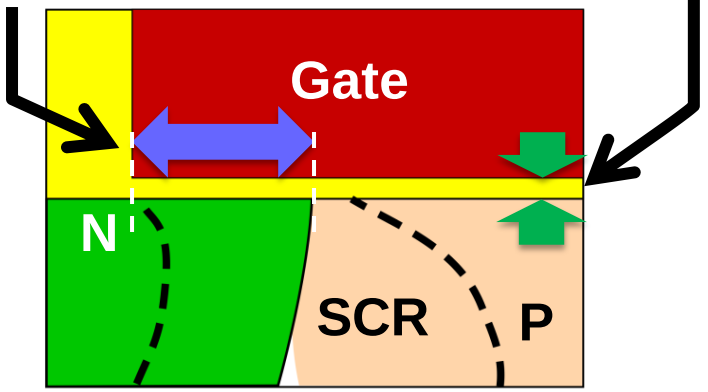
Main Radiation Effects:
Dark Current Increase

- **Standard PD: 10^7X dark current rise @10kGy (1Mrad)**
  - no longer functional at higher radiation dose
- **Gate Overlap: best performances over the whole range**



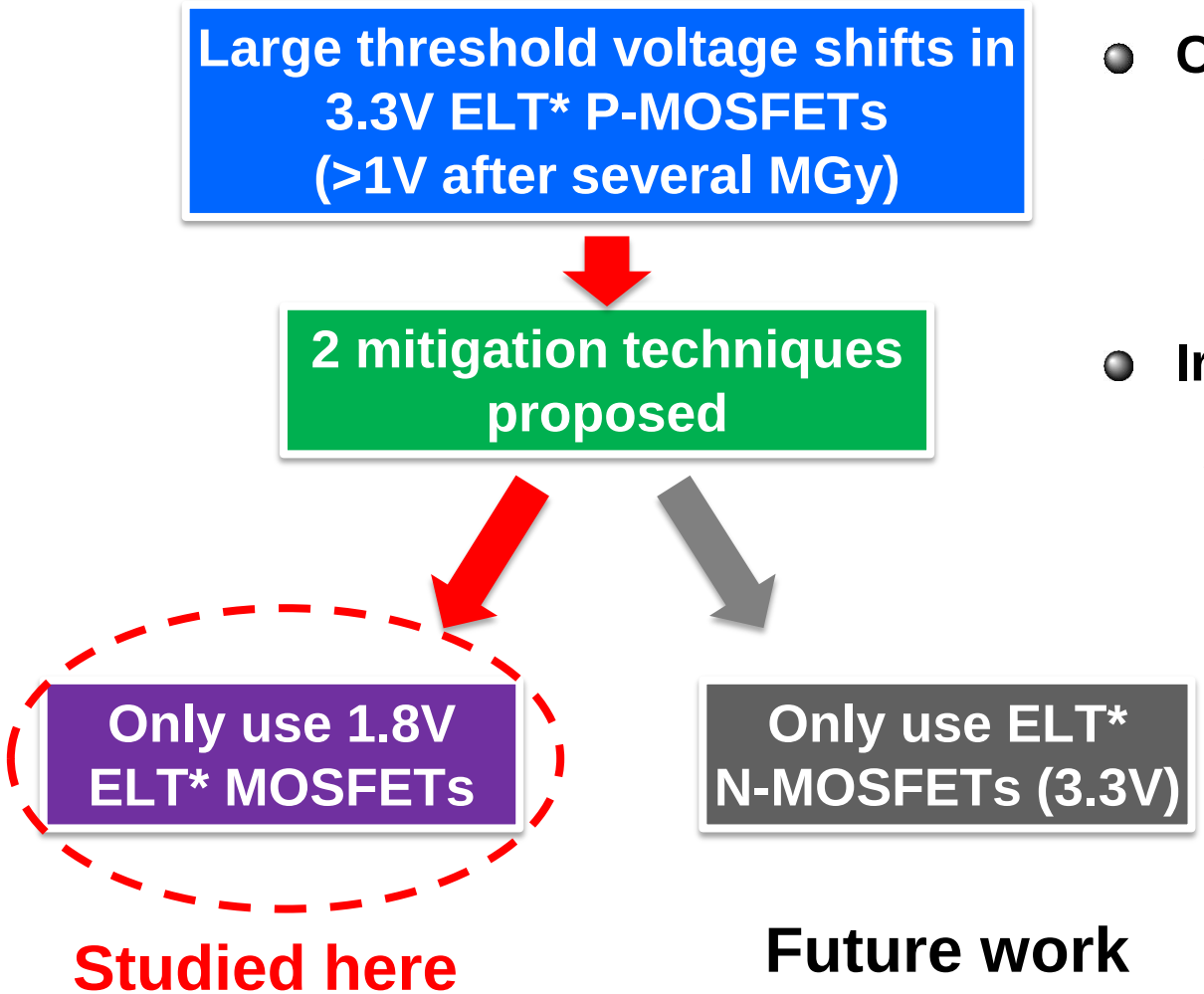
Possible further improvements:

- **Thinner gate oxide (GO2 ➡ GO1)**
- **Overlap distance optimization**



10X or more possible improvement?

Strategy for Hardness Improvement

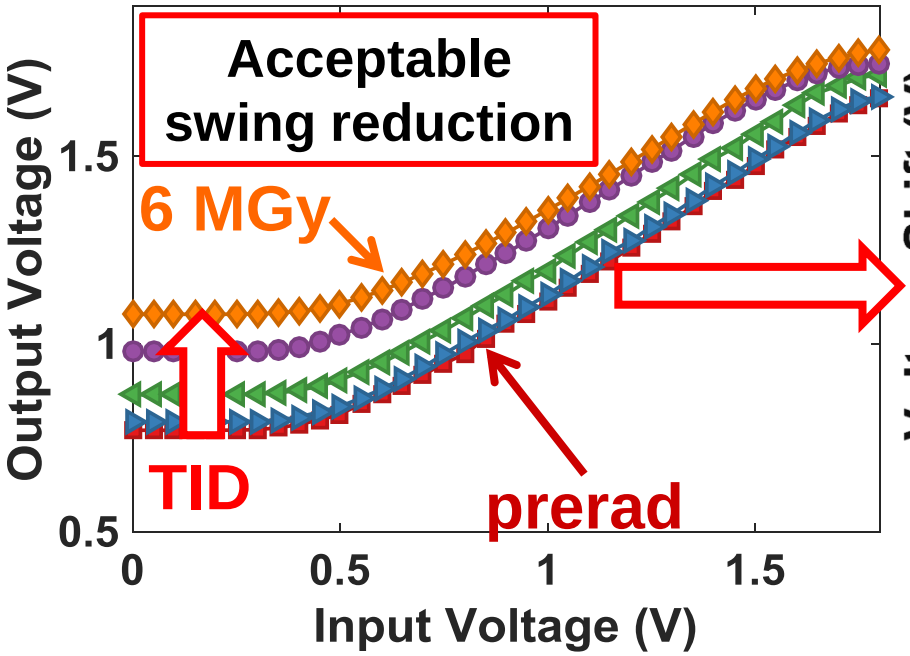


- **CMOS process:**
  - ✦ Commercial CMOS Image Sensor 180 nm
- **Irradiation:**
  - ✦ ^{60}Co gamma irradiation (SCK-CEN) up to 6MGy(SiO_2) (600Mrad)

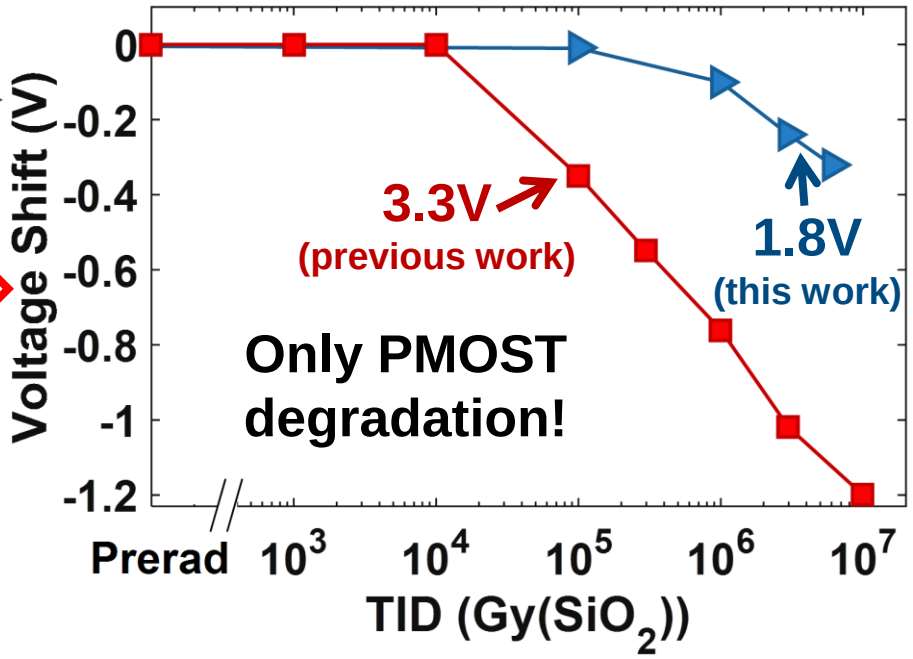
*** = Enclosed Layout Transistor**

RHBD Analog Readout Chain: Hardness Improvement

Electrical Transfer Function



ELT P-MOSFET $\Delta V_{threshold}$

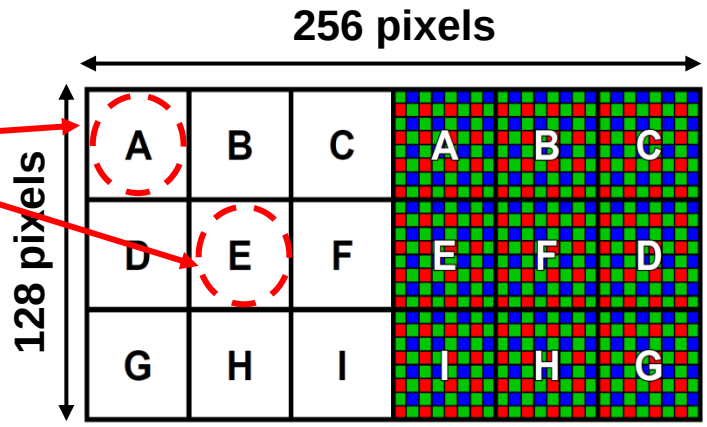


1.8V architecture

clear radiation hardness improvement

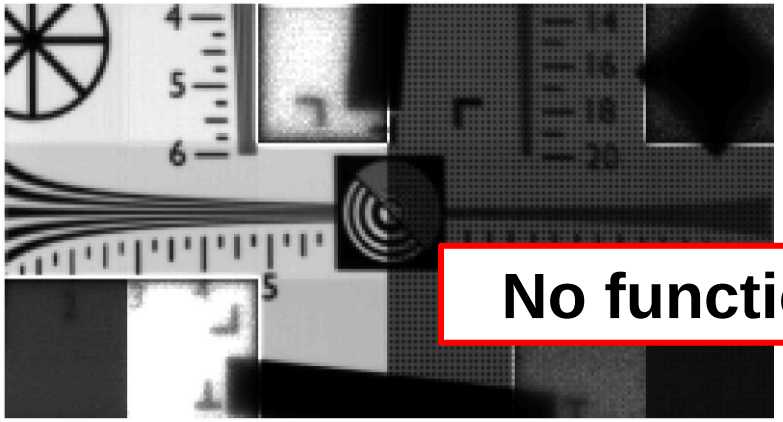
1.8V RHBD pixel array organization

- 9 pixel design variations
- 2 discussed here (A and E)
- Half of the sensor covered by a Color Filter Array (CFA)

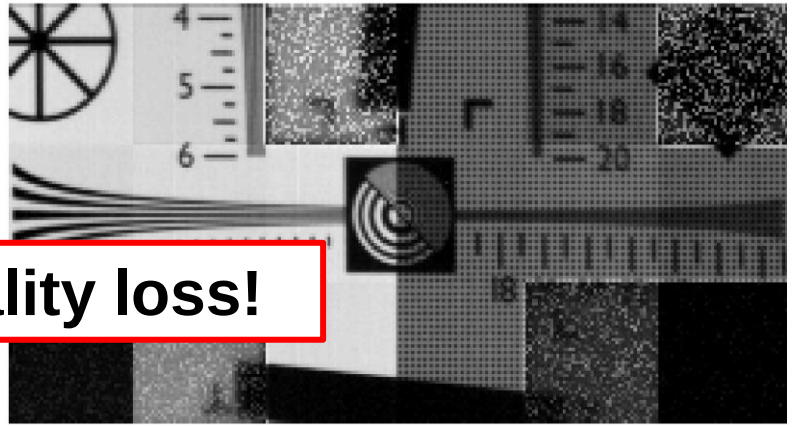


Raw images captured by the manufactured CMOS image sensor:

Non-irradiated



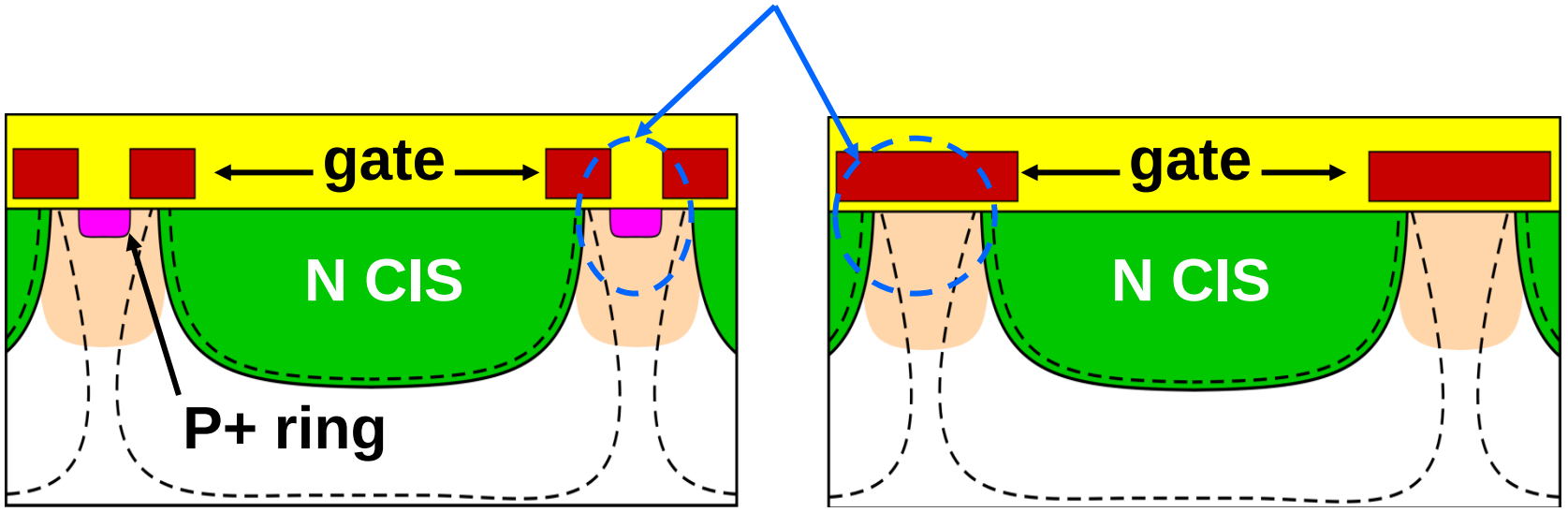
6 MGy(SiO_2) / 600 Mrad



No functionality loss!

Studied RHBD photodiode designs

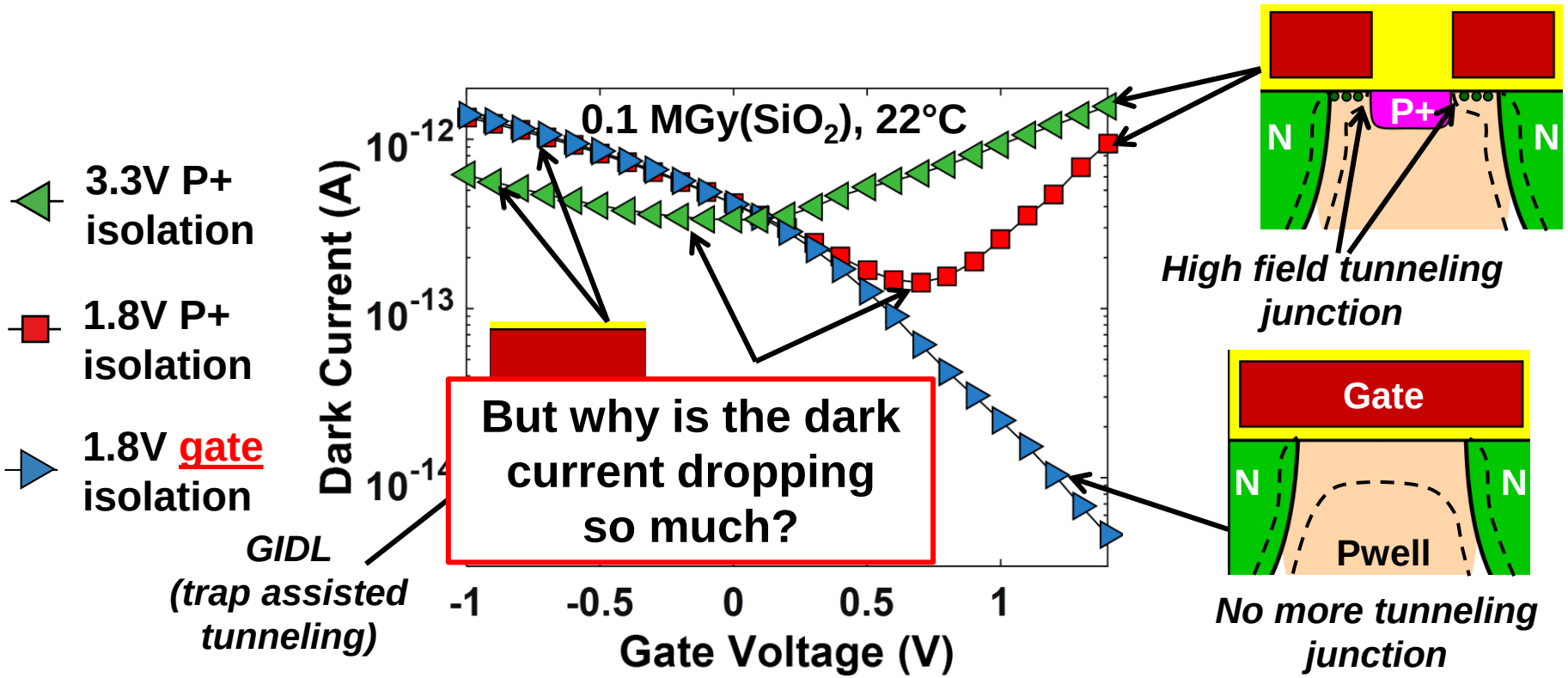
- **Two gated photodiodes:**
  - ✦with an **overlap** between the gate and the N region
- **Which differ by their pixel-to-pixel isolation**



Pixel A: P+ isolation

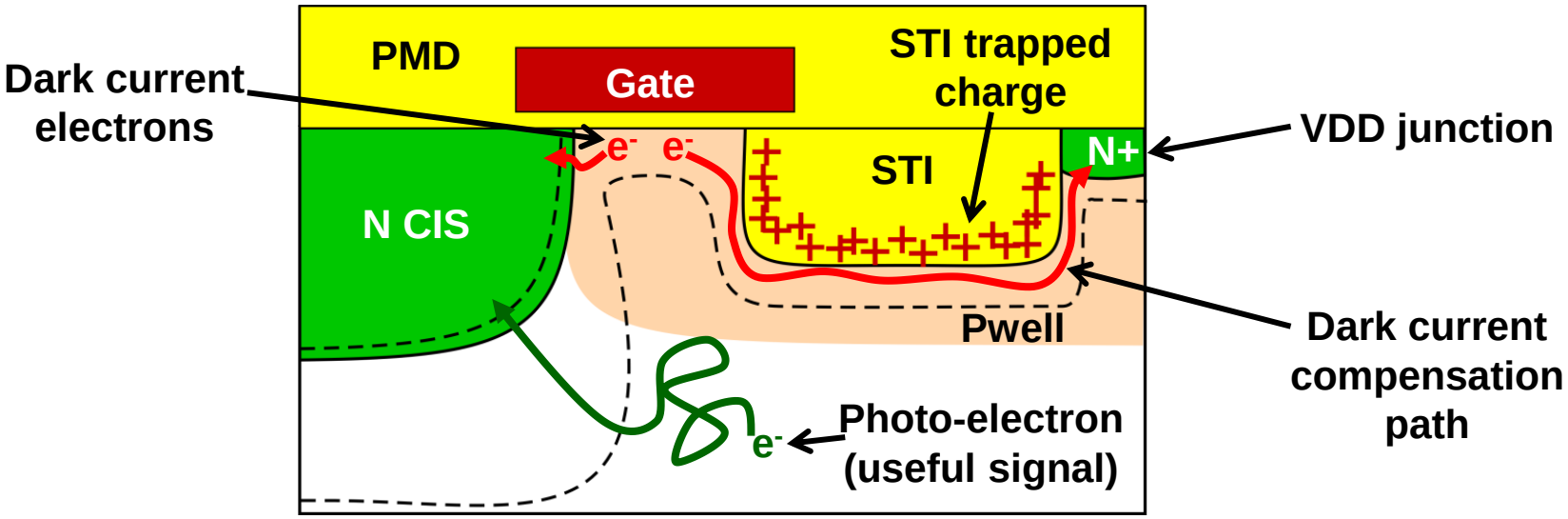
Pixel E: gate isolation

Dark Current: Influence of Gate Voltage



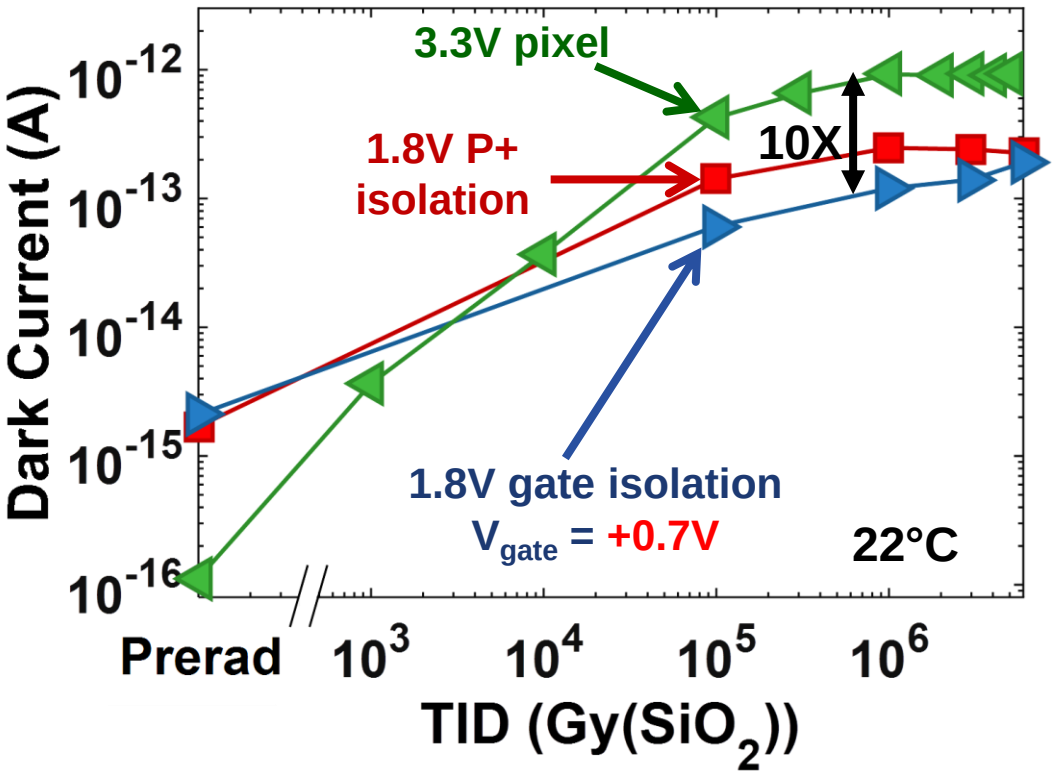
- Similar behavior between 3.3V and 1.8V pixels
- Same behavior between P+ and gate isolation for $V_{gate}<0$
- Gate isolation pixel : large dark current reduction for $V_{gate}>0$

Dark Current Compensation Mechanism?



- **Possible explanation:**
  - **When the gate is depleted, part of the dark electrons diffuse toward the nearest N+ VDD contact through the STI weak inversion region**
  - **Photo-electron are not collected by STI thanks to the P-Well barrier**

Dark Current: Evolution with TID

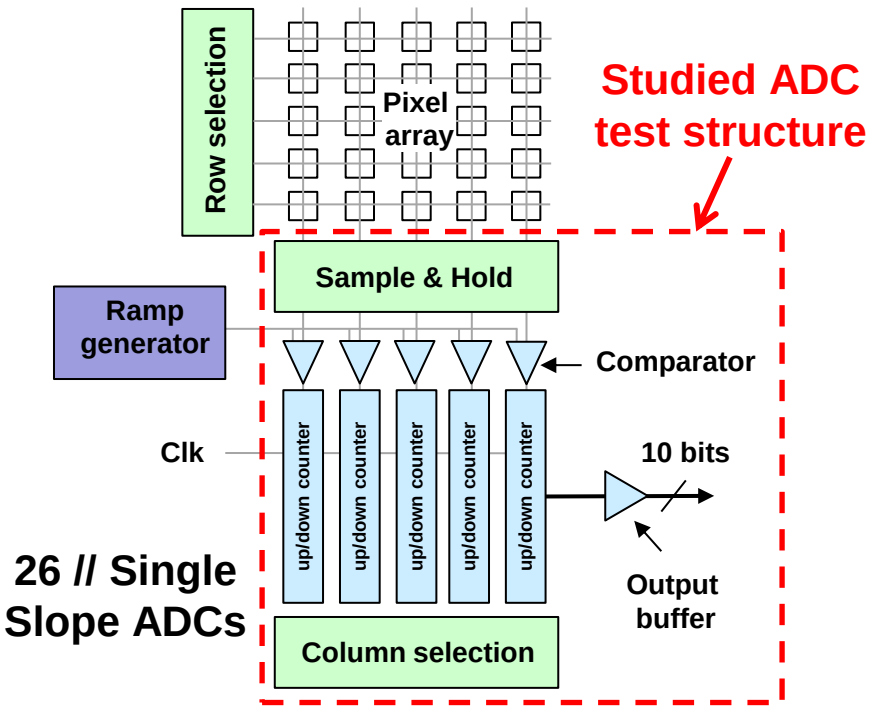


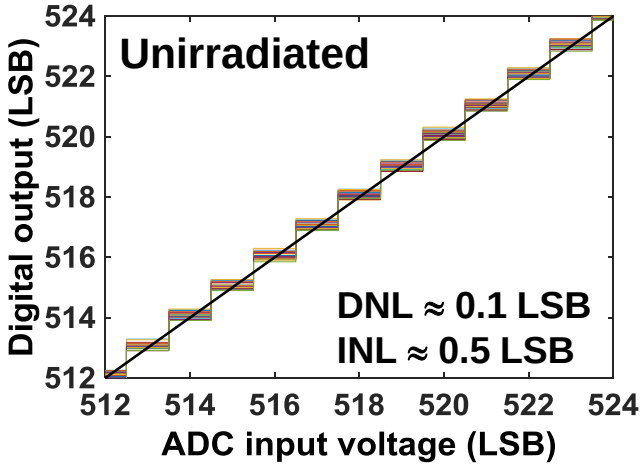
After irradiation

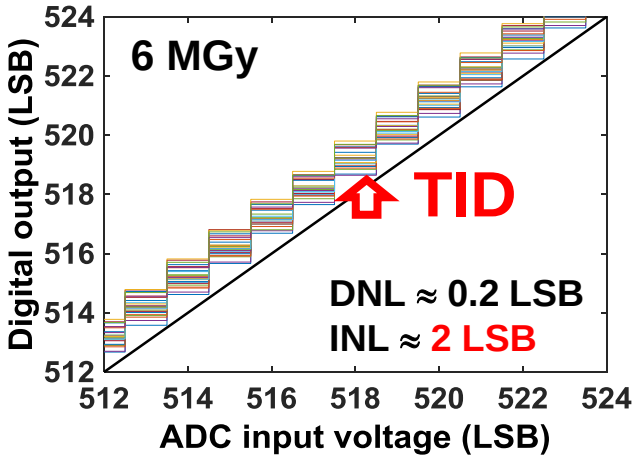
- **1.8V design**
  - ➡ **≈ 5X reduction**
- **Gate isolation pixel**
  - ➡ **≈ 2X further reduction**
    - **Even larger reduction if V_{gate} is increased further**

Between 5X and 10X dark current reduction compared to previous 3.3V design

RHBD Analog to Digital Converter (ADC)

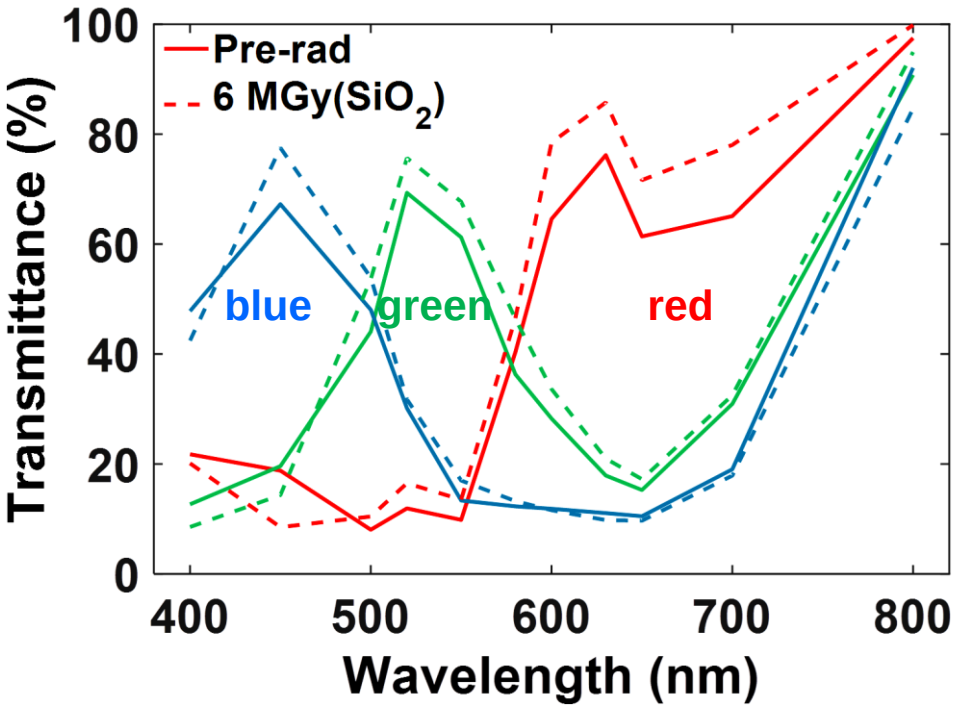




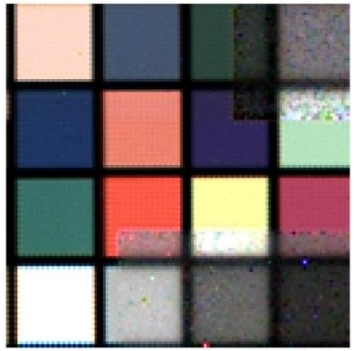


- Reasonable degradation after 6 MGy
- Not limiting the performance

Color Filter Array:
Radiation Hardness Evaluation



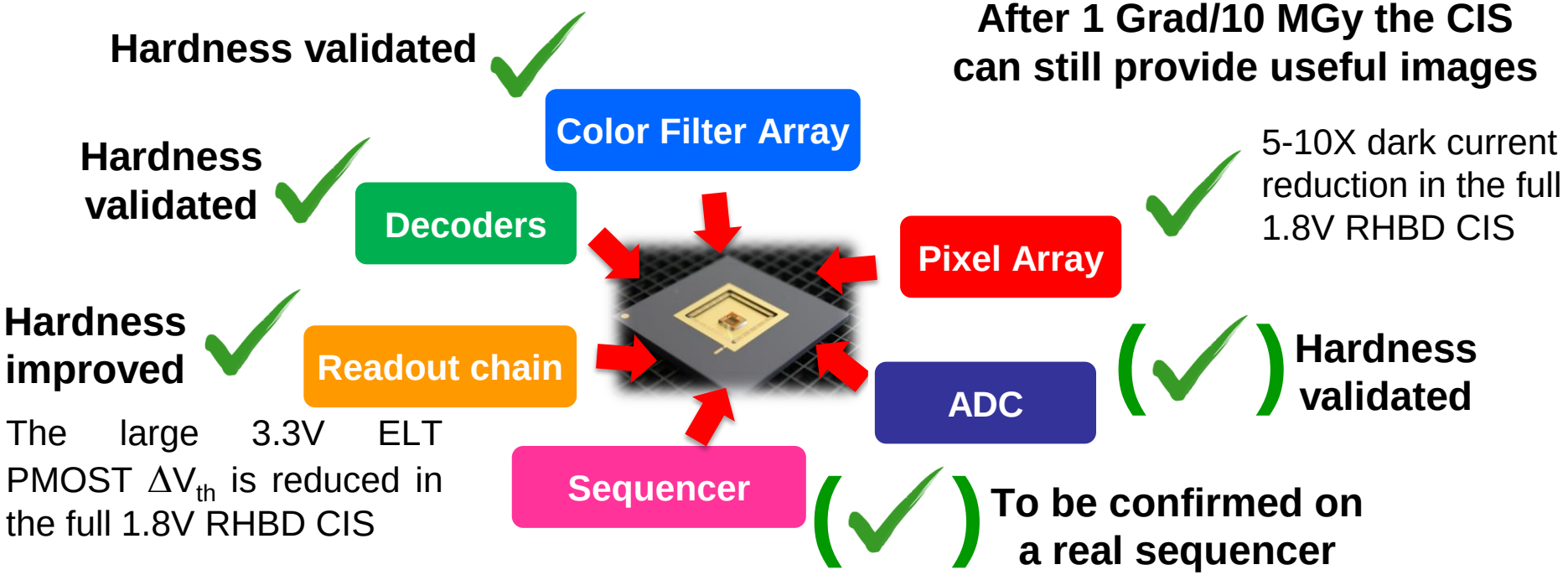
Color images captured by the manufactured CMOS image sensor:



Unirradiated **6 MGy(SiO_2)**

- **No significant color filter degradation**

Conclusions



- **Multi MGy Rad-Hard Color Digital Camera-on-a-chip appears feasible**
- **Development shall continue:**
  - **Integrate all the functions in a single HD sensor**
- **Exploration of alternative solutions to improve further the performances (e.g. dark current? dynamic range?)**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Thank you!