Space and Nuclear Radiation Effects on CMOS Image Sensors

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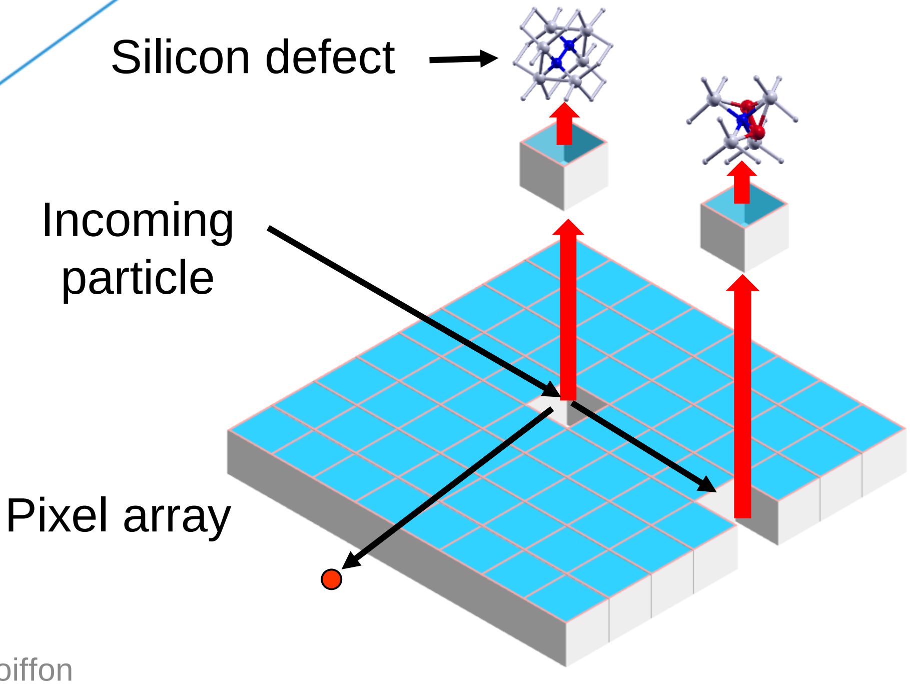


Starting Background

- Introduction to Radiation Effects on Microelectronic Devices
  - Dr Giulio Borghello Monday’s lecture on “Radiation Issues in Microelectronics”

- Introduction to CMOS Image Sensor Technology
  - Prof Albert Theuwissen Tuesday’s lecture on “Advances in CMOS Image Sensors”

Imaging in Ionizing Radiation Environment

Space

Medical Imaging

Jupiter's Moons

Electron Microscopy

Nuclear Waste Storage

Nuclear Fusion

Particle Physics

Nuclear Power Plants

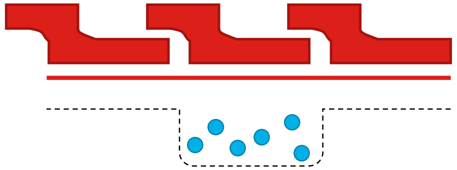
100 rad 1 krad 10 krad 100 krad 10 Mrad 100 Mrad 1 Grad

Accessible to Humans

Requires Radiation Hardened Electronics

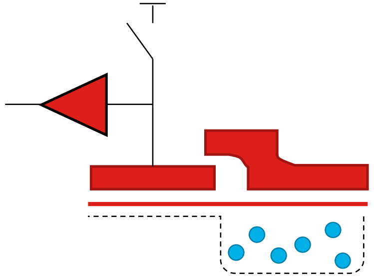
Accessible to Commercial Electronics

CMOS vs CCD vs CID
The Radiation Hardness Point of View

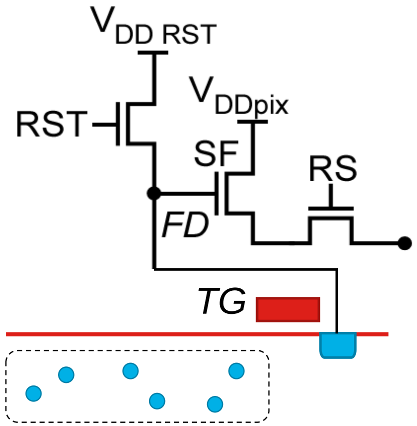


- CCD are radiation soft
  - Thicker oxides/Higher voltages than CMOS
  - Massive use of charge transfer
    - Charge transfer very sensitive to TID and DD
  - “Only a pixel array”
    - No in-pixel or on-chip integration capability

Not relevant for radiation environment



- Charge Injection Devices (CID) : more radiation tolerant than CCD
  - But lower performances than CIS
  - Radiation Hardness Limited to 1-5 Mrad



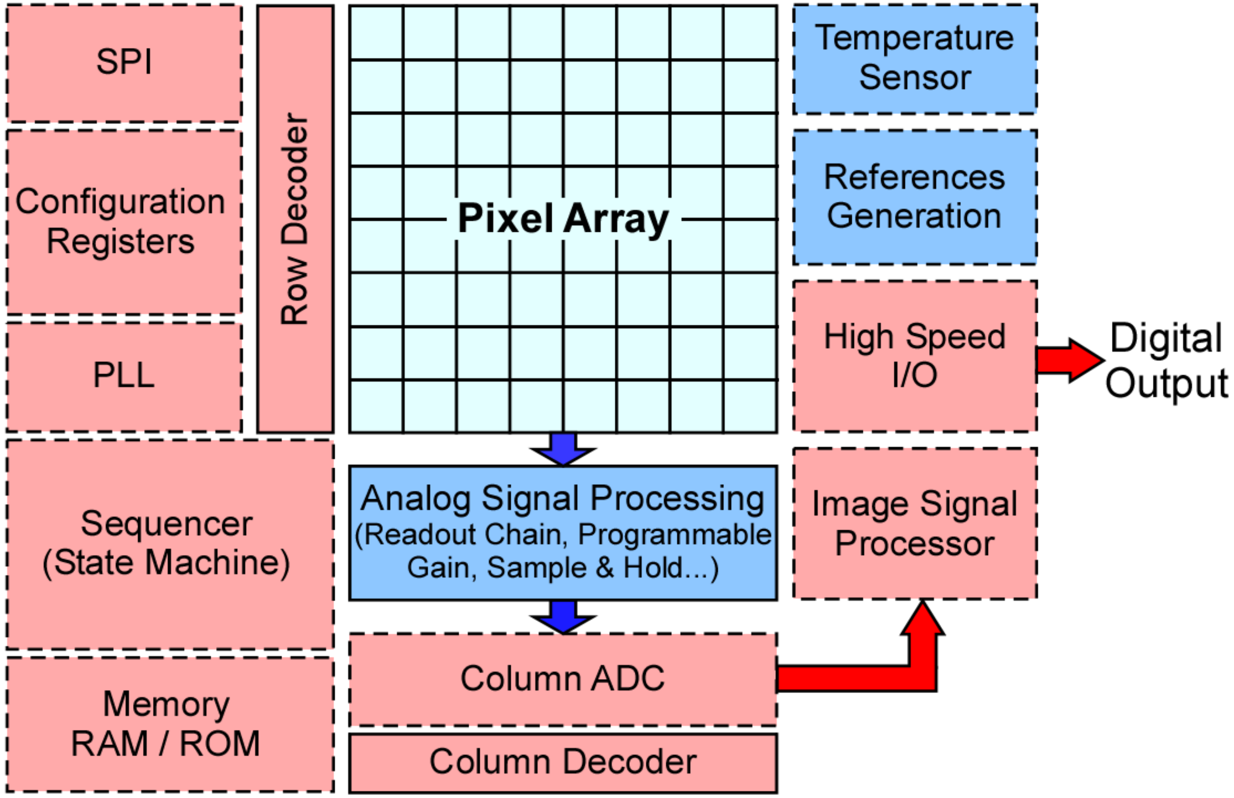
- CIS = high potential for radiation hardening
  - Highest intrinsic radiation hardness
    - Lower voltages
    - Thinner oxides
    - Up-to-date state-of-the-art technology
  - Great design freedom
    - Room for radiation hardening !
  - High performance
  - Wide variety of integrated features
  - Better than CCD and CID at nearly everything and can do so much more!

Best choice for imaging in radiation environment

CIS Technology: an overview

- CMOS Image Sensors (CIS)
  - CMOS **Mixed-Signal** Integrated Circuit
  - Designed for optical imaging applications
  - Manufactured with a CMOS process optimized for imaging

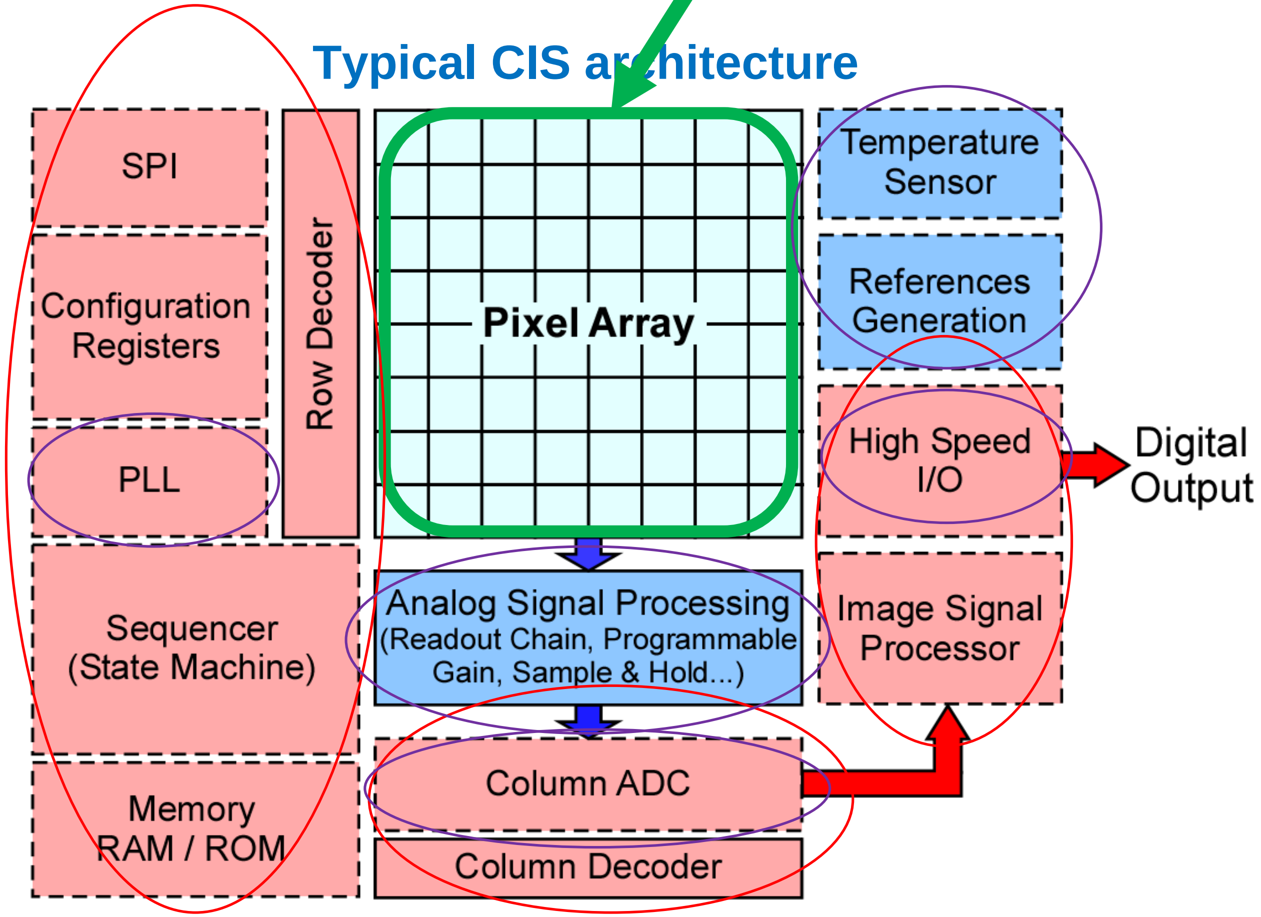
Typical CIS architecture



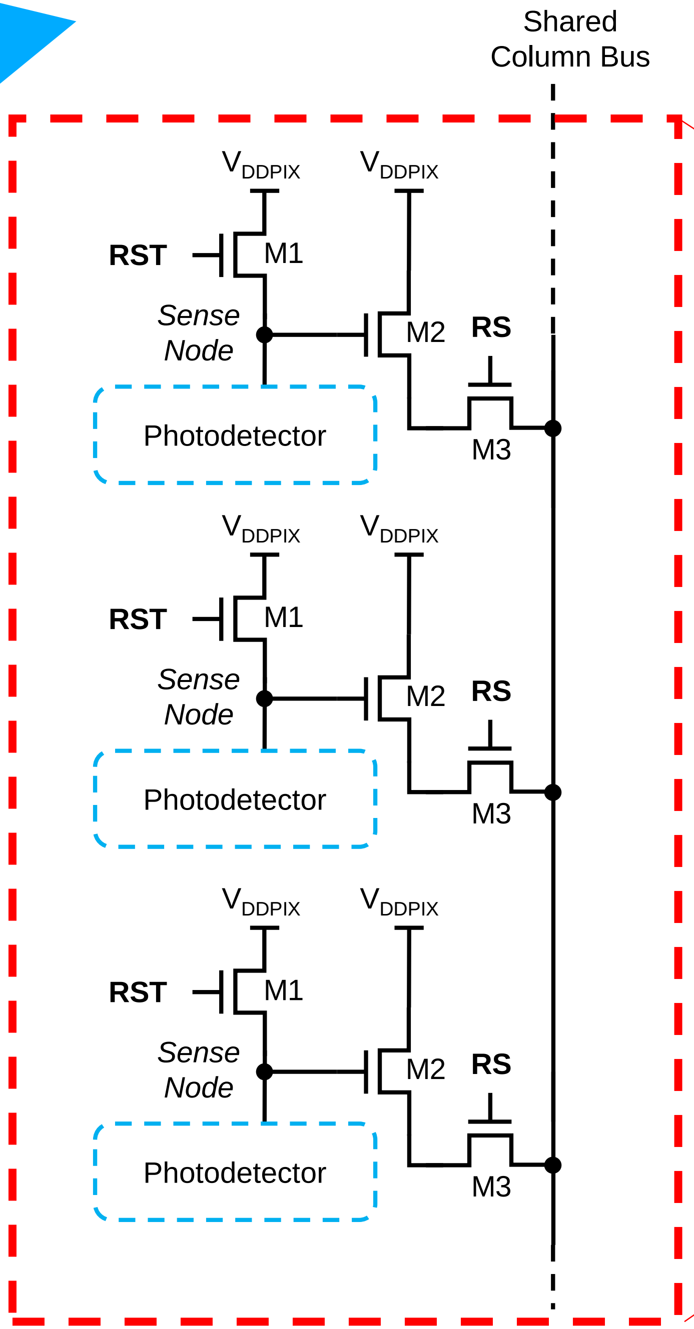
CIS Technology: an overview

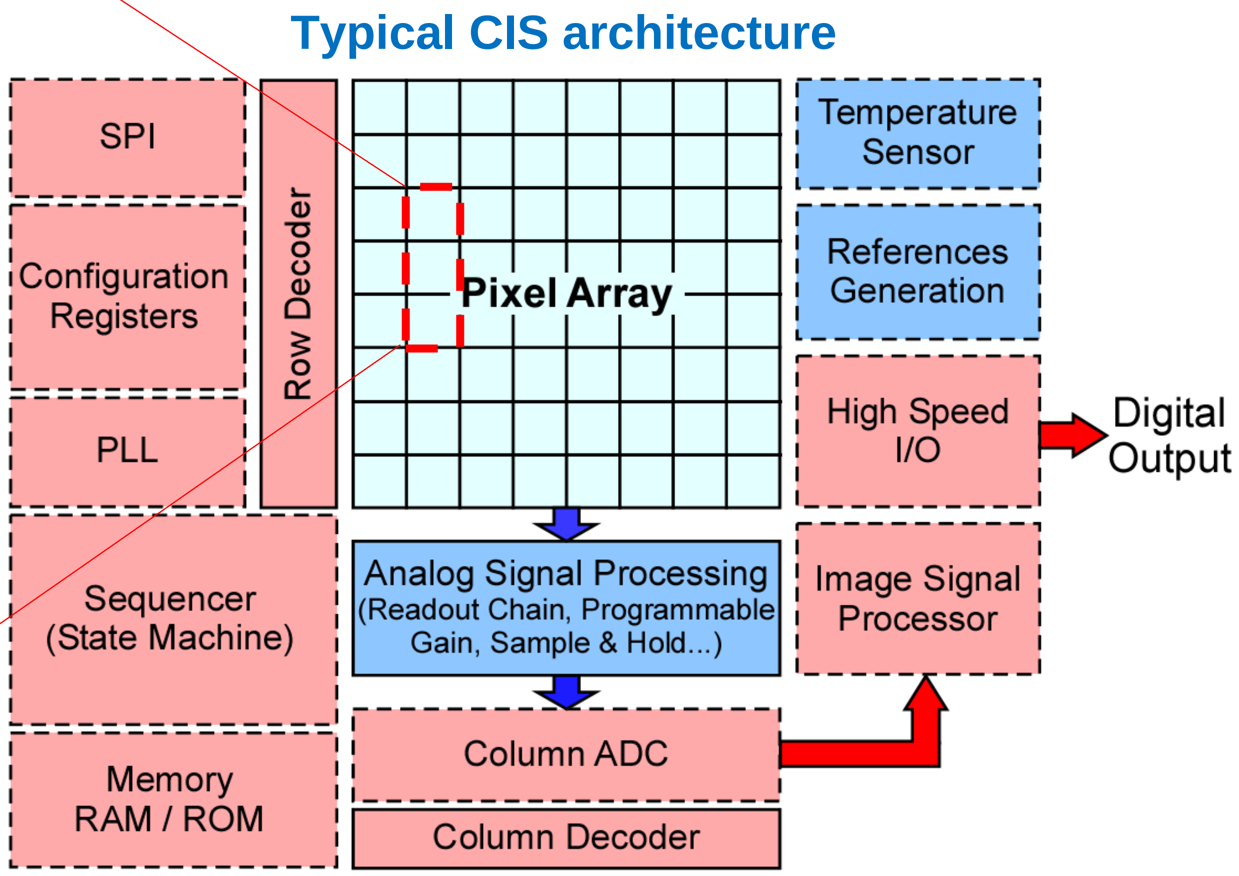
- CIS = system-on-chip constituted of
  - Digital Circuits
    - Memory/Registers
    - Sequencer
    - Main radiation effects: **SEE**
  - Analog/Mixed Signal Circuits
    - Readout Chain
    - A/D converters
    - Phase Locked Loops
    - Main radiation effects: **TID & SEE**
  - Analog Pixel Array

This Talk
TID/DD/SET & SEL
In Pixel Arrays



Basic CIS Pixel Architecture





Typical CIS architecture

SPI

Configuration
Registers

PLL

Row Decoder

Pixel Array

Temperature
Sensor

References
Generation

High Speed
I/O

Digital
Output

Sequencer
(State Machine)

Analog Signal Processing
(Readout Chain, Programmable
Gain, Sample & Hold...)

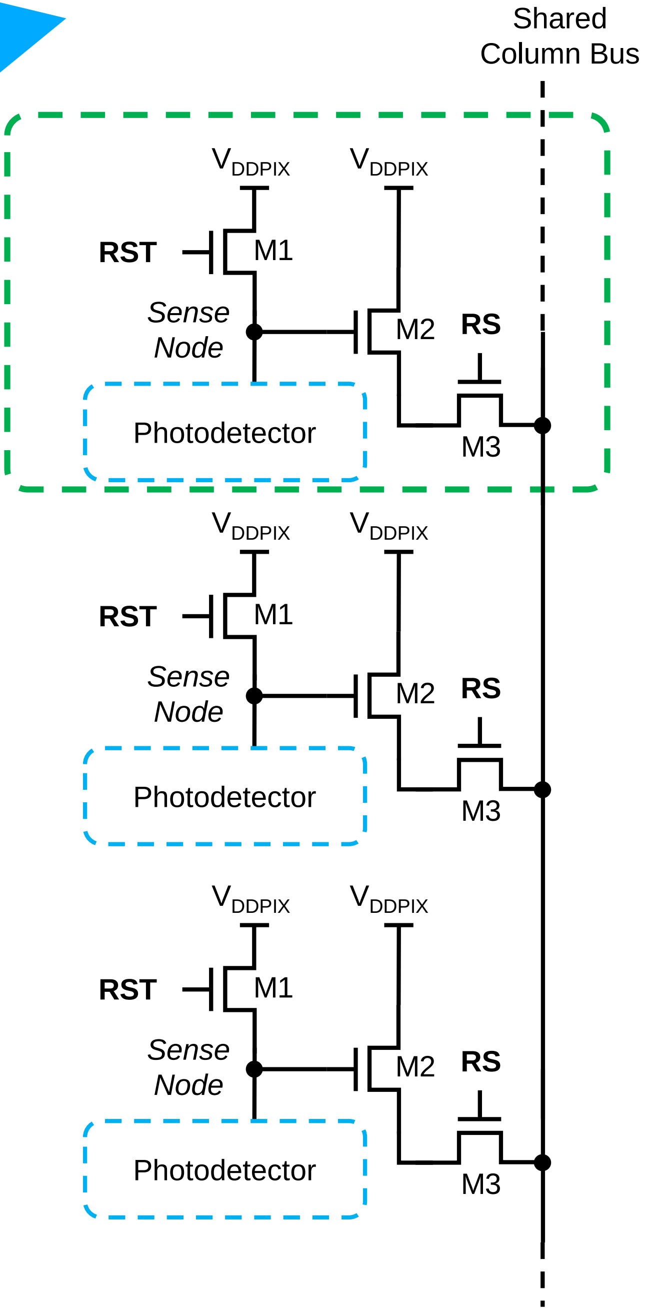
Image Signal
Processor

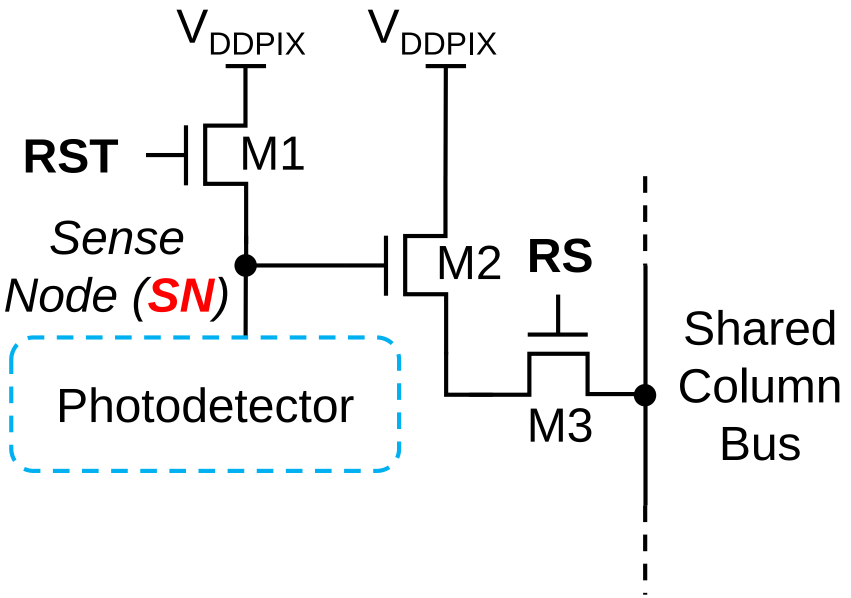
Memory
RAM / ROM

Column ADC

Column Decoder

Basic CIS Pixel Architecture

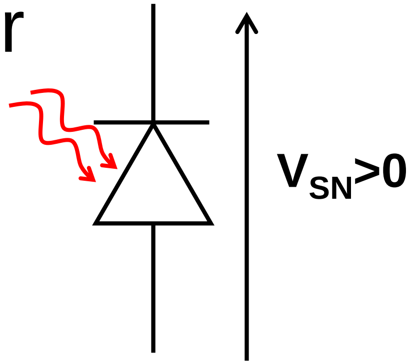


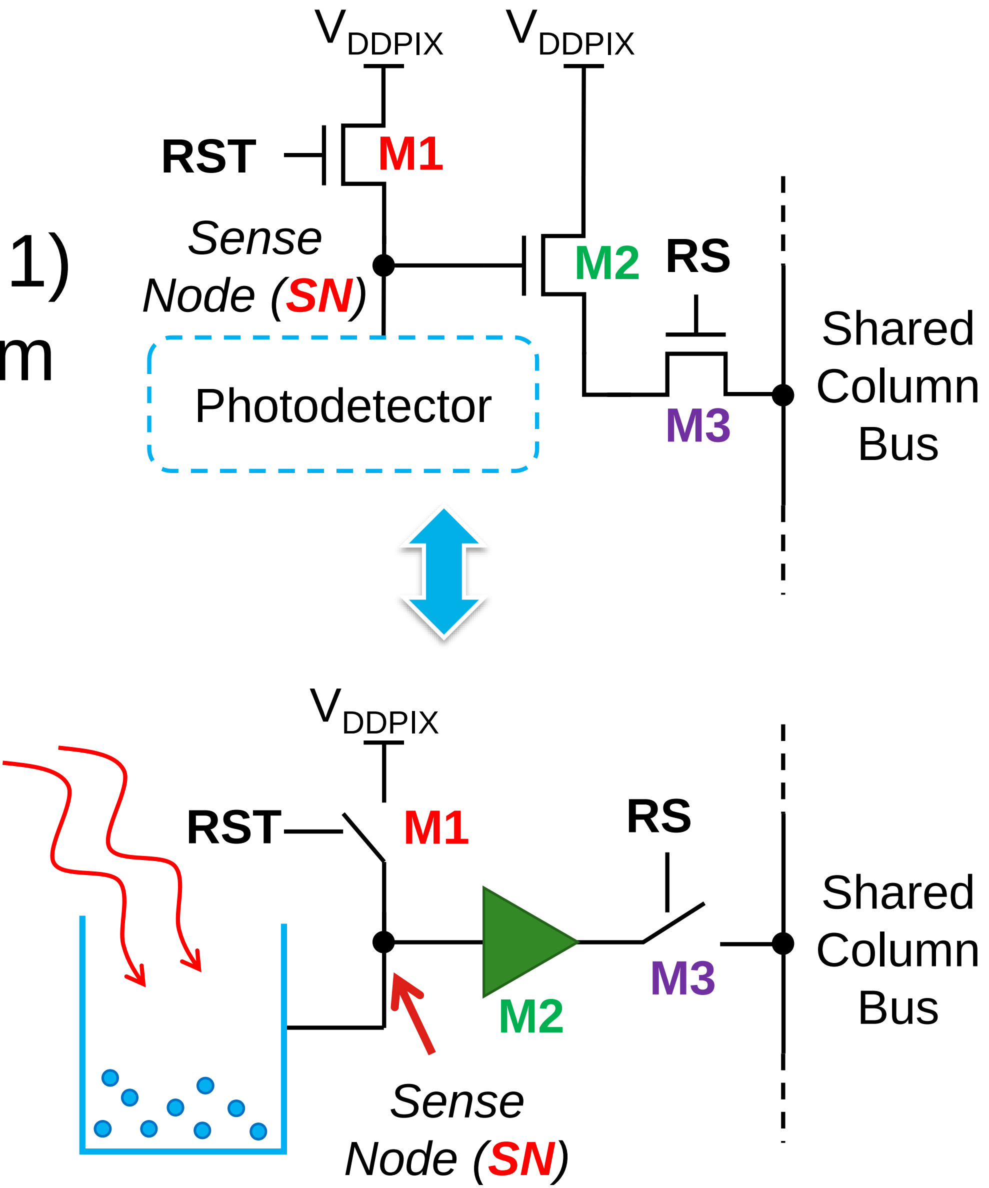


Basic Pixel Architecture

- 3 Transistors per Pixel (at least)
  - One to **reset** the photodetector (M1)
  - One to **isolate** the sense node from the rest of the circuit (M2)
    - Source Follower Amplifier
  - One to **select** the pixel (M3)

- And one photodetector
  - A **reverse biased PN junction**
  - (can include an additional MOSFET)

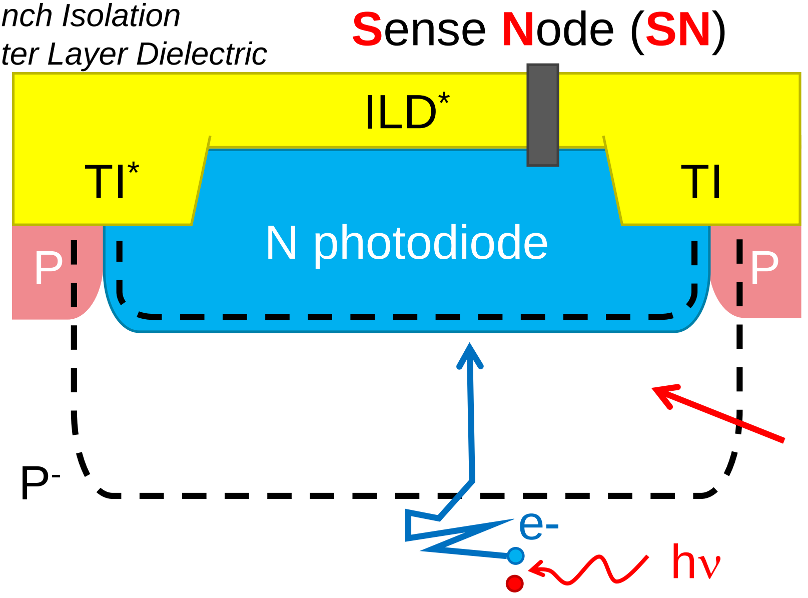




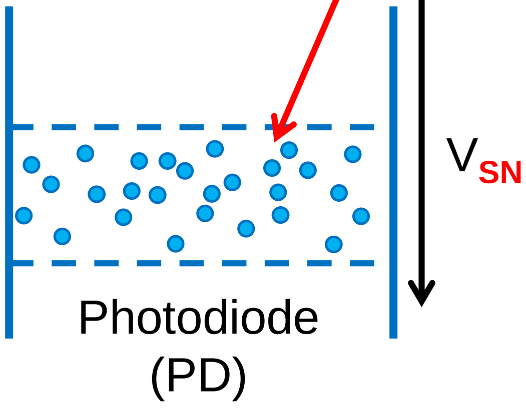
2 Main CIS Photodetector Technologies

Conventional Photodiode

**TI = Trench Isolation*
**ILD = Inter Layer Dielectric*

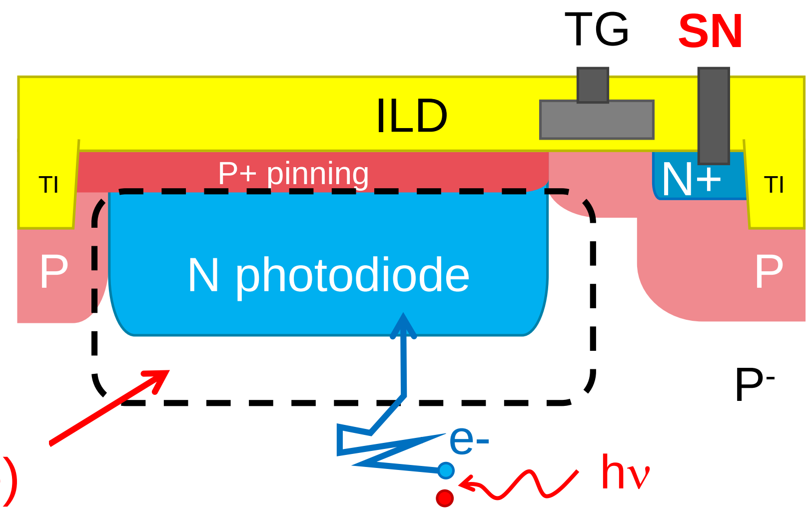


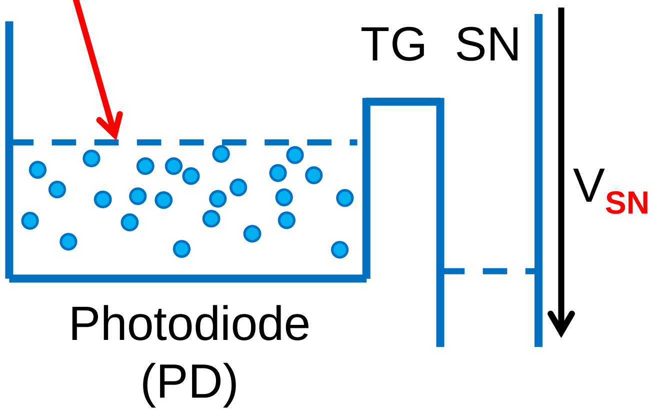
Depleted Region
(Collection volume)



Sense Node
=
Collection Node

Pinned Photodiode + Transfer Gate



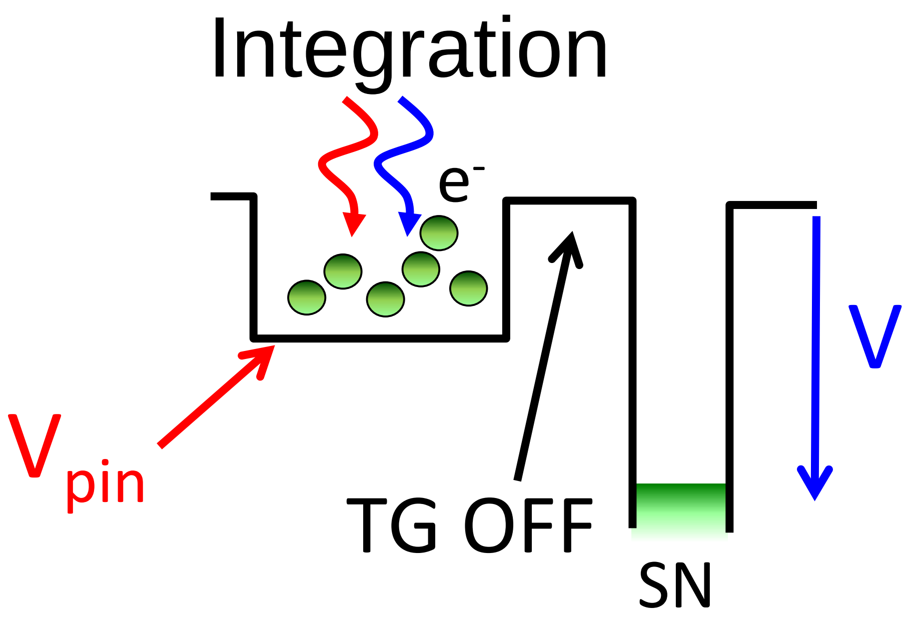


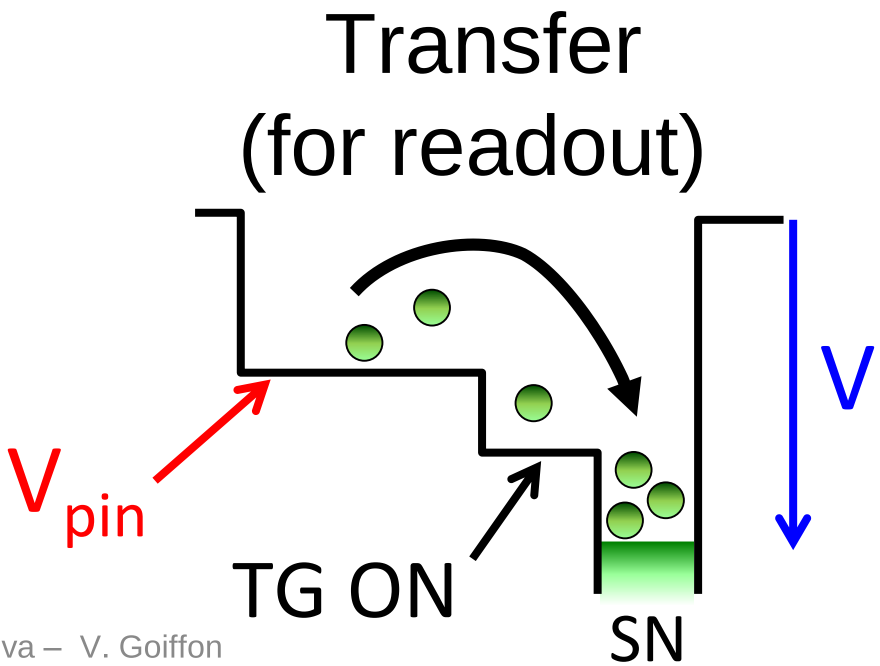
Sense Node
≠
Collection Node

Requires one charge transfer

PPD-TG pixel principle

- The pinned photodiode behaves like an ideal potential well
  - Photogenerated electrons are collected into the potential well
  - At the end of the integration time, the **Transfer Gate** is enabled to transfer the collected charge to a node (the **S**ense **N**ode) where it can be measured

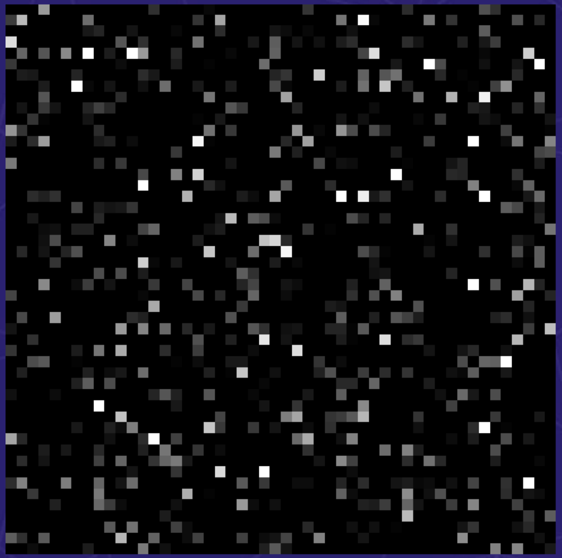




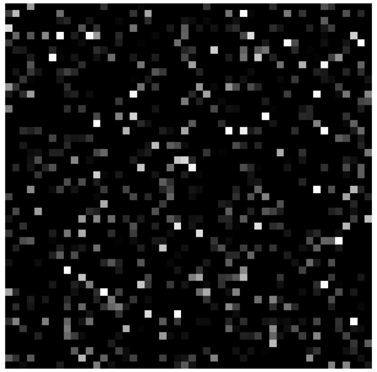
Talk Outline

- Dark Current (DC) in Solid-State Image Sensors
- Total Ionizing Dose (TID) Effects on CIS
- Displacement Damage (DD) Effects on CIS
- Single Event Effects (SEE) in CIS Pixel Arrays
- Summary and Conclusion

Dark Current in Solid State Image Sensors



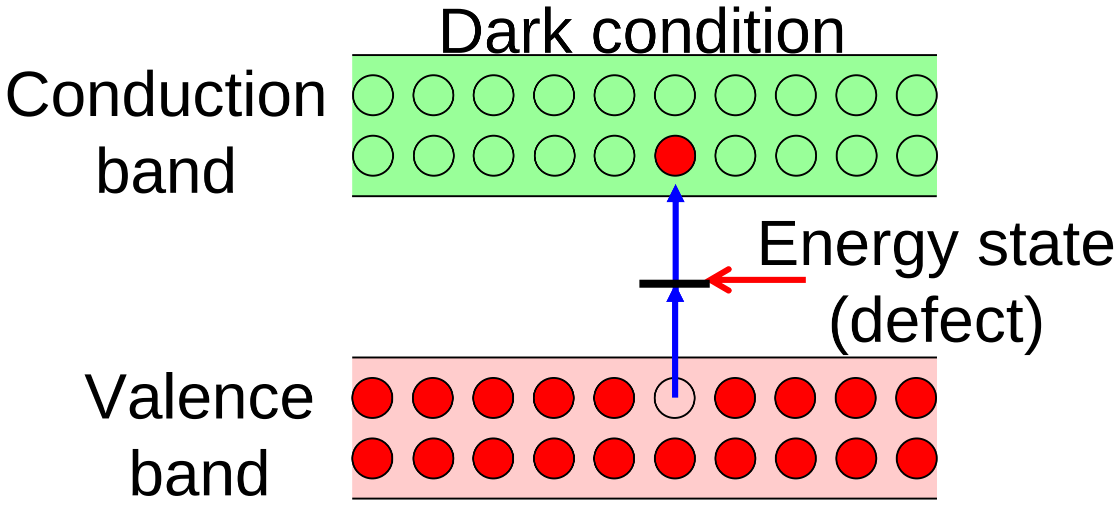
Dark Current



- Parasitic Leakage Current leading to a non-zero output signal in absence of illumination
- Main mechanism of interest for radiation induced dark current

Shockley-Read-Hall (SRH) generation mechanism in depletion regions

- Principle:
  - Thermal agitation allows valence band electrons to "jump" to the conduction band through an energy state in the forbidden bandgap
    ➔ parasitic **electron/hole pair generation!**
  - This energy state is coming from lattice defects
  - A **single defect** in a depletion region can lead to a **huge increase** in electron/hole pair **generation rate**



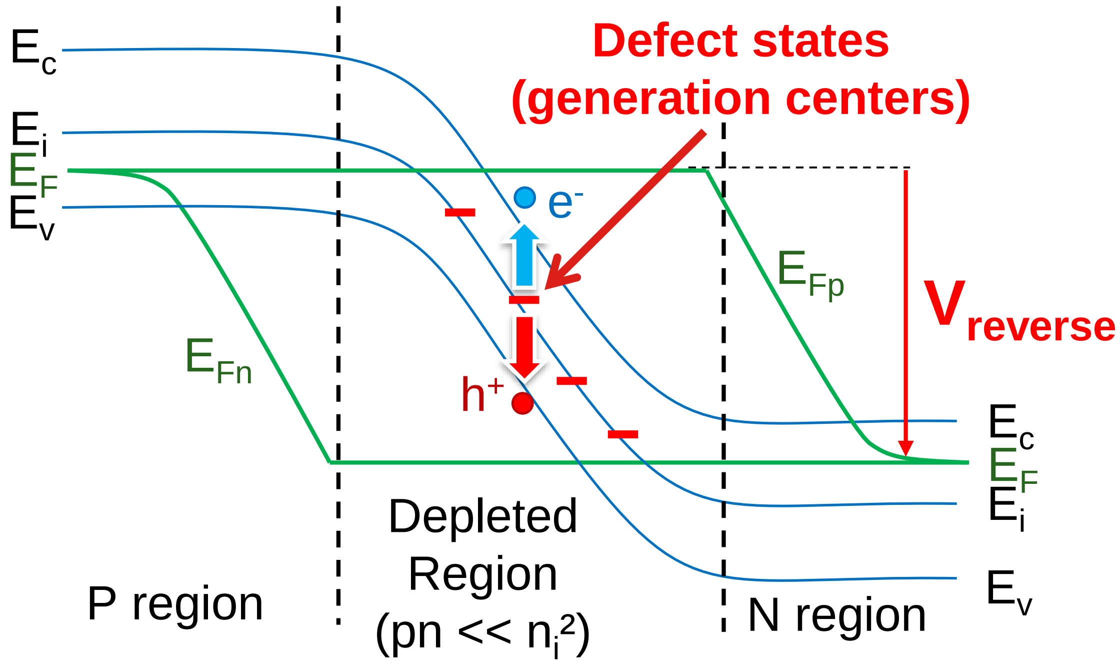
Case of the Reverse Biased PN Junction

- SRH Generation Rate U :

$$U = \frac{\sigma_n \sigma_p v_{th}(n_i^2 - pn)}{\sigma_n \left[n - n_i exp\left(\frac{E_t - E_i}{kT}\right)\right] + \sigma_p \left[p - n_i exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

- In the depletion region of a reverse biased PN junction (with $\sigma_n = \sigma_p$)
  - $pn << n_i^2$

➔ $$U = \sigma v_{th}\sqrt{N_c N_v} \times exp\left(-\frac{\frac{E_g}{2} + |E_i - E_t|}{kT}\right)$$



- The generation rate U is maximum for midgap defects ($E_t \approx E_i$)
- The activation energy E_A of the generation rate is related to the trap energy through

➔ $$\boxed{E_A \approx 0.63 + |E_t - E_i|}$$

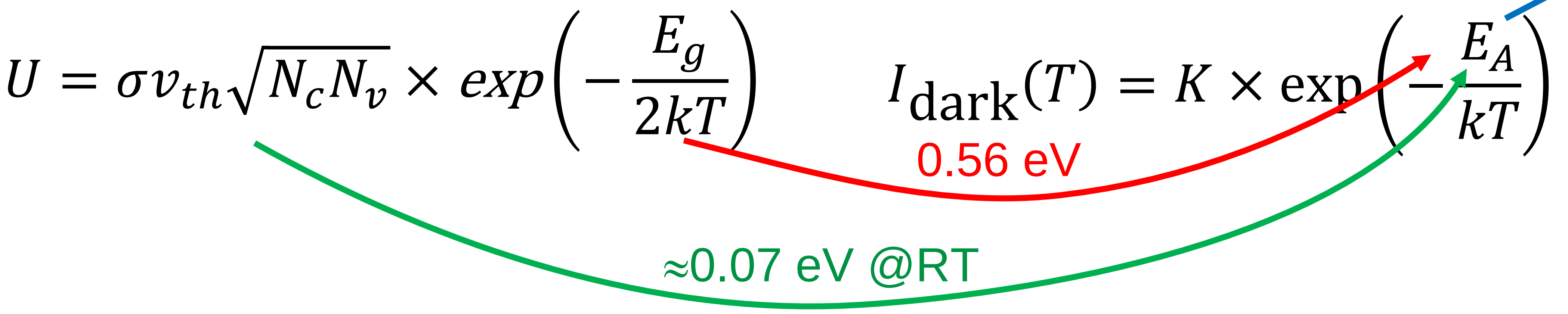
Midgap states ➔ $E_A \approx 0.63$ eV

Why $E_A \neq 0.56$ eV for midgap defects?

- Because of the temperature dependence of the exponential prefactor that increases the apparent activation energy by about 0.07 eV @ room temperature

Generation rate for a mid-gap defect
in a depletion region with $pn \ll n_i^2$

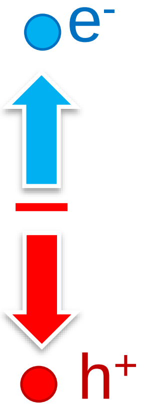
The activation energy E_A
defined by the Arrhenius law :



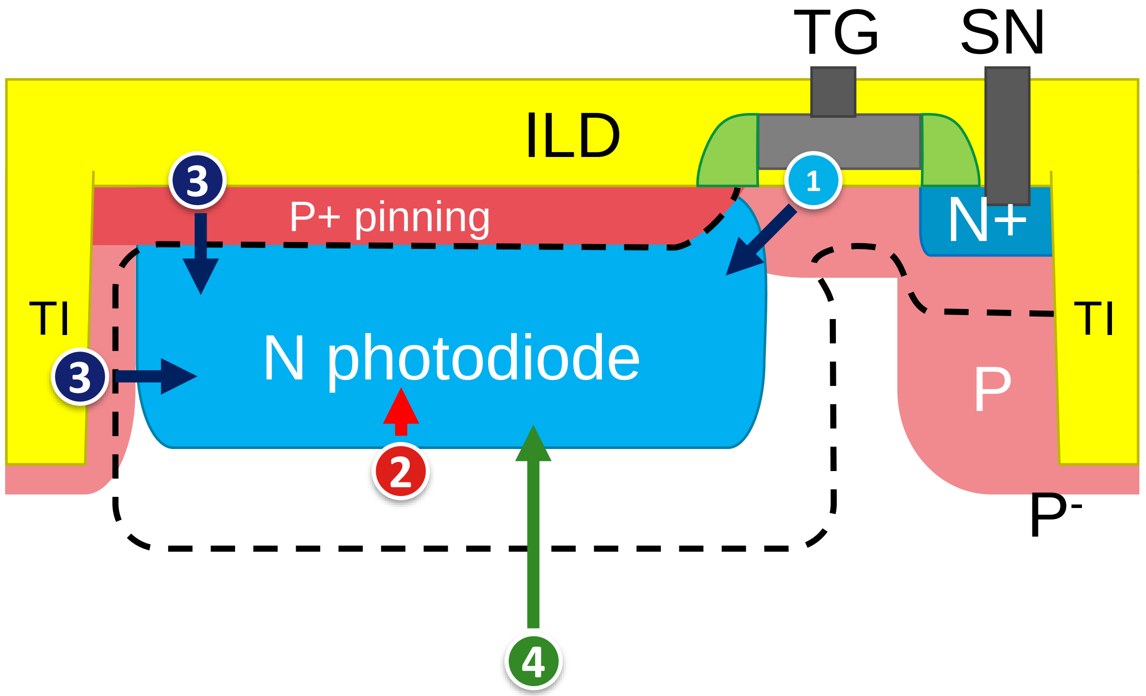
$$U = \sigma v_{th}\sqrt{N_c N_v} \times exp\left(-\frac{E_g}{2kT}\right)$$

$$I_{\mathrm{dark}}(T) = K \times \exp\left(-\frac{E_A}{kT}\right)$$

Dark Current Sources in a Pixel



- The “dark” e-/h+ generation can come from various locations in a pixel



① From depleted Si/SiO_2 interfaces

② From the photodiode depletion region

③ From quasi-neutral Si/SiO_2 interfaces

④ From quasi-neutral substrate

Dark Current Contributions In A Pinned Photodiode CMOS Sensor

Backup Material

- Four main sources

V. Goiffon, 2021 IEEE NSREC Short Course, Part III, Hardening Techniques for Image Sensors.

① Interface state generation dark current

$$I_{itgen} = \frac{1}{2} q\sigma v_{th}\sqrt{N_c N_v}\exp\left(-\frac{E_g}{2kT}\right) A_{itdep} \times N_{it}$$

② Bulk generation dark current (midgap trap)

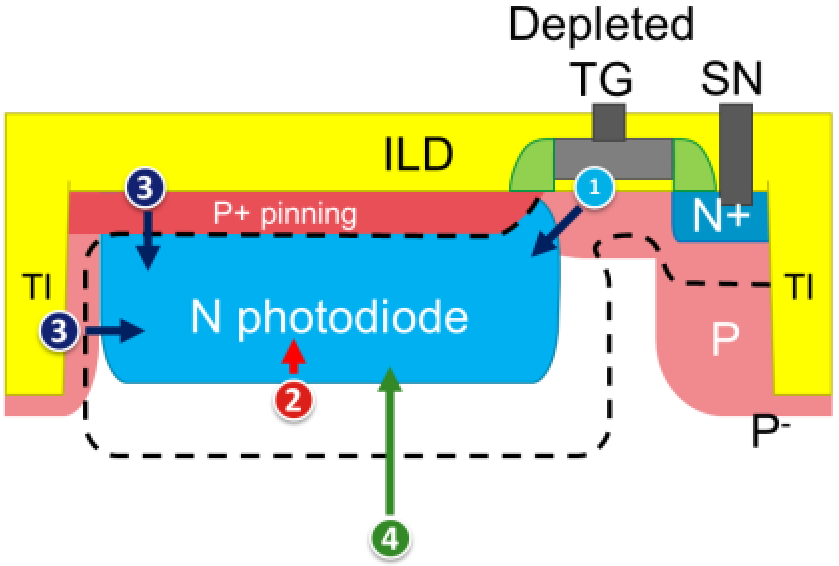
$$I_{bkgen} = \frac{q\sigma v_{th}\sqrt{N_c N_v}}{2} V_{dep} \exp\left(-\frac{E_g}{2kT}\right) \times N_t$$

③ Interface state diffusion dark current

$$I_{itdiff} = q\sigma v_{th} N_c N_v \exp\left(-\frac{E_g}{kT}\right) \frac{A_{it} \times N_{it}}{N_{A,D}\left(1 + \frac{x_{SiO2}\sigma v_{th}}{D_{n,p}} \times N_{it}\right)}$$

④ Bulk diffusion dark current

$$I_{bkdiff} = \frac{q D_n n_i^2}{L_n N_A} = \frac{q\sqrt{\sigma v_{th} D_n}(N_c N_v)^{5/4}}{N_A^{3/2}} \times \exp\left(-\frac{5}{4}\frac{E_g}{kT}\right) \times \sqrt{N_t}$$



Bonus: Interface state generation dark current in inverted regions (not represented here)

$$I_{itgen(inv)} = \frac{q\sigma v_{th} N_c N_v}{n}\, exp\left(-\frac{E_g}{kT}\right) \times N_{it}$$

Inverted channel density (electron channel here)

G. R. Hopkinson, "Radiation-induced dark current increases in CCDs", in RADECS 93. Second European Conference on Radiation and its Effects on Components and Systems, sept. 1993, p. 401-408.

Electric Field Enhancement of SRH Generation

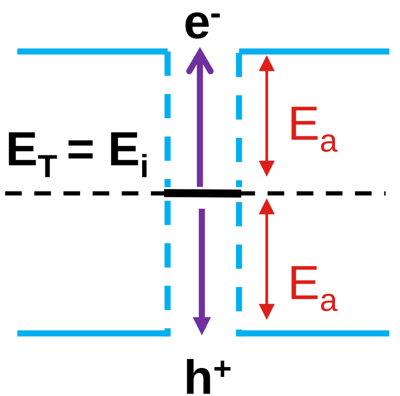
- High Electric Field Magnitudes enhance the generation rate and lower the apparent activation energy

$$I_{dc} \propto e^{-\frac{E_A}{kT}}$$

“Pure” SRH Generation in the SCR

Low E-Field

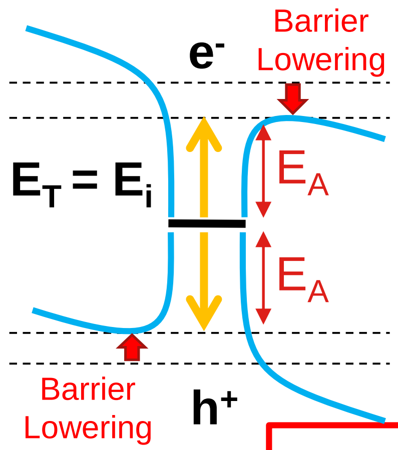
Midgap defect



$E_A \approx E_g/2$

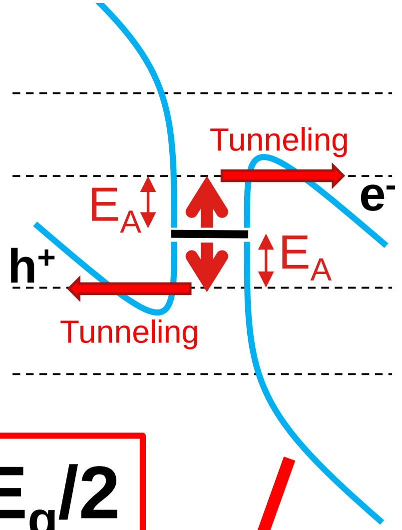
Poole Frenkel Effect

Moderate E-Field



Phonon-Trap-Assisted-Tunneling

High E-Field



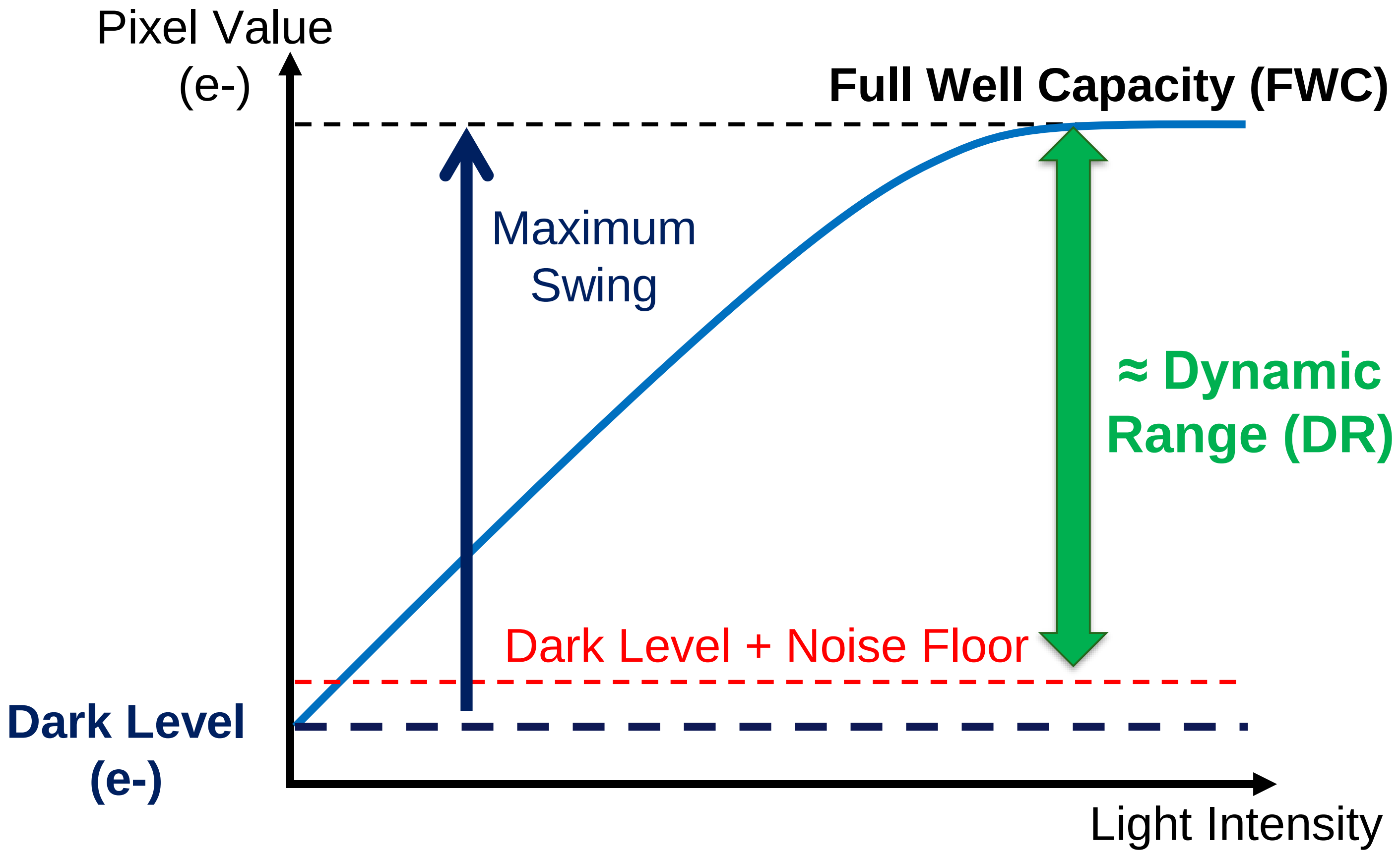
$0 < E_A < E_g/2$

Electric Field Enhancement (**EFE**) of SRH Generation Rate

Why does dark current matter after all?

Dynamic Range Discussion

- Dynamic Range: Working range of a camera
  - Ratio between the maximum and minimum measurable light intensities (in a single frame)



Dynamic Range

$$DR = 20\log\left(\frac{\text{Maximum Swing}}{\text{Noise Floor}}\right)$$

- Maximum swing = FWC – Dark Level
- Minimum detectable signal = Noise Floor

Dynamic Range vs Dark Current (1)

Integration time
(i.e. exposure time)

- Dark Level (in e$^-$): $\boxed{\text{Dark Level} = I_{\text{dark}} \times t_{\text{int}}}$

Dark Current (e-/s)

- Dark Current Shot Noise (e$^-$ rms): $\boldsymbol{\sigma}_{\textbf{dark}} = \sqrt{\text{Dark Level}} = \sqrt{I_{\text{dark}} \times t_{\text{int}}}$

- Noise Floor (e- rms):

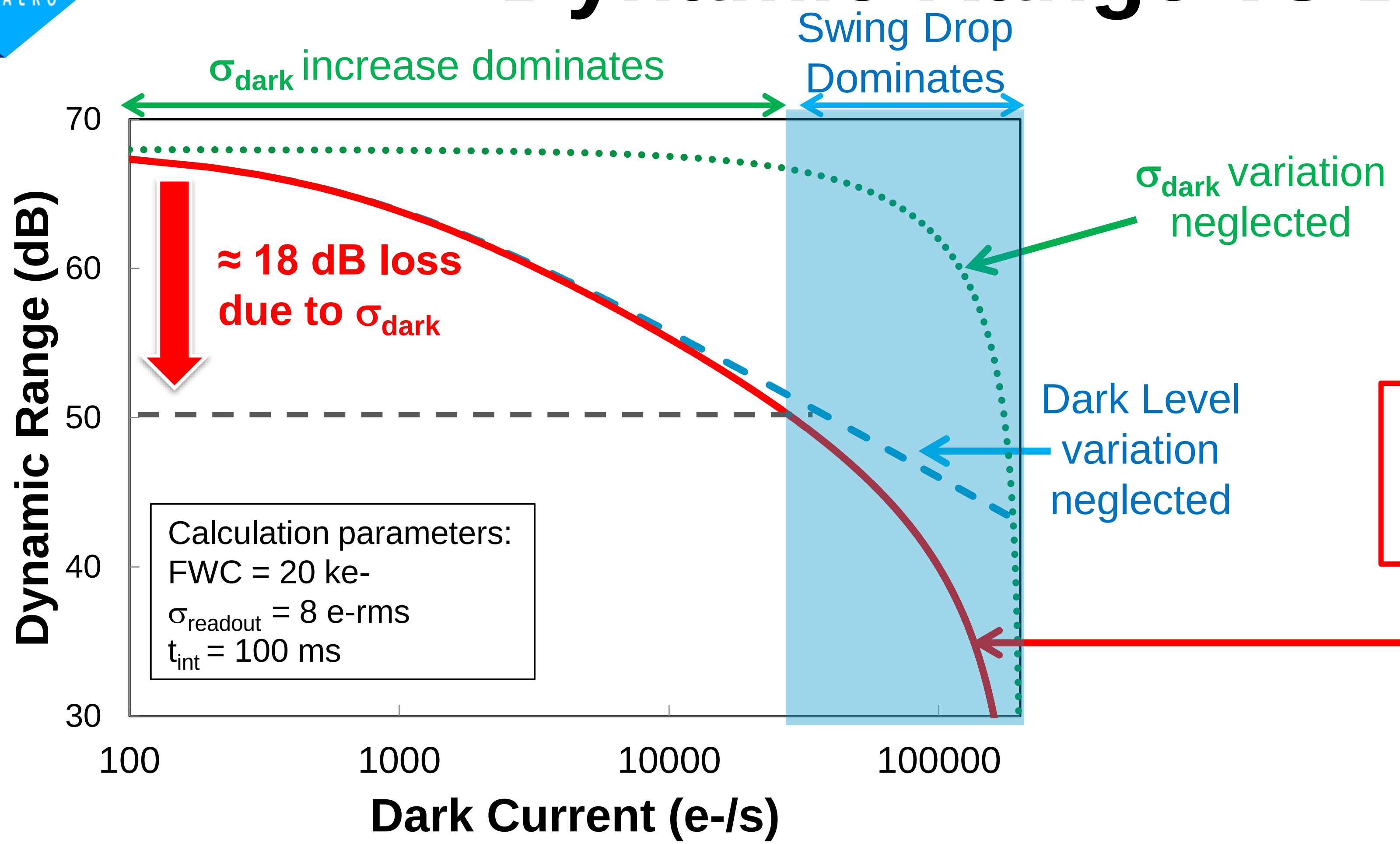
$$\sigma_{\text{floor}} = \sqrt{\sigma^2{}_{\text{readout}} + \boldsymbol{\sigma}^2{}_{\textbf{dark}}}$$

Noise of the readout electronics

When the dark current becomes significant

$$\boxed{\sigma_{\textbf{floor}} \approx \boldsymbol{\sigma}_{\textbf{dark}} = \sqrt{I_{\textbf{dark}} \times t_{\textbf{int}}}}$$

Dynamic Range vs Dark Current (2)



Full DR calculation

$$DR = 20\log\left(\frac{FWC - \text{Dark Level}}{\sqrt{\sigma^2{}_{\text{readout}} + \sigma^2{}_{\text{dark}}}}\right)$$

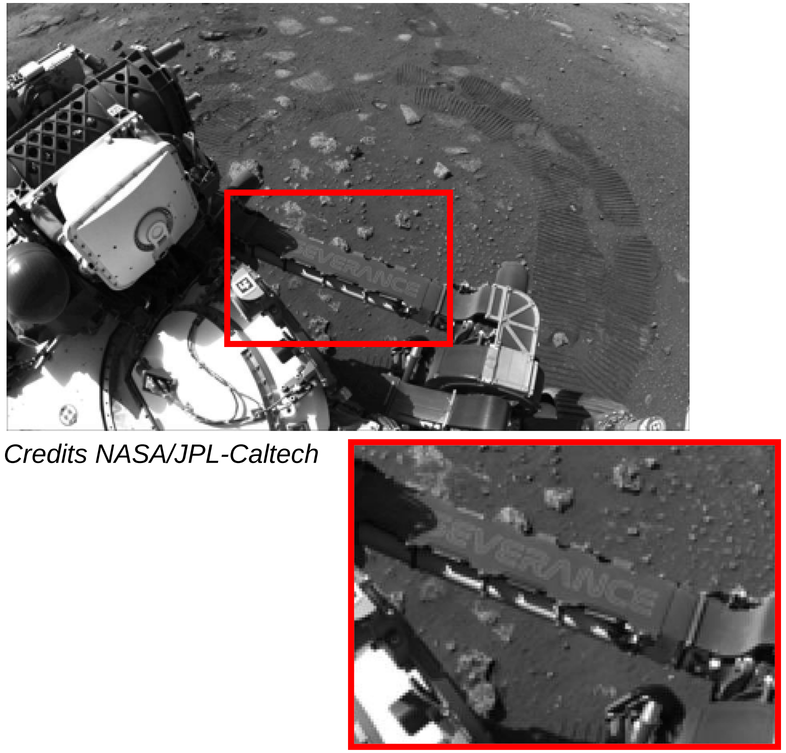
$$\text{Dark Level} = I_{\text{dark}} \times t_{\text{int}}$$

$$\sigma_{\text{dark}} = \sqrt{I_{\text{dark}} \times t_{\text{int}}}$$

- The dark current increase degrades severely the Dynamic Range
  - Dark current **shot noise** is **the main issue !!**
  - Mean dark current level matters only when most of the DR is already lost !!

Dynamic Range vs Dark Current Illustration

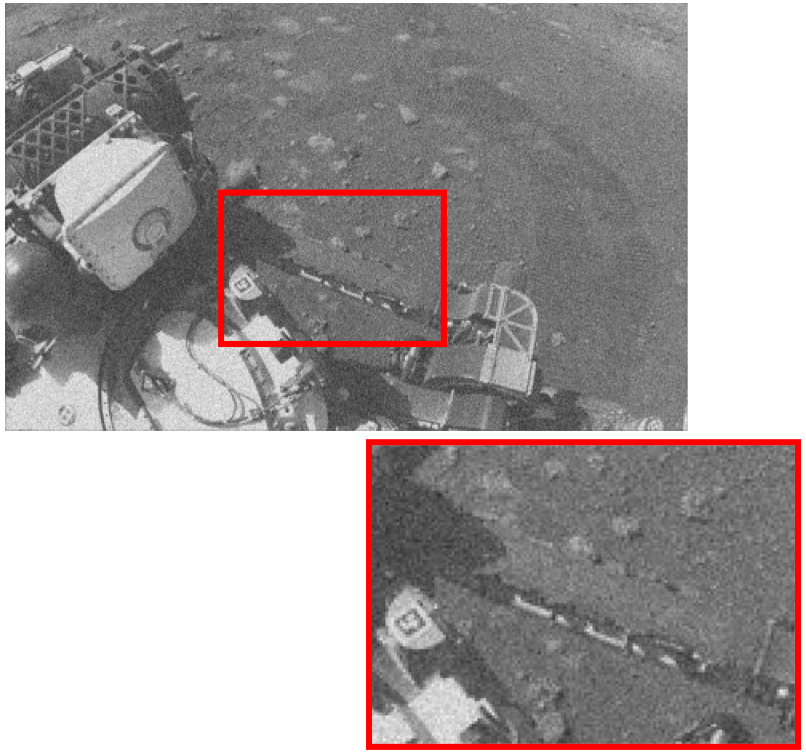
Original Image



Credits NASA/JPL-Caltech

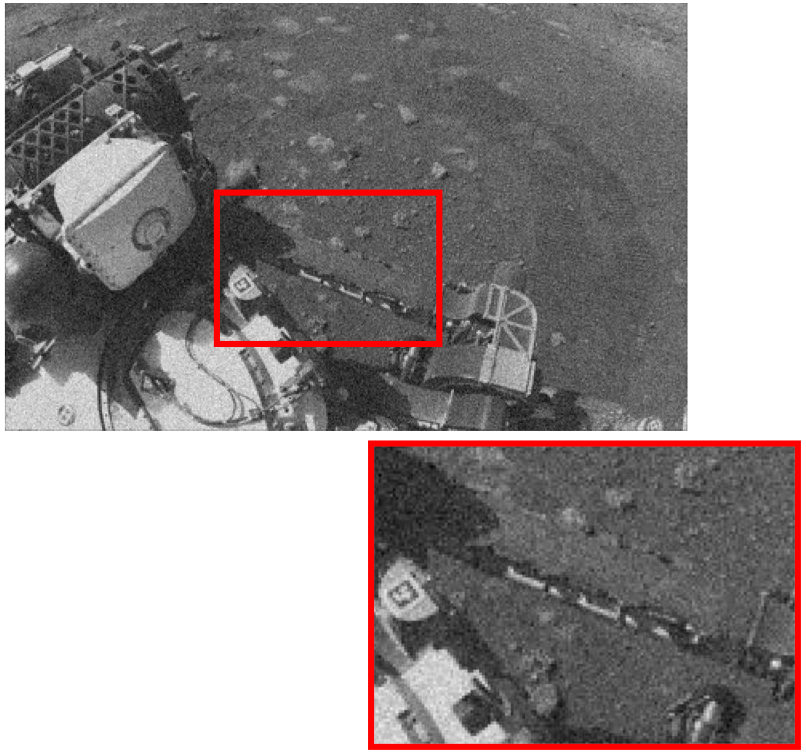
- “Perseverance” can be read

With radiation induced dark current increase



- Details lost
- Grey dark areas

After mean dark current subtraction



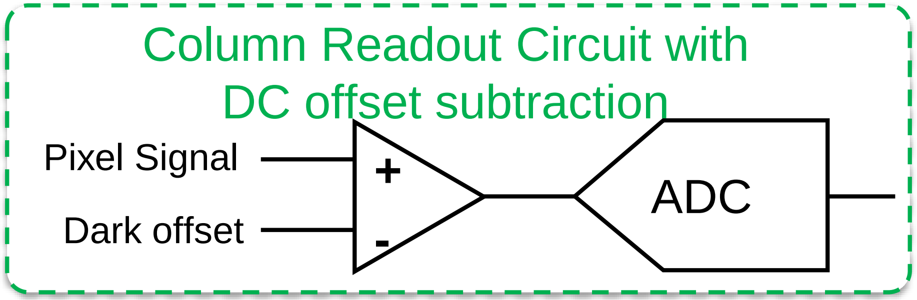
- Darker “black”
- No real improvement

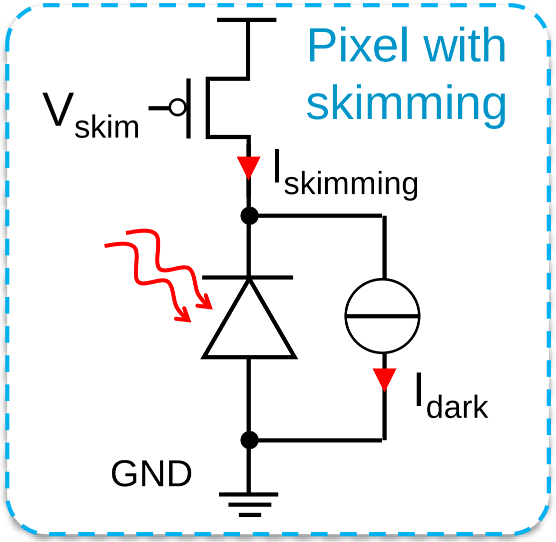
Radiation Hardening by Design (RHBD): Fighting Dark Current Increase

- Many DC subtraction techniques
  - Digital subtraction of an average offset
  - Dark frame subtraction
  - On-chip DC offset subtraction
  - In-pixel dark current skimming

➡ ***Do not reduce DC shot noise!***

- Not efficient against the early DR degradation
  - But can help keeping a sensor alive after having lost most of the Dynamic Range


Column Readout Circuit with DC offset subtraction


Pixel with skimming

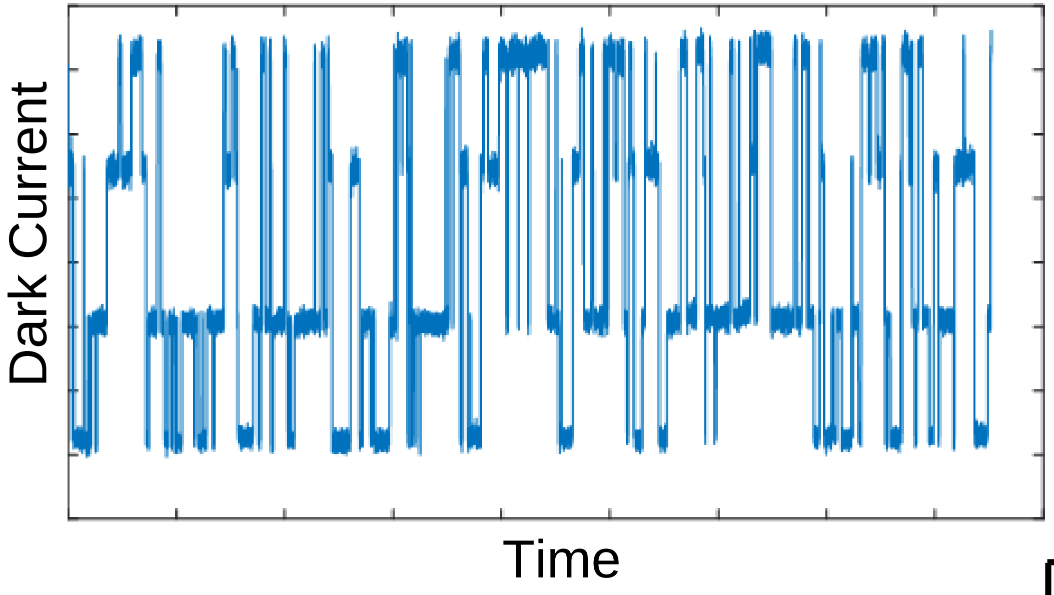
To keep a reasonable Dynamic Range

➡ The physical source must be **extinguished**

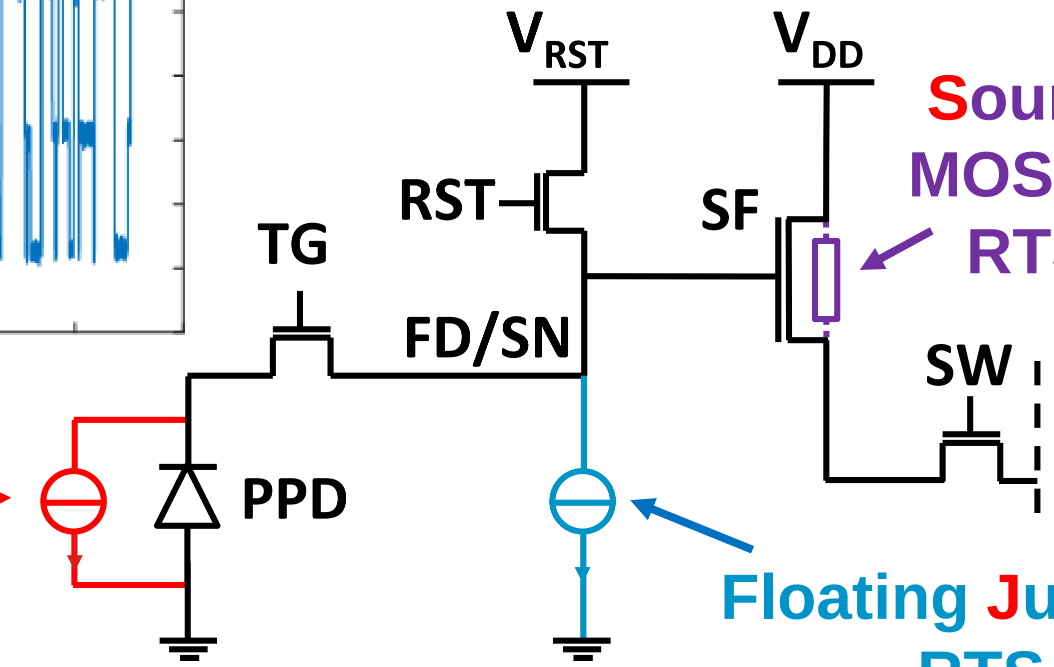
(not simply subtracted/compensated)

Random Telegraph Signal (RTS) Sources in CIS

- RTS = random discrete switching of signal offset
- 3 main sources of RTS in CMOS Image Sensors


Typical DC-RTS Trace

4T pinned photodiode pixel



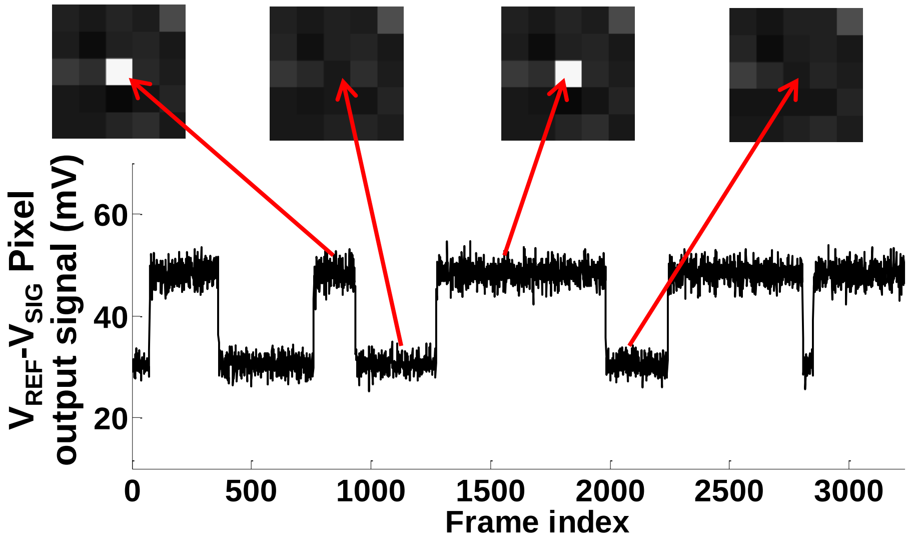
Source Follower MOSFET Channel RTS (SF-RTS)

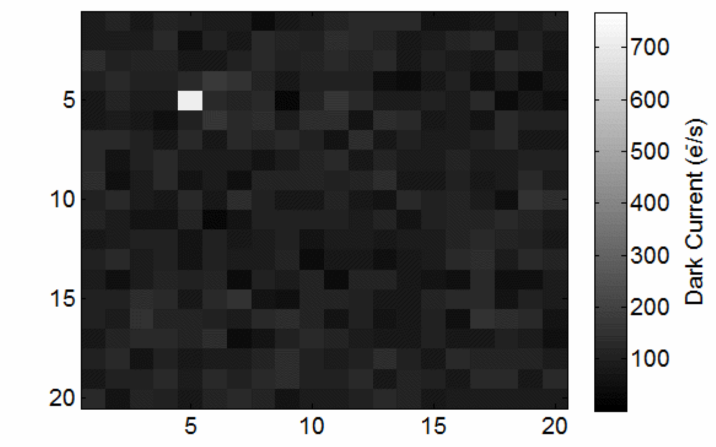
Dark Current RTS (DC-RTS)

Floating Junction Leakage RTS (JL-RTS)

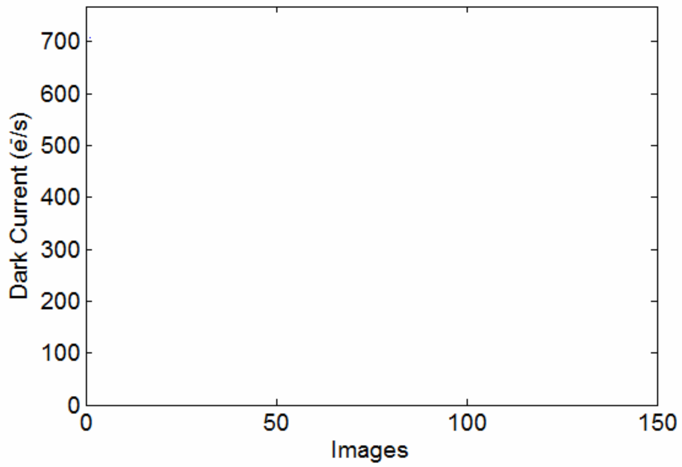
Dark Current Random Telegraph Signals (DC-RTS)

- Dark current is not always stationary
- In some particular pixels, it can randomly switch between several discrete levels leading to:
  - **Blinking pixels**
  - A dark current temporal trace that behaves like a **R**andom **T**elegraph **S**ignal (**RTS**)
- It is a major issue for high-end low light level applications
- Underlying physics is not clear





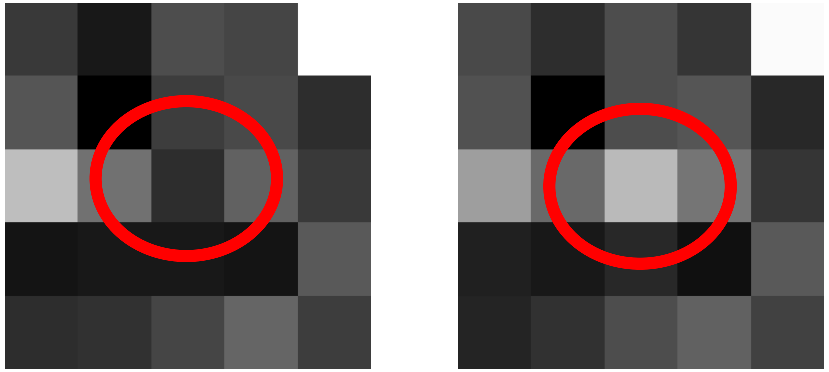
Courtesy of C. Durnez



DC-RTS After Dark Current Calibration

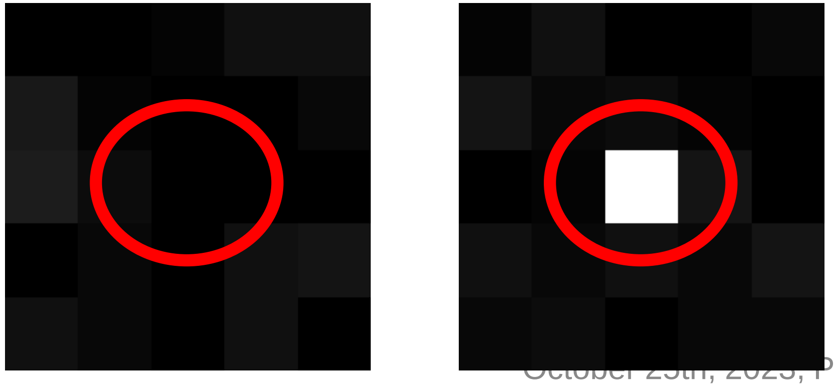
Even blinking pixels that are not “white pixels” (or bright/hot pixels) can be an issue

- **Raw dark frames :** $V_{\text{dark}}(t) = V_{\text{pix}}(t)$



The low amplitude blinking pixel is hardly visible

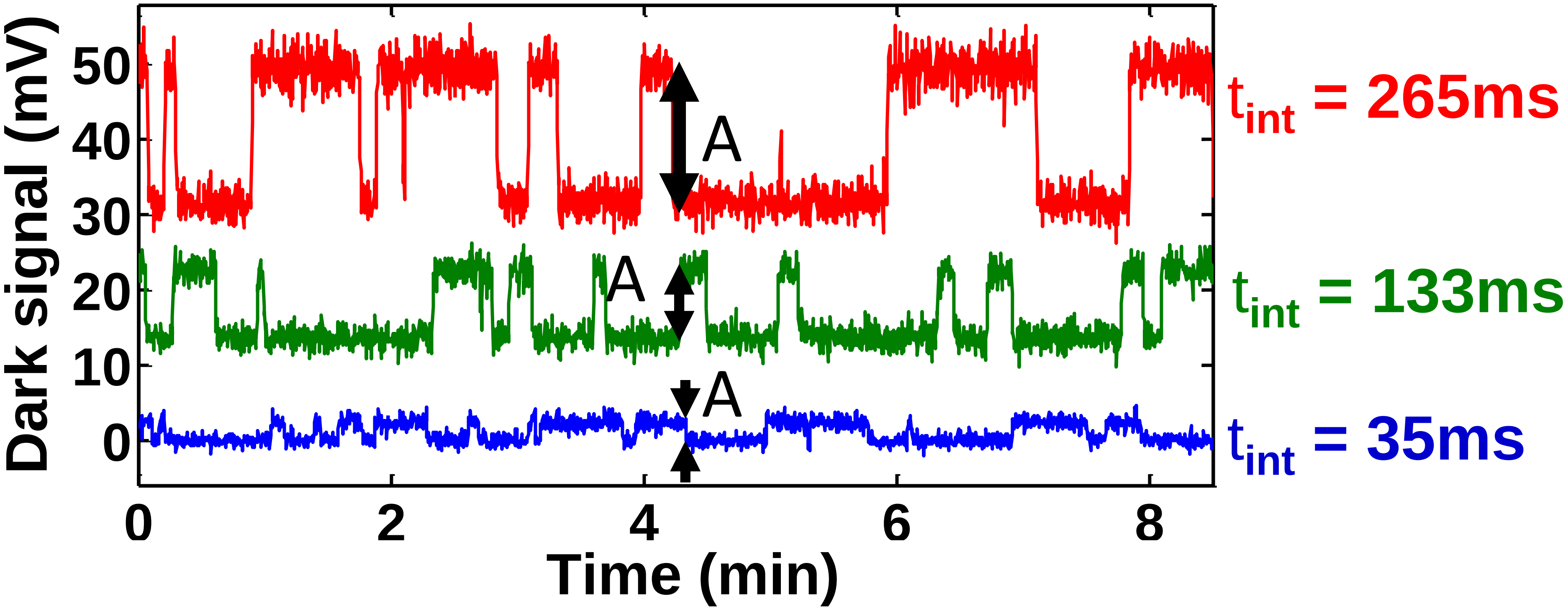
- **After average dark frame subtraction:** $V_{\text{dark}}(t) = V_{\text{pix}}(t) - \overline{V_{\text{pix}}}$ **(typical for high end applications)**



The low amplitude blinking pixel is clearly visible

DC-RTS : Effect of Integration Time

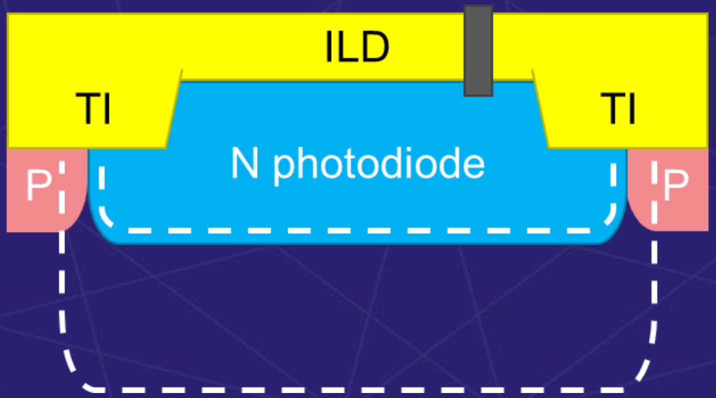
- **One RTS pixel output dark signal VS time (frames) for 3 different integration durations (t_{int}) :**



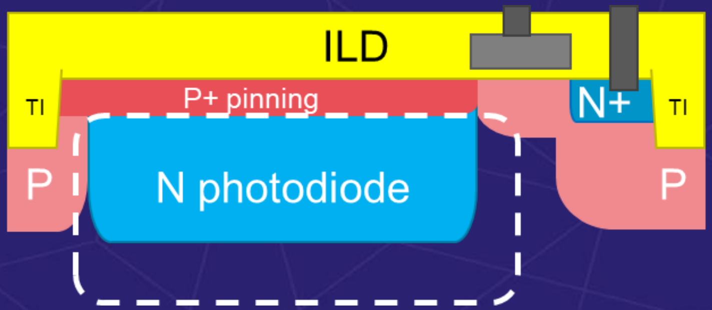
- **RTS behavior clearly recognizable**
- **RTS amplitude directly proportional to PD integration time**

Total Ionizing Dose (TID) effects on CIS

Part I :
Conv. Photodiode



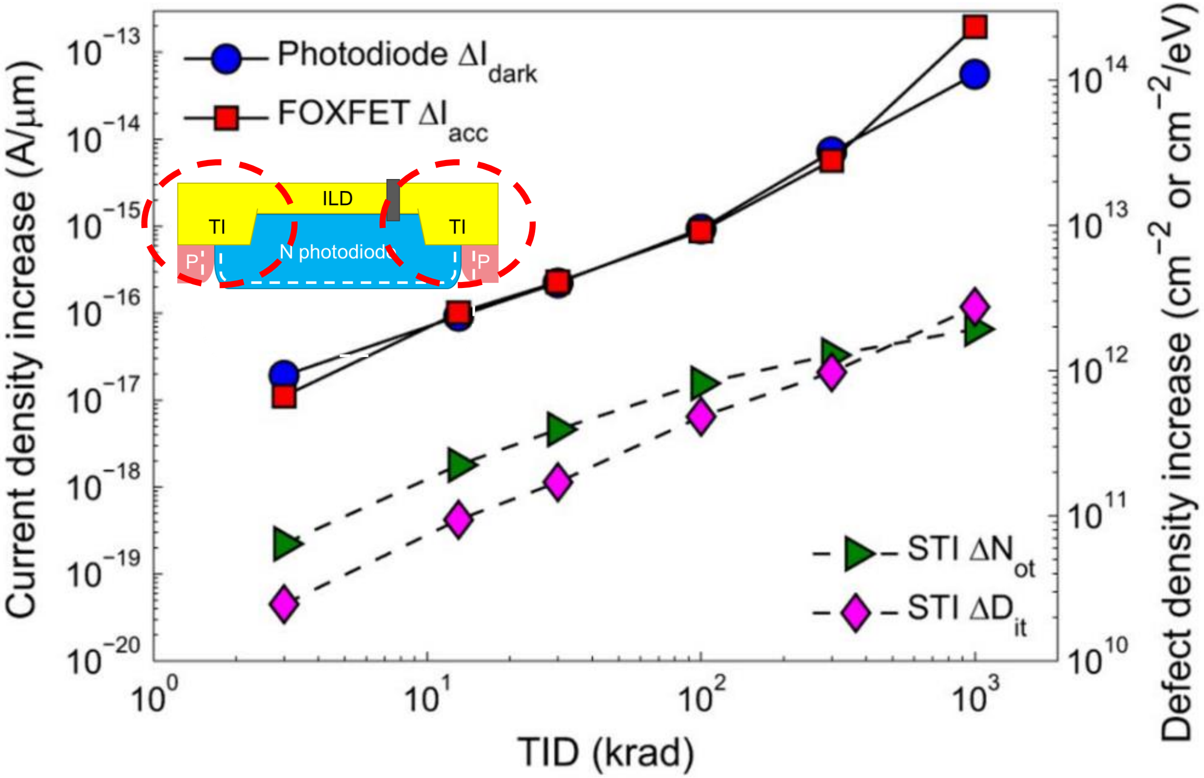
Part II :
Pinned Photodiode



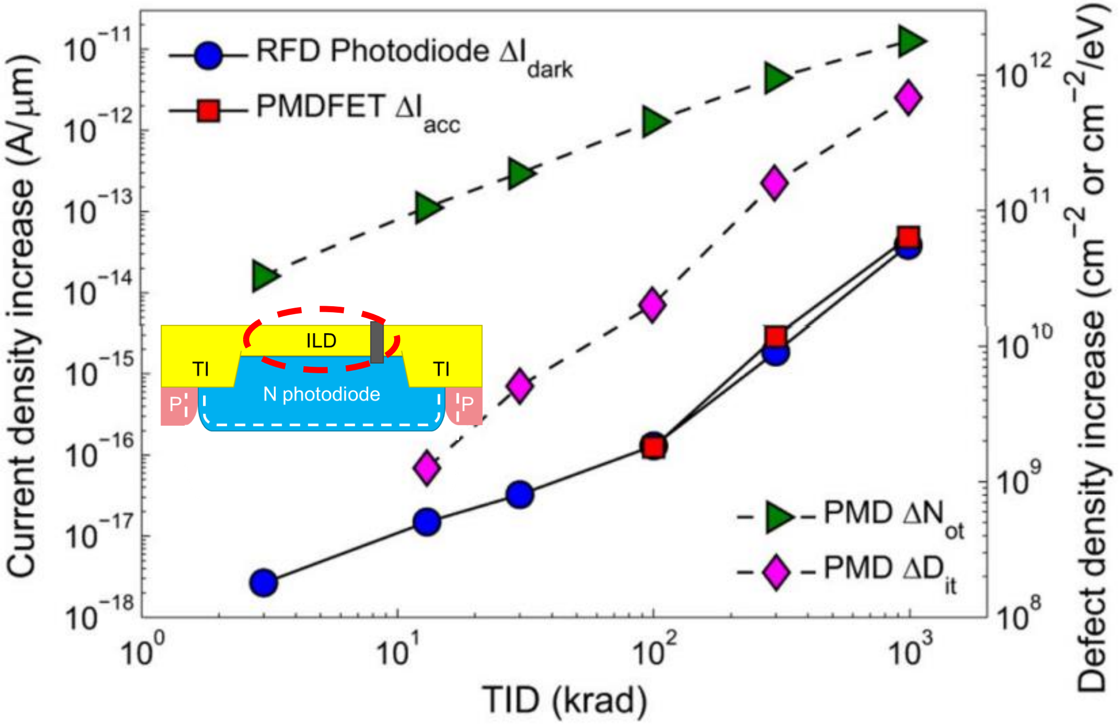
TID Induced Defect Densities in CIS Relevant Dielectrics

- As in MOSFET Gate Oxide, N_{it} and N_{ot} rise with TID in photodiode oxides

Peripheral Oxide (STI)



Top Oxide (ILD/PMD)

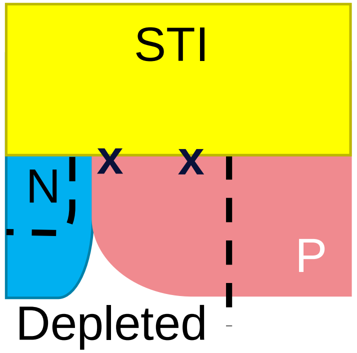


Goiffon, V., Virmontois, C., Magnan, P., Girard, S., & Paillet, P. (2010). Analysis of total dose-induced dark current in CMOS image sensors from interface state and trapped charge density measurements. IEEE Transactions on Nuclear Science, 57(6), 3087-3094.

TID Effects in Conventional Photodiodes

≈ 0-100 krad

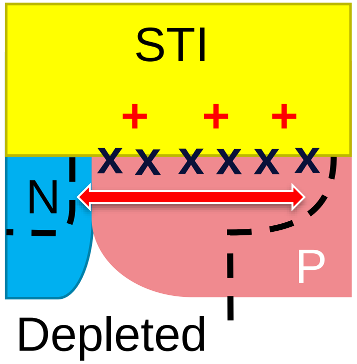
Dark current increase ($\propto N_{it}$)



≈ 50 krad - 5 Mrad

- Dark current increase (N_{it})
- Depleted interface extension (N_{ot})

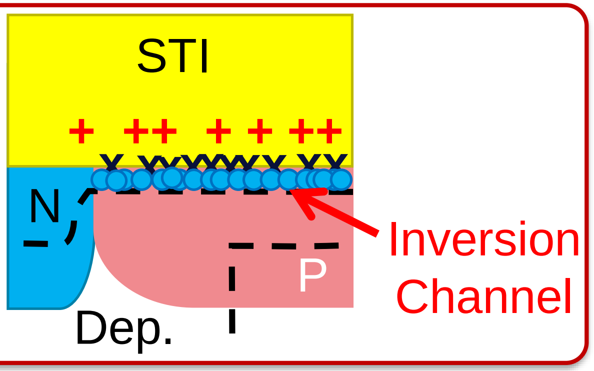
➡ Faster DC increase



> 1-10 Mrad

STI inversion (N_{ot})

➡ Short Circuits

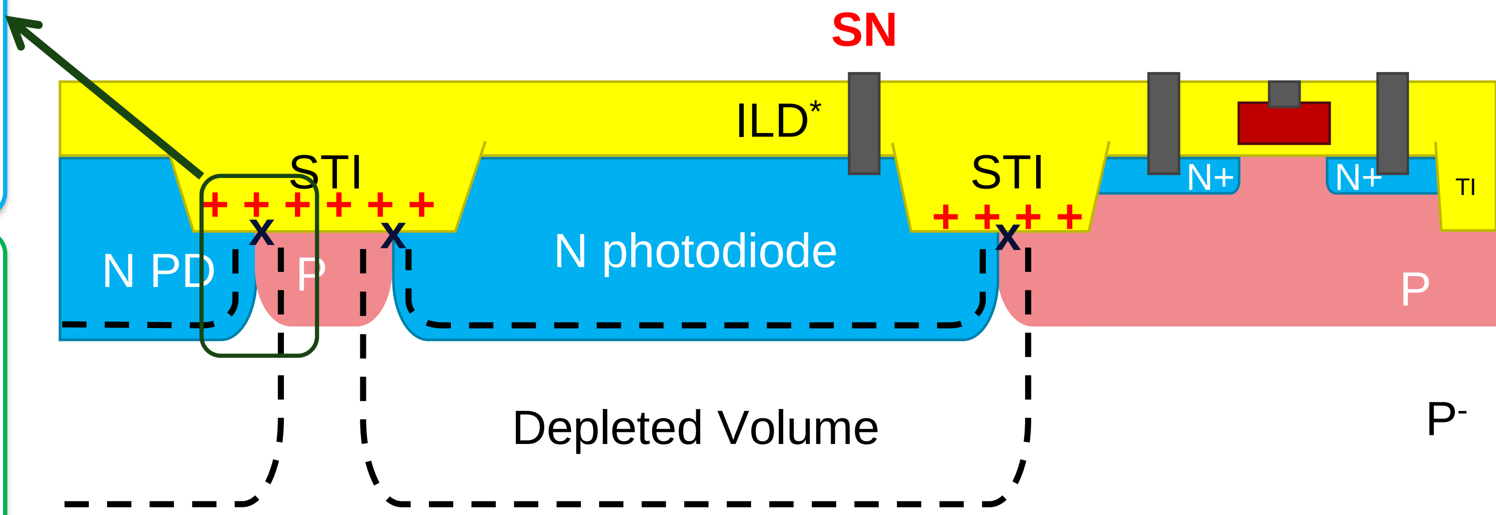


+ : Oxide Positive Trapped Charge (N_{ot})

x : Interface Trap (N_{it})

**STI = Shallow Trench Isolation*

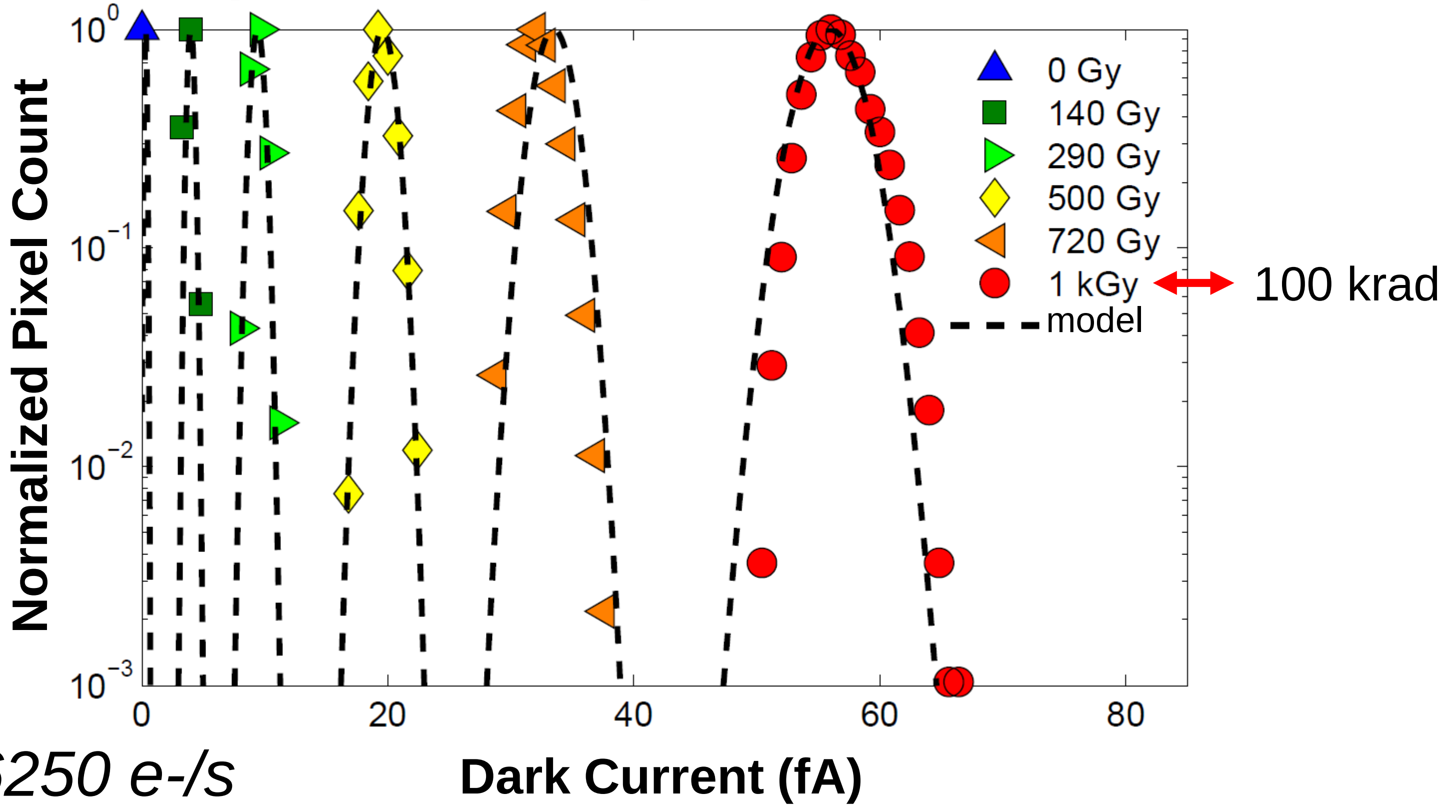
**ILD = Inter Layer Dielectric*



- Main Issues
  - **Dark current increase**
  - Short circuit at high TID

Radiation Induced Dark Current Increase in Conv. Photodiode: Illustration

Distribution of dark current values over an entire pixel array exposed to TID

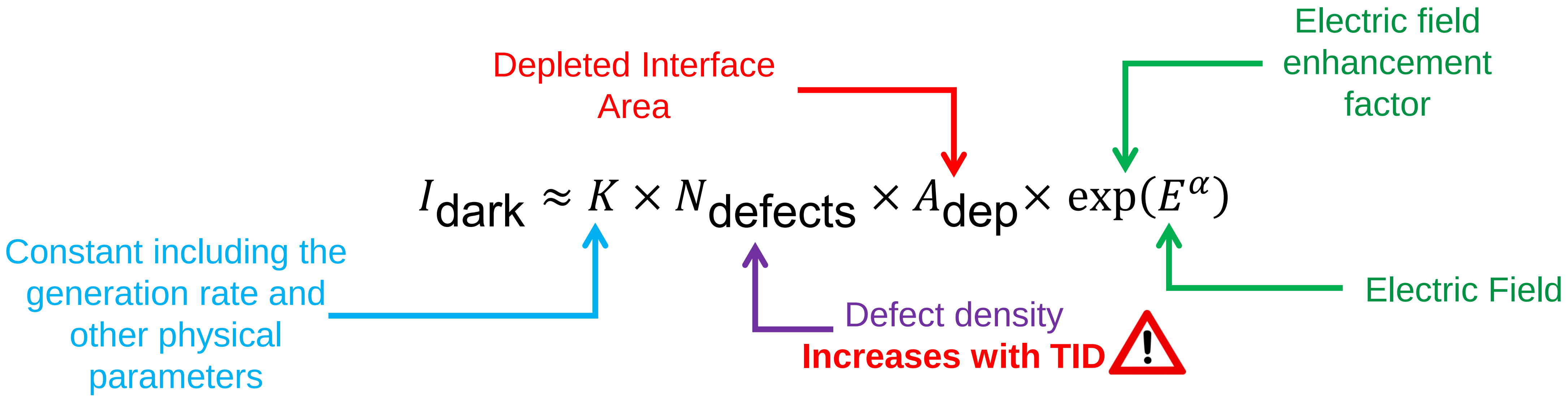


1 fA = 6250 e-/s

Dark current turns dark images into gray or even white saturated images

Turning Off TID induced DC: Golden Rule

- Simplified CIS SRH Dark Current equation



$$I_{\text{dark}} \approx K \times N_{\text{defects}} \times A_{\text{dep}} \times \exp(E^{\alpha})$$

Depleted Interface Area

Electric field enhancement factor

Constant including the generation rate and other physical parameters

Defect density

Increases with TID ⚠

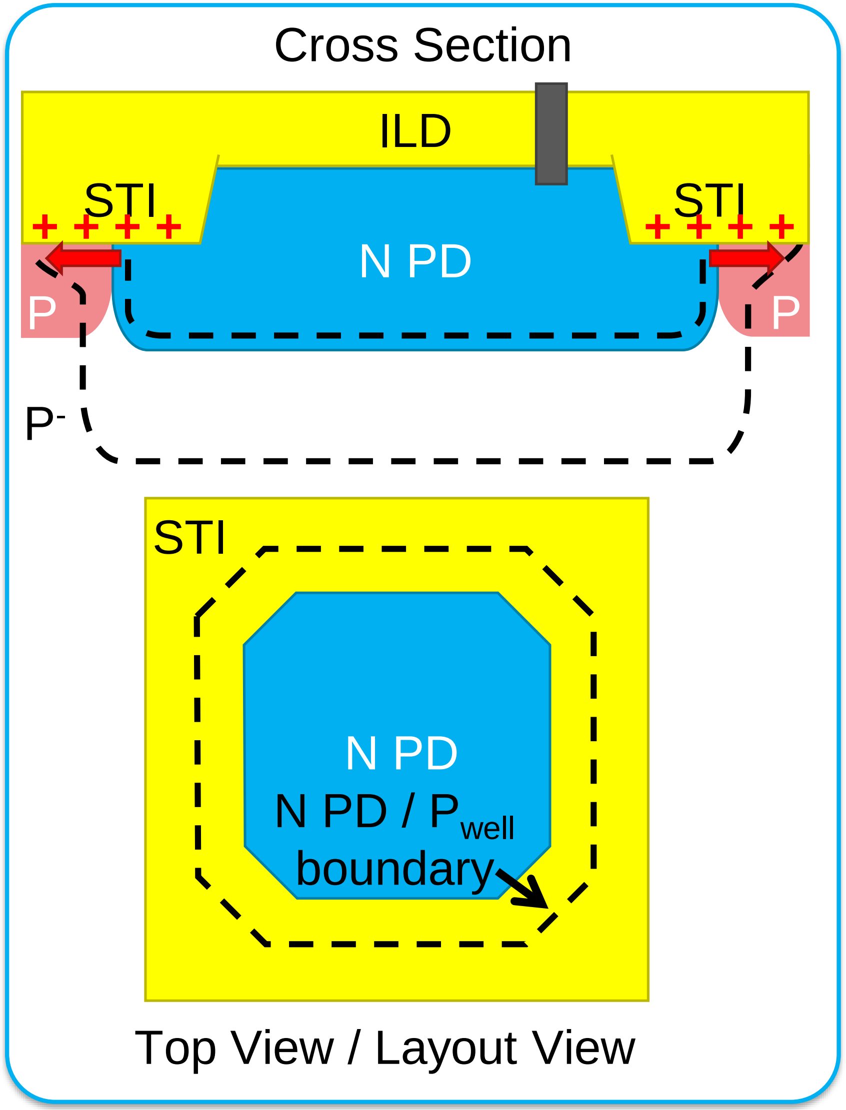
Electric Field

To improve the radiation hardness of CIS conventional PD:

1. Lower the Electric Field magnitude E
2. Reduce the depleted interface area A_{dep}
3. Must stays true when TID ↗
4. (cannot prevent $N_{\text{defects}} = N_{\text{it}}$ from rising)

Conventional Photodiode RHBD Technique:

Standard Layout

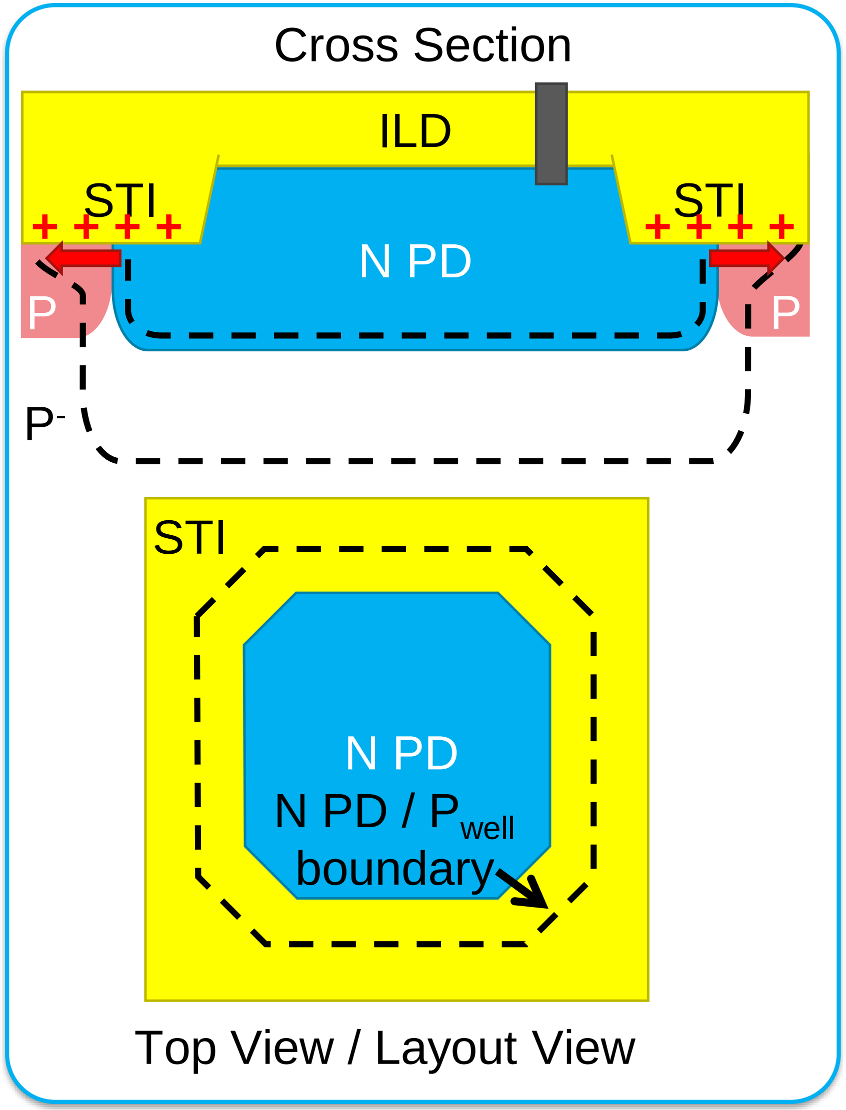


- **The problem**: TID induced N_{ot} in the STI extends the depleted interface A_{dep}

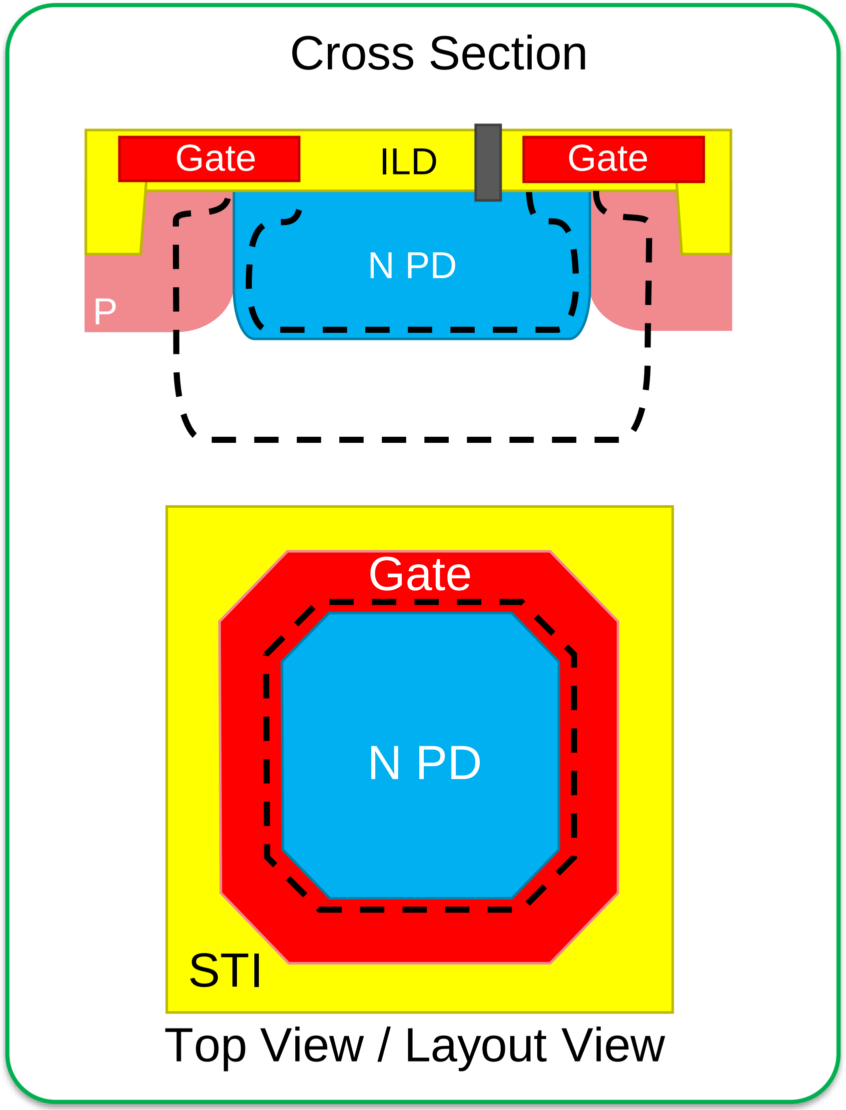
- **One solution:** get rid of the peripheral thick oxide
  - One way of doing that is to surround the photodiode by a thin gate oxide and polysilicon gate (see next slide)

A Selected RHBD Option: The Gated Photodiode

Standard Layout



Gated Photodiode Design



Pros

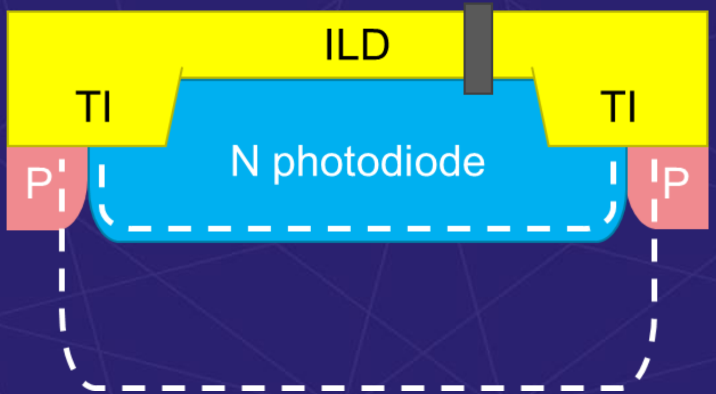
- ✓ Very efficient

Cons

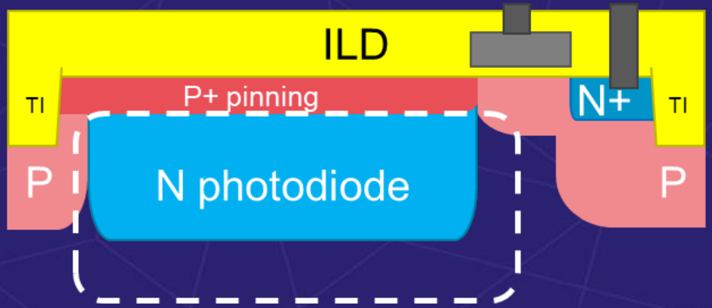
- ✗ Higher prerad current if no process optimization
- ✗ Tricky to optimize
- ✗ Violate design rules

Total Ionizing Dose (TID) effects on CIS

Part I :
Conv. Photodiode



Part II :
Pinned Photodiode

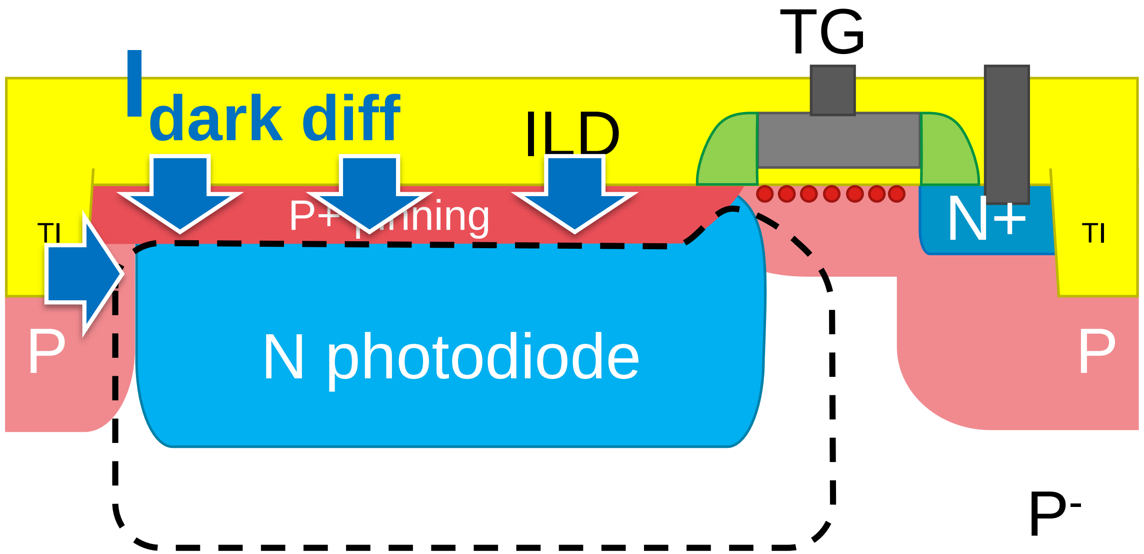


Low TID Effects on PPD

- Low TID ≈ 0-100 krad → Interface Trap Density Increase

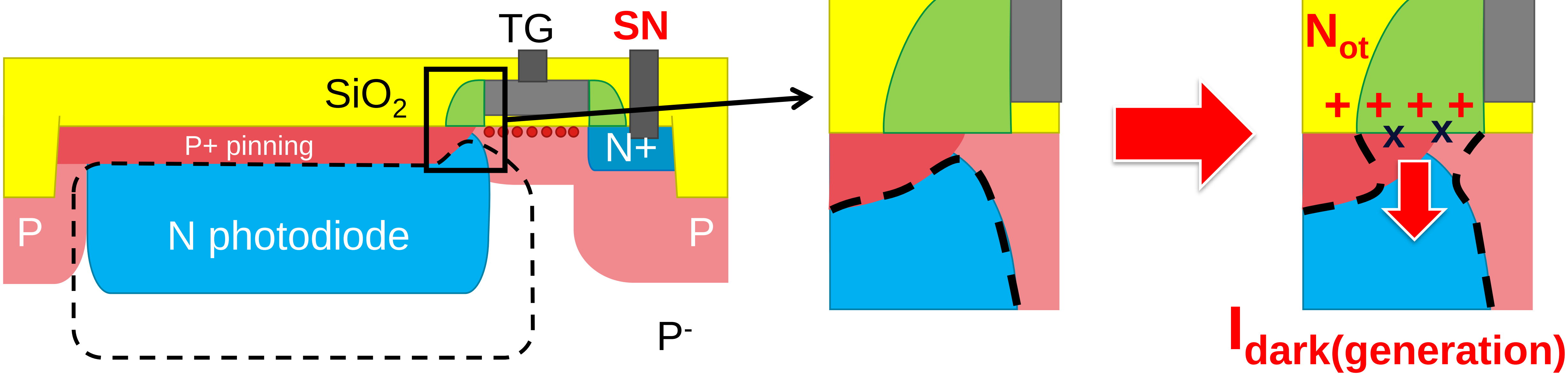
↓

Interface Diffusion Dark Current Increase



High TID Effects on PPD

- High TID > 100 krad → **Spacer Interface Depletion**



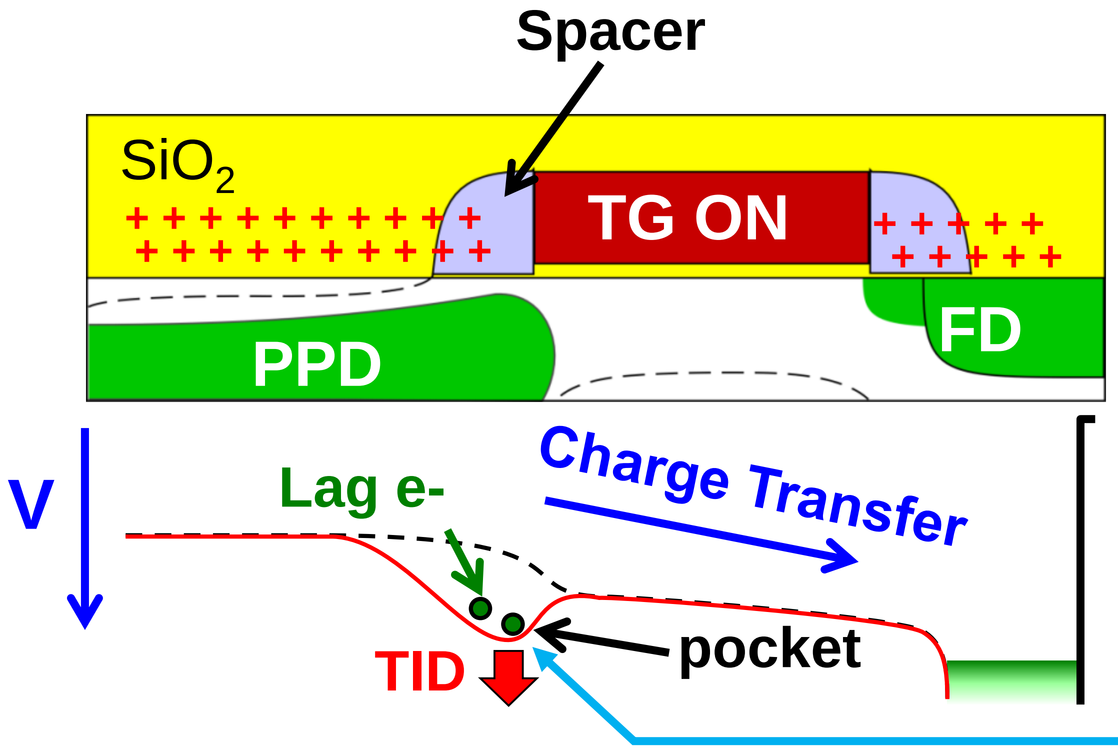
- Generation dark current from depleted interface

➔Faster Dark Current Increase

- Signal e- can be trapped in the created potential pocket

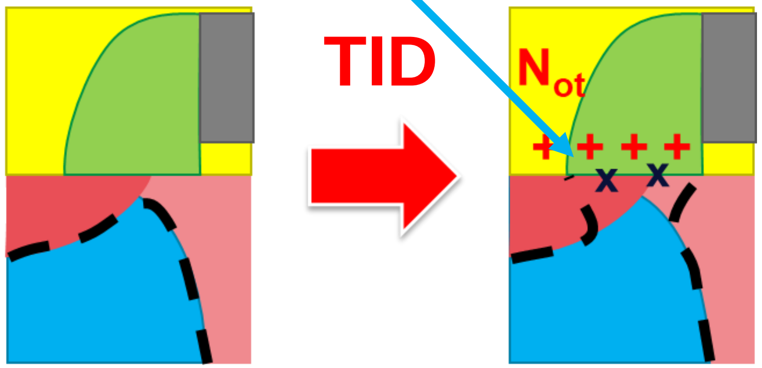
➔Charge Transfer Degradation

PPD Transfer Degradation

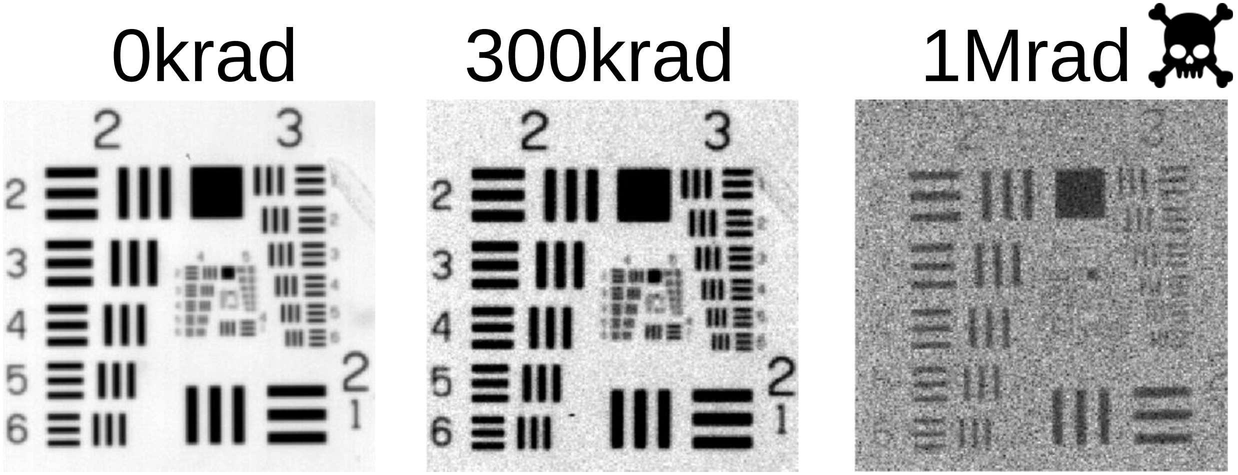


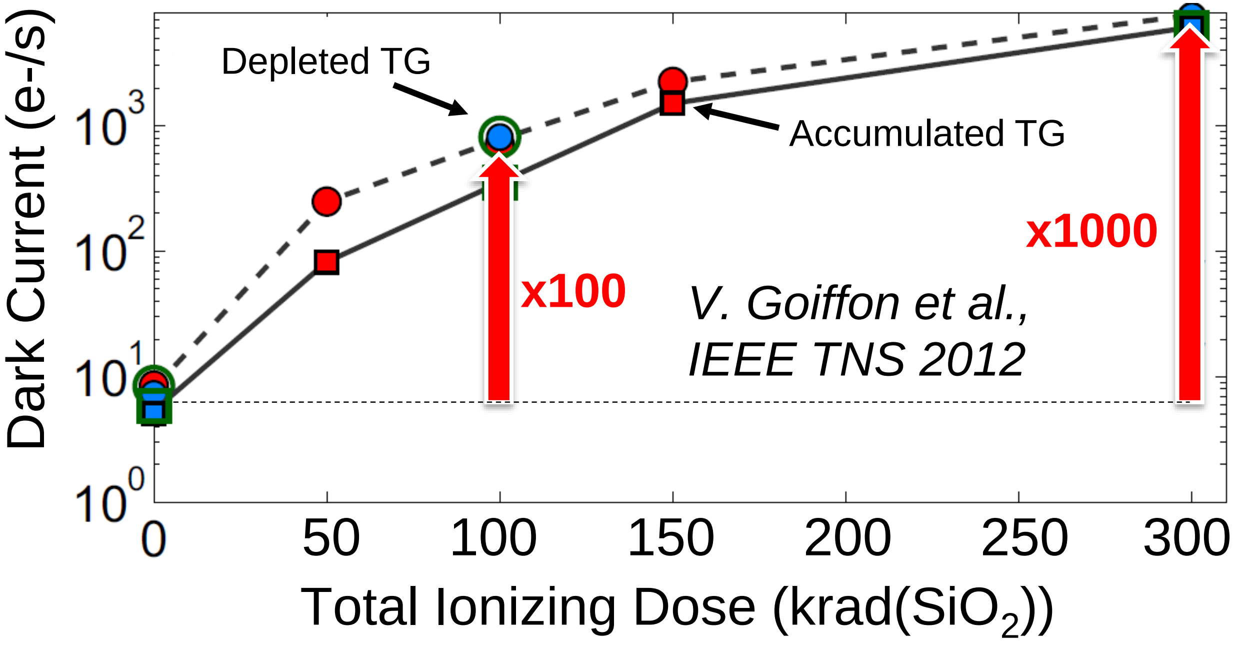
- SiO_2 trapped charge increases the potential in the PPD, especially below the spacer (lower P doping concentration)

- It creates a potential pocket that retains signal charges and increases the Charge Transfer Inefficiency (CTI)

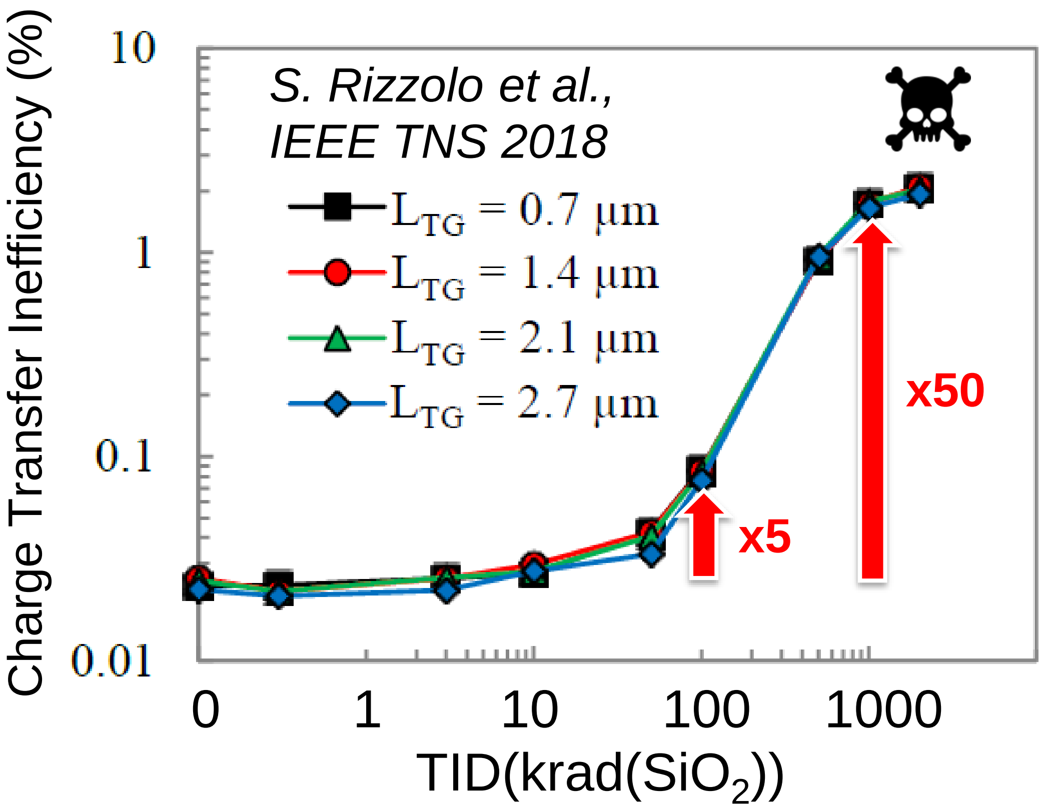


TID Effects on Pinned Photodiode Orders of Magnitude





V. Goiffon et al.,
IEEE TNS 2012



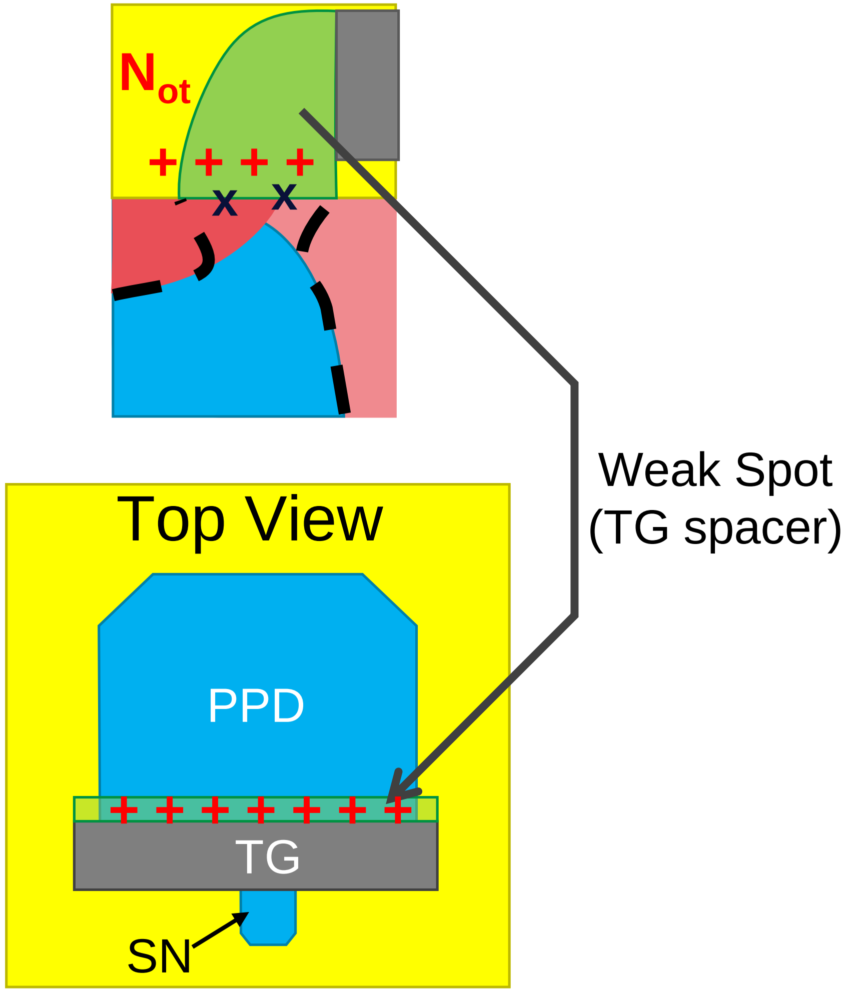
S. Rizzolo et al.,
IEEE TNS 2018

5X degradation @ 100 krad
50X degradation @ 1 Mrad

TID Effects on PPD: RHBD?

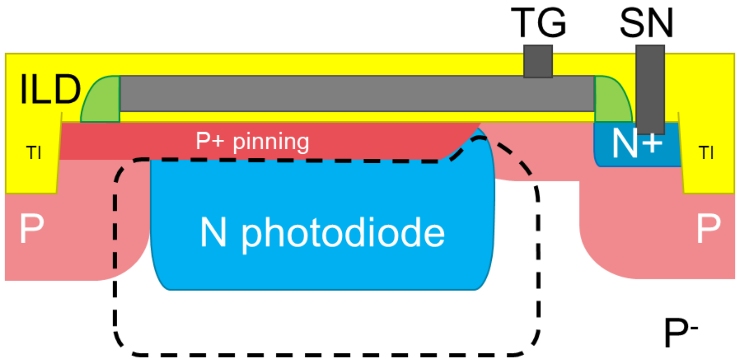
- Weak Spot = Transfer Gate Spacer
- Not much can be done by design
- Good practice:
  - Avoid wide Transfer Gates
  - Avoid adding extra Transfer Gates
    - e.g. anti blooming gates

Planar Pinned Photodiodes are not (yet?) suitable for high and ultra high TID applications



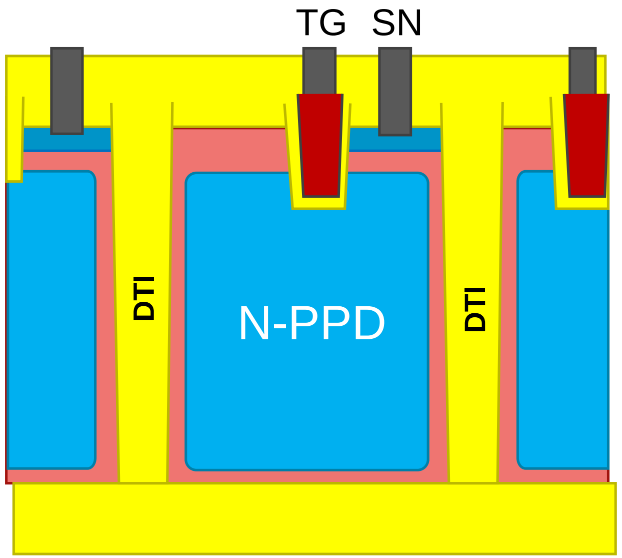
PPD Radiation Hardening by Process Modification/Evolution

PPD fully covered by the Transfer Gate
(no more spacer issue)



- ✓ Transfer Degradation mitigated
- ✓ High TID DC increase mitigated
- ✗ Radiation induced diffusion dark current not mitigated
- ✗ Requires a process modification
- ✗ Technology not available / developed / tested

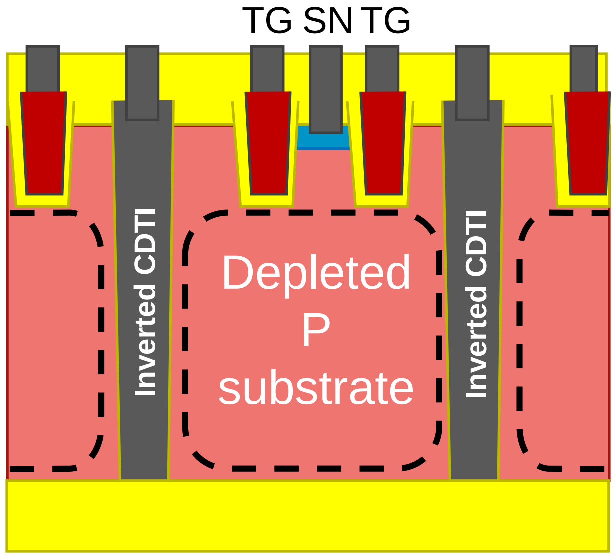
Vertical PPD + Vertical TG



- ✓ Mature technology (in your smartphone)
- ✓ Spacer issue mitigated
- ✗ Radiation induced diffusion dark current not mitigated
- ✗ New radiation effects can be expected
- ✗ Small pixel pitch only

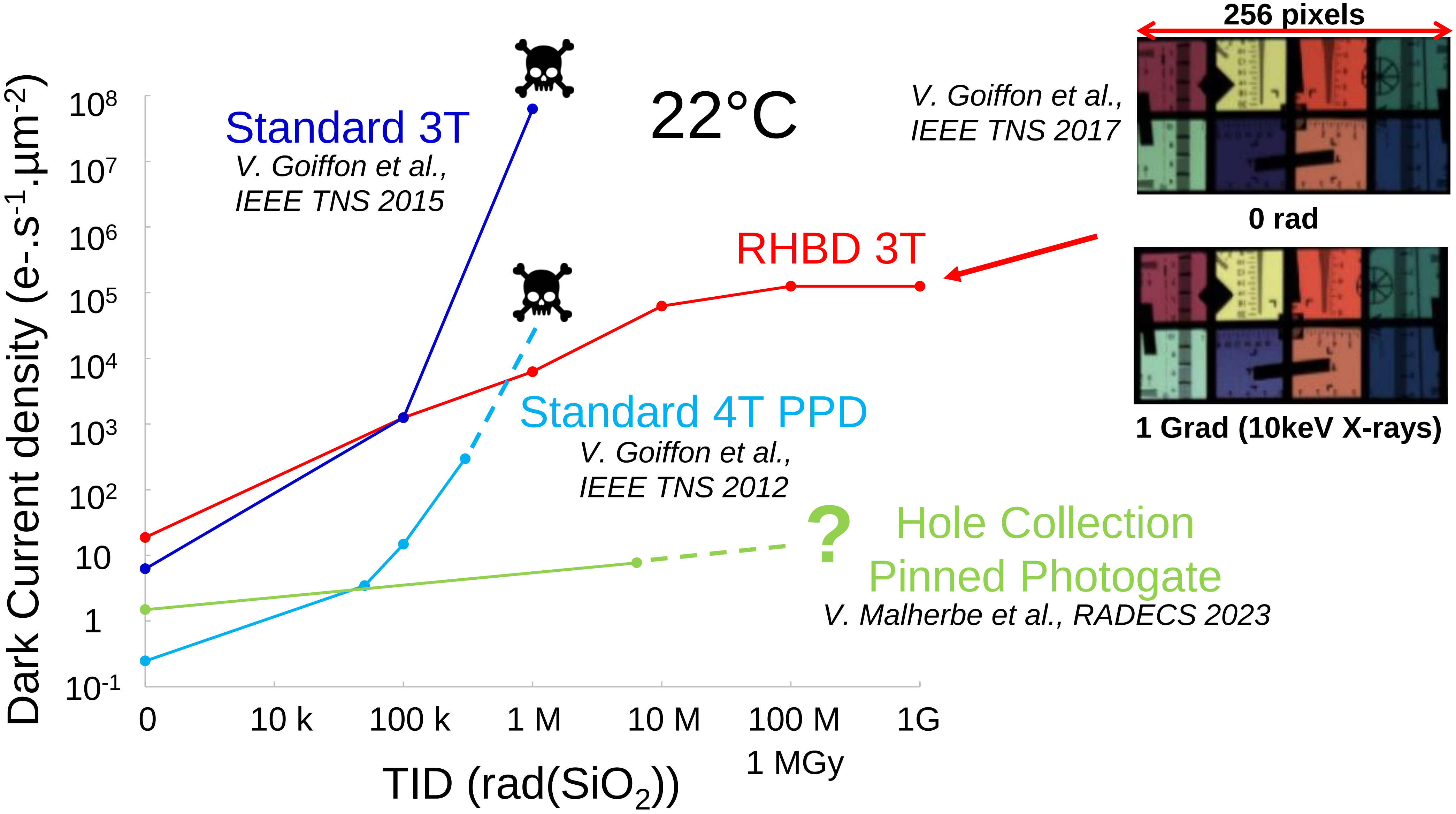
Hole Collection Pinned Photogate

R. Roy, mdpi Sensors 2020
V. Malherbe et al., IEEE TNS 2022,
A. Antonsanti et al. IEEE TNS 2023



- ✓ Mitigate all the PPD issues
- ✗ Requires a dedicated process

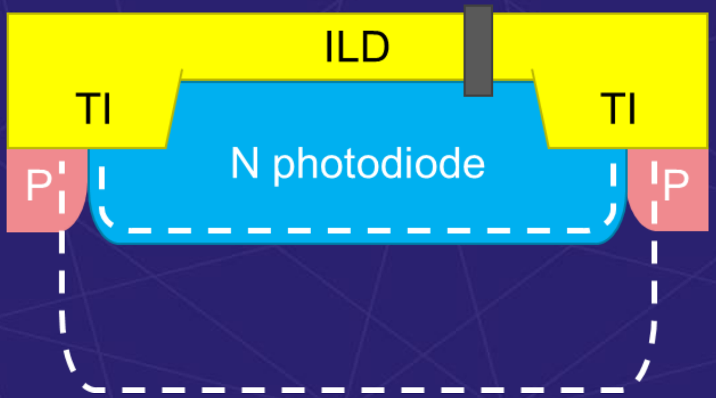
Illustration of the TID Radiation Hardness of CIS



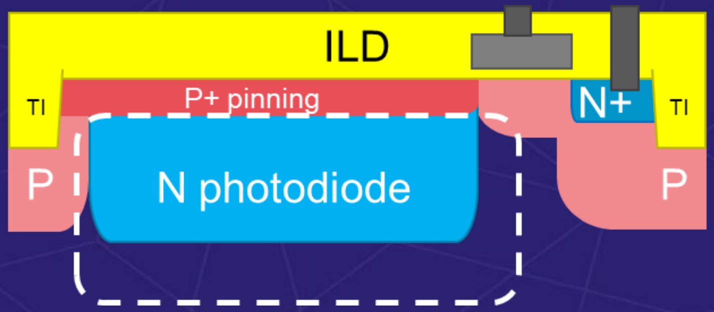
Total Ionizing Dose (TID) effects on CIS

Part III : Common Effects

Part I :
Conv. Photodiode

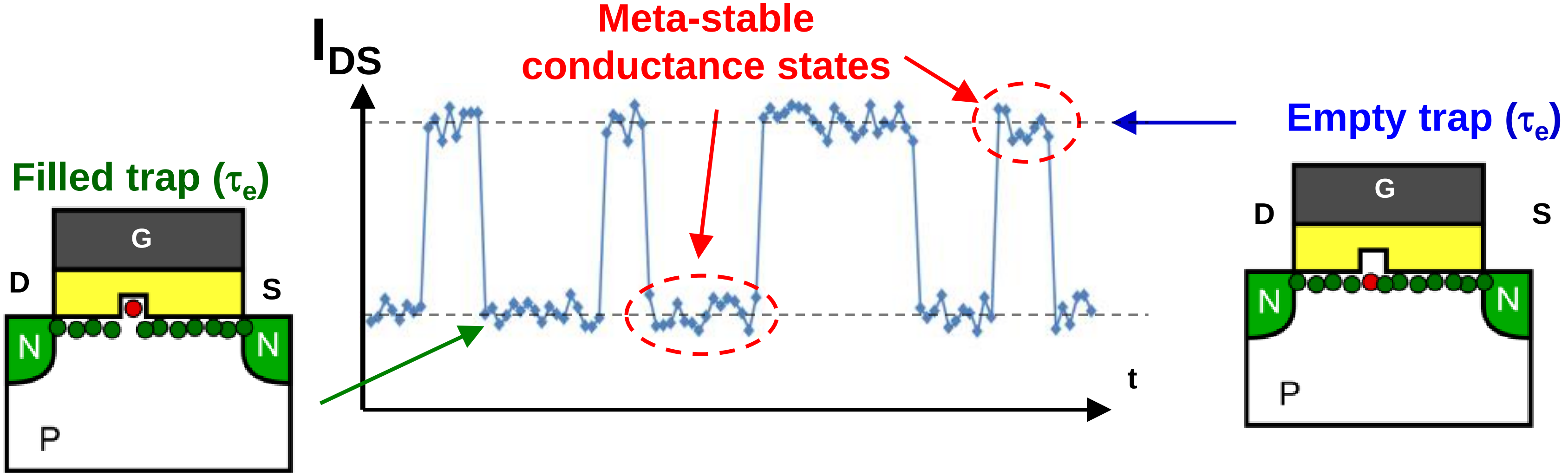


Part II :
Pinned Photodiode



TID Effect on MOSFET Channel RTS

- Origin of MOSFET Channel RTS:
  - Trapping and emission of a **single** channel carrier (electron or hole)
  - Modulation of the channel conductance

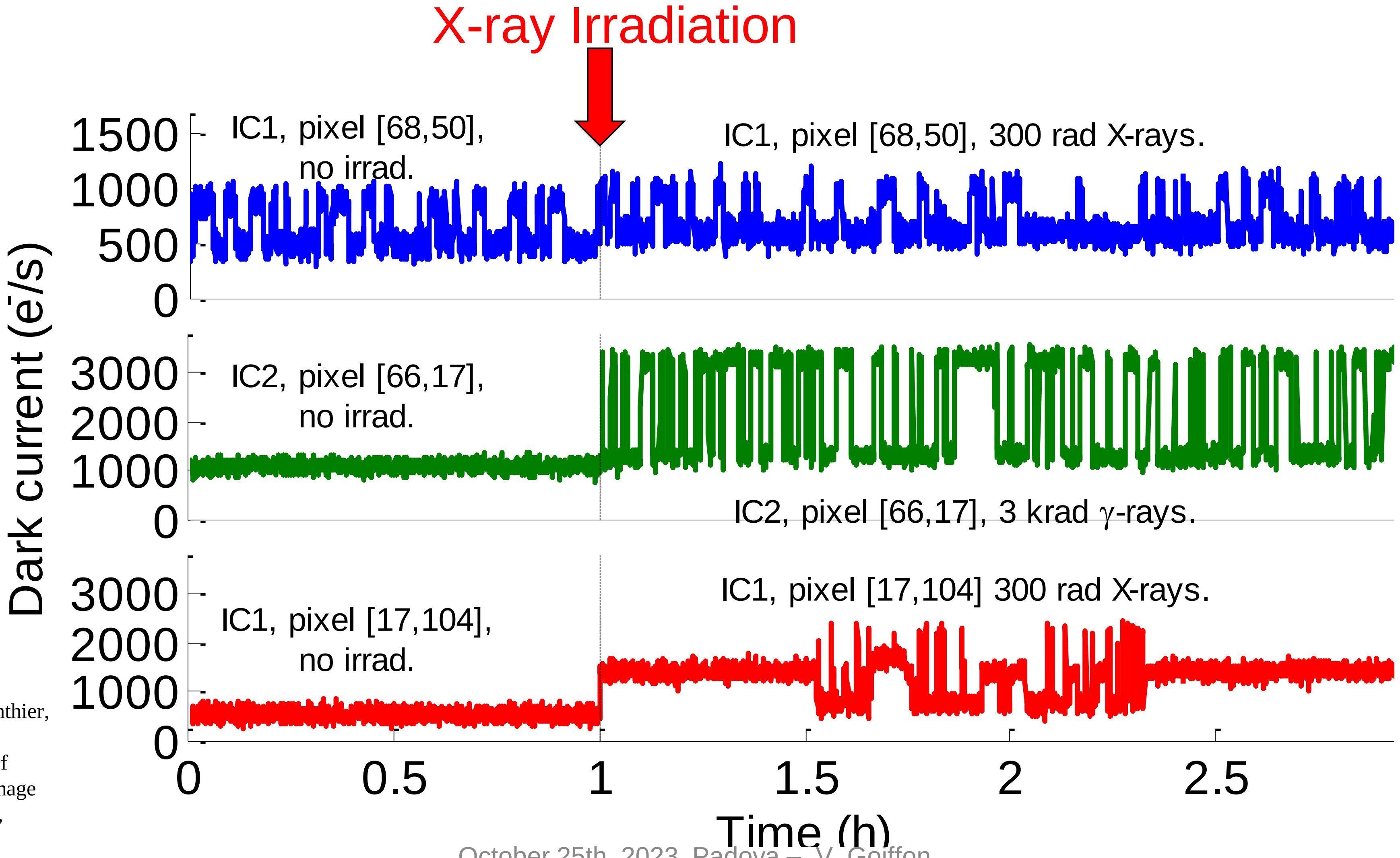


- In CMOS Image Sensors, even at TID as high as 1 Mrad (i.e. 10-100x typ. space doses): no obvious evolution of this noise

Ionizing Radiation does not seem to increase this RTS

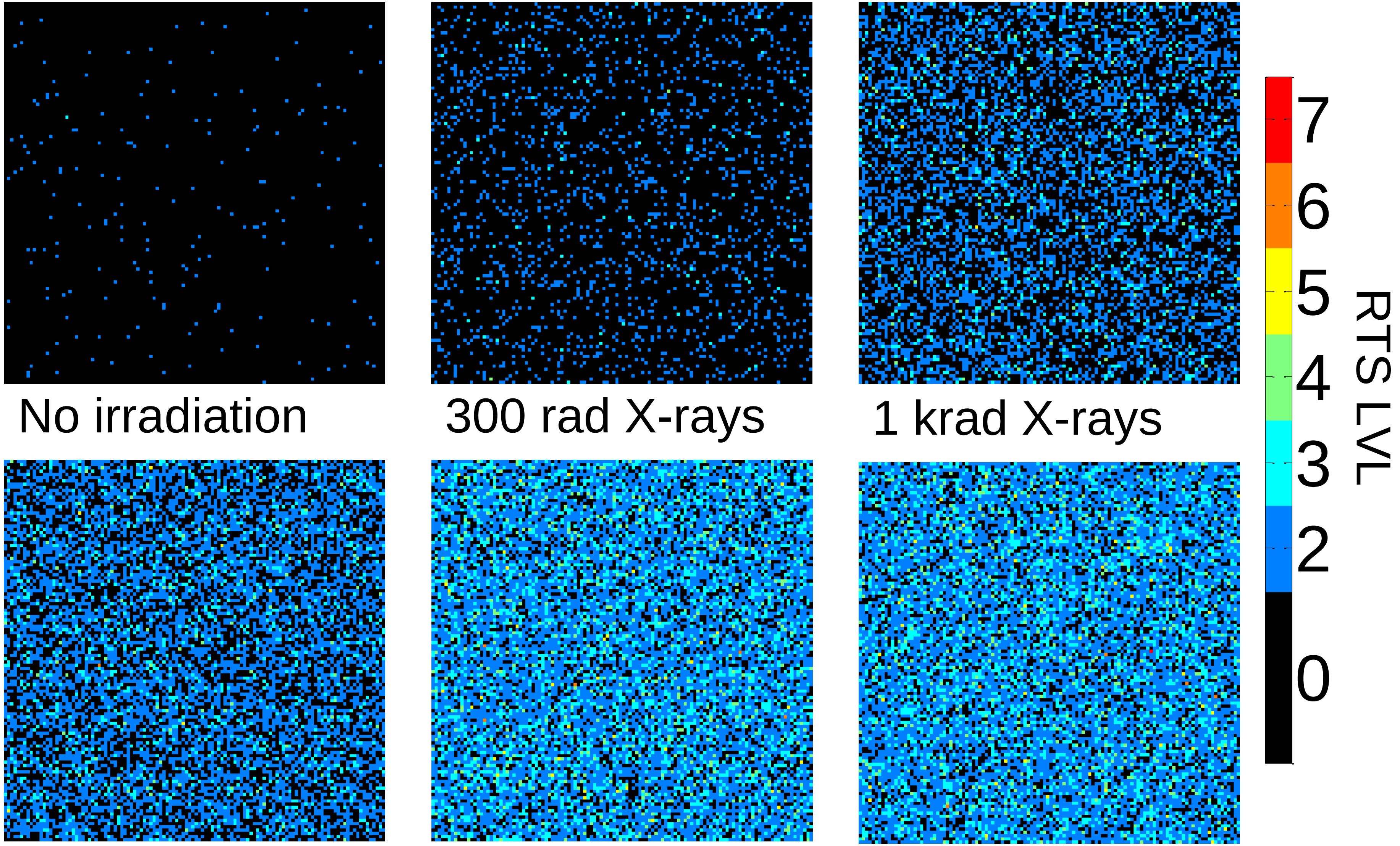
TID induced DC-RTS

- Ionizing Radiation (TID) **create DC-RTS center** in image sensor pixels!



Goiffon, V., Magnan, P., Martin-Gonthier, P., Virmontois, C., & Gaillardin, M. (2011). Evidence of a novel source of random telegraph signal in CMOS image sensors. IEEE electron device letters, 32(6), 773-775.

TID Induced DC-RTS



No irradiation

300 rad X-rays

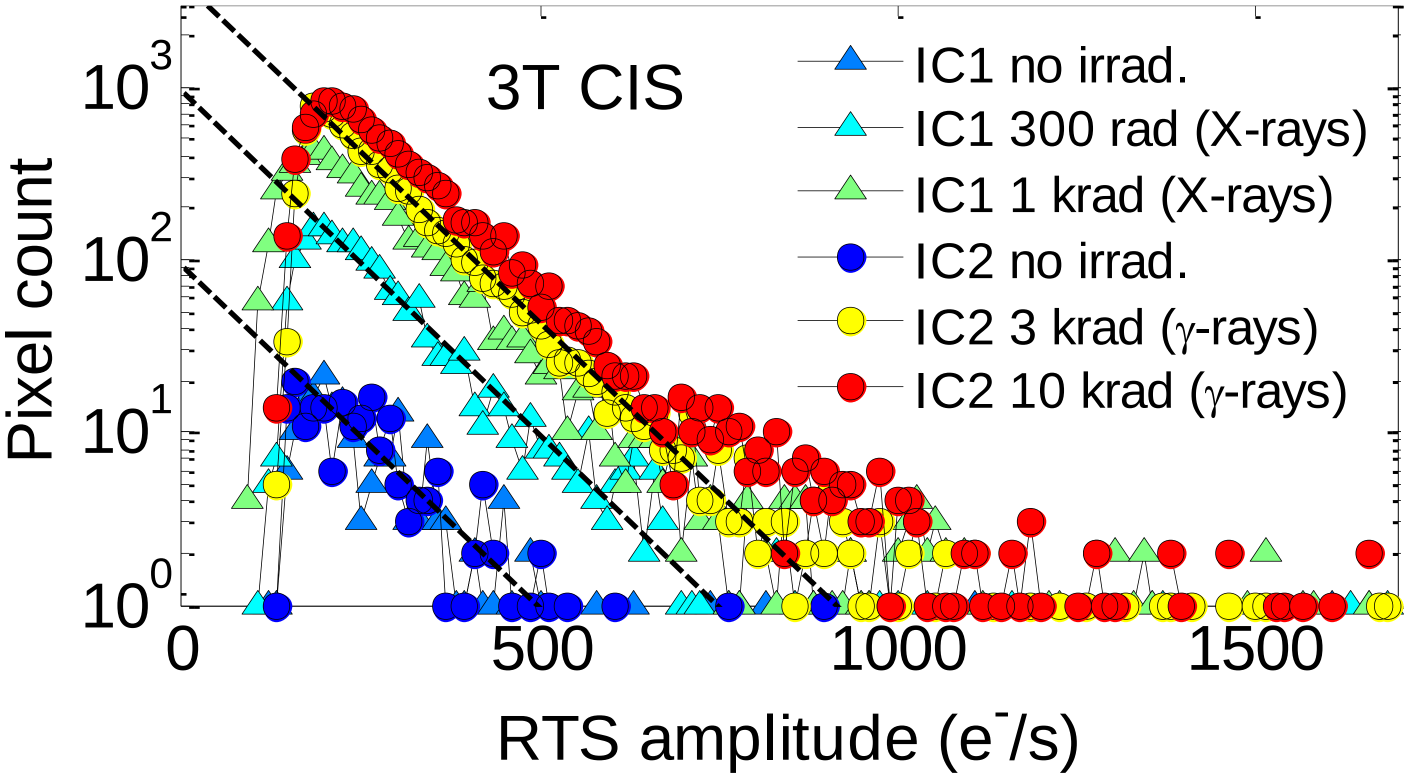
1 krad X-rays

3 krad γ-rays

10 krad γ-rays

30 krad γ-rays

TID Induced DC-RTS Amplitude Distribution

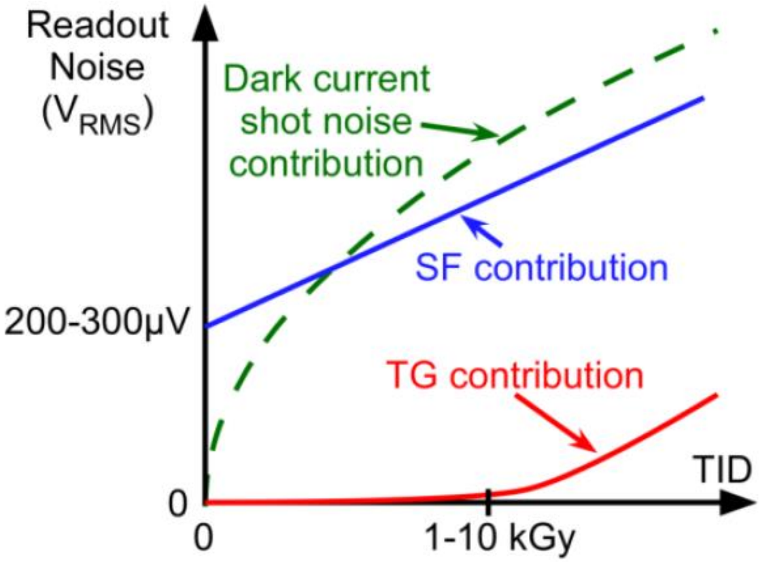


Goiffon, V., Magnan, P., Martin-Gonthier, P., Virmontois, C., & Gaillardin, M. (2011). Evidence of a novel source of random telegraph signal in CMOS image sensors. IEEE electron device letters, 32(6), 773-775.

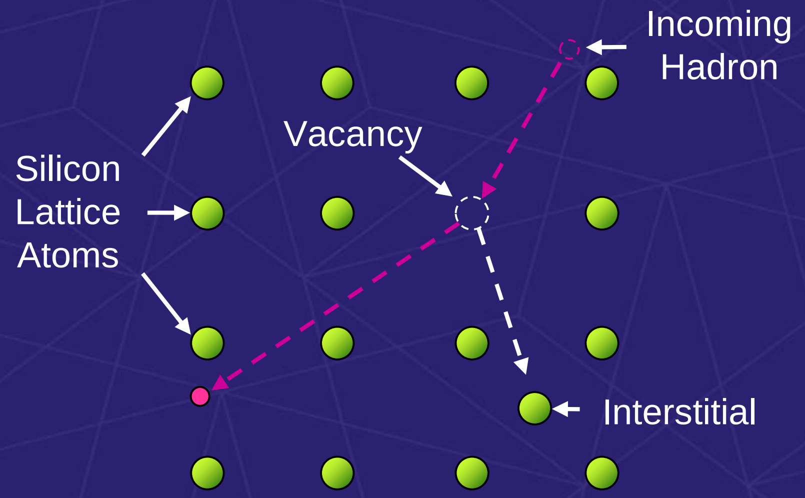
- **TID induced DC-RTS amplitudes** are exponentially distributed:
  - ➔Oxide DC-RTS mean amplitude ≈ 110-120 e-/s
- **RTS** Amplitudes increase exponentially with temperature with $E_a \approx 0.6$ eV
- Ionizing radiation generates efficiently **DC-RTS** centers at depleted Si/SiO$_2$ interfaces

Other secondary radiation effects in CIS

- TID induced **Quantum Efficiency** (QE) degradation
  - Generally very weak effect due to increased surface recombination mainly impacting blue/near UV QE at high TID
- TID induced **Full Well Capacity** (FWC) Variation
  - Generally negligible /can slightly increase or decrease depending on the pixel architecture/operating point
- TID induced **Noise** increase
  - Mainly the Source-Follower noise and the dark current shot noise
- TID induced **Sense Node Leakage** (and **RTS**)
  - Could be a major issue for global shutter applications, even at low TID *(Le Roch et al. IEEE Transactions on Nuclear Science, 66(3), 616-624.)*
- In-Pixel RTS MOSFET **subthreshold leakage**
  - Can degrade the performances even at low TID if subthreshold operation is used

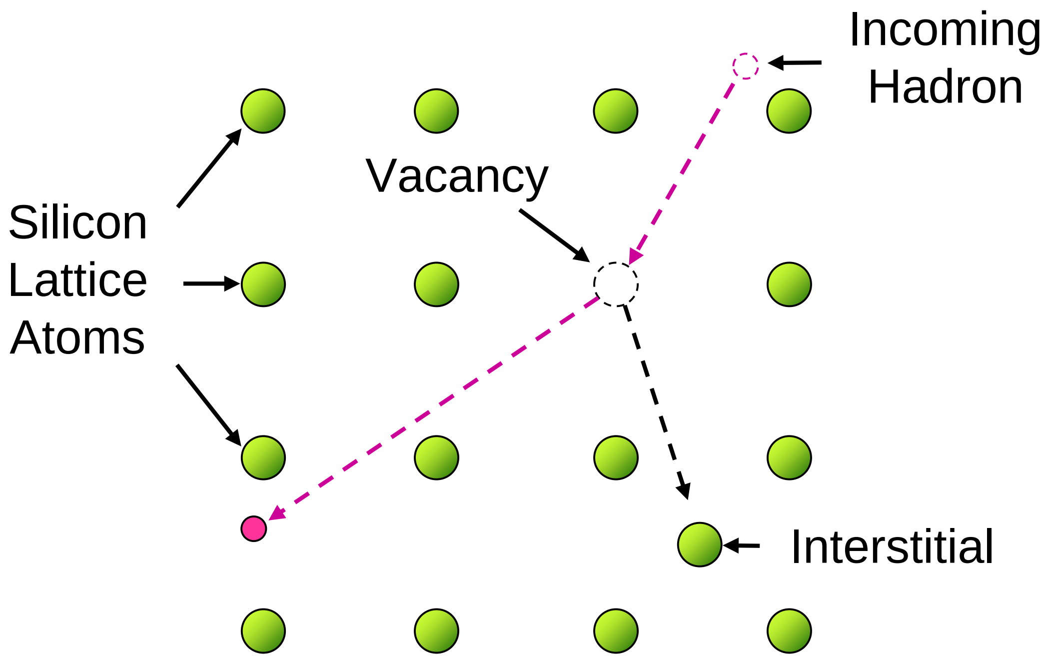


Displacement Damage Effects



Displacement Damage (DD)

- Energetic hadrons (e.g. neutrons, protons, ions…) can transfer part of their energy by displacing atoms from the semiconductor lattice



Incoming Hadron

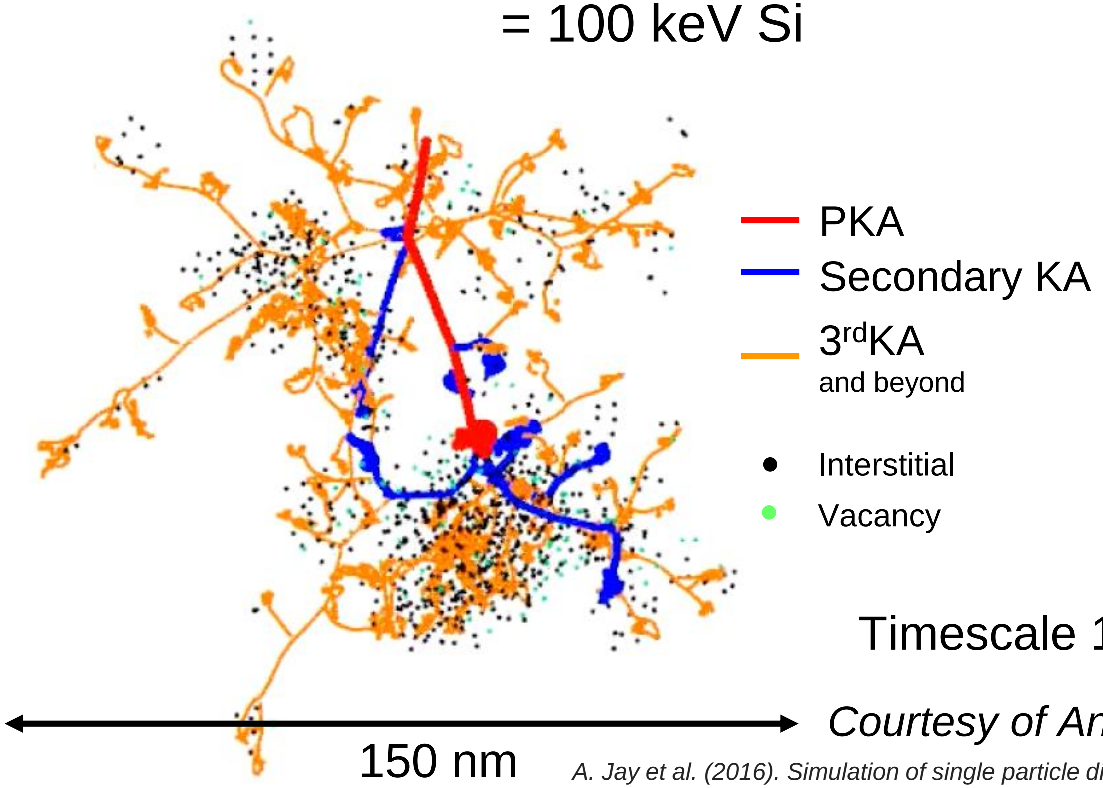
Vacancy

Silicon Lattice Atoms

Interstitial

DD Atomic Scale Simulation

Primary Knock-On Atom (PKA)
= 100 keV Si



Timescale 1 ps

Courtesy of Antoine Jay

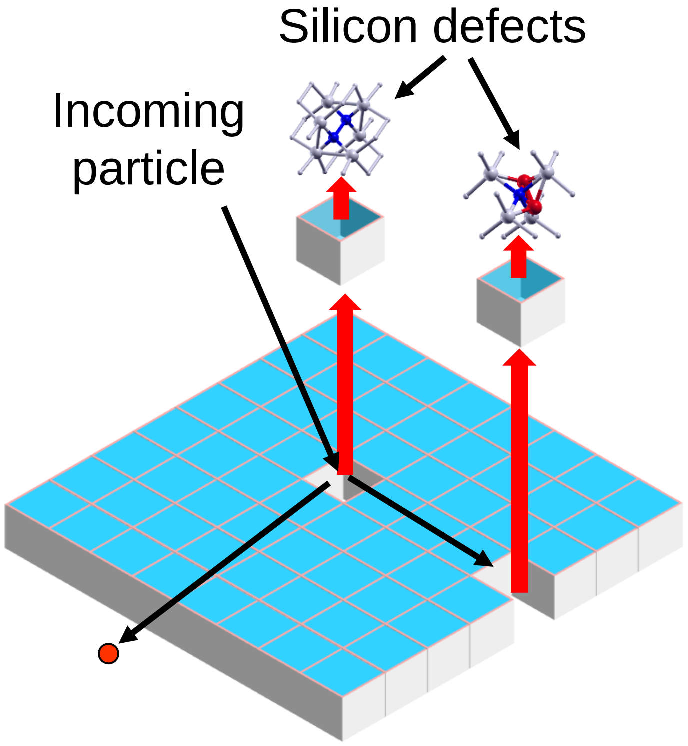
A. Jay et al. (2016). Simulation of single particle displacement damage in silicon–Part II: Generation and long-time relaxation of damage structure. IEEE TNS, 64(1), 141-148.

Displacement Damage in Image Sensors

- Typical particle fluences (MeV range):
  - **< 10^{12}** proton/cm^2 for space applications
  - Up to **10^{16}** neutron/cm^2 for nuclear/ particle physics applications
- Displacements of lattice atoms in CIS

➡ Creation of permanent silicon bulk defects

➡ If in the PD sensitive depletion volume…



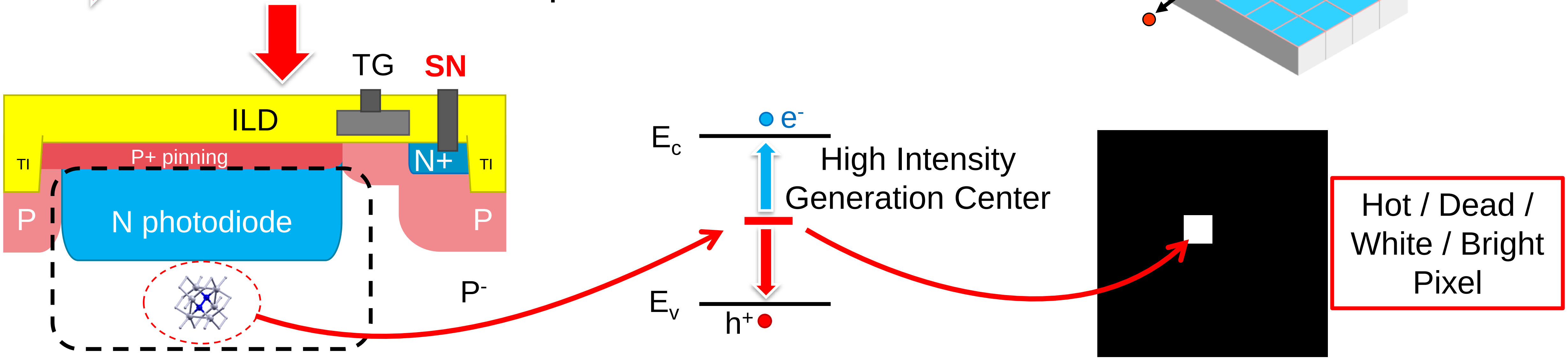
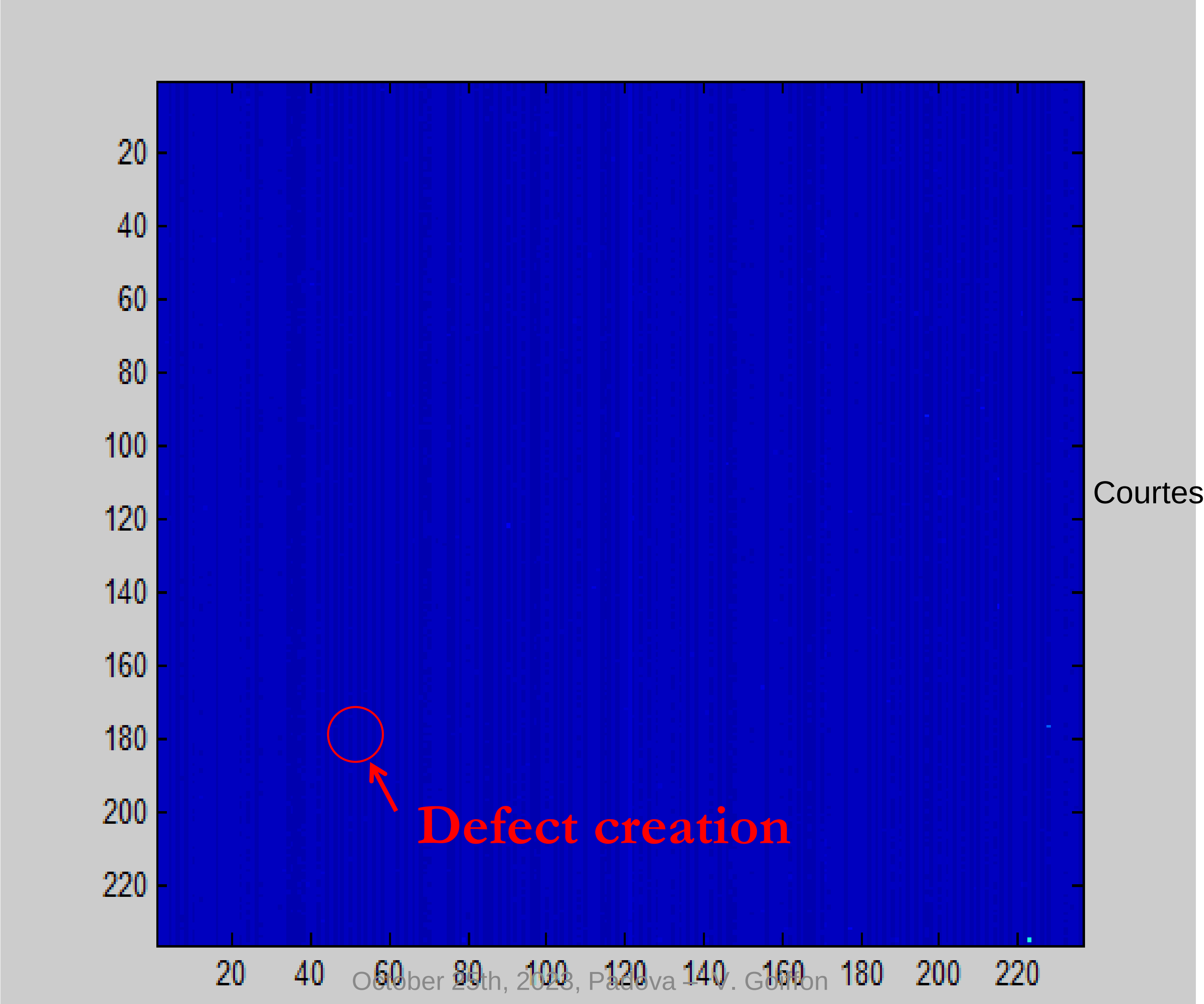


Illustration: Dark Frames Acquisition During Irradiation



Courtesy of Jean-Marc Belloir

Displacement Damage Induced Mean Dark Current: Universal Damage Factor (UDF)

- Srour and Lo Universal Damage Factor* applied to CIS

(equivalent to the α damage factor used in Si particle detectors⬩)

Damage Factor

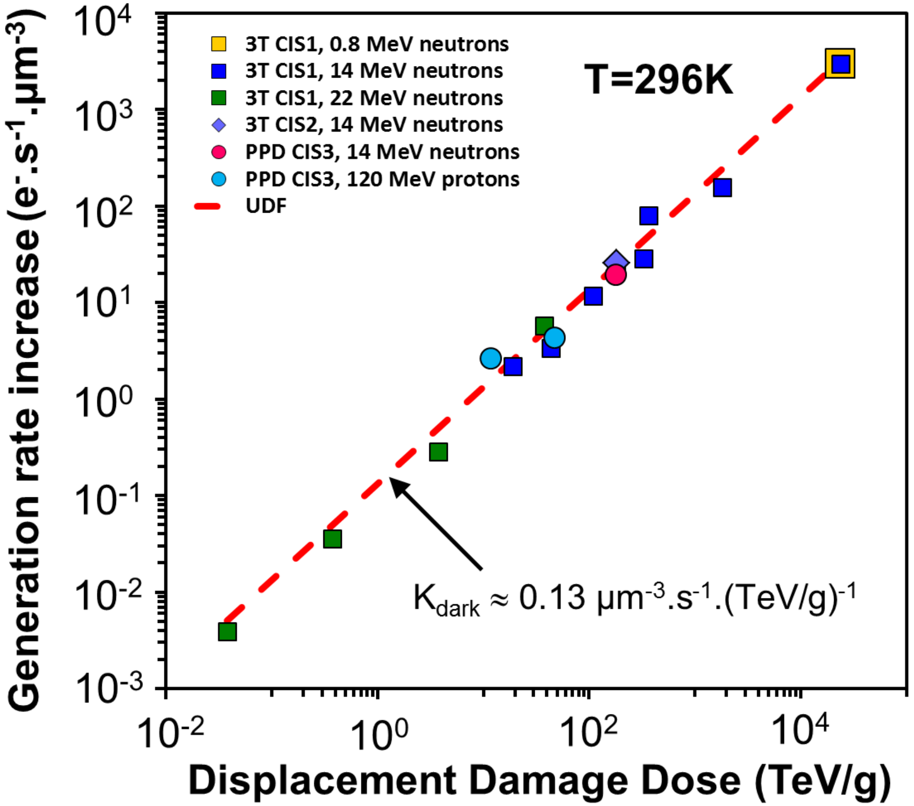
Displacement Damage Dose = NIEL x Fluence

$$\Delta I_{obs} = q \cdot K \cdot V_{dep} \cdot D_{dd}$$

Mean dark current increase

Depletion volume

- At 23°C: $K = 1.4 \pm 0.5\ \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1} \cdot (\mathrm{MeV/g})^{-1}$
- Verified on CIS (and CCDs) from many foundries up to $\approx 10^{13}$ n/cm² (1 MeV eq.)
- Temperature and annealing time can be taken into account



C. Virmontois et al., IEEE TNS Aug. 2012

1 MeV/g ≈ 500 n/cm^{-2} (1 MeV eq.)

J.R. Srour and D. H. Lo, IEEE TNS, Dec. 2000.

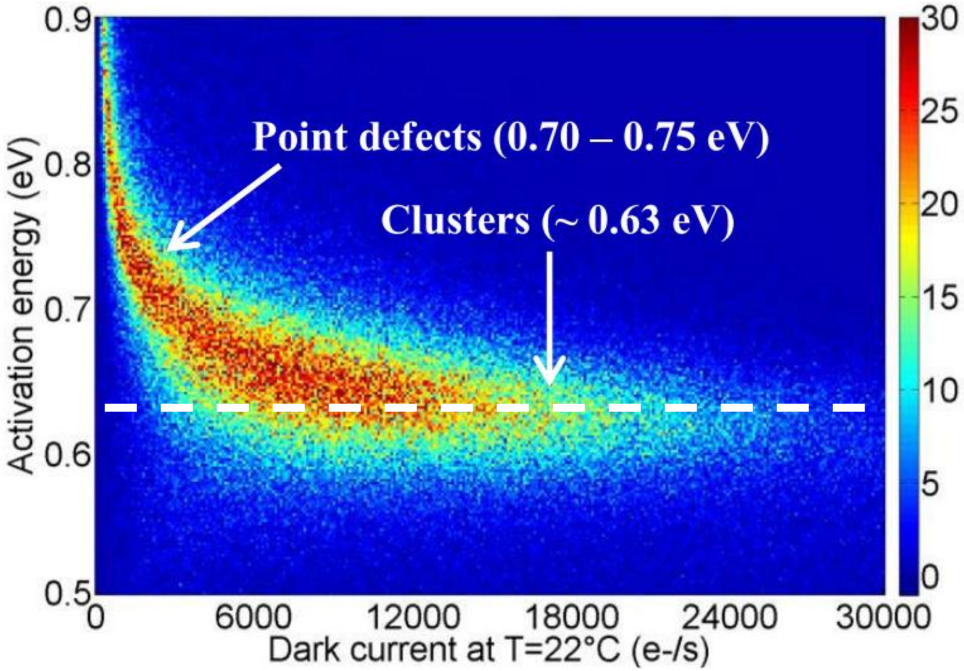
⬩*M. Moll PhD. Thesis, 1999*

DD Induced Dark Current Activation Energy

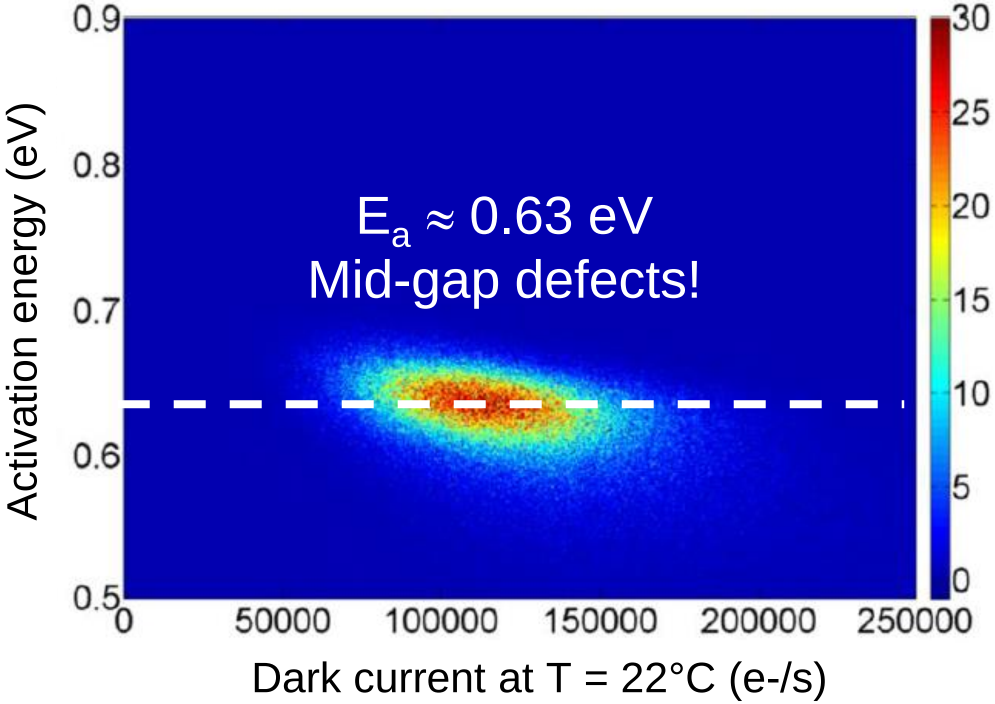
- Dark current is thermally activated following an Arrhenius Law ➡ $I_{\mathrm{DC}} \propto e^{-\frac{E_a}{kT}}$
- DD induced Dark Current activation energy $E_a \approx 0.63$ eV

➡ Signature of defect energy states located at the middle of the bandgap

22 MeV neutron fluence: 10^{12} cm^{-2}



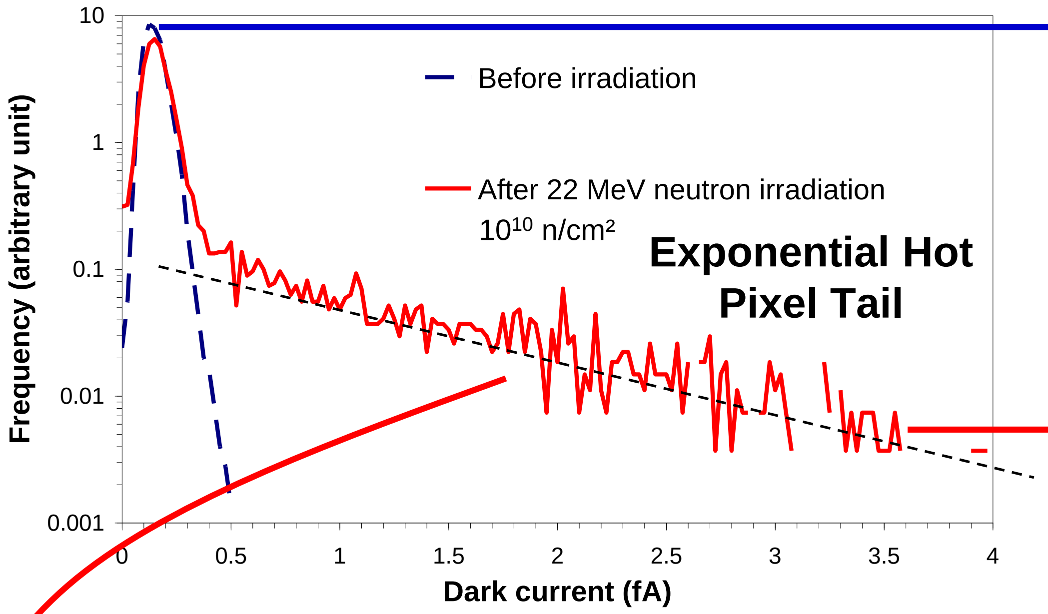
22 MeV neutron fluence: 10^{13} cm^{-2}

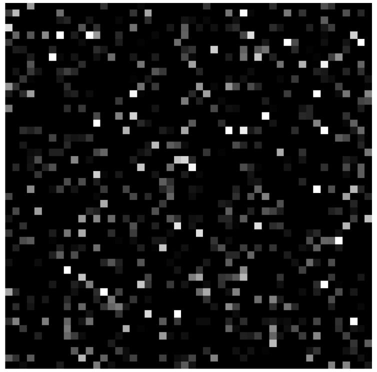


Belloir, J. M., Goiffon, V., Virmontois, C., Paillet, P., Raine, M., Molina, R., ... & Magnan, P. (2016). Dark current spectroscopy in neutron, proton and ion irradiated CMOS image sensors: From point defects to clusters. *IEEE Transactions on Nuclear Science*, *64*(1), 27-37.

Belloir, J. M., PhD Thesis, 2016

Displacement Damage Induced Dark Current Increase Distribution





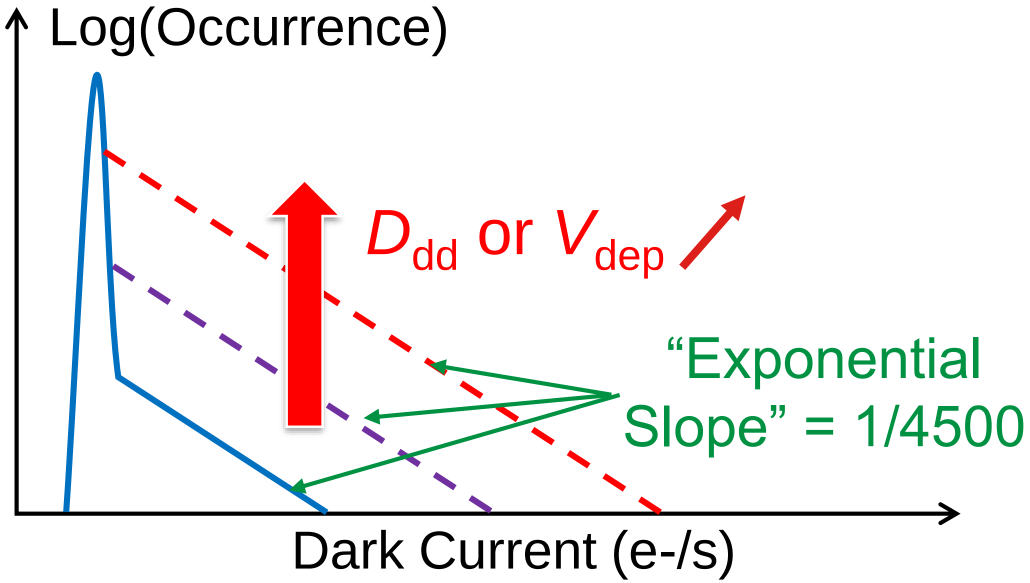
Dark Frame after 10^{10} n/cm² 22 MeV n irrad.

Displacement Damage Dose

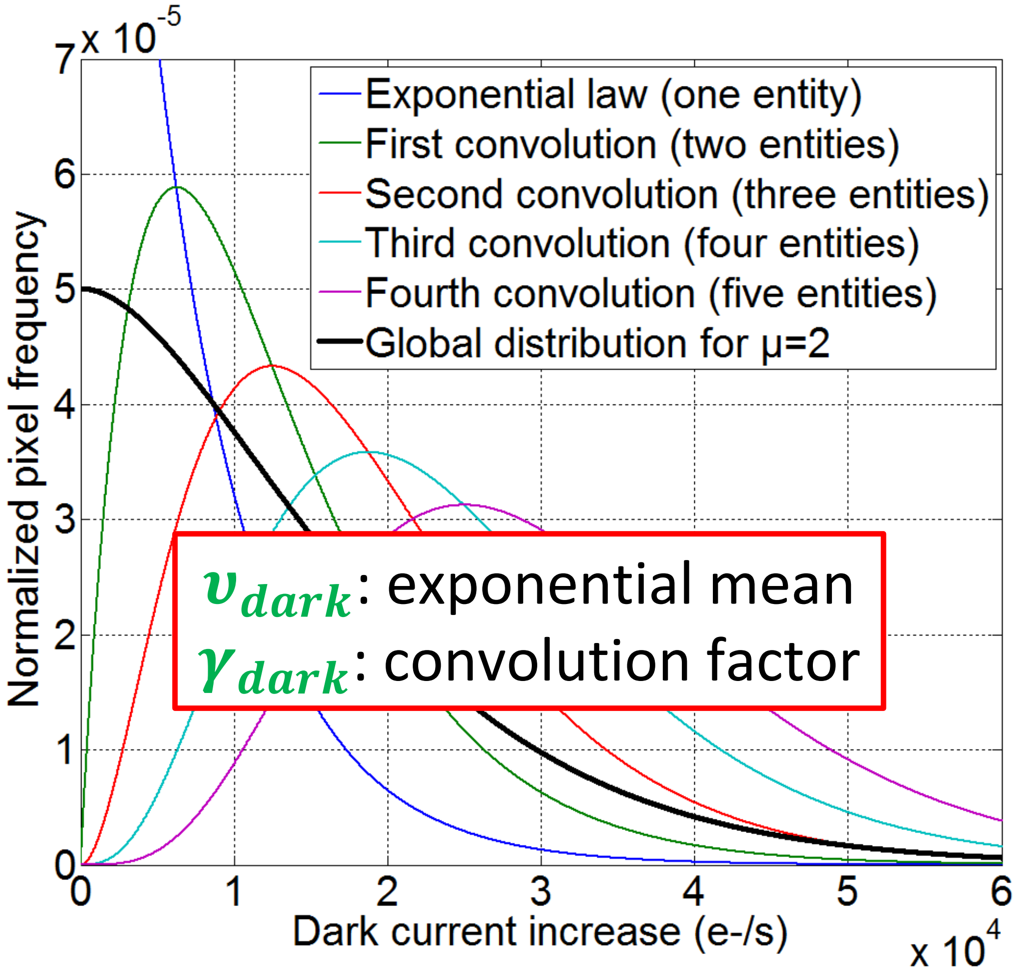
$$y \approx \overbrace{K \times \frac{1}{\nu_{\text{dark}}} \exp\left(-\frac{x}{\nu_{\text{dark}}}\right)}^{\text{“Fixed” Physical Exponential Distribution}} \times D_{\text{dd}} \times V_{\text{dep}}$$

$\upsilon_{dark} \approx$ 4500 e-/s @ 23°C (≈ 0.7 fA @ 23°C)

Can be predicted a priori if V_{dep} is known



Displacement Damage Effects on CIS: Empirical Forecasting Model*



$\boldsymbol{\upsilon_{dark}}$: exponential mean

$\boldsymbol{\gamma_{dark}}$: convolution factor

- **Exponential** dark current **Probability Density Function (PDF)** for low doses and small volumes (< 1 dark current source per pixel):

$$f_{\upsilon_{dark}}(x) = \frac{1}{\boldsymbol{\upsilon_{dark}}} \exp\left(-\frac{x}{\boldsymbol{\upsilon_{dark}}}\right)$$

- **Convolution** of the PDF at higher doses and larger volumes (superimposition of several dark current sources per pixel):

$$f_{\Delta I_{obs}}(x) = Poisson(k=1,\mu) \times f_{\upsilon_{dark}}(x) + Poisson(k=2,\mu) \times f_{\upsilon_{dark}}(x) * f_{\upsilon_{dark}}(x) + \cdots$$

- $\boldsymbol{\mu} = \boldsymbol{\gamma_{dark}} \times \boldsymbol{V_{dep}} \times \boldsymbol{DDD}$ is the convolution parameter and represents the **mean number of sources per pixel**

*Virmontois et al., IEEE TNS, Aug. 2012

*Belloir et al., Optics Express, Feb. 2016

Displacement Damage Effects on CIS: Empirical Prediction Model

- In the same way as the Universal Damage Factor, the two parameters of this empirical model $\boldsymbol{\upsilon_{dark}}$ and $\boldsymbol{\gamma_{dark}}$ *:
  - Appear to be constant for neutron/protons/ions of a few MeV to 500 MeV

    ➡ NIEL scaling appears to apply on the distribution as well!
  - In fact $\boldsymbol{\gamma_{dark}}$ is not a free parameter* it is given by K_{dark} / $\boldsymbol{\upsilon_{dark}}$
- In practice, this empirical model can be used to anticipate the absolute DD induced dark current distribution
  - Without any parameter adjustment
- Parameter values (*depends on the annealing time and T!*)* :

Average dark current per source

$$\upsilon_{\text{dark}} \approx 4500 \text{ e-/s @ } 23°\text{C}$$

1 TeV/g ≈ 5×10^{8} n/cm^{-2} (1 MeV neq.)

$$\gamma_{\text{dark}} \approx \frac{1}{50{,}000}\ \mu\text{m}^{-3}\,(\text{TeV/g})^{-1}$$

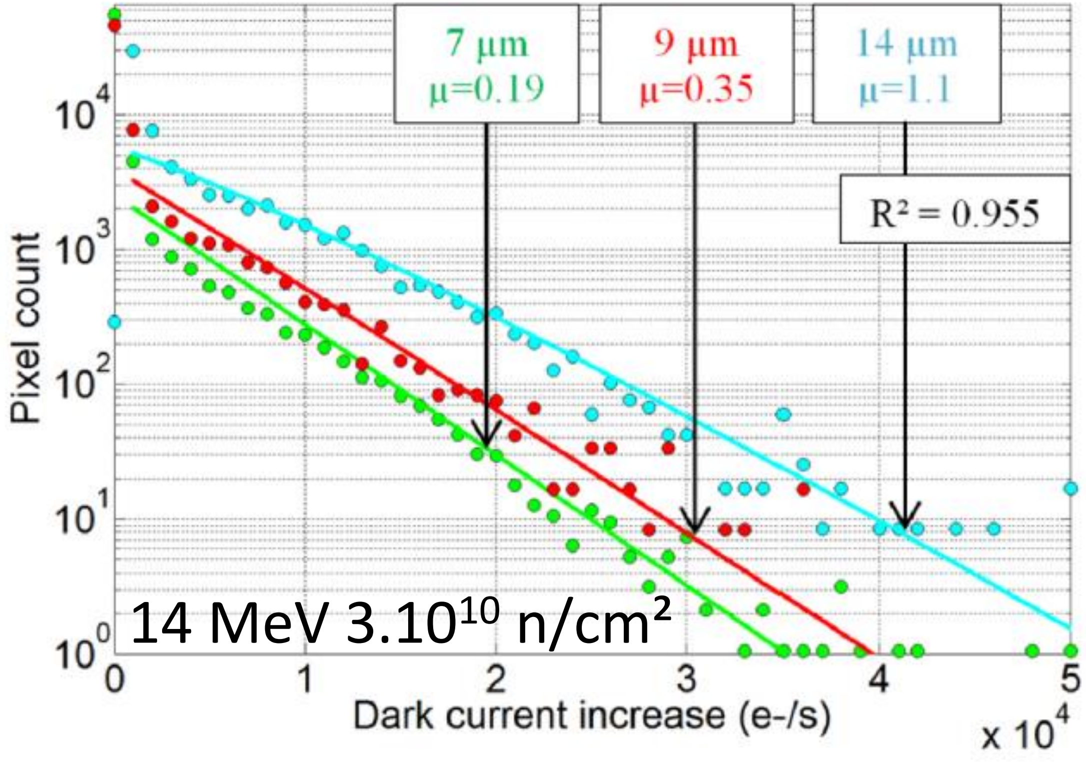
⇕

1 D_{dd} induced DC source per pixel for a 1 MeV n_{eq} fluence of 2.5×10^{11} cm^{-2} in a 100 µm^{3} depleted volume

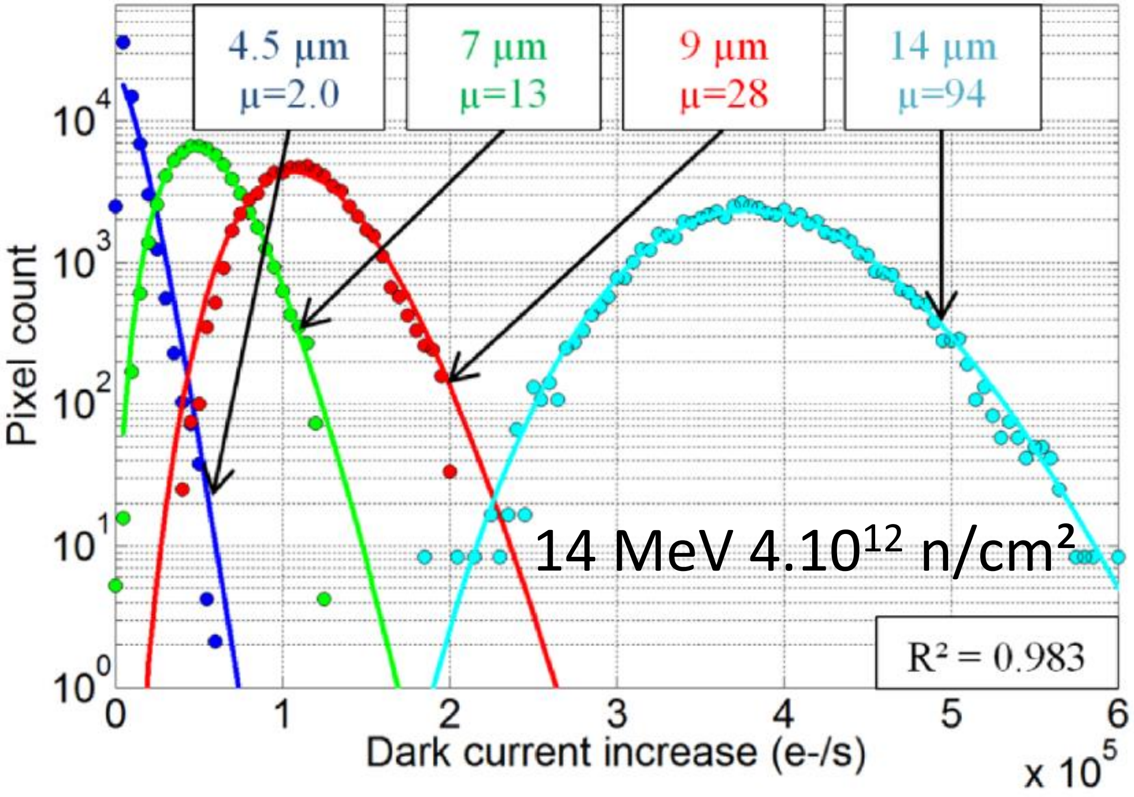
*Belloir et al., Optics Express, Feb. 2016

Displacement Damage Effects on CIS: Empirical Prediction Model

- Typical results of the prediction model:
  - 4 CIS with 4 different pixel pitches (4.5 / 7 / 9 and 14 µm)
  - At low (3.10^{10}) and high (4.10^{12}) fluence



14 MeV 3.10^{10} n/cm²

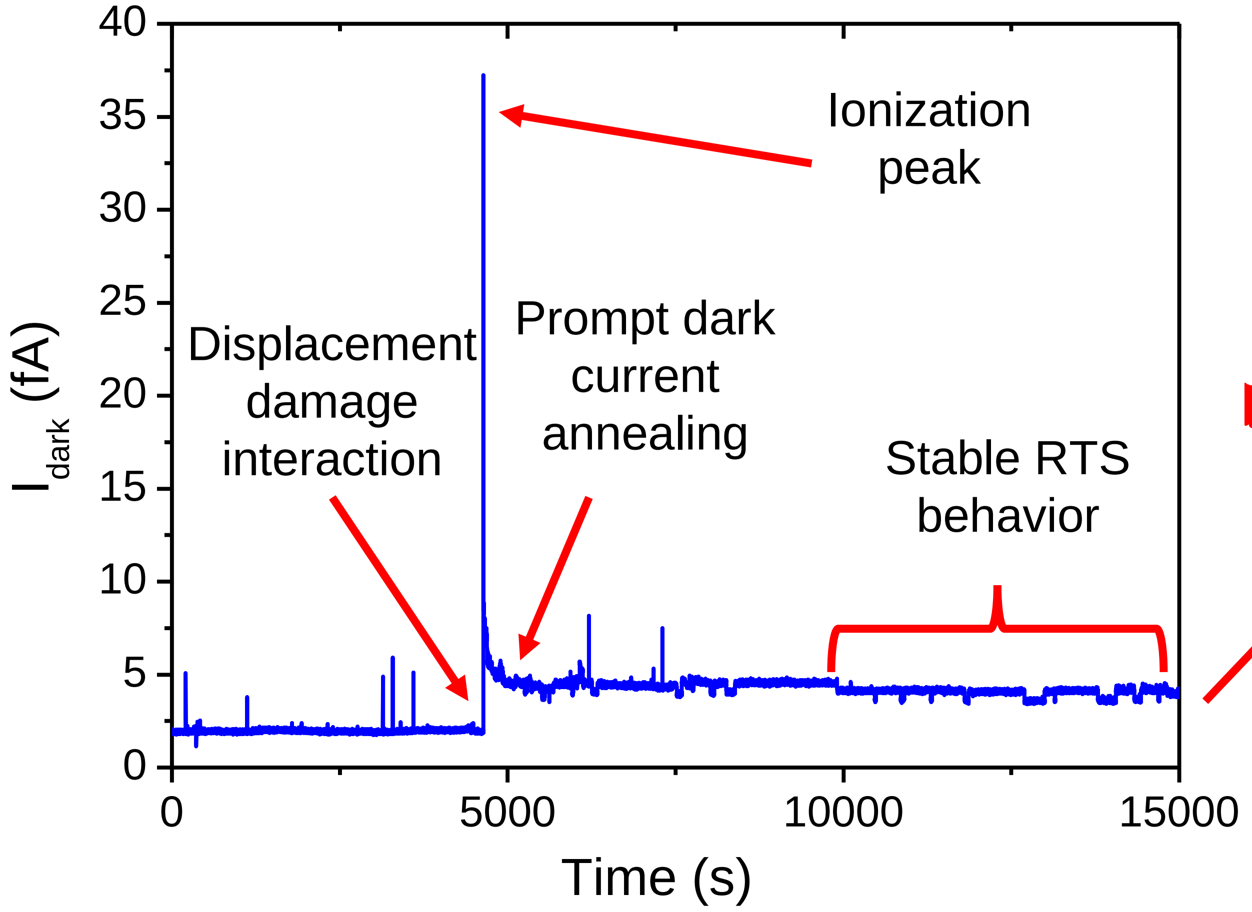


14 MeV 4.10^{12} n/cm²

*Belloir et al., Optics Express, Feb. 2016

Displacement Damage Induced DC-RTS

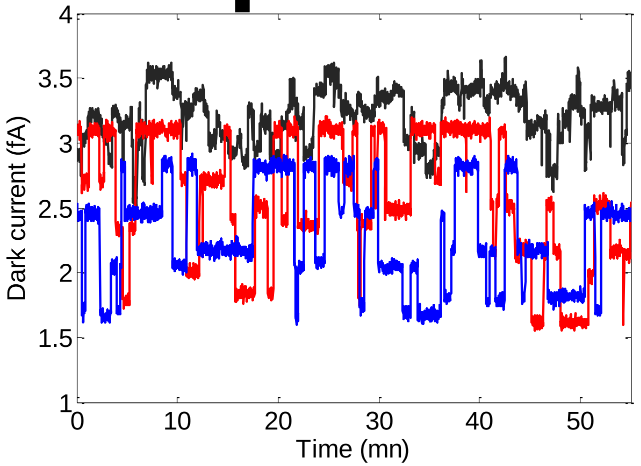
- Displacement Damage Interaction can also lead to the creation of blinking pixels (= Dark Current RTS)



M. Raine *et al.*, "Exploring the Kinetics of Formation and Annealing of Single Particle Displacement Damage in Microvolumes of Silicon," in *IEEE Transactions on Nuclear Science*, vol. 61, no. 6, pp. 2826-2833, Dec. 2014, doi: 10.1109/TNS.2014.2364397.

DD Induced DC-RTS Amplitude

- DC-RTS pixels # rises **proportionally** to DDD (NIEL scaling!)
- E_a = 0.6 eV (midgap signature) & centers located in SCR
- Can take much more than 2 discrete levels
- DC-RTS Amplitudes are exponentially distributed as well!



Displacement Damage Dose [MeV/g]

Depletion Volume [cm^3]

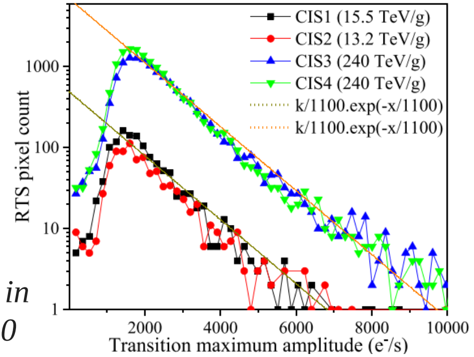
Number of DC-RTS center created by unit DDD:
30-35 centers.cm^{-3}.$(MeV/g)^{-1}$

1 D_{dd} induced RTS center per pixel for V_{dep} = 100 μm^3 and for 1.5 10^{11} n_{eq}/cm^{-2}

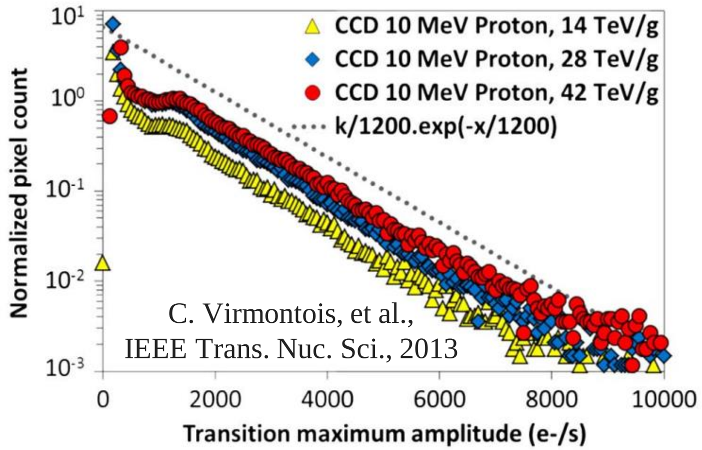
$$f'(x) = \frac{DDD \times V_{dep} \times K_{RTS}}{A_{RTS}} exp\left(-\frac{x}{A_{RTS}}\right)$$

Mean RTS Amplitude induced by DD interaction:
1100 – 1200 e-/s @22°C a few weeks after exposure

Technology independent!



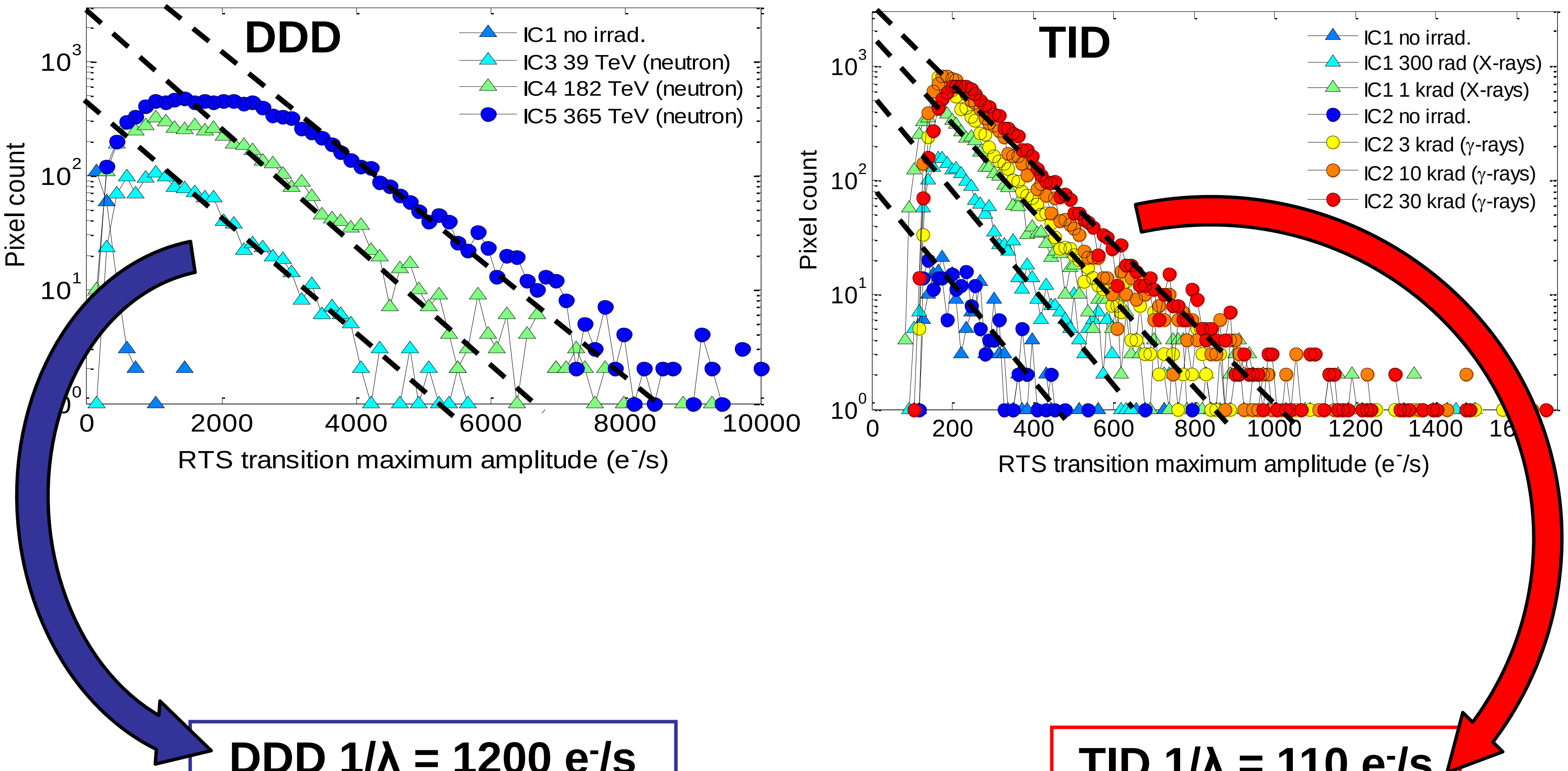
Liu, B. et al., *Results in Physics, 2020*



C. Virmontois, et al., IEEE Trans. Nuc. Sci., 2013

DDD vs TID Induced DC-RTS

Virmontois, C., Goiffon, V., Magnan, P., Saint-Pé, O., Girard, S., Petit, S., ... & Bardoux, A. (2011). Total ionizing dose versus displacement damage dose induced dark current random telegraph signals in CMOS image sensors. *IEEE Transactions on Nuclear Science*, *58*(6), 3085-3094.

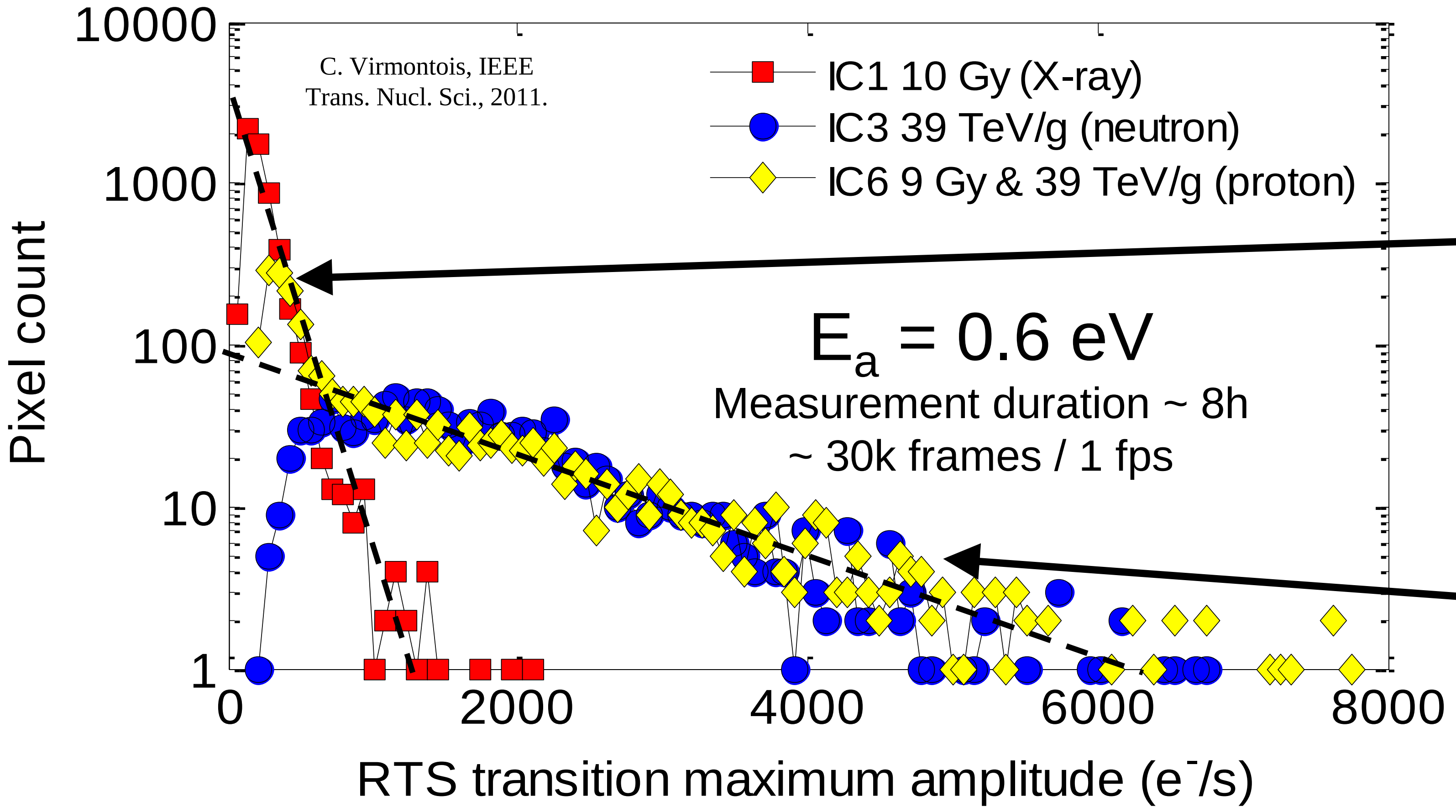


DDD 1/λ = 1200 e^-/s

TID 1/λ = 110 e^-/s

DDD vs TID Induced DC-RTS

- Proton irradiations induce both TID and DDD effects
  - Two contributions → Two exponential distributions



C. Virmontois, IEEE Trans. Nucl. Sci., 2011.

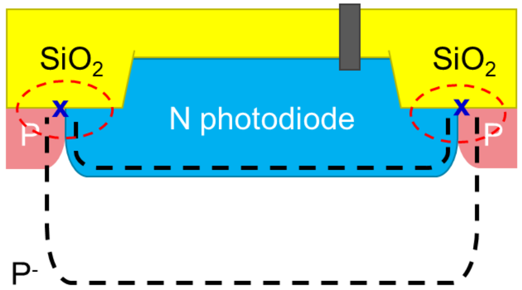
$E_a = 0.6$ eV

Measurement duration ~ 8h

~ 30k frames / 1 fps

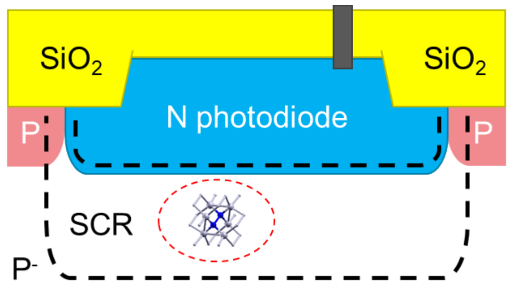
TID = 110 e-/s

Interface States



DDD = 1200 e-/s

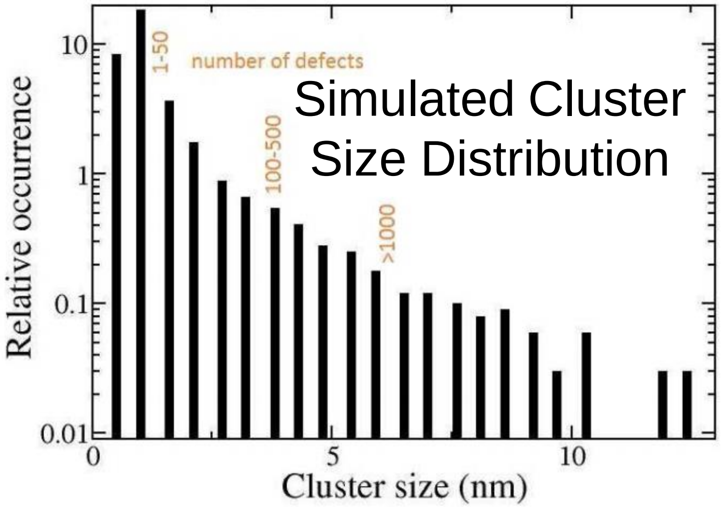
Bulk Defects



Possible Origin of DDD induced DC and RTS in Si Photodiodes

DDD induced DC and DC-RTS are likely due to clusters of intrinsic defects

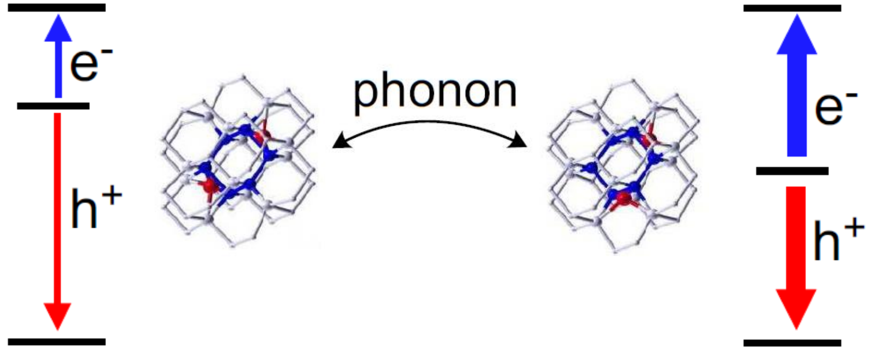
- Doping has no influence
- Point defects cannot explain the observed distributions and extreme leakage values
- Extended defects like dislocations not expected in Si without a high temperature annealing
- Cluster size seems exponentially distributed
- Midgap centers dominate in clusters
- Clusters distribution only depends on the radiation dose (not on the particle nature or energy)
- Giant emission rates are expected in clusters



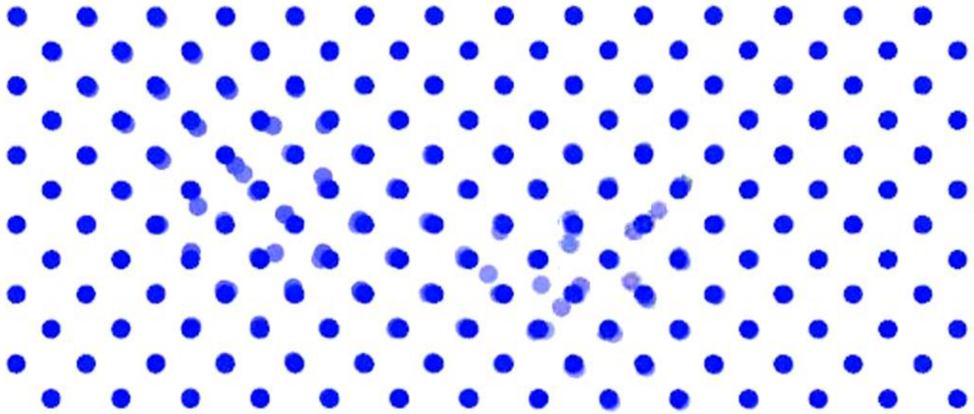
Simulated Cluster Size Distribution

Likely Cause of RTS Metastability

Defect Cluster
Structural Fluctuation



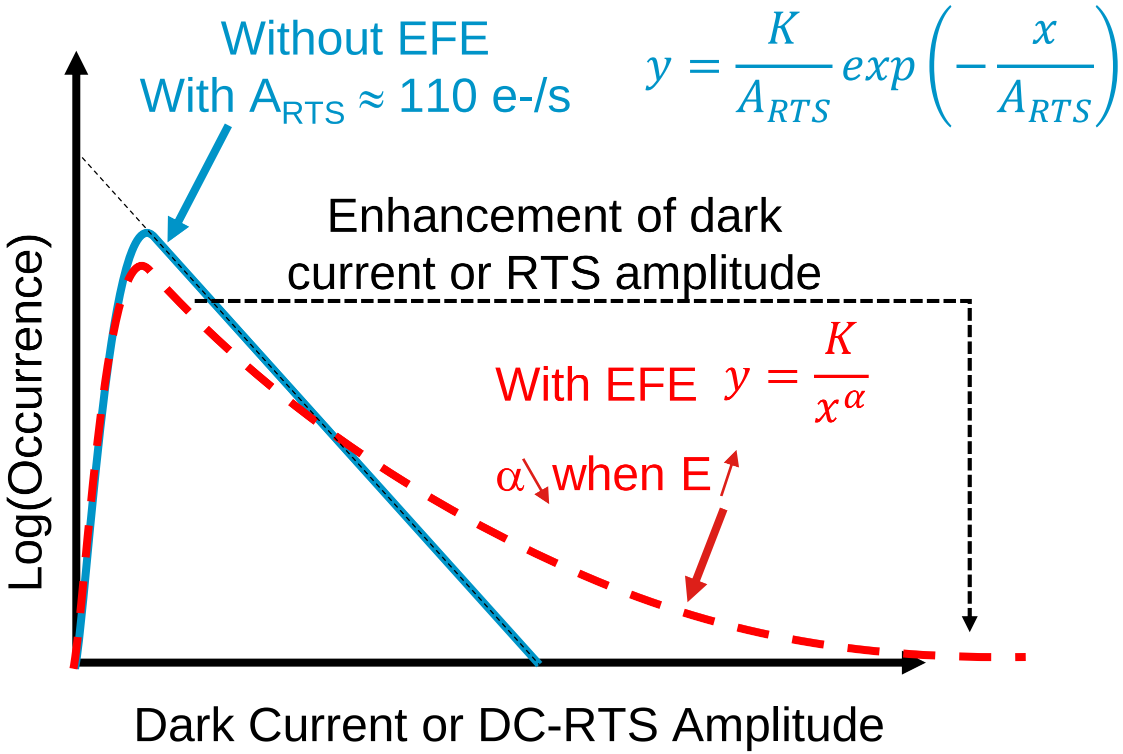
Atomic scale simulation of spontaneous structural fluctuation of small defect clusters (Si)



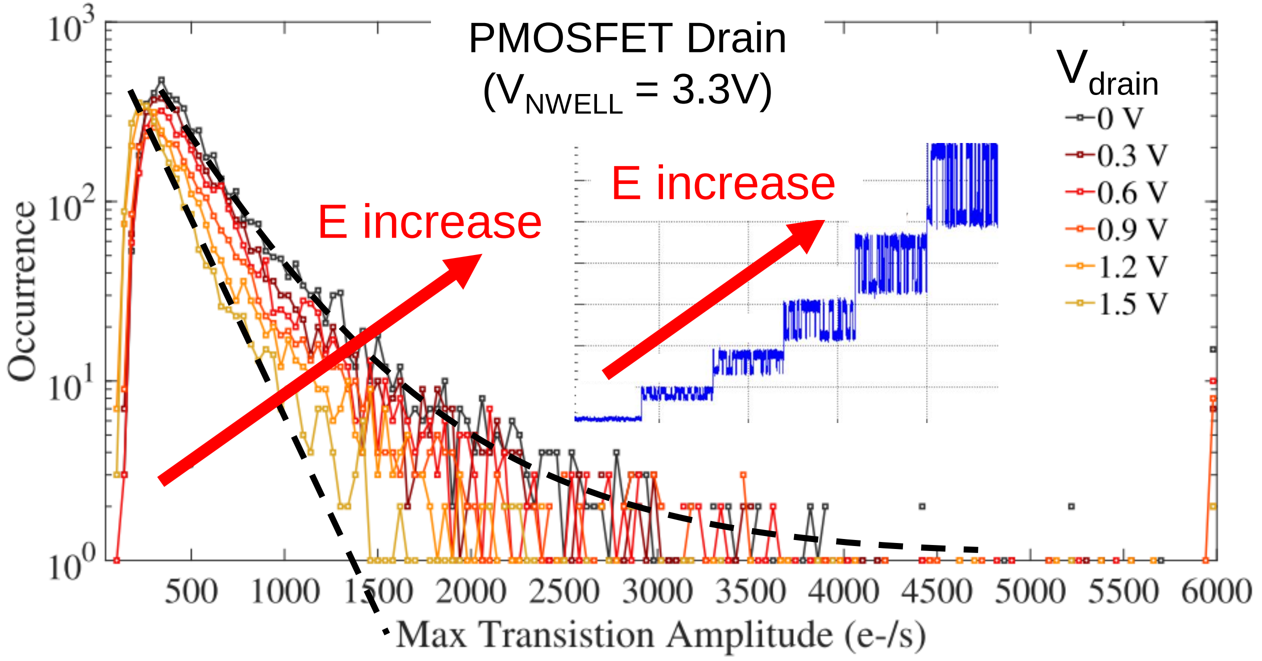
Courtesy of Antoine Jay

High Electric Field Effects on Exponential DC and DC-RTS distributions

- High Electric Field magnitudes enhance the defects e-/h+ generation rate
  - Electric Field Enhancement of Dark Current and RTS amplitudes
  - Intrinsic exponential distributions bend toward K/x^{α} distributions at high E-Field
  - Transition from SRH generation to Electric Field Enhanced SRH generation

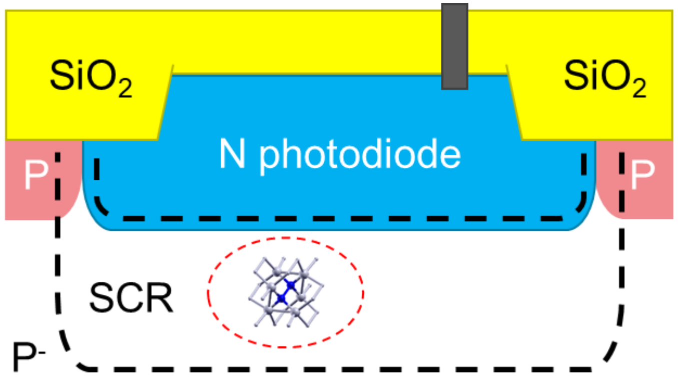


Experimental example on a DC-RTS distribution:

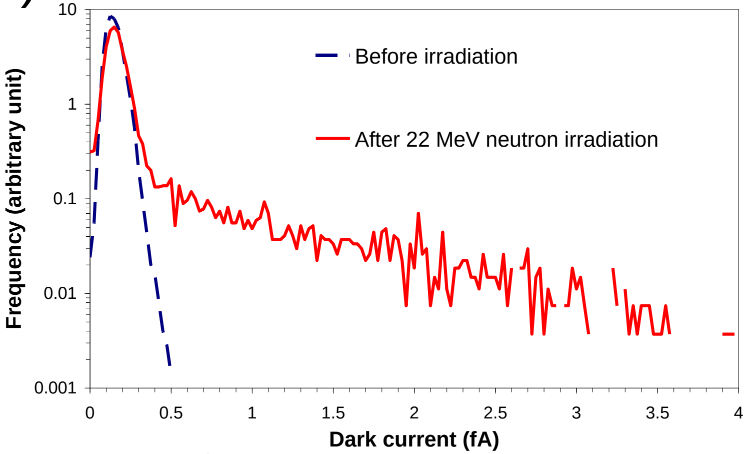


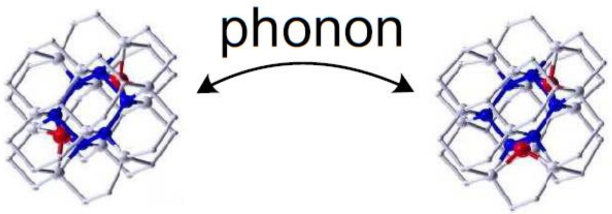
H. Dewitte et al., *IEEE Trans Nucl. Sci., 2021*

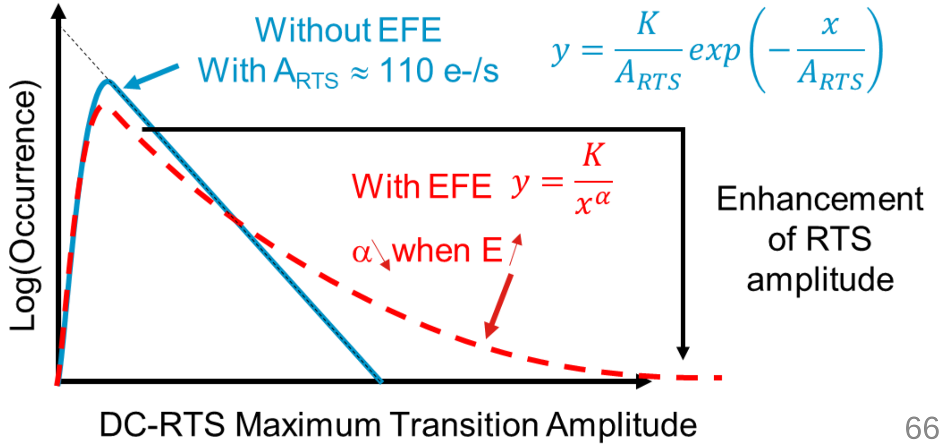
Displacement Damage in Silicon in a Nutshell



- No Charge Transfer degradation (contrary to CCDs)
- Dark Current Increase & Dark Current RTS
  - Dominated by **SCR SRH midgap centers** (E_a = 0.6 eV)
  - Proportional to DDD (i.e. # of initially displaced atoms)
  - Follow the Srour & Lo's Universal Damage Factor
  - "Universal" Exponential Distribution shifted by DDD
    - Possibly explained by defect cluster size distribution
  - Can be enhanced by high electric field (EFE)
    - Bending of the exponential distribution
  - RTS behavior possibly coming from thermally activated structural fluctuations (≠ trapping & emission or a free carrier)



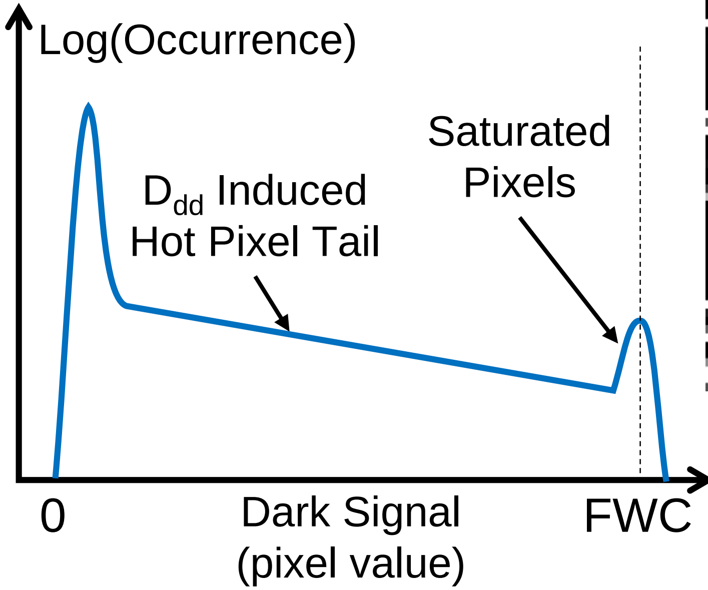


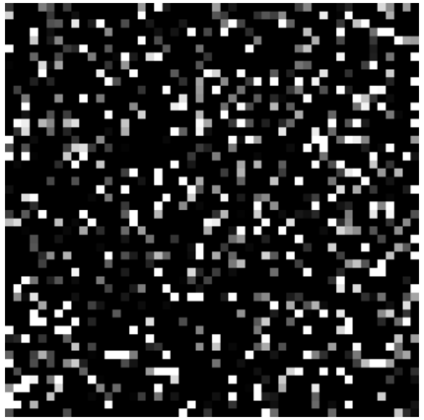


Displacement Damage RHBD ?

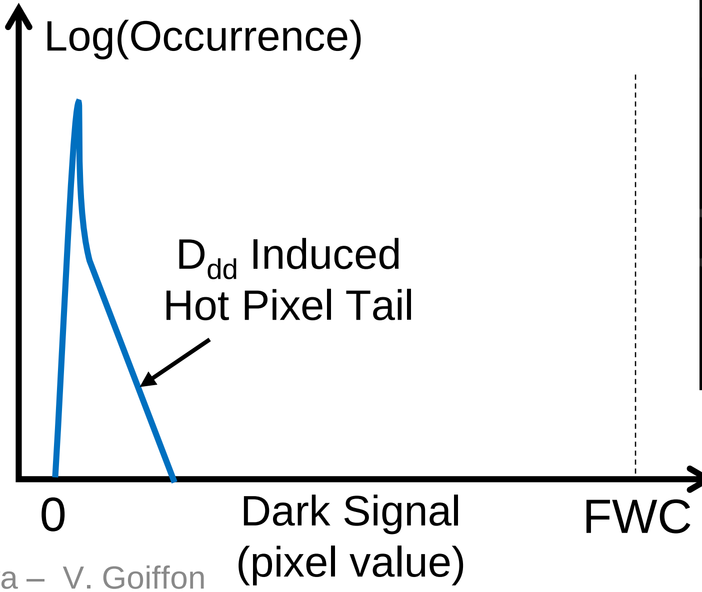
- 1^{st} RHBD Technique: Increase the Full Well Capacity and Lower the Gain
  - ✓ Larger pixels
  - ✓ Reduce the relative impact of D_{dd} (hot pixels and RTS)
  - ✓ Reduce the extremes
  - ✗ **High System Impact** (lowers the sensitivity)
  - (Applicable to TID effects mitigation as well)

High Gain/Low FWC Pixel



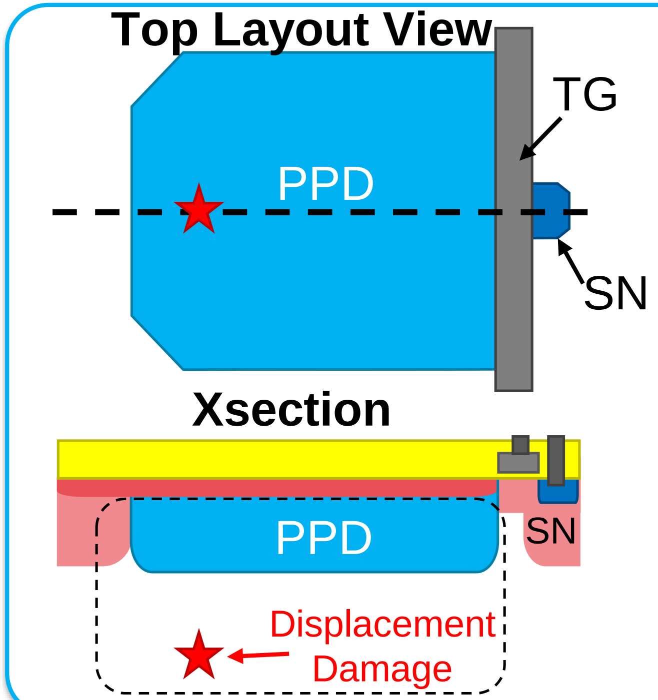


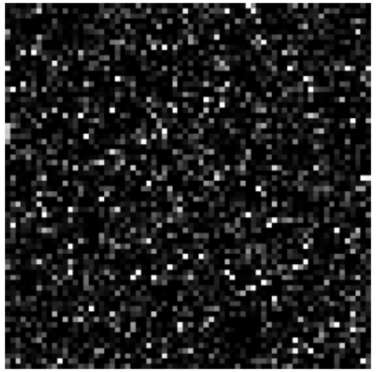
Low Gain/High FWC Pixel



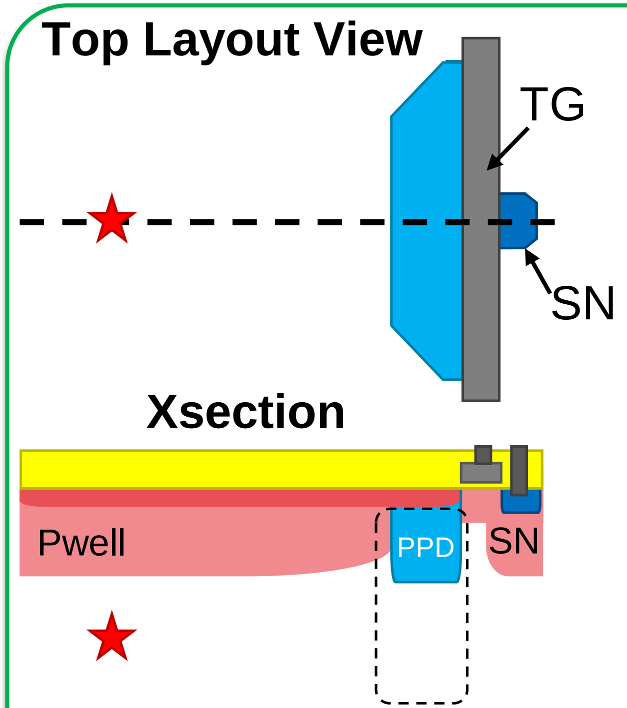
Reducing the DD Sensitivity Without Degrading the Performances

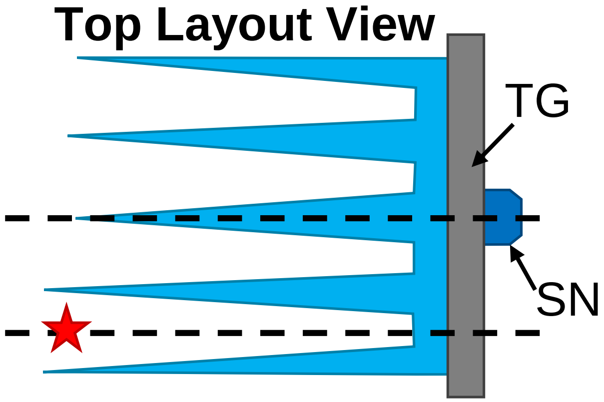
- 2^{nd} RHBD Technique: Decrease the Depletion Volume V_{dep}





Standard PPD Layout





PPD “comb” layout

✓ Reduced depleted volume
➡ Higher tolerance to DD
✓ No Collection Efficiency Loss!

Reduced PPD Area

✓ Reduced depleted volume
➡ Higher tolerance to DD
✗ Reduced Collection efficiency

Real RHBD technique against DD with nearly no side effect!

Hardening Against Displacement Damage
Final Thoughts

- The previous discussions hold in absence of high electric field regions in the photodetector
  - (as often the case in modern CIS)
  - If high electric field regions exist in the depleted silicon volume ➔ the first RHBD technique shall be to get rid of these!
- Dark current increases exponentially with temperature
  - A common technique to reduce Displacement Damage induced Dark Current in irradiated sensors is to **lower the sensor operating temperature**

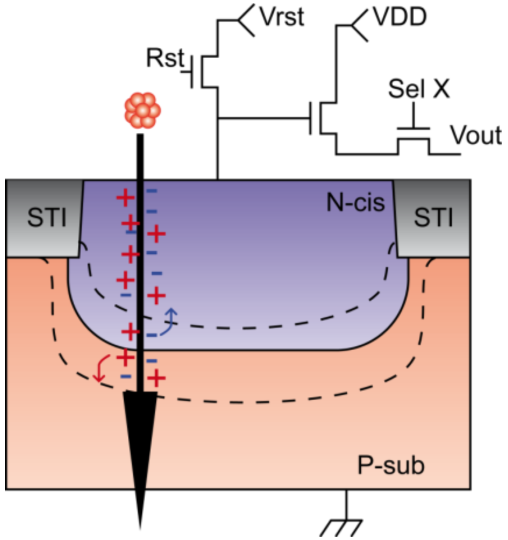
DD induced dark current
is reduced by 2X every ≈ - 8°

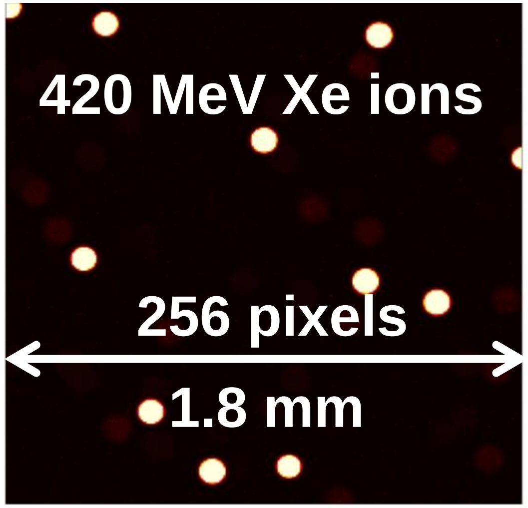
- Conclusions also applicable to other leakage sensitive ICs...

Single Event Effects (SEE)

SEEs in pixel arrays

- What kind of SEE CIS are sensitive to?
  - **In theory: all kinds**, as any CMOS Mixed-Signal ICs
- Outside the pixel array:
  - Each function has to be analyzed independently
- For basic pixel architecture :
  - No SEL (no in-pixel PMOSFET) / No SEU (no in-pixel memory)
  - **Only Single Event Transient (SET)**
- Other **pixel array effects** are **generally not an issue**:
  - SET in decoders or readout chain are infrequent and only corrupt one pixel or one row of **a single frame**
- CIS are generally **resistant to SEL**
  - But can be hardened further by design (same for SEU)





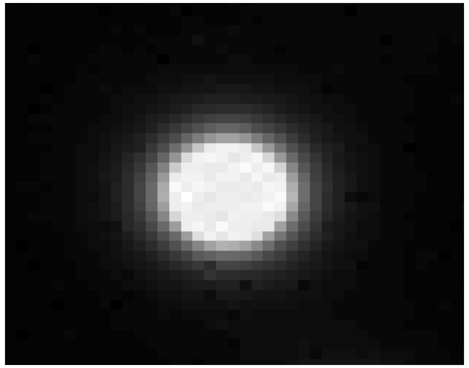
V. Lalucaa Phd Thesis

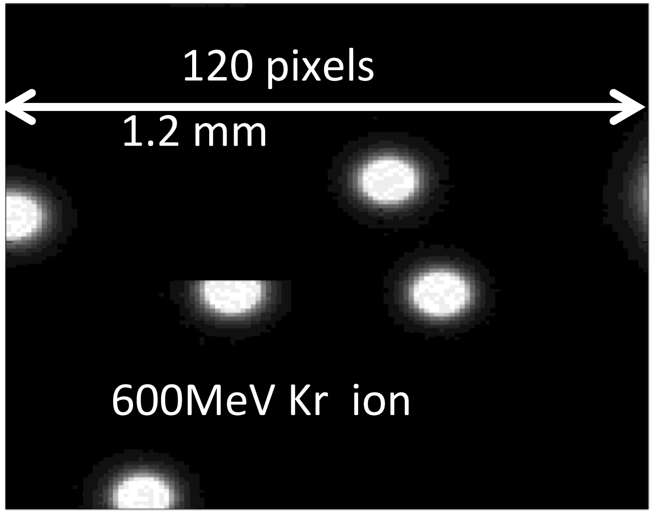
Mitigating Pixel SET: RHBD?

- SET due to ion induced charge collection by the photodiode
- To reduce this charge by design/layout:
  - Reduce the collection area

  ➔ reduce the quantum efficiency ✗
  - Add charge drains

  ➔ also drain the useful photocharge ✗
- Not much can be done by design without degrading the detection efficiency

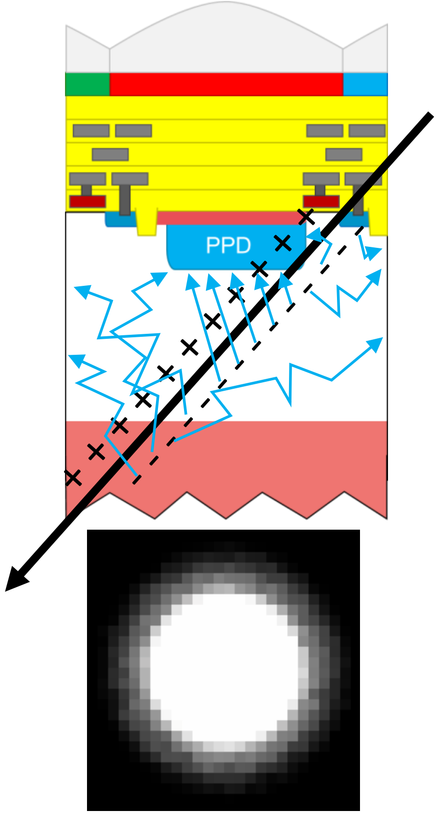




V. Lalucaa Phd Thesis

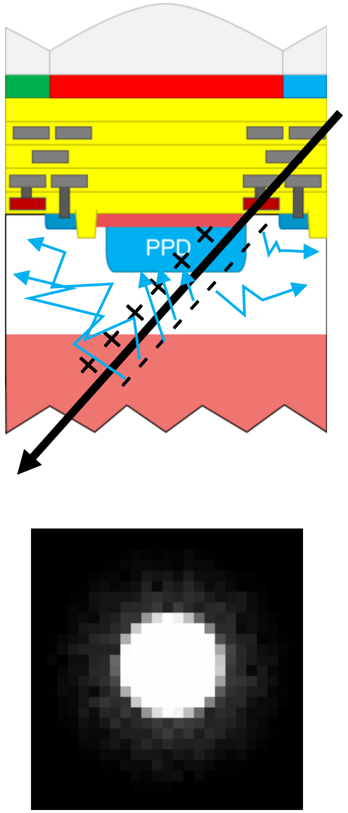
Mitigating Pixel SET: Manufacturing Options

Thick P- epitaxy on P+ substrate



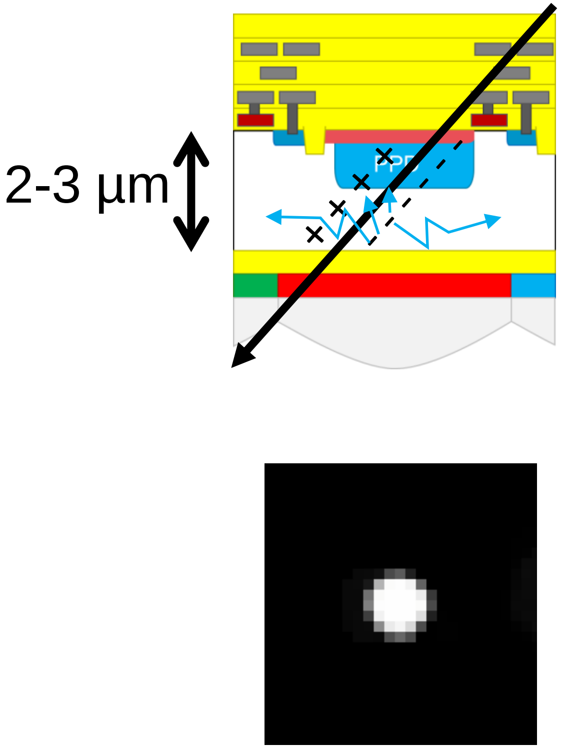
Large area disturbed (epi + substrate contributions)

Thin P- epitaxy on P+ substrate



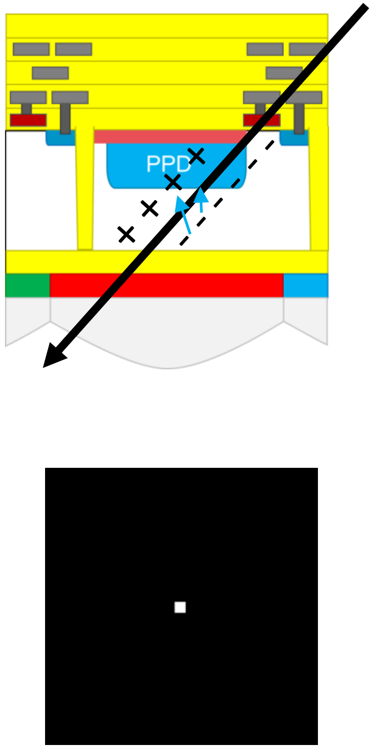
Reduced epitaxy contribution

Back Side Illuminated (No substrate)



Substrate contribution suppressed

BSI + Deep Trench Isolation (DTI)

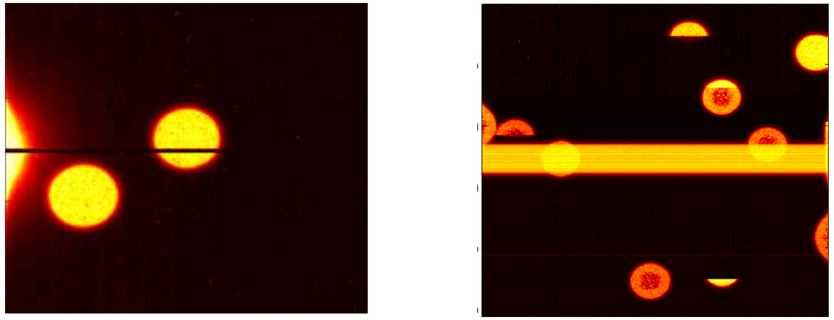


Pixel-to-pixel diffusion cancelled
Only one pixel disturbed!

Also efficient against Gamma induced “snow”

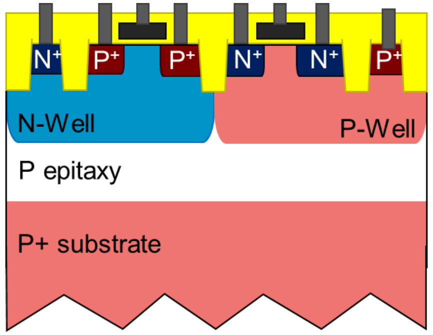
Single Event Latchup: The CMOS Sensor Case

- SEL does not occur in pixel arrays
- SEL outside the pixel ⬄ Same as in any CMOS IC
  - Classical RHBD techniques can be used
- However, classical CIS features provide **intrinsic resistance to SEL**
  - Those features can be used/adjusted to strengthen this intrinsic hardness



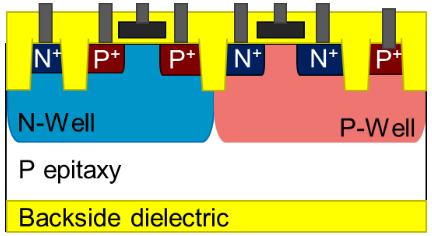
V. Lalucaa Phd Thesis

Epitaxy on highly doped substrate



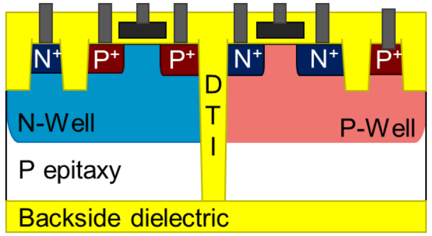
Thinner Epitaxy
- ➡ Higher Holding Voltage
- ➡ Less collected charge

Back Side Illuminated sensor (**COTS** case)



- ✓ Much less collected charge
- ✗ High epi–layer resistance
- ? Uncertain result (lack of comparative data) ⚠

Use of DTI isolation (custom design)



DTI between N and P-MOSTs
- ✓ Higher Holding Voltage
- ✓ Immune to SEL if the DTIs go all the way down (BSI case)

Radiation Effects on CIS: Summary

Meaning of Radiation Hardness?

- Radiation Hardness is Application Dependent

What is the most rad-hard structure against Displacement Damage?

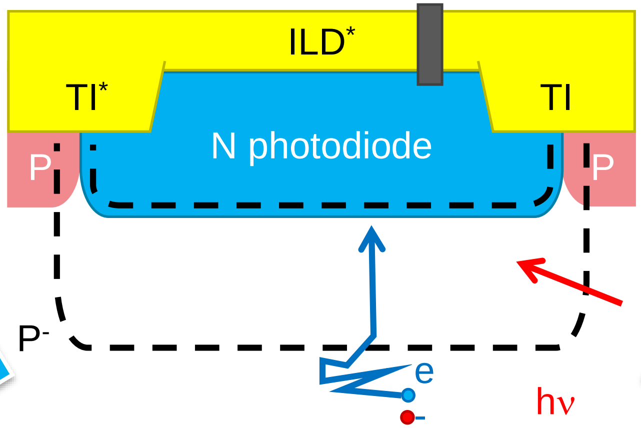


Image Sensors

(Sensitive to ultra low leakage current)

Minimum possible depleted volume and low E Field

➔ reduce DD induced dark current

Exact Same CMOS Reverse Biased Photodiode

Opposite RHBD approaches !

Particle Detectors

(Sensitive to charge trapping by bulk defects)

Largest possible depletion volume and high E Field

➔ reduce charge trapping by DD induced traps in neutral region

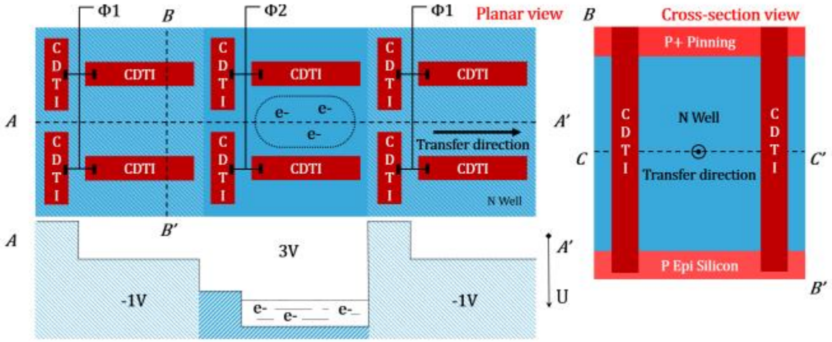
Radiation Effects on CIS: A Summary

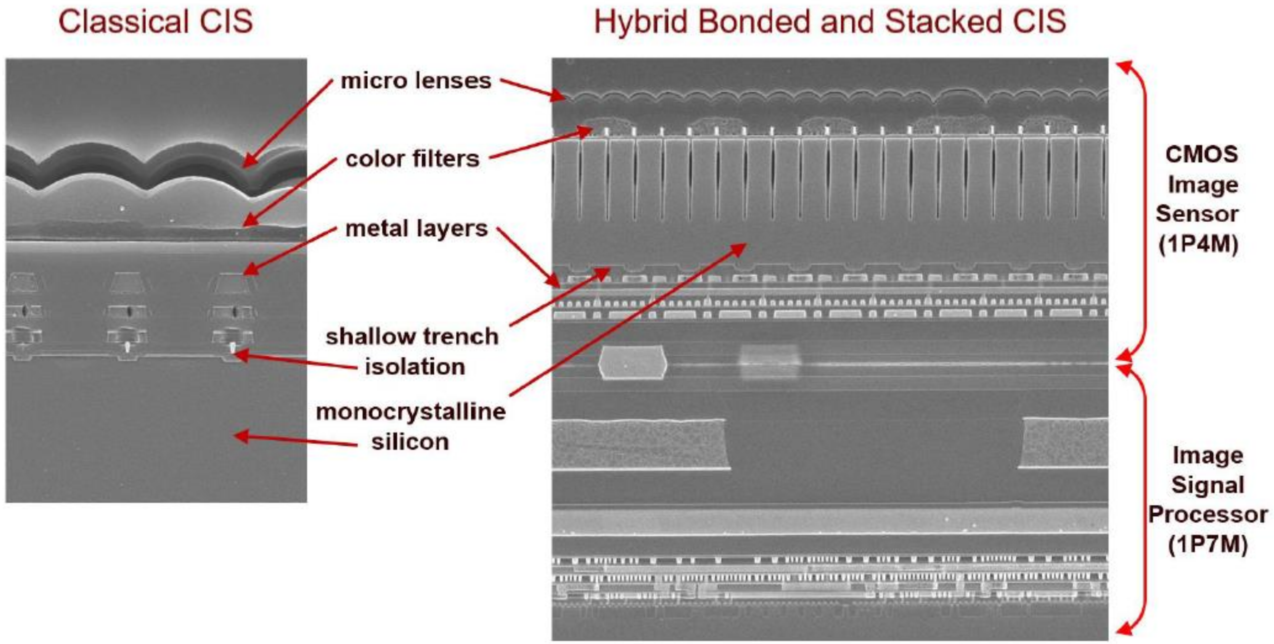
- CMOS Image Sensor pixel performances are degraded by both ionizing radiation dose (TID) and displacement damage dose (DDD)
  - Below 1kGy /100 krad : TID induced degradations are generally not limiting
  - With RHBD ➔ can be pushed to 1 Grad at the cost of degraded performances
  - Displacement damage in pixel arrays is a performance limiting factor for high end applications ➔ a single displacement damage interaction can kill a pixel!
  - Displacement Damage related degradation can be accurately predicted using the Universal Damage Factor and an empirical exponential distribution model
- Single Event Effects at the pixel level are generally not a critical issue
- Compared to other solid-state visible image sensor technologies the CMOS Image Sensor technology has a strong potential for applications in radiation environment…

Near Future

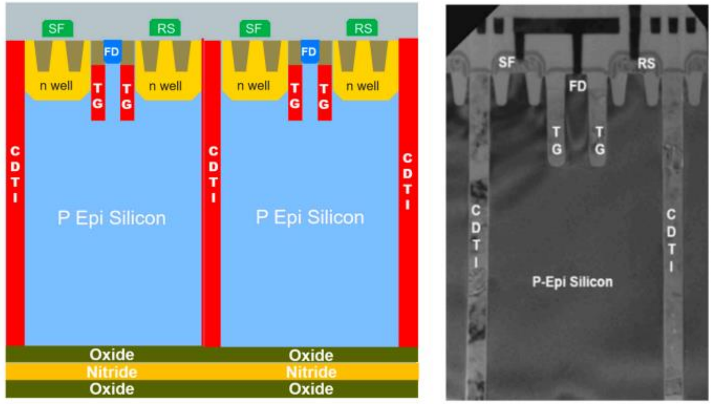
- … but new challenges arise with the increasing use of highly integrated commercial devices in radiation environments
- and the use of new devices/topologies/isolations inside the pixel leading to new radiation effects

Touron, P., Roy, F., Magnan, P., Marcelot, O., Demiguel, S., & Virmontois, C. (2020). Capacitive Trench-Based Charge Transfer Device. *IEEE Electron Device Letters*, *41*(9), 1388-1391.





Courtesy of Albert Theuwissen (Harvest Imaging) and Ray Fontaine (Techinsights)



Roy, F., Suler, A., Dalleau, T., Duru, R., Benoit, D., Arnaud, J., … & Lu, G. N. (2020). Fully Depleted, Trench-Pinned Photo Gate for CMOS Image Sensor Applications. *Sensors*, *20*(3), 727.

Further Reading:

- Book chapter with full list of references therein:
  - V. Goiffon, *Radiation Effects on CMOS Active Pixel Image Sensors*. In: Ionizing Radiation Effects in Electronics. CRC Press, pp. 295- 332, 2015.
  - Download link: https://oatao.univ-toulouse.fr/14554/7/Goiffon_14554.pdf
- V. Goiffon, 2021 IEEE NSREC Short Course, Part III, *Hardening Techniques for Image Sensor*
- Software for forecasting displacement damage in pixel arrays (dark current and RTS) and links to download tutorial and papers:
  - https://pagespro.isae-supaero.fr/vincent-goiffon (Work In Progress, to be updated soon with all the links)

Thank you for your attention !

Join us at ISAE-SUPAERO in Toulouse, France, for the RADOPT 2023 workshop on Radiation Effects on Optoelectronics and Photonics Technologies on Nov. 29 & 30 ! https://www.comet-cnes.fr/evenements/radopt

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Backup Slides

Non Ionizing Energy Loss (NIEL) Displacement Damage Dose

- As for ionization damage, the amount of displacement damage can be quantified by using the Displacement Damage Dose concept (similar to the TID concept but for displacements)
- As for ionizing energy loss, an energy loss factor can be defined for atomic displacement interactions (non-ionizing interactions): the Non Ionizing Energy Loss (NIEL) factor

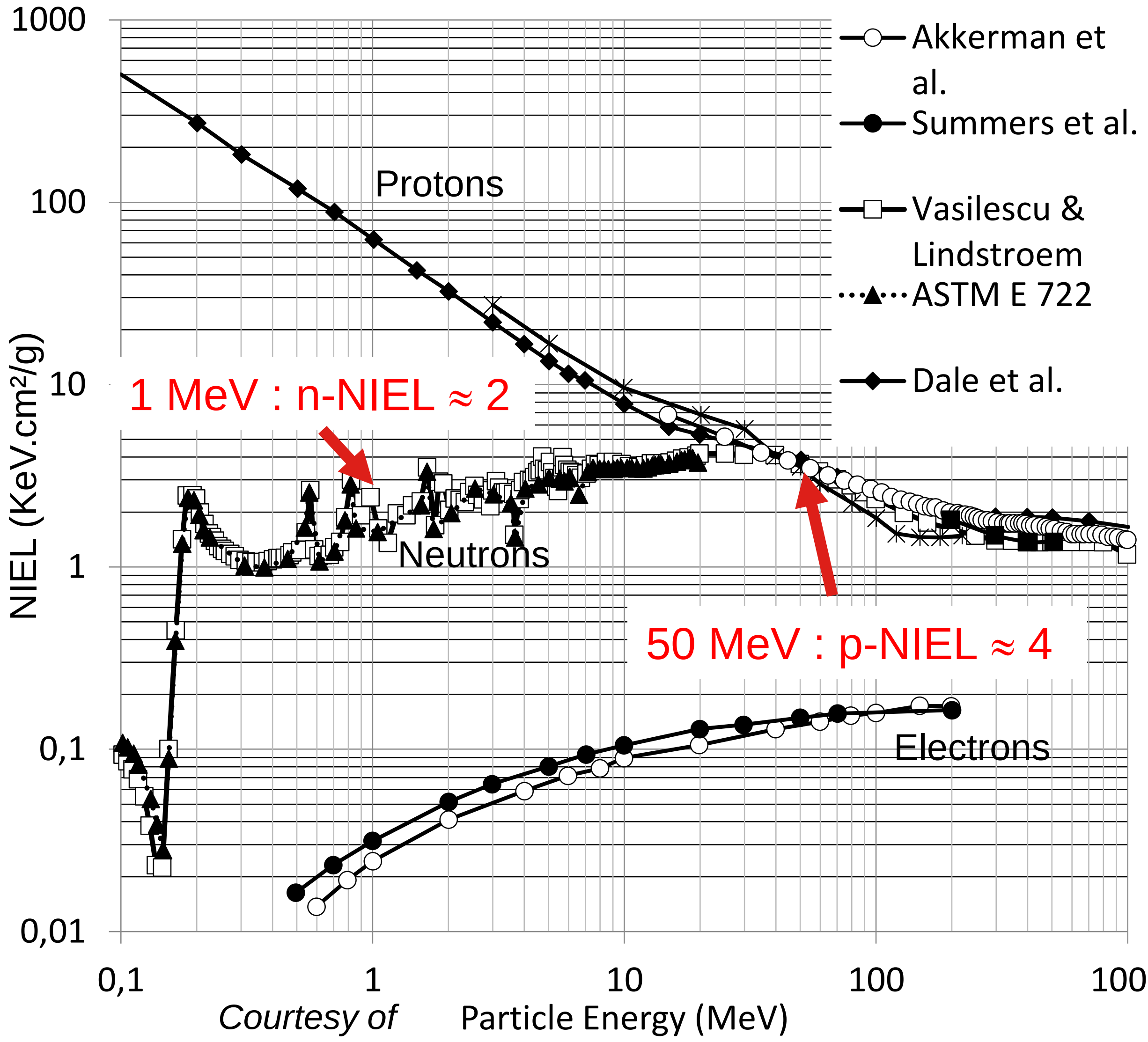
$$\mathrm{NIEL} \approx \left(-\frac{dE}{dx}\right)_{\mathrm{nucl.}} \longleftarrow \textbf{Energy lost by interactions with the material nuclei}$$

$$\mathrm{eV.g^{-1}} \longrightarrow \boldsymbol{DDD} = \underset{\uparrow\ \mathrm{eV.cm^{2}.g^{-1}}}{\boldsymbol{NIEL}} \times \Phi \longleftarrow \mathrm{cm^{-2}}$$

Displacement Damage Dose Units Equivalence

- Typical units used in the literature are J/kg, eV/g or
  1 MeV equivalent neutron fluence
  - i.e. the fluence of 1 MeV neutrons that would lead to the same
  - An example:

50 MeV proton fluence (cm^{-2})	TID (krad(Si))	TID (J/kg)	DDD (J/kg)	DDD (TeV/g)	1 MeV equ. Fluence (cm-^{2})
10^{11}	16	160	6×10^{-14}	400	2×10^{11}



1 MeV : n-NIEL ≈ 2

50 MeV : p-NIEL ≈ 4

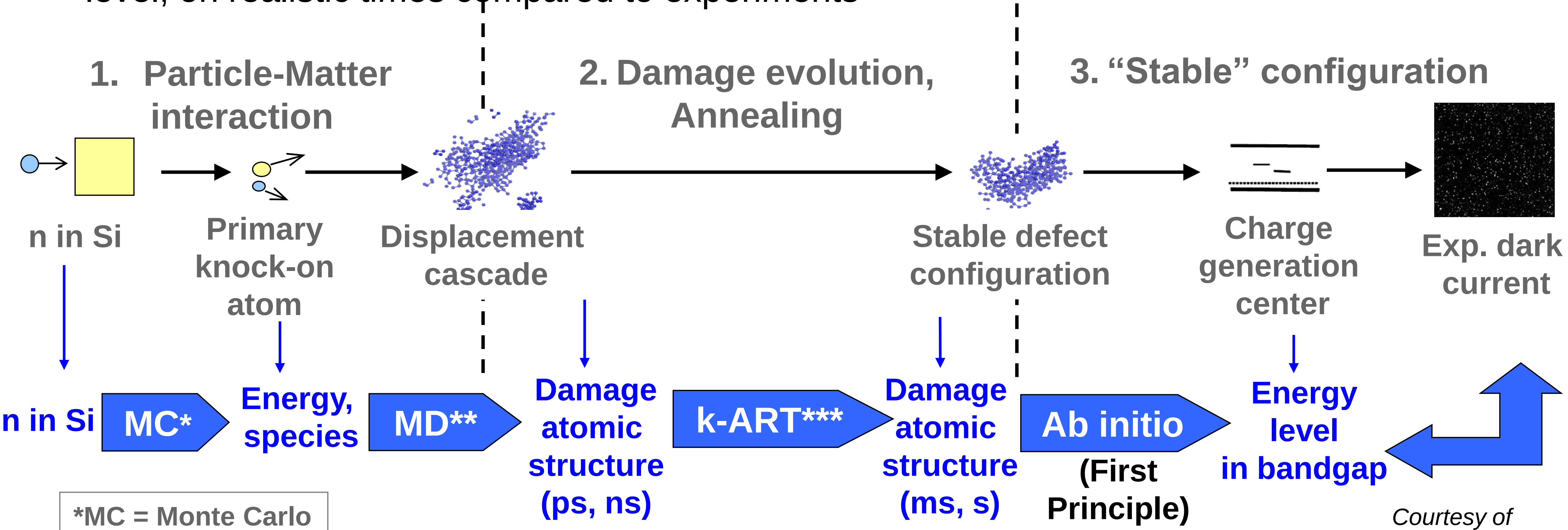
Courtesy of Alexandre Le Roch

Displacement Damage Multi Scale Simulation Project

Raine, M., et al. (2016). Simulation of single particle displacement damage in silicon–part I: global approach and primary interaction simulation. IEEE TNS, 64(1), 133-140.

A. Jay et al. (2016). Simulation of single particle displacement damage in silicon–Part II: Generation and long-time relaxation of damage structure. IEEE TNS, 64(1), 141-148.

- Aim : Develop a simulation method to study displacement damage events at the atomic level, on realistic times compared to experiments



1. Particle-Matter interaction

2. Damage evolution, Annealing

3. “Stable” configuration

n in Si → Primary knock-on atom → Displacement cascade → Stable defect configuration → Charge generation center → Exp. dark current

n in Si → **MC*** → **Energy, species** → **MD**** → **Damage atomic structure (ps, ns)** → **k-ART***** → **Damage atomic structure (ms, s)** → **Ab initio** (First Principle) → **Energy level in bandgap**

Courtesy of M. Raine (CEA DAM)

*MC = Monte Carlo

**MD = Molecular Dynamics

***k-ART = Kinetic Activation-Relaxation Technique

Annealing Behavior of DD Induced Dark Current: Point Defects

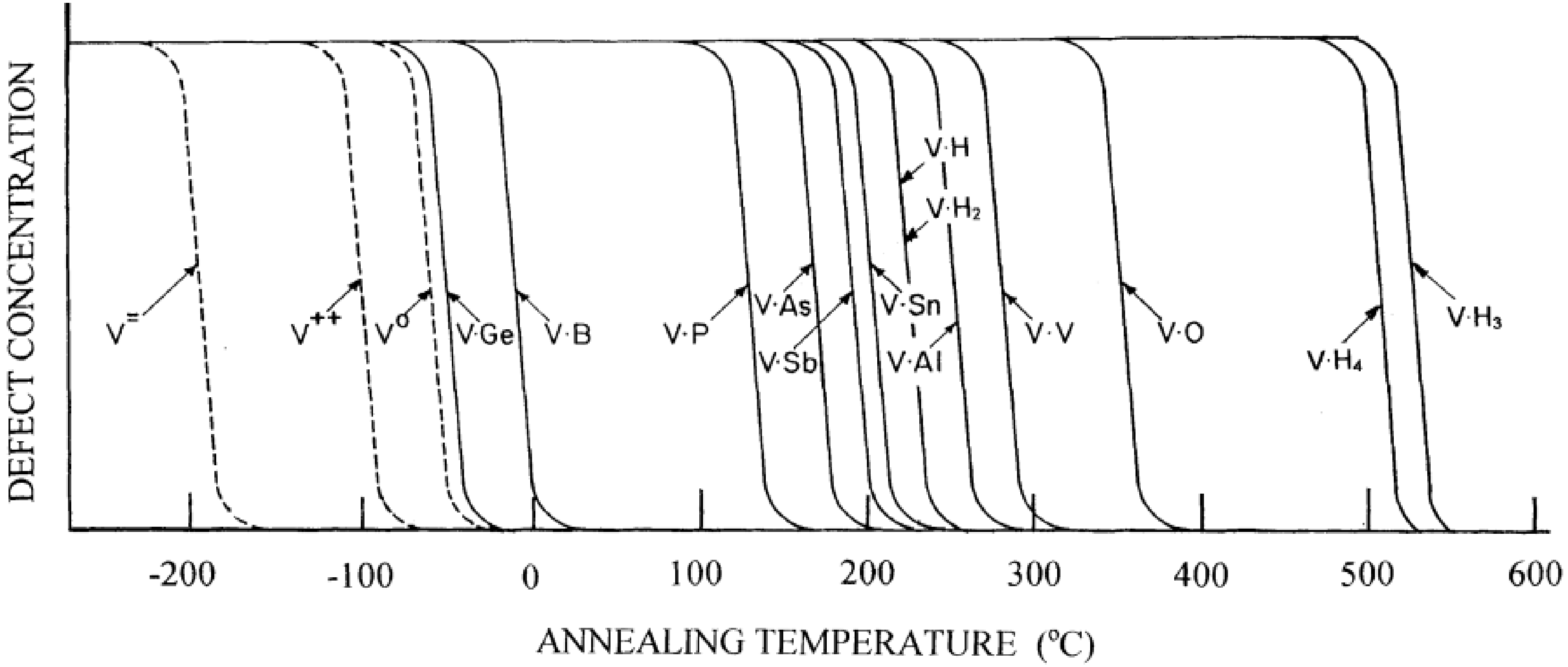
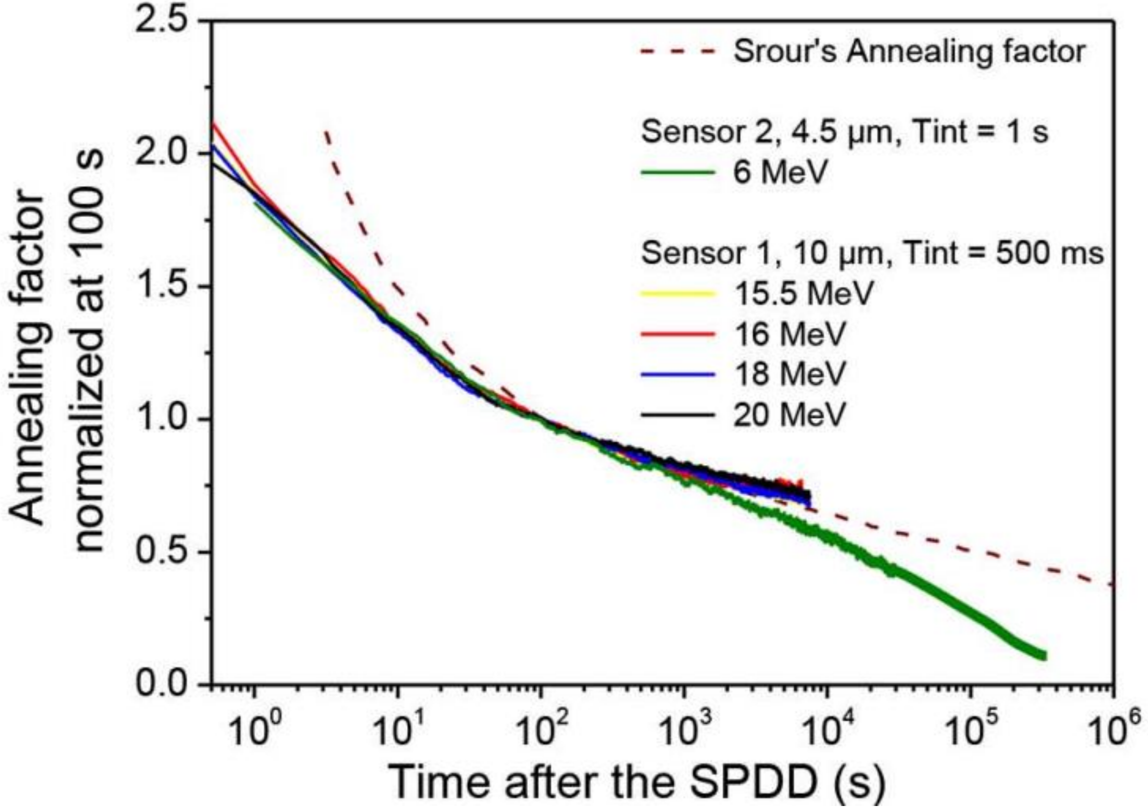


Fig. 4. Schematic of vacancy and vacancy-defect pair annealing stages (~15–30 min isochronal), from Ref. [5].

Watkins GD. In: Hull R, editor. Properties of crystalline silicon. London: INSPEC, 1999 [Chapter 11.1].

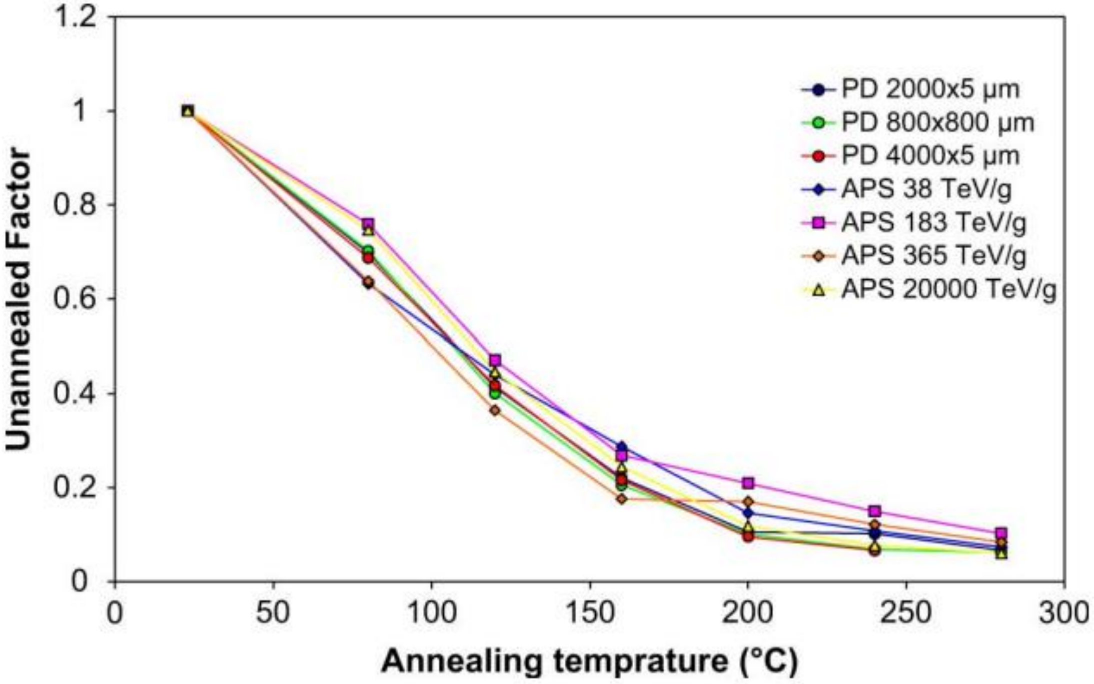
Annealing Behavior of DD Induced Dark Current: Defect Clusters

Room temperature annealing of DD induced dark current (cluster dominated)



M. Raine *et al*., "Exploring the Kinetics of Formation and Annealing of Single Particle Displacement Damage in Microvolumes of Silicon," in *IEEE Transactions on Nuclear Science*, vol. 61, no. 6, pp. 2826-2833, Dec. 2014, doi: 10.1109/TNS.2014.2364397.

Annealing of DD induced dark current (cluster dominated) VS Temperature



Virmontois, C., Goiffon, V., Magnan, P., Girard, S., Inguimbert, C., Petit, S., ... & Saint-Pé, O. (2010). Displacement damage effects due to neutron and proton irradiations on CMOS image sensors manufactured in deep submicron technology. IEEE Transactions on Nuclear Science, 57(6), 3101-3108.

Annealing Behavior of TID Induced Dark Current

- DC anneals gradually with temperature
  - Even at room temperature
  - Accelerates above 70°C
  - More than 90% recovery above 200°C
- Contrary to MOSFET Gate Oxide, in Photodiode isolation oxides:
  - Interface states anneal out at lower temperature than the positive trapped charge!
  - Very high temperature are required to get rid of the positive trapped charge
- **Very different behavior** than the classical gate oxide!

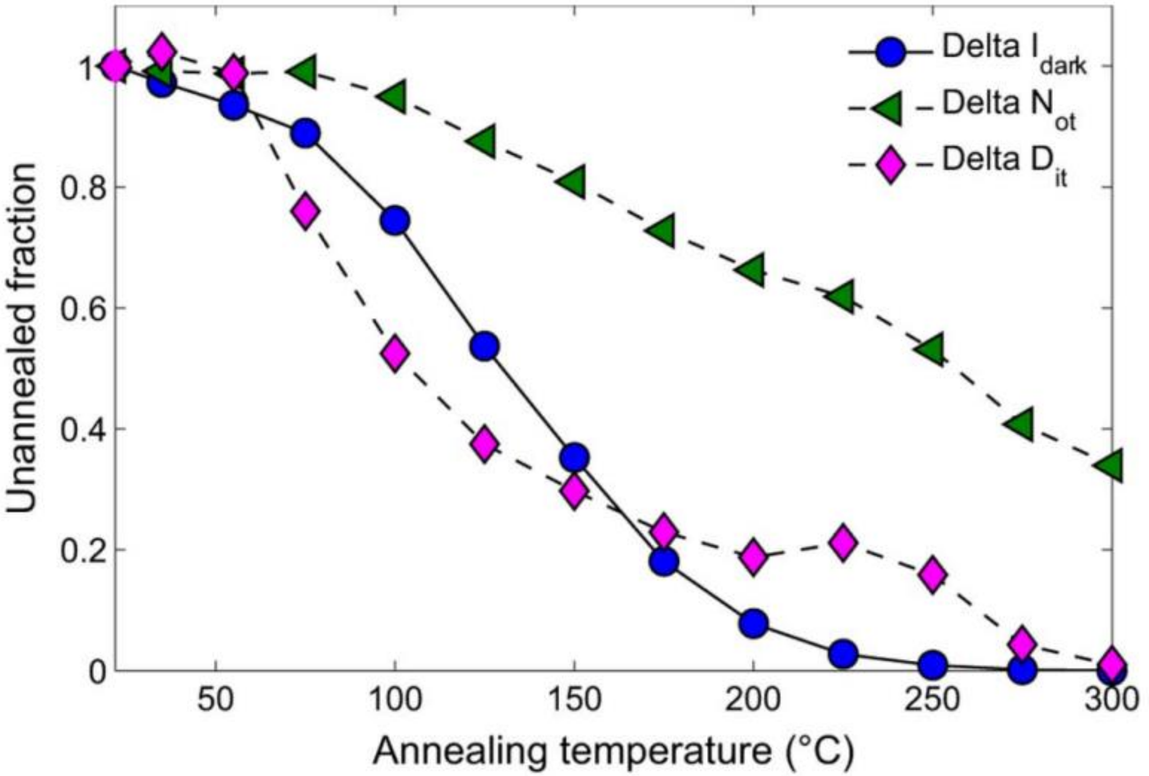


Fig. 11. Radiation induced photodiode dark current, trapped charge density and interface state density evolution during the isochronal annealing experiment (30 min isochronal annealing step duration).

Goiffon, V., Virmontois, C., Magnan, P., Girard, S., & Paillet, P. (2010). Analysis of total dose-induced dark current in CMOS image sensors from interface state and trapped charge density measurements. IEEE Transactions on Nuclear Science, 57(6), 3087-3094.

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