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SPACE RADIATION INDUCED DARK CURRENT DEGRADATION IN 5T PINNED PHOTODIODE 0.18µm CMOS IMAGE SENSORS

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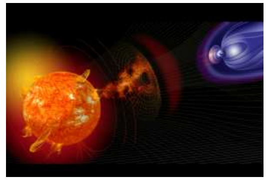
CONTEXT & GOALS OF THE STUDY

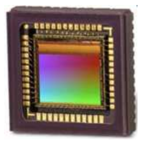
Context



- Radiation qualification methodology
  - A key issue for imaging sensors selection for space applications
  - Noticeable difference between on-ground and in-orbit dark current degradations (Penquer *et al*., IEEE TNS 2009)
- Previous study on SPOT 5 flight model CCDs (Martin *et al.*, IEEE TNS 2011)
  - Biasing condition and dose rate during ionizing irradiation have both a significant impact on the dark current degradation
  - Using on-ground irradiation test conditions as close as possible as in-orbit has provided a better real degradation estimation, still being conservative
  - ⇒ a possible way to improve on-ground test evaluation of imaging sensors

Study goals

- Main parameter of study : dark current
- Apply this methodology and investigate dose rate and biasing condition during ionizing irradiation on CMOS Image Sensors (CIS) based on 5T pinned photodiode (5T-PPD) pixels



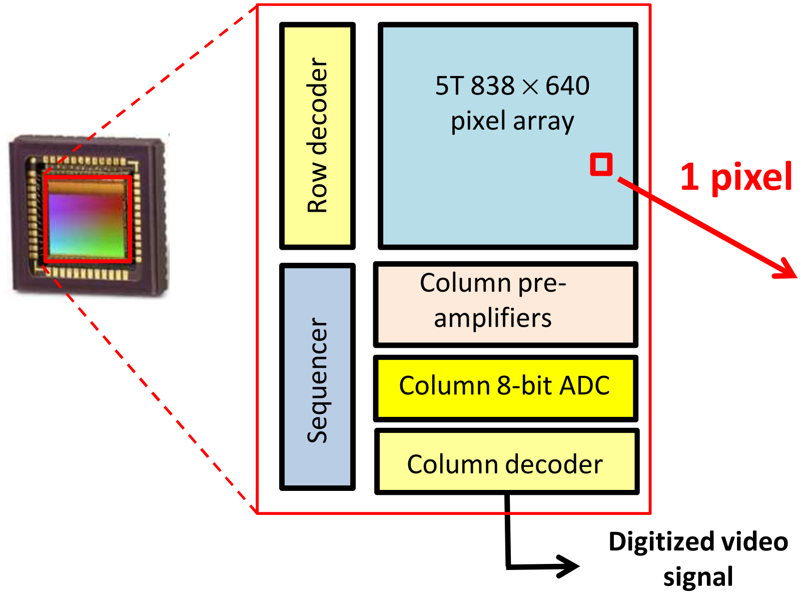
- Get an overview of displacement damage effects on 5T-PPD CIS
- Study Dark Current Random Telegraph Signal (DC-RTS) characteristics after Co^{60} and proton irradiations

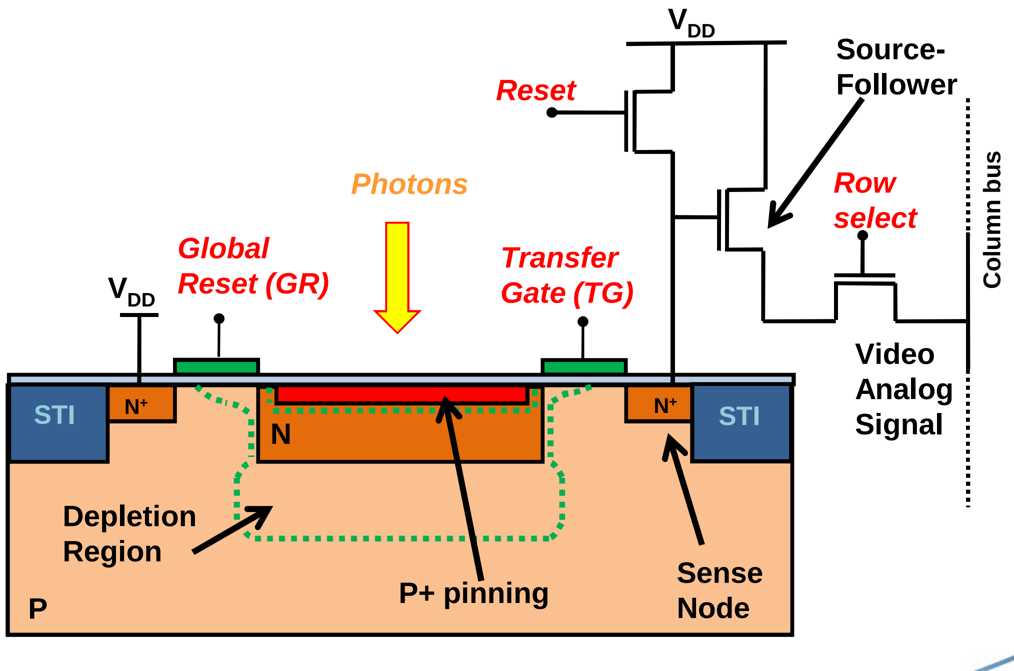
DEVICE FEATURES (1/2)

CMOS Image Sensors (CIS) based on pinned photodiode (PPD) pixel reach very high performances in terms of dark current and readout noise ⇒ serious candidates for space applications

5T-PPD CIS features

- 5T-PPD COTS device (EV76C454) from e2v (UK)
- 0.18 µm CMOS foundry process
- 838 × 640 pixel array
- 5.8 µm pixel pitch
- Column 8-bit ADC
- Not specifically radiation hardened





5T-PPD pixel

DEVICE FEATURES (2/2)

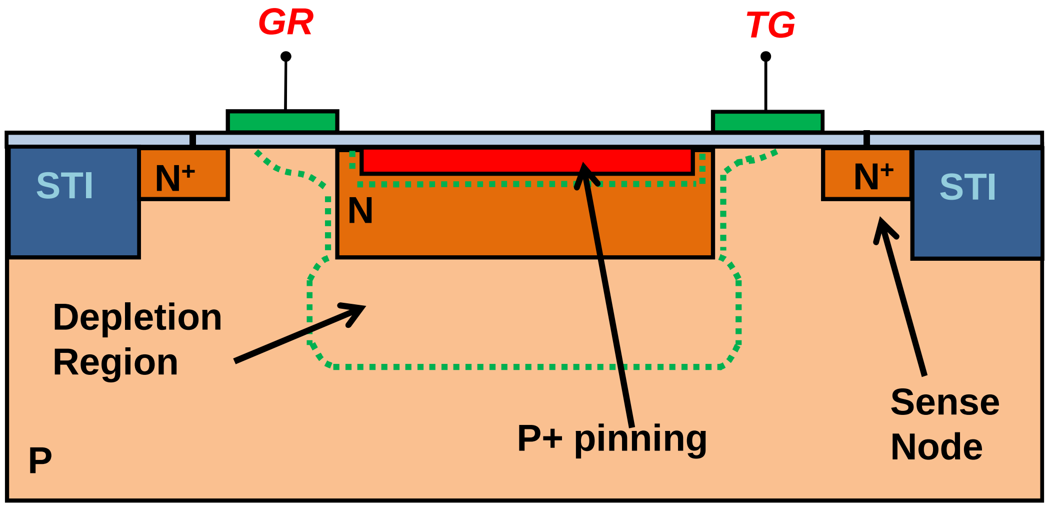
Sensor operating conditions

- Global reset mode
- In-pixel antiblooming during integration (GR~100s mV)
- All dark signal measurements performed at 23℃

Particular attention to TG and GR off-voltages

- During integration
  - TG off-state = 0 V
  - GR off-state ~ few mV (for antiblooming)

  ⇒ Both TG and GR are in depleted mode during integration
- So the PPD depletion region extends below the gate oxides of TG and GR
- As COTS devices, no modification of TG and GR off-state voltages is allowed

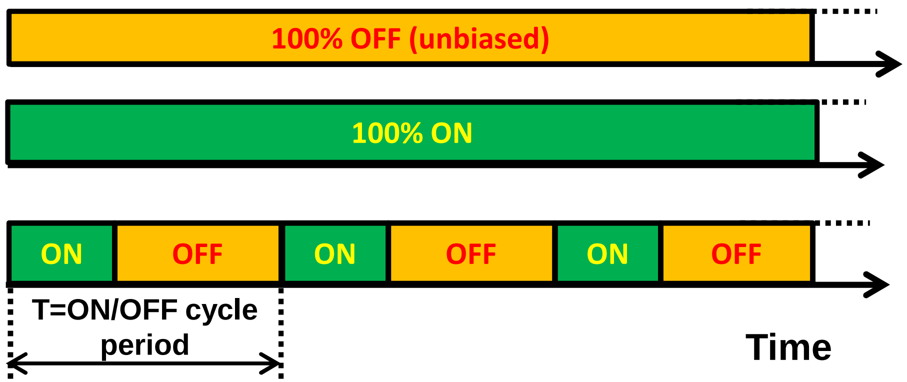


IRRADIATION PLAN

Co^{60} γ-rays irradiations

- Total Ionizing Dose (TID) : up to 32 krad(SiO_2) at room temperature
- 3 distinct dose rates
- 3 biasing condition during irradiation

7% ON/OFF bias duty cycle is representative of SPOT5 mission in-flight operation



Dose rate (rad/h)	Biasing condition during irradiation				
	Off	7% ON with a period of 50 s	7% ON with a period of 500 s	7% ON with a period of 1000 s	100% ON
36	CIS 6	CIS 2	CIS 3	CIS 4 CIS 5	CIS 1
200		CIS 10			
10,000	CIS 9	CIS 8			CIS 7

Proton irradiations

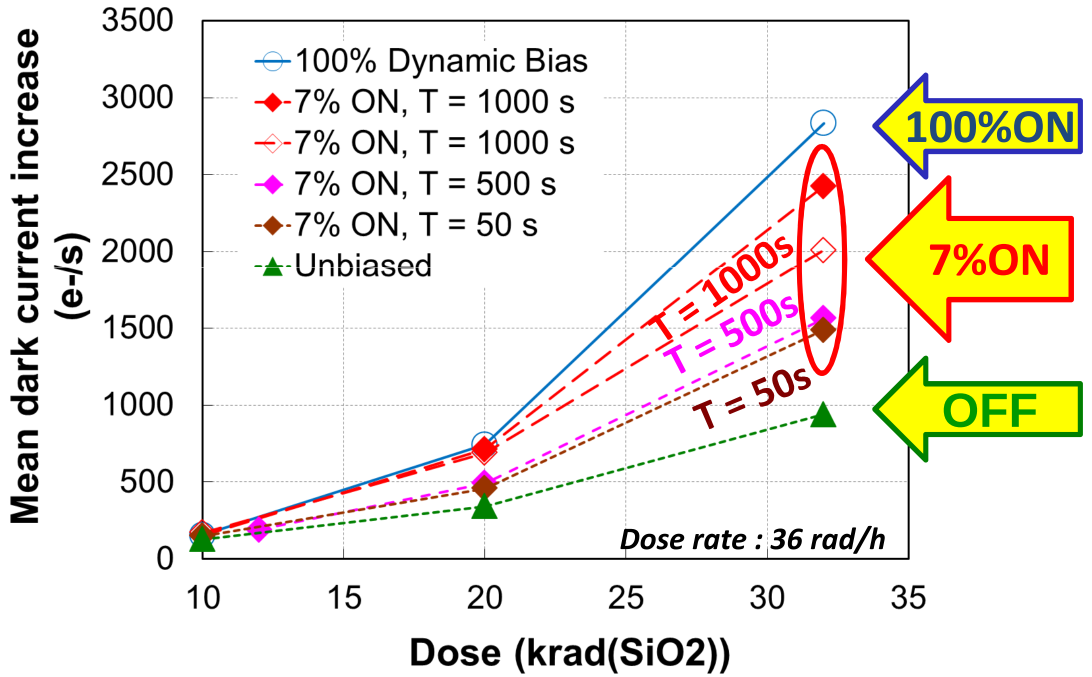
- Unbiased during irradiation
- 4 protons energies
- Displacement Damage Dose (DDD)
  - From 212 to 1020 TeV/g
- TID
  - also up to 32 krad

Device #	Proton energy (MeV)	TID (krad(SiO_2))	DDD (TeV/g)
CIS 11	185	10	319
		32	1020
CIS 12	120	10	264
		32	854
CIS 13	60	10	262
		32	838
CIS 14	30	10	212
		32	677

Co^{60} γ-RAYS IRRADIATION TEST RESULTS (1/4)

Effects of Biasing during irradiation (1/2)

- Biasing effects observed from 20 krad
- Worst case degradation for 100% ON biased device
- Enhancement of degradation with the ON/OFF cycle period



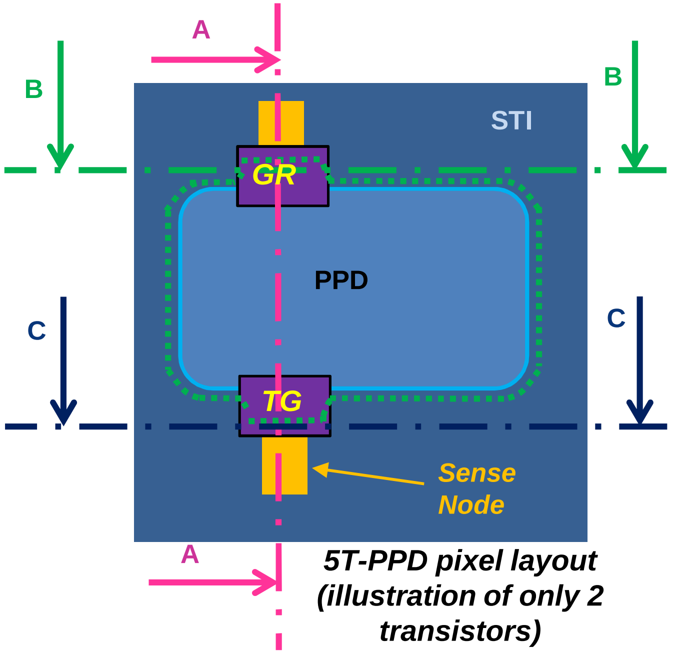
⇒7%ON degradation is bounded between unbiased and 100%ON degradation

⇒ Significant effect of biasing during irradiation on this device, why ?

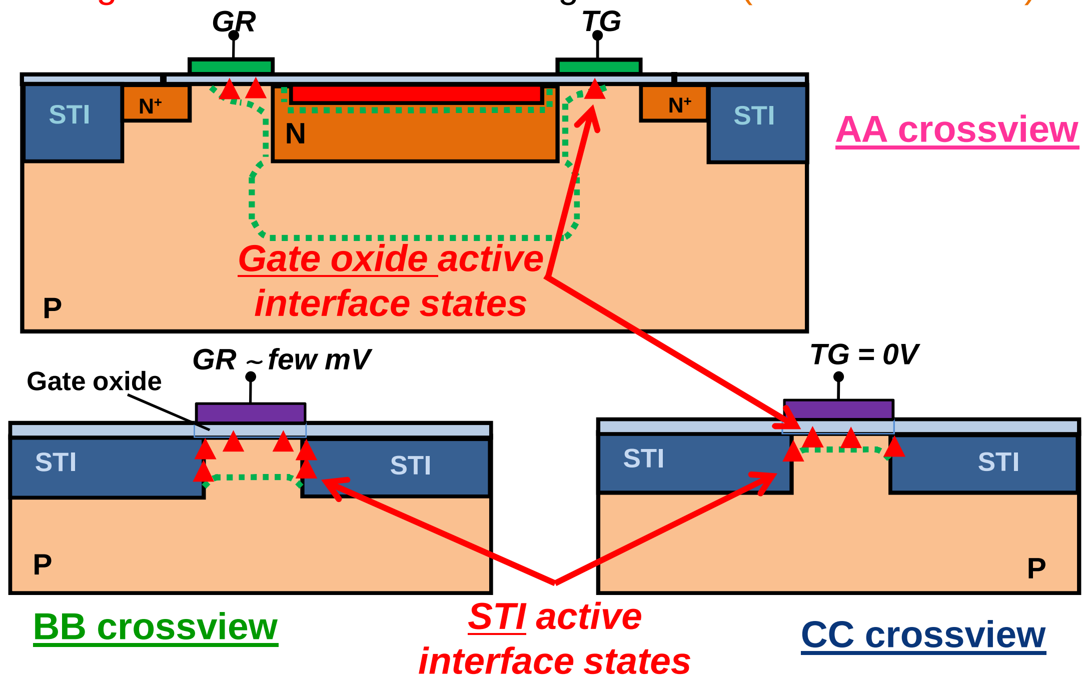
Co^{60} γ-RAYS IRRADIATION TEST RESULTS (2/4)

Biasing effects during irradiation (2/2)

- In the 5T-PPD CIS studied, most of the time TG and GR are in off-state mode (more than 99.99% of the complete { integration + readout } time)
- TG (off-state) = 0 V ⇒ very low electric field in TG gate oxide (= unbiased case)
- GR (off-state) ~ few mV ⇒ quite significant electric field in GR gate oxide (≠ unbiased case)



5T-PPD pixel layout (illustration of only 2 transistors)

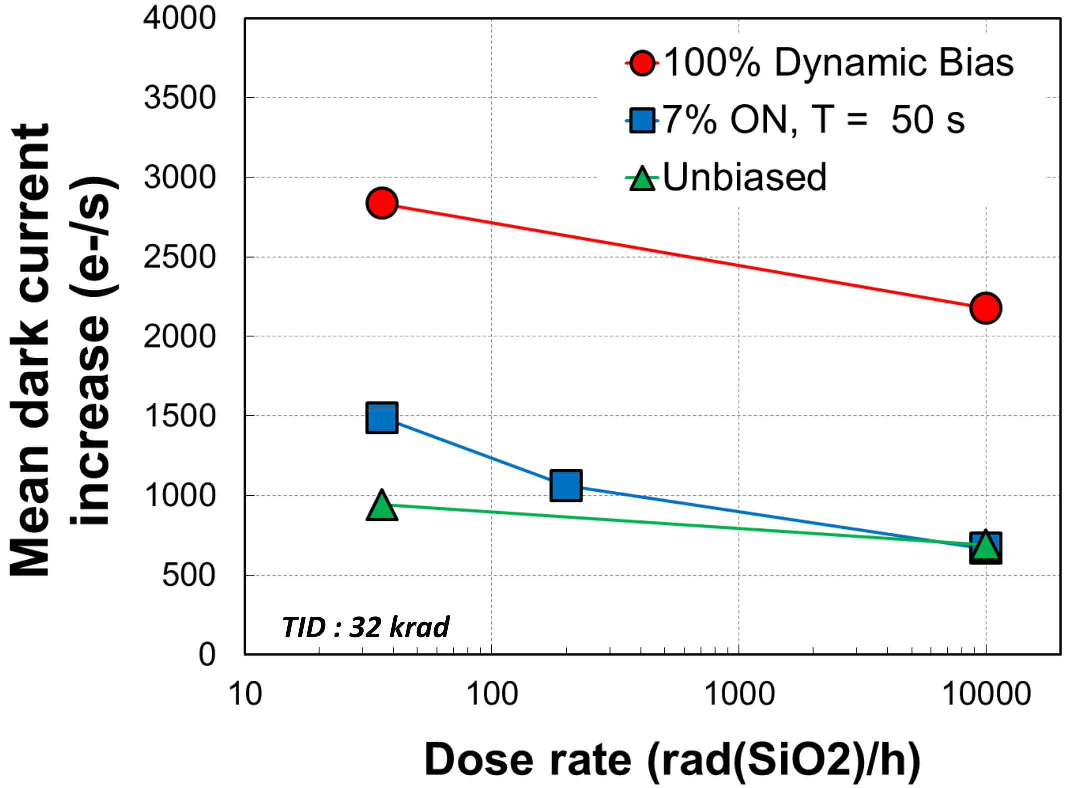


⇒ **Effect of biasing during irradiation probably due to active interface states located at Si-SiO_2 interface in the GR surrounding area (STI or gate oxide)**

⇒ **Cause reinforced by the fact that no biasing effect is observed in 4T-PPD CIS up to 1000 krad (Goiffon *et al.*, IEEE TNS 2012)**

Co^{60} γ-RAYS IRRADIATION TEST RESULTS (3/4)

Dose rate effect



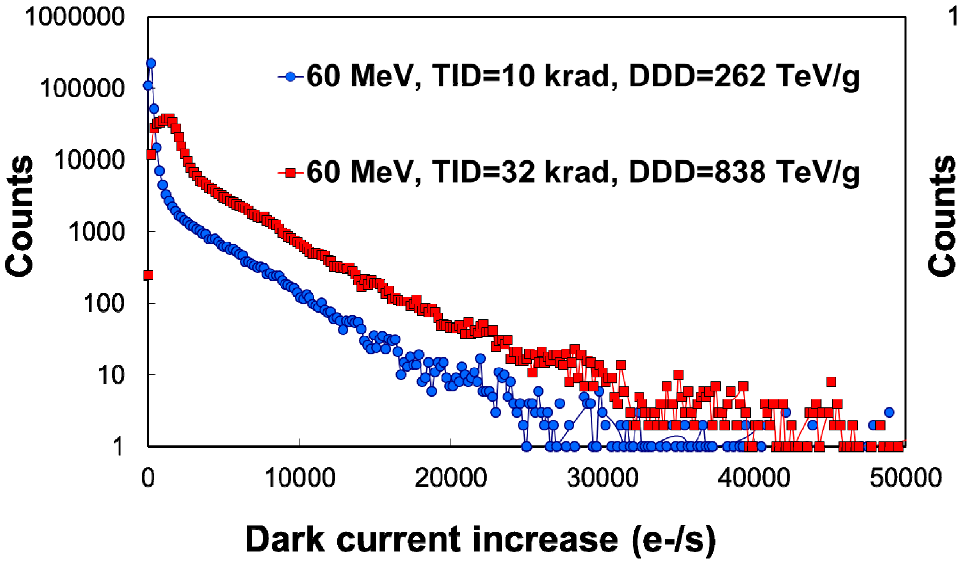
⇒ **Low dose rate presents more degradation than the high dose rate for all devices**

PROTON IRRADIATION TEST RESULTS (1/2)

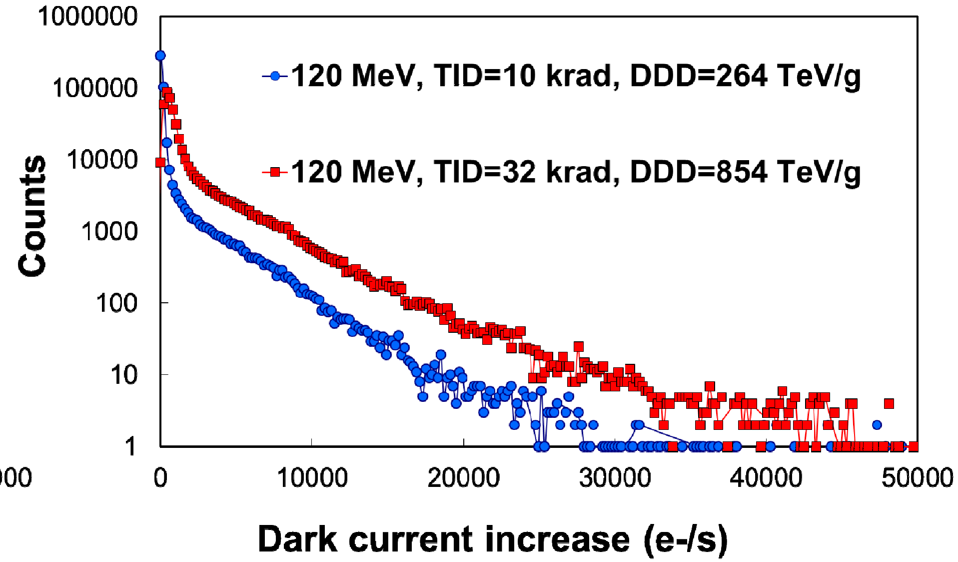
Dark Signal Non-Uniformity (DSNU)

- Presence of hot pixel tail with exponential tendency
- At a given TNID, the hot pixel tail is quite similar in the deposited fluence range for all the proton energy

60 MeV proton



120 MeV proton

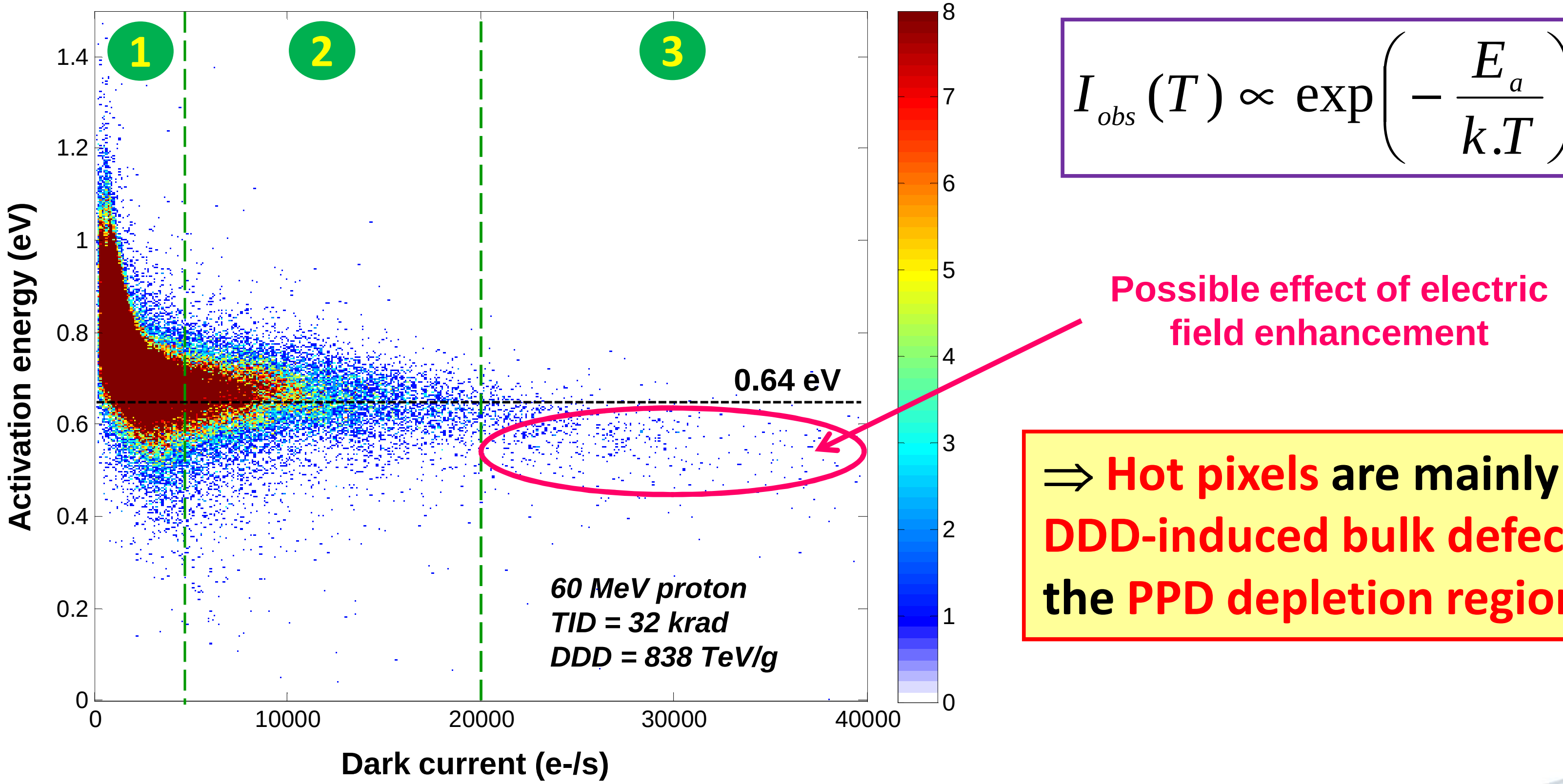


⇒ Mean dark current increase and the number of hot pixels both increase with the displacement damage dose (DDD)

PROTON IRRADIATION TEST RESULTS (2/2)

Dark current (I_{obs}) activation energy (E_a)

- E_a allows identifying the different mechanisms at the origin of dark current in the pixel
- Pixel population #1 : I_{obs} < 4000 e-/s (84% of all pixels) ⇒ diffusion and generation current
- Pixel population #2 : 4000 < I_{obs} < 20000 e-/s ⇒ mainly generation current
- Pixel population #3 : I_{obs} > 20000 e-/s ⇒ possible effect of electric field enhancement



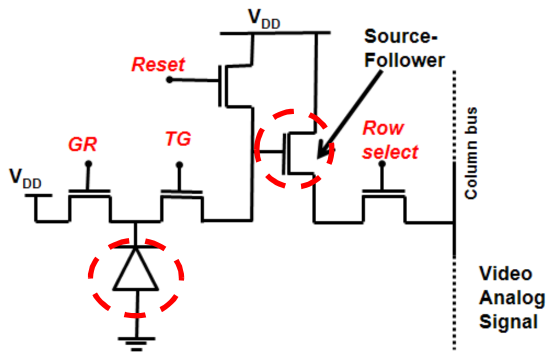
$$I_{obs}(T) \propto \exp\left(-\frac{E_a}{k.T}\right)$$

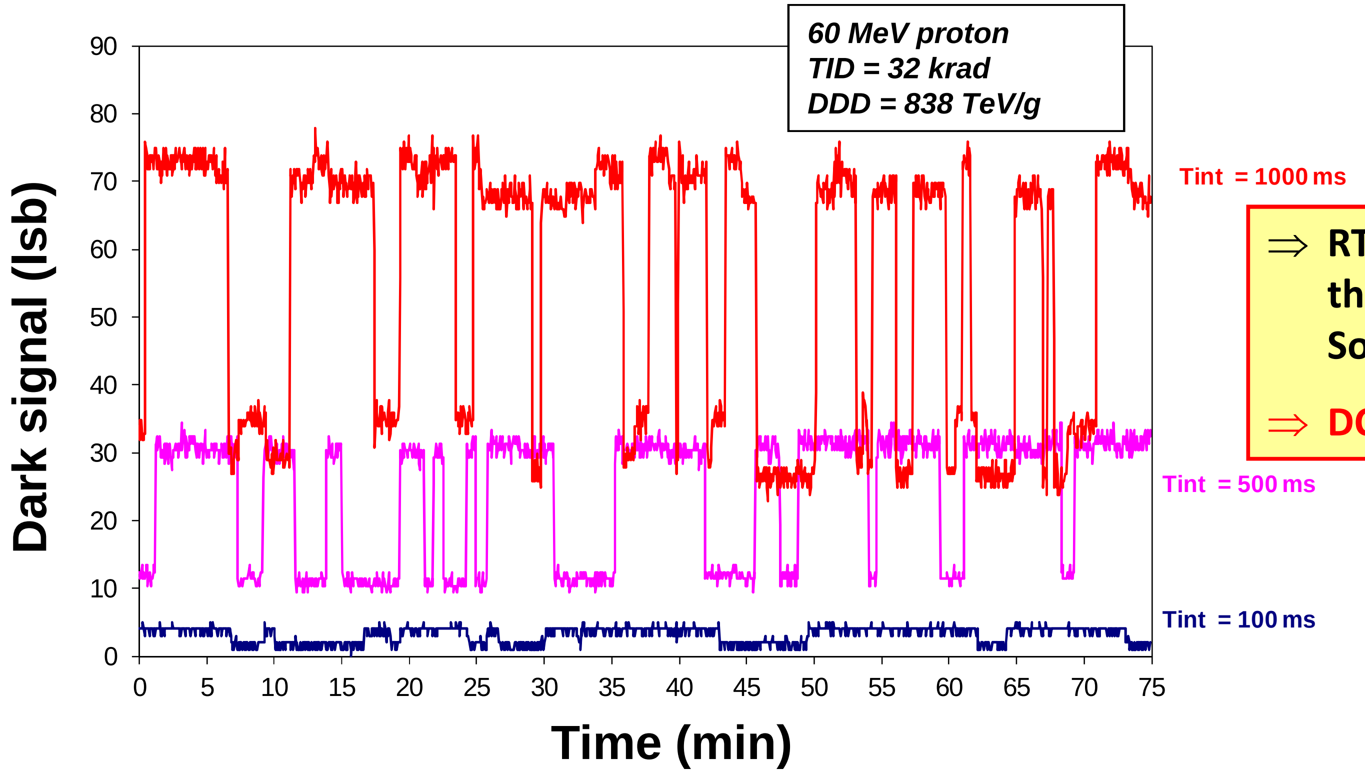
⇒ **Hot pixels are mainly due to DDD-induced bulk defects in the PPD depletion region**

DARK CURRENT RANDOM TELEGRAPH SIGNAL (DC-RTS) (1/4)

DC-RTS phenomenon

- Pixels exhibiting RTS noise are detected using sharp edge detection method (Goiffon *et al.*, IEEE TNS 2009)
- In 4T-PPD CIS, ionizing dose (Goiffon *et al.*, IEEE TNS 2012) and displacement damage dose (Virmontois *et al.*, IEEE TNS 2012) induce DC-RTS pixels
- What about DC-RTS in 5T-PPD CIS ?





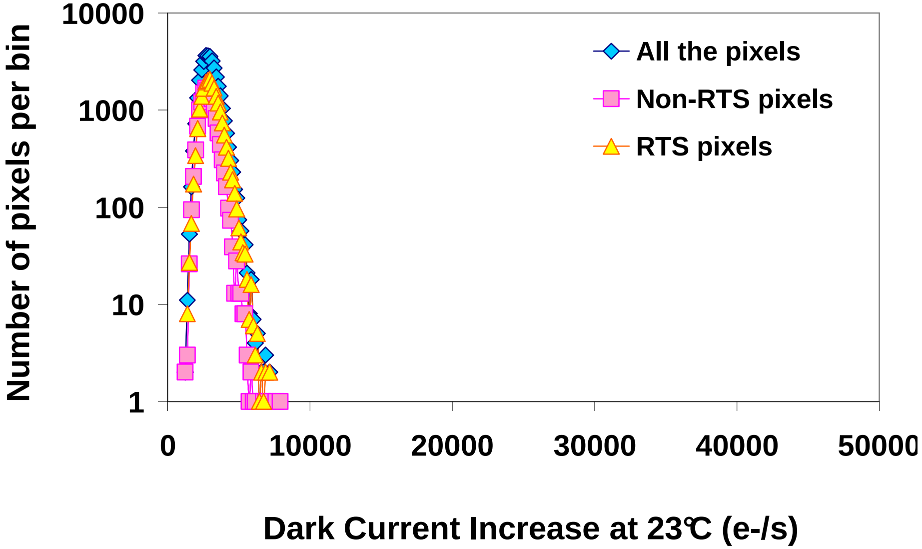
⇒ **RTS behaviour comes from the PPD (not from the in-pixel Source-Follower transistor)**

⇒ **DC-RTS (Dark current RTS)**

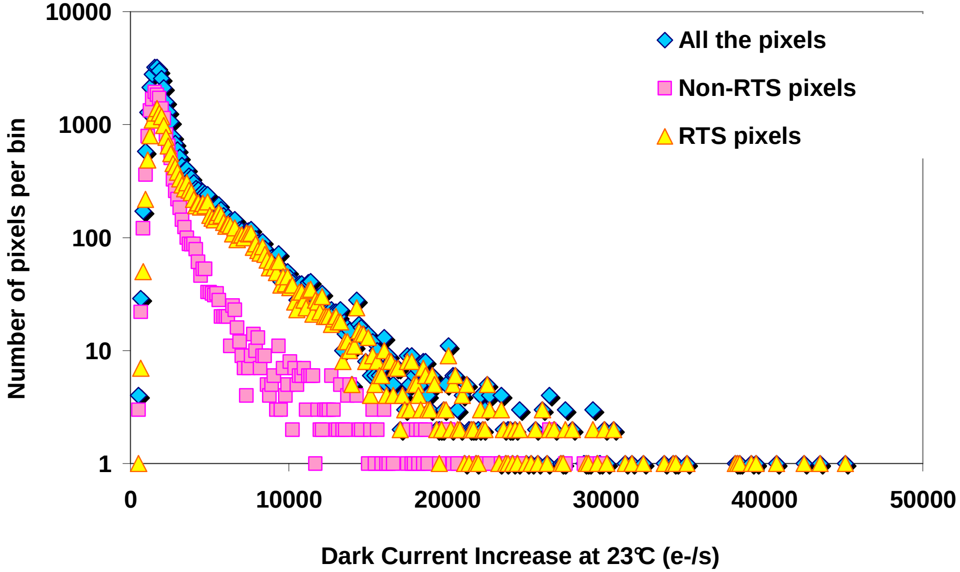
DARK CURRENT RANDOM TELEGRAPH SIGNAL (DC-RTS) (3/4)

Dark current degradation of RTS pixels

Co^{60} γ-rays
TID = 32 krad
7%ON biased (T = 1000 s)



60 MeV protons
TID = 32 krad
DDD = 838 TeV/g



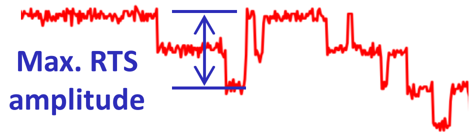
$\Rightarrow$ Similar distributions of non-RTS and RTS pixels

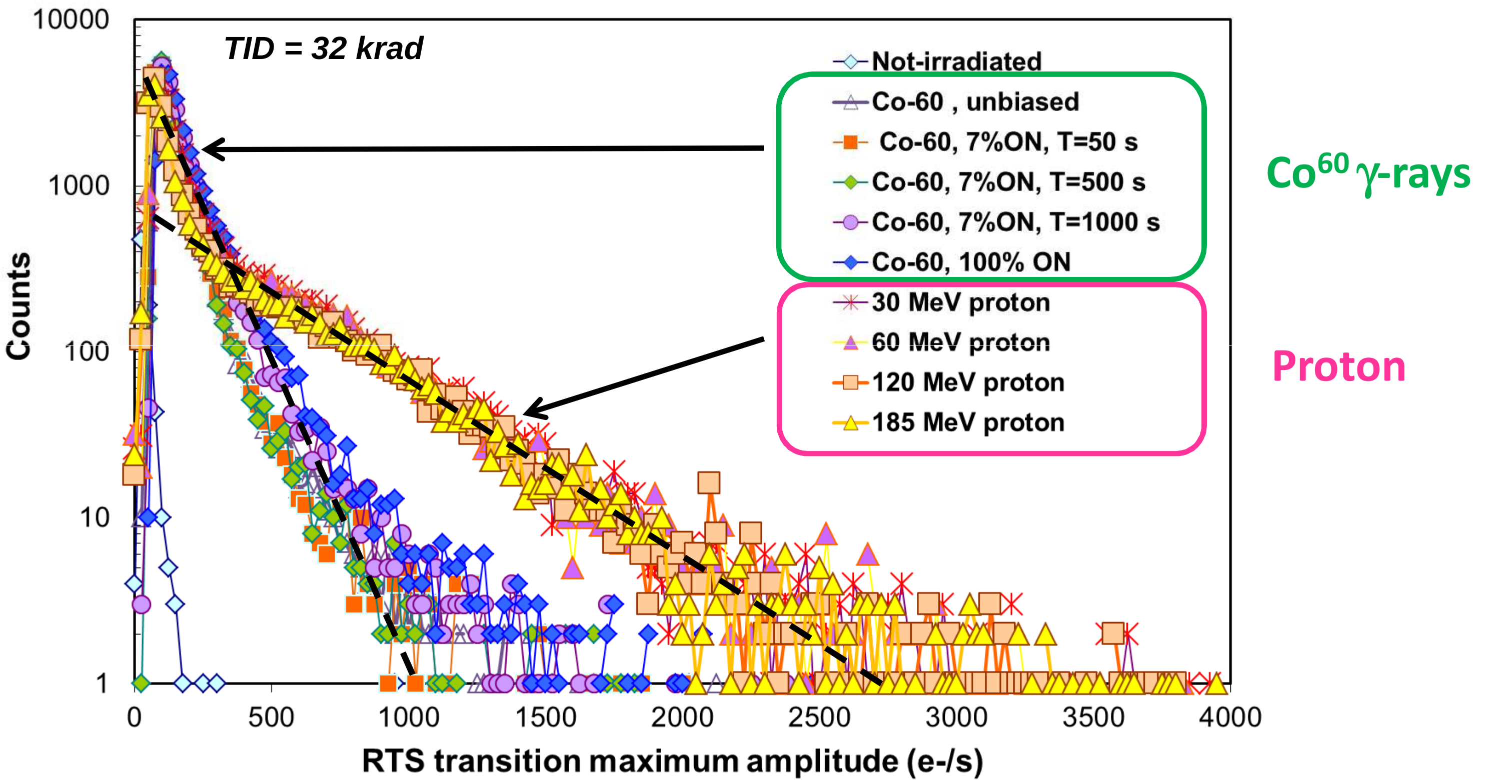
$\Rightarrow$ Hot pixels are RTS pixels in majority

DARK CURRENT RANDOM TELEGRAPH SIGNAL (DC-RTS) (4/4)

RTS transition maximum amplitude

- Allows studying only one metastable defect





⇒ **RTS fluctuation amplitudes ~3-4 times greater after proton irradiation in comparison to Co^{60}**

⇒ **2 exponential slopes according irradiation type as observed in 3T-PD (Virmontois *et al.,* IEEE TNS 2011)**

CONCLUSIONS

Total ionizing dose effects

- Effects of biasing during irradiation
  - Probably due to GR off-state voltage implementing in-pixel antiblooming function $\Rightarrow$ active interface states in GR surrounding area (STI and gate oxide)
  - Operating GR (and TG) in accumulated mode (off-state voltage <0V) could reduce or suppress the biasing effect (to be checked) as the PPD depletion region do not extend below GR and TG in this case
- Effects of dose rate
  - Probable involvement of thick oxide with weak electric field (such as the STI surrounding the PPD)

Displacement damage effects

- Presence of hot pixel tail with exponential tendency on the dark current distributions as observed in 3T-PD and 4T-PPD CIS

DC-RTS

- Hot pixels are mainly RTS pixels
- DDD induced RTS transition amplitudes are greater than TID induced ones at a given total dose

THANK YOU

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