Total Ionizing Dose Effects on a CDTI based CCD-on-CMOS through Buildup of Interface Traps and Oxide Charges

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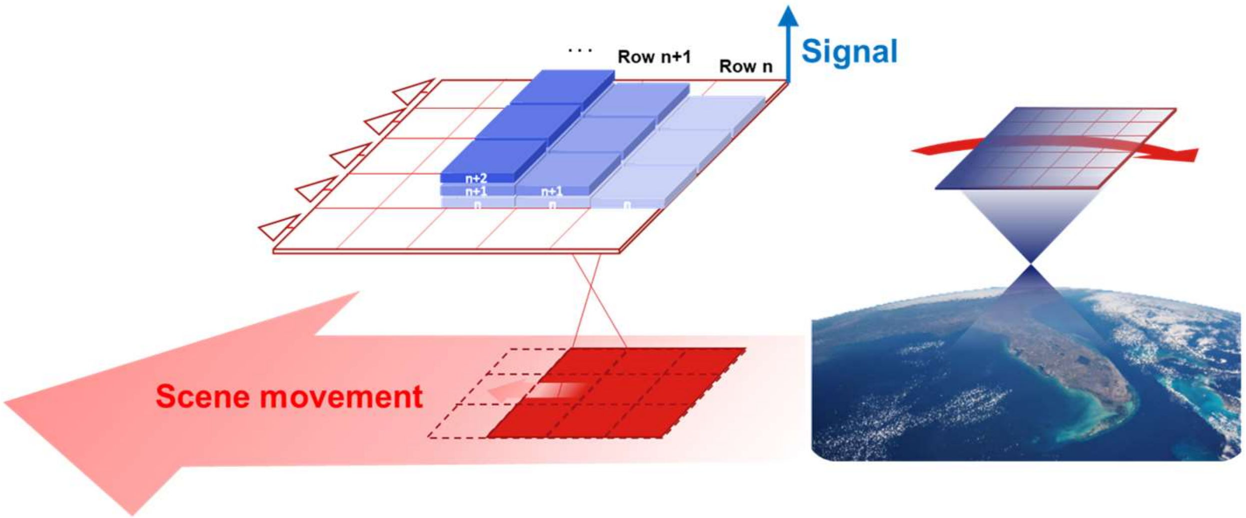
1 – Introduction

Motivations for developing CCD-on-CMOS devices

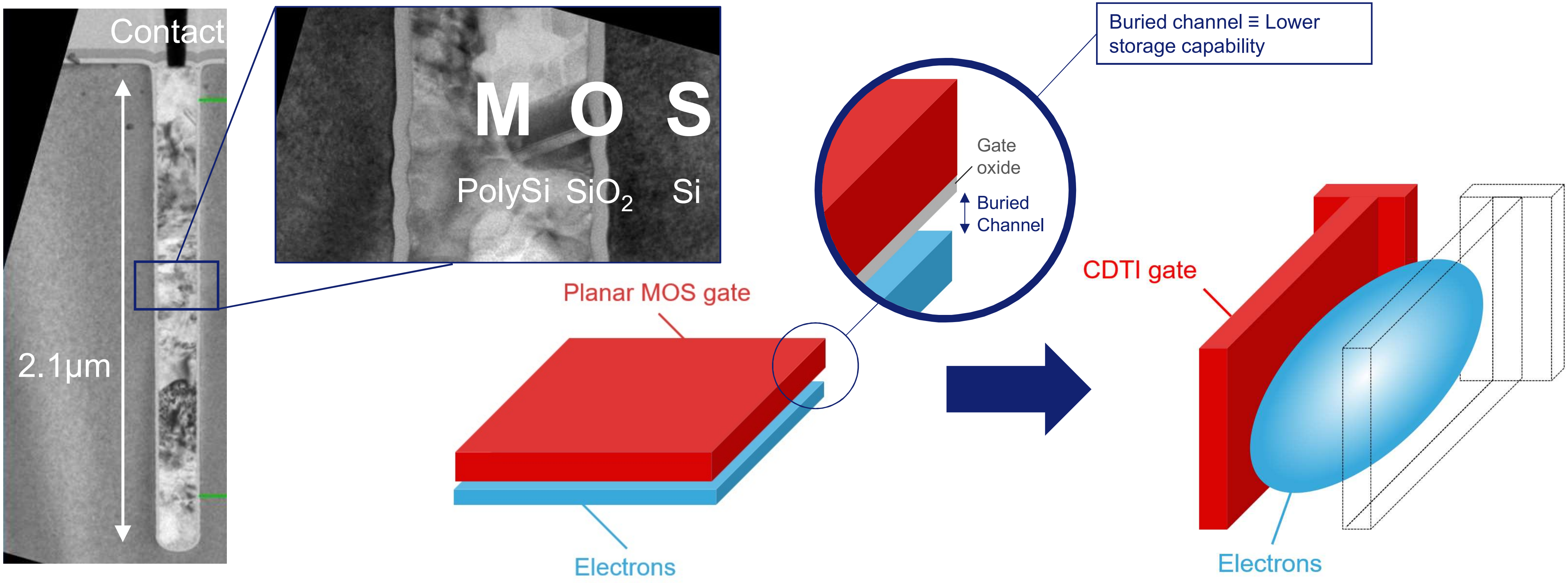
- **CIS :** High-Tech manufactoring process, high level of integration, low voltages and radiation hardness.
- **CCD-on-CMOS :** Perform « CCD missions » requiring charge domain operations : transfer, binning, avalanche etc…
- **Example :** High Resolution Earth imaging using Time Delay Integration (TDI)



- **The Investigation of TID effects is beneficial for :**
  - Assessing Space environment compatibility,
  - Improving the understanding of the device physical properties,
  - Informing on the hardness of CDTI based structures.

2 – Device description

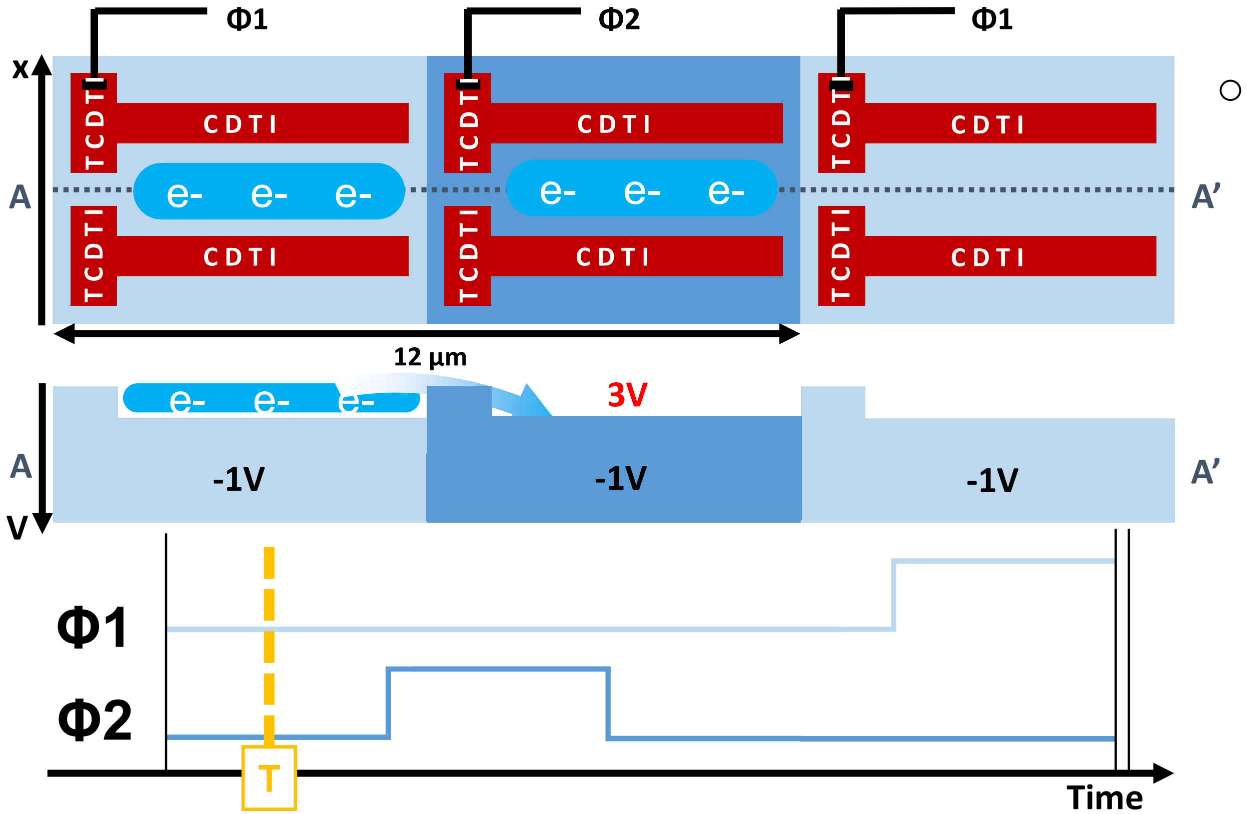
Capacitive Deep Trench Isolation (CDTI)



- Thanks to CDTIs the silicon bulk can be fully depleted by use of small voltages in a very large volume enhancing a large storage capability with electrical and optical crosstalks reduction.

2 – Device Description

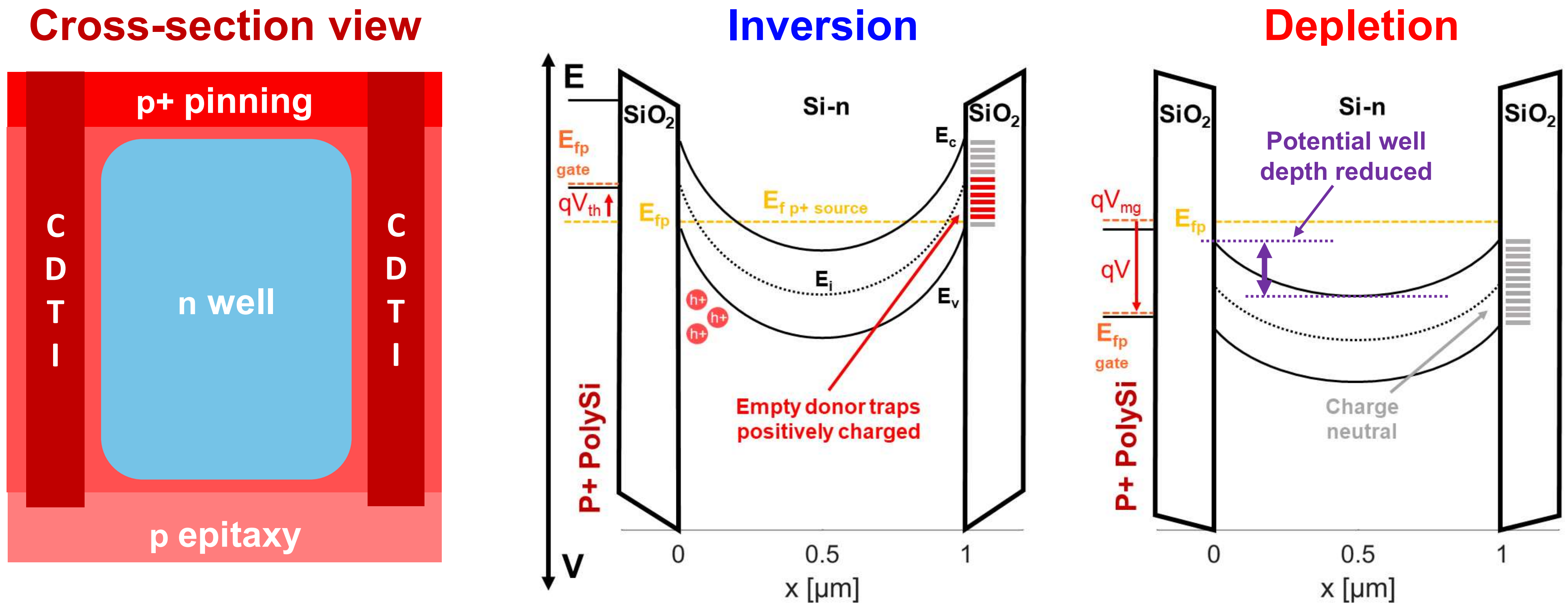
Charge Transfer Operation



- **2-Phase CCD :**
  - Low State : CDTI **inverted** ➔ Low Dark current.
  - High State : CDTI **depleted** ➔ High Dark current.
  - Short transfer time : Fully passivated ➔ **Multi-Pinned Phase Mode** (MPP).

2 – Device Description

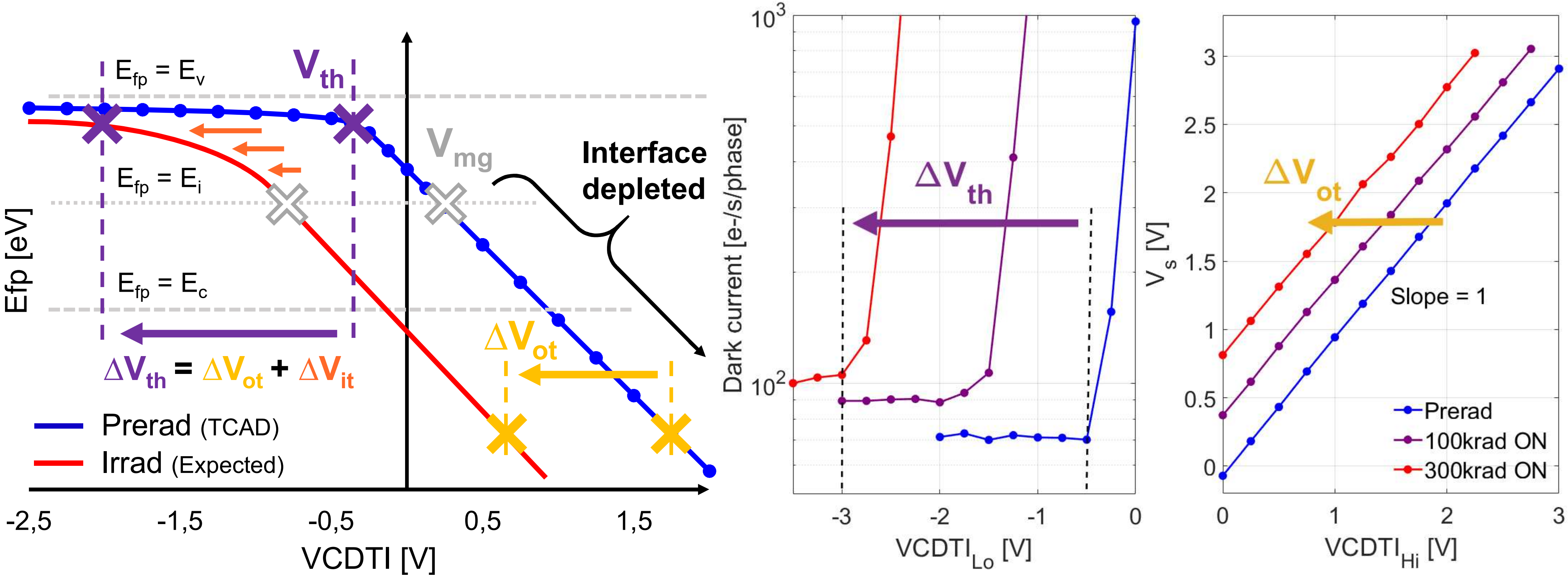
Band Diagram under full depletion



- The CCD is operated with interfaces inverted during storage and depleted during transfer. As a consequence, the interface trapped charge only fully contribute to the threshold voltage at inversion.

2 – Device Description

ΔV_{ot} and ΔV_{it} contributions and separation technique



- The studied shifts are dominated by ΔV_{ot} except when reaching inversion. ΔV_{it} is derived by subtracting ΔV_{ot} to the measured ΔV_{th}. ΔV_{ot} is obtained through potential barrier measurements under full depletion.

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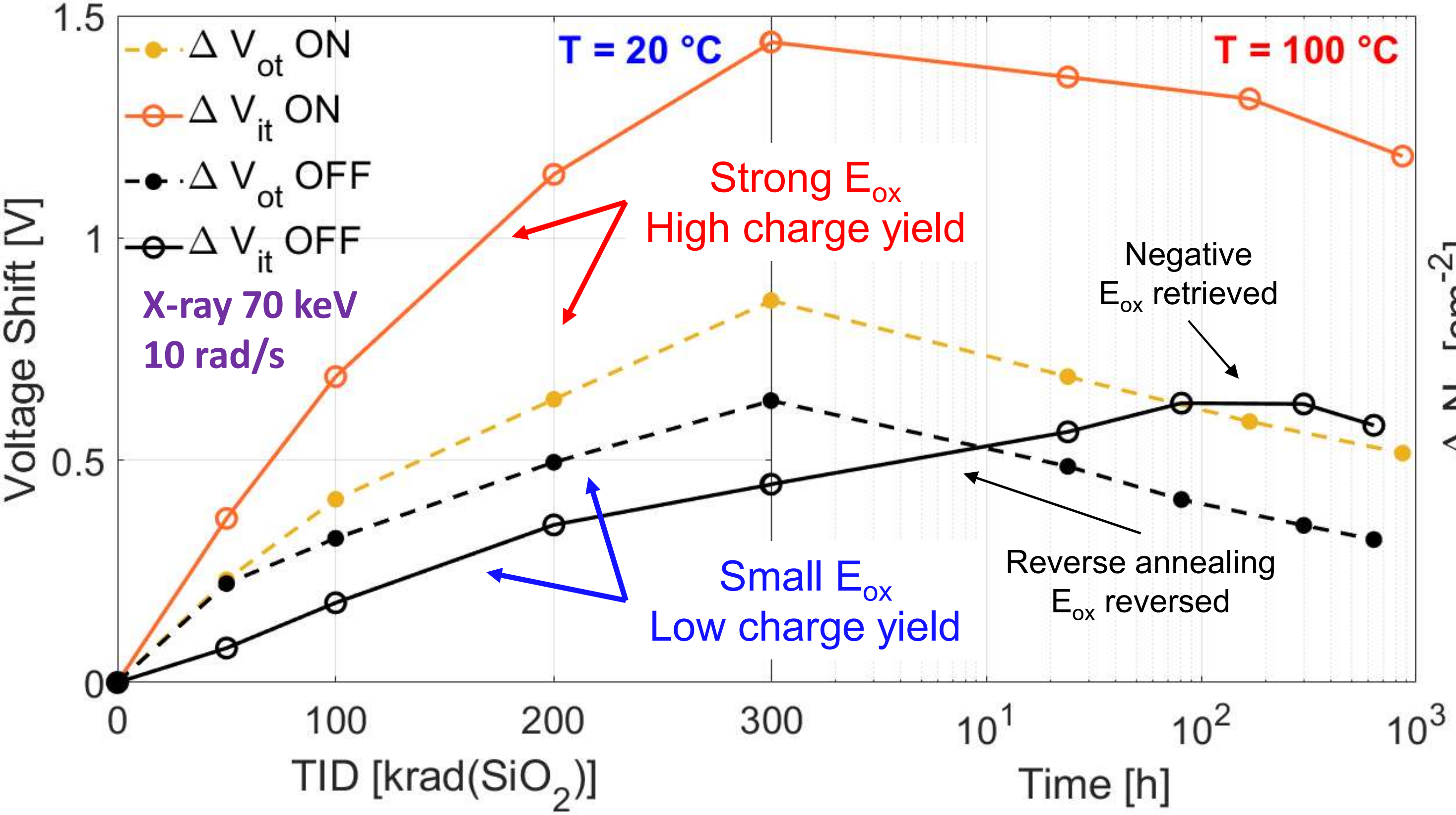
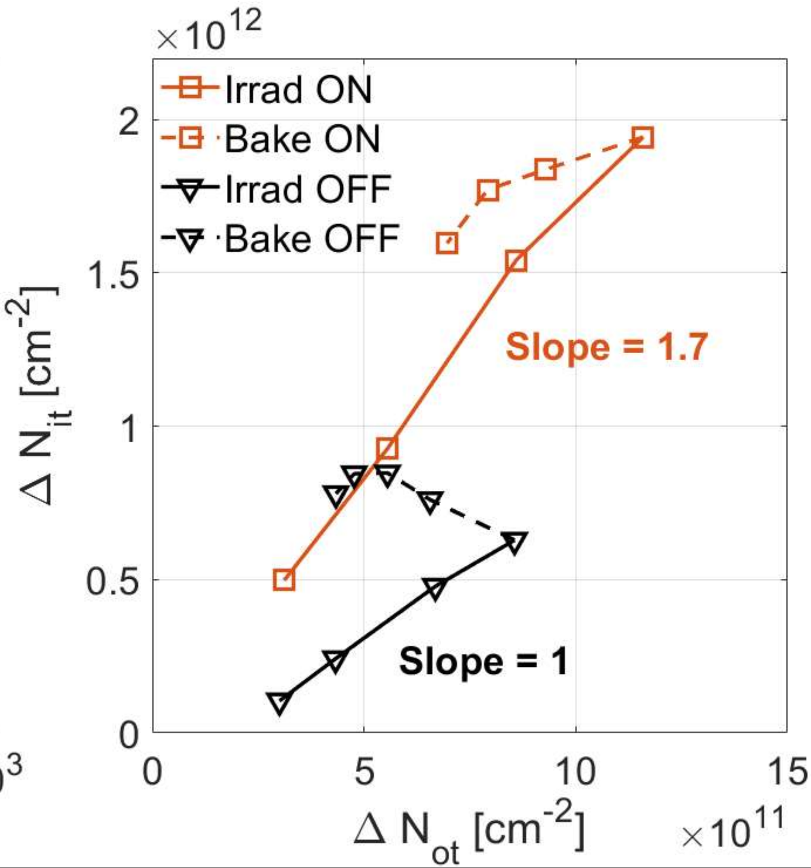
3 – Results

ΔV_{ot}, ΔV_{it}, ΔN_{ot} and ΔN_{it} versus TID and annealing

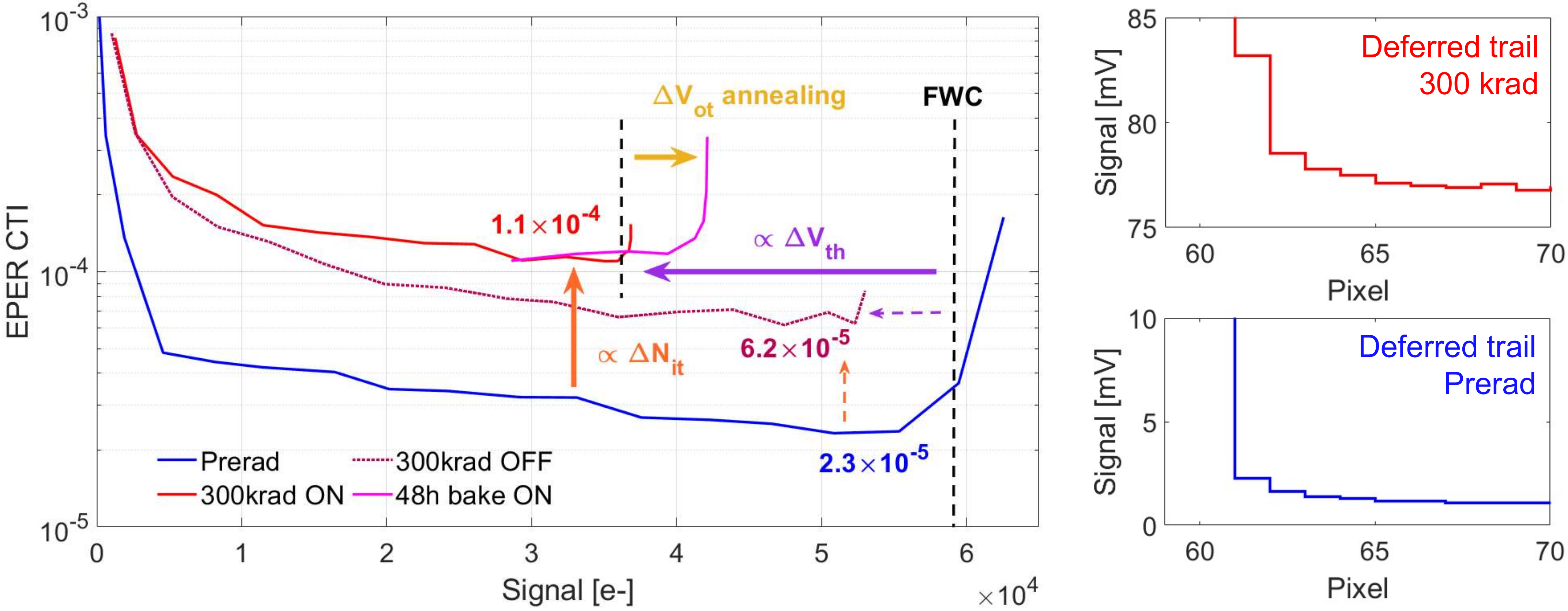




○ Charge yield and space charge effects in the oxide are noticeable during irradiation. ΔV_{ot} annealing is similar regarding both biasing, whereas ΔV_{it} exhibits some reverse characteristics when grounded.

3 – Results

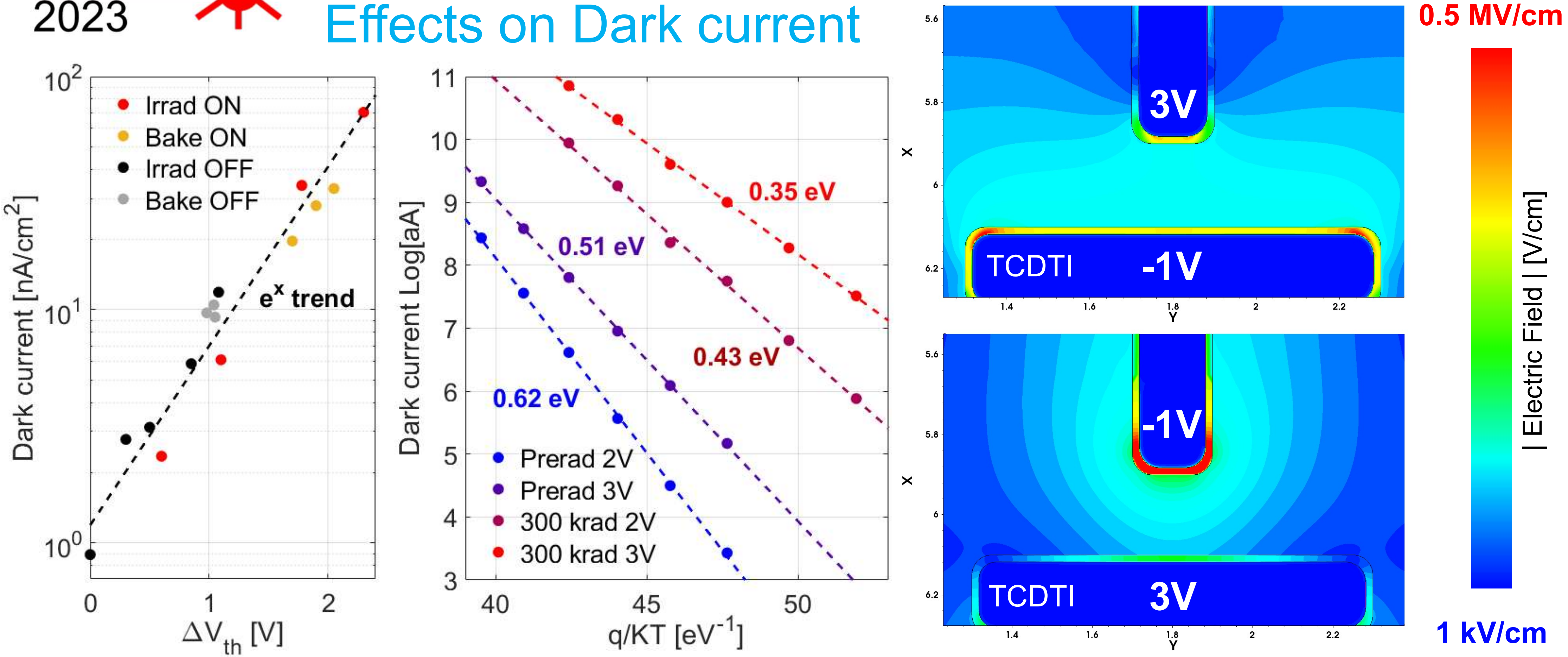
Effects on CTI and FWC



- FWC is reduced $\propto \Delta V_{th}$ (no time for detrapping) and CTI is increased $\propto \Delta N_{it}$. Annealing restores mostly FWC through ΔV_{ot} annealing (biased case). The OFF device is logically degraded in a lesser extent.

3 – Results

Effects on Dark current



○ Dark current exhibits an Electric field dependence with a reduced activation energy E_a. It originates from the surface potential difference yielded by two neighbour gates at V_{lo} and V_{hi} during charge transfer.

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4 – Conclusion

Takeaway notes

- A simple technique based on the properties of a Fully Depleted **CDTI-based CCD-on-CMOS** is successfully used to discriminate the role of **interface states (ΔNit)** and **oxide charges (ΔNot)**.

- By exploring biasing conditions and annealing, TID effects on **Dark current, FWC and CTI** are correlated to the respective trap concentrations buildup.

- Up to **300 krad under worst case scenario**, **no critical Ionizing Dose effects are observed :**
  - The device takes profit of the CMOS intrinsic radiation hardness and of the MPP mode mitigating surface dark current.
  - Effects on FWC and Dark current can be partially reversed by adapting biasing.

  ➔ Reducing further **E_{ox}** and **biases** is mandatory to yield the best performances.

*Biased during irradiation		**This Work***	DG SOI MOSFET (FG)* [B. Jun *et al.* IEEE TNS 2004]	Rad-Hard CCD* [D. Burt *et al.* SPIE 2009]
<ΔV_{th}/krad> [mV/krad]	<ΔV_{ot}/krad>	2.85	7.5	6
	<ΔV_{it}/krad>	4.81		-
<Dark current> @RT [pA/cm²/krad]		5 (1µs transfer)	-	20

Thank you for your attention

Workshop on Radiation Effects on Optoelectronics and Photonics Technologies

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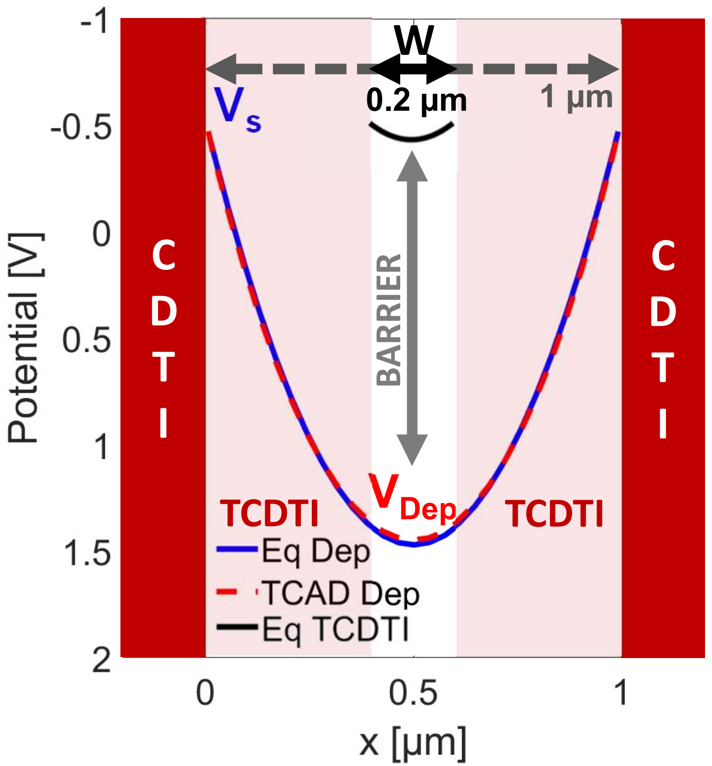
Backup Slides

2 – Device Description

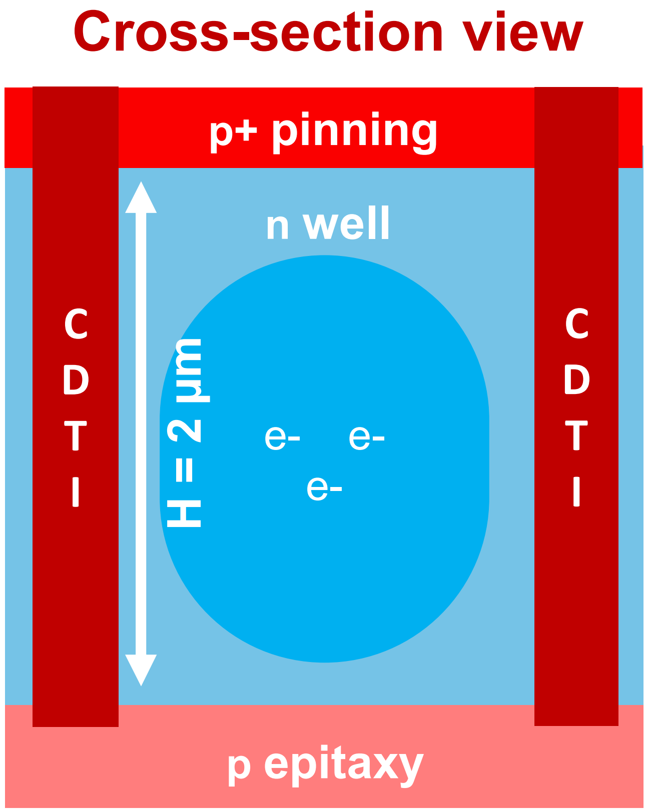
CDTI based pixel

Parabolic potential well :

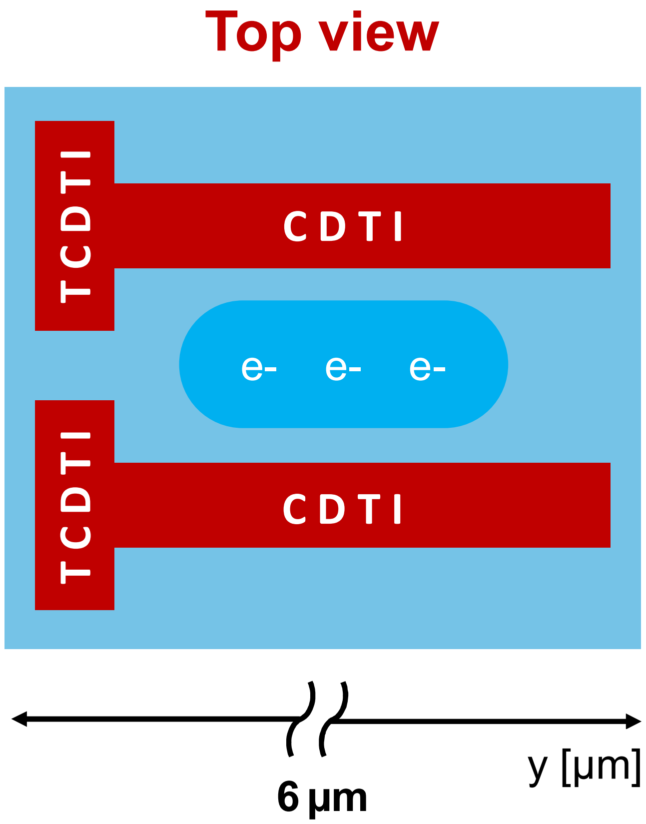
$$U(x) = \frac{-N_d q}{2\epsilon}(x^2 - \mathbf{W}x) + \mathbf{V_s}$$



Fully Depleted deep N-well Buried Channel :

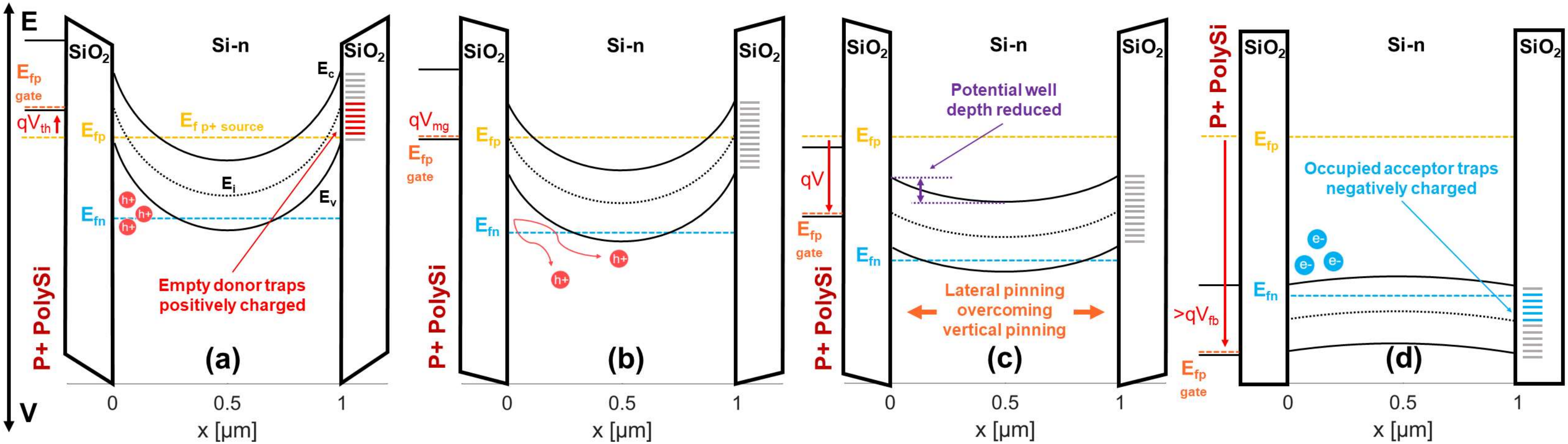


Phase design and pitch :



2 – Device Description

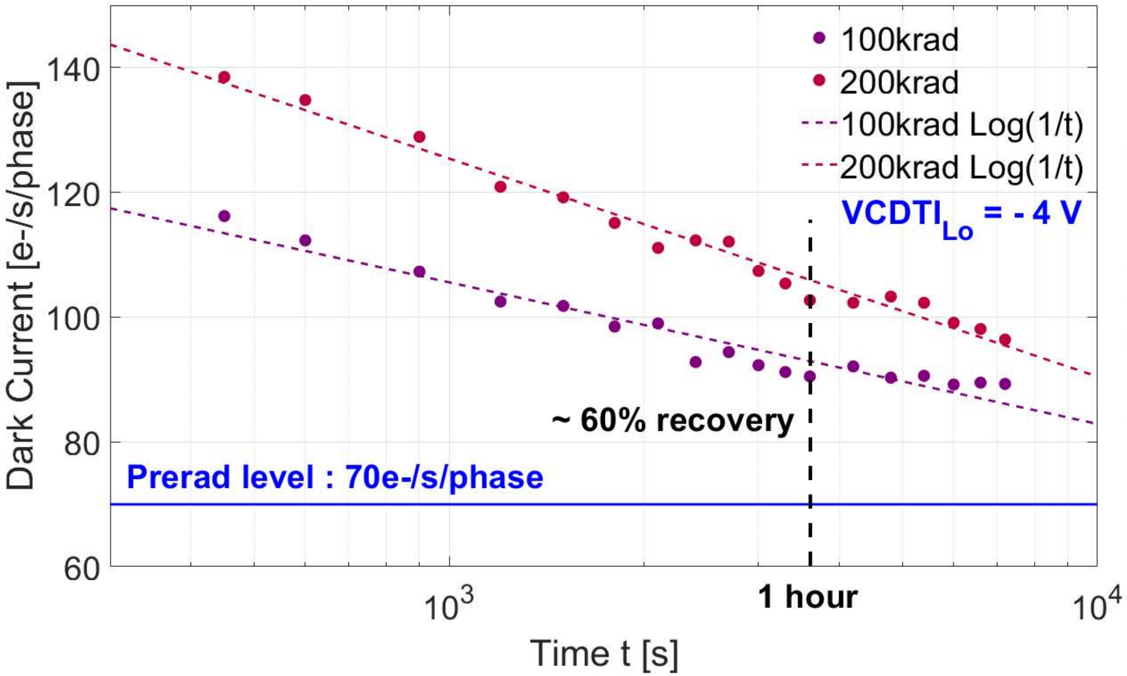
Band Diagram under full depletion

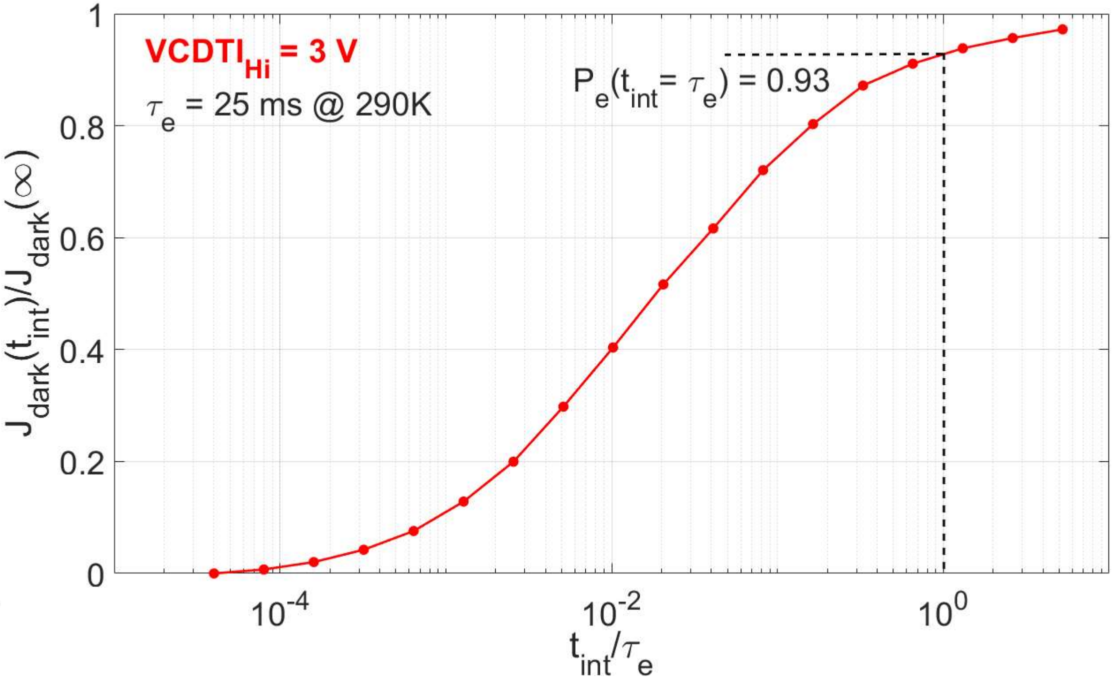


- The CCD is operated with interfaces inverted during storage and depleted during transfer. As a consequence, the interface trapped charge only fully contribute to the threshold voltage at inversion.

3 – Experimental Details

RT Annealing & depletion dark current



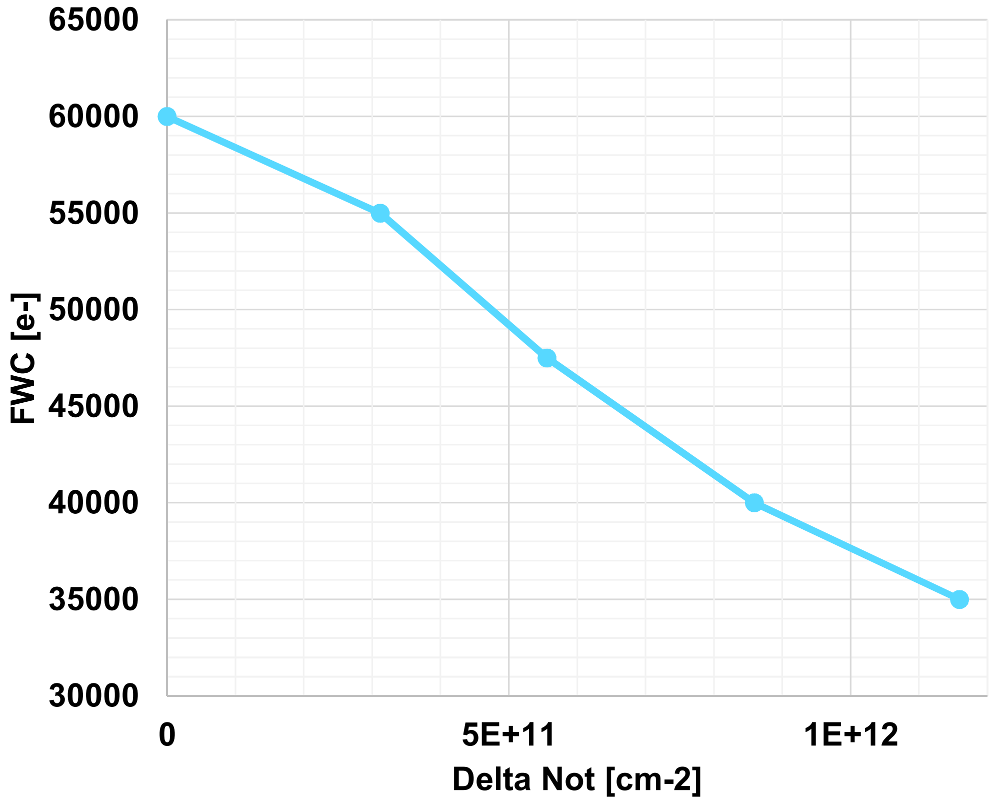


- RT annealing shows 60% dark current recovery after 1 hour. An other hour is needed for measurements, leaving two hours in between exposures (ESCC22900). Depleted dark current is steady after 2 to 3 τ_e.

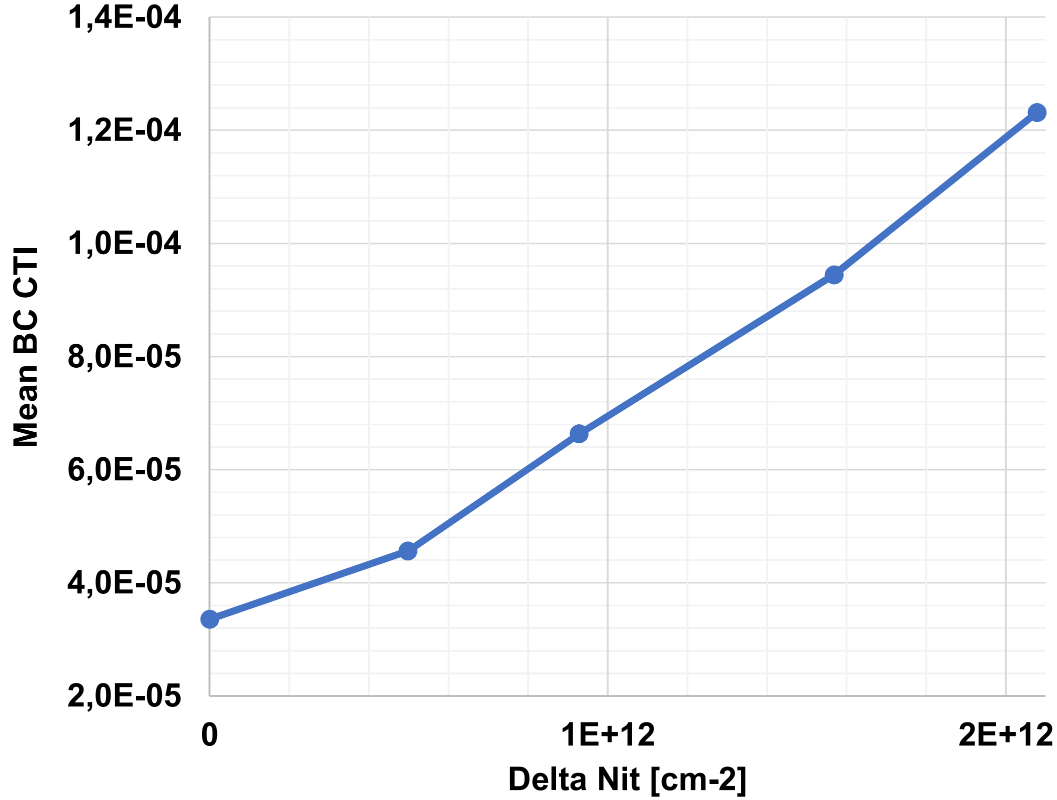
3 – Results

Effects on CTI and FWC

- **CTI : FWC vs Not**

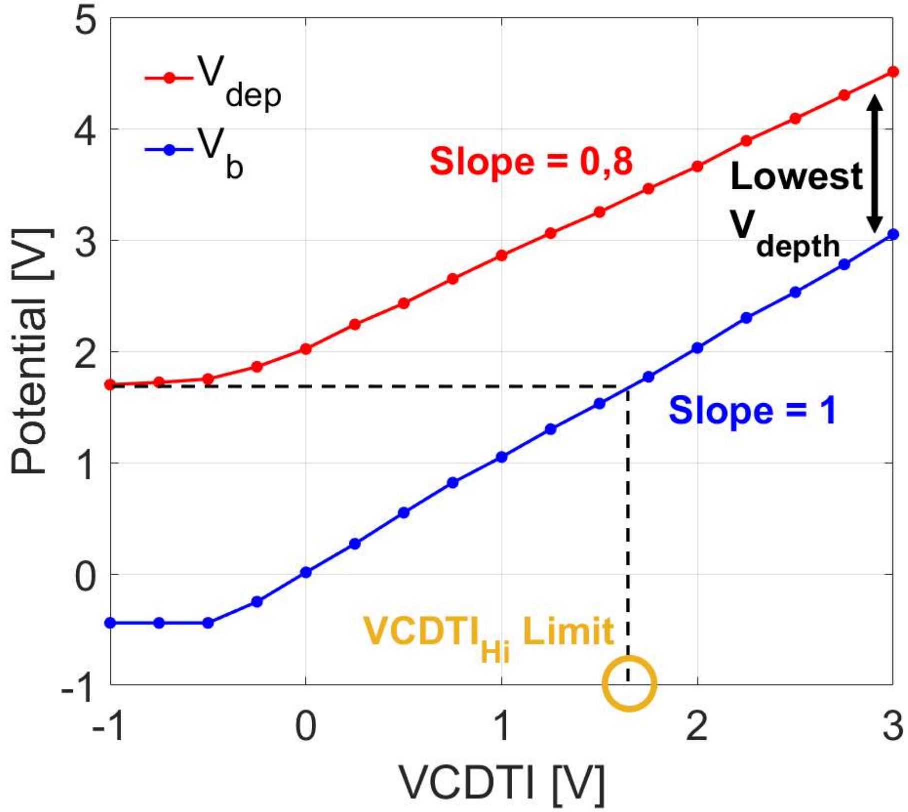


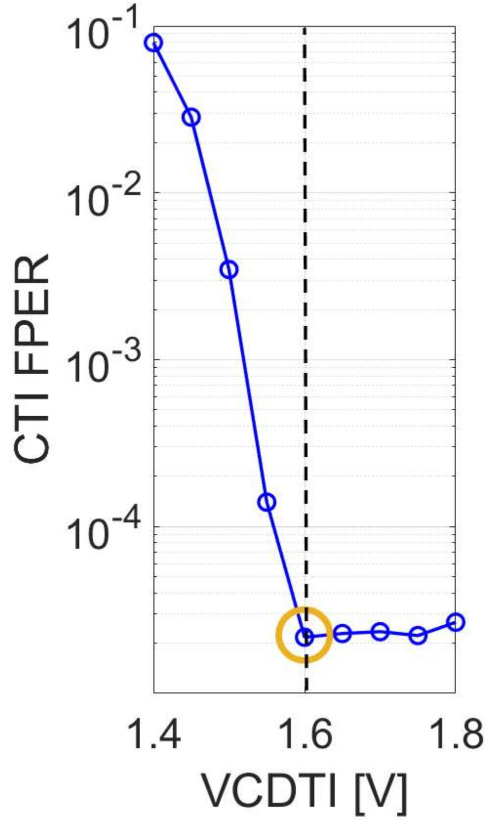
- **CTI : CTI vs Nit**



2 – Device Description

Charge Transfer Operation

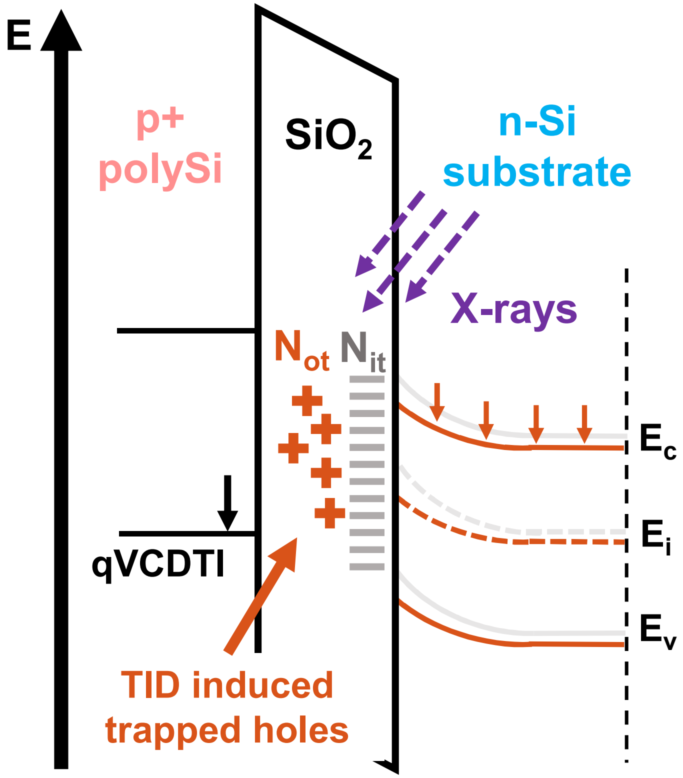


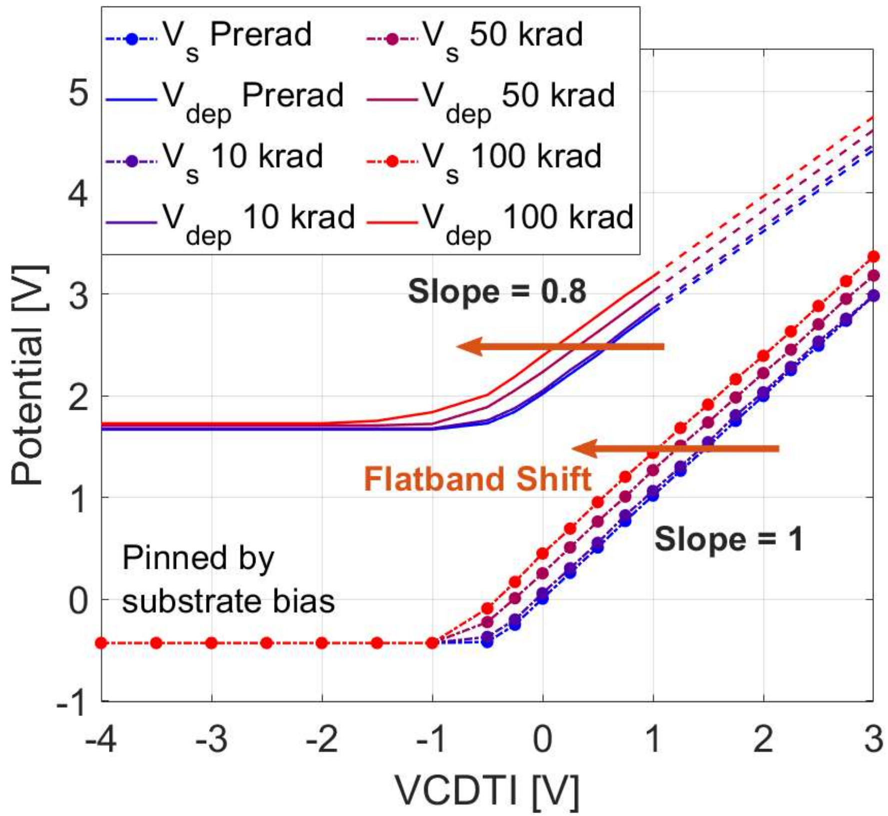


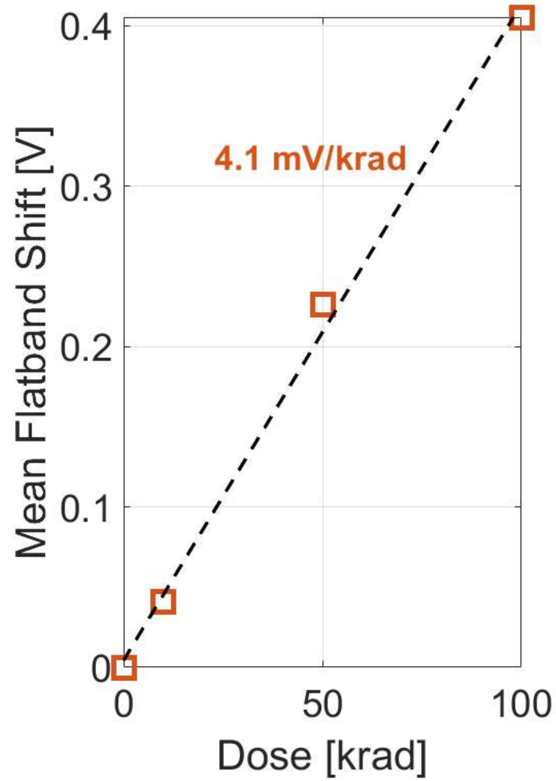
- 2-phase Multi-Pinned Phase (MPP) operation made possible by keeping all phases inverted during integration. The charge transfer operation requires a minimum $VCDTI_{Hi}$ whose V_{depth} is dependant.

5 – Radiation Effects

TID – Flatband Shift



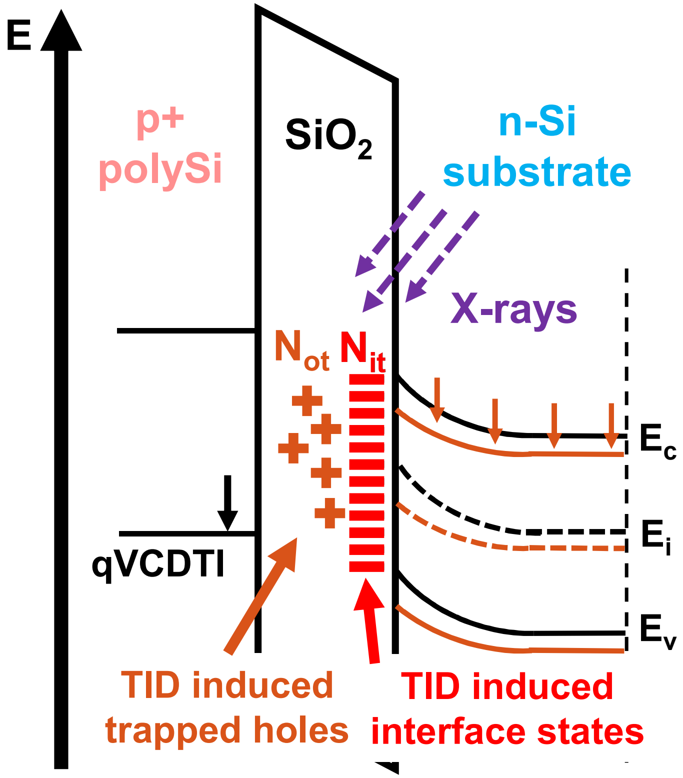


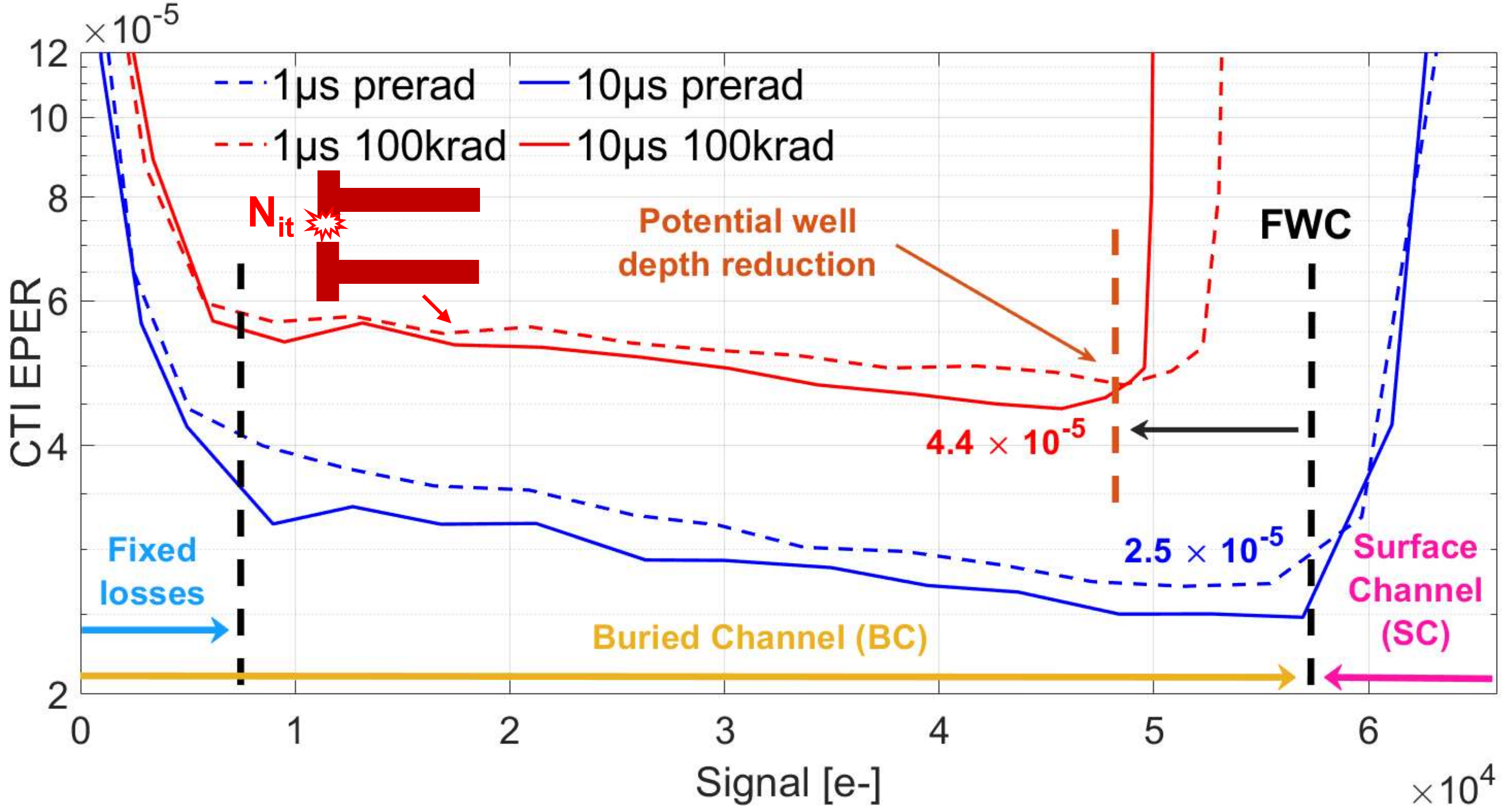


- TID induces a shift on the surface potential V_S which in turn shifts V_{dep}. The average value is 4.1 mV/krad. V_S and V_{dep} get closer as VCDTI increases meaning V_{depth} and FWC are reduced.

5 – Radiation Effects

TID – Charge Transfer Efficiency

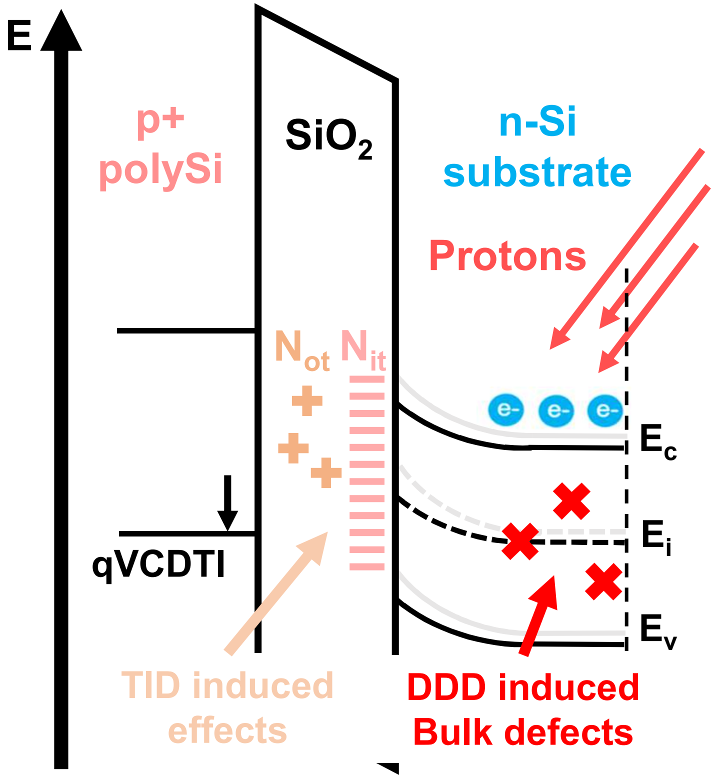


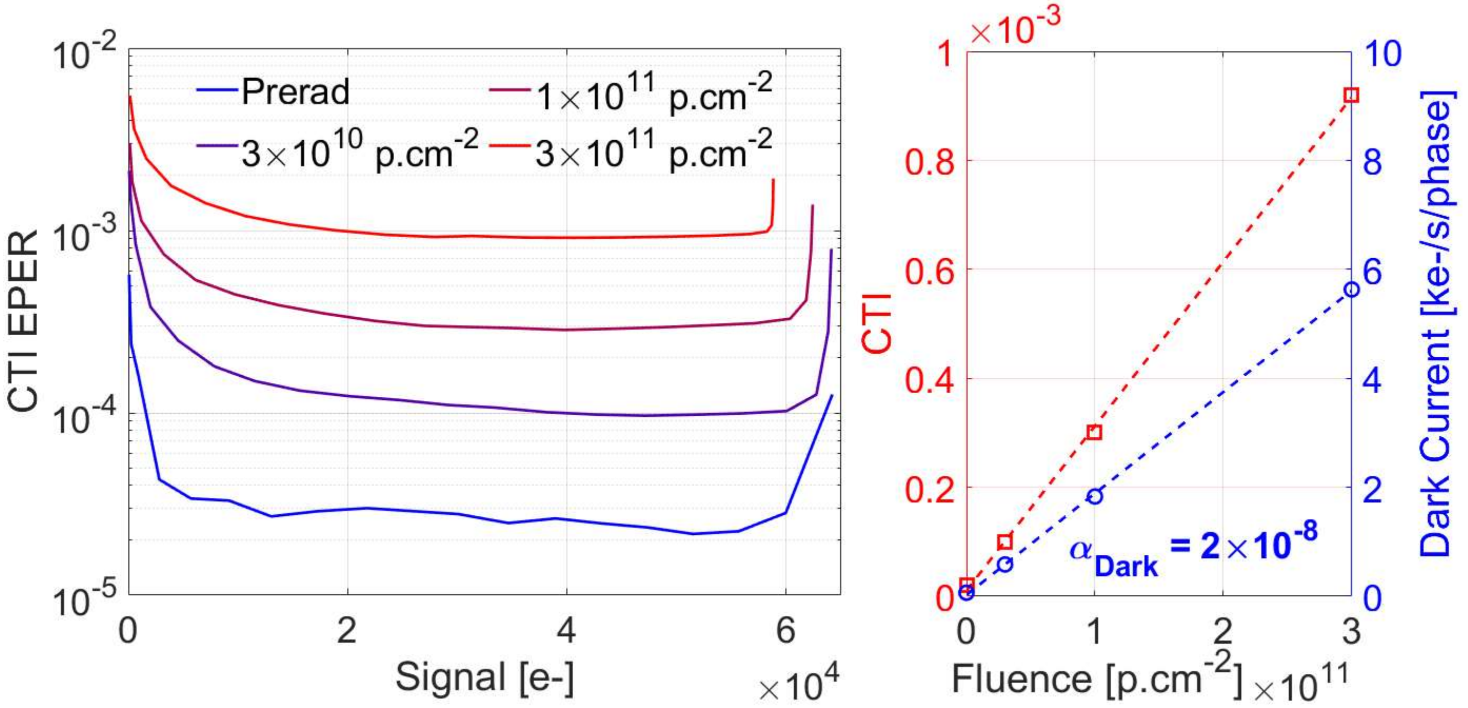


- TID induces trapped holes in the oxide and interface traps buildup. The former causes a FWC reduction because of flatband shift. The later is responsible for a CTI deterioration, supposely at the TCDTI level.

5 – Radiation Effects

DDD - Displacement Damage Effects





$$K_{Dark} = \frac{\alpha_{Dark}}{V_{dep} NIEL_{62MeV}} = \mathbf{1.85 \times 10^5}\ \mathrm{e^{-}.cm^{-3}.sec\ per\ MeV.g^{-1}}$$

- Protons induce defects in the Si bulk that are both responsible for a linear increase of Dark Current and CTI with respect to the Fluence. A K_{dark} close to the Universal Damage Factor is retrieved (1.9×10^5).