Device Simulations of Silicon Detectors: a Design Perspective

D. Passeri[1,2], P. Placidi[1,2], L. Verducci[1,2], F. Moscatelli[1,2]
P. Ciampolini[1,3], G. Matrella[1,3], A.Marras[3], G.M. Bilei[1]

(1) Istituto Nazionale di Fisica Nucleare
Sezione di Perugia - Italy

(2) Dipartimento di Ingegneria Elettronica e dell'Informazione
Università degli Studi di Perugia - Italy

(3) Dipartimento di Ingegneria dell'Informazione
Università di Parma - Italy

Outline

- Introduction.
- Device-Level Simulation:
  - Motivations.
  - Modeling characteristics.
- Applications (Design Issues):
  - Radiation Damage Analysis.
  - Design of CMOS Pixel Detectors.
- Conclusions.

Device-Level Simulation: Motivations

- Device simulation:
  - numerical solution of semiconductor transport equations;
  - accurate physical modeling;
  - distributed domain (spatial, temporal).
- Allows for:
  - fast and inexpensive prediction of device performance;
  - microscopic behavior insight;
  - virtual work-benching and optimization;
- Link between microscopic and macroscopic effects.

Device Simulation: Physical Models

- Drift-diffusion approximation of current densities.
- Radiation-induced carrier-generation term.
- Radiation-induced deep-level traps.
- Contribution of trapped carriers to the charge density.

$$\nabla \cdot \left(-\varepsilon_s \nabla \varphi \right) = q \left(N_D^+ - N_A^- + p - n + p_d - n_a \right)$$

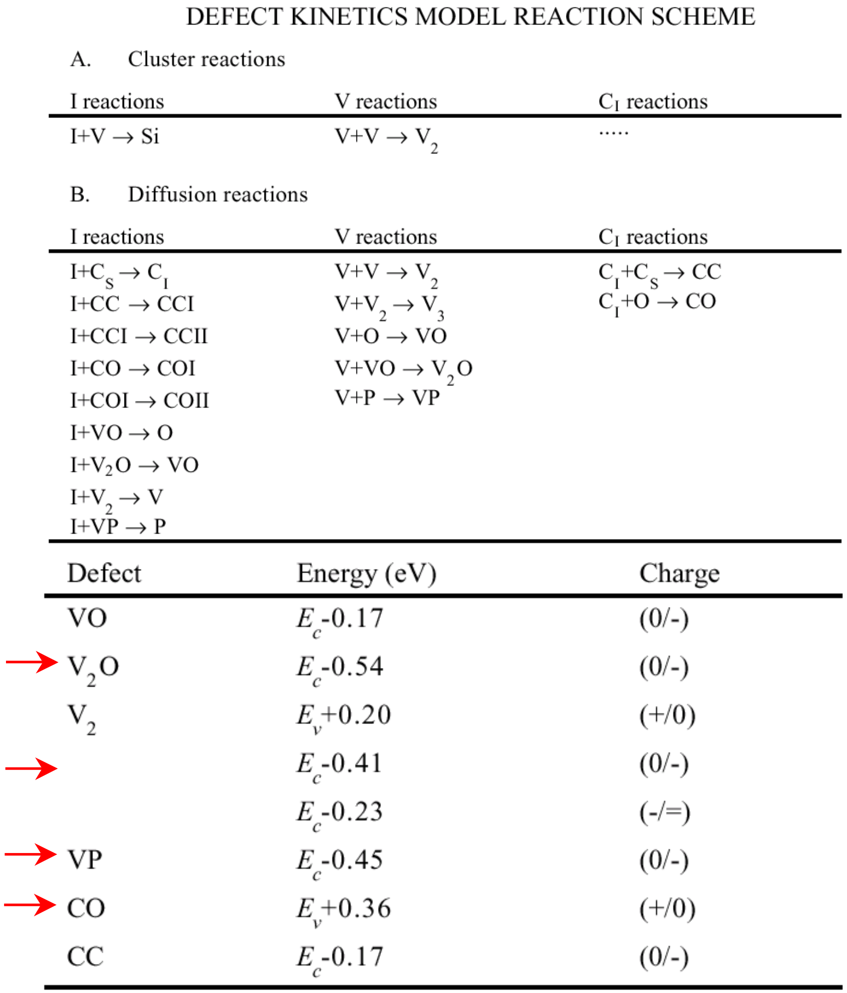
- Continuity equations for free and trapped charges.

$$\frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_n = -U_n \qquad \frac{\partial n_a}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_{na} = -U_{na}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_p = -U_p \qquad \frac{\partial p_d}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_{pd} = -U_{pd}$$

Radiation Damage Analysis

- Deep-level radiation induced traps:
  - N_t, E_t, σ_n, σ_p
- SRH statistics.
- Donor removal.
- Hierarchical approach:
  - complexity/comprehensiveness;
  - accurate prediction of device behavior;
  - most parameters physically meaningful;
  - experimental characterization feasible.



DEFECT KINETICS MODEL REACTION SCHEME

A. Cluster reactions

I reactions	V reactions	C_I reactions
$I+V \rightarrow Si$	$V+V \rightarrow V_2$	·····

B. Diffusion reactions

I reactions	V reactions	C_I reactions
$I+C_S \rightarrow C_I$	$V+V \rightarrow V_2$	$C_I+C_S \rightarrow CC$
$I+CC \rightarrow CCI$	$V+V_2 \rightarrow V_3$	$C_I+O \rightarrow CO$
$I+CCI \rightarrow CCII$	$V+O \rightarrow VO$	
$I+CO \rightarrow COI$	$V+VO \rightarrow V_2O$	
$I+COI \rightarrow COII$	$V+P \rightarrow VP$	
$I+VO \rightarrow O$		
$I+V_2O \rightarrow VO$		
$I+V_2 \rightarrow V$		
$I+VP \rightarrow P$		

	Defect	Energy (eV)	Charge
	VO	E_c-0.17	(0/-)
→	V_2O	E_c-0.54	(0/-)
	V_2	E_v+0.20	(+/0)
→		E_c-0.41	(0/-)
		E_c-0.23	(-/=)
→	VP	E_c-0.45	(0/-)
→	CO	E_v+0.36	(+/0)
	CC	E_c-0.17	(0/-)

Radiation Damage Modeling

- The model should allow for reproducing the electrical behavior of heavily irradiated device in terms of:
  - effective doping concentration depending on fluence;
  - depletion region profiles;
  - increase of the leakage current;
  - charge collection reduction.
- Enhanced, device-level radiation damage modeling scheme featuring:
  - four "dominant" deep levels (related to $V_2^{(-/0)}$, C_iO_i, V_2O, E(70)).
  - donor removal mechanism ($c*N_D = 0.05\ cm^{-1}$).
  - direct charge exchange between $V_2^{(-/0)}$ and E(70).
- All parameters are physically meaningful and experimentally characterized.
- Suitable for use within general purpose device simulators (i.e. spatial and time-domain analysis feasible).

Radiation Damage Modeling (2)

Four levels Vs. three levels modeling

Direct charge exchange

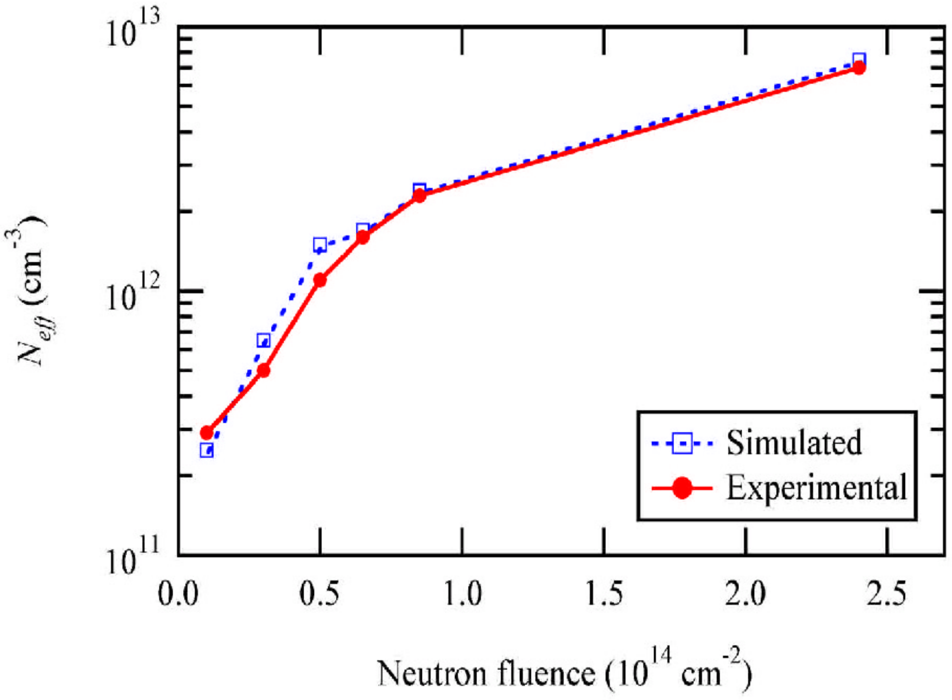
Parameter	$V_2^{0/-}$	E70	$V_2O^{0/-}$	$C_iO_i^{+/0}$
E [eV]	$E_c - 0.42$	$E_c - 0.45$	$E_c - 0.50$	$E_v + 0.36$
σ_p [cm^2]	$2 \cdot 10^{-15}$	$1 \cdot 10^{-14}$	$1 \cdot 10^{-15}$	$1 \cdot 10^{-16}$
σ_n [cm^2]	$1 \cdot 10^{-16}$	$1 \cdot 10^{-15}$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-15}$
η [cm^{-1}]	1	0.4	0.08	1

- Higher computational effort
- Computational limitations for off-range conditions:
  - high fluences (> 10^{14} n/cm^2)
  - low temperature.

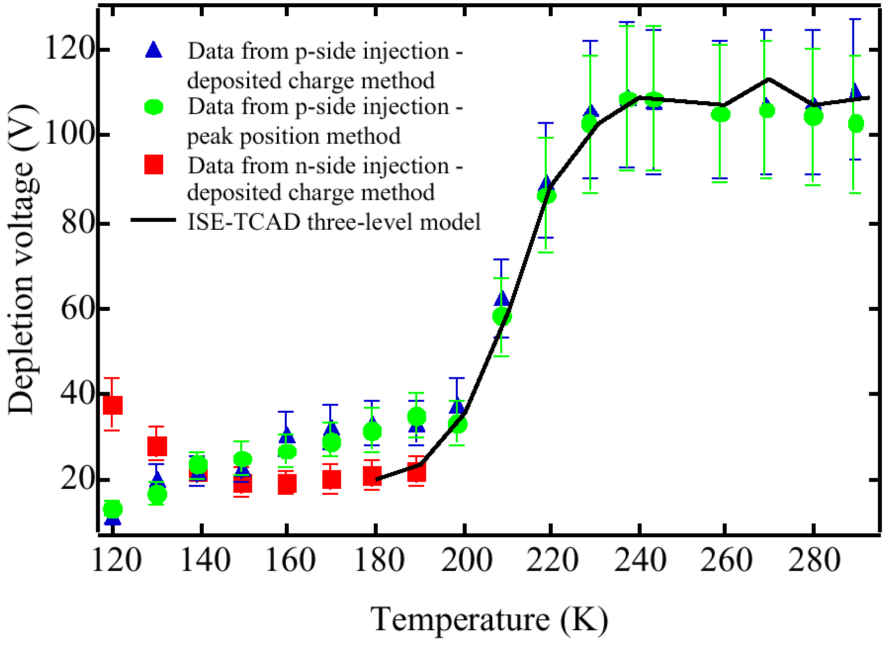
Parameter	$V_2^{0/-}$	$V_2O^{0/-}$	$C_iO_i^{+/0}$
E [eV]	$E_c - 0.42$	$E_c - 0.50$	$E_v + 0.36$
σ_p [cm^2]	$8 \cdot 10^{-15}$	$1 \cdot 10^{-15}$	$1 \cdot 10^{-16}$
σ_n [cm^2]	$1 \cdot 10^{-16}$	$1 \cdot 10^{-16}$	$1 \cdot 10^{-15}$
η [cm^{-1}]	26	0.08	1

- Fitted values of V_2 parameters to reproduce the "cluster effect".
- Suitable for high fluences and low temperature analyses.

Radiation Damage Modeling Applications



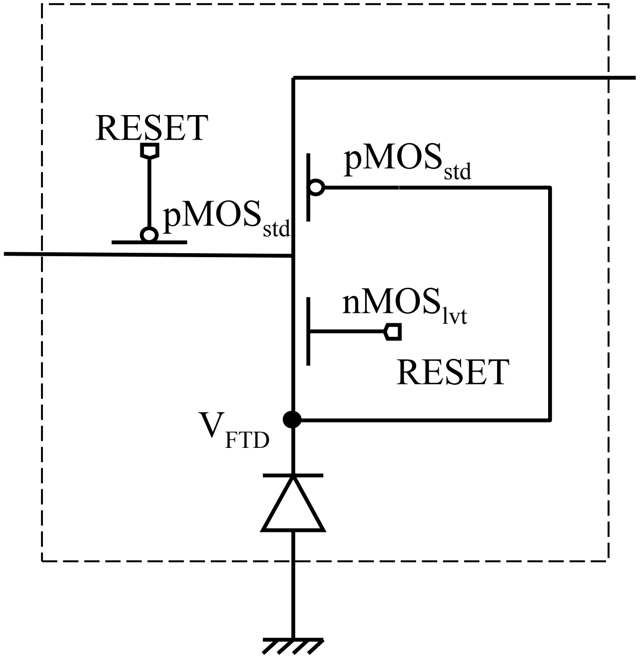
Comparison between predictions of ISE-TCAD three-level model (squares) and experimental data (circles) for N_{eff} as a function of neutron fluence.

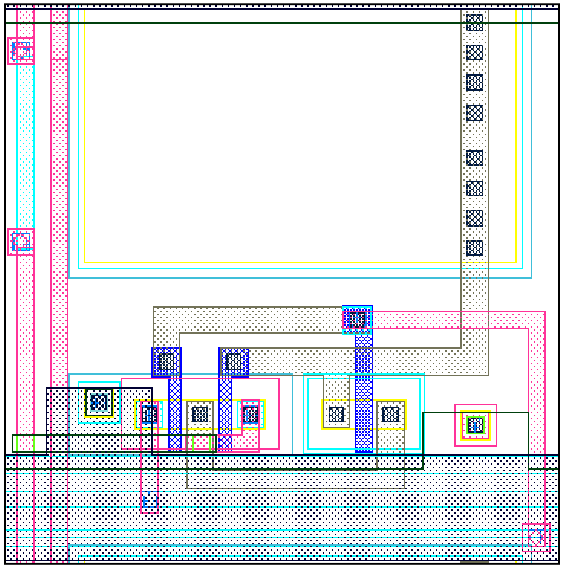


Experimental data and predictions of ISE-TCAD three-level model for N_{eff} as a function of temperature for an irradiated device ($6.2 \cdot 10^{13}$ 1MeV n).

Design of CMOS Pixel Detectors

- Assessment of CMOS deep submicron technology suitability for fabrication of charged particle detectors.
- Optimization of the sensitive element.

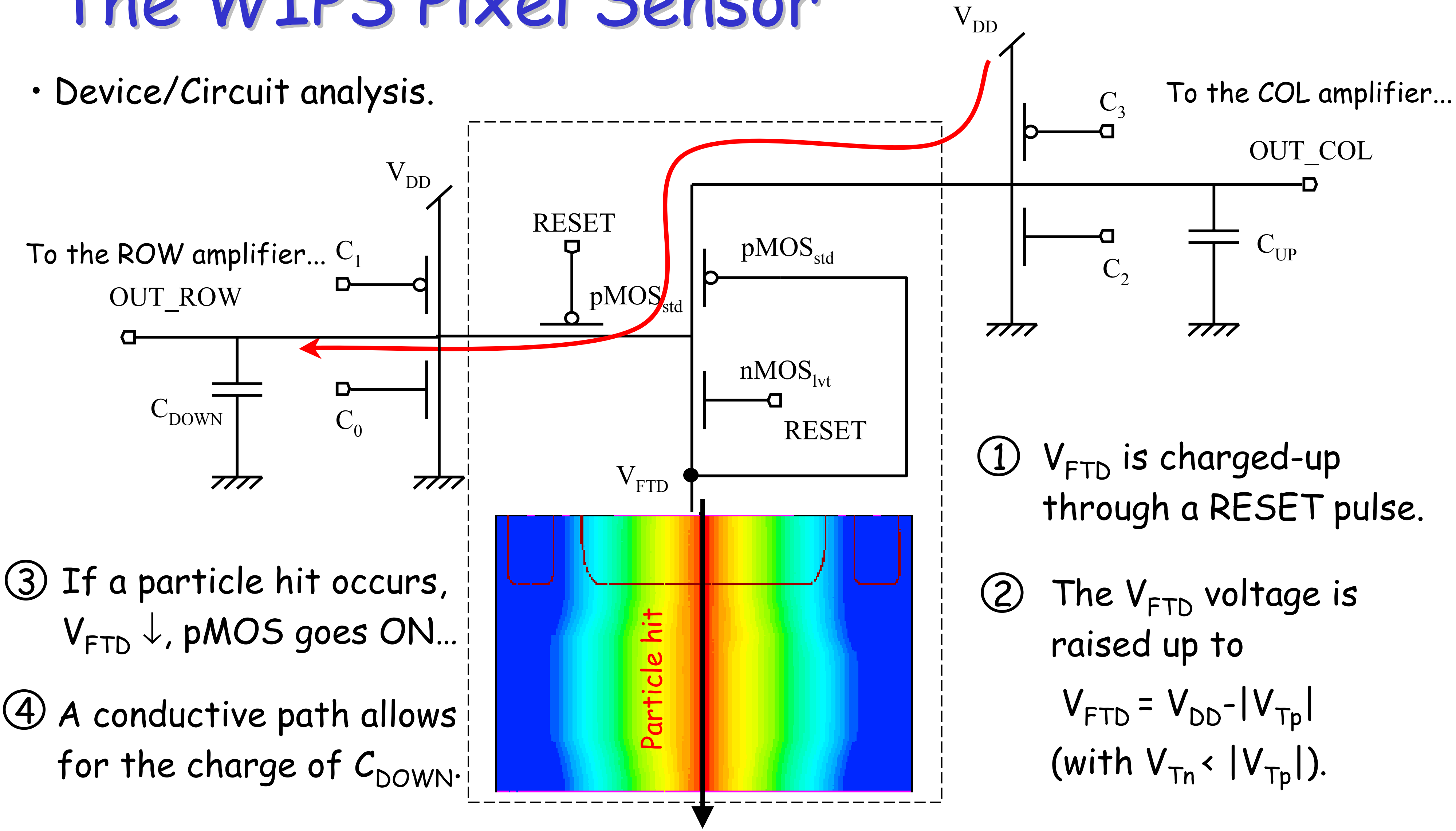




- Innovative active pixel detection scheme: the WIPS idea.

The WIPS Pixel Sensor

- Device/Circuit analysis.



① V_{FTD} is charged-up through a RESET pulse.

② The V_{FTD} voltage is raised up to

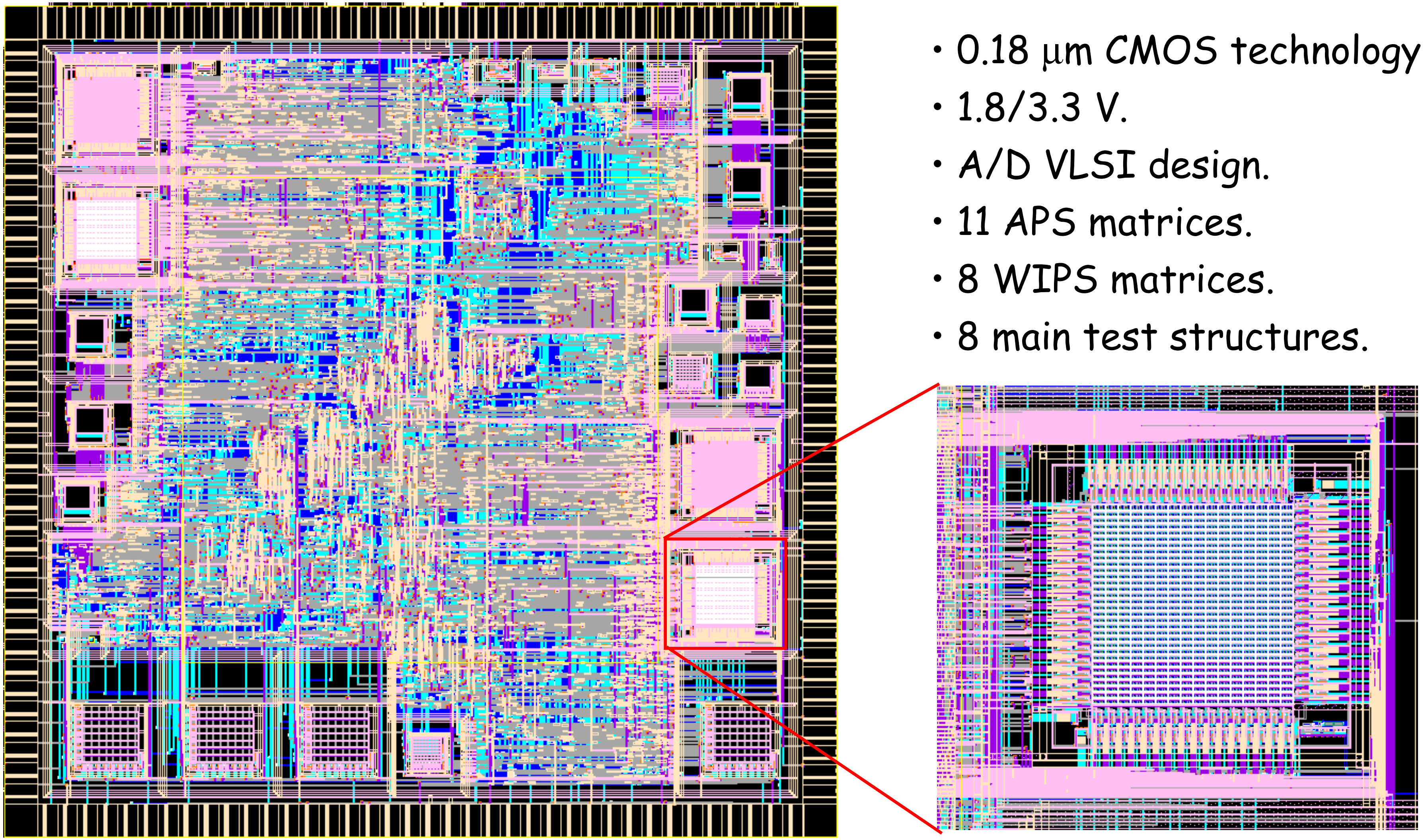
$$V_{FTD} = V_{DD} - |V_{Tp}|$$

(with $V_{Tn} < |V_{Tp}|$).

③ If a particle hit occurs, V_{FTD} ↓, pMOS goes ON...

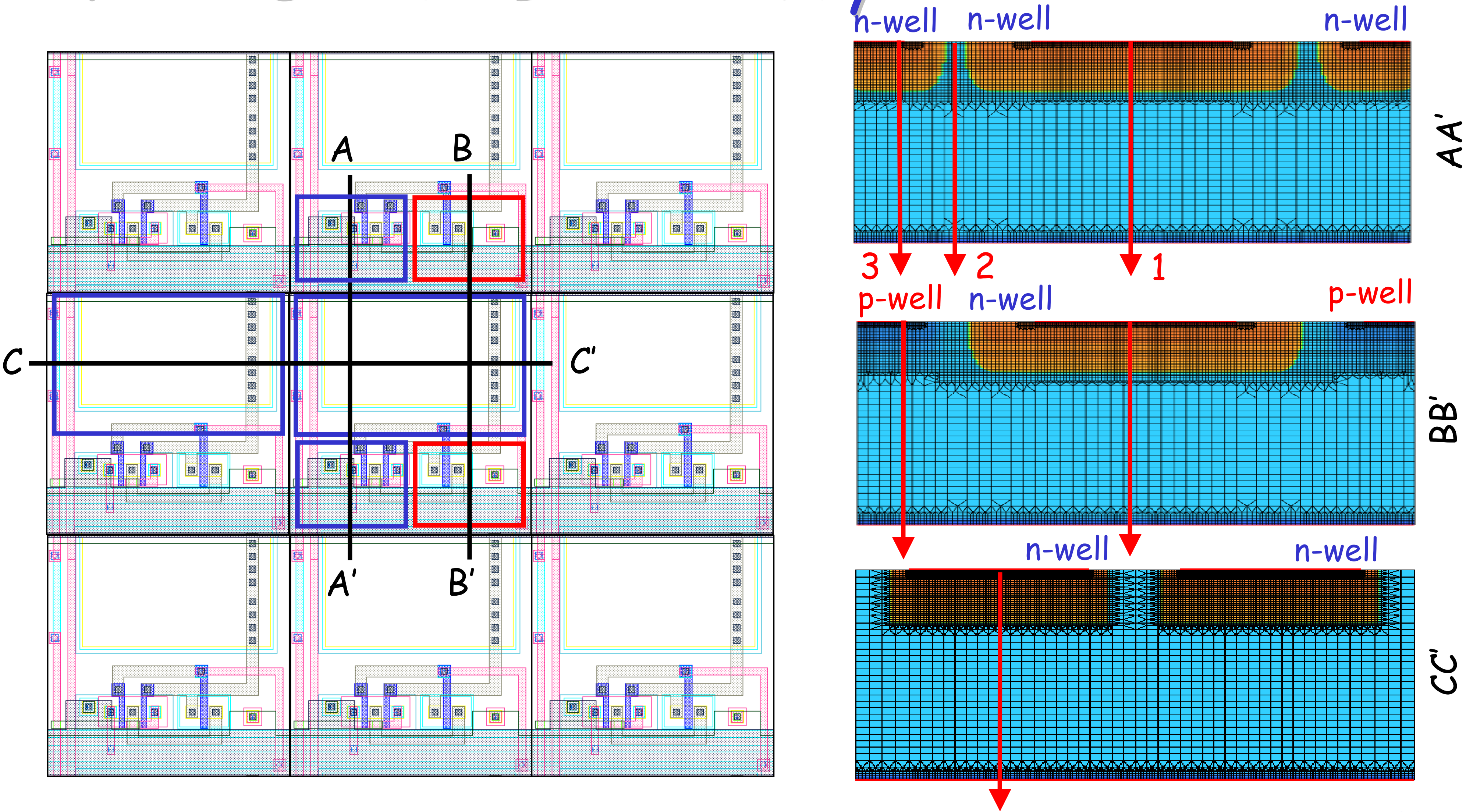
④ A conductive path allows for the charge of C_{DOWN}.

RAPS01 Chip Layout



- 0.18 μm CMOS technology.
- 1.8/3.3 V.
- A/D VLSI design.
- 11 APS matrices.
- 8 WIPS matrices.
- 8 main test structures.

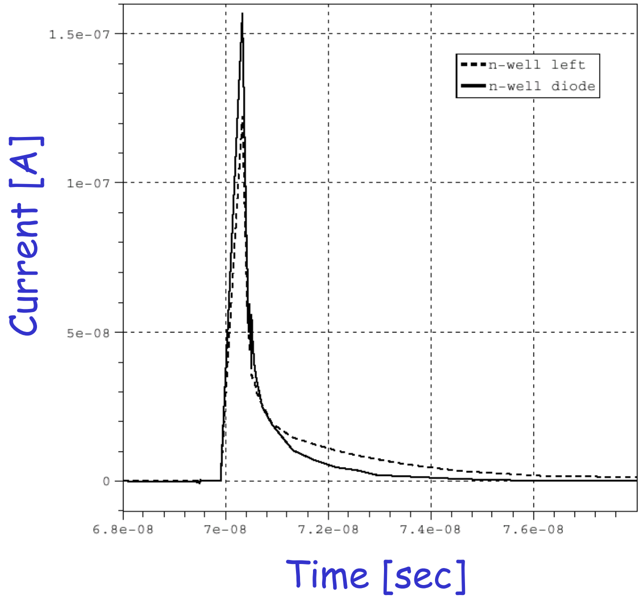
WIPS Device-Level Analysis



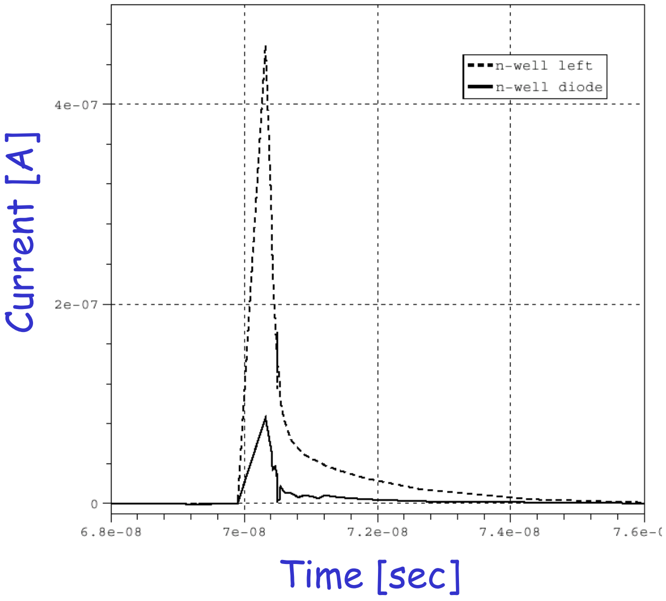
WIPS Device-Level Analysis (2)

Current responses of the “sensitive elements” (n-wells) to a particle hit depending on the particle trajectory (AA’ section).

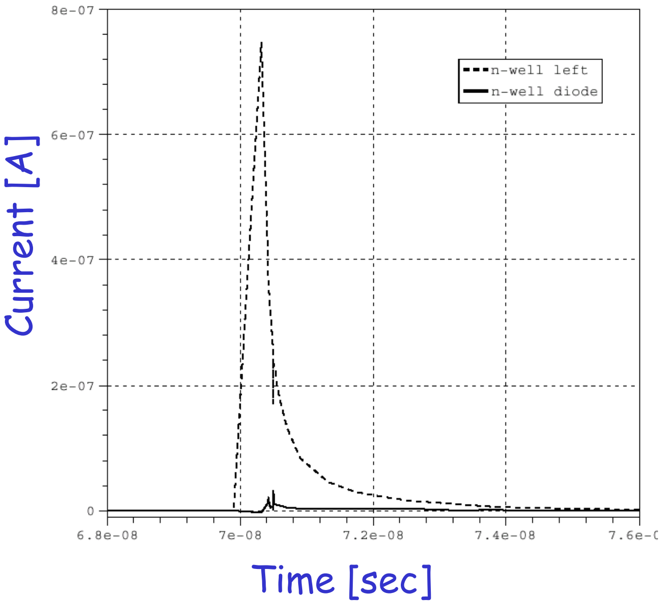
Track # 1



Track # 2



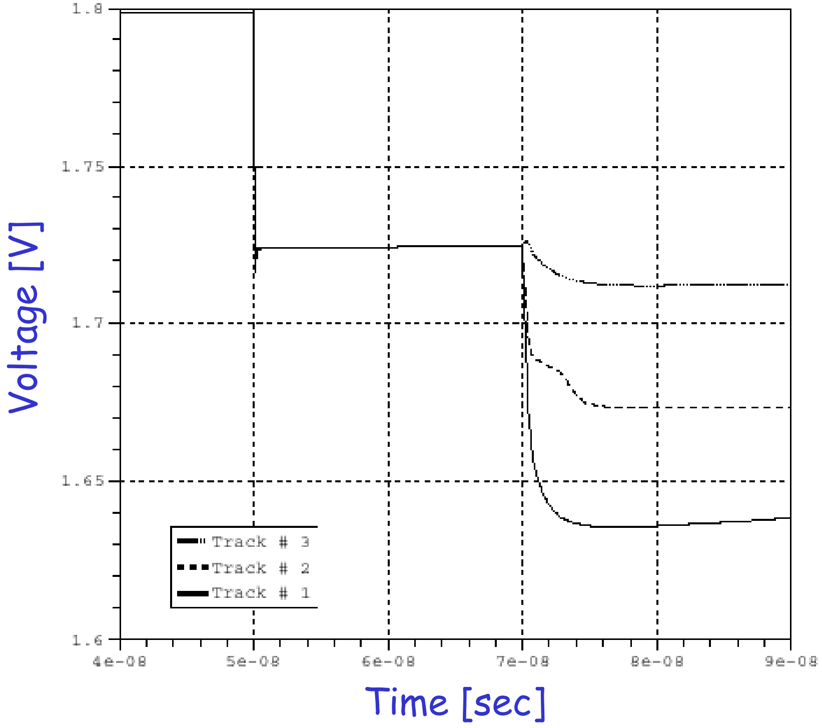
Track # 3



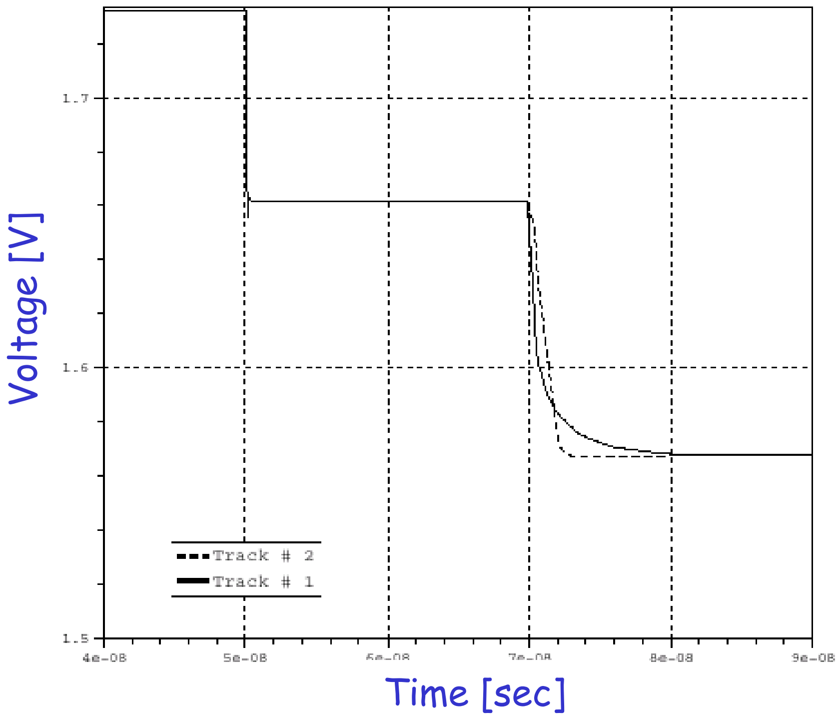
WIPS Device-Level Analysis (3)

Voltage drops at the photodiode inner node, as a function of the impact point

AA' section (n-n-n)



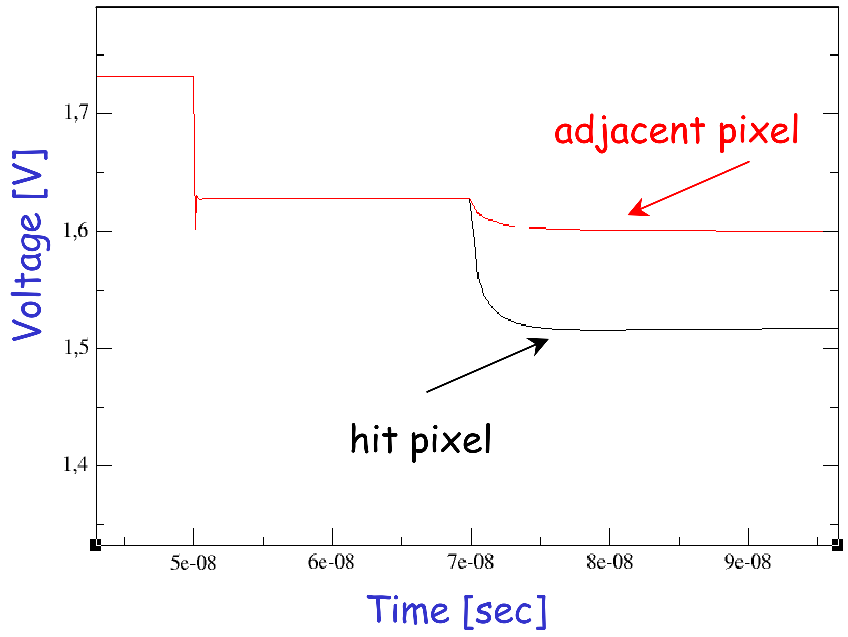
BB' section (p-n-p)



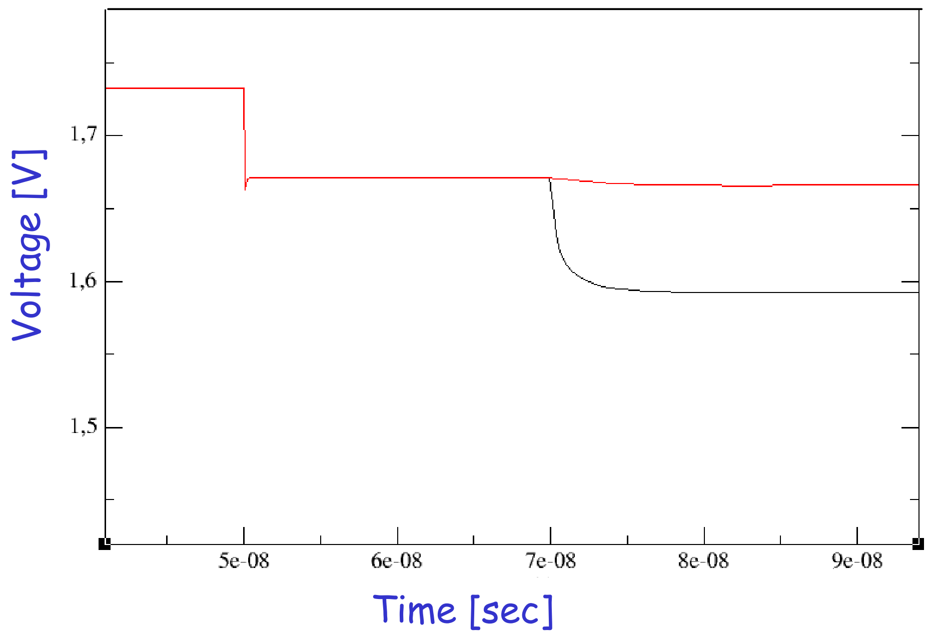
WIPS Device-Level Analysis (4)

Voltage drops at the photodiode inner nodes (CC' section)

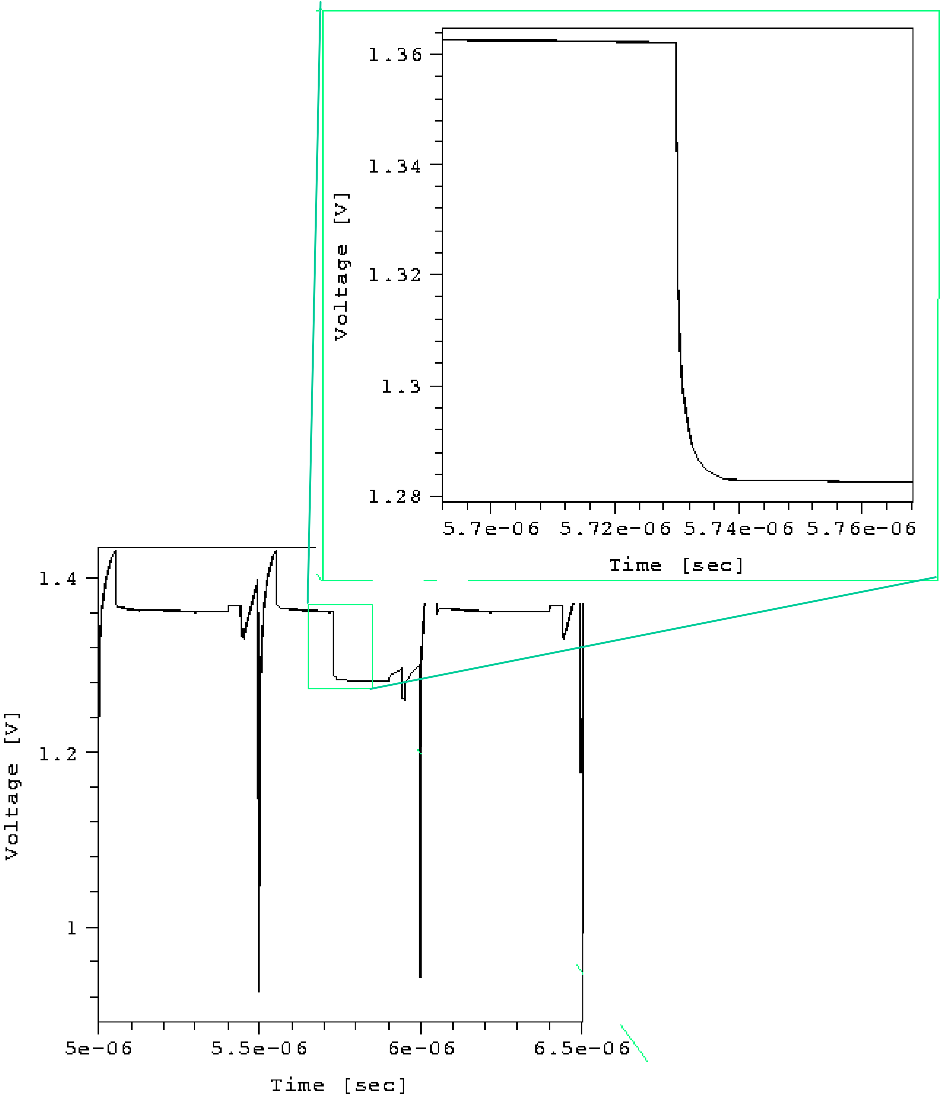
no guardring

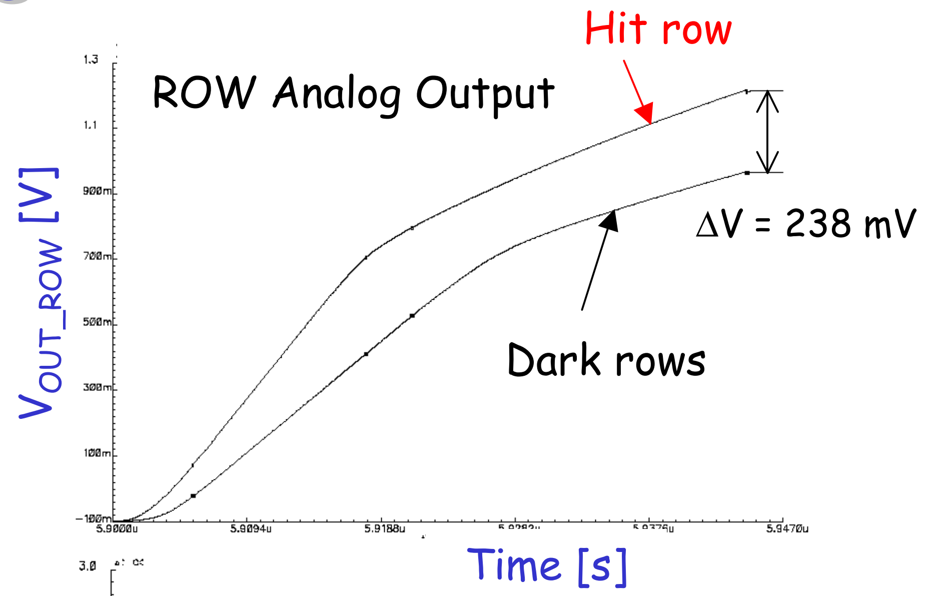


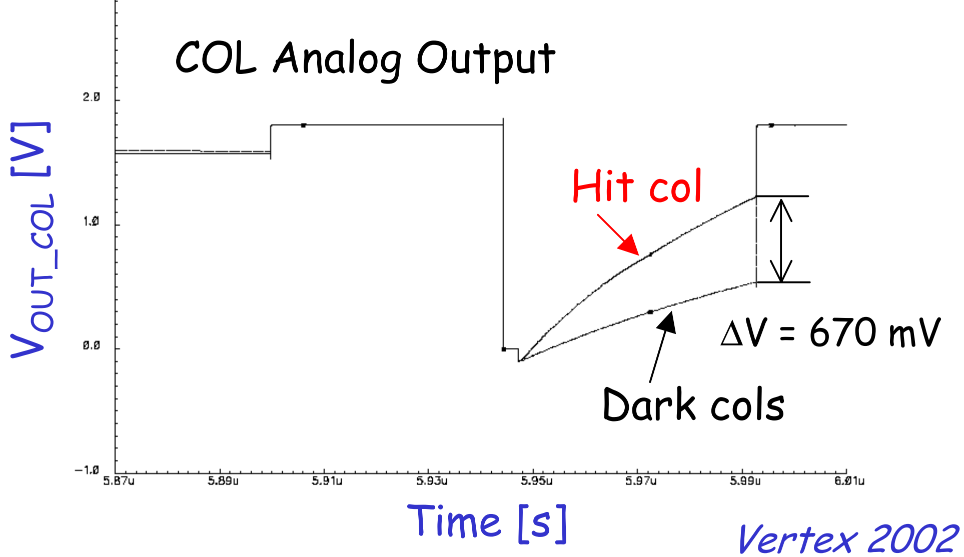
guardring



WIPS Circuit Analysis

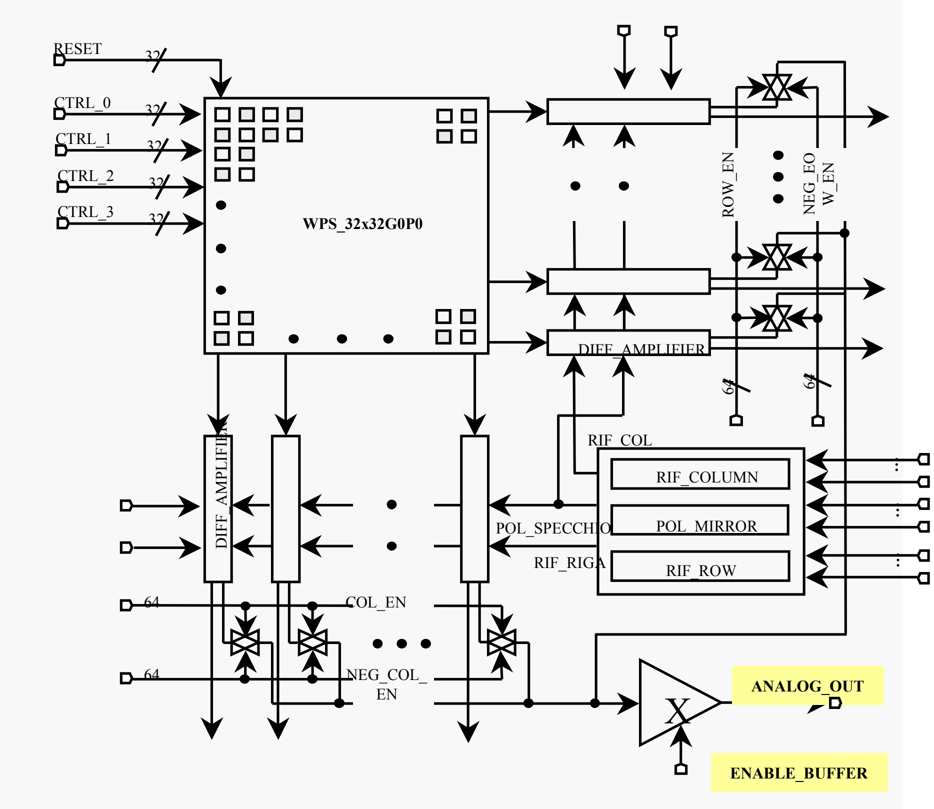


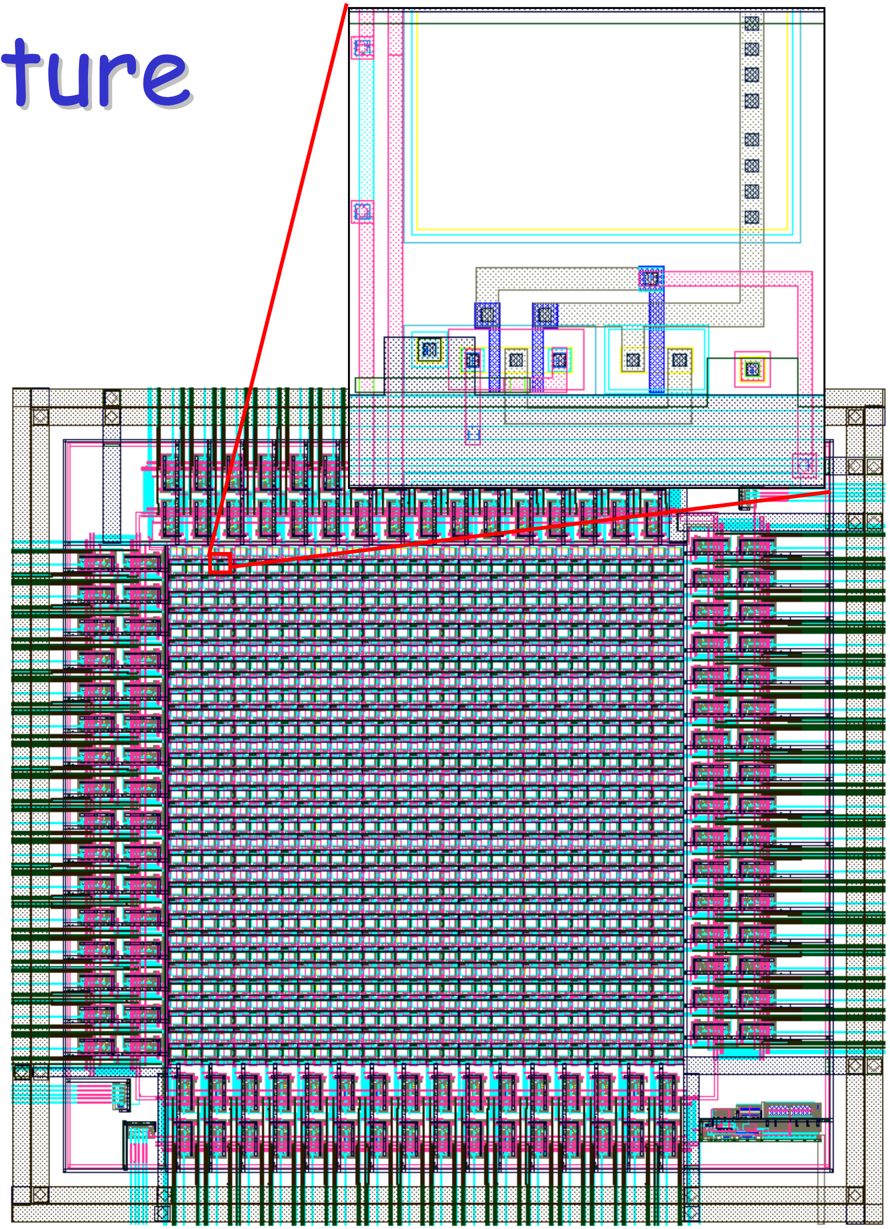




WIPS Matrix Architecture

- Pixel size 10 x 10 μm^2
- Single row scan / serial out: (n + n) x T_{CLOCK}





Conclusions

Numerical device-level simulation has been assessed as powerful tool for analysis and design of particle detectors.

Fast and inexpensive performance prediction, as well as physical and intuitive interpretation of device behavior can be obtained.

A comprehensive, device-level radiation damage modeling scheme, based on a hierarchical approach, has been devised, allowing for a broad range of application issues.

Coupled device- and circuit-level analyses have been extensively exploited within a conventional CMOS VLSI design flow for the realization of innovative pixel detectors.