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Advanced European Infrastructures for Detectors at Accelerators

Update on TCAD Radiation Damage Modeling in Silicon Detectors for HL-LHC: Test and Simulation

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Outline

- Motivations
- Experimental Measurements after X-rays irradiations
  - Different test structures
  - Different substrates
- Simulation Results
  - Update of the TCAD surface damage model
    - Interstrip Resistance
    - Gated Control Diode

    } Simulations vs Measurements
  - Bulk + Surface TCAD damage model
    - Charge Collection Efficiency (with/without Acceptor Removal)
- Conclusions

Motivations (1)

- ✓ INFN and University of Perugia are involved in WP7.
- ✓ 7.2 TCAD simulations:
  - development of a TCAD model for the study of radiation damage effect in silicon detectors valid up to the particle fluences expected at the end of HL-LHC operations in the inner layers of the pixel systems (ATLAS/CMS).
- ✓ Main goal synopsis:
  - extension of the past "Perugia" TCAD model to simulate the effects of radiation damage on solid-state silicon devices;
  - development of a comprehensive bulk damage as well as surface trap states build up modelling for a particle fluence > 2×10^{16} 1MeV n_{eq}/cm^2.
- ✓ Participants: G.M. Bilei (INFN PG staff), D. Passeri (UniPG staff), F. Moscatelli (CNR-IMM staff), E. Fiandrini (UniPG staff), A. Morozzi (UniPG PhD student).

Motivations (2)

- Simulate the effects of radiation damage on silicon devices at very high fluences (HL-LHC operation up to 2×10^{16} 1MeV n_{eq}/cm^2).
- Development of a combined bulk damage effect and interface trap states build up numerical TCAD model:
  - Physically grounded approach,
  - Extend the predictive capability to high fluences,
  - Keep low the number of traps (e.g. Avoiding fitting parameter / minimize the number of traps),
  - Compatibility with already developed bulk damage model
  - No over-specific modelling (e. g. device and technology independent)
- Extraction from simple test structures of relevant parameters to be included within the model
- Validation of the new modeling scheme through comparison with measurements of different test structures before and after irradiation.

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    (Interstrip Resistance, Gated Control Diode: Simulations vs Measurements)
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Setting-up the measurements

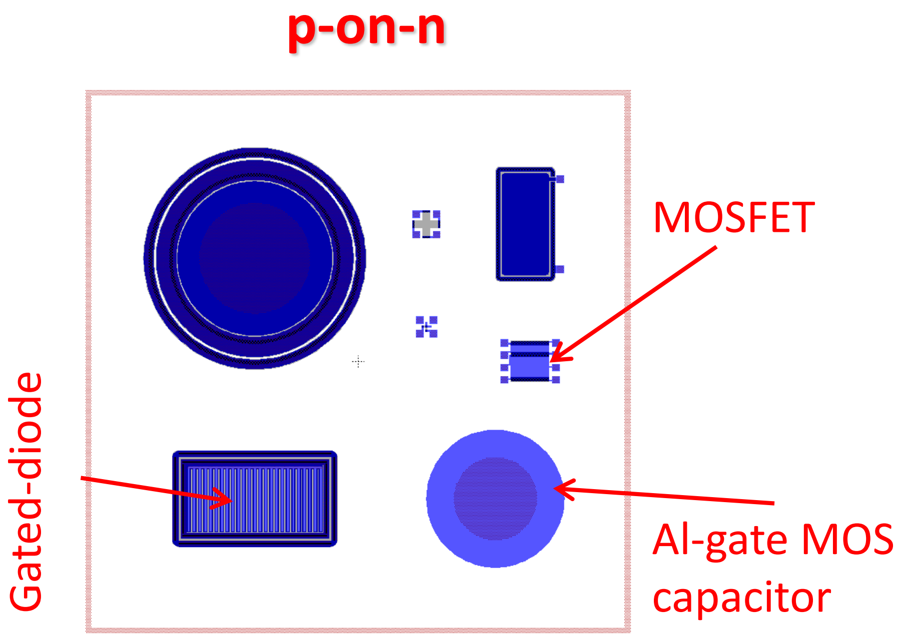
- ✓ Measurement Campaign: X-ray irradiation
  - carried out in Padova (IT)
  - doses range:
    - 50 krad-10 Mrad (SiO_2)
    - 1 Mrad-20 Mrad (SiO_2)

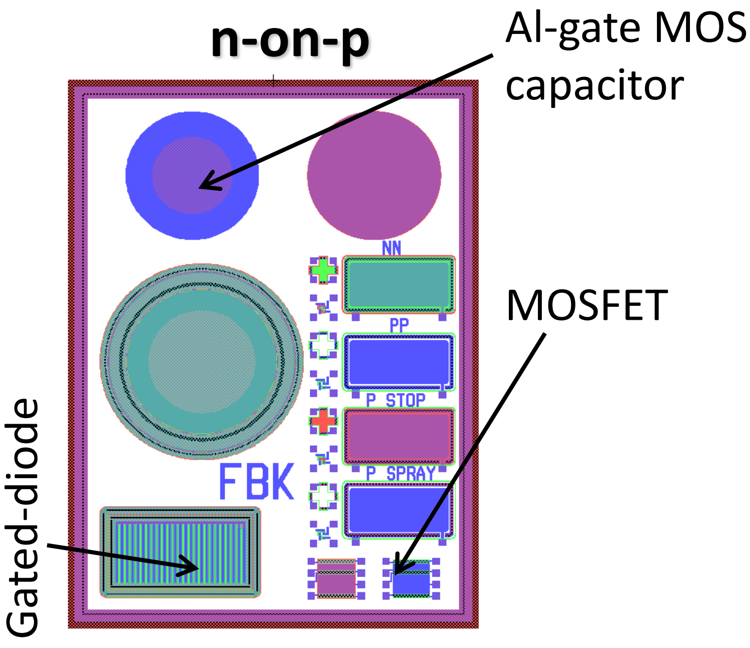
- ✓ MOS capacitors, Gate-Controlled Diode (GCD), MOSFETs during irradiation steps.
  - different substrates (p-on-n and n-on-p)

- ✓ Measurements after irradiation / annealing 80°C 10 min.

Test Structures

FBK

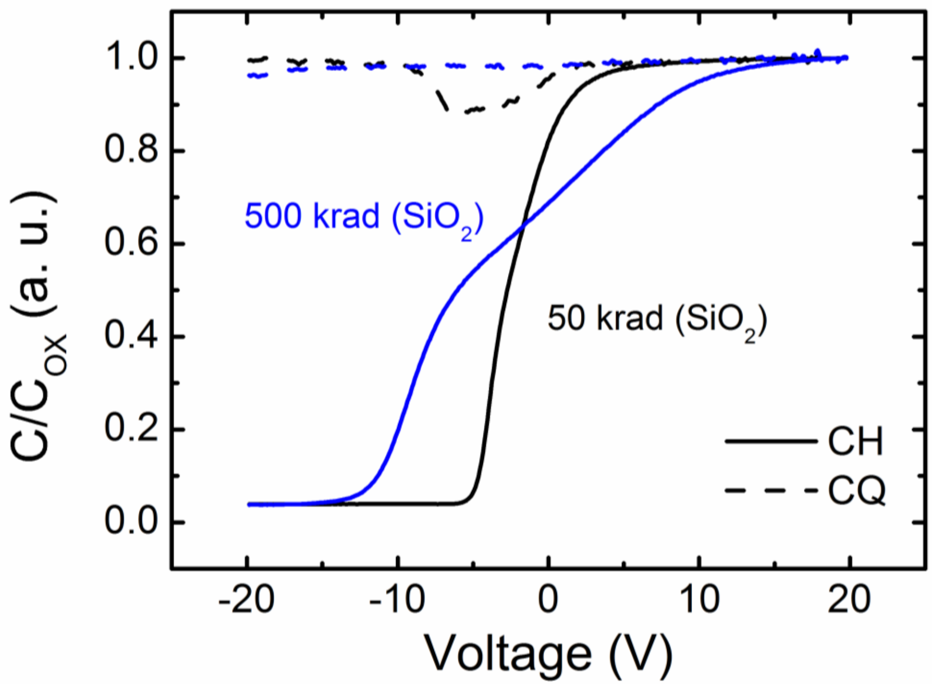




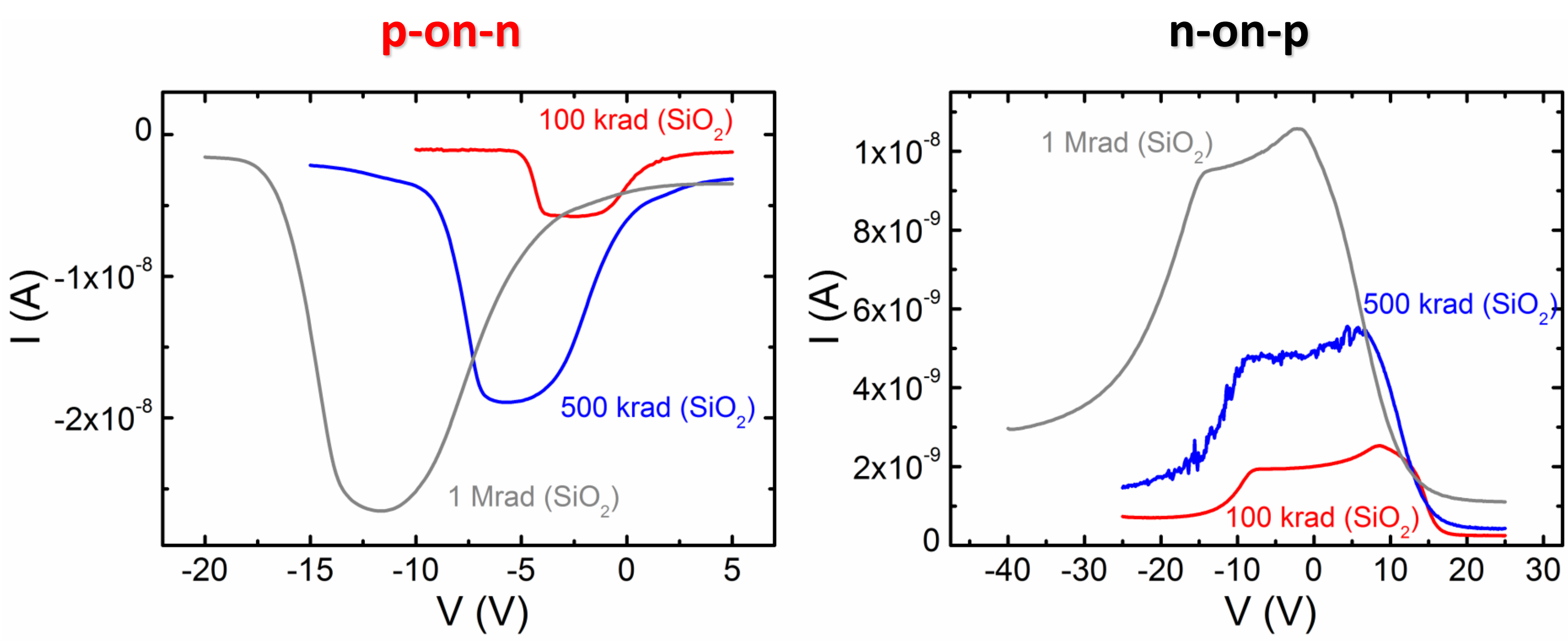
- Test Structures: MOS capacitors, Gated Diodes, MOSFETs
- Substrates: n and p
- Strip Isolation: p-spray (for p-type substrate)

FBK MOS Capacitors after X-rays

- p-on-n structures
- HF measurements at 100 kHz with a small signal amplitude of 15 mV.
- The QS characteristics were measured with delay times of 0.7 s using a voltage step of 100 mV.
- The D_{IT} was estimated by using the C-V High-Low method.



FBK GCD after irradiation



- Annealing 80°C 10 min
- Surface velocity s_0 evaluated as a function of the dose

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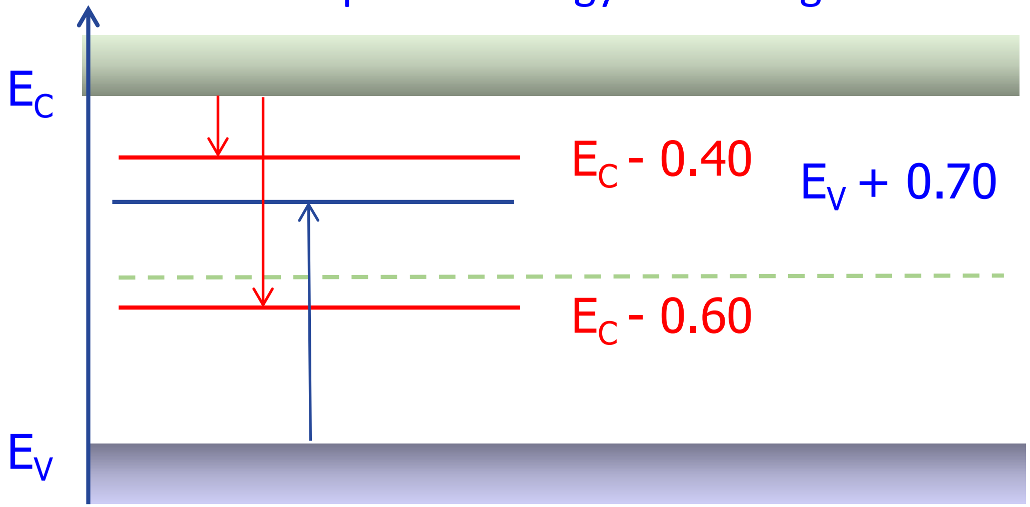
Surface Damage Model: Levels

- Interface trap state energy modelling

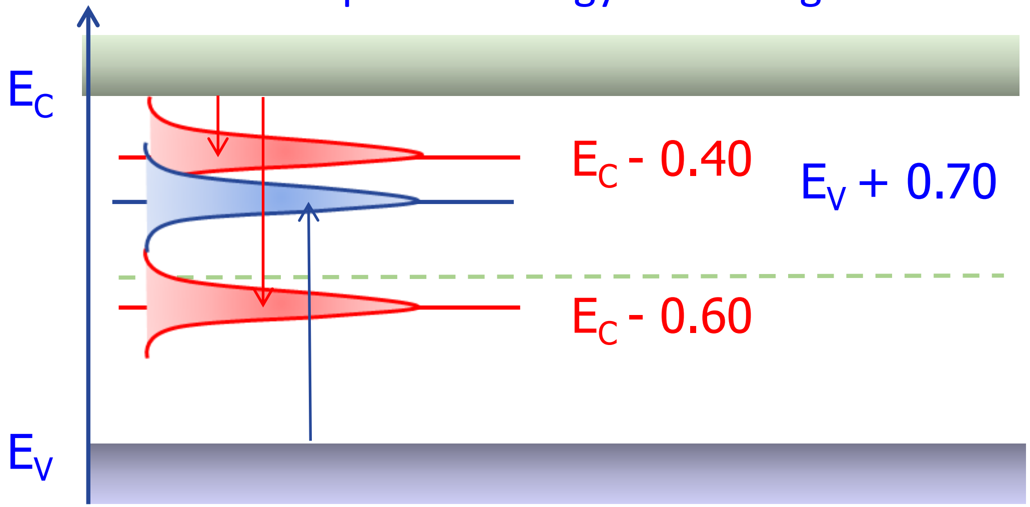


Type	Peak Energy (eV)	Concentration (cm^{-2})
Acceptor	E_C - 0.40	40% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)
Acceptor	E_C - 0.60	60% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)
Donor	E_V + 0.70	100% of donor N_{IT} ($N_{IT}=M \cdot N_{OX}$)

[1] J. Zhang, "X-ray radiation damage studies and design of a silicon pixel sensor for science at the XFEL," Ph.D. dissertation, Universität Hamburg, Hamburg, Germany, 2013.

Surface Damage Model: Gaussian

- Interface trap state energy modelling



Type	Peak Energy (eV)	Concentration (cm^{-2})	σ (eV)
Acceptor	E_C - 0.40	40% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)	0.07
Acceptor	E_C - 0.60	60% of acceptor N_{IT} [1] ($N_{IT}=M \cdot N_{OX}$)	0.07
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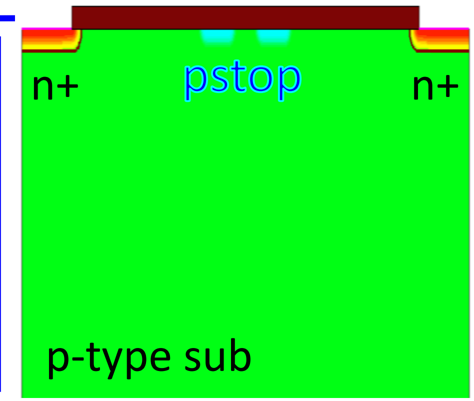
Interstrip Resistance (Isolation)

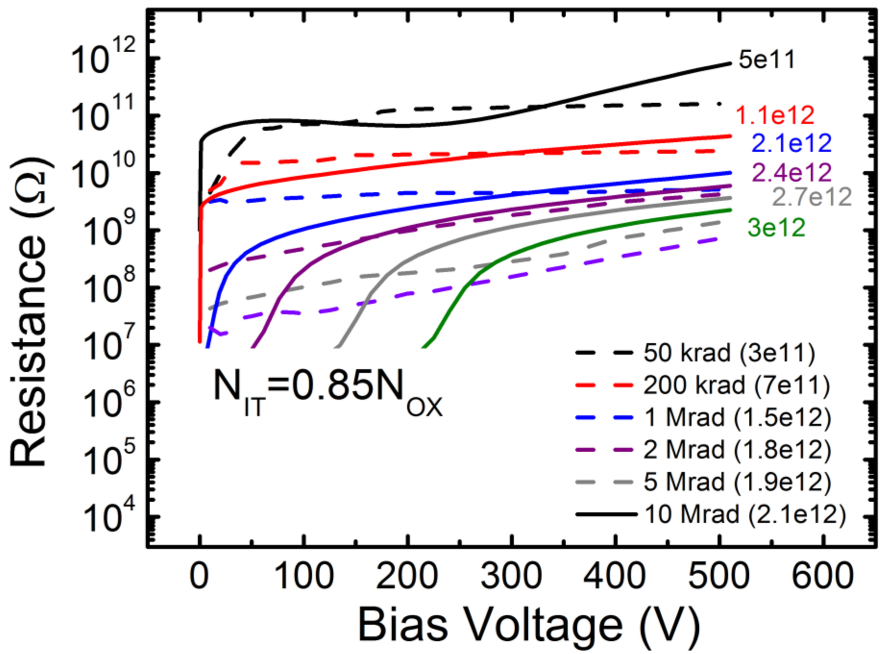
Simulations vs. Measurements
($T=T_{ROOM}$ /annealing at 80°C for 10 min)

Test Structure Overview

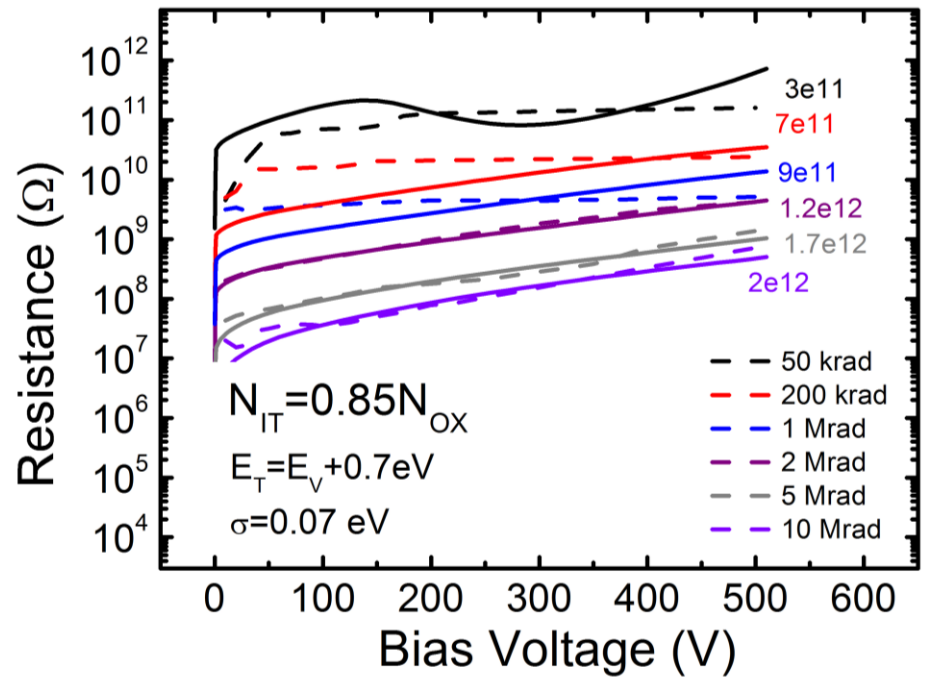
- HPK process
  - $Nsub=8x10^{12}$ cm^{-3}
  - $pstopPeak=5x10^{15}$ cm^{-3}
  - Thickness = 120 µm



Trap Levels



Gaussian Distribution

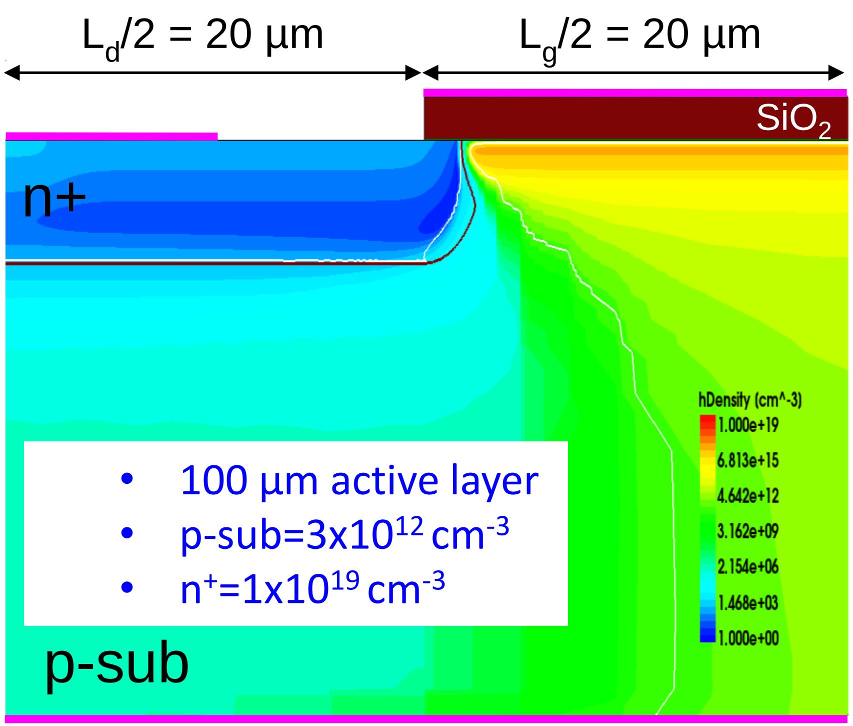


Gated Controlled Diode (non-irradiated)

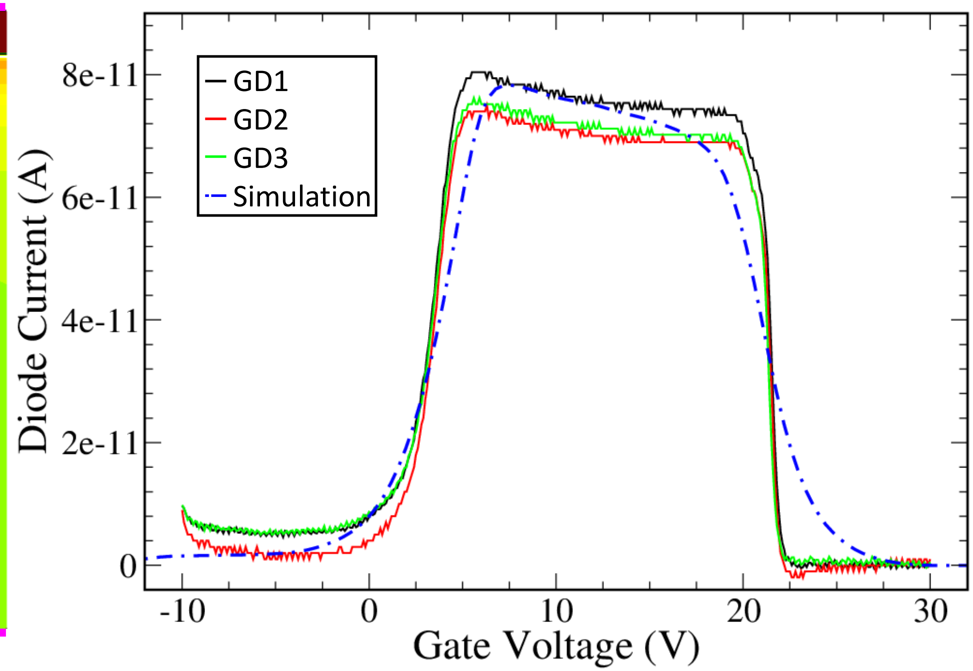
- ✓ I-V measurements compared to simulations
  - ✓ FBK test structures
  - ✓ p-spray
  - ✓ $T=T_{ROOM}$

s_{0meas} = 3.3 cm/s

s_{0sim} = 3.4 cm/s

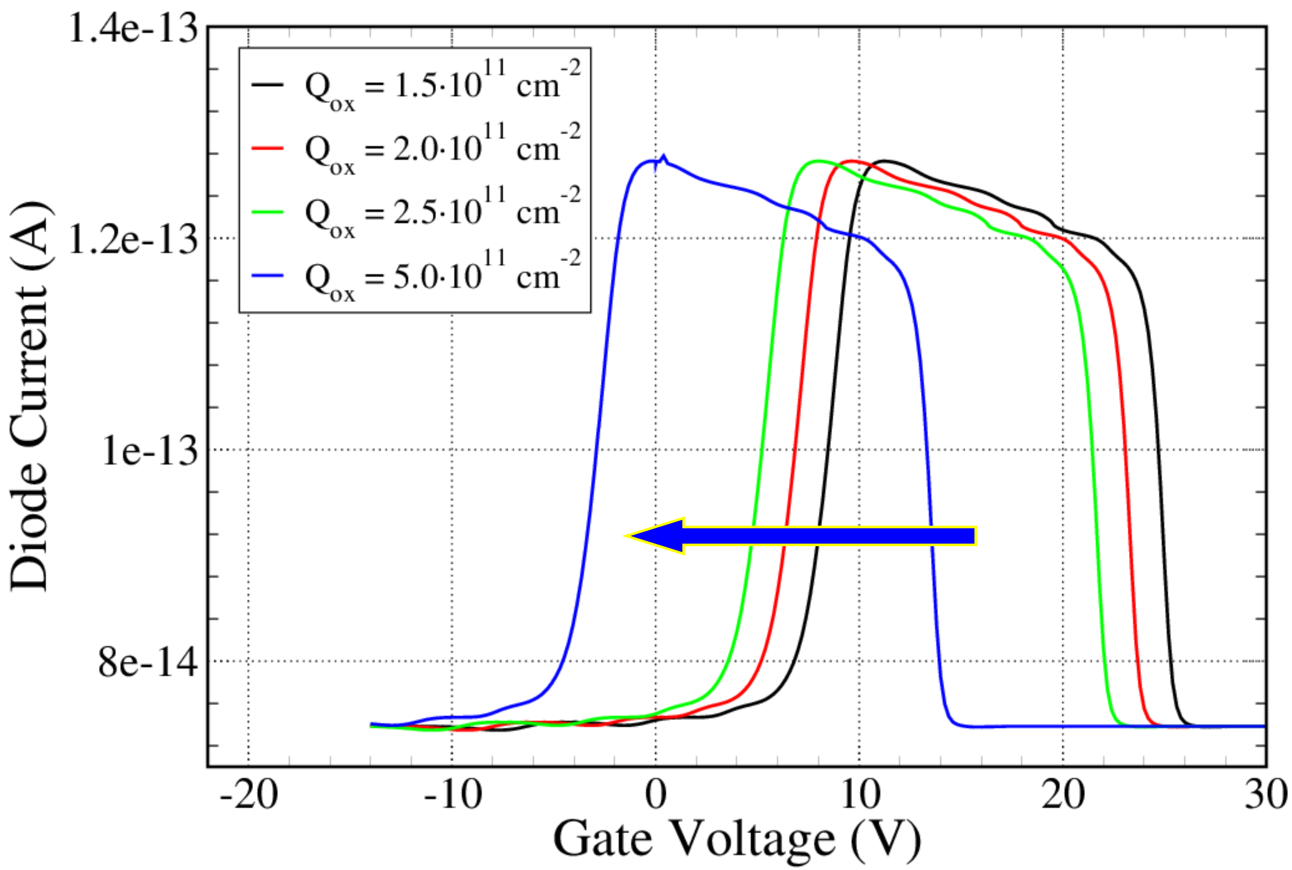


Surface TCAD model



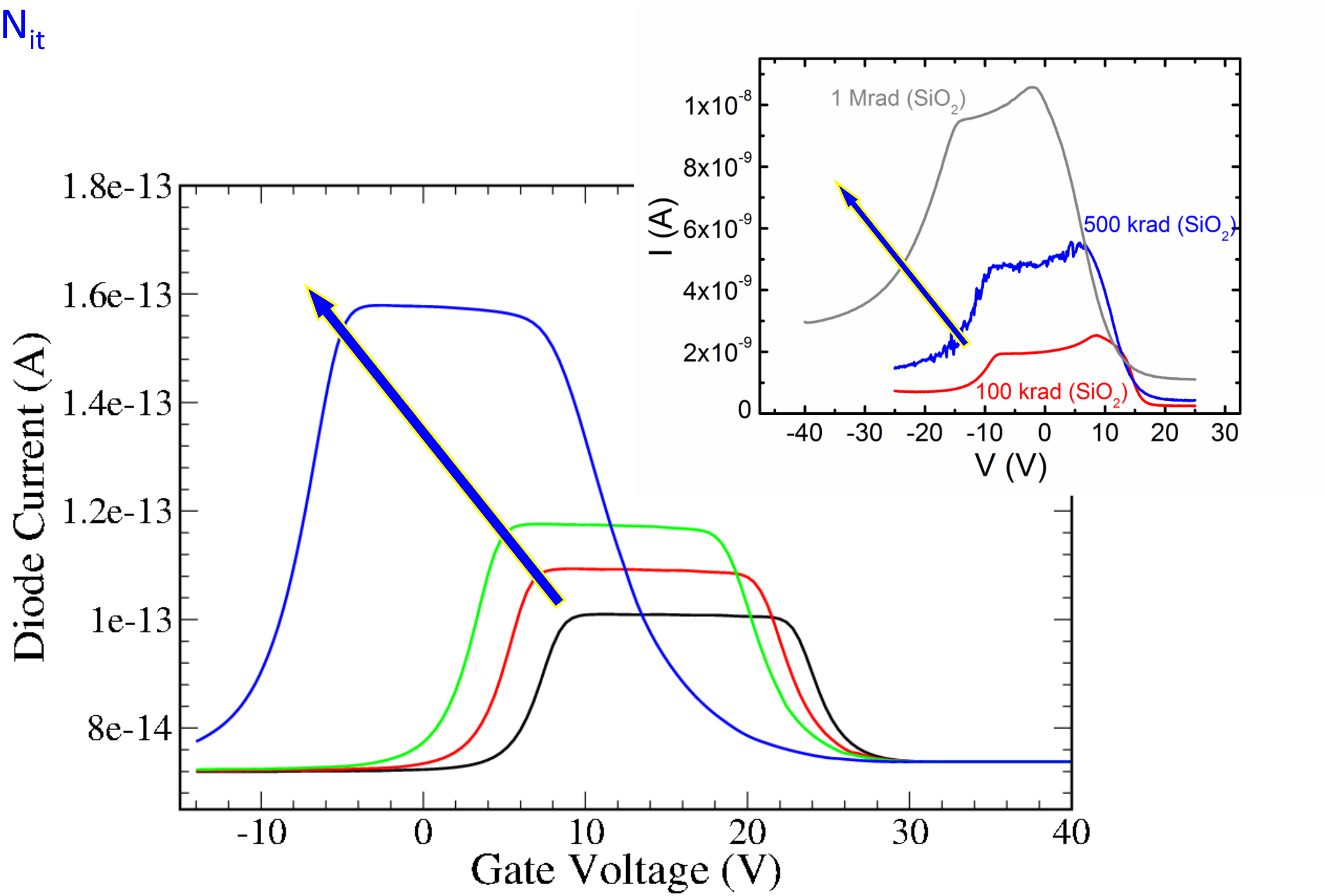
Sensitivity Analysis: Effect of the only Q_{ox}

- ✓ Q_{ox} only



Effect of Q_{ox} + TCAD Surface Model

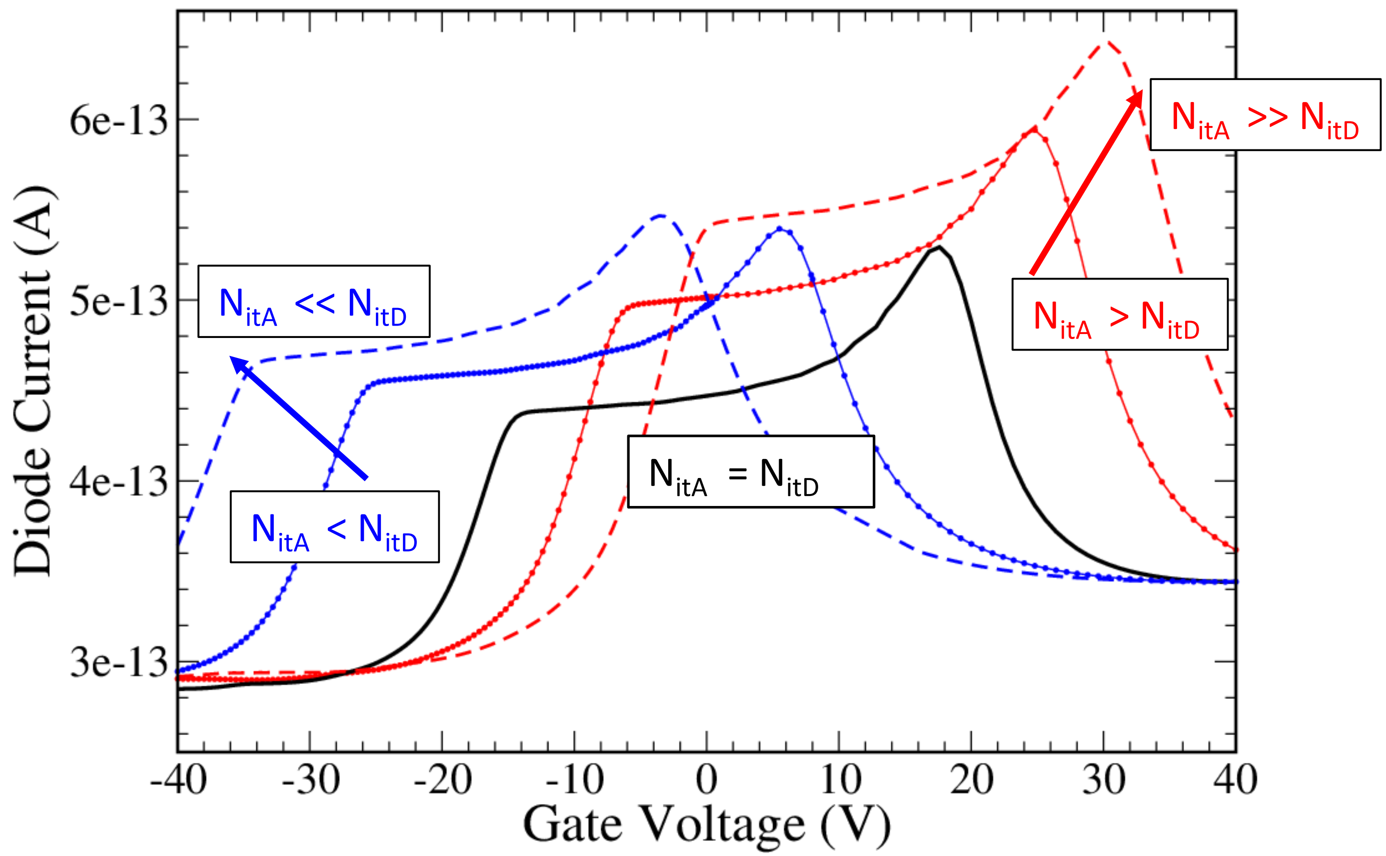
✓ $Q_{ox} + N_{it}$



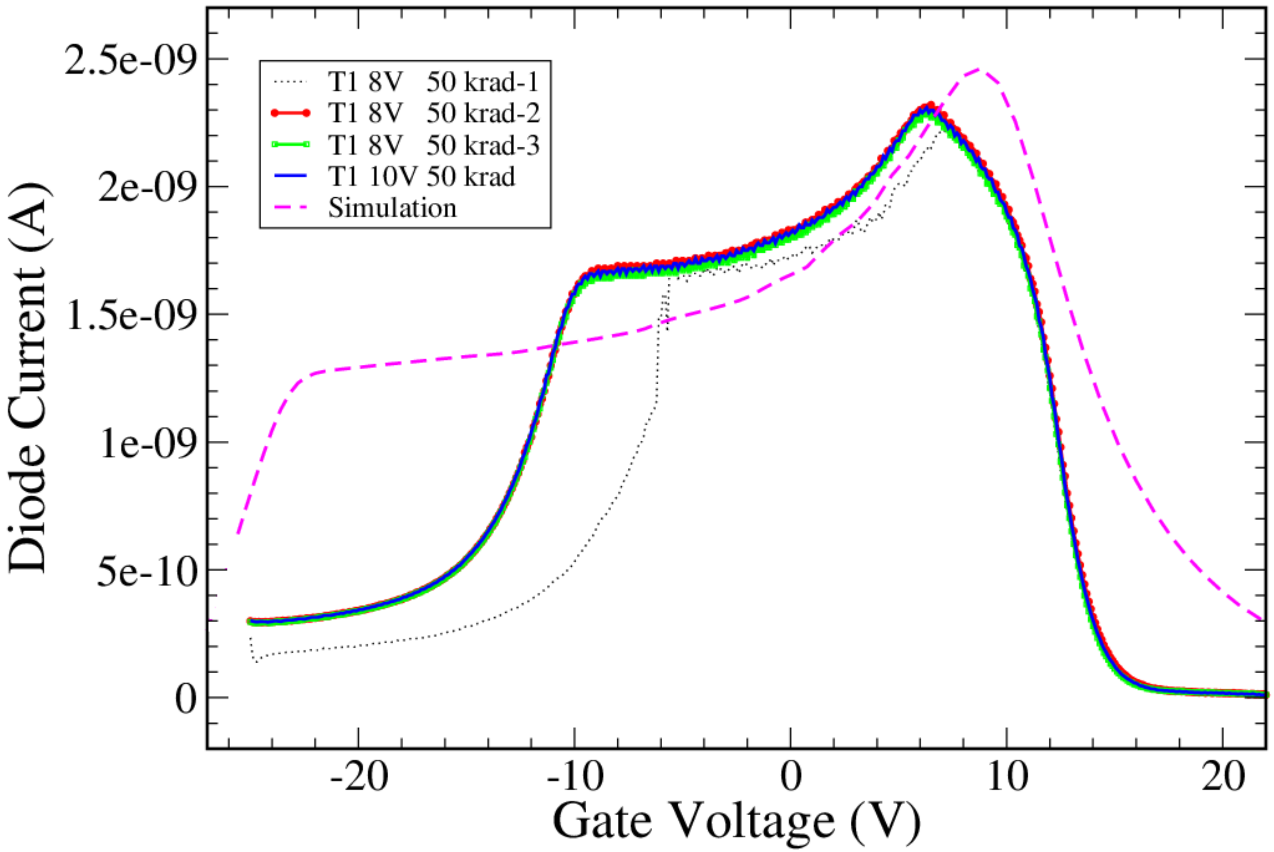
Effect of the Interface Traps

Sensitive Analysis of the Surface TCAD Model:

- N_{itA} Density of the acceptor trap states
- N_{itD} Density of the donor trap state



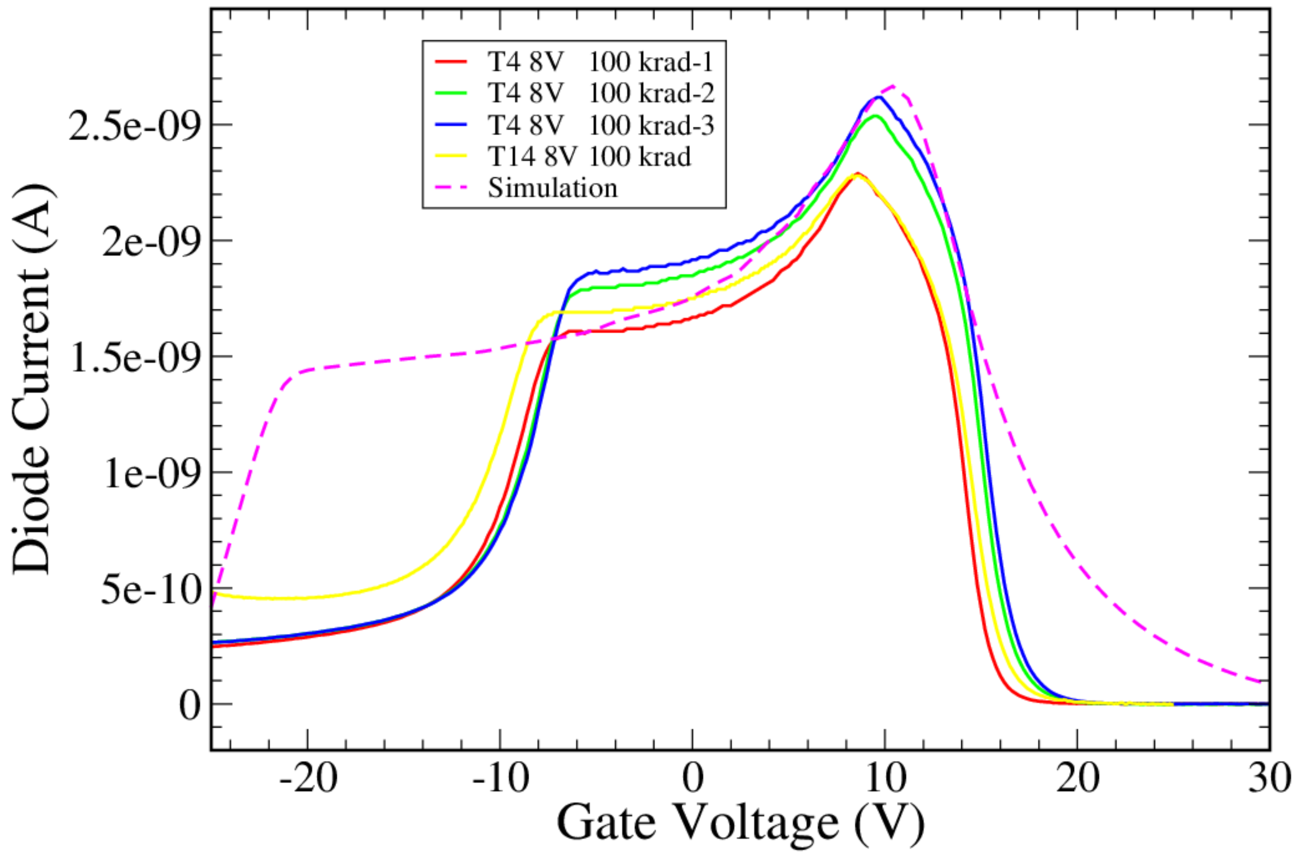
GD post X-rays - @ 50 krad



s_{0meas} = 100 cm/s

s_{0sim} = 106 cm/s

GD post X-rays - @100 krad



s_{0meas} = 113 cm/s

s_{0sim} = 115 cm/s

Radiation Damage Model

Bulk damage model*.

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	E_C - 0.42	1.0×10^{-15}	1.0×10^{-14}	1.613
Acceptor	E_C - 0.46	$1.5\div7\times10^{-15}$	$1.5\div7\times10^{-14}$	0.9
Donor	E_V + 0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

*F. Moscatelli, et al, "Combined Bulk and Surface Radiation Damage Effects at Very High Fluences in Silicon Detectors: Measurements and TCAD Simulations," *Trans. Nucl.* Sci., Volume 63 Issue 5.

- Avalanche ON: Van Overstraeten – de Man (default)

Surface damage model.

- $N_{OX} = 2x10^{12}$ cm^{-2} for fluences > $2x10^{14}$ 1 MeV n/cm^2

Type	Energy (eV)	Concentration (cm^{-2})	σ (eV)
Acceptor	E_C - 0.40	40% of acceptor N_{IT} ($N_{IT}=0.85\cdot N_{OX}$)	0.07
Acceptor	E_C - 0.60	60% of acceptor N_{IT} ($N_{IT}=0.85\cdot N_{OX}$)	0.07
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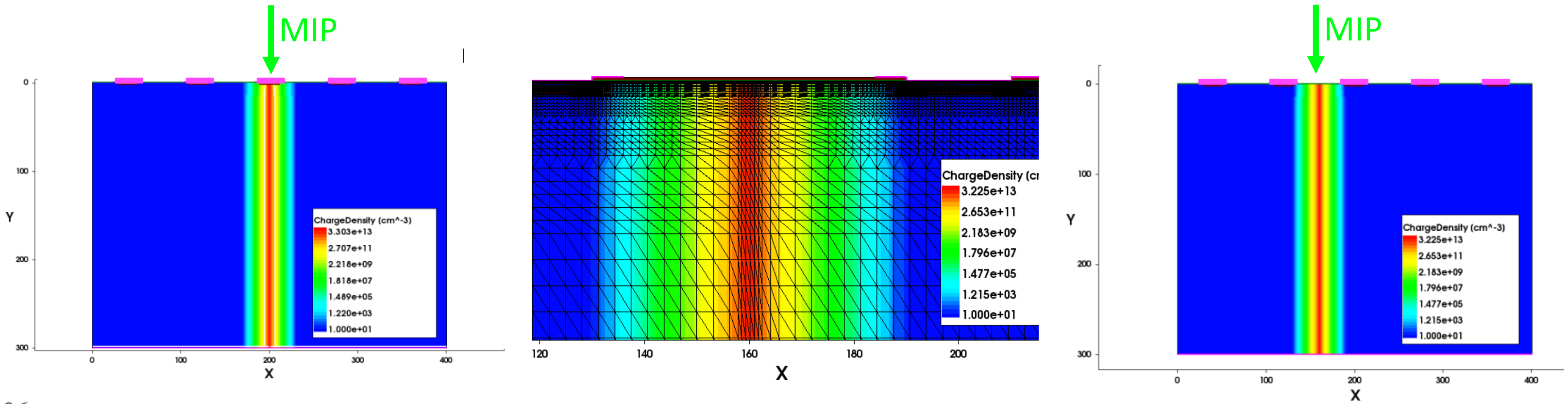
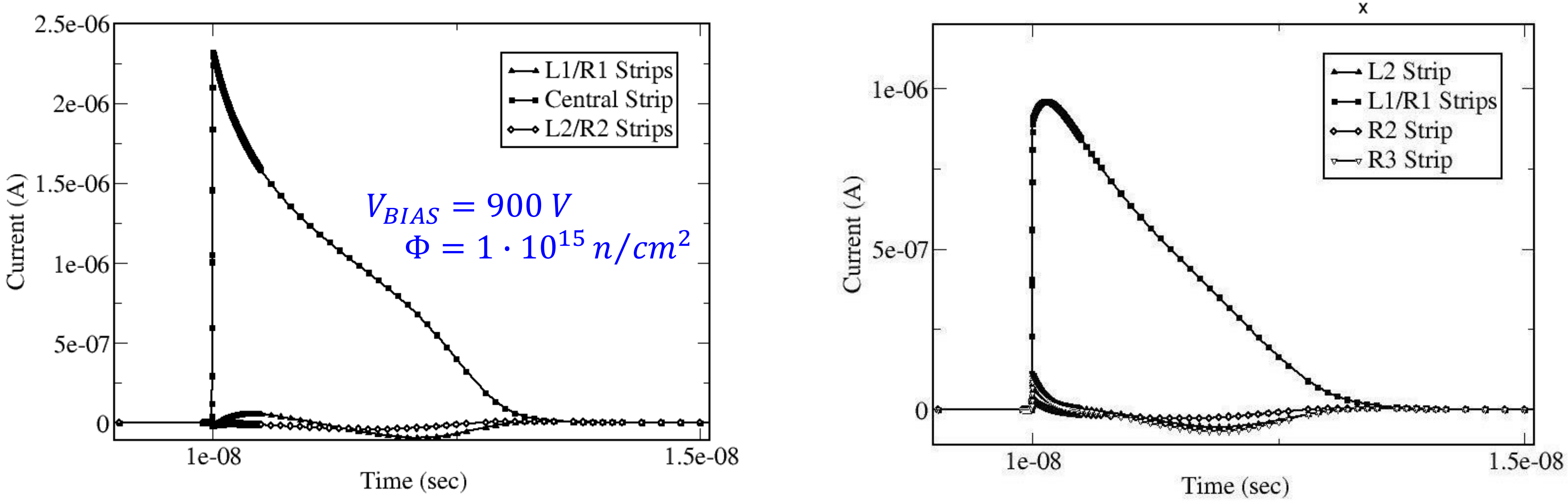
Transient Analysis: MIP Response

✓ Central hit strip vs. lateral hit (in between two strips)

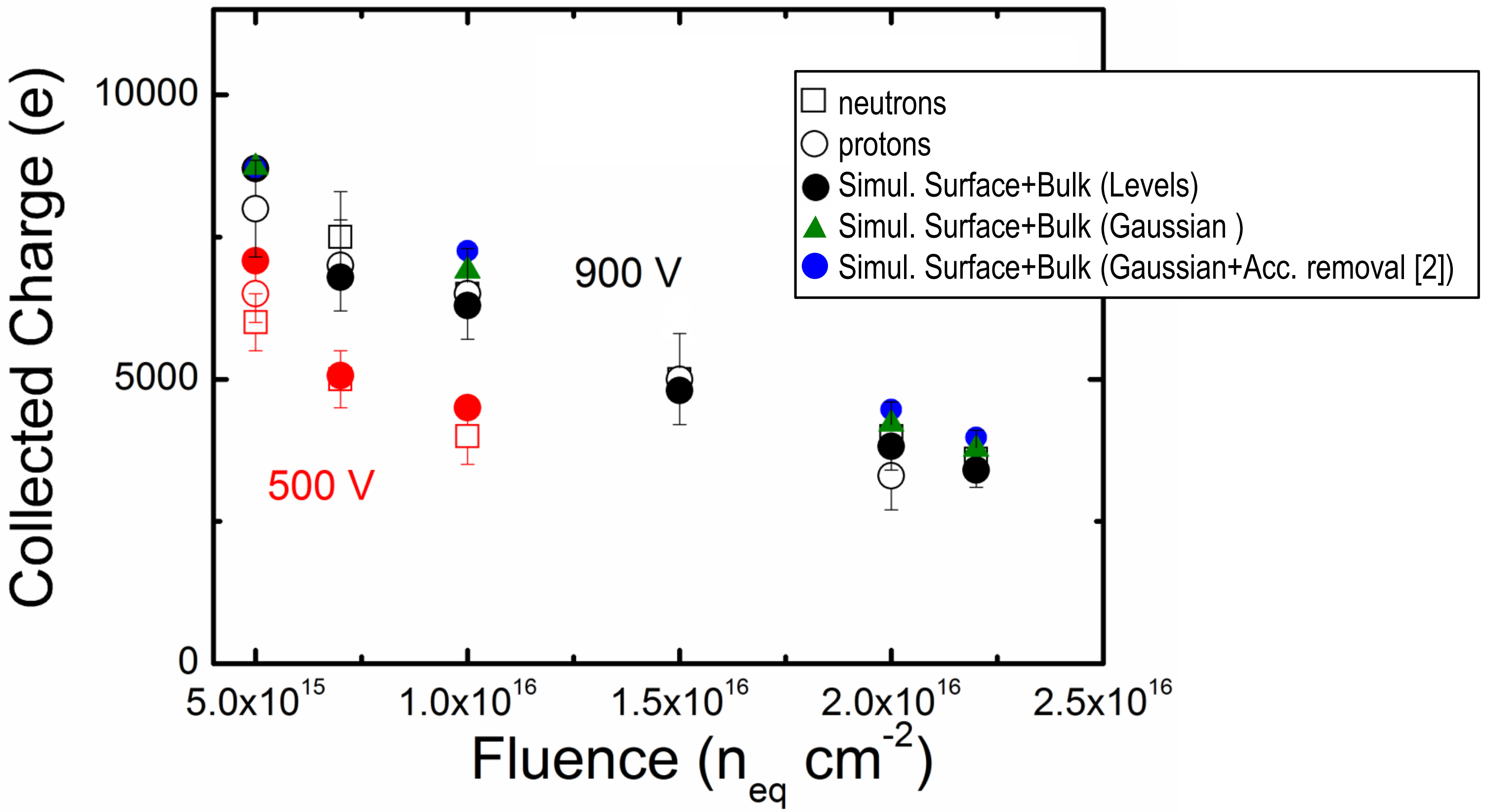




Charge Collection Efficiency

✓ Simulations vs. Measurements (T=248K)

- bulk + surface model (+ acceptor removal*)

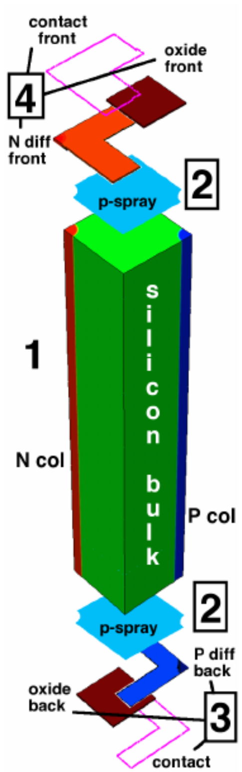


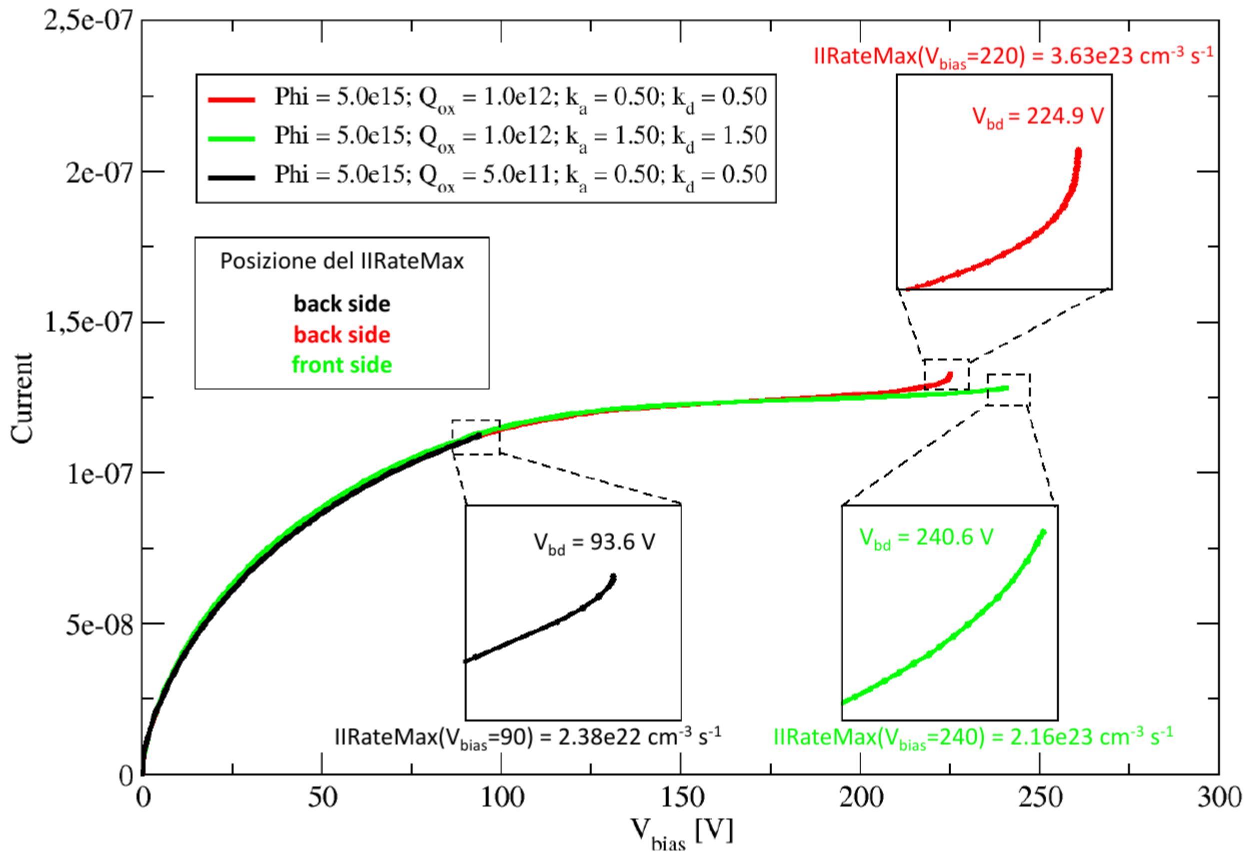
Measurements from Affolder et al., "Collected charge of planar silicon detectors ..." NIM A, Vol. 623 (2010), pp. 177-179.

[2] N. Cartiglia, 12th "Trento" Workshop on Advanced Silicon Radiation Detectors.

3D Detectors simulations

TCAD Radiation Damage Model for the study of V_{bd}





Data from G. Giugliarelli et al., “TCAD simulations of breakdown voltage and isolation properties of 3D sensors”, 12th “Trento” Workshop on Advanced Silicon Radiation Detectors.

Work Plan: Simulations

- ✓ Bulk radiation damage modelling:

  - extension of the three-level UniPG modelling (capture cross sections, charge multiplication, avalanche effects).

- ✓ Surface radiation damage modelling:

  - oxide fixed charge and interface trap state @dose;
  - systematic study of acceptor/donor states at different energies.

- ✓ Technology (process) dependent effect -> deep level parameterization, oxide charge density, interface trap energy and density, cross sections (e/h), trap type (acceptor or donor) effects.

- ✓ Comparison with literature data/dedicated measurements in terms of static behaviour (R, C) and charge collection properties.

- ✓ Comprehensive modelling (bulk + interface, 2D/3D).

Work Plan: Measurements

- ✓ Measurements on dedicated test structures e.g. gated diodes, MOS capacitors and MOSFETs on p-stop and p-spray/different substrates.
- ✓ Different technologies (e.g. FBK, IMM, HPK, other …).
- ✓ High-Frequency and Quasi-Stationary C, MOSFET V_{FB} and I-V characteristics, …
- ✓ Irradiation campaign with gammas, *x*-rays and neutrons/(protons).
- ✓ Measurements after irradiation -> trap parameter extraction, TCAD model validation.
- ✓ Predictive application of the model -> sensor design and optimization

✓ Completed	✓ Added
✓ On going	✓ To do.

Conclusions

- ✓ Application of the model to (planar) multistrip and 3D structures simulation (collaboration FBK Trento).
- ✓ Comparative analysis with alternative TCAD approach (Sentaurus vs. Silvaco comparative simulations – collaboration LNPHE Paris).
- ✓ Comparison with measurements on p-type/n-type structures/devices irradiated at high doses (20Mrad).
- ✓ Next steps:
  - bulk model refinement;
  - Comprehensive irradiation plan (γ- , x-rays + neutrons) for global modeling validation (IV, V_{dep}, CCE);
  - Deliverable D7.4 TCAD model radiation damage (month 46).