Modelling radiation damage in TCAD

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Outline

- √ Motivations and background.
- √ TCAD radiation damage modelling: discussion.
- √ Simulation results and comparison with experimental data:
  - DC (steady-state) -> Diodes / Gate Controlled Diodes.
  - AC (small-signals) -> MOS Capacitors.
  - Time (transient) -> Multi-strip structures.
- √ Conclusions.

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Motivations

- √ Modern TCAD tools(1) offer a wide variety of approaches, characterized by different combinations among physical accuracy and comprehensiveness, application versatility and computational demand -> mixed-mode approaches can be efficiently followed.
- √ A number of different physical damage mechanisms actually may interact in a non-trivial way. Deep understanding of physical device behavior therefore has the utmost importance, and device analysis tools may help to this purpose.
- √ Bulk and surface radiation damage have been taken into account by means of the introduction of deep level radiation induced traps whose parameters are physically meaningful and whose experimental characterization is feasible.
- √ Within a hierarchical approach, increasingly complex models have been considered, aiming at balancing complexity and comprehensiveness.

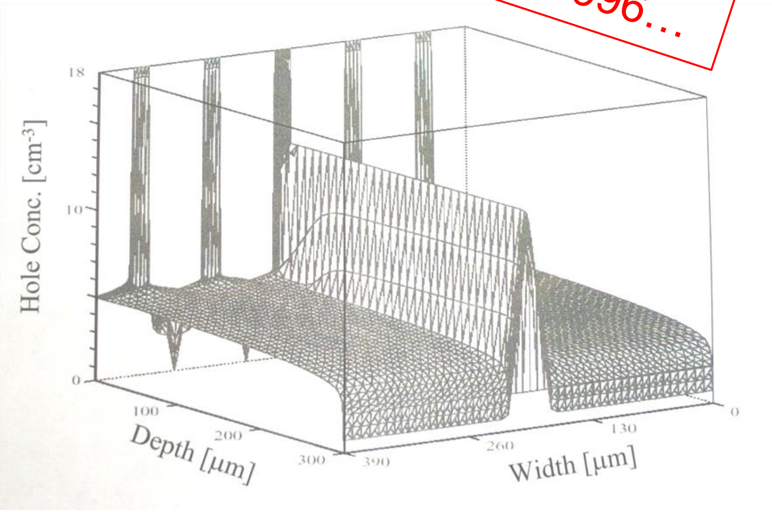
(1) Sentaurus Device SYNOPSYS®

Once upon a time… (1996)

- √ Numerical analysis and physical modelling of semiconductor devices -> application in High Energy Physics domain…
- √ Modelling of the interaction between ionizing particle / silicon substrate compatible with Box Integration Method simulation scheme.

$$
\begin{cases}
\nabla \cdot \left(-\varepsilon_s \nabla \varphi\right) = q\left(N_D^+ - N_A^- + p - n\right) \\
\dfrac{\partial n}{\partial t} - \dfrac{1}{q} \nabla \cdot \vec{J}_n = G - R \boxed{+ G^{rad}} \\
\dfrac{\partial p}{\partial t} + \dfrac{1}{q} \nabla \cdot \vec{J}_p = G - R \boxed{+ G^{rad}}
\end{cases}
$$

- √ G^{rad} can be distributed in time and space according to the numerical spatial and time discretization algorithms.



TCAD applications in HEP in 1996…

Radiation damage modelling

- √ Numerical modelling of radiation damage effects in semiconductor devices.
- √ Deep-level recombination centres / traps radiation induced.
- √ Explicit contribution of the trapped charges to the charge density (modified Poisson equation):

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

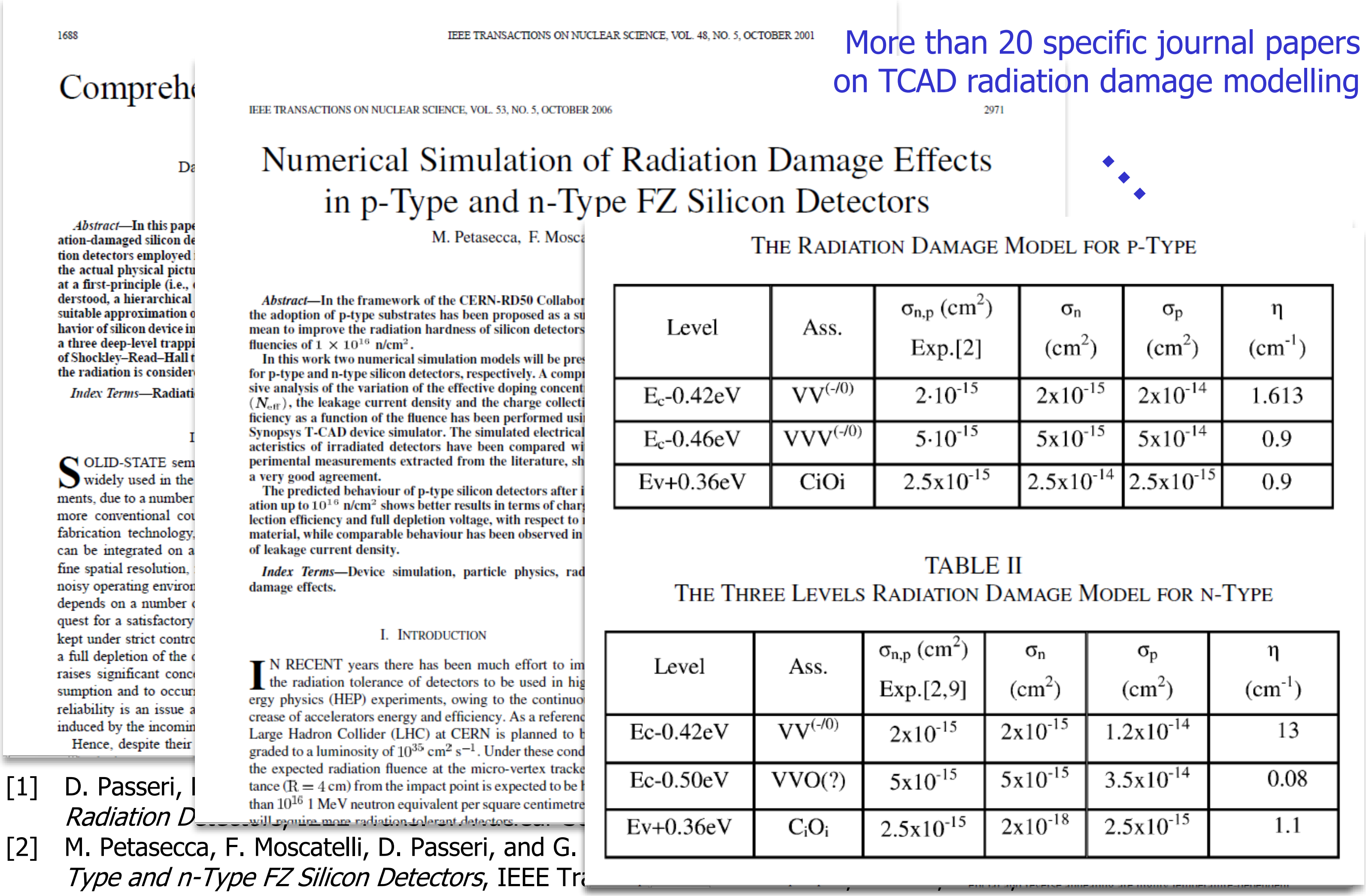
- √ Continuity equation for both free and trapped carriers:

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

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

“University of Perugia” model

More than 20 specific journal papers on TCAD radiation damage modelling



1688 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 48, NO. 5, OCTOBER 2001

Comprehe

Da

Abstract—In this pape
ation-damaged silicon de
tion detectors employed
the actual physical pictu
at a first-principle (i.e.,
derstood, a hierarchical
suitable approximation o
havior of silicon device in
a three deep-level trappi
of Shockley–Read–Hall t
the radiation is consider

Index Terms—Radiati

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SOLID-STATE sem
widely used in the
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more conventional co
fabrication technology,
can be integrated on a
fine spatial resolution,
noisy operating environ
depends on a number o
quest for a satisfactory
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a full depletion of the
raises significant conc
sumption and to occur
reliability is an issue a
induced by the incomin
Hence, despite their

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 53, NO. 5, OCTOBER 2006 2971

Numerical Simulation of Radiation Damage Effects in p-Type and n-Type FZ Silicon Detectors

M. Petasecca, F. Mosca

Abstract—In the framework of the CERN-RD50 Collabor
the adoption of p-type substrates has been proposed as a su
mean to improve the radiation hardness of silicon detectors
fluencies of 1×10^{16} n/cm^2.
In this work two numerical simulation models will be pres
for p-type and n-type silicon detectors, respectively. A compr
sive analysis of the variation of the effective doping concent
($N_{\rm eff}$), the leakage current density and the charge collecti
ficiency as a function of the fluence has been performed usi
Synopsys T-CAD device simulator. The simulated electrical
acteristics of irradiated detectors have been compared wi
perimental measurements extracted from the literature, sh
a very good agreement.
The predicted behaviour of p-type silicon detectors after i
ation up to 10^{16} n/cm^2 shows better results in terms of char
lection efficiency and full depletion voltage, with respect to
material, while comparable behaviour has been observed in
of leakage current density.

Index Terms—Device simulation, particle physics, rad
damage effects.

I. INTRODUCTION

IN RECENT years there has been much effort to im
the radiation tolerance of detectors to be used in hig
ergy physics (HEP) experiments, owing to the continuo
crease of accelerators energy and efficiency. As a referen
Large Hadron Collider (LHC) at CERN is planned to b
graded to a luminosity of 10^{35} cm^2 s^{-1}. Under these cond
the expected radiation fluence at the micro-vertex tracke
tance (R = 4 cm) from the impact point is expected to be h
than 10^{16} 1 MeV neutron equivalent per square centimetre
will require more radiation-tolerant detectors.

THE RADIATION DAMAGE MODEL FOR P-TYPE

Level	Ass.	$\sigma_{n,p}$ (cm^2) Exp.[2]	σ_n (cm^2)	σ_p (cm^2)	η (cm^{-1})
E_c-0.42eV	VV$^{(-/0)}$	$2\cdot10^{-15}$	2x10^{-15}	2x10^{-14}	1.613
E_c-0.46eV	VVV$^{(-/0)}$	$5\cdot10^{-15}$	5x10^{-15}	5x10^{-14}	0.9
Ev+0.36eV	CiOi	2.5x10^{-15}	2.5x10^{-14}	2.5x10^{-15}	0.9

TABLE II
THE THREE LEVELS RADIATION DAMAGE MODEL FOR N-TYPE

Level	Ass.	$\sigma_{n,p}$ (cm^2) Exp.[2,9]	σ_n (cm^2)	σ_p (cm^2)	η (cm^{-1})
Ec-0.42eV	VV$^{(-/0)}$	2x10^{-15}	2x10^{-15}	1.2x10^{-14}	13
Ec-0.50eV	VVO(?)	5x10^{-15}	5x10^{-15}	3.5x10^{-14}	0.08
Ev+0.36eV	C_iO_i	2.5x10^{-15}	2x10^{-18}	2.5x10^{-15}	1.1

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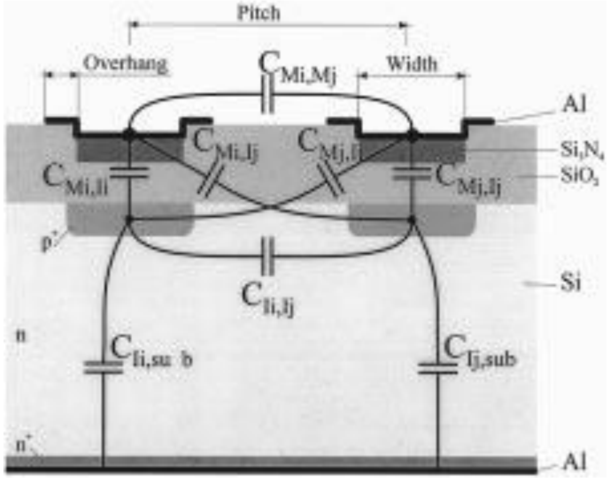
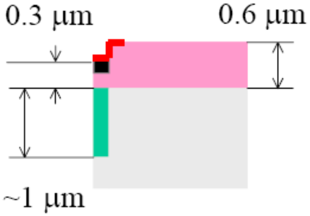
[1] D. Passeri, I
Radiation D

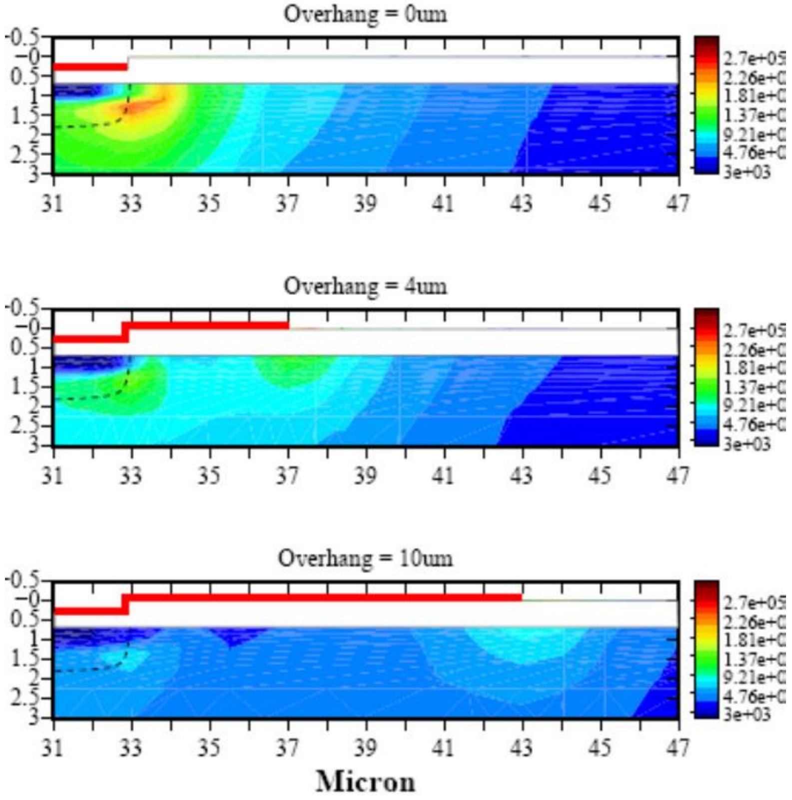
[2] M. Petasecca, F. Moscatelli, D. Passeri, and G.
Type and n-Type FZ Silicon Detectors, IEEE Tra

LHC CMS Si Tracker design

- √ Choice of the Si-Strip detector substrate resistivity.
- √ Strip geometry optimization (w/p, metal overhang).







Critical Electric Fields (within Si) reduction

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- √ Conclusions.

TCAD radiation damage models

√ Pennicard et al., *Simulations of radiation-damaged 3D detectors for the Super-LHC*, NIM A 592 (2008) 16–25 .

- 3 levels, increased capture cross-sections σ_n, σ_p.

√ E. Verbitskaya et al., *Operational voltage of silicon heavily irradiated strip detectors utilizing avalanche multiplication effect*, JINST 7 C02061, 2012.

- 2 levels, avalanche multiplication, 1D “analytical” approach.

√ Delhi University (R. Dalal et al., Vertex - 2014, 23rd RD50 CERN, Nov. 2013)

- 5 levels + Q_F / 2 levels + Q_F + $Q_{it.}$

√ RD50 Collaboration (T. Peltola PSD2014 / RESMDD2014)

- defect models tuned by R. Eber from V. Eremin et al., *Avalanche effect in Si heavily irradiated detectors: Physical model and perspectives for application*, NIM A 658 (2011) for $\Phi_{eq}=1.0\times10^{14}$ - 1.5×10^{15} cm^{-2} at fixed T=253 K;

- 3-level model within 2 µm of device surface + proton model in bulk.

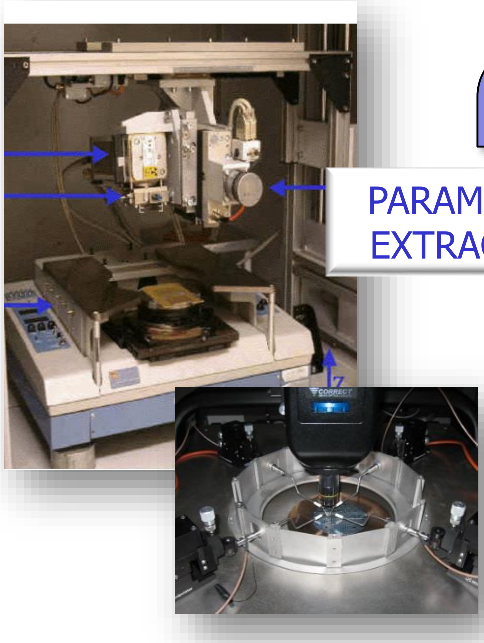
√ Hamburg model J. Schwandt, R. Klanner – Global parameter optimization (27th RD50 Workshop, December 2-4, 2015).

New "University of Perugia" model

- √ Extend the predictive capabilities to HL-LHC radiation damage levels (e.g. fluences > 2.0×10^{16} cm^{-2} 1 MeV neutrons).
- √ Keep low the number of traps (e.g. fitting parameters).
- √ New effects (e.g. charge multiplication <- avalanche effects).
- √ Physically grounded approach.
- √ No over-specific modelling (one model fits all…).
- √ Predictive capabilities @Φ, @T, @V_{bias}, …

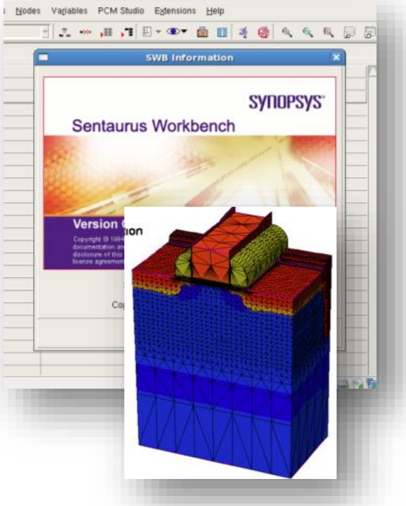
New “University of Perugia” model

TEST STRUCTURE MEASUREMENTS



PARAMETERS EXTRACTION

MODEL



MODEL VALIDATION

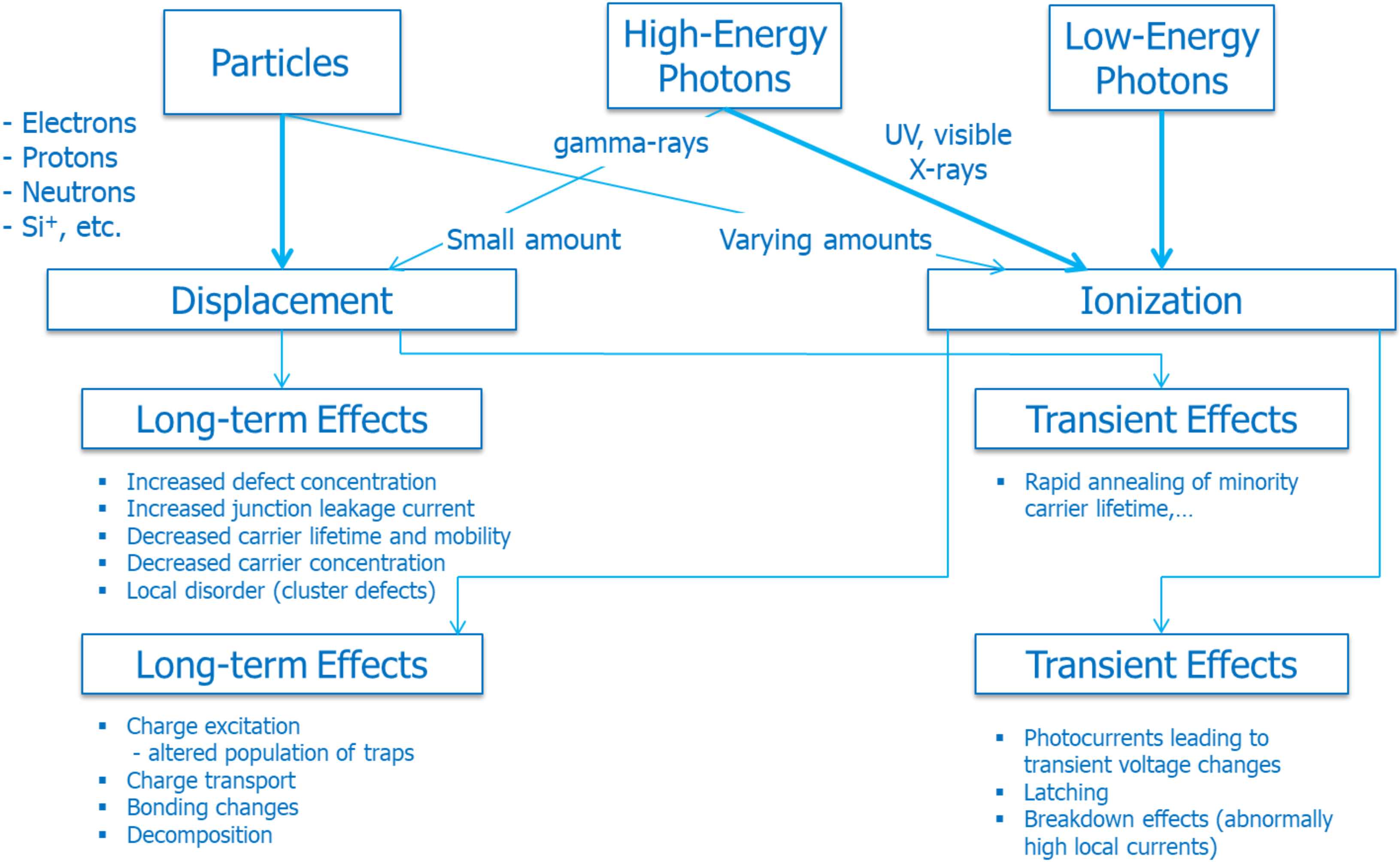
DETECTOR OPTIMIZATION

CHARGE COLLECTION

√ Modelling the effects of the radiation damage.

√ Predictive insight of the behaviour of detectors, aiming at their performance optimization.

Radiation damage effects



Particles

- Electrons
- Protons
- Neutrons
- Si$^+$, etc.

High-Energy Photons

Low-Energy Photons

gamma-rays

UV, visible X-rays

Small amount

Varying amounts

Displacement

Ionization

Long-term Effects

- Increased defect concentration
- Increased junction leakage current
- Decreased carrier lifetime and mobility
- Decreased carrier concentration
- Local disorder (cluster defects)

Transient Effects

- Rapid annealing of minority carrier lifetime,…

Long-term Effects

- Charge excitation
  - altered population of traps
- Charge transport
- Bonding changes
- Decomposition

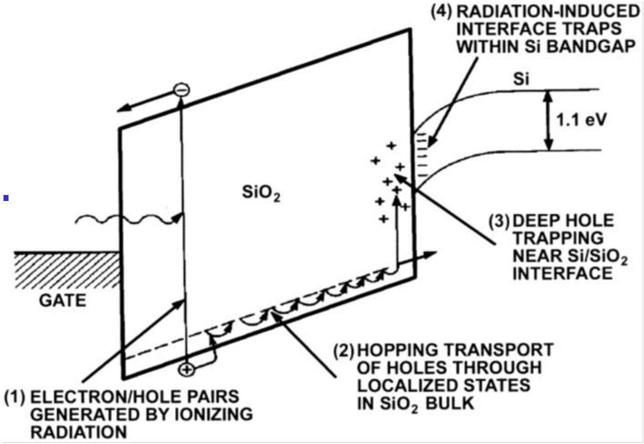
Transient Effects

- Photocurrents leading to transient voltage changes
- Latching
- Breakdown effects (abnormally high local currents)

Radiation damage effects (2)

√ Ionization -> SURFACE damage

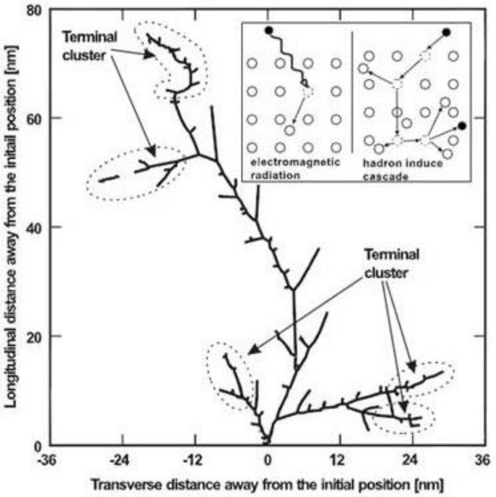
- build-up of trapped charge in the oxide;
- increase in the number of bulk oxide traps.
- increase in the number of interface traps;
- Q_{OX}, N_{IT}



T. R. Oldham, F. B. McLean, *Total Ionizing Dose Effects in MOS Oxides and Devices*, IEEE Trans. on Nuclear Science, vol. 50, no. 3, June 2003

√ Atomic Displacement -> BULK damage

- silicon lattice defect generations;
- point and cluster defects;
- increase of deep-level trap states;
- N_T



Traps characteristics

√ Traps provide allowed energy states within the band-gap, affecting the device behavior to many respects, e.g. by altering the effective doping, by enhancing recombination, by increasing leakage…

√ Several models, e.g. Shockley–Read–Hall recombination, depend on traps implicitly

$$R_{net}^{SRH} = \frac{np - n_{i,eff}^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

$$p_1 = n_{i,eff} e^{\left(\frac{-E_{trap}}{kT}\right)}$$

$$n_1 = n_{i,eff} e^{\left(\frac{E_{trap}}{kT}\right)}$$

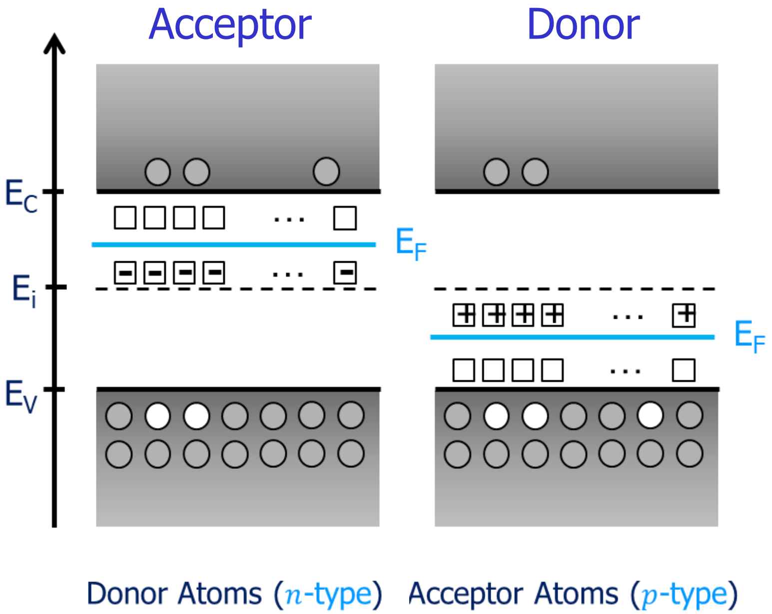
$$\tau_{n,p} = \tau_{dop} \frac{f(T)}{1 + g_{n,p}(F)}$$

√ Traps can be specified in terms of:

- √ **Type** (Acceptor, Donor)
- √ **Energy Distribution** (Level, Gaussian, Uniform, …)
- √ Capture cross-sections (electrons, holes)
- √ Concentration / Spatial distributions

Traps type

- √ **Acceptor** traps are uncharged when unoccupied (empty) / negatively charged when occupied (they carry the charge of one electron when fully occupied).
- √ **Donor** traps are uncharged when unoccupied (empty) /positively charged when occupied (they carry the charge of one hole when fully occupied).



E_{T_A} neutral if above E_F ($E_{T_A} > E_F$)

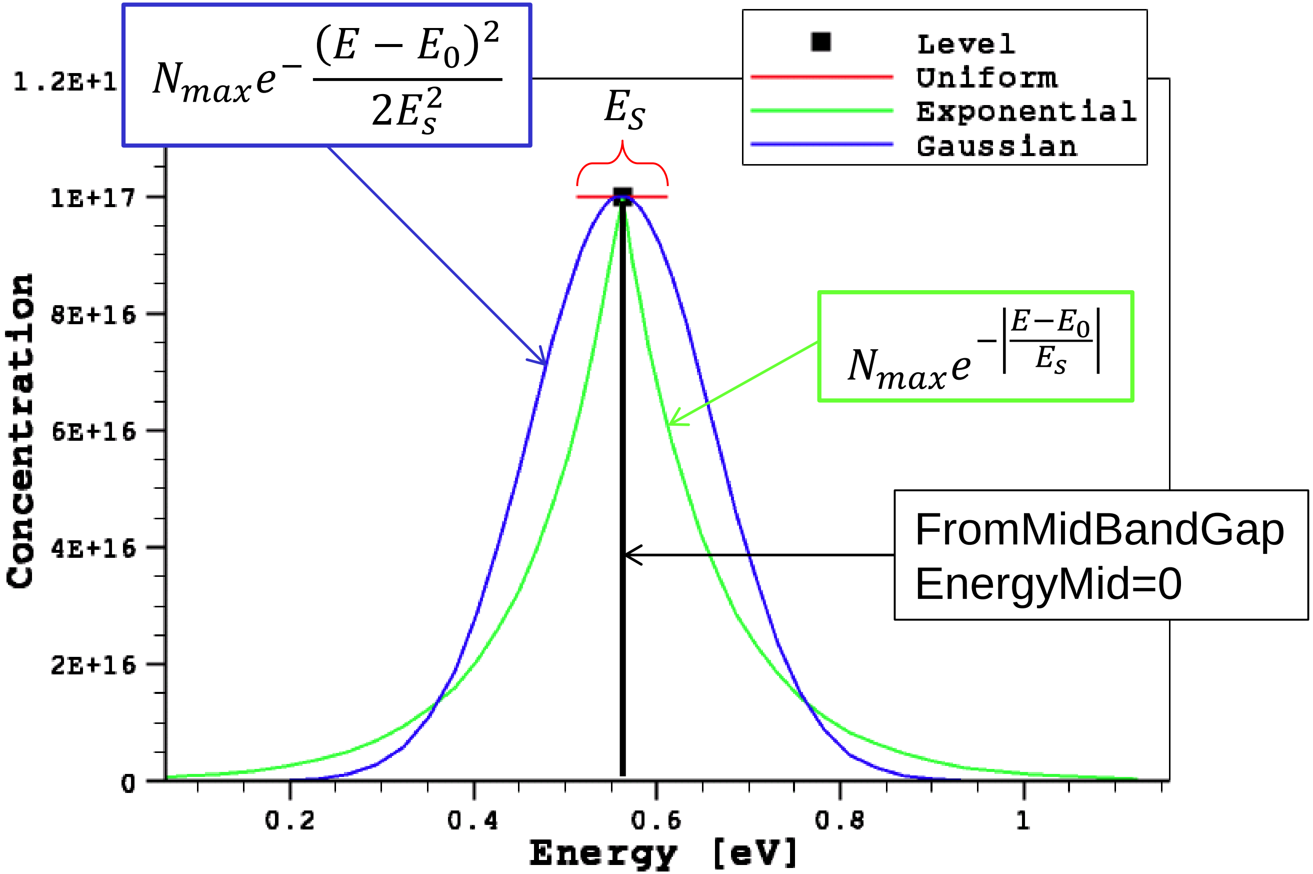
E_{T_A} charged (-) if below E_F ($E_{T_A} < E_F$)

E_{T_D} charged (+) if above E_F ($E_{T_D} > E_F$)

E_{T_D} neutral if below E_F ($E_{T_D} < E_F$)

Traps energy distribution

√ Traps energetic parametrization.



$$N_{max}e^{-\frac{(E-E_0)^2}{2E_S^2}}$$

$$E_S$$

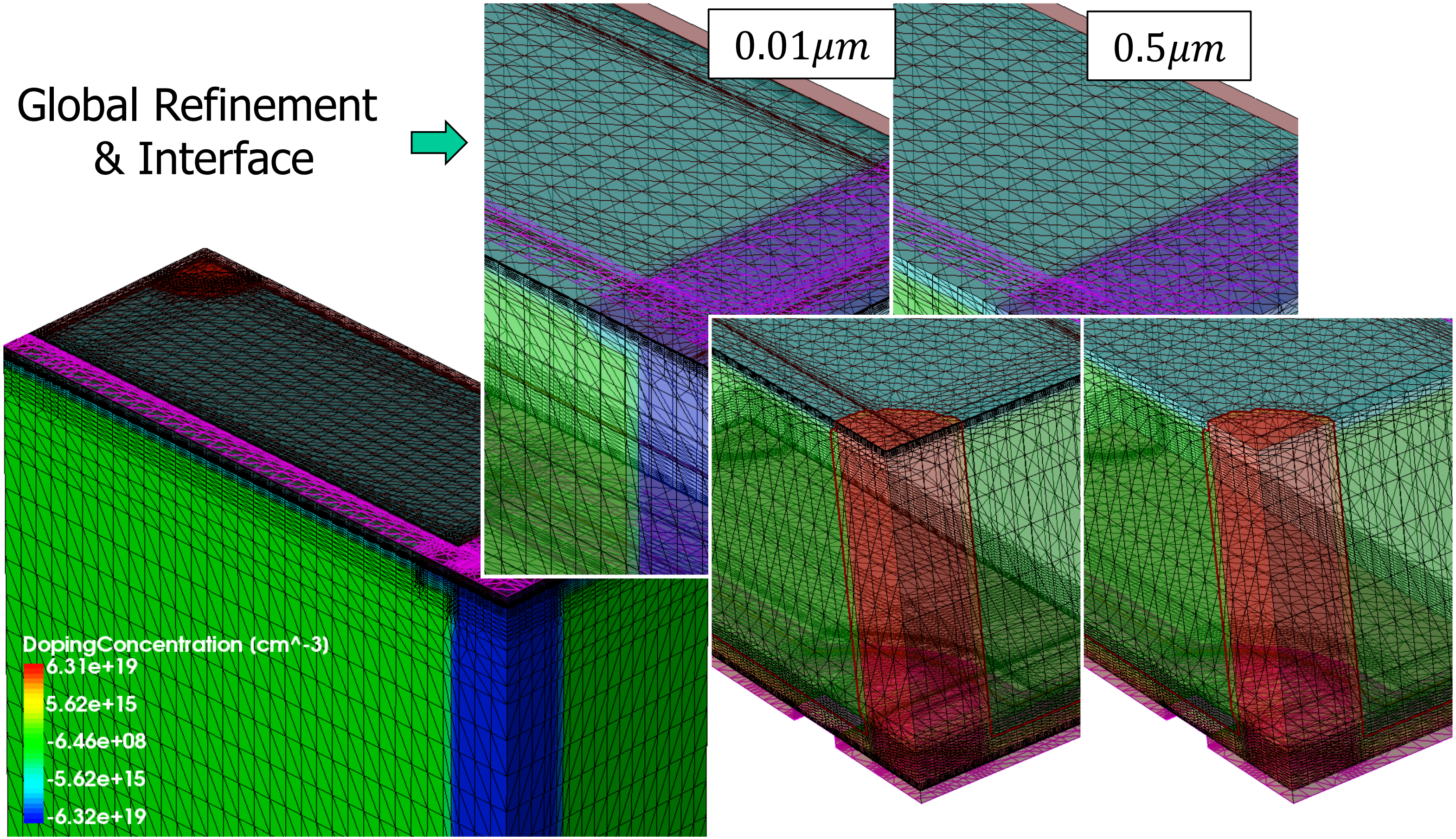
$$N_{max}e^{-\left|\frac{E-E_0}{E_S}\right|}$$

FromMidBandGap
EnergyMid=0

The space discretization issue

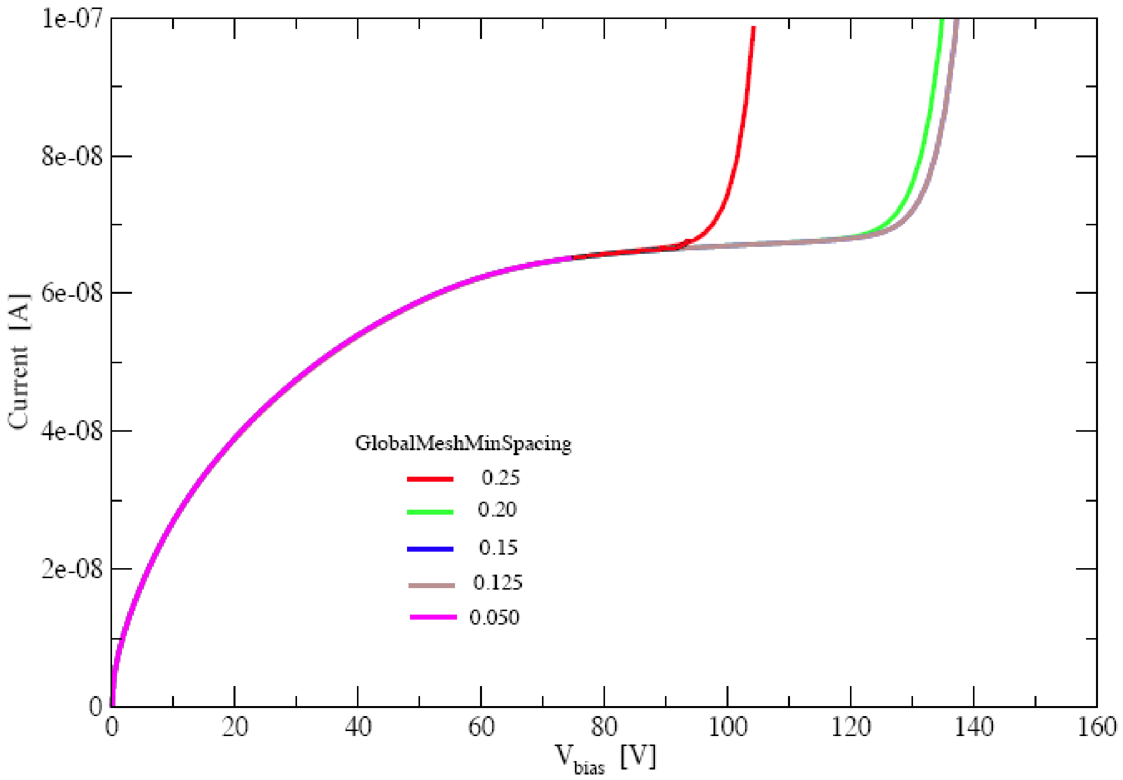
√ Mesh (grid) definition is crucial for simulation accuracy.

Global Refinement
& Interface



The space discretization issue (2)

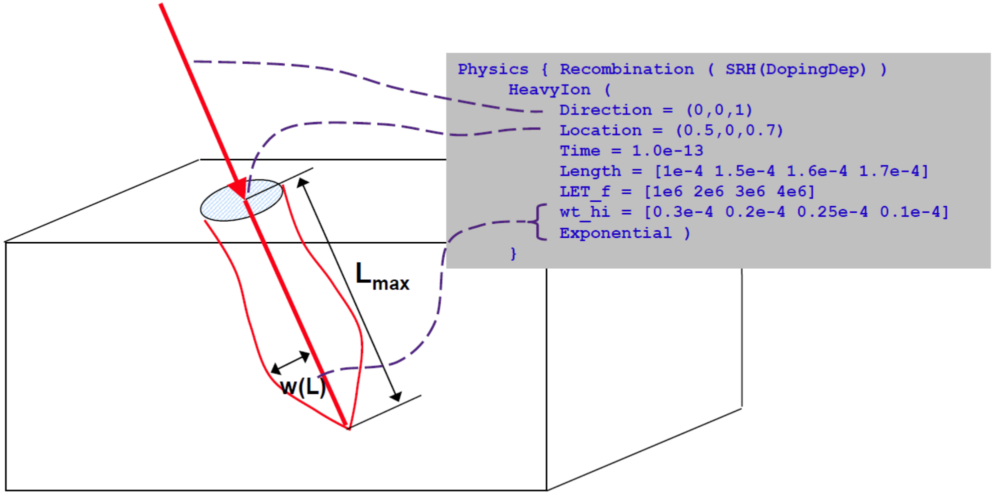
√ Mesh (grid) definition is a crucial for simulation accuracy / simulation convergence.



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

The time discretization issue

MIP DISCRETIZATION



```
Physics { Recombination ( SRH(DopingDep) )
     HeavyIon (
          Direction = (0,0,1)
          Location = (0.5,0,0.7)
          Time = 1.0e-13
          Length = [1e-4 1.5e-4 1.6e-4 1.7e-4]
          LET_f = [1e6 2e6 3e6 4e6]
          wt_hi = [0.3e-4 0.2e-4 0.25e-4 0.1e-4]
          Exponential )
     }
```

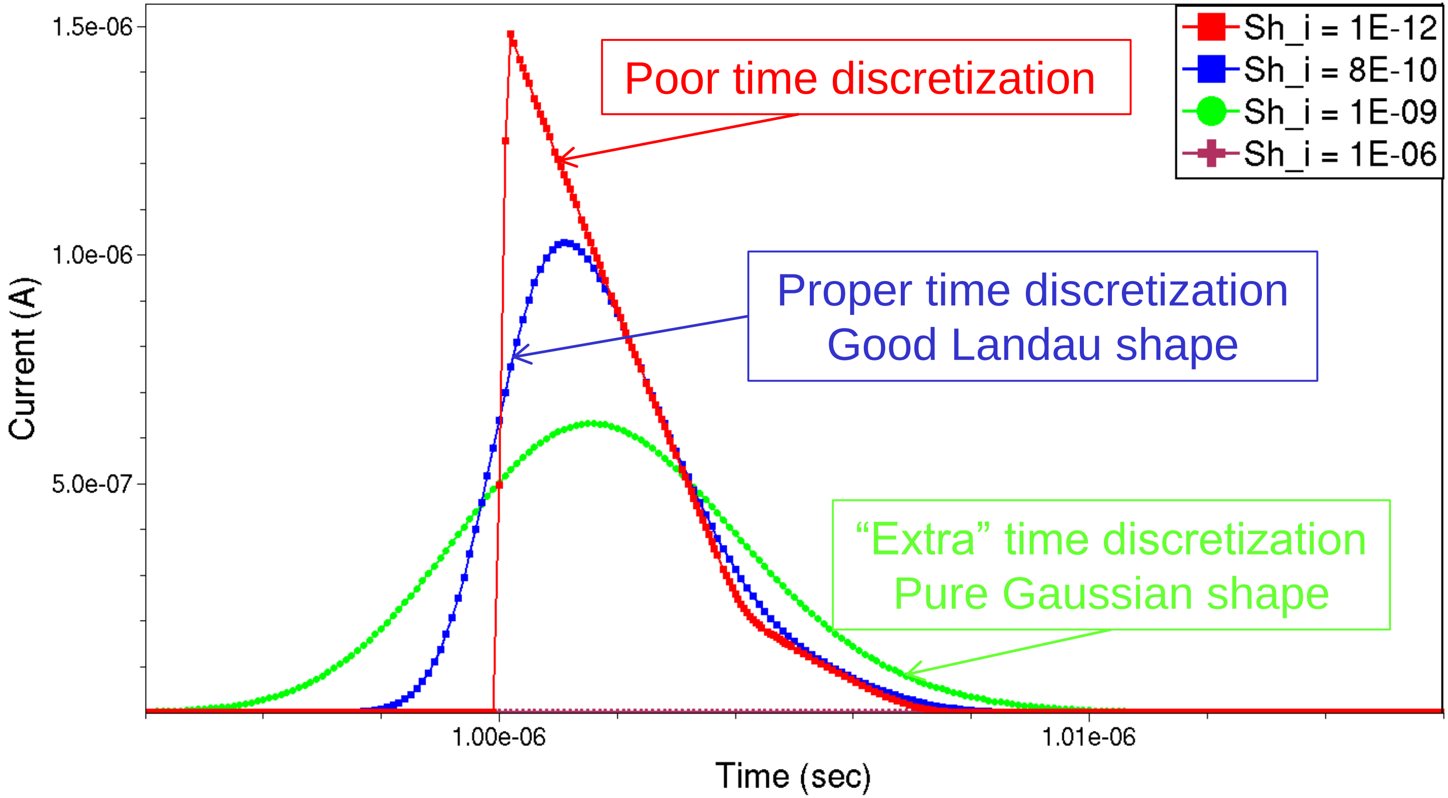
$$G(l, w, t) = G_{\mathrm{LET}}(l)\underbrace{R(w, l)}\underbrace{T(t)}$$

$$\boxed{R(w, l) = \exp\left(-\frac{w}{w_{\mathrm{t}}(l)}\right)}$$

$$\boxed{T(t) = \frac{2 \cdot \exp\left(-\left(\frac{t - t_0}{\sqrt{2} \cdot s_{\mathrm{hi}}}\right)^2\right)}{\sqrt{2} \cdot s_{\mathrm{hi}}\sqrt{\pi}\left(1 + \mathrm{erf}\left(\frac{t_0}{\sqrt{2} \cdot s_{\mathrm{hi}}}\right)\right)}}$$

The time discretization issue (2)

- √ Time discretization of the charge generation…
- √ Numerical issues in charge generation -> charge collection evaluation.



Poor time discretization

Proper time discretization
Good Landau shape

"Extra" time discretization
Pure Gaussian shape

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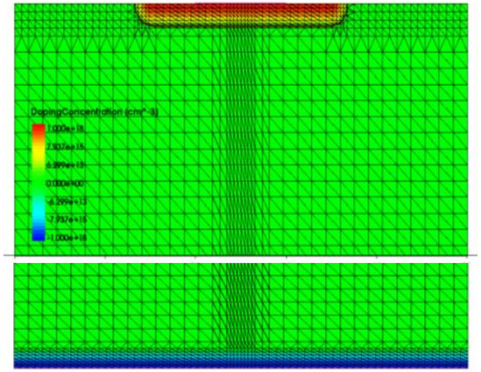
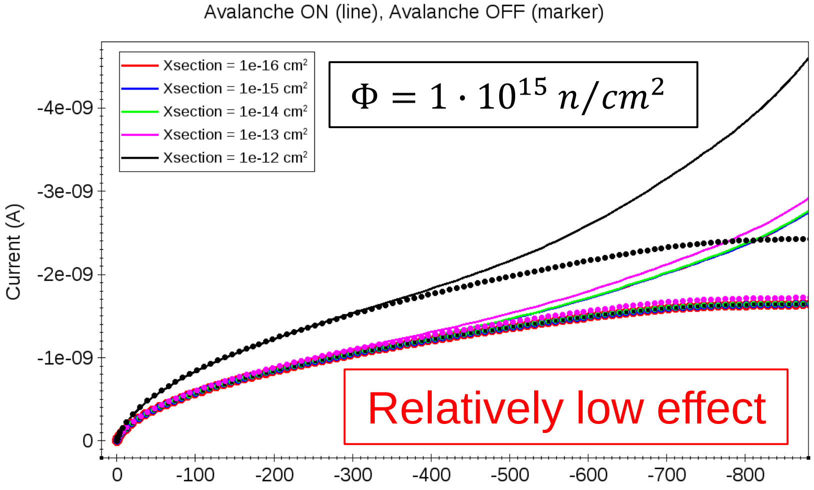
Diode simulation: leakage current

- √ Effect of the capture cross-sections variation combined with impact ionization (simplified n-on-p single strip structure).

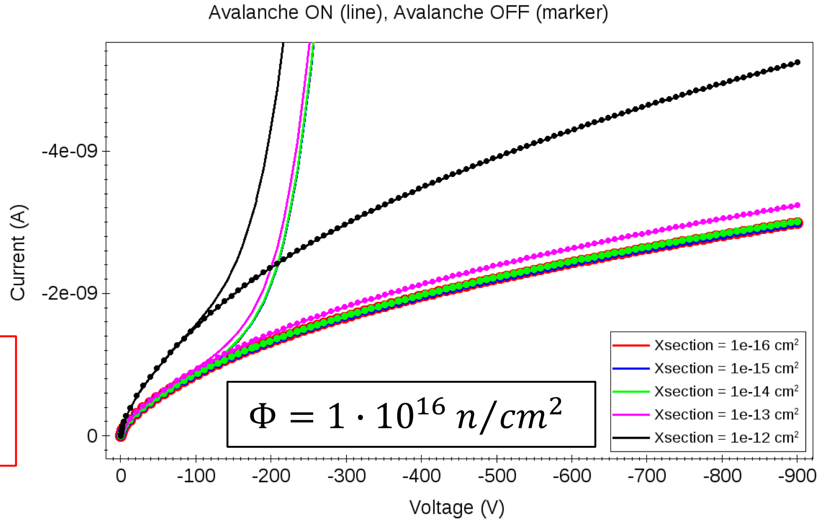


Significant effect of the impact ionization at high fluences



$$\Phi = 1 \cdot 10^{15}\, n/cm^2$$

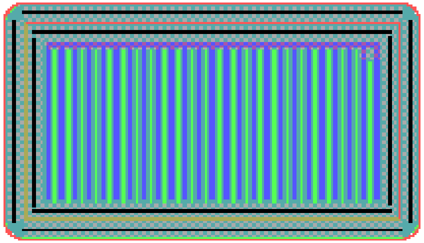
Relatively low effect

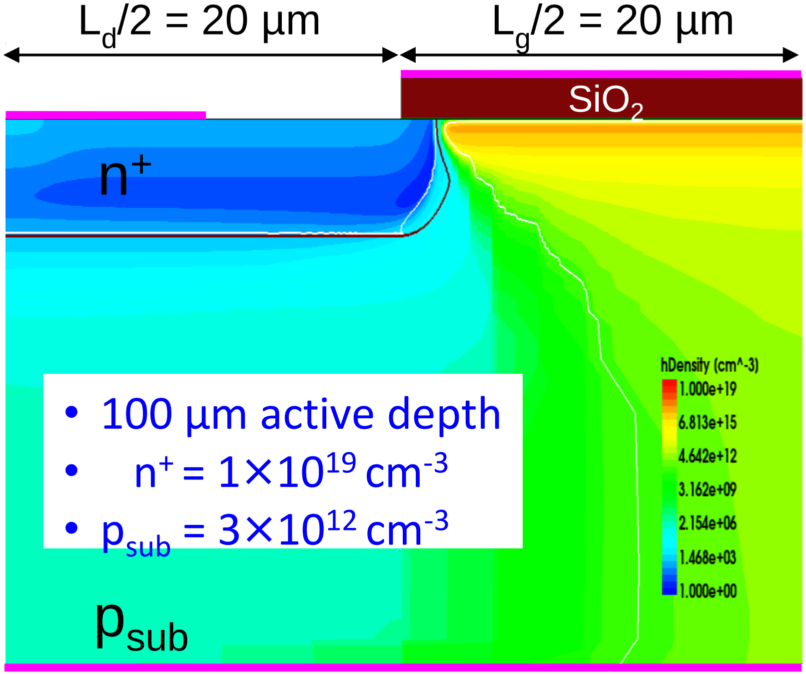


$$\Phi = 1 \cdot 10^{16}\, n/cm^2$$

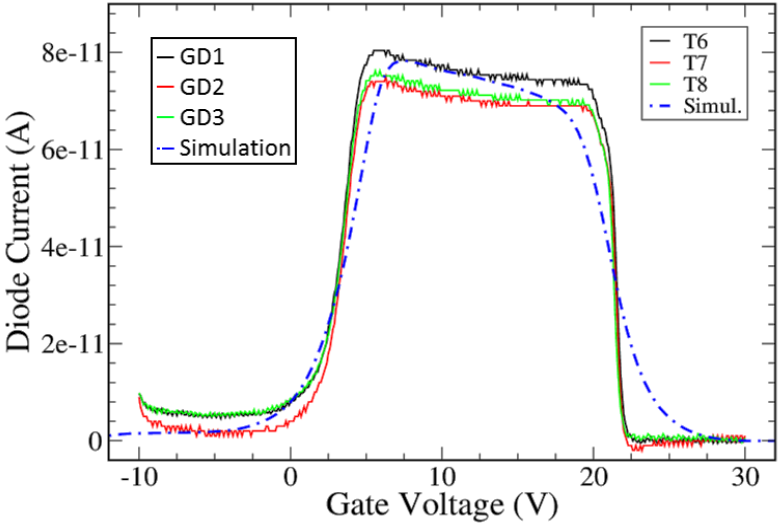
Gate Controlled Diode

√ Non-irradiated structures.



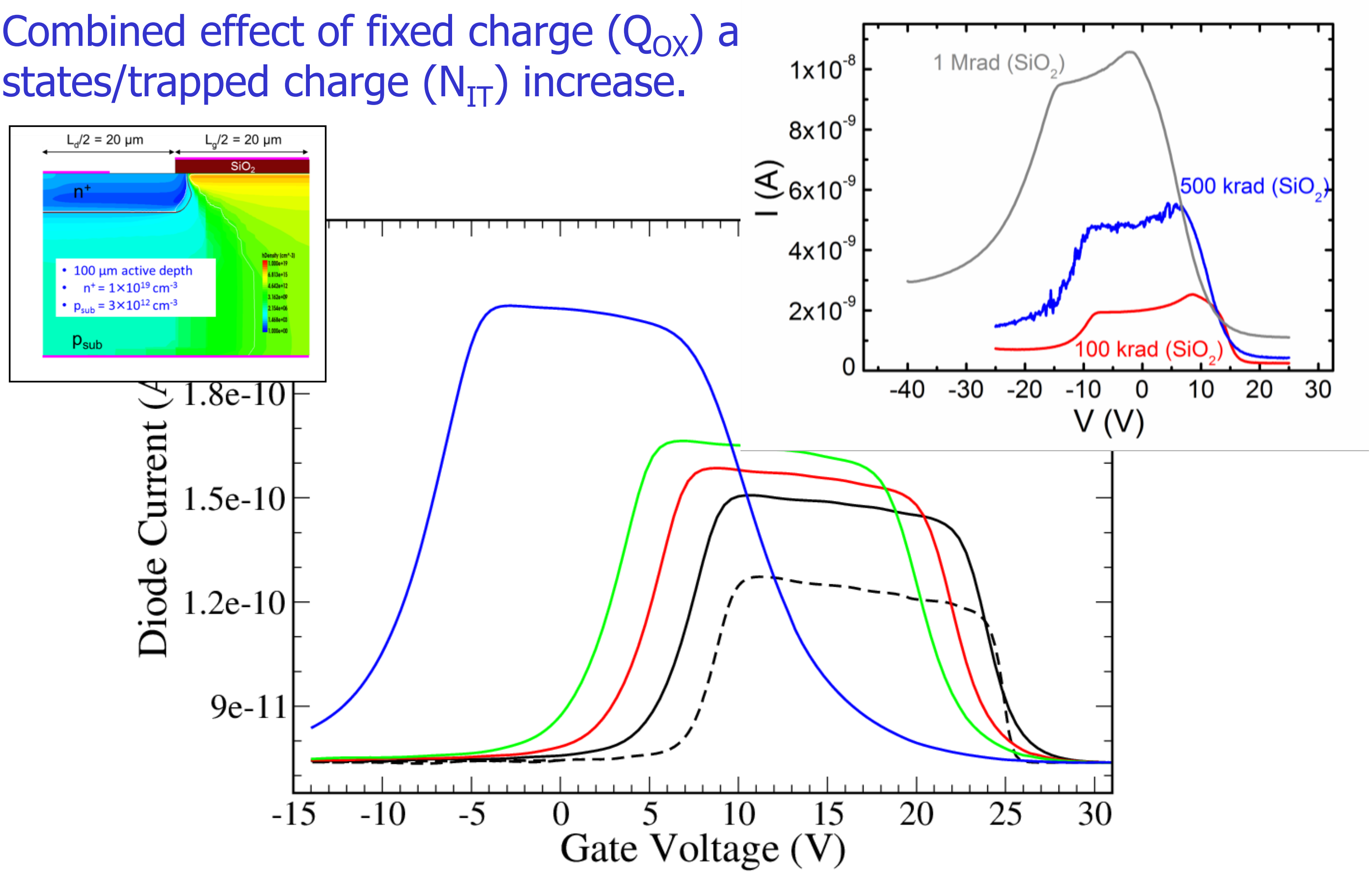


- 100 µm active depth
- $n^+ = 1\times10^{19}$ cm^{-3}
- $p_{sub} = 3\times10^{12}$ cm^{-3}



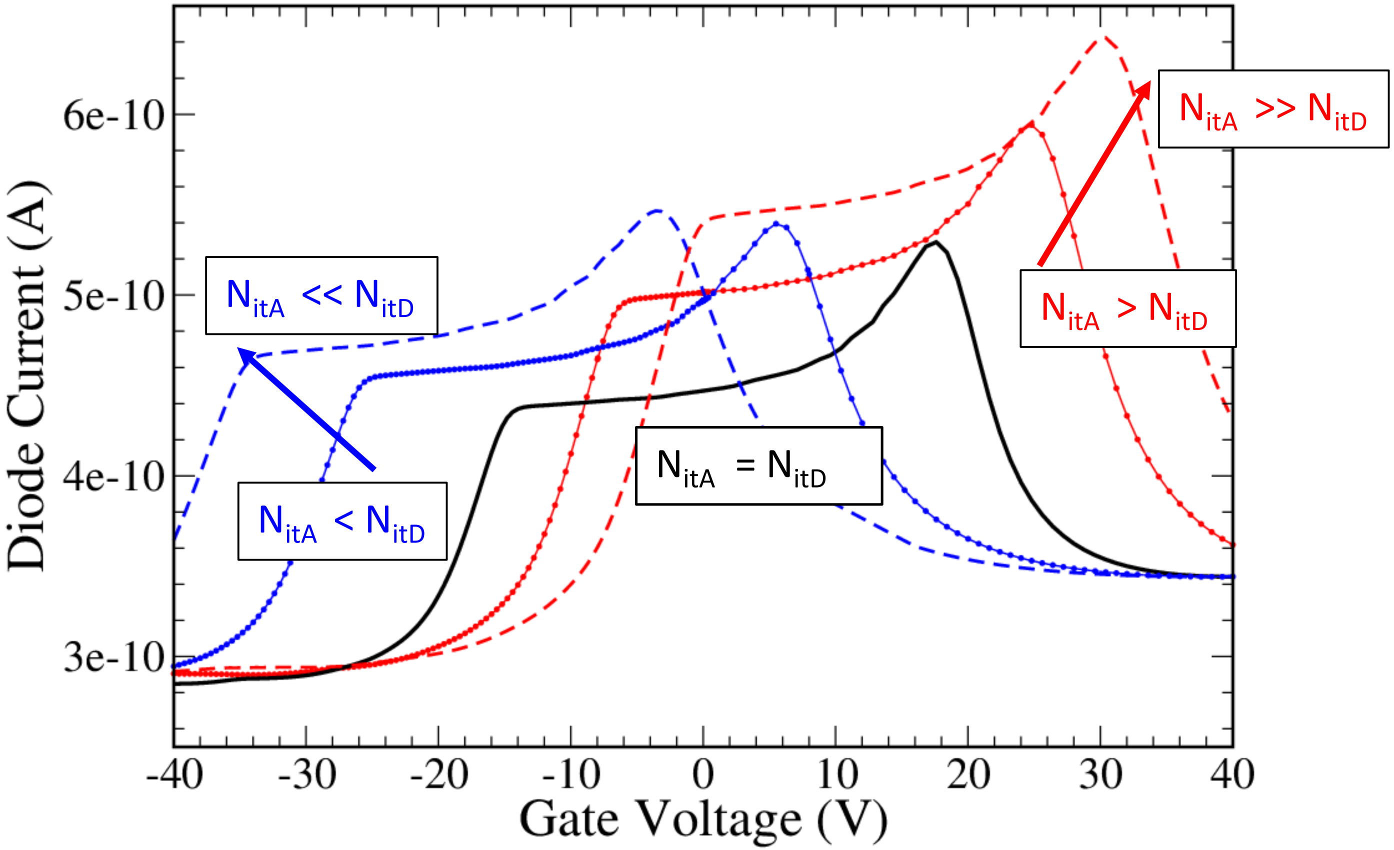
Sensitivity analysis: Q_{OX} + N_{IT}

- √ Combined effect of fixed charge (Q_{OX}) a states/trapped charge (N_{IT}) increase.



Effect of Interface Trap type

√ N_{ITA} acceptor type traps, N_{ITD} donor type traps.



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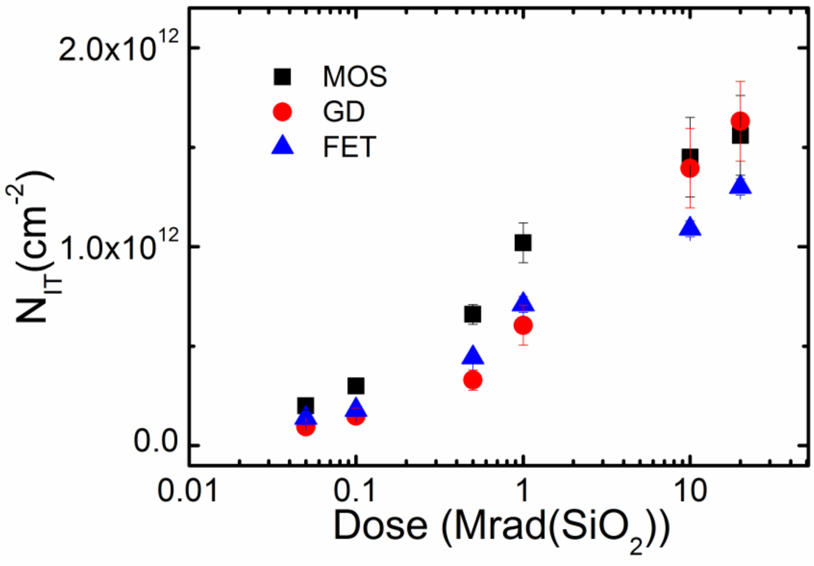
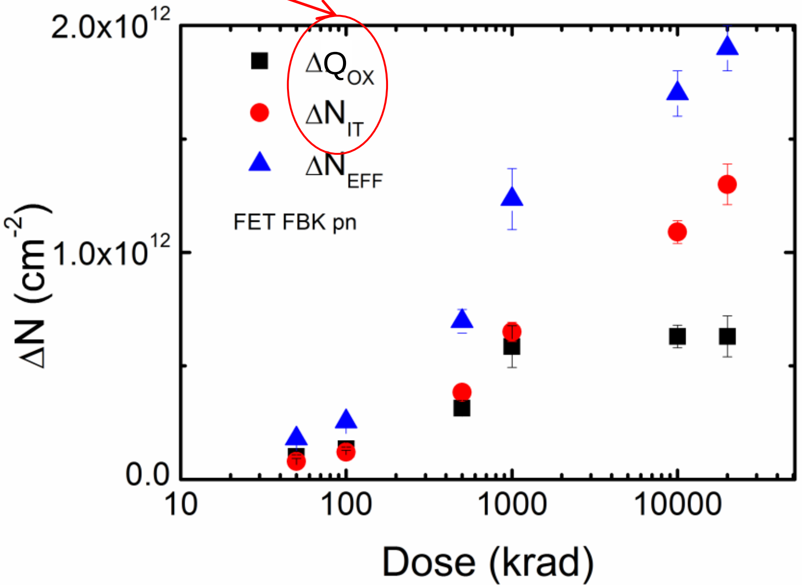
MOS Capacitor measurements

- √ Q_{OX} and N_{IT} evaluation (from C_{HF} - C_{QS} measurements).
- √ N_{IT} evaluation from p-type substrate (MOS C, GD) and pMOSFET.

Following the method proposed in P. J. McWhorter and P. S. Winokur in Applied Physics Letters 48, 133 (1986), it is possible to separate the two contributions of Q_{OX} and N_{IT}.

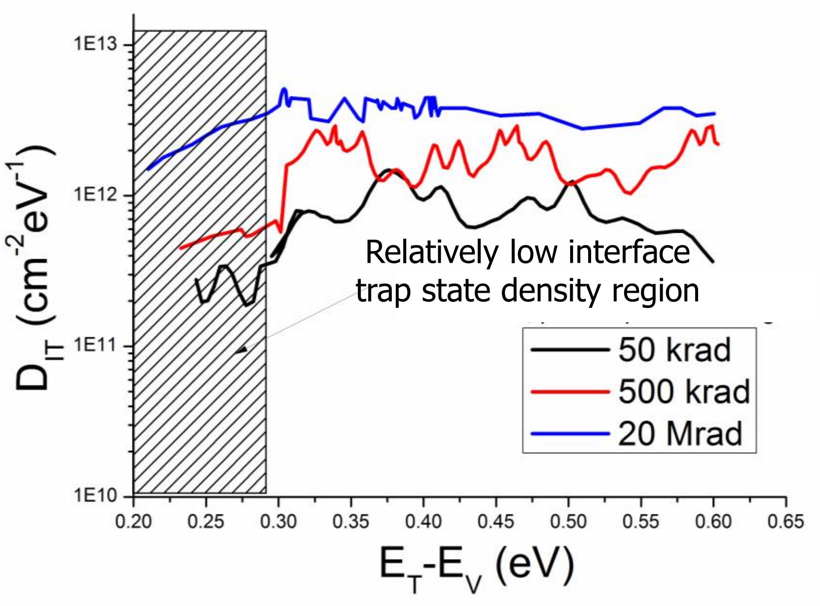




Interface Trap density measurements

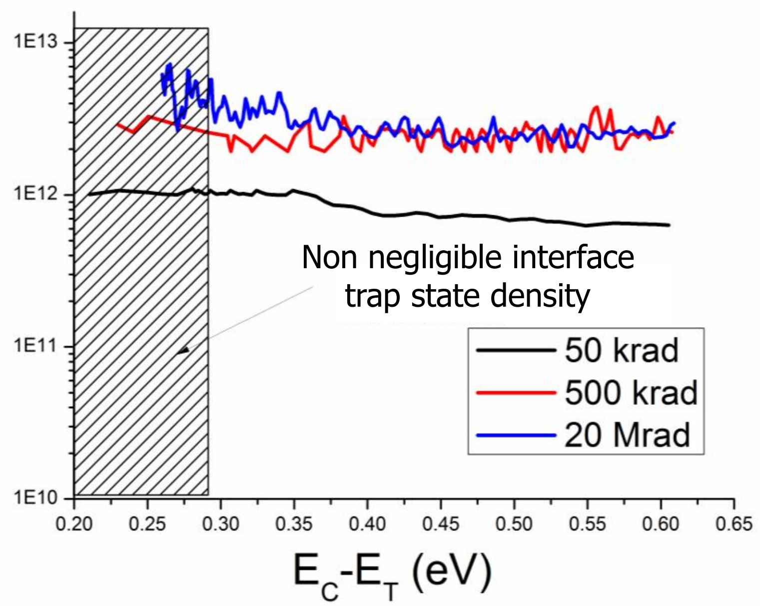
√ N_{IT}/D_{IT} evaluation (from C_{HF} - C_{QS} measurements).

Donor interface trap states from p-type substrates



Relatively low interface trap state density region

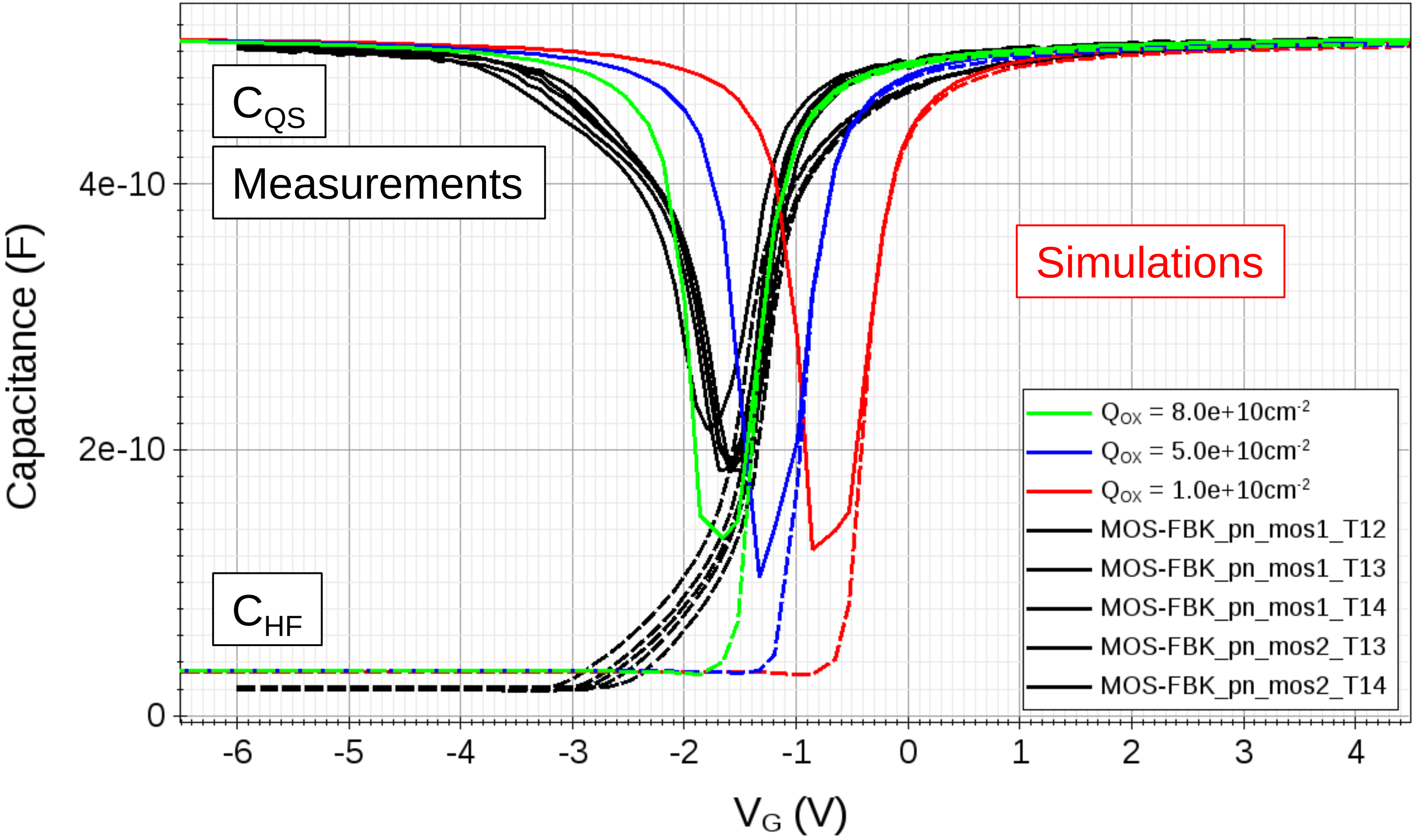
Acceptor interface trap states from n-type substrates



Non negligible interface trap state density

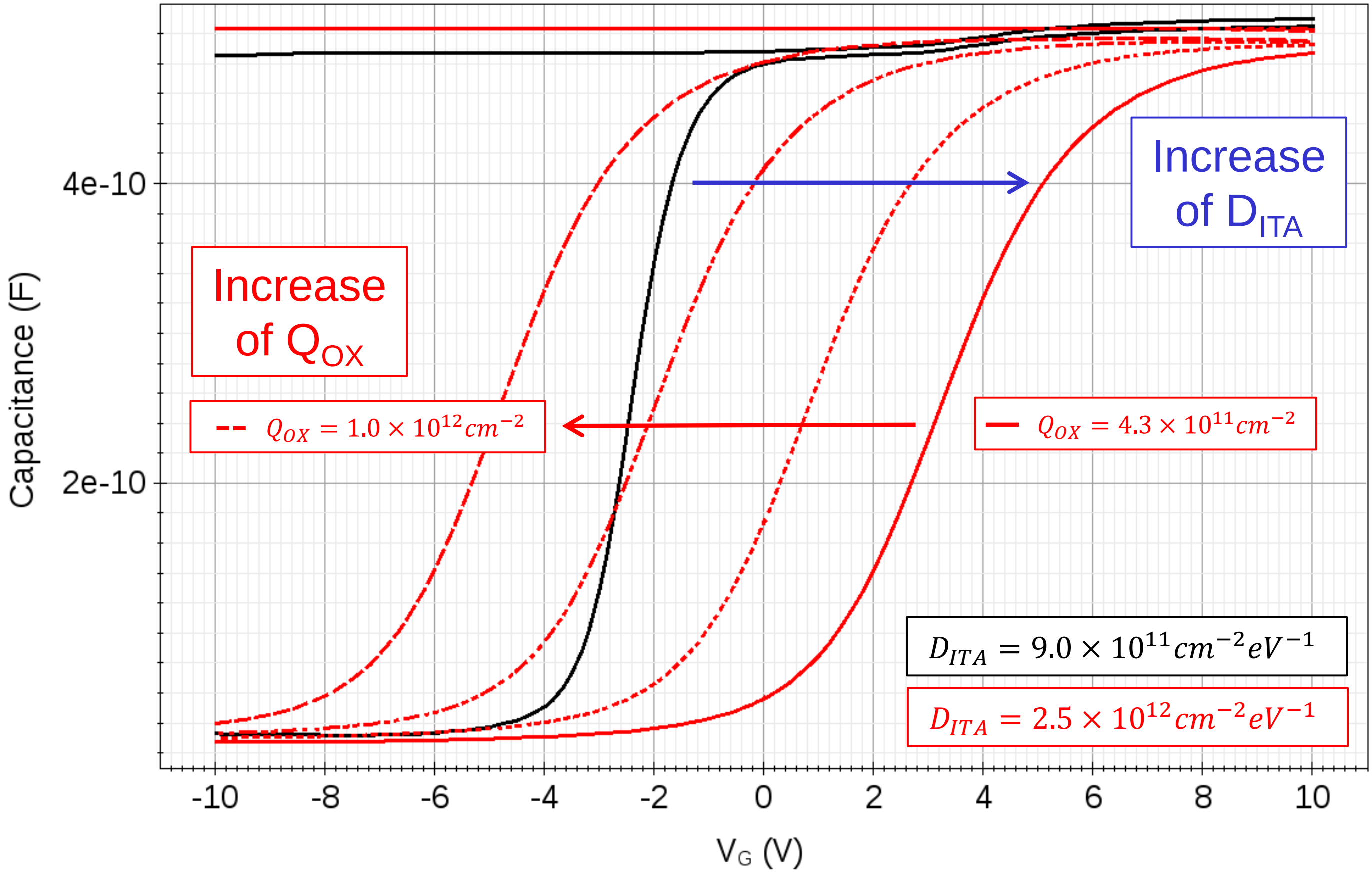
MOS Capacitor simulations

√ Non-Irradiated structures.



MOS Capacitor simulations

√ Sensitivity analysis: effect of Q_{OX} and D_{IT}.



Increase of Q_{OX}

-- $Q_{OX} = 1.0 \times 10^{12} cm^{-2}$

— $Q_{OX} = 4.3 \times 10^{11} cm^{-2}$

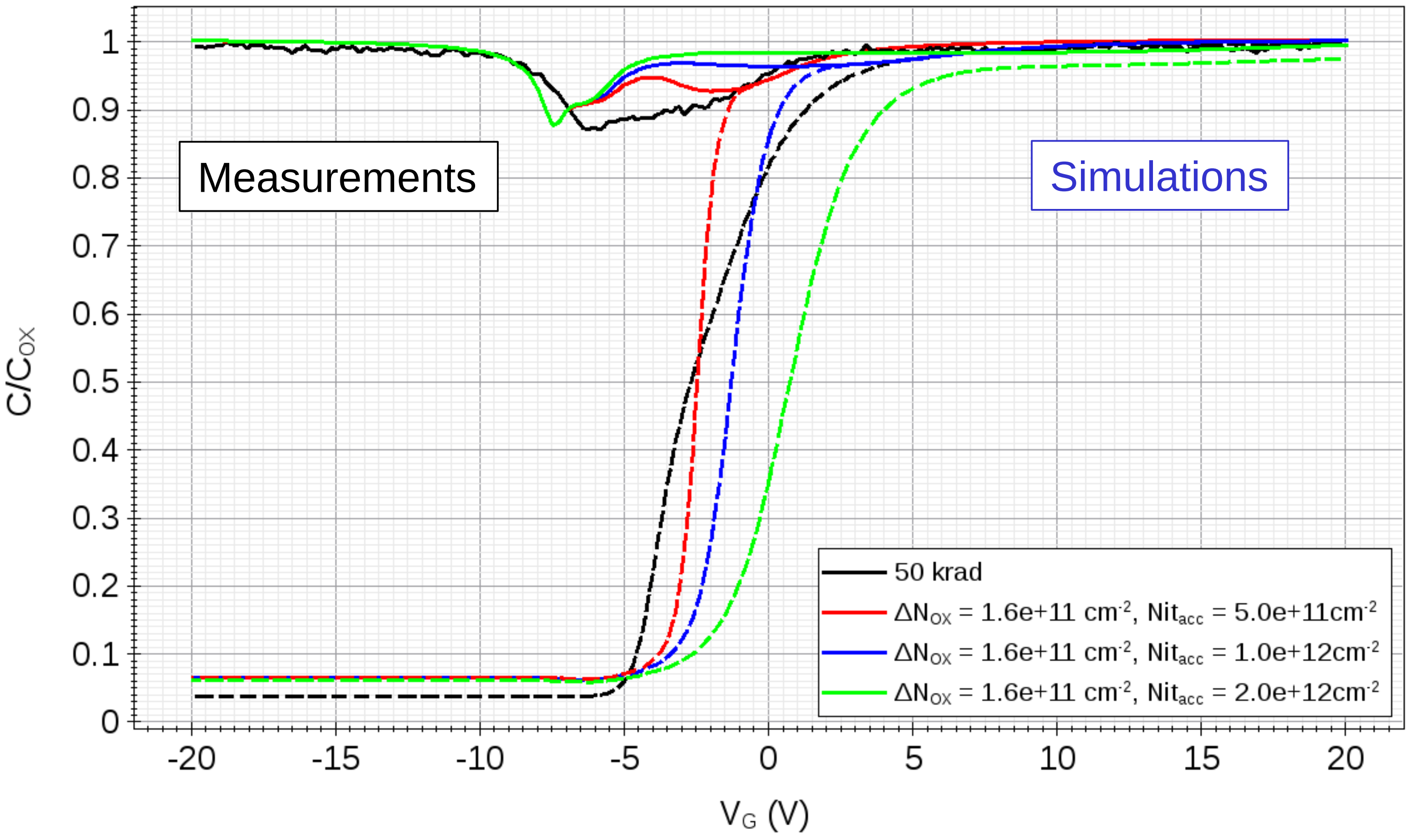
Increase of D_{ITA}

$D_{ITA} = 9.0 \times 10^{11} cm^{-2} eV^{-1}$

$D_{ITA} = 2.5 \times 10^{12} cm^{-2} eV^{-1}$

MOS Capacitor simulations

√ Irradiated structures.

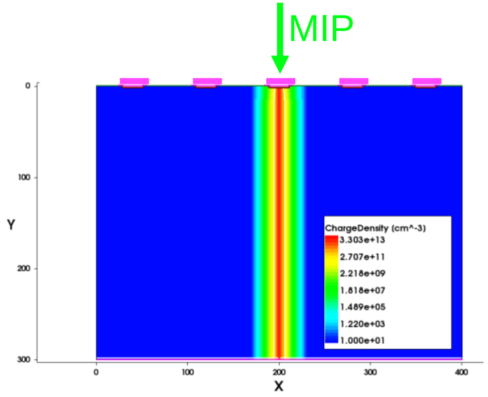


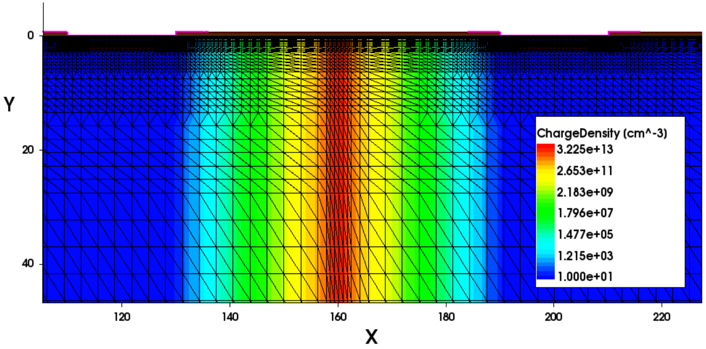
Outline

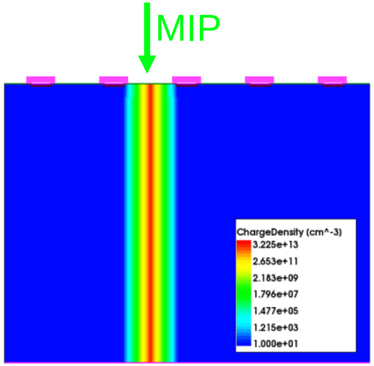
- √ Motivations and background.
- √ TCAD radiation damage modelling: discussion.
- √ Simulation results and comparison with experimental data:
  - - DC (steady-state) -> Diodes / Gate Controlled Diodes.
  - - AC (small-signals) -> MOS Capacitors.
  - - Time (transient) -> Multi-strip structures.
- √ Conclusions.

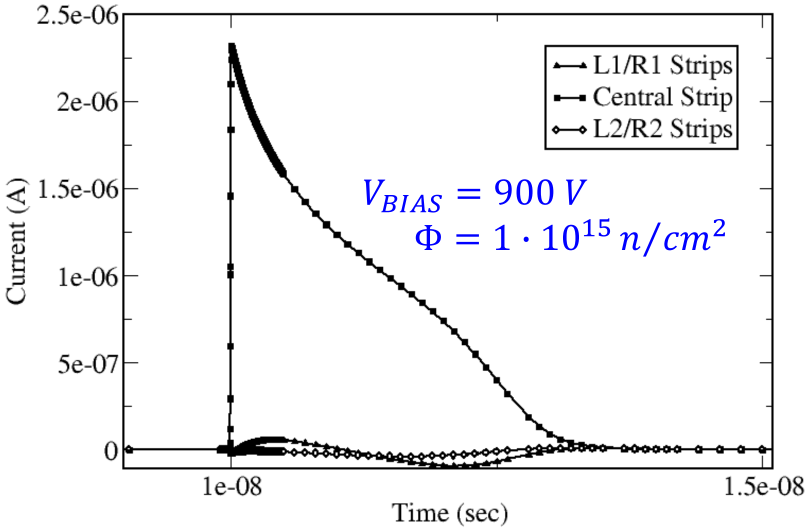
MultiStrips simulation: MIP response

√ Current responses to different impact locations.



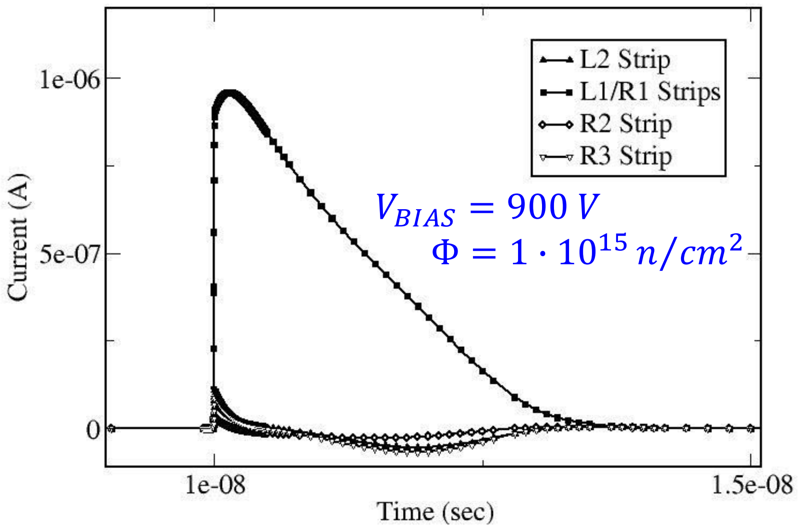






$V_{BIAS} = 900\ V$

$\Phi = 1 \cdot 10^{15}\, n/cm^2$

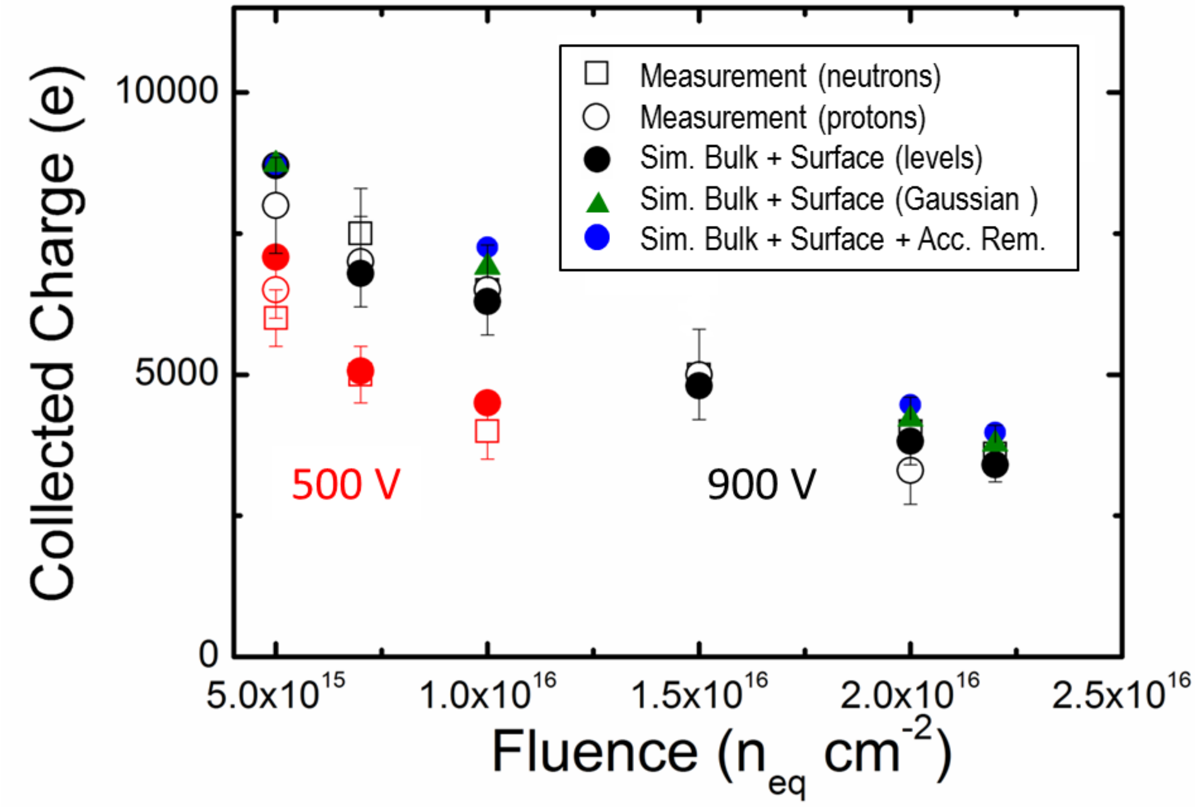


$V_{BIAS} = 900\ V$

$\Phi = 1 \cdot 10^{15}\, n/cm^2$

Transient analysis: Charge Collection

√ Charge collection: simulations vs. measurements at different biasing voltages (T = 248 K)



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

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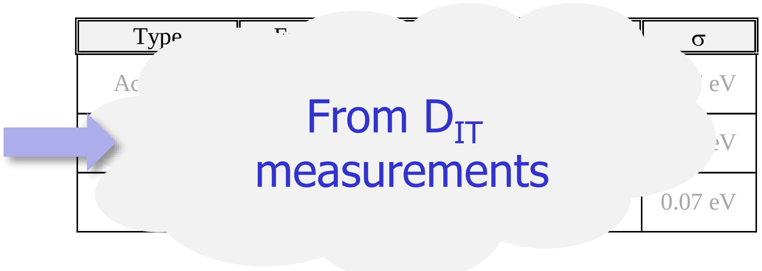
The model

√ Surface damage (+ Q_{OX})

F. Moscatelli; D. Passeri; A. Morozzi; S. Mattiazzo; G. -F. Dalla Betta; M. Dragicevic; G. M. Bilei, *Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC*, IEEE Transactions on Nuclear Science, 2017, Vol. 64, Issue: 8, 2259 - 2267

Type	Energy	Concentration	σ
Acceptor	E_C-0.4 eV	40% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Acceptor	E_C-0.6 eV	60% of acceptor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV
Donor	E_V+0.7 eV	100% of donor N_{IT} (N_{IT}=0.85·N_{OX})	0.07 eV



From D_{IT} measurements

√ Bulk damage

(up to 7.0×10^{15} n/cm^2)

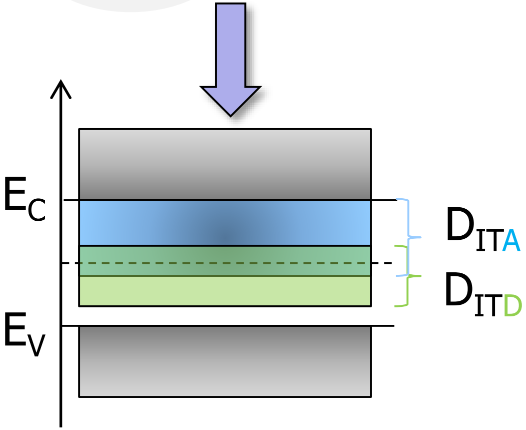
Type	E (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	1.0×10^{-15}	1.0×10^{-14}	1.6
Acceptor	Ec-0.46	7.0×10^{-15}	7.0×10^{-14}	0.9
Donor	Ev+0.36	3.2×10^{-13}	3.2×10^{-14}	0.9

(7.0×10^{15} ÷ 1.5×10^{16} n/cm^2)

Type	E (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	1.0×10^{-15}	1.0×10^{-14}	1.6
Acceptor	Ec-0.46	3.0×10^{-15}	3.0×10^{-14}	0.9
Donor	Ev+0.36	3.2×10^{-13}	3.2×10^{-14}	0.9

(1.6×10^{16} ÷ 2.2×10^{16} n/cm^2)

Type	E (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	1.0×10^{-15}	1.0×10^{-14}	1.6
Acceptor	Ec-0.46	1.5×10^{-15}	1.5×10^{-14}	0.9
Donor	Ev+0.36	3.2×10^{-13}	3.2×10^{-14}	0.9



Conclusions

√ Modelling radiation damage effects is a hard task!

√ Radiation damage modelling scheme (bulk + surface), suitable for commercial TCAD tools (e.g. Synopsys Sentaurus).

√ Predictive capabilities extended to HL-LHC radiation damage levels (e.g. fluences $> 2.0\times10^{16}$ cm^{-2} 1 MeV neutrons).

√ Further validation with experimental data comparisons -> model refinement.

√ Application to the optimization of (pixel) detectors (3D detectors, 2D planar detectors, …).