Comprehensive Radiation Damage Modeling of Silicon Detectors

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In the framework of RD50-CERN Collaboration

OUTLINE

- development of the 3-level radiation damage model for n-type silicon
- development of the 2-level radiation damage model for p-type silicon
- simulation of Charge Collection Efficiency (CCE) in irradiated (n-type) silicon detectors

Simulation tool:

ISE-TCAD – discrete time and space solution of drift/diffusion and continuity equations

Damage modelling:

- Deep levels: E_t, σ_n and σ_p
- SRH statistics
- Uniform density of defect concentration

Radiation damage Effects to simulate:

- The increasing of the Leakage Current
- The increasing of the Full Depletion Voltage
- The decreasing of the Charge Collection Efficiency

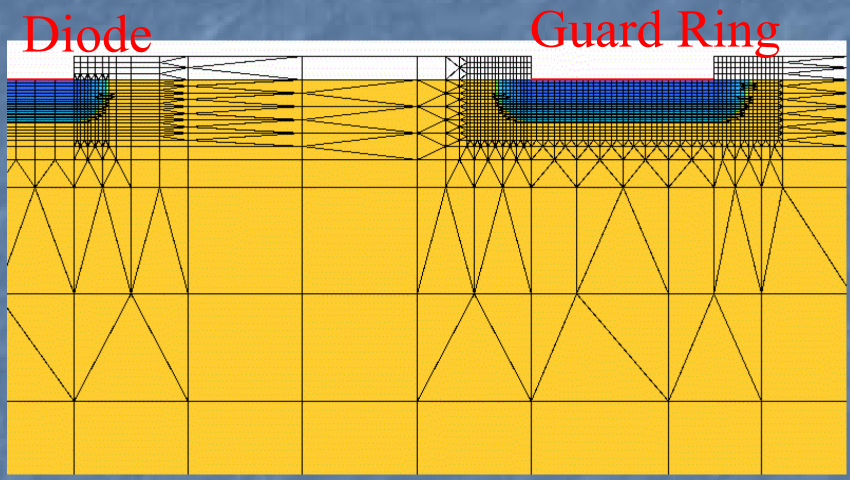
Simulation setup

Simulated device structure and parameters:

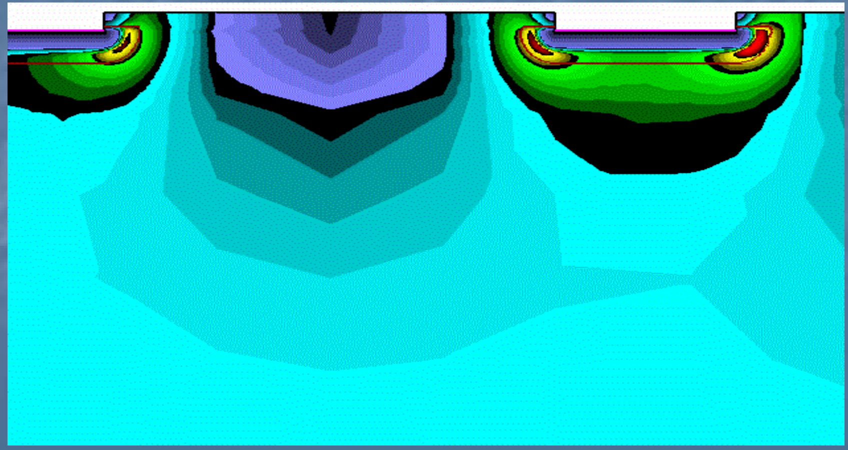
- Doping profiles:
  - N and P doped substrates (7×10^{11} cm^{-3})→ **6kΩcm**.
  - Charge concentration at the silicon-oxide interface of :
    - 4 $\times10^{11}$ cm^{-3} pre-irradiation
    - 1 $\times10^{12}$ cm^{-3} post-irradiation
- Optimized variable mesh definition
- Temperature = 300 K
- D (thickness) = 50-100-300 um

Simulation setup

- Variable mesh definition:
  - the mesh is better refined in correspondence of the **critical points** of the device to improve simulator performance.

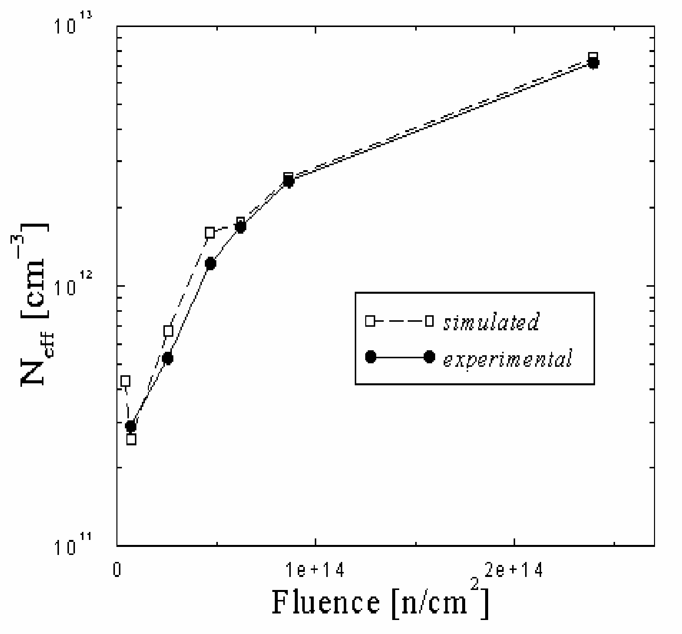


- The typical electric field distribution at the depletion voltage of the diode.



The n-type (modified) 3-Level Radiation Damage Model*

Level [eV]	Assignment	σ_n [cm^{-2}]	σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42	$VV^{(-/0)}$	$1\cdot10^{-16}$	$8\cdot10^{-15}$	**26***
E_c-0.50	$VVO^{(-/0)}$	$1\cdot10^{-16}$	$1\cdot10^{-15}$	0.1
E_v+0.36	$C_iO_i^{(+/0)}$	$1\cdot10^{-15}$	$1\cdot10^{-16}$	1



$\sigma_{n/p}$ [cm^{-2}]: cross section

η [cm^{-1}]: introduction rate

* η=26 takes into account cluster defects

* Angarano, Bilei, Giorgi, Ciampolini, Mihul, Militaru, Passeri, Scorzoni, CERN, Geneve, CMS CR 2000/006, 2000

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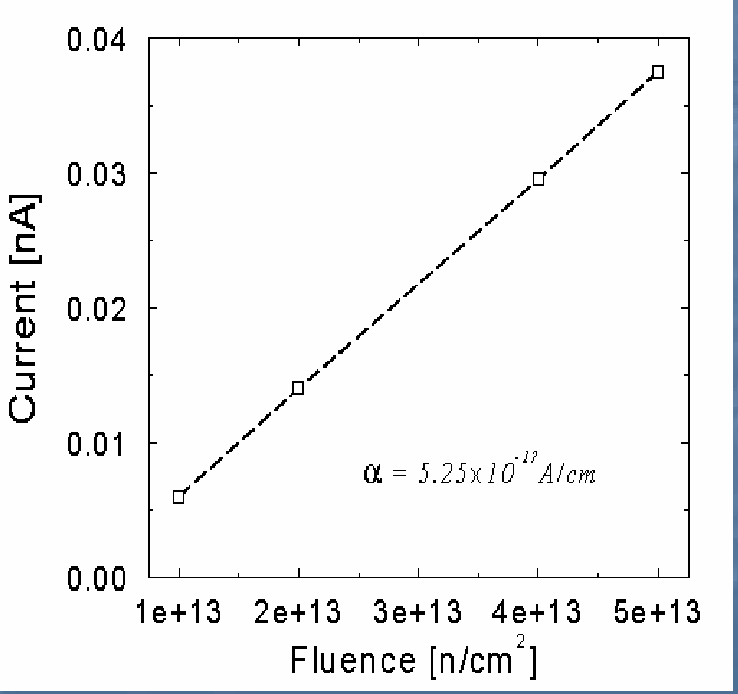


* η = 26 takes into account cluster defects

α [A/cm] simulated	α [A/cm] experimental*
$5.25\pm0.02\cdot10^{-17}$	$5.4\div6.7\cdot10^{-17}$

$\alpha_{80/60}$ [A/cm] ROSE-RD48
$4.0\cdot10^{-17}$

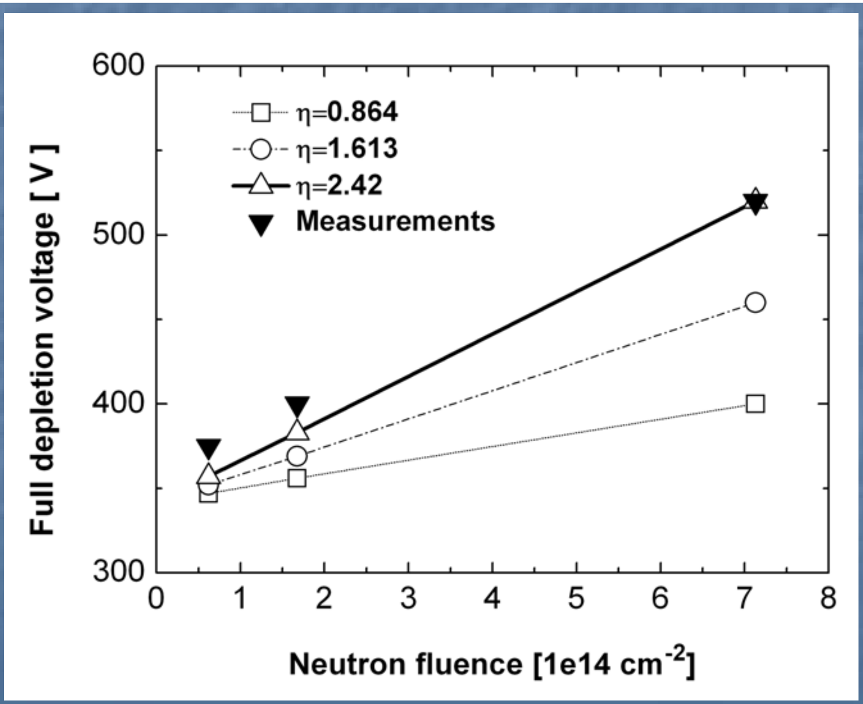
* [Angarano, Bilei, Giorgi, Ciampolini, Mihul, Militaru, Passeri, Scorzoni, CERN, Geneve, CMS CR 2000/006, 2000]

The p-type One-Level Radiation Damage Model

(*) [N. Zangenberg, et al.,Nuc. Instr. And Meth B 186 (2002) 71-77]
[M. Ahmed, et al., Nuc. Instr. And Meth A 457 (2001) 588-594]

Level*	Ass.	σ_n [cm^{-2}] Experimental*	σ_p [cm^{-2}] Experimental*	σ_n [cm^{-2}]	**σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	$VV^{(-/0)}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-13}$	2.42

** 2 order of magnitude higher



Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

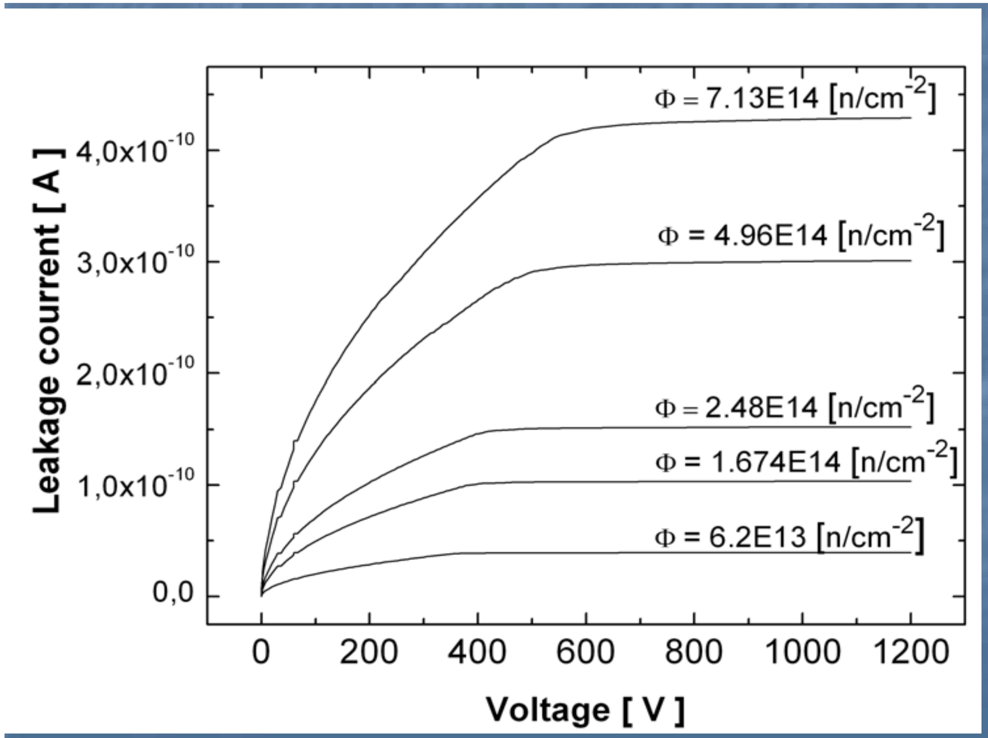
β [cm^{-1}] simulated
$3,72 \cdot 10^{-3}$

β [cm^{-1}] experimental
$4,0 \pm 0,4 \cdot 10^{-3}$

The p-type One-Level Radiation Damage Model

(*) [N. Zangenberg, et al.,Nuc. Instr. And Meth B 186 (2002) 71-77]
[M. Ahmed, et al., Nuc. Instr. And Meth A 457 (2001) 588-594]

Level*	Ass.	σ_n [cm^{-2}] Experimental*	σ_p [cm^{-2}] Experimental*	σ_n [cm^{-2}]	σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	$VV^{(-/0)}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-13}$	2.42



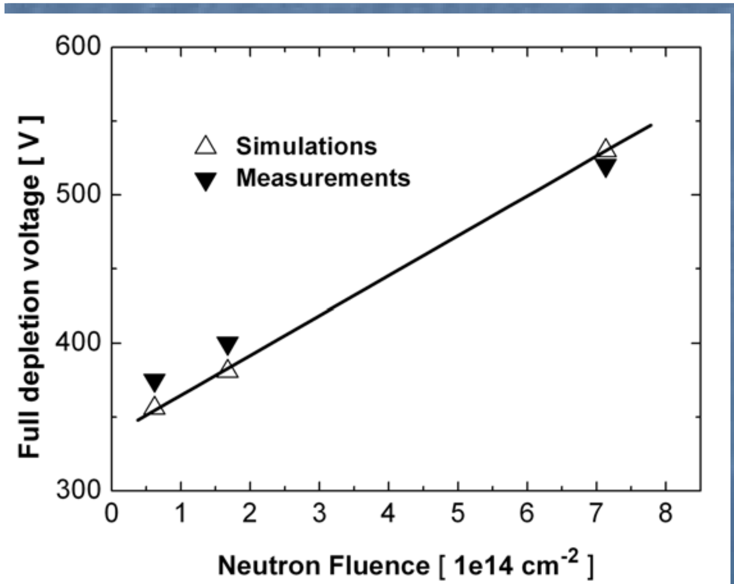
α [A/cm] simulated
$6,6 \cdot 10^{-17}$
α [A/cm] experimental
$6,52 \pm 0,11 \cdot 10^{-17}$

Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

The p-type Two-Level Radiation Damage Model

[(**) Levels selected from: M. Ahmed, et al., Nuc. Instr. And Meth A 457 (2001) 588-594
S.Pirolo et al., Nuc. Instr. And Meth. A 426 (1996) 126-130]

Level**	Ass.	σ_n [cm^{-2}] Experimental	σ_p [cm^{-2}] Experimental	σ_n [cm^{-2}]	*σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	$VV^{(-/0)}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-14}$	1.613*
E_c-0.46eV	$VVV^{(-/0)}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-14}$	0.96*



Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

*η Moll = 0.9÷1.8

* 1 order of magnitude higher

β [cm^{-1}] simulated
$3.98 \cdot 10^{-3}$
β [cm^{-1}] experimental
$4,0 \pm 0,4 \cdot 10^{-3}$

The p-type Two-Level Radiation Damage Model

[(**) Levels selected from: M. Ahmed, et al., Nuc. Instr. And Meth A 457 (2001) 588-594
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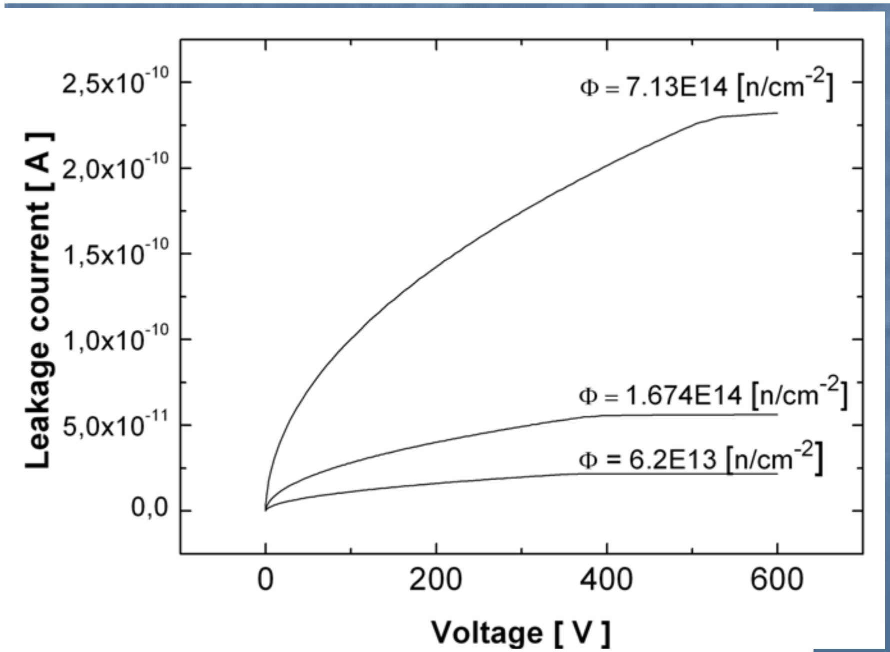
Level**	Ass.	σ_n [cm^{-2}] Experimental	σ_p [cm^{-2}] Experimental	σ_n [cm^{-2}]	*σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	VV$^{(-/0)}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-14}$	1.613
E_c-0.46eV	VVV$^{(-/0)}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-14}$	0.96



* 1 order of magnitude higher

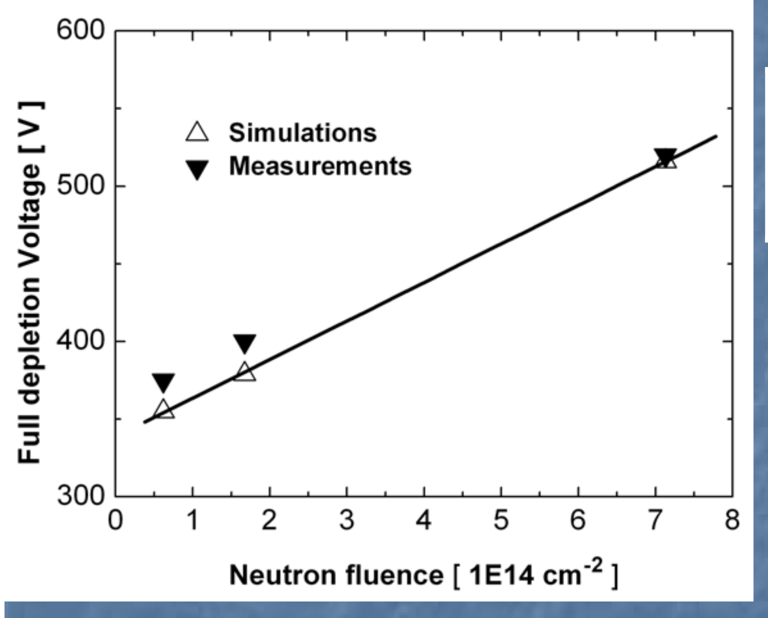
α [A/cm] simulated
$3.75\cdot10^{-17}$
α [A/cm] reported (*?)
$6,52\pm0,1 \cdot10^{-17}$

Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

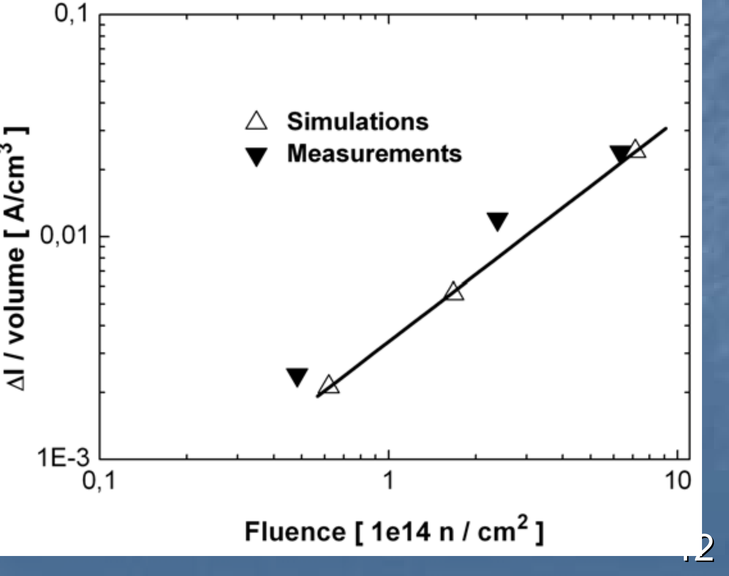
The p-type Three-Level Radiation Damage Model: no improvement due to the donor defect level

Level	Ass.	σ_n [cm^{-2}] Experimental	σ_p [cm^{-2}] Experimental	σ_n [cm^{-2}]	*σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	$VV^{(-/0)}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-15}$	$2 \cdot 10^{-14}$	1.613
E_c-0.46eV	$VVV^{(-/0)}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-15}$	$5 \cdot 10^{-14}$	0.96
E_v+0.36eV	? C_iO_i?	$2.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-15}$	$2.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-15}$	0.9

* 1 order of magnitude higher
Measures extracted from [M. Lozano, et al., RD50 workshop, Firenze, Oct 2004]

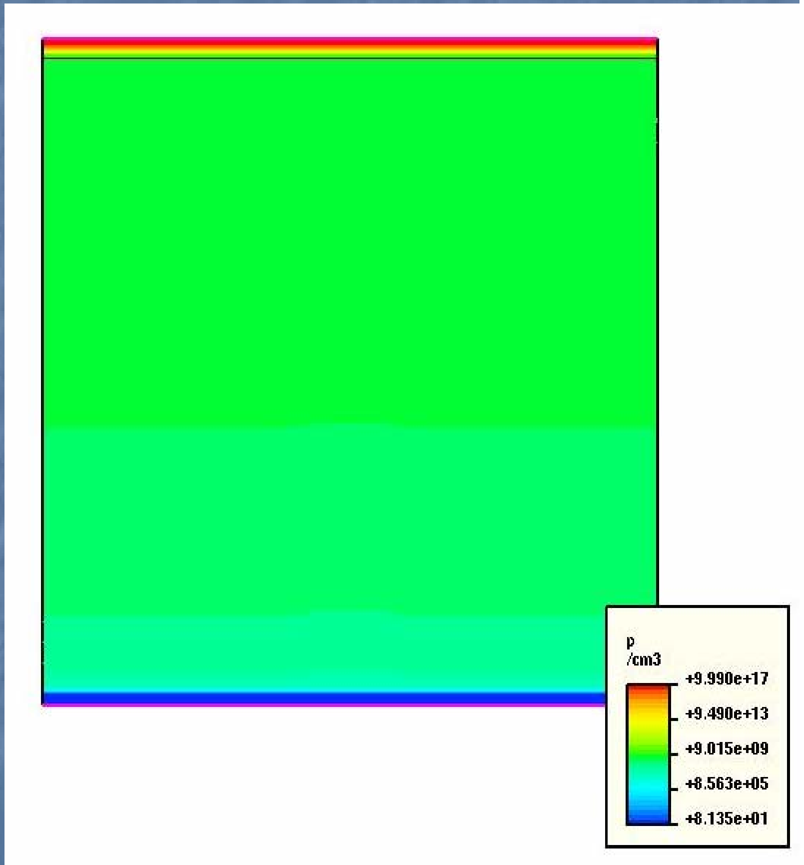


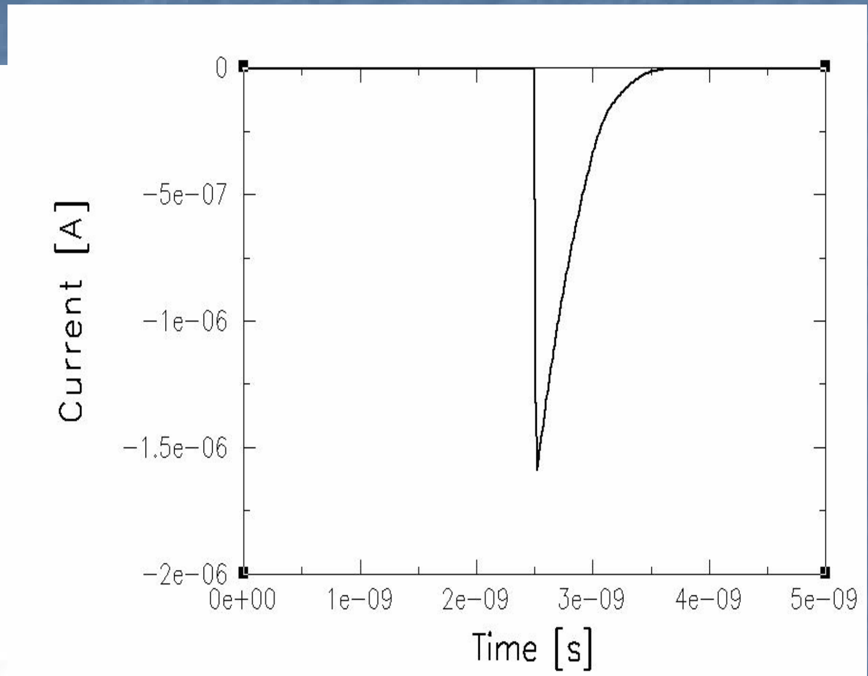
β [cm^{-1}] simulated	β [cm^{-1}] experimental
$3.98 \cdot 10^{-3}$	$4{,}0 \pm 0{,}4 \cdot 10^{-3}$



α [A/cm] experimental	α [A/cm] simulated
$6{,}52 \pm 0{,}11 \cdot 10^{-17}$	$3.75 \cdot 10^{-17}$

CCE Simulation

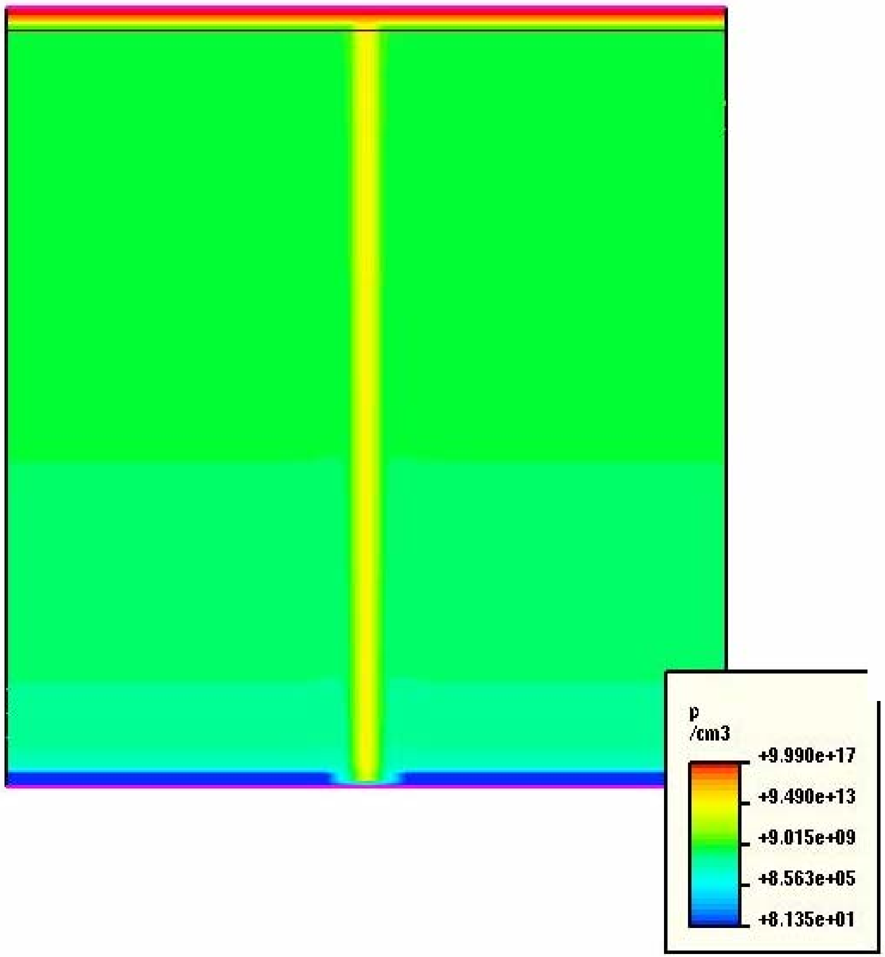


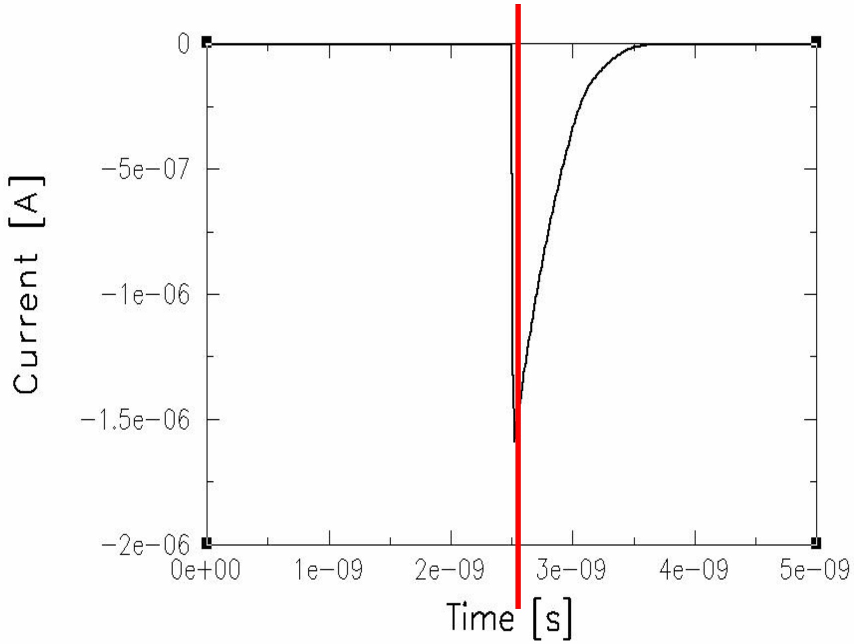


$$Q = \int I(t)dt$$

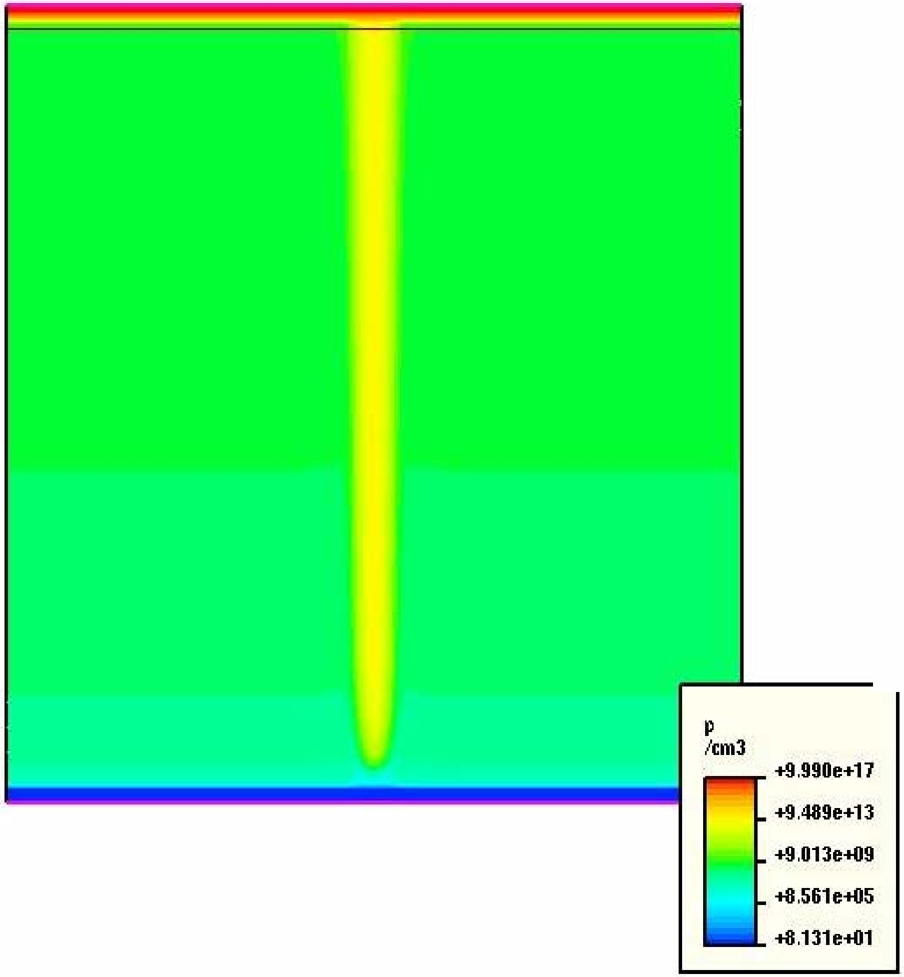
MIP: 80 e-h pairs/ µm
cylinder diameter = 2µm

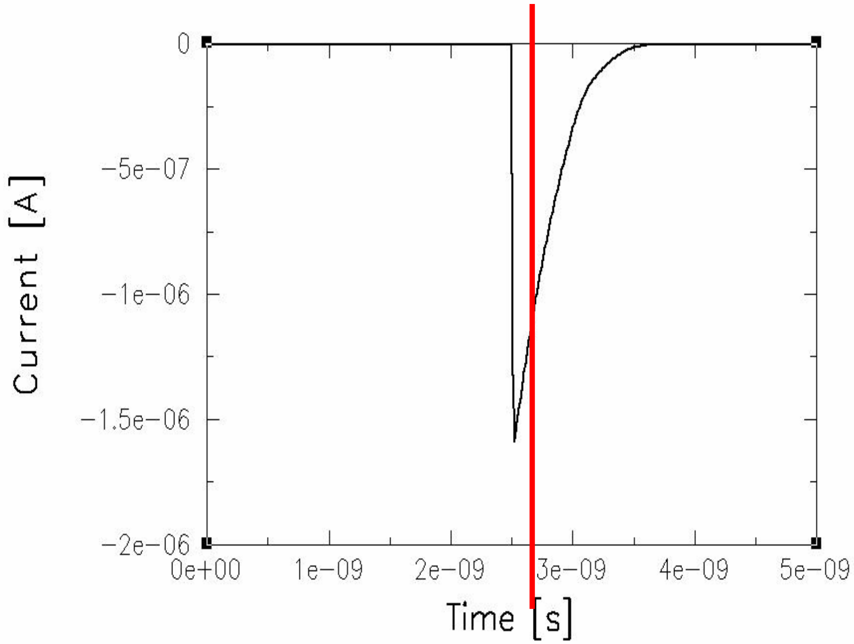
CCE Simulation





CCE Simulation





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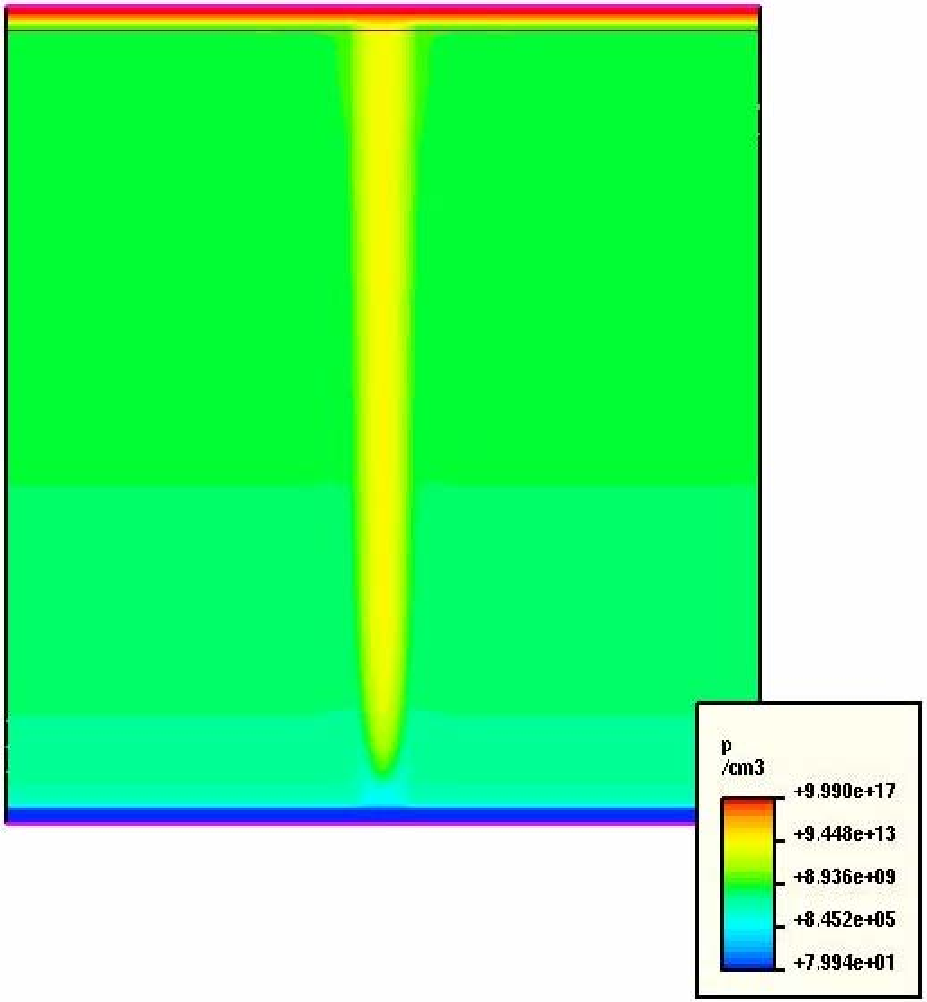

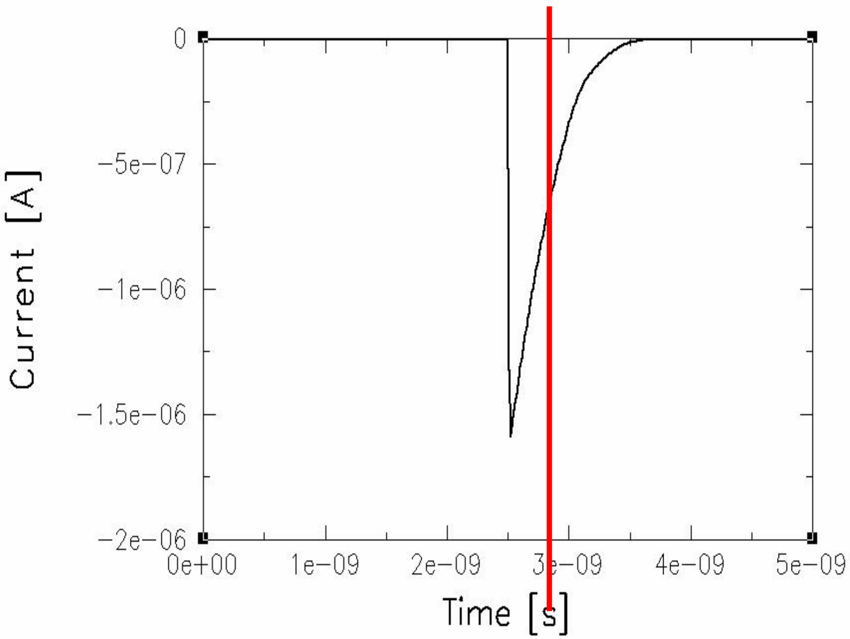

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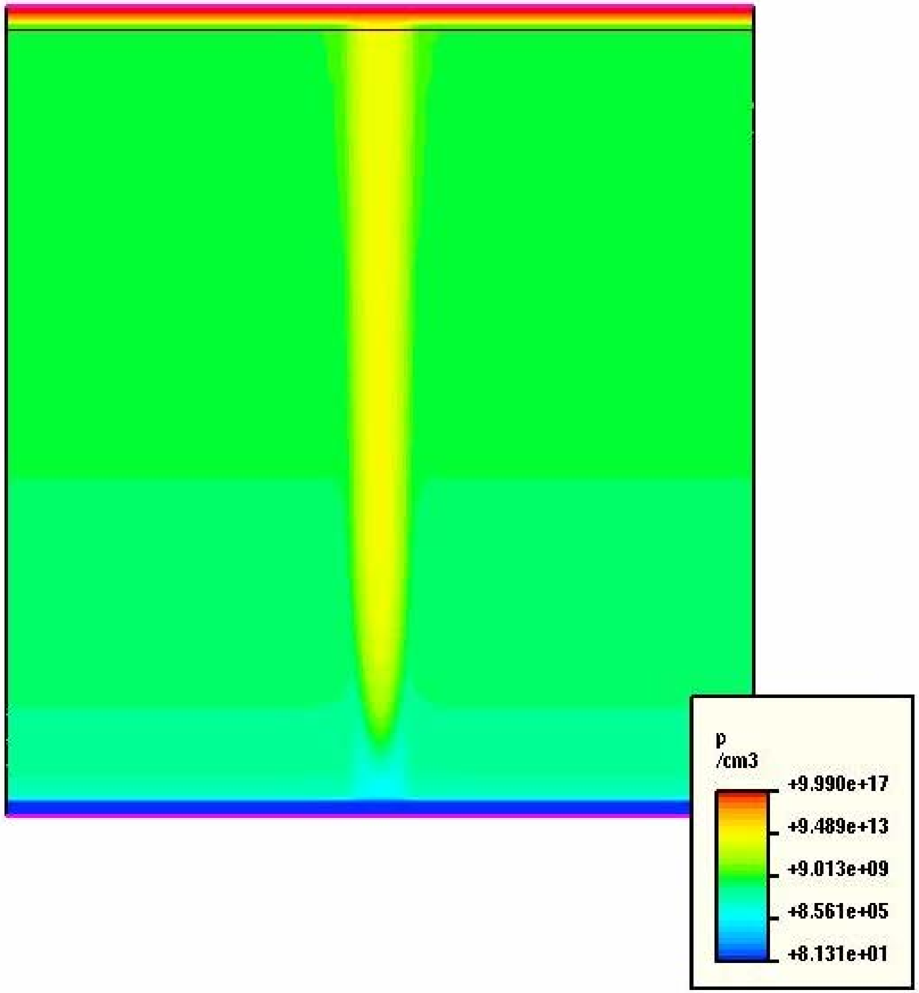

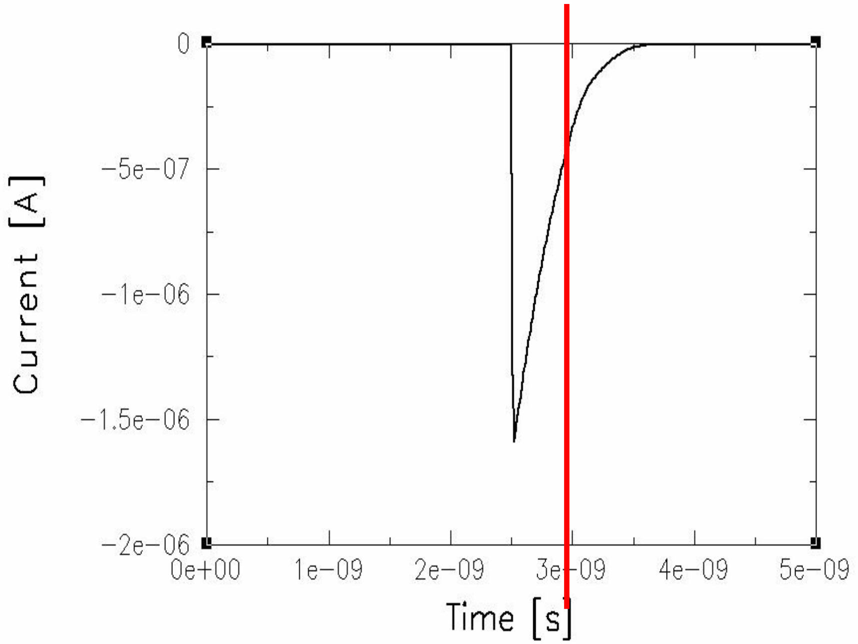

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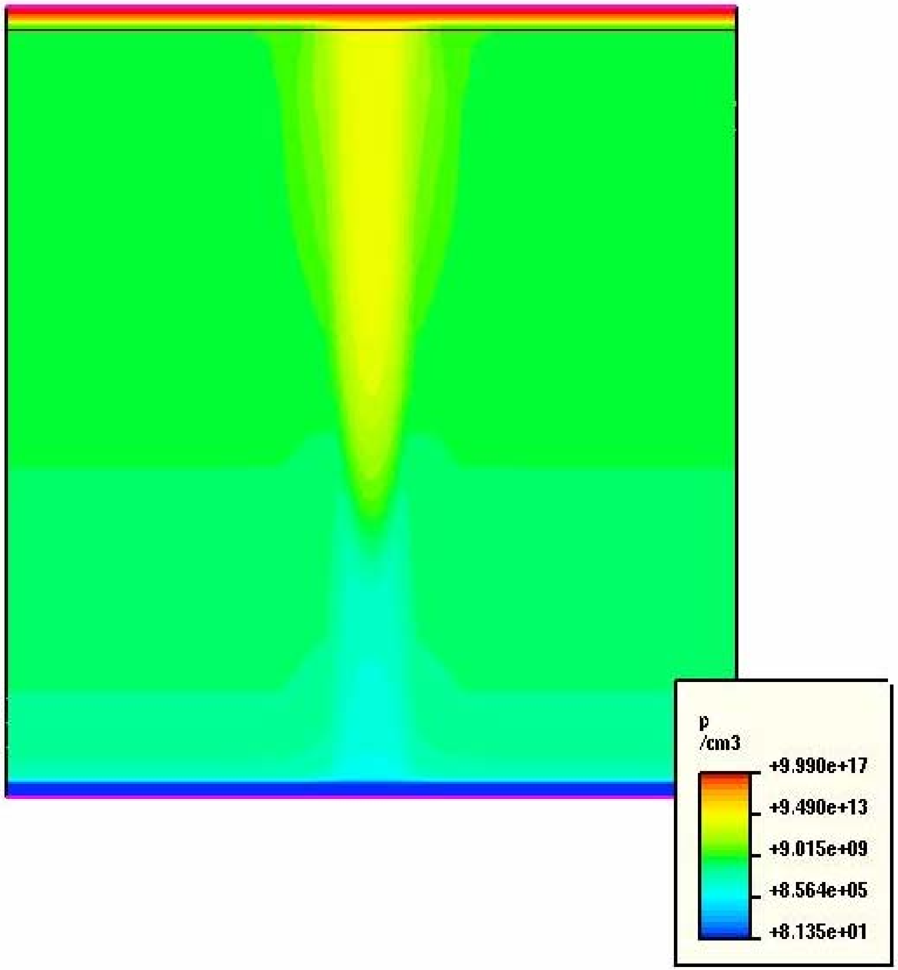

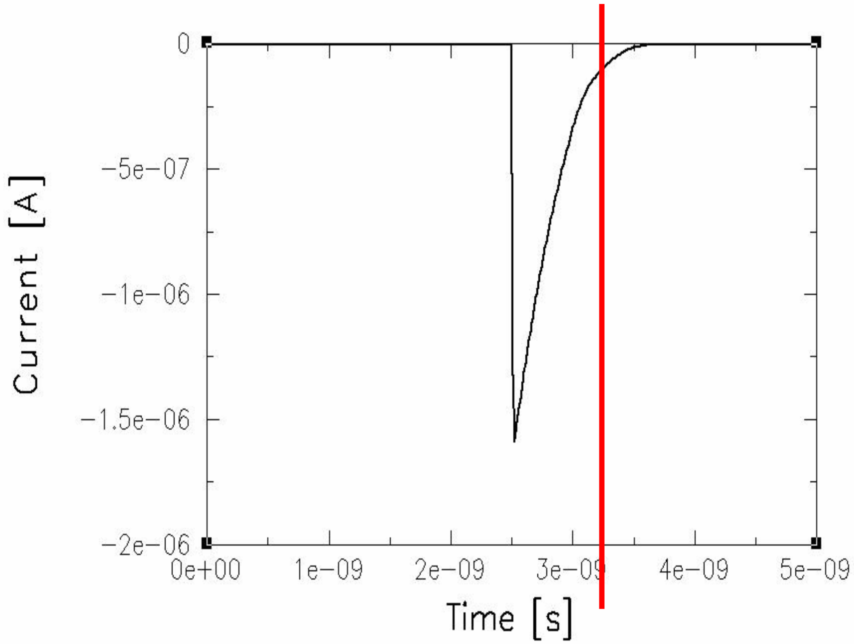

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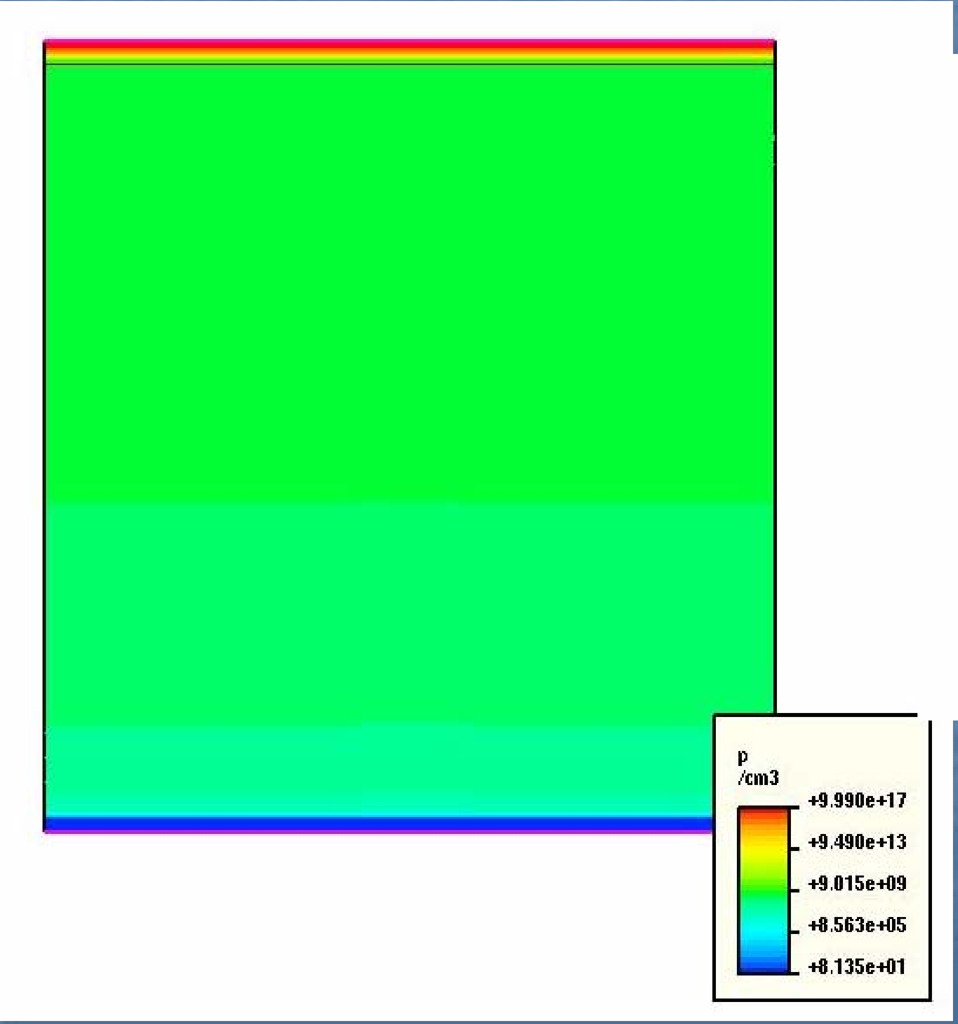
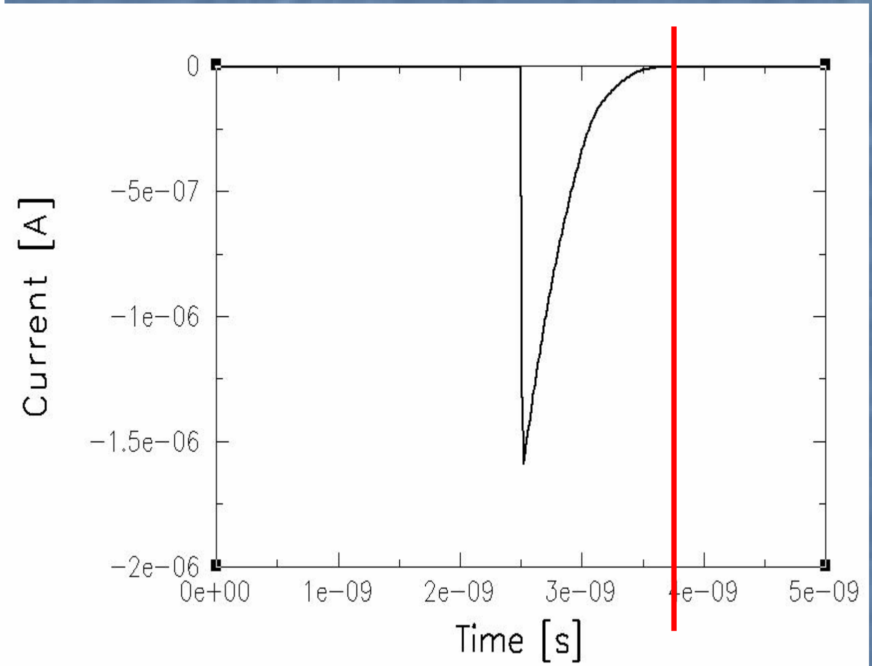
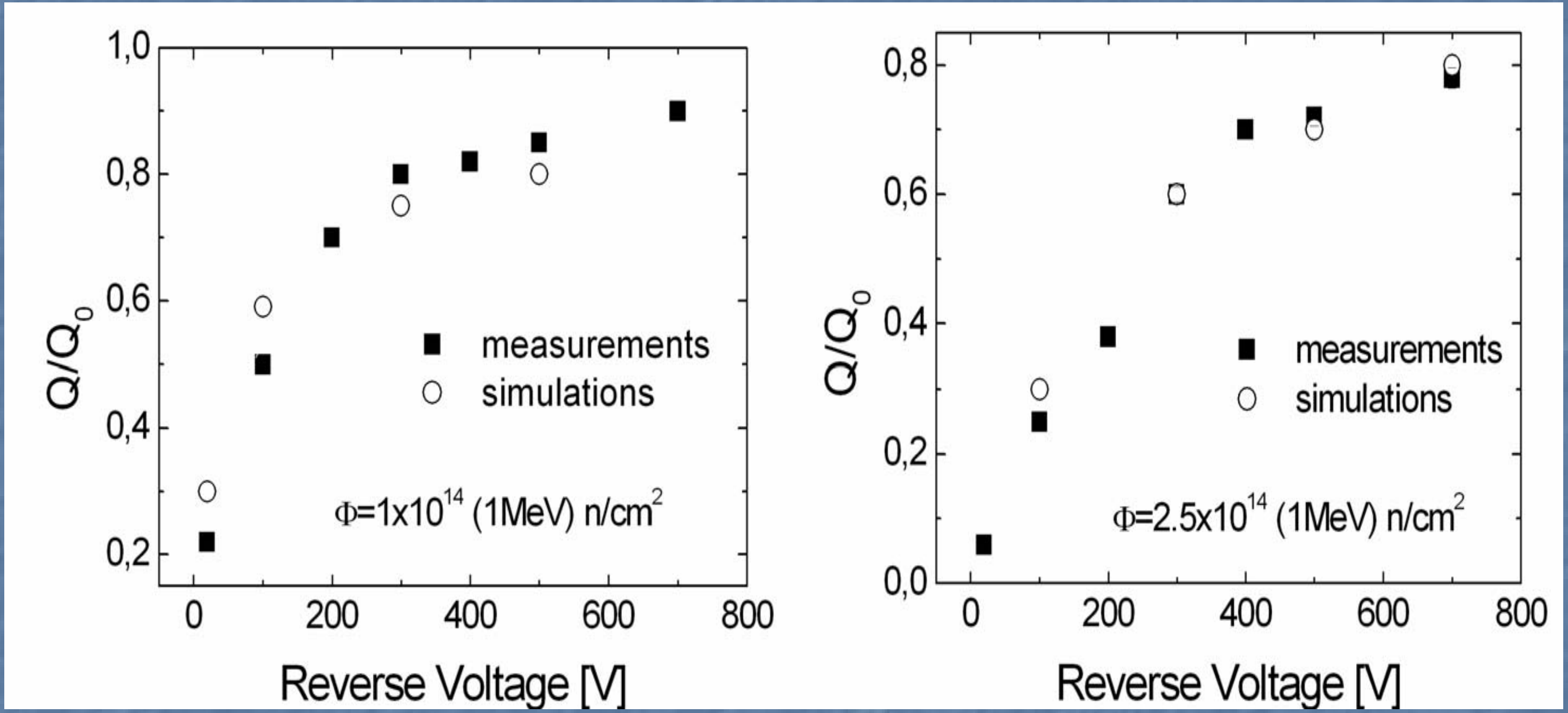




CCE vs BIAS voltage for n-type silicon

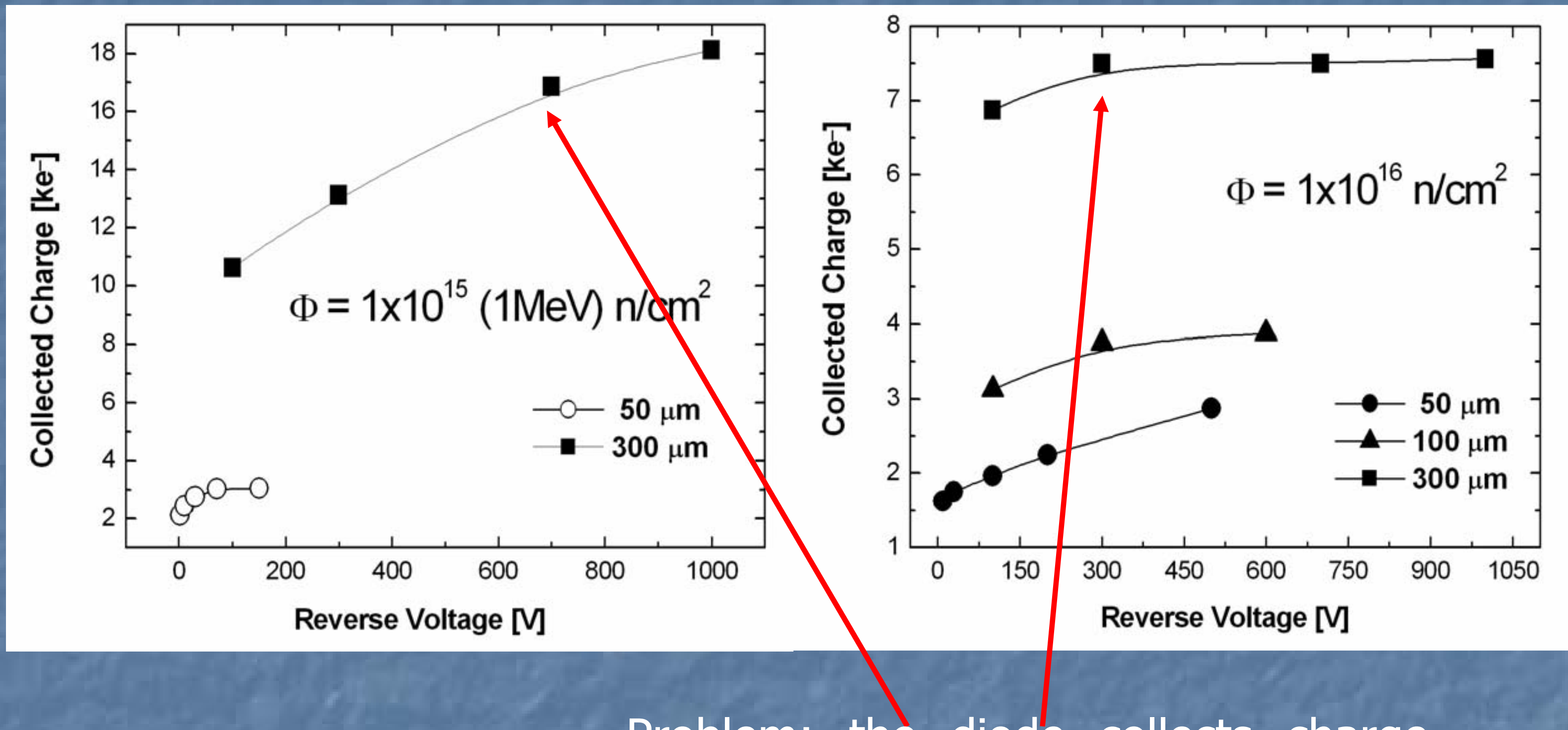
Simulation data well reproduce experimental* measure at the fluences of $1 \cdot 10^{14}$ n/cm^2 and $2.5 \cdot 10^{14}$ n/cm^2



* Measurements from Allport, Casse et al. NIMA 501 (2003) 146-152

CCE vs BIAS for n-type

Simulation data at Fluence of $1 \cdot 10^{15}$ n/cm^2 and $1 \cdot 10^{16}$ n/cm^2



Problem: the diode collects charge also in the not depleted area.

At a fluence of $5 \cdot 10^{14}$:

Simulated CCE = 75%

Estimated (*) = 55%

(*) [Bloch et al, NIMA 517 (2004) 121-127]

CCE vs BIAS for n-type

Discussion about the ISE T-CAD Recombination Time model

$$\begin{cases} R^{SRH} = \dfrac{np - n_{i,eff}^2}{\tau_p\left(n + n_{i,eff}^2 e^{\frac{E_{trap}}{kT}}\right) + \tau_n\left(p + p_{i,eff}^2 e^{\frac{E_{trap}}{kT}}\right)} \\ \tau_{n/p} = \tau_{dop} F(T,E) \\ \tau_{dop}(N_{eff}) = \tau_{\min} + \dfrac{\tau_{\max_{e/h}} - \tau_{\min}}{1 + \left(\dfrac{N_{eff}}{N_{REF}}\right)^{\gamma}} \end{cases}$$

(*) J.G.Fossum, D.S. Lee, Solid-State Electronics, vol.25,no.8 (1982).

Default parameters of the Scharfetter model:

$N_{REF}=10^{16}$ cm^{-3}, $\gamma=1$,

$\tau_{min}=0$, $\tau_{max(e)}=3$ μs, $\tau_{max(h)}=10$ μs

change the N_{REF} parameter in order to obtain the correct value of the recombination time

From RD50 status Report (2004):

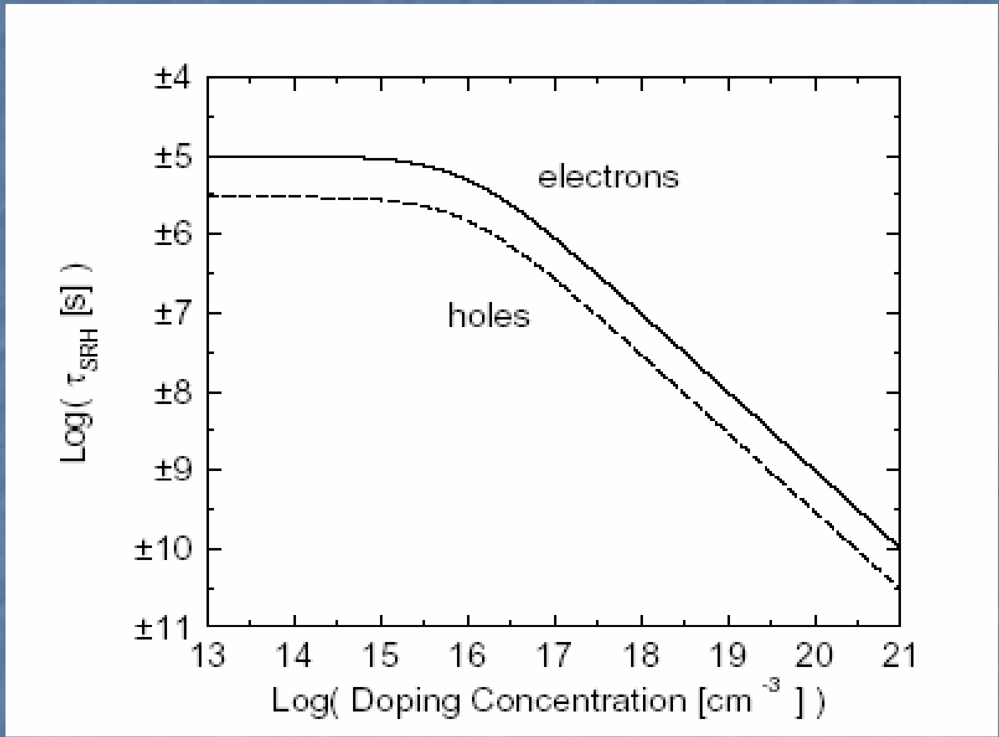
$$\frac{1}{\tau_{eff}} = \beta_{e/h} \cdot \Phi_{eq}$$

where

β_e [10^{-16} cm^2/ns]	β_h [10^{-16} cm^2/ns]
5.16 + 0.16	5.04 + 0.16

Scharfetter

ISE T-CAD Recombination Time model



Default parameters:

$N_{REF}=10^{16}$ cm-^{3}, γ=1,

$\tau_{min}=0$,

$\tau_{max(e)}$ =3 μs,

$\tau_{max(h)}$ =10 μs

Aim: modify/adapt the Scharfetter model to simulate the effect of deep-level defects on the reduction of carrier life-time

$$\tau_{dop}(N_{eff}) = \tau_{\min} + \frac{\tau_{\max} - \tau_{\min}}{1 + (N_{eff} / N_{ref})^{\gamma}}$$

(one pole in the TF)

Conclusions

- Irradiated diodes have been analyzed considering a three levels simulation model for p-type and n-type Si substrates:
  - The two-level model for the p-type and the three-level for n-type fit experimental data for the Leakage Current and Full Depletion Voltage
  - The C_iO_i acceptor level for p-type silicon seems to be un-influential (at Room Temperature)
  - The three-level for n-type fits CCE experimental data only for fluences up to $2.5 \cdot 10^{14}$ n/cm^2.
- Scharfetter recombination time empirical model can be eventually adapted to fit CCE experimental data at higher fluences (first good point @1e15 n/cm^2).