Numerical simulation of radiation damage effects in p-type silicon detectors

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6th RD50 Workshop

OUTLINE

- development of the radiation damage model for p-type silicon
- simulation of the Leakage Current and Depletion Voltage as a function of the Fluence
- simulation of the Charge Collection Efficiency (CCE) on irradiated silicon detectors as a function of the Fluence

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

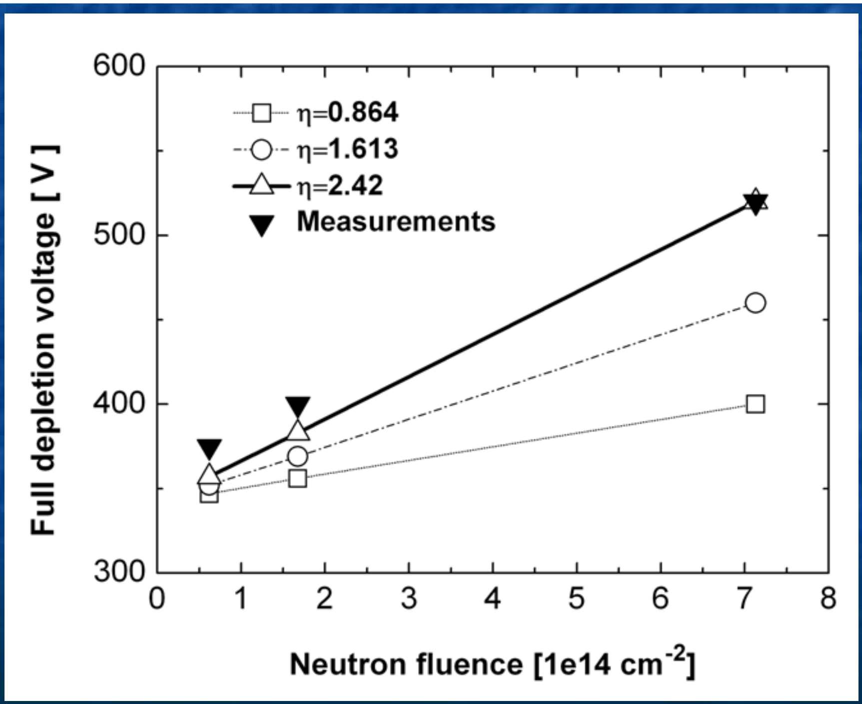
Simulated device structure and parameters:

- Doping profiles:
  - 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) = 300 um

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

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

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

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

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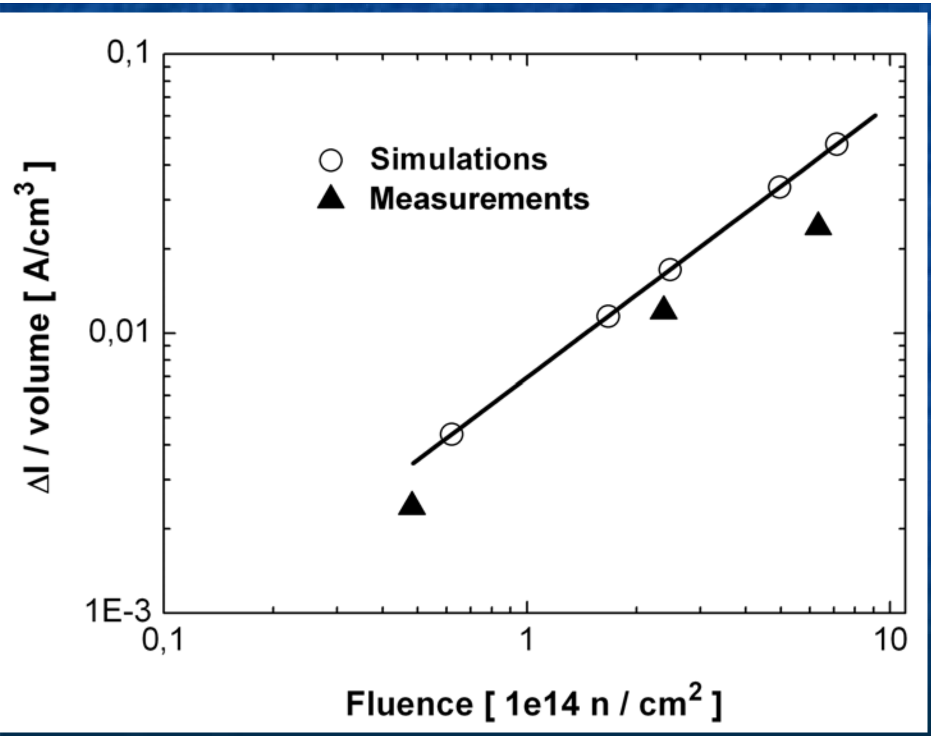


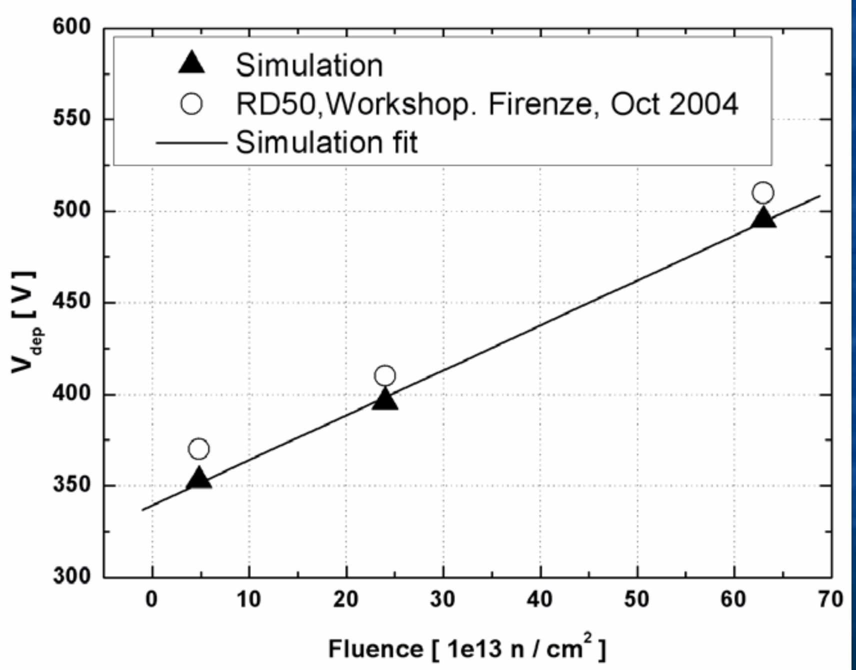
α [A/cm] simulated
$6,6\cdot10^{-17}$
α [A/cm] experimental
$4,0\pm0,11\cdot10^{-17}$

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	$VV^{(-/0)}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-14}$	1.613
E_c-0.46eV	$VVV^{(-/0)}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-14}$	0.9



* 1 order of magnitude higher

β [cm^{-1}] simulated
$3.98\cdot10^{-3}$
β [cm^{-1}] experimental
$4,0\pm0,4 \cdot10^{-3}$

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
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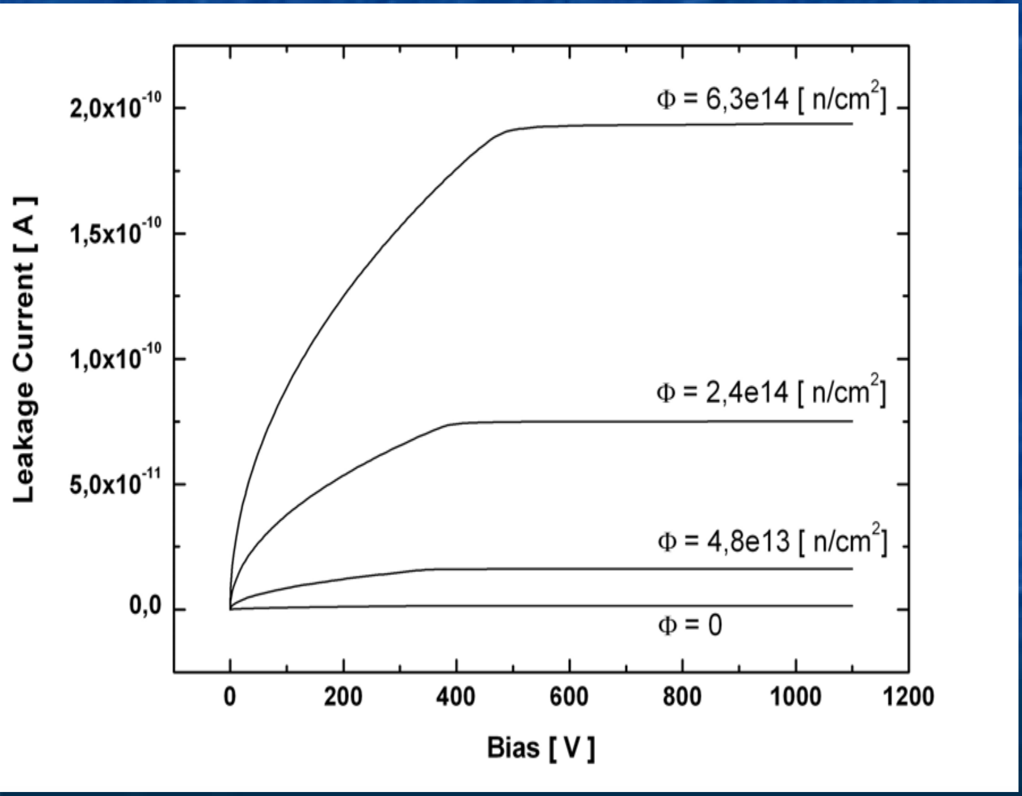
Level**	Ass.	σ_n [cm^{-2}] Experimental	σ_p [cm^{-2}] Experimental	σ_n [cm^{-2}]	*σ_p [cm^{-2}]	η [cm^{-1}]
E_c-0.42eV	$VV^{(-/0)}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-14}$	1.613
E_c-0.46eV	$VVV^{(-/0)}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-14}$	0.9

* 1 order of magnitude higher



α [A/cm] simulated
$3.75\cdot10^{-17}$
α [A/cm] reported (*)
$4{,}0\pm0{,}1\cdot10^{-17}$

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

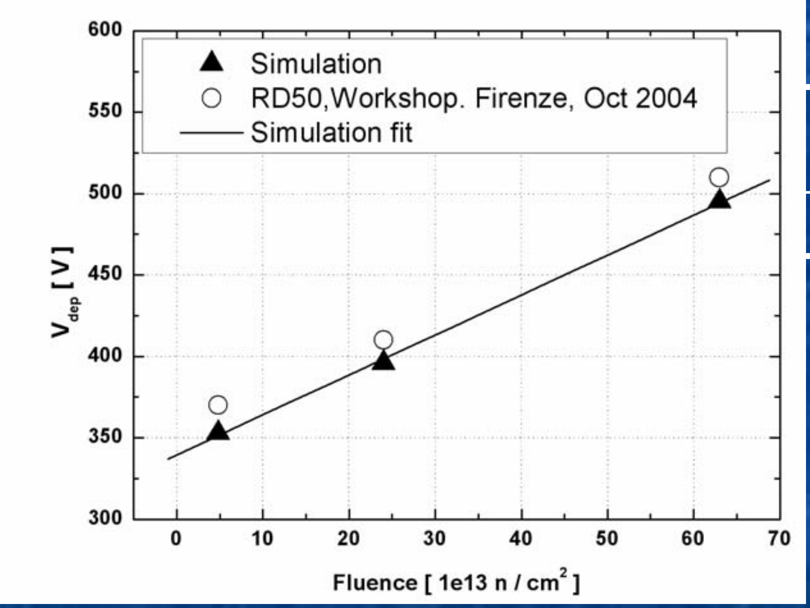
The p-type Three-Level Radiation Damage Model:

no improvement for the Vdep and Leackage Current 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	$VV^{(-/0)}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-15}$	$2\cdot10^{-14}$	1.613
E_c-0.46eV	$VVV^{(-/0)}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-15}$	$5\cdot10^{-14}$	0.9
E_v+0.36eV	? C_iO_i?	$2.5\cdot10^{-14}$	$2.5\cdot10^{-15}$	$2.5\cdot10^{-14}$	$2.5\cdot10^{-15}$	0.9

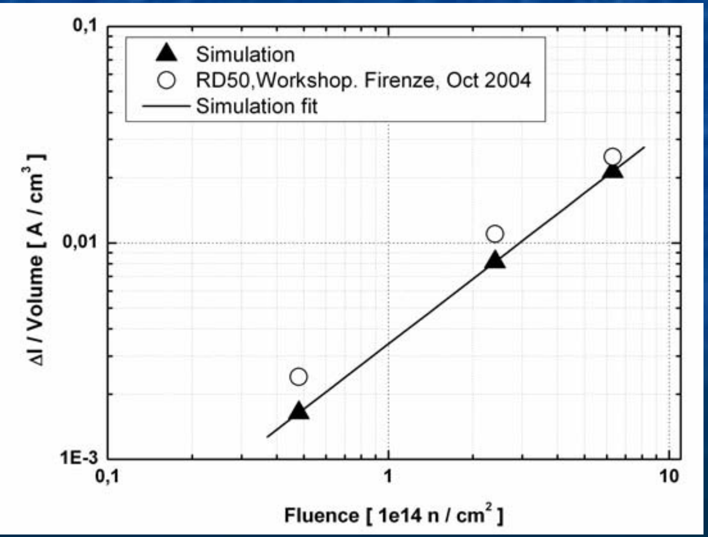
* 1 order of magnitude higher

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



β [cm^{-1}] simulated
$3.98\cdot10^{-3}$

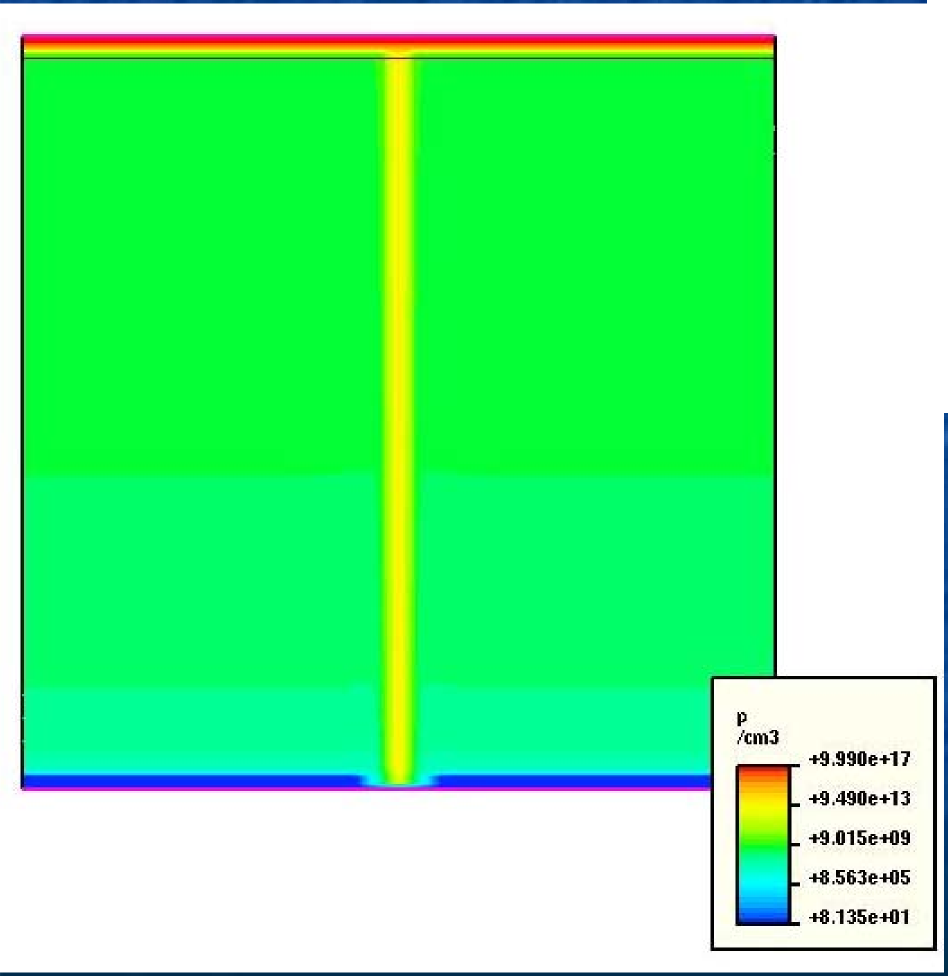
β [cm^{-1}] experimental
$4{,}0\pm0{,}4\cdot10^{-3}$

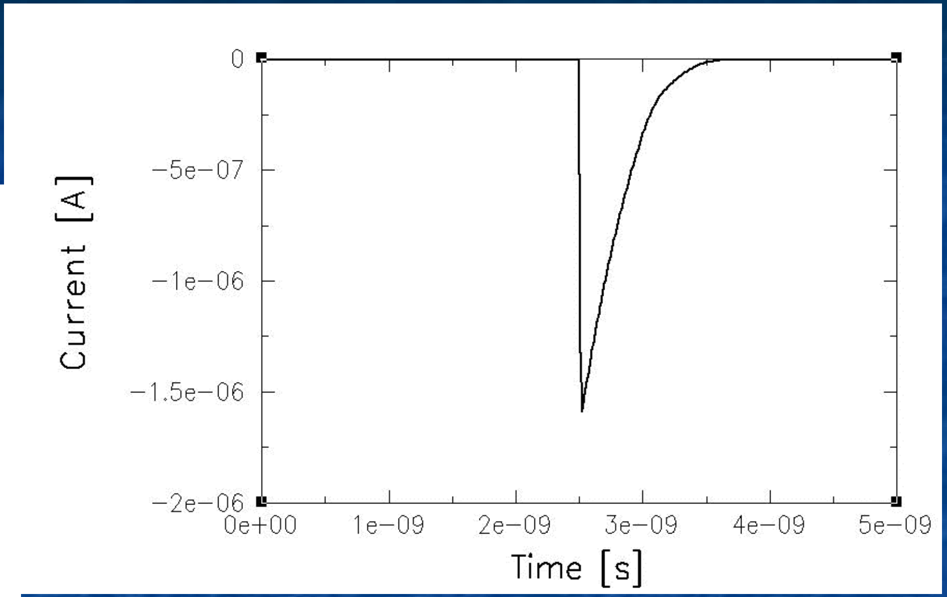


α [A/cm] experimental
$4\pm0{,}11\cdot10^{-17}$

α [A/cm] simulated
$3.75\cdot10^{-17}$

CCE Simulation





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

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

CCE Simulation

The Ricombination implemented in DESSIS simulator is based on a model called Scharfetter/Auger Trapped Assisted

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

change the $c_{n/p}^{TAA}$ parameters in order to obtain the correct value of the recombination time for high resistivity substrates

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

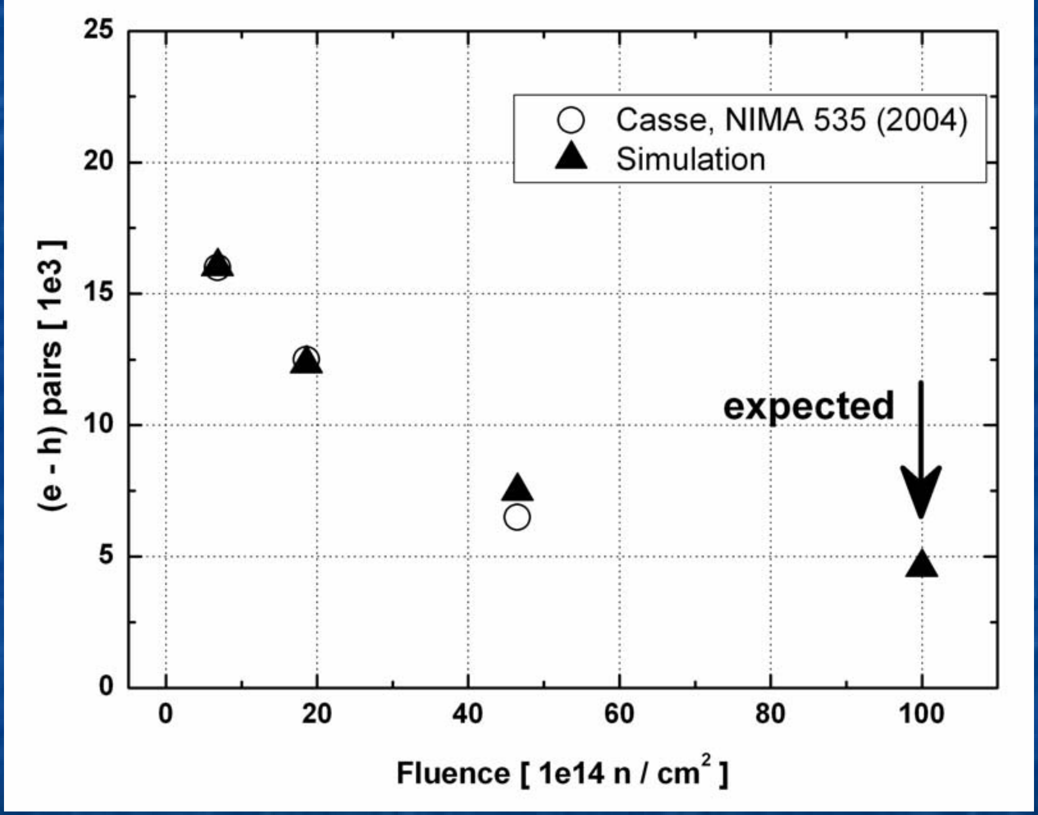
where

From RD50 status Report (2004):

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

CCE vs Fluence for p-type silicon device

Simulation data well reproduce experimental* measure:



Simulations obtained using the **three-level radiation damage model**:

the donor defect level allows to reduce numerical convergence problems of the transient simulations.

Expected CCE at a fluence of $1 \cdot 10^{16}$ n/cm^2 is <4200 (probably over-estimated) e-h pairs!

* Measurements from Casse et al. NIMA 535 (2004)

Conclusions

- Irradiated diodes have been analyzed considering a three levels simulation model for p-type Si substrates:
  - The two-level model for the p-type fits experimental data for the Leakage Current and Full Depletion Voltage
  - The C_iO_i donor level for p-type silicon seems to be un-influential (at Room Temperature) to simulate the leackage current and the full depletion voltage as a function of the fluence, but has an important function for the transient simulations stability (CCE simulation).
  - The three-level for p-type fits CCE experimental data for fluences up to $4.85 \cdot 10^{15}$ n/cm^2 at the full depletion voltage.
- Next step is to develop a technique to solve the problems to simulate the CCE vs BIAS voltage (up to $1 \cdot 10^{16}$n/cm^2) for p and n type Si substrates partially undepleted.