New research activity “Silicon detectors modeling in RD50”: goals, tasks and the first steps

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Motivation

1. The practical goal of RD50 – engineering of semiconductor radiation hard detectors

2. The detector engineering is based on:

- Physical study
- Microscopic and macroscopic data
- Physical models
- Mathematical calculations (original and industrial packages)

3. Development of common understanding on- the modeling procedure and cross-test the software

The main tasks

1. Input data systematization:
    - microscopic properties of irradiated silicon,
    - transport properties of irradiated silicon,
    - parameterization of the effects.
2. Development of physical models for simulation
    - reverse current,
    - electric field,
    - current pulse response,
    - CCE,
3. Evaluation systematization and interpretation of the experimental results with the developed models
4. Data base for input data, parameterizations, results of the modeling and key experimental results.

One goal and Two approaches

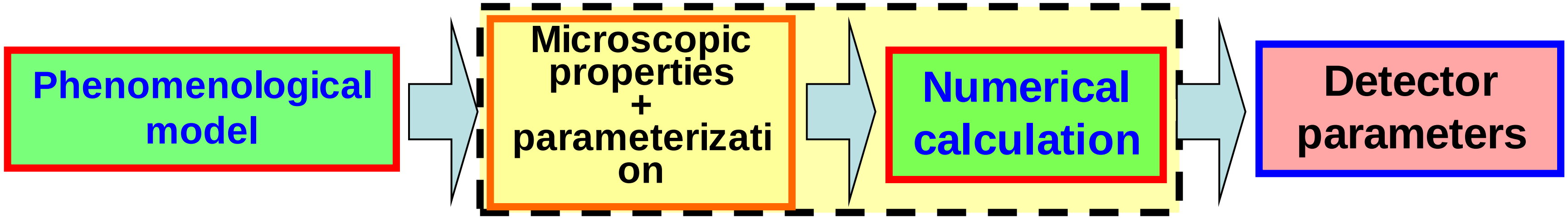
Microscopic approach

Microscopic properties

Gray Box software

Detector parameters

Phenomenological approach



Phenomenological model

Microscopic properties + parameterization

Numerical calculation

Detector parameters

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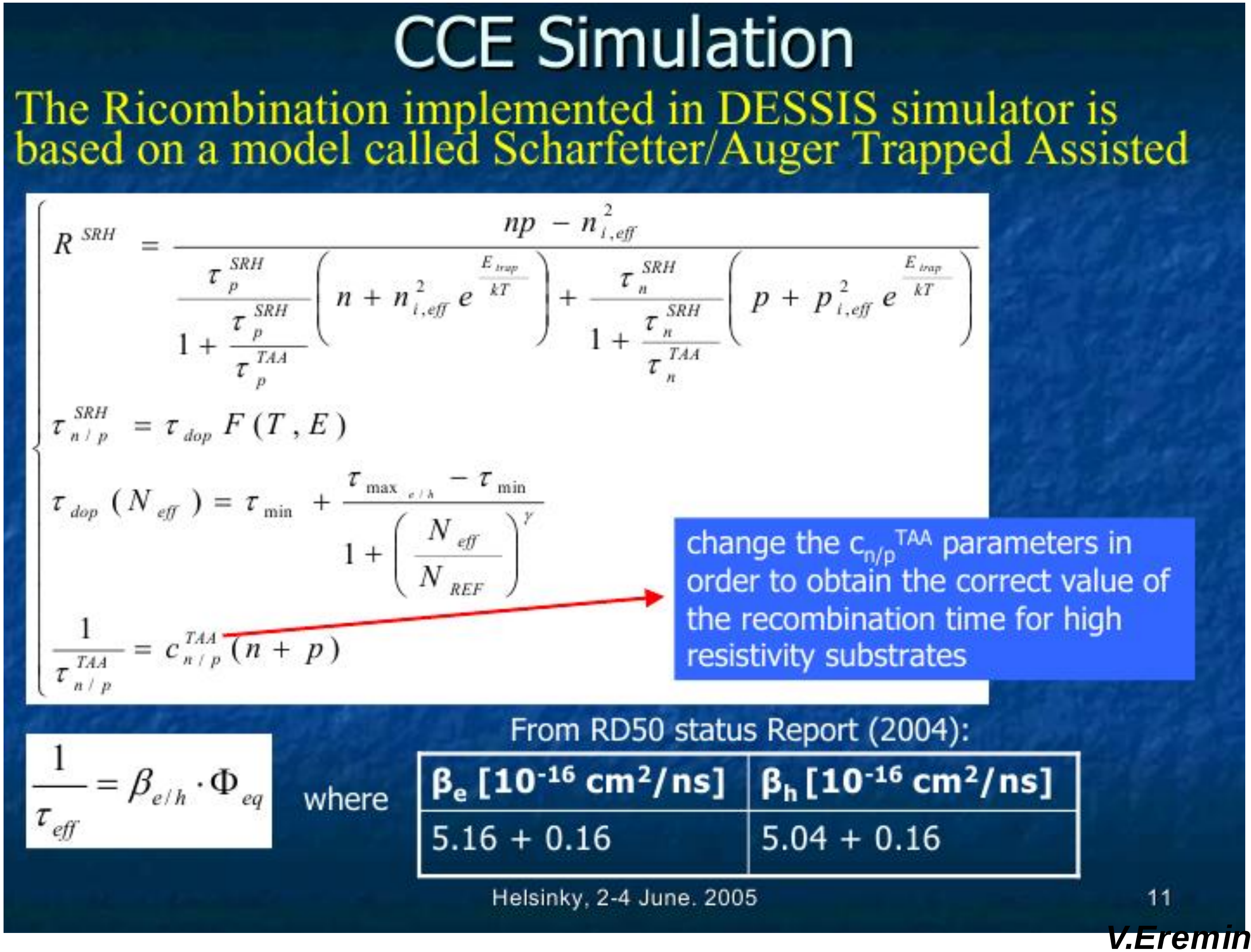
Recombination phenomenon description in DESSIS simulator

From: Petasecca M., et al., “Numerical simulation of radiation damage effect in P-Type silicon” RD50 workshop, June 2005.



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

Helsinky, 2-4 June. 2005

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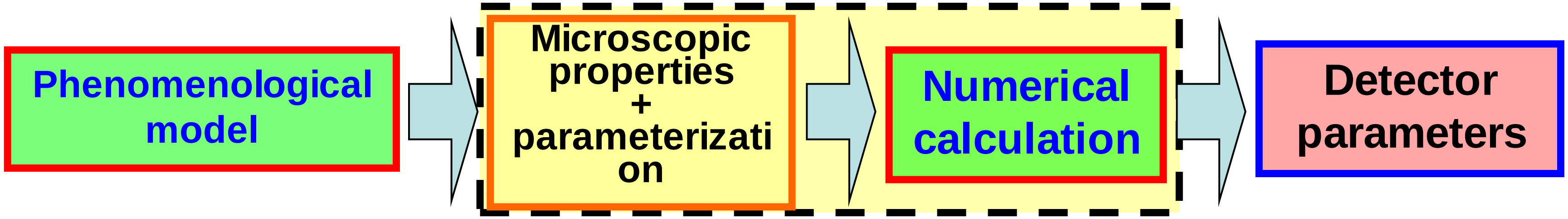
Phenomenological approach



Phenomenological model

Microscopic properties + parameterization

Numerical calculation

Detector parameters

Linear models for major fluence dependent microscopic properties:

- Concentration of current generated levels is proportional to fluence
- Trapping probability is proportional to fluence
- SRH statistics for the occupancy of radiation induced levels

Parameterization/approximation of:

- Bulk generation current via SHR statistics
- Trapping time (from experiment)

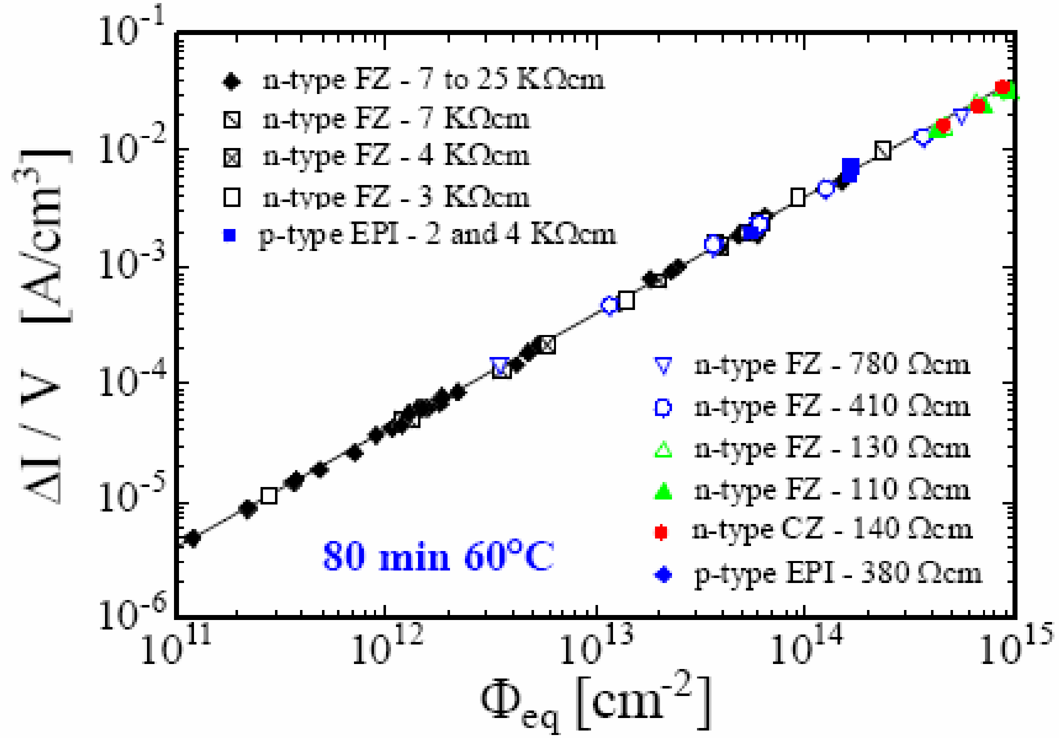
Solution of 1D equations set :

- Poisson
- Continuity
- Occupancy equations

Detector parameters:

- Electric field distribution (V, F, T),
- CCE (V, F, T) for PAD detector
  and with Ramo's weighting electric field then
- CCE (V, F, T) for strip detector along the strip axes

Fluence dependence of reverse current



$J_{gen} \sim N_{mgl} * \sigma * \exp(-E_{mgl}/kT)$

$N_{mgl} = \Sigma\,(F \times G_{mgl}^{i}) \sim$ fluence

A striate line fit of J(F) is a strong argument to use a linear dependences of the radiation induced defects concentration on F.

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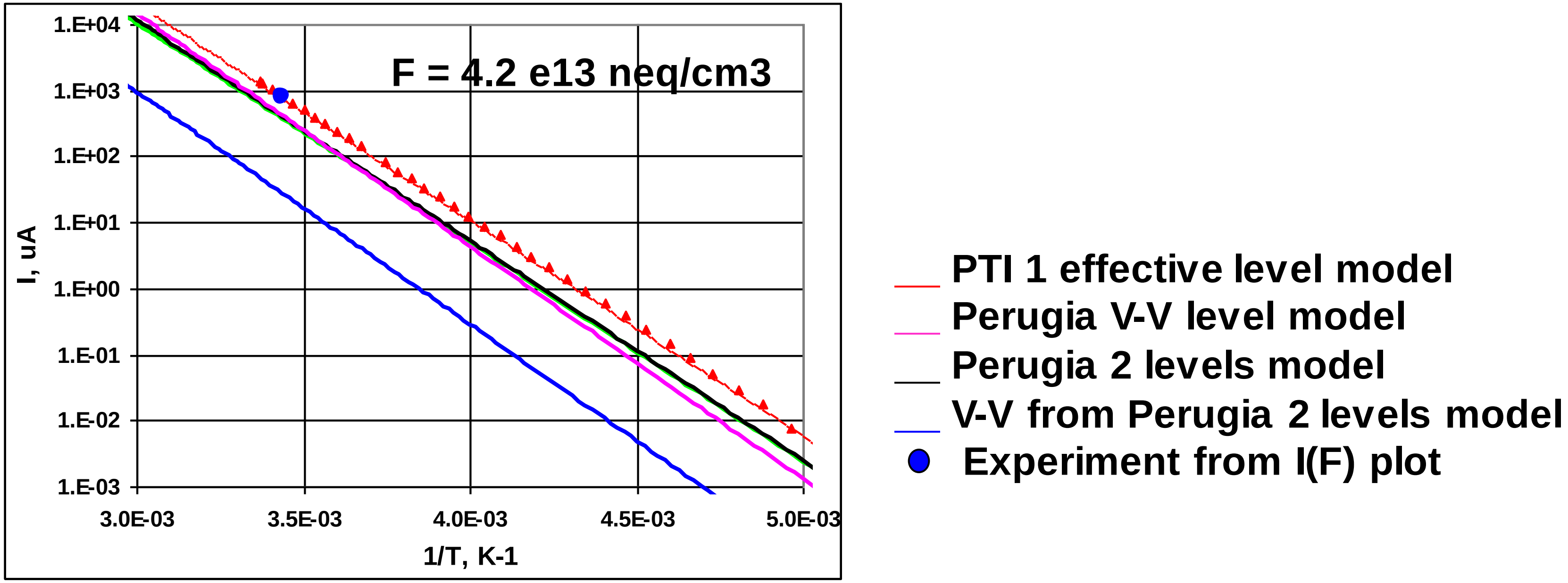
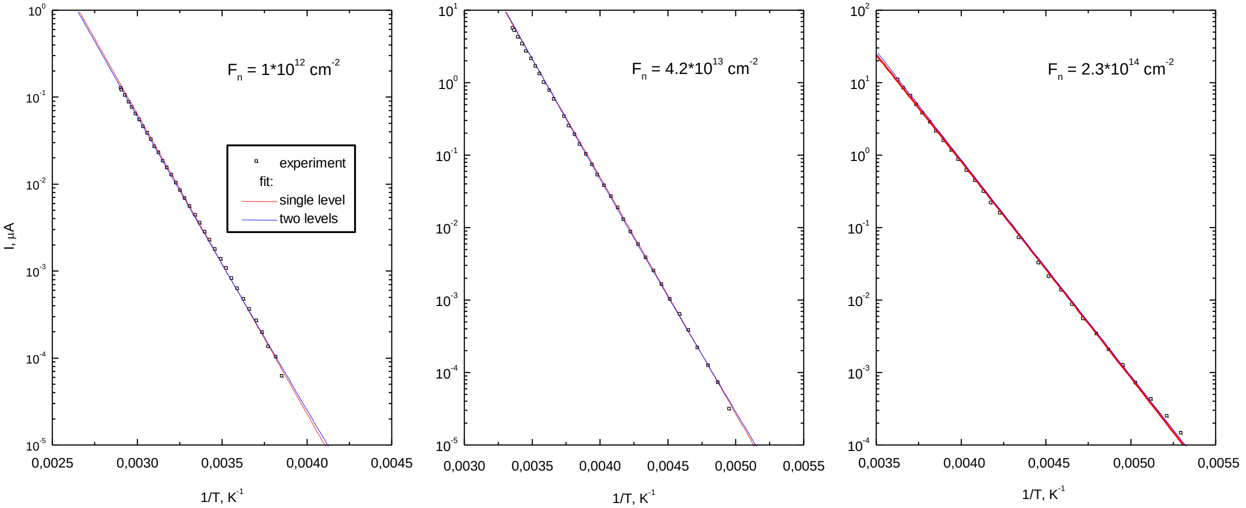
Comparison of 1 level and 2 levels models for bulk generated current



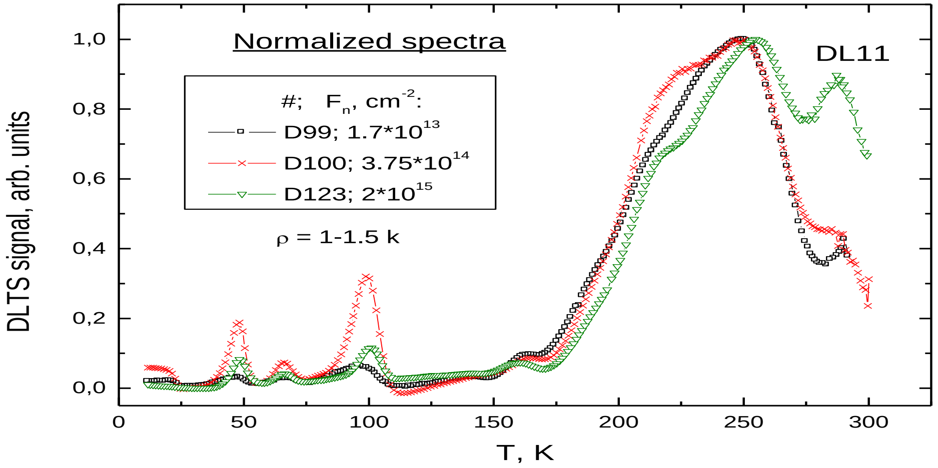
	Single level model					
	PTI	Perugia	Perugia 2 levels model			
DL #	V-V-V?	V-V	DL #	V-V	V-V-V	TOTAL
Ec-Et, [eV]	0.470	0.420	Ec-Et, [eV]	0.420	0.46	
Et-Ev, [eV]	0.650	0.700	Ec-Et, [eV]	0.700	0.660	
sig e,[cm2]	1.00E-13	2.00E+15	sig e,[cm2]	2.00E+15	5.00E-15	
sig h,[cm-2]	1.20E-13	2.00E-13	sig h,[cm-2]	2.00E-14	5.00E-14	
Mdl[cm-3]	4.20E+13	1.02E+14	Mdl[cm-3]	6.72E+13	3.78E+13	
η, 1/cm	1	2.42		1.6	0.9	

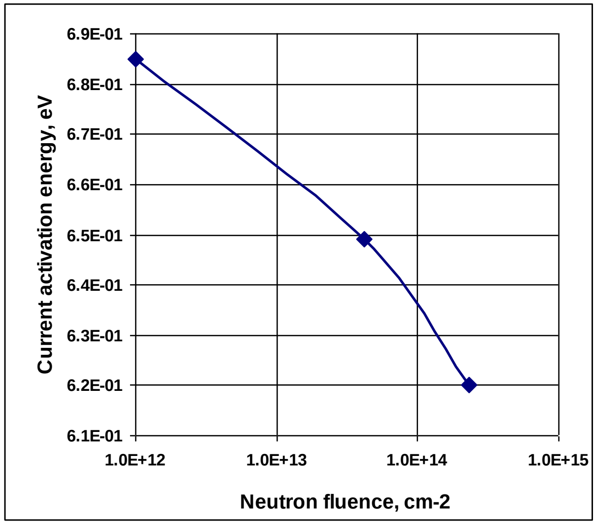
V.Eremin, RD50, Nov 2011

Reverse current at different fluences in neutron irradiated detectors



F_n, cm^{-2}	$1\cdot10^{12}$	$4.2\cdot10^{13}$	$2.3\cdot10^{14}$
E_a, eV	0.685	0.649	0.620





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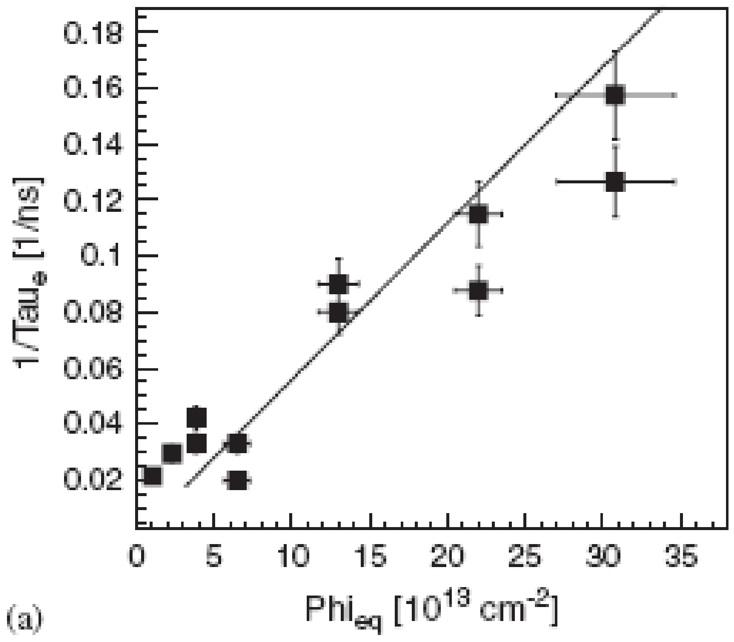
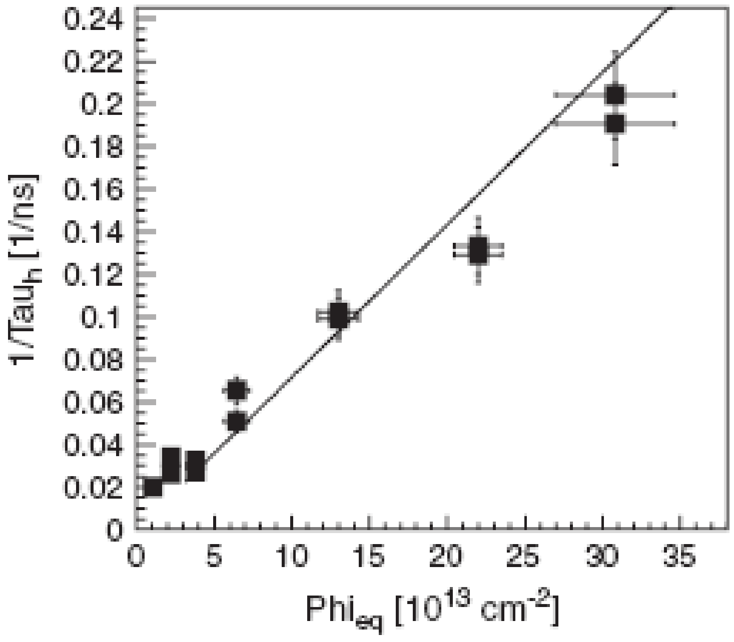
Trapping probability

$$\tau^{-1} = 1/\tau 0 + \sigma * Vth * Ntr = \beta F$$



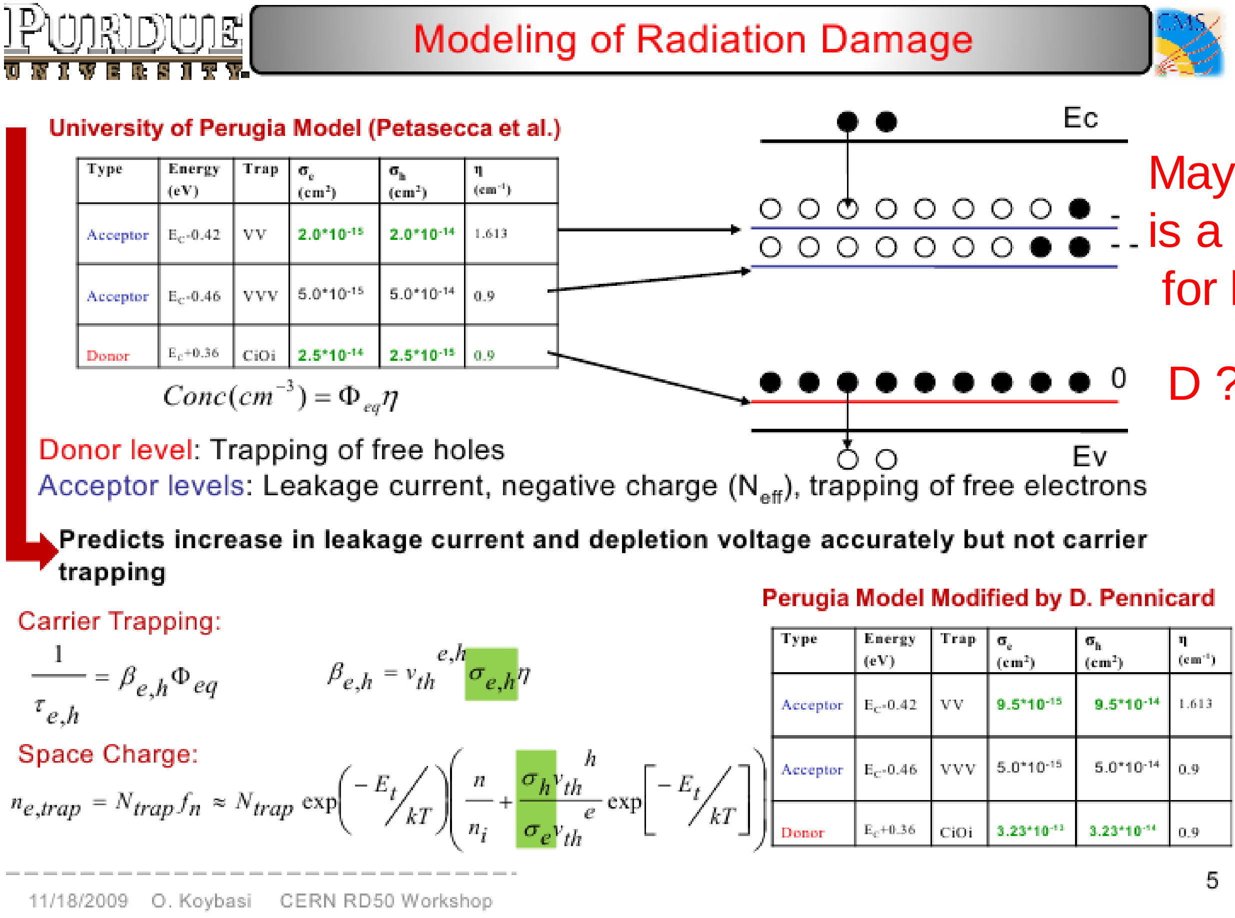
(a)



A. Bates and M. Moll, NIM A 555 (2005) 113–124

Trapping probability (protons)	
$1/t_e0$, [s-1]	$3x10^{-3}$
β_e	$3.2x10^{-7}$
$1/t_h0$, [s-1]	$3x10^{-3}$
β_h	$3.5x10^{-7}$

Where is hole trapping center?



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Modeling of Radiation Damage

University of Perugia Model (Petasecca et al.)

Type	Energy (eV)	Trap	σ_e (cm²)	σ_h (cm²)	η (cm⁻¹)
Acceptor	E_C-0.42	VV	2.0*10⁻¹⁵	2.0*10⁻¹⁴	1.613
Acceptor	E_C-0.46	VVV	5.0*10⁻¹⁵	5.0*10⁻¹⁴	0.9
Donor	E_C+0.36	CiOi	2.5*10⁻¹⁴	2.5*10⁻¹⁵	0.9

$$Conc(cm^{-3}) = \Phi_{eq}\eta$$

Donor level: Trapping of free holes

Acceptor levels: Leakage current, negative charge (N_{eff}), trapping of free electrons

Predicts increase in leakage current and depletion voltage accurately but not carrier trapping

Carrier Trapping:

$$\frac{1}{\tau_{e,h}} = \beta_{e,h}\Phi_{eq} \qquad \beta_{e,h} = v_{th}^{e,h}\sigma_{e,h}\eta$$

Space Charge:

$$n_{e,trap} = N_{trap} f_n \approx N_{trap}\exp\left(-E_t/kT\right)\left(\frac{n}{n_i} + \frac{\sigma_h v_{th}^h}{\sigma_e v_{th}^e}\exp\left[-E_t/kT\right]\right)$$

Perugia Model Modified by D. Pennicard

Type	Energy (eV)	Trap	σ_e (cm²)	σ_h (cm²)	η (cm⁻¹)
Acceptor	E_C-0.42	VV	9.5*10⁻¹⁵	9.5*10⁻¹⁴	1.613
Acceptor	E_C-0.46	VVV	5.0*10⁻¹⁵	5.0*10⁻¹⁴	0.9
Donor	E_C+0.36	CiOi	3.23*10⁻¹³	3.23*10⁻¹⁴	0.9

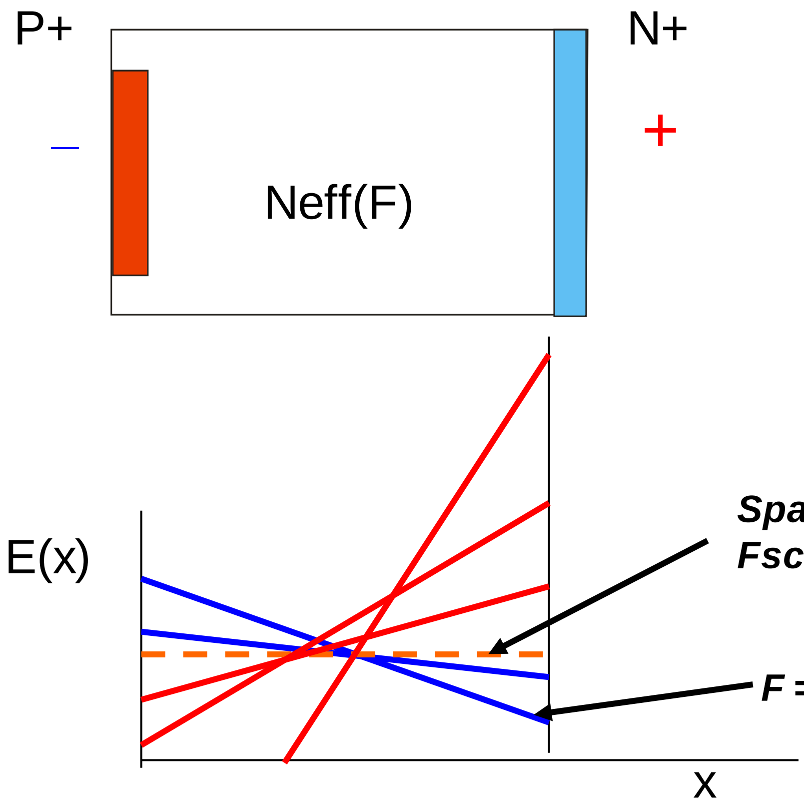
11/18/2009 O. Koybasi CERN RD50 Workshop 5

May be MGA
is a trapping center
for holes??

D ???

Estimation: at F=1e15neq/cm3, Nmgl = 1e15 1/cm3:
Vth=1e17 cm-2 and Trapping cross-section = 1e-14cm2 and τ = 10 ns, instead of 3 ns.

Electric field evolution with fluence in Hamburg model

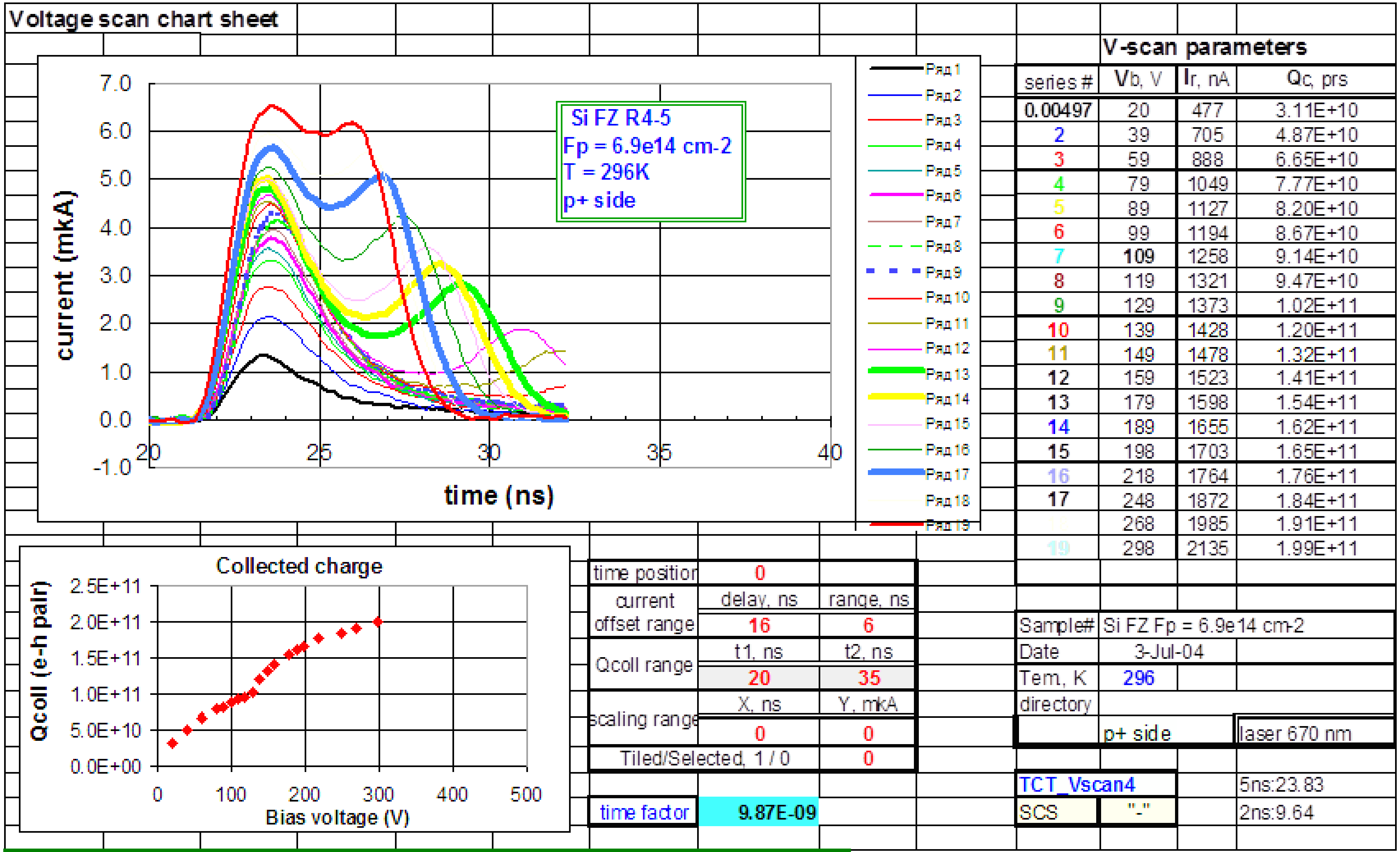


Space Charge Sigh Inversion (SCSI)
Fscsi ~1e13 n/cm2

F = 0

Detector signal at high proton fluence

High proton fluence, 24 GeV, $7\cdot10^{14}$ cm^{-2}, p^{+} side: DP shape, peaks become equal



Voltage scan chart sheet

V-scan parameters

series #	Vb, V	Ir, nA	Qc, prs
0.00497	20	477	3.11E+10
2	39	705	4.87E+10
3	59	888	6.65E+10
4	79	1049	7.77E+10
5	89	1127	8.20E+10
6	99	1194	8.67E+10
7	109	1258	9.14E+10
8	119	1321	9.47E+10
9	129	1373	1.02E+11
10	139	1428	1.20E+11
11	149	1478	1.32E+11
12	159	1523	1.41E+11
13	179	1598	1.54E+11
14	189	1655	1.62E+11
15	198	1703	1.65E+11
16	218	1764	1.76E+11
17	248	1872	1.84E+11
18	268	1985	1.91E+11
19	298	2135	1.99E+11

time position	0	
current offset range	delay, ns	range, ns
	16	6
Qcoll range	t1, ns	t2, ns
	20	35
scaling range	X, ns	Y, mkA
	0	0
Tiled/Selected, 1 / 0		0
time factor	9.87E-09	

Sample#	Si FZ Fp = 6.9e14 cm-2	
Date	3-Jul-04	
Tem, K	296	
directory		
	p+ side	laser 670 nm
TCT_Vscan4		5ns:23.83
SCS	"-"	2ns:9.64

E. Verbitskaya et al., 5 RESMDD, Florence, Oct 10-13, 2004

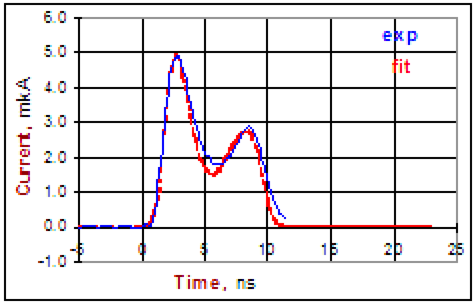
V.Eremin, RD50, Nov 2011

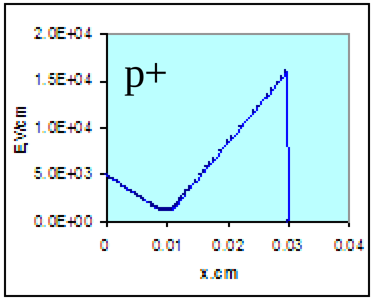
Simulation of TCT pulse and E(x)

p+ side

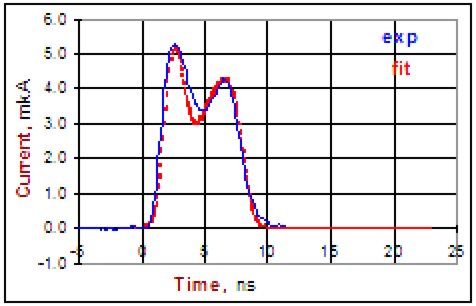
P+ side

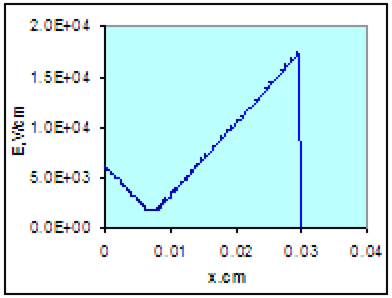
V = 179 V



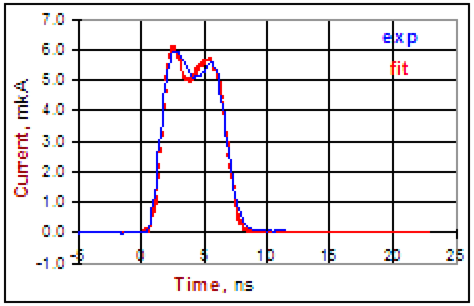


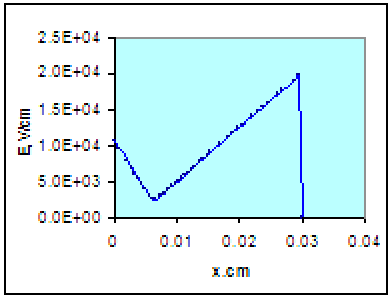
V = 218 V





V = 268 V





Protons 24 GeV,
$F_p = 6.9 \cdot 10^{14}$ cm^{-2}

Carrier trapping considered

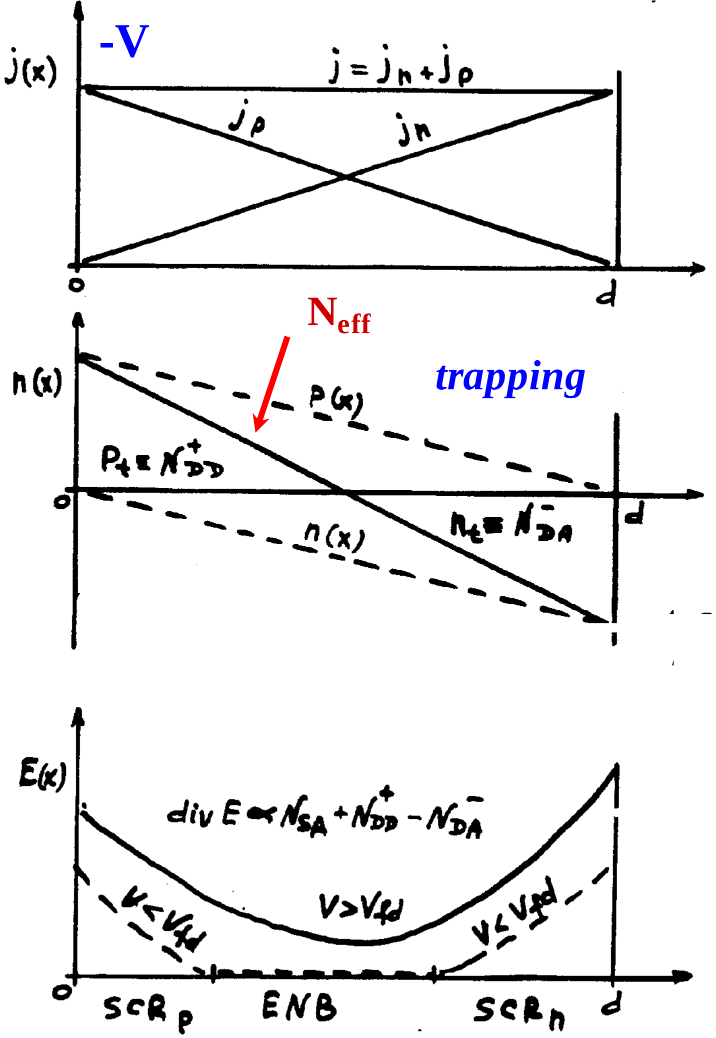
Parameters derived from fits

	179 V	**218 V**	**268 V**
W1 (mkm)	90	65	60
Wn (mkm)	18	15	8
W2 (mkm)	192	220	232
Eb	1250	1800	2600
Neff1	1.83E+12	2.53E+12	6.03E+12
Neff2	4.65E+12	4.24E+12	4.24E+12

E. Verbitskaya et al.,
5 RESMDD, Florence, Oct 10-13, 2004

PTI model for electric field distribution in irradiated detectors

V. Eremin, E. Verbitskaya, Z. Li. "The Origin of Double Peak Electric Field Distribution in Heavily Irradiated Silicon Detectors", *NIM A 476 (2002) 556.*



Trapping of free carriers from detector reverse current to midgap energy levels of radiation induced defects leads to DP E(x)

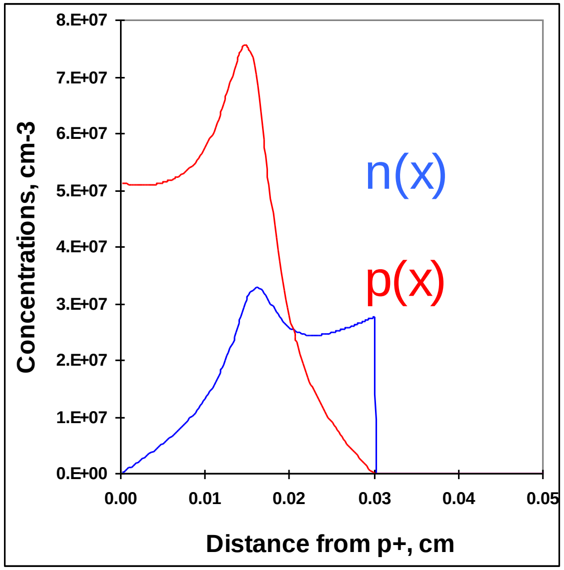
DLs responsible for DP E(x) are midgap DLs:

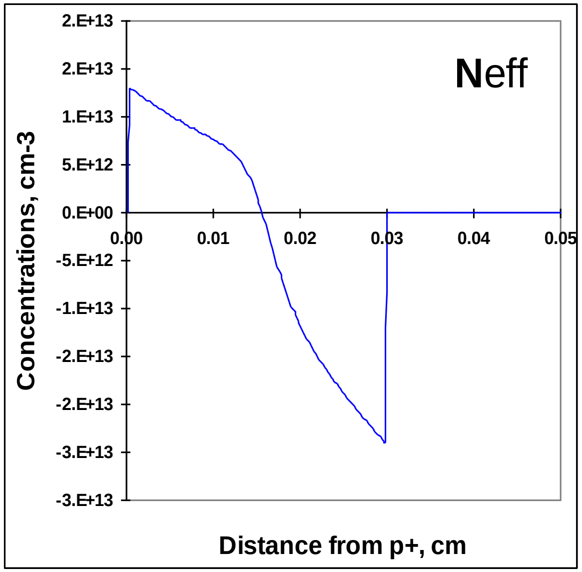
DD: $E_v + 0.48$ eV

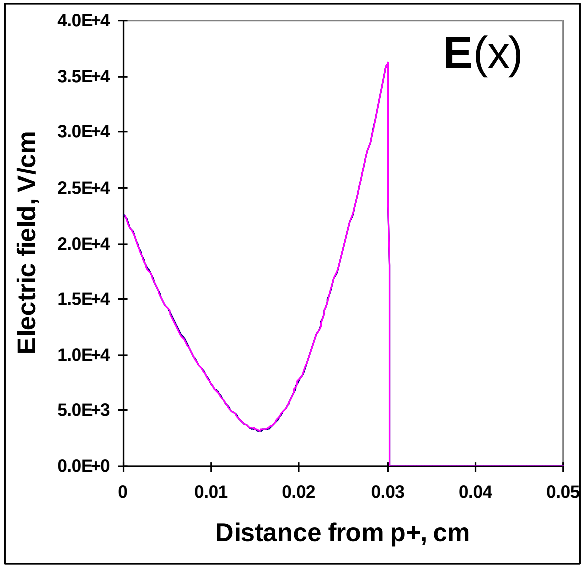
DA: $E_c - (0.52 - 0.595)$ eV

Simulated electric field in irradiated detector in the frame of PTI model

F=1e15, V=400V, d=300 um, T=260K







MGL parameters in the PTI model

DL #	Ci-Oi		Deep donor		V-V		Deep acceptor	
D/A, 0/1	0		0		1		1	
	electrons	holes	electrons	holes	electrons	holes	electrons	holes
Et=Edl-Ev	0.36	0.76	0.48	0.64	0.7	0.42	0.595	0.525
sig/e[cm2]	1.00E-15		1.00E-15		1.00E-15		1.00E-15	
sig/h[cm2]		1.00E-15		1.00E-15		1.00E-15		1.00E-15
Ndl[cm-3]	0.00E+00		2.00E+15		0.00E+00		1.00E+15	
Sig*Vth	1.93E-08	1.47E-08	1.93E-08	1.47E-08	1.93E-08	1.47E-08	1.93E-08	1.47E-08
detrap.prob.	8.31E-04	1.42E+04	1.76E-01	6.73E+01	3.23E+03	3.66E-03	2.98E+01	3.97E-01

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Hot problems

- Why the reverse current activation energy is sensitive to fluence?
- Which level is responsible for trapping?
- Revision of experimental data for detector properties: J(F, T, radiation), τ(F),
- PF effect at high E and the trapped carriers emission efficiency,
- Comparison of E(x) simulated by EXL and TCAD for planar detector
- Cross sections for the MGLs and their introduction rates.

Steps forward

1. Current parameterization
2. Trapping time parameterization
3. Adjust TCAD for 1D modeling of E(X) (boundary conditions on the left and right edges,
4. Cross tests TCAD with not professional softwares.

List of participants and tasks

Institution	Package1	Package2	Ir(T,F)	Ttr (V, F)	{E(x)}(F)	
Ioffe PTI, St. Petersburg	Original, EXL	TCAD		TCT, alphas	TCT, response reconstruction	

Thank you for your attention and for suggestions on the project