Universität Hamburg

Effect of Microscopic Defects in n-type Irradiated MCz Silicon Detectors: Impact on Macroscopic Parameters

Ajay K. Srivastava, E. Fretwurst, D. Eckstein, R. Klanner

Institute for Experimental Physics (Detector Laboratory)
Hamburg University

14th RD50 Workshop (03-05th june 2009), Freiburg, Germany

Outline

Universität Hamburg

- Introduction
- Experimental Measurements
- Device Structure and Physical Models
- Simulation Procedure
- Numerical Modeling of Radiation Damage
- Simulation Work Done:
  - ⇨Comparison Data to Simulation

"Two-Dimensional Numerical Modeling of n-type MCz Si PAD sensor (as-irradiated) "

- Irradiation (5 $\times 10^{13}$, 1×10^{14}, $3\times 10^{14} n_{eq.}/cm^2$)
- Summary and Next Step

Macroscopic Radiation Damage in Silicon Detectors

- Bulk (crystal) damage due to Non Ionizing Energy Loss (NIEL)

  - displacement damage, crystal defects/microscopic defect

  (Threshold energy $\gtrsim$ 300 keV)

  I. Change of effective doping concentration N_{eff} (higher full depletion voltage V_{fd})

  II. Increase of leakage current (increase of shot noise, thermal runaway)

  III. Increase of charge carrier trapping (reduced charge collection efficiency (CCE)

- Surface damage due to Ionizing Energy Loss (IEL)

  I. Charge build-up in SiO_2

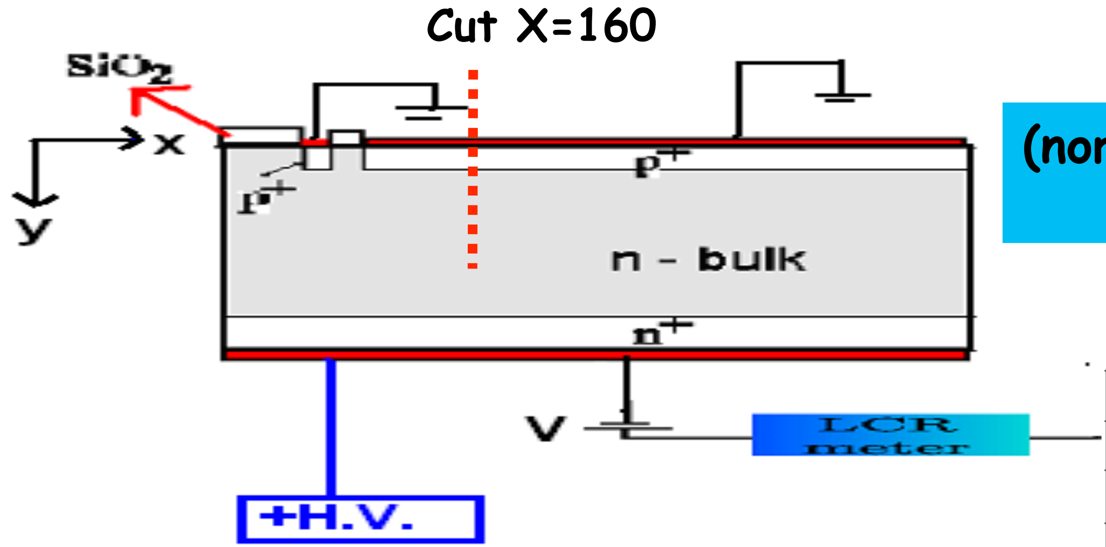
  II. Traps of Si-SiO_2 interface

  } (shift of flatband voltage V_{fb}, breakdown of critical corners)

  III. Surface generation current (increase shot noise)

Experimental measurements (I/V and C/V)

Universität Hamburg



(normalized p⁺ active area) A_{p+}=0.25 cm^2

List of Physical parameters 300K

S.No.	Physical paramaters	Values
1.	Doping concentration(N_D)	4.94 x10^{12} cm^{-3}
2.	Oxide thickness (t_{ox})	0.5 µm
3.	Junction depth (X_j)	1µm
4.	Guard ring spacing(GS)	10 µm
5.	guard ring width (GW)	100 µm
6.	Device depth	280 µm
7.	Thickness of (W_{n+})	1 µm
8.	Fixed oxide charge(Q_f)	1 x 10^{12} cm^{-2}

⇨ Circuit used for I/V and C/V,f simulation

Device simulation

Aim: Detailed simulation of sensor (p^+ PAD Si with one guard ring with all useful physical and geometrical parameters taken from measurements) including bulk radiation damage effects (deep trap parameters; E_t, N_t, $\sigma_{n,p}$)

⇨Link between microscopic defects and macroscopic paramaters

Software: 2-D device simulation with synopsis T-CAD

Physical model used

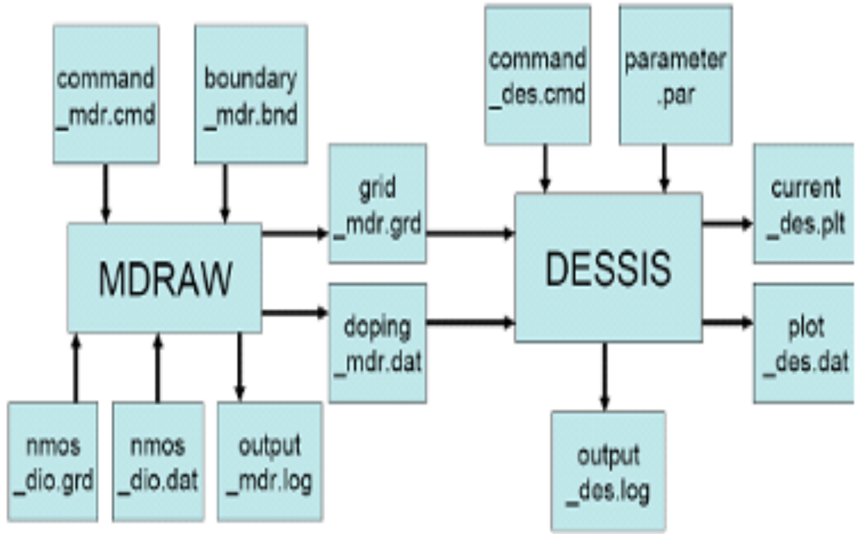
Universität Hamburg

- SRH (Shockley-Read-Hall) recombination statistics
  ⇨ Recombination through deep level traps
- Impact ionization
- Trap model
- Doping dependent mobility and high field saturation model
- Trap to trap interaction model for charge exchange
- Interface physics model at Si/SiO_2 interface and <u>rest all useful models</u>

Simulation procedure

Procedure

1. Design structure in MDRAW
2. Feed results into DESSIS
3. Combine simulation of device (DESSIS) and circuit (SPICE)



→ Compare results to analytical calculations for cross-check

Numerical modeling of radiation damage of Si sensor based on emission-capture dynamics of deep trap

Universität Hamburg

⇨ **The leakage current at full depletion (V_{FD}) and effective doping concentration can be calculated by following expressions;**

(i) ⇨ $I(V_{fd})(T) = qAW(e_p \Sigma n_T(donors) + e_n \Sigma n_T(acceptors))$

(ii) ⇨ $\Delta N_{eff} = N_D + \Sigma(n_T(donors) - \Sigma(n_T(acceptors)$

$$n_T(T) = N_T \frac{e_{n,p}}{e_n + e_p}$$

$$e_{n,p}(T) = c_{n,p}(T) N_{C,V}(T) \exp(\pm \frac{E_a(T) - E_{C,V}}{k_b T})$$

List of experimental observed deep trap parameter in n-type MCz Si : four level deep trap model for n-tpe MCz Si Sensor

Universität Hamburg

S.No.	Trap type	Energy level (eV)	$\sigma_{n,p}$ (cm^2) from exp.	σ_n (cm^2) (*)	σ_p (cm^2) (*)	η (cm^{-1})
1.	$E_5^{(-/0)}$	E_c-0.46	1.00x10^{-14} , 1.00x10^{-13} (estimated)	3.00x10^{-15}	4.00x10^{-15}	0.6 12.4
2.	H152K$^{(0/-)}$	E_v+0.42	Unknown, 2.3x10^{-14}	3.05x10^{-13}	3.1x10^{-13} * 1.0x10^{-13}	0.06
3.	$C_iO_i^{(+/0)}$	E_v+0.36	2.05x10^{-18} , 1.64x10^{-14}	1.64x10^{-14}	2.24x10^{-14}	1.1
4.	E30K$^{(0/+)}$	E_c-0.1	2.3x10^{-14} , 2.7x10 $^{-15}$	2.77x10^{-15}	2.0x10^{-15}	0.017

Ref. i. "M. Petasecca et al"; IEEE TNS VOL. 53, NO. 5,2006
ii. F.Moscatelli at al., NIMB, 186, 2002, 171-175

⇨ ***Modified model for n-type MCz Si sensor @RT=300K β_n= 3.66*10^{-16} cm^2/ns and β_p= 4.92*10^{-16} cm^2/ns**

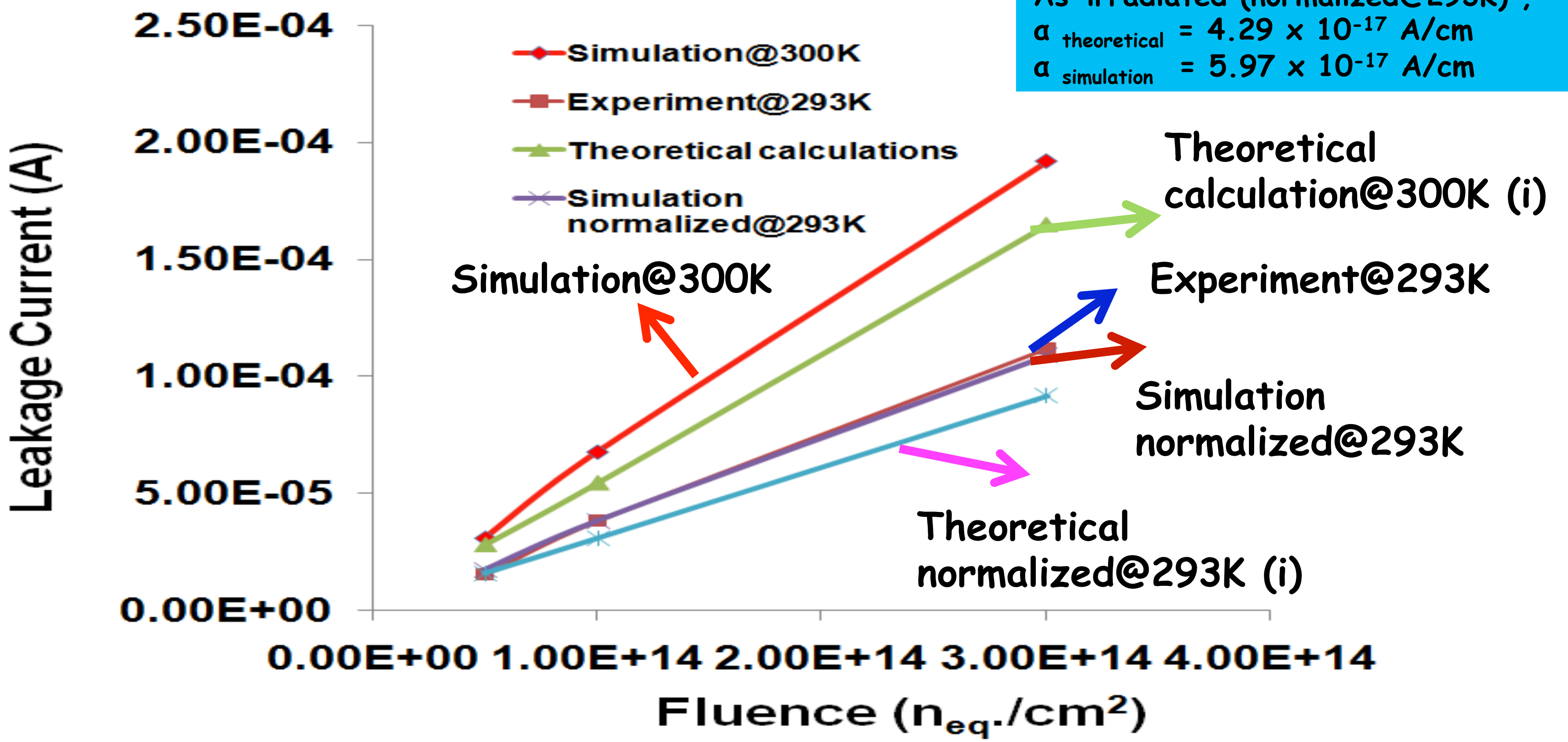
⇨ *σ_p used as fitting parameter for H152K

⇨ **Cluster effect taken into account by increasing one order magnitude of cluster related defect center E_5 ,**

Comparison of data to simulation (I/V): Irradiated n-type MCz PAD Si sensor (as-irradiated)

No charge exchange taken in $E_5^{(-/0)}$ ←----→ $H152K^{(0/-)}$

As-irradiated (normalized@293K) ,
$\alpha_{theoretical}$ = 4.29 x 10^{-17} A/cm
$\alpha_{simulation}$ = 5.97 x 10^{-17} A/cm

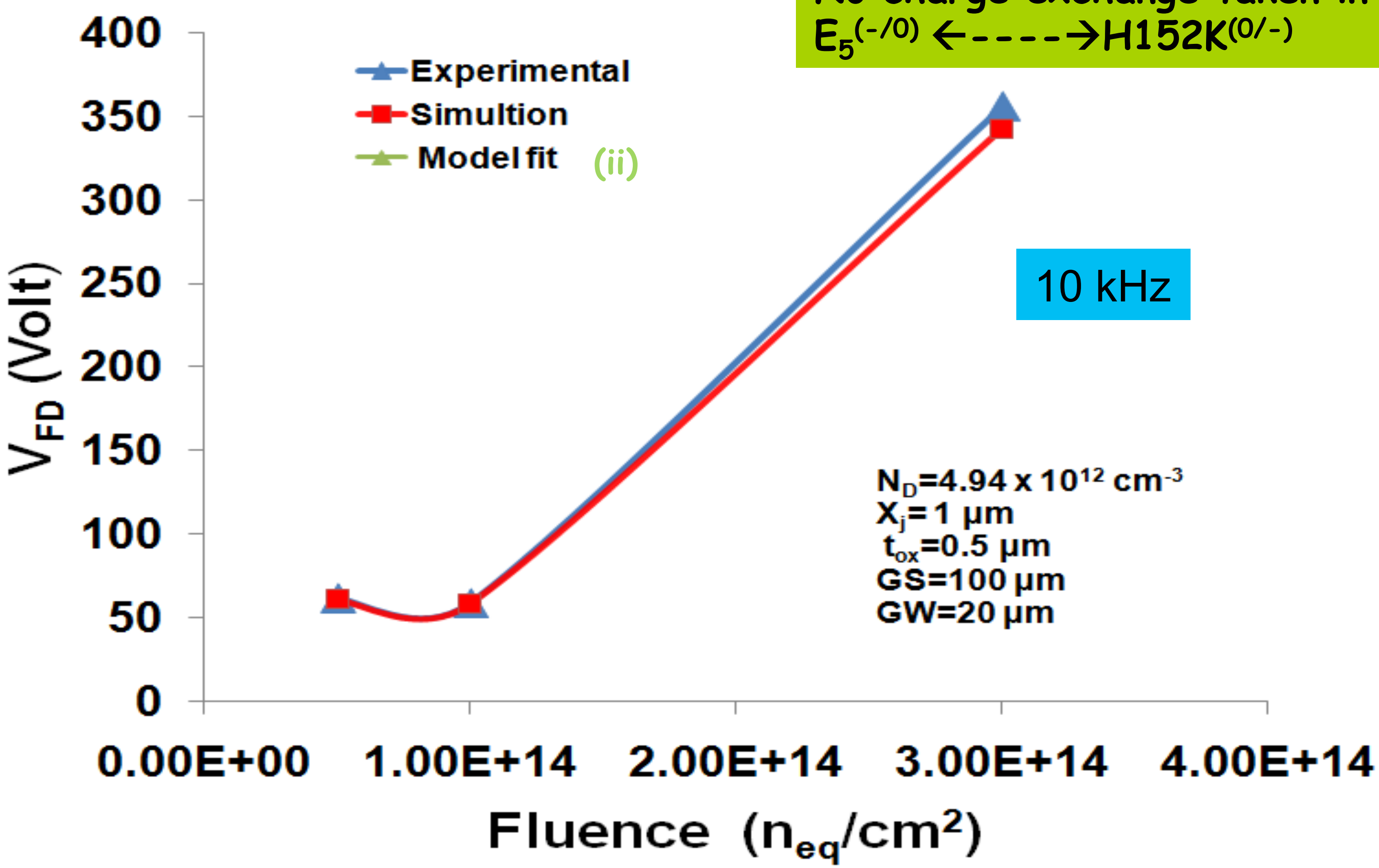


⇨ Good agreement in current after simulation normalized @RT=293K(20^{0}C) and experimental result

⇨ little estimation of theoretical current than simulated and experimental current(293K)

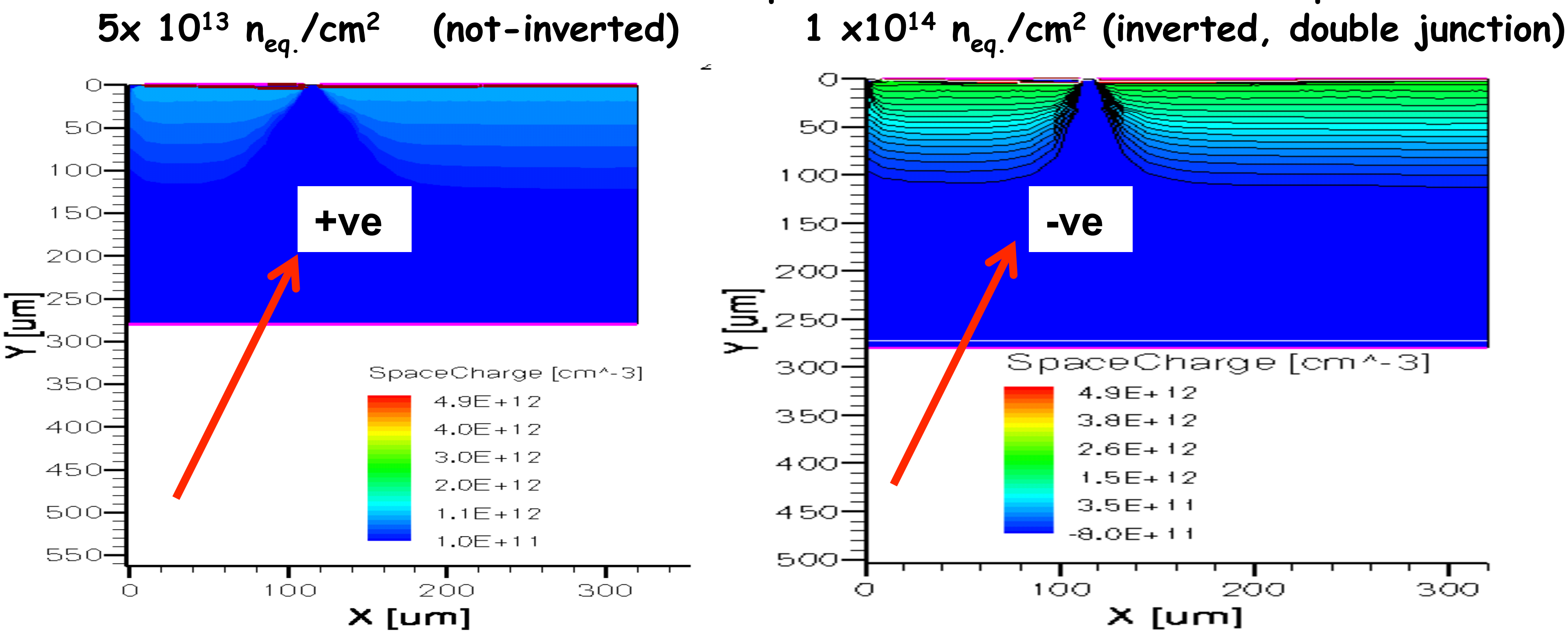
Comparison of data to simulation (C/V): Irradiated n-type MCz PAD Si sensor (as-irradiated)

No charge exchange taken in $E_5^{(-/0)}$ ←----→ $H152K^{(0/-)}$



⇨ ***Good agreement in simulation, experimental and model (ii)***

Space charge for 5×10^{13} n_{eq}/cm^2 and 1×10^{14} n_{eq}/cm^2



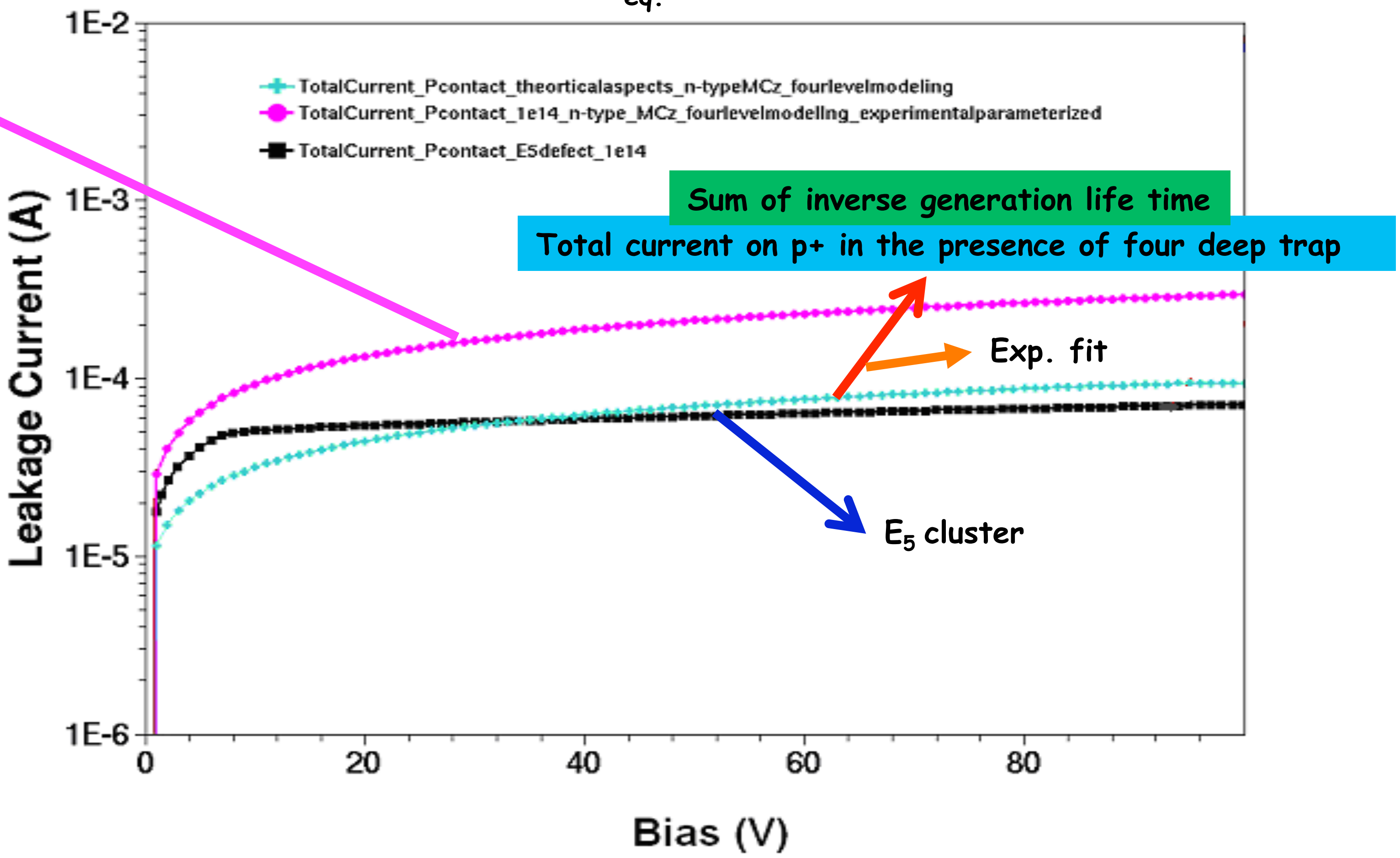
⇨ *Space charge sign inversion (SCSI) observed in 1×10^{14} $n_{eq.}/cm^2$*

Effect of E_5 cluster on I/V

$$\Sigma \frac{1}{\tau_{n,p}} = \beta_{n,p} \Phi_{eq}$$

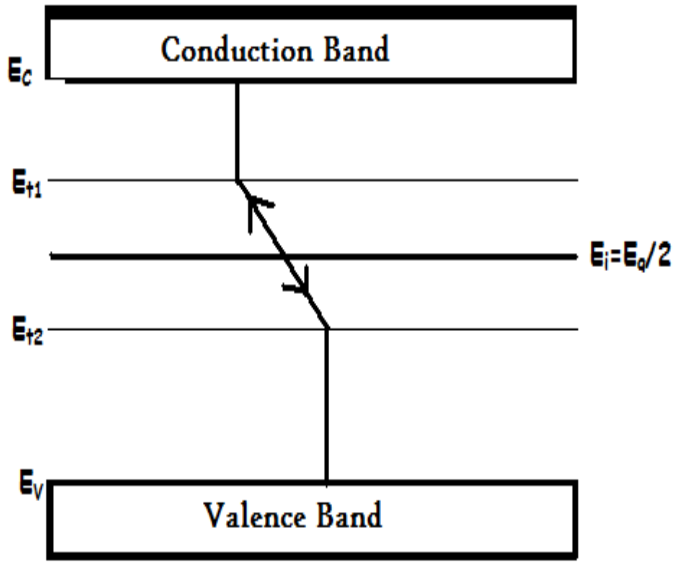
overestimated

For 1 $\times 10^{14}$ $n_{eq.}$ /cm^2



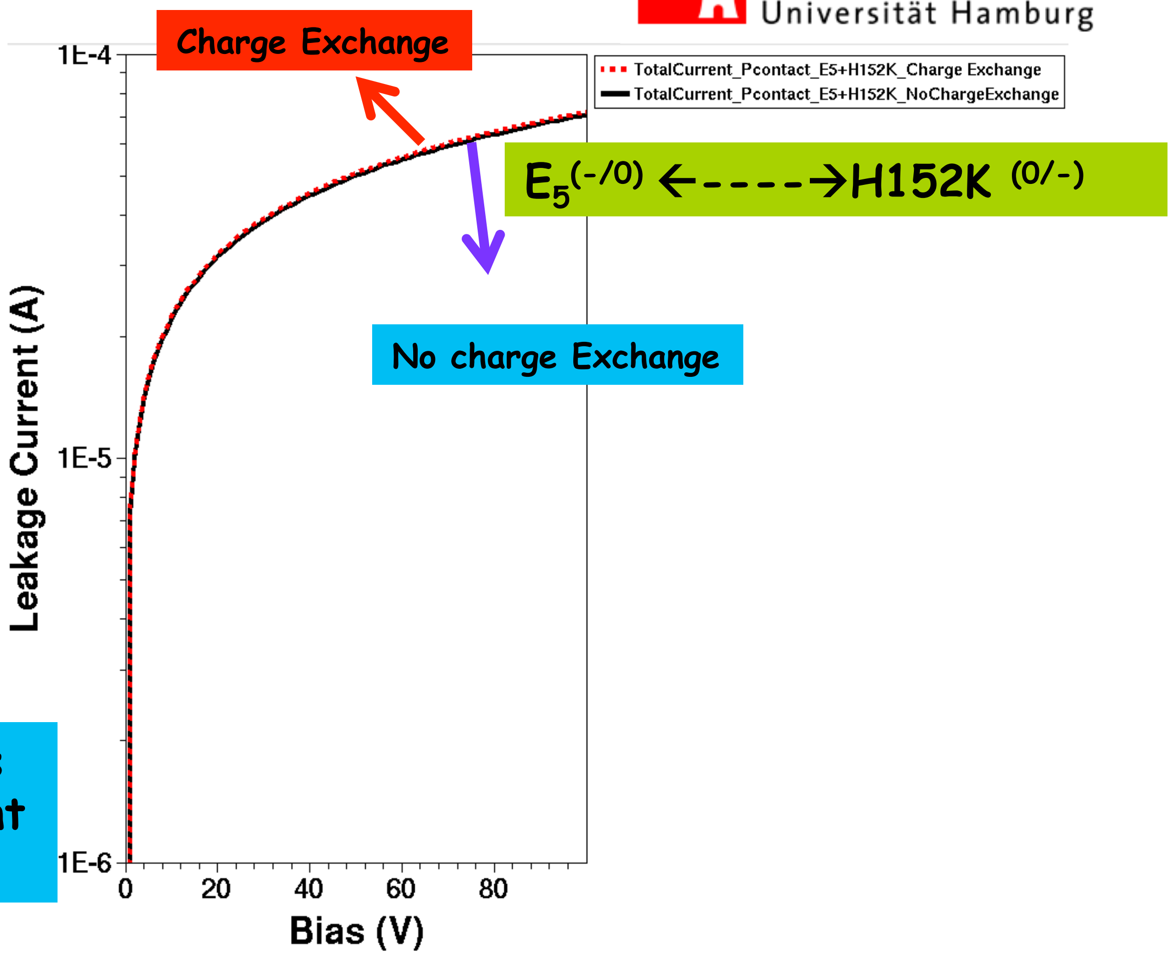
- ➪ E_5 cluster relevant for increase of leakage current in n-type MCz Si PAD sensor
  - Max. contribution from E_5 and rest due to surface current
- ➪ $\Sigma \frac{1}{\tau_{n,p}} = \beta_{n,p} \Phi_{eq}$,overestimation may be due to number of deep level trap/Si

Charge Exchange Mechanism



Effect on macroscopic parameters
- Increases of leakage current
- Change of N_{eff}/V_{FD}

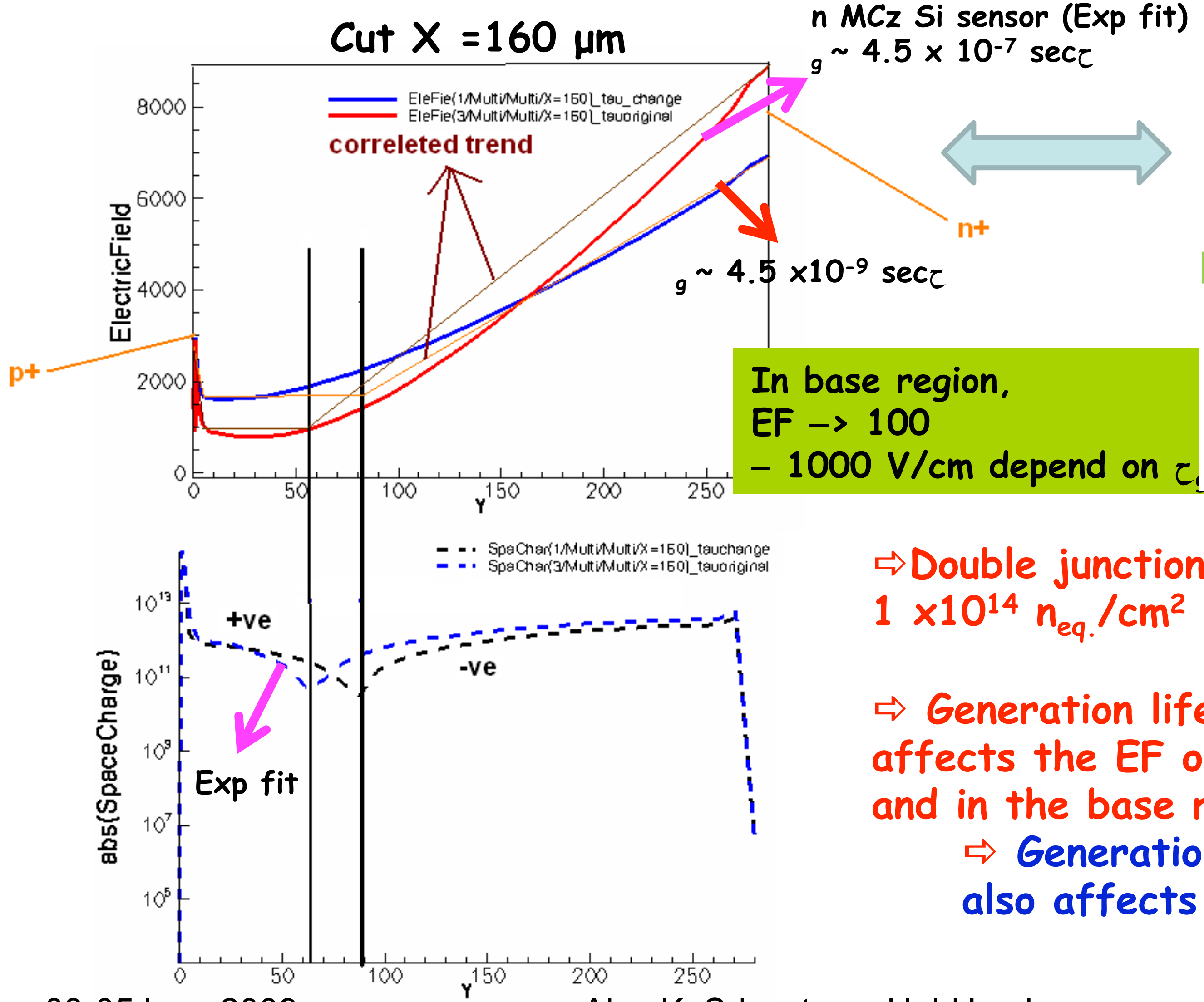
For 1e14 n_{eq} /cm²



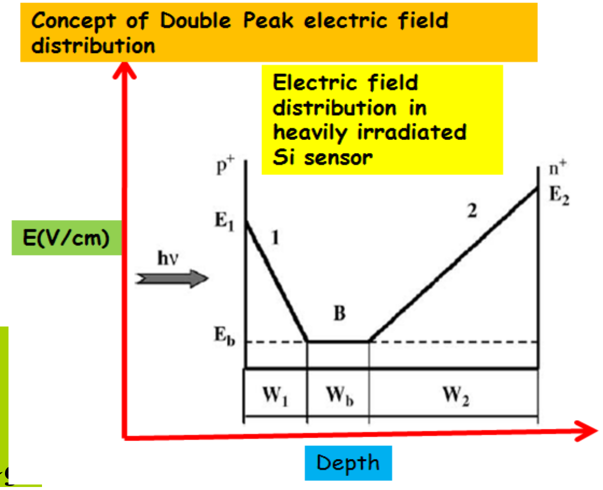
⇨ Charge exchange model included in the program
⇨ No enhancement in leakage current
⇨ we can say no charge exchange observed in $E_5^{(-/0)}$ ←----→ H152K$^{(0/-)}$

Effect of generation life time on EF profile for 1 $\times 10^{14}$ $n_{eq.}/cm^2$

No injection from p^+ PAD



In base region,
EF –> 100
– 1000 V/cm depend on τ_g



⇨Double junction observed for fluence of 1 $\times 10^{14}$ $n_{eq.}/cm^2$

⇨ Generation life time (deep traps) affects the EF on rear side of junction and in the base region of Si sensor

⇨ Generation life time (deep traps) also affects the $\Delta N_{eff}/V_{FD}$

Summary

Universität Hamburg

⇨Good agreement observed in experimental data and simulation results for n-type MCz PAD Si sensor

- Leakage current
- Full depletion voltage
- Double junction observed at fluence of $1x10^{14}$ $n_{eq}./cm^2$
- E_5 cluster relevant to increase of leakage current
- Generation life time (deep traps) changes the EF on rear side of junction and in base region
- Generation life time (deep traps) also affects the $\Delta N_{eff}/V_{FD}$

⇨Detailed study ongoing for understanding of microscopic defects on macroscopic parameters

Next step

⇨Detailed CV,f simulation for four trap model for n –type MCz PAD Si sensor

⇨ Donor removal mechanism/Hamburg model will be implemented in synopsis T-CAD

- as –irradiated
- Time-kinetics (annealing)

⇨ Detailed EF analysis in heavily irradiated Si detector (through a TCT @5MeV)

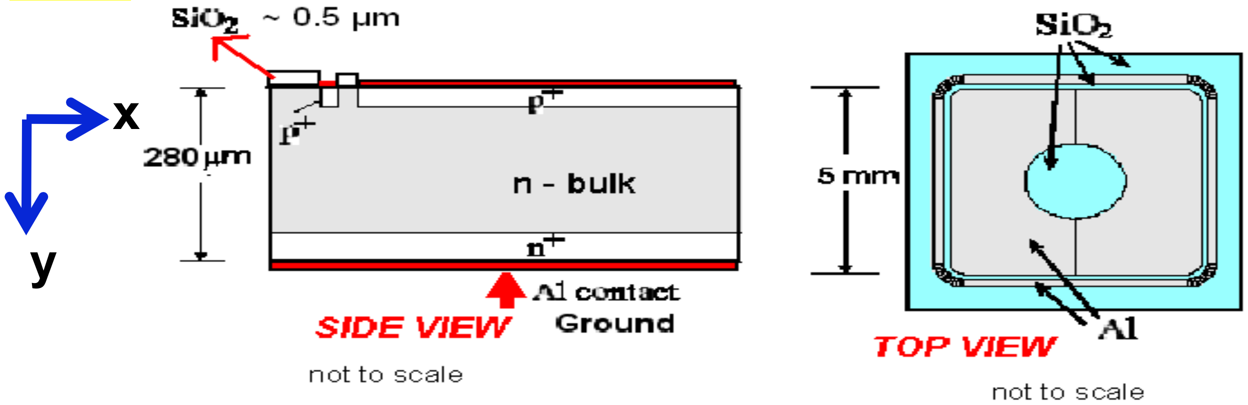
Spare Slides

Device structure and Physical model

Table.1 List of geometrical parameters used in the present simulation work

S.No.	Geometrical paramaters	Values
1.	P^+ width(W)	200µm
2.	Pitch of structure (P)	320µm
3.	W/P	0 .625
3.	Full volume of Si sensor (2-D), Default length=1µm Diode area=200µm²	X=320µm Y=280µm
4.	Active are of p^+	0.25 cm²

2-D



Cross-section of PAD Si sensor structures used in the present simulation work (normalized p^+ active area)

Table.2 List of Physical parameters

S.No.	Physical paramaters	Values
1.	Oxide thickness (tox)	0.5 µm
2.	Junction depth (Xj)	1µm
3.	GS	10 µm
4.	GW	100 µm
3.	Metal-overhang width ( )	0 µm
5.	Thickness of (W_{n+})	1 µm
7.	Bias voltage (Vbias)	100-500 V (I/V), 100 -500V(C/V) depend on V_{FD}
8.	AC voltage (VAC)	50 mV
9.	Fixed oxide charge(Q_f)	1 x 10^{12} cm-2
10.	Frequency (f) @RT=300K	10kHz/for CV,f analysis- up to 1MHz

02-05 june 2009 Ajay K. Srivastava, Uni-Hamburg 16

Physical model used

- **SRH (Shockley-Read-Hall) recombination statistics**

  ⇨ **Recombination through deep level traps**

- **Auger recombination with generation**
- **Impact ionization**
- **Surface recombination**
- **Trap model**
- **Doping dependent mobility and high field saturation model,**
- **band to band tunneling**
- **Trap Assisted Tunnelling**
- **CW model for carrier carrier scattering**
- **Trap to trap interaction model for charge exchange**
- **Interface physics model at Si/SIO2 interface**

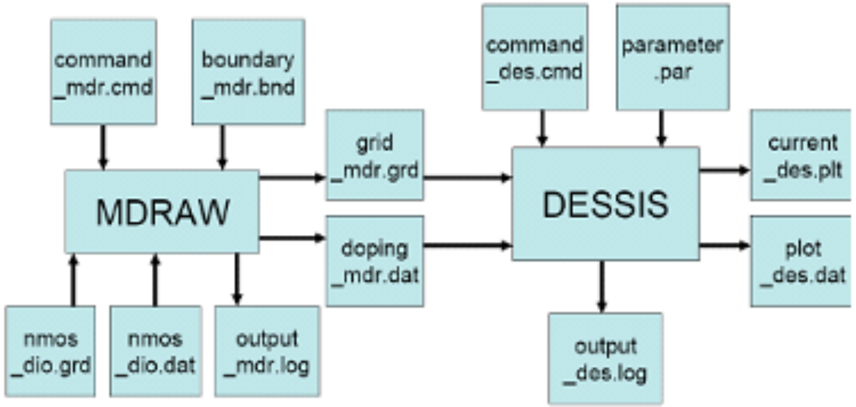
Suitable boundary conditions: In ISE T-CAD DESSIS, Dirichlet boundary conditions are applied at ohmic contact, whereas Neumann (reflecting) boundary conditions are applied at non- contacted edges of Si sensor

02-05 june 2009 Ajay K. Srivastava, Uni-Hamburg 17

Simulation procedure

Procedure

1. Design structure in MDRAW
2. Feed results into DESSIS
3. Combine simulation of device (DESSIS) and circuit (SPICE)



Mixed-model simulations: Device using DESSIS and circuit (SPICE)

AC analysis: to obtain small signal admittance (Y) matrix-current response at a Node to a small signal voltage (v) at another of the form

$$\rightarrow i = Y \times v = A \times v + j\omega C \times v$$

Where i- small signal curent vector (at all nodes), v- voltage vector DESSIS output is conductance (A) matrix and capacitance (C) matrix.

Parallel mode capacitance and conductance $\rightarrow C_p, G_p$

→ **Compare results to analytical calculations for cross-check**

Numerical modelling of radiation damage of Si sensor based on emission-capture dynamics of deep trap

- The leakage current at full depletion (V_{FD}) and effective doping concentration can be calculated by following expressions;

$$N_T = \Phi_{eq}\eta$$

$$\Sigma\frac{1}{\tau_{n,p}} = \beta_{n,p}\Phi_{eq}$$

$$\tau_g = \frac{2Cosh(E_t - E_i)/KT}{v_{th}\sigma_p N_T}$$

$$\beta_{n,p} = v_{th,n,p}\,\sigma_{n,p}\,\eta$$

$$c_{n,p}(T) = \sigma_{n,p}(T)v_{th\,n,p}(T)$$

$$\beta_{n,p} = \beta_{n,p}(T_0)\left(\frac{T}{T_0}\right)^{\kappa_{n,p}}$$

$$n_T(T) = N_T\frac{e_{n,p}}{e_n + e_p}$$

- $\kappa_n = 2.86 \pm 0.06$
  $\kappa_p = -1.52 \pm 0.07$

$$e_{n,p}(T) = c_{n,p}(T)N_{C,V}T)\exp\left(\pm\frac{E_a(T) - E_{C,V}}{k_b T}\right)$$

- $I(T) = I(T_0).\left(\frac{T}{T_0}\right)^2 \exp\left(-\frac{E_g}{2k_B}\left[\frac{1}{T} - \frac{1}{T_0}\right]\right)$ i.e. I(300K) =1.76 x I(293K)

(i) $\Delta N_{eff} = N_D + \sum(n_T(Donors) - \sum(n_T(acceptors))$

(ii) $I(V_{fd})(T) = qAW(e_p\Sigma n_T(donors) + e_n\Sigma n_T(acceptors))$

02-05 june 2009 Ajay K. Srivastava, Uni-Hamburg 19

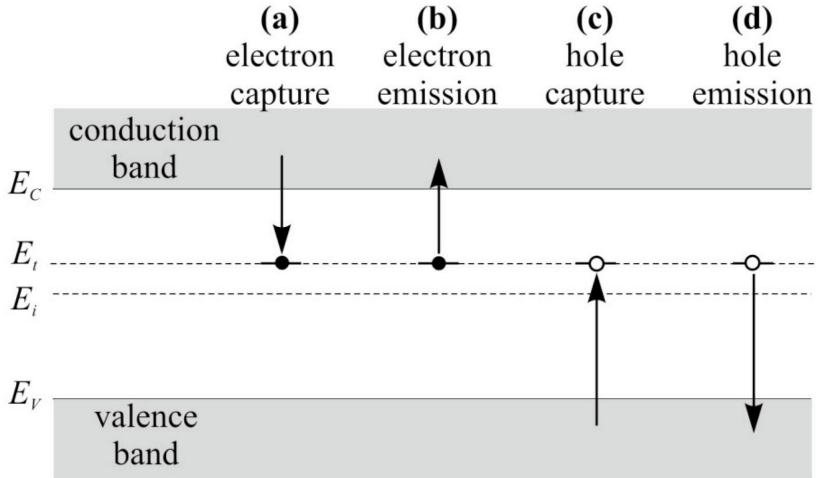
Shockley-Read-Hall statistics

- Occupation of a defect states wth concentration N_t, energy level E_t and average occupation probability P_t

  density of occupied defects $n_t = N_t P_t$

  density of non occupied defects $p_t = N_t - n_t$

- Change of a defect occupancy possible by
  - *electron capture* with rate $R_n = c_n n p_t$
  - *electron emission* with rate $G_n = e_n n_t$
  - *hole capture* with rate $R_p = c_p p n_t$
  - *hole emission* with rate $G_p = e_p p_t$



- Defect parameters (besides E_t) that are determened by DLTS or TSC method:
  - capture coefficients $\rightarrow c_{n,p} = v_{n,p}\sigma_{n,p}$
  - emission probabilities $\rightarrow e_{n,p}$

- The rate of change of the defect ocupancy

$$\frac{dn_t}{dt} = \overbrace{(G_p - R_p)}^{\text{hole excess generation rate}} - \overbrace{(G_n - R_n)}^{\text{electron excess generation rat}}$$

Shockley-Read-Hall statistics

♦ Thermal equilibrium
- P_t = Fermi function
- steady state → $dn_t/dt = 0$
- **no current** → no net flow of electrones or holes between conduction and valence band → $R_p = G_p$, $R_n = G_n$

$$e_n = n_i c_n \exp\left(\frac{E_t - E_i}{k_B T}\right)$$
$$e_p = n_i c_p \exp\left(-\frac{E_t - E_i}{k_B T}\right)$$

Relations between $e_{n,p}$ and $c_{n,p}$ remain valid non-equilibrium conditions → defect is fully described by E_t and $\sigma_{n,p}$

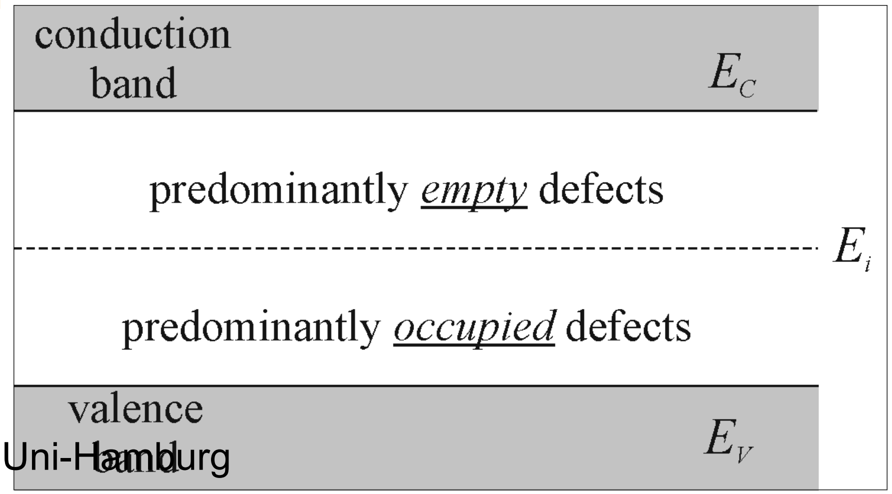
♦ Space charge region in steady state
- carrier concentration negligible: $p,n \sim 0$ → **capture processes can be neglected**
- steady state → $dn_t/dt = 0$

extraction of $P_t \rightarrow E_i$ acts like E_F in thermal equilibrium

electron traps

generation centers (leakage current)

hole traps



Traps in Synopsis T-CAD

- For each trap level, dessis simulates:
- Proportion of trap states occupied by electrons and holes
  - NB – “not filled by electron”=“occupied by hole”
  - This affects charge distribution, and so has to be included in Poisson equations
- Rate of trapping / emission between conduction band and trap, and between valence band and trap
  - These then have to be included in the carrier continuity equations

Poisson

$$\varepsilon_S \nabla . \underline{E} = \rho = q(p - n + p_{DonorTrap} - n_{AcceptorTrap} + N_D - N_A)$$

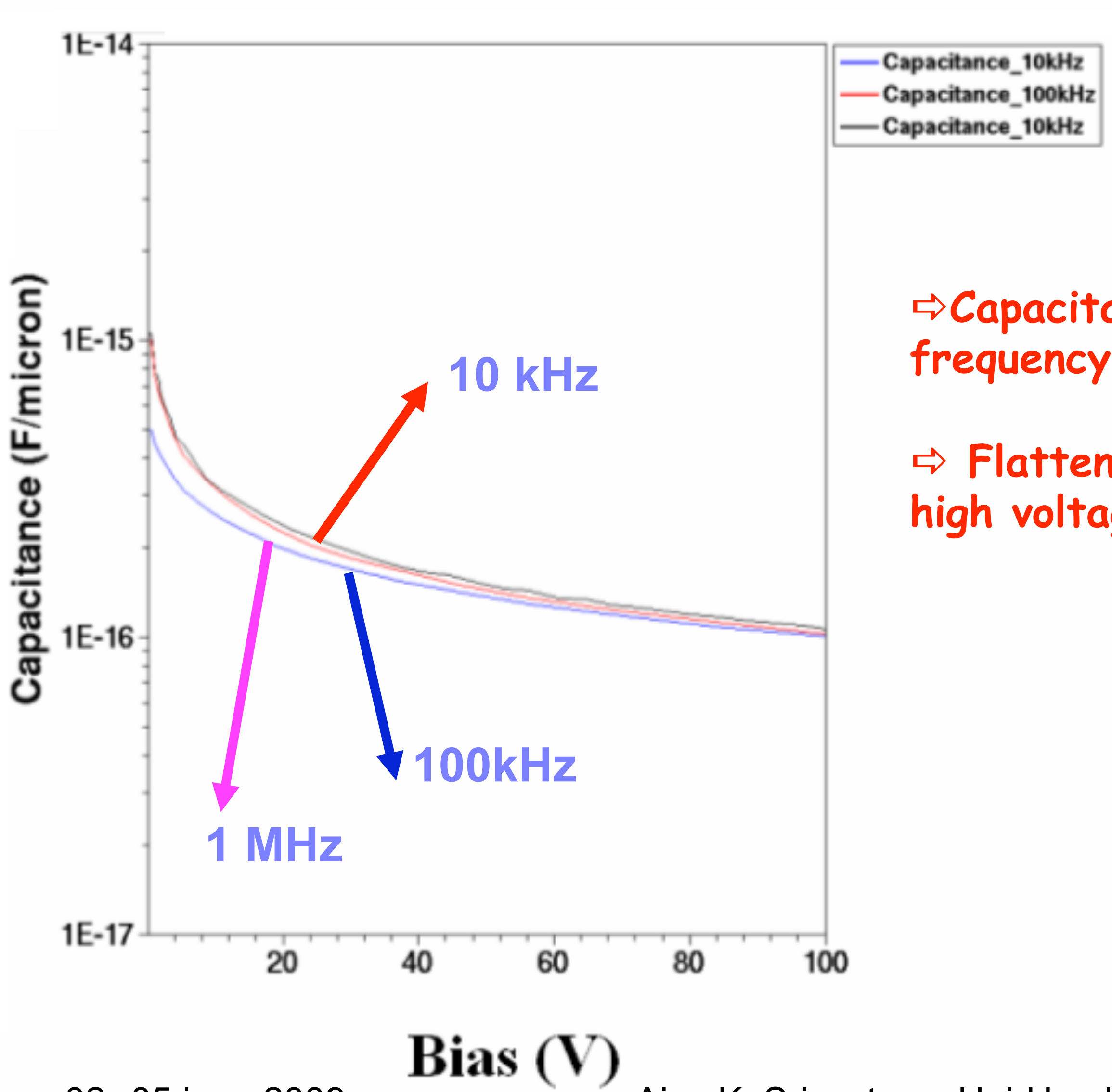
Electron continuity

$$-\frac{1}{q}\nabla . \underline{J}_n - G_{SRH} + R_{SRH} + r_{nTrap} + \frac{\partial n}{\partial t} = 0$$

Hole continuity

$$\frac{1}{q}\nabla . \underline{J}_p - G_{SRH} + R_{SRH} + r_{pTrap} + \frac{\partial p}{\partial t} = 0$$

Preliminary simulation result of n MCz PAD Si sensor (C/V,f) for fluence 1e14 $n_{eq.}$/cm2

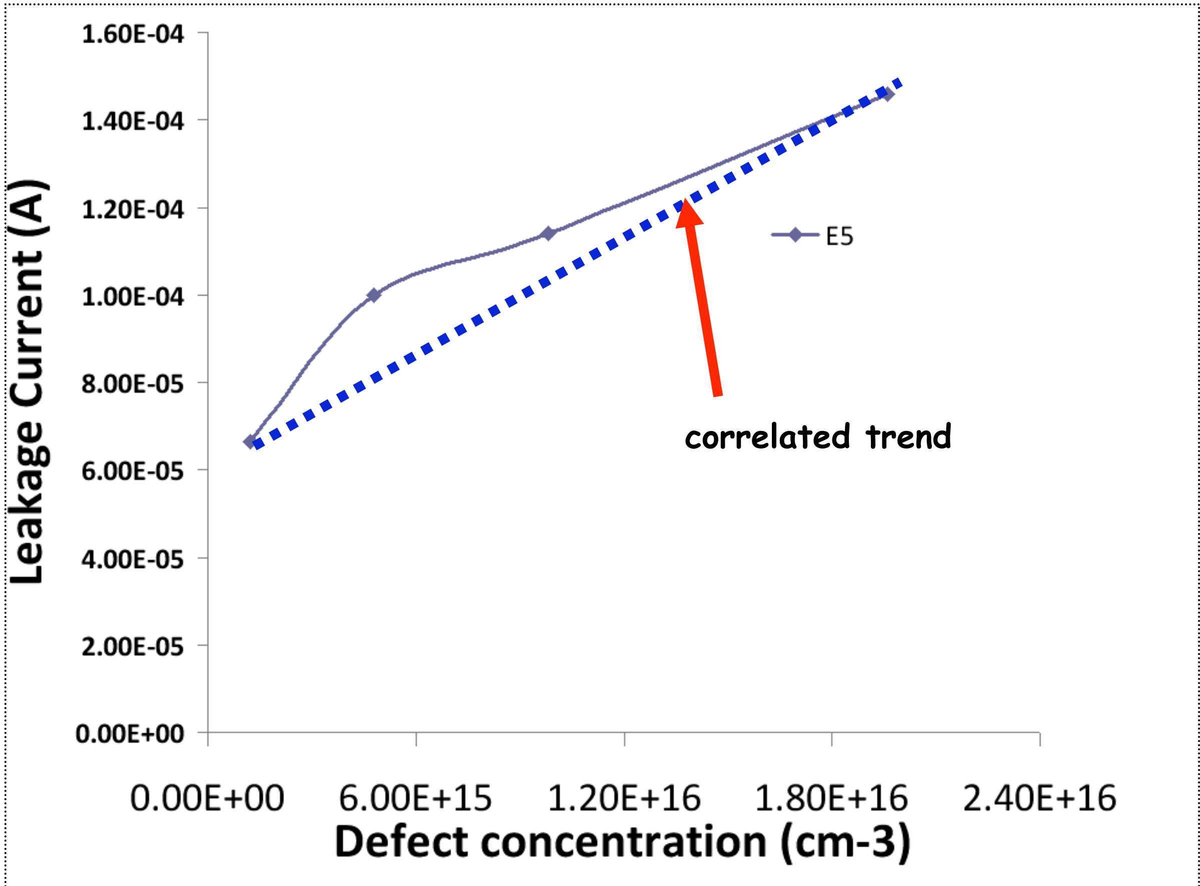


⇨Capacitance decreases with increases frequency

⇨ Flattening of C/V curve observed at high voltage

Defect cluster source for dark current

1e14 n_{eq} /cm2



➪ **Leakage current increases with E_5 defect concentration increases**

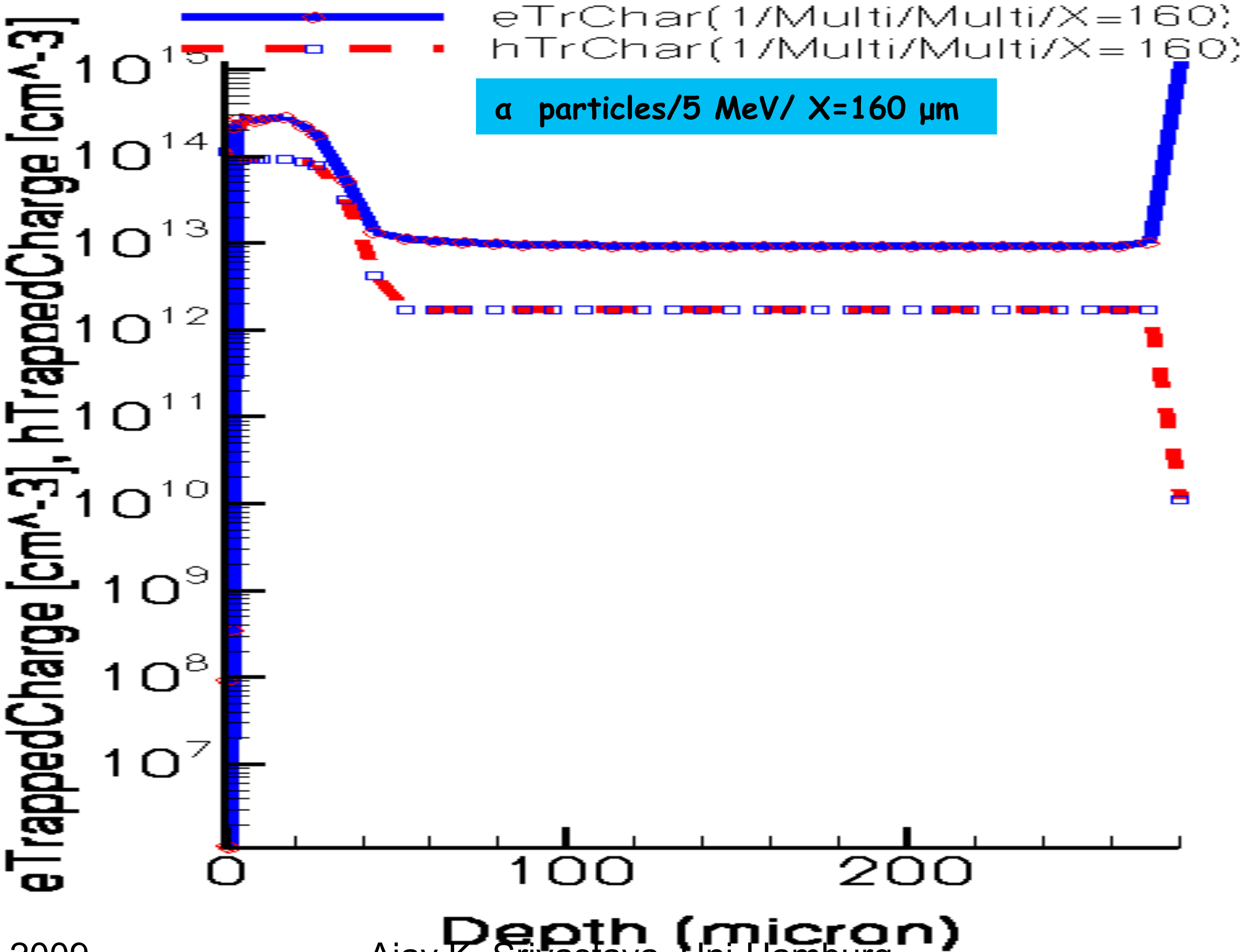
24

The total defect occupancy of four level defects

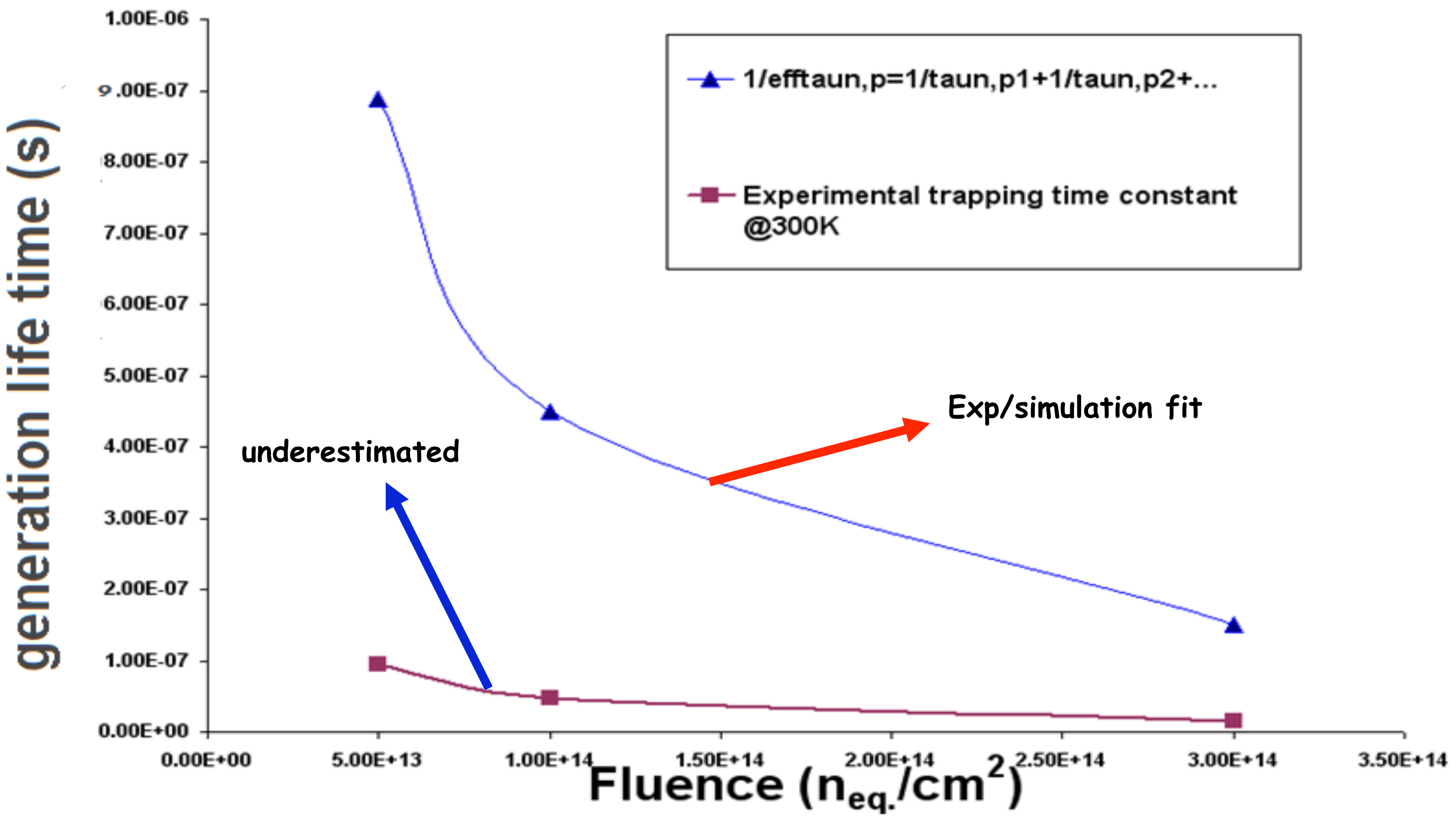
For 1 x10^{14} n_{eq} /cm^2

Cut X=160 **µm**

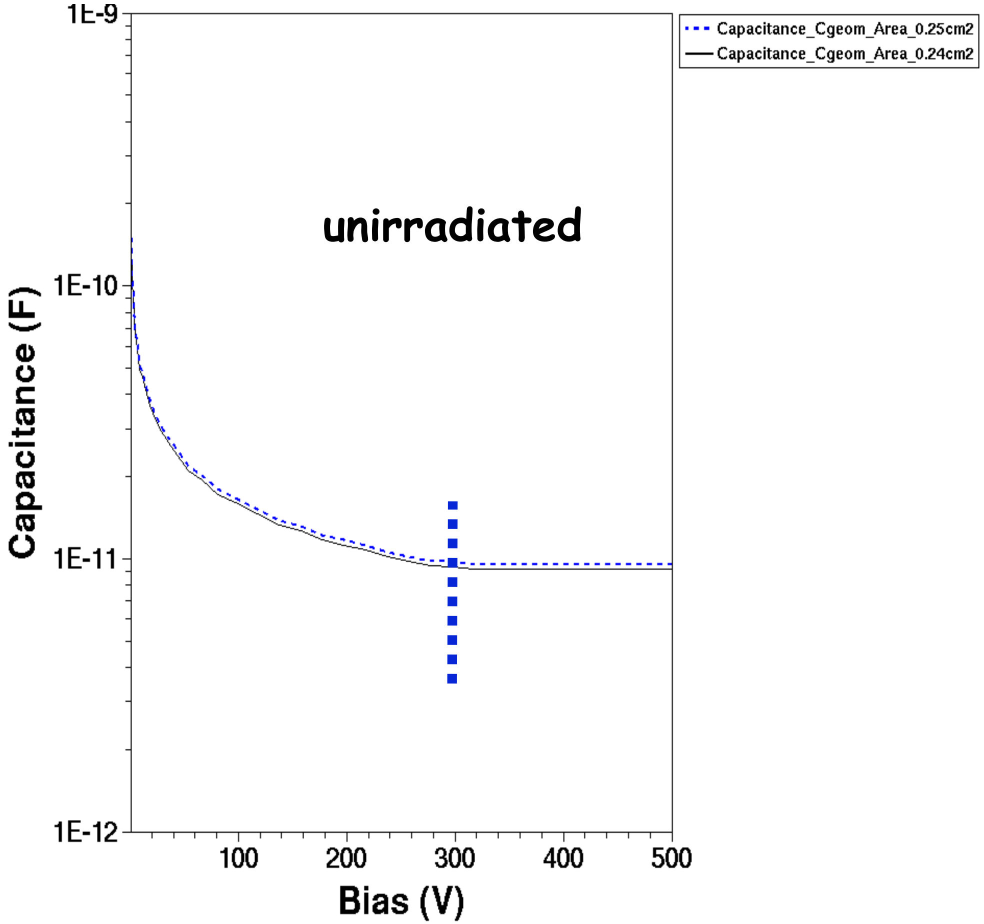
no charge exchange taken in E_5(-/0) ←----→H152K(0/-)



Generation lifetime versus fluence in four level deep trap n-type MCz Si sensor



⇨ **Generatetion life time decreases with fluences**



⇨ **Good agreement in theoretical calculations and simulation result for unirradiated sensor**

→ **C_{geom} = 9.2 pF (when no surface charges and no deep level trap)**