Simulation of electric field profile in Si irradiated detectors with a consideration of carrier generation parameters

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Outline

- Goals
- Model of *E(x)* profile in Si heavily irradiated detectors developed in PTI
- Alternative methods of simulation
- Comments on lifetime
- Results on *I*, τ_{gen}, N_{eff} and *E(x)* based on PTI approach
- Impact of bulk generation on *E(x)* profile

Conclusions

Goals

Goals:

- Analysis of the impact of carrier generation (bulk generation current) on the electric field profile in Si irradiated detectors
- Finding the correct approach for *E(x)* simulation

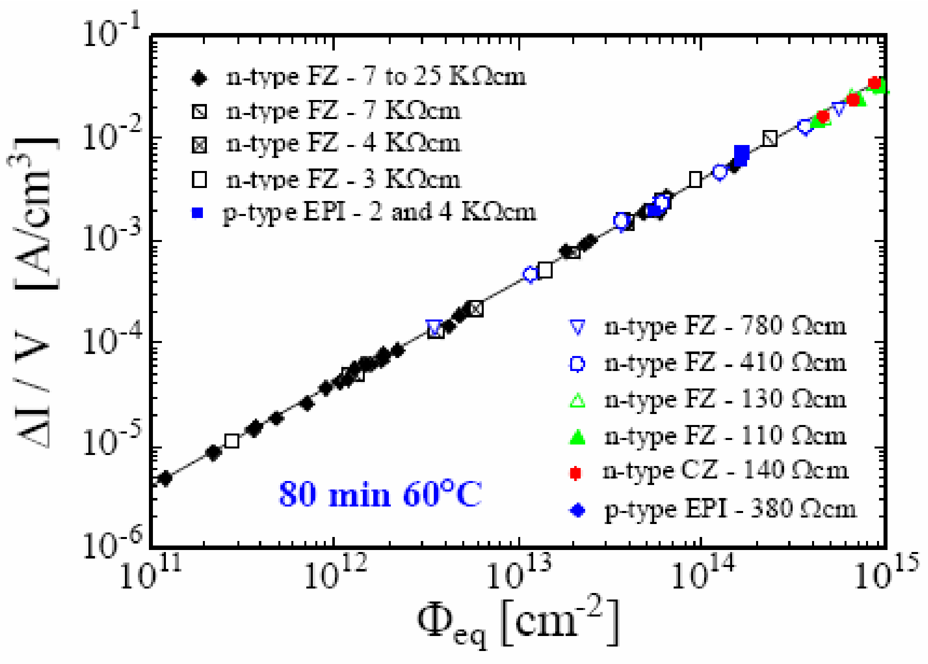
Importance:

Correct *E(x)* is required for adequate calculation of CCE

Earlier/Related results:

- Temperature dependences of reverse current: activation energy of generation current of 1 MeV neutron and 23 GeV proton irradiated detectors was estimated as 0.65 eV (E. Verbitskaya, et al., 20 RD50 workshop)
- Recent results on *I(T)* scaling: simulation and experiment; A. Chilingarov, RD50 notes and presentation at 18 RD50 workshop, May 2011, Liverpool
- Presentations in Bari on electric field simulation

Global result of RD50 collaboration



$\Delta I/Vol = \alpha F_{eq}$

α = 3.7x10^{-17} A/cm

Linear fit of *I(F)* is a strong argument to use linear dependence of the concentration of energy levels, which act as generation centers, on F_{eq}

G. Lindström, NIM A 512 (2003) 30

Approach for calculation of E(x) profile (PTI model)

We consider two independent processes which control $E(x)$ profile

1. Equilibrium carrier generation (bulk generation current, τ_{gen}):

$$I_{bgen} = en_i Vol/\tau_{gen}$$

Generation occurs in SCR via **effective generation level** (0.65 eV), introduction rate $M_j = 1\ \mathrm{cm}^{-1}$,

$\sigma_e = \sigma_h = 1\mathrm{x}10^{-13}\ \mathrm{cm}^2$, $\sigma(T) = \sigma_o(T/T_o)^{-2}$

(defined from our I(T) data)

$divJ_{gen} = G;\ G = n_i/\tau_g$

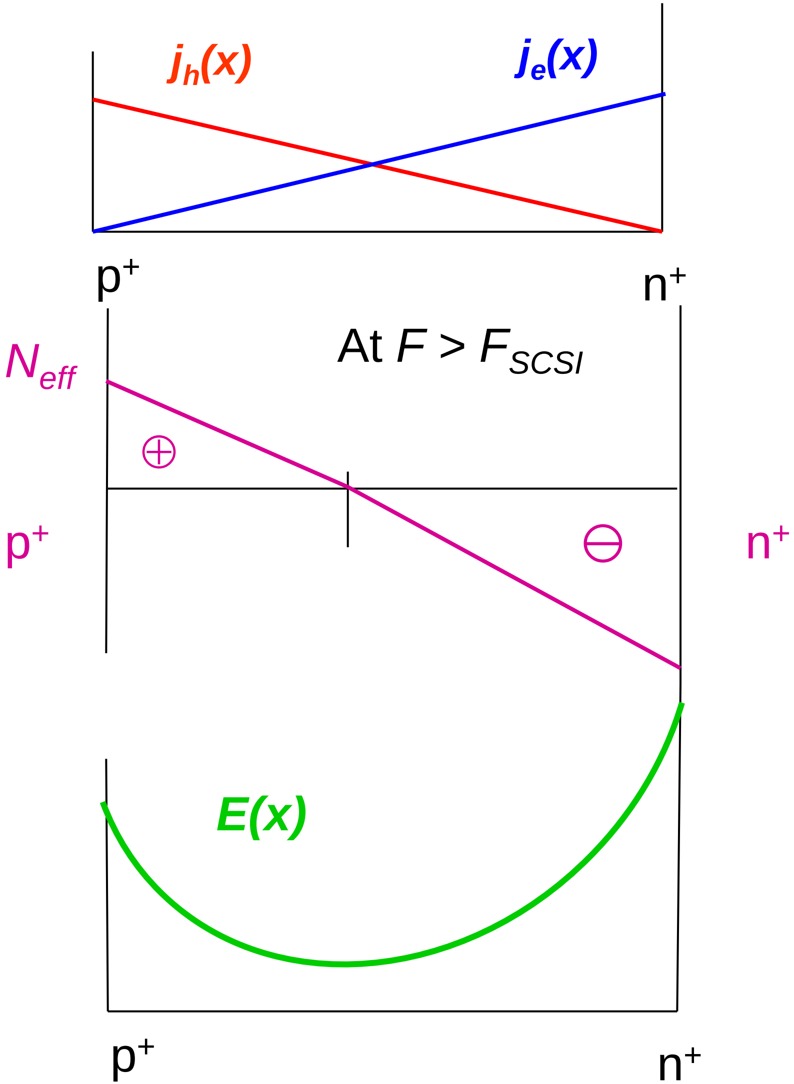
G – generation rate

$j_{gen} \sim G\mathrm{x}depth$

Electron and hole components

$j_e(x) = Gx;\ j_h(x) = G(d - x)$

This level does not contribute to N_{eff}



Approach for calculation of E(x) profile

2. Trapping to deep levels

DDs: E_v + 0.48 eV;
DAs: E_c – (0.525±0.005) eV
– midgap levels used in all PTI simulations and fits

Filling factors are calculated for DDs and DAs which **charged fractions contribute to N_{eff}**

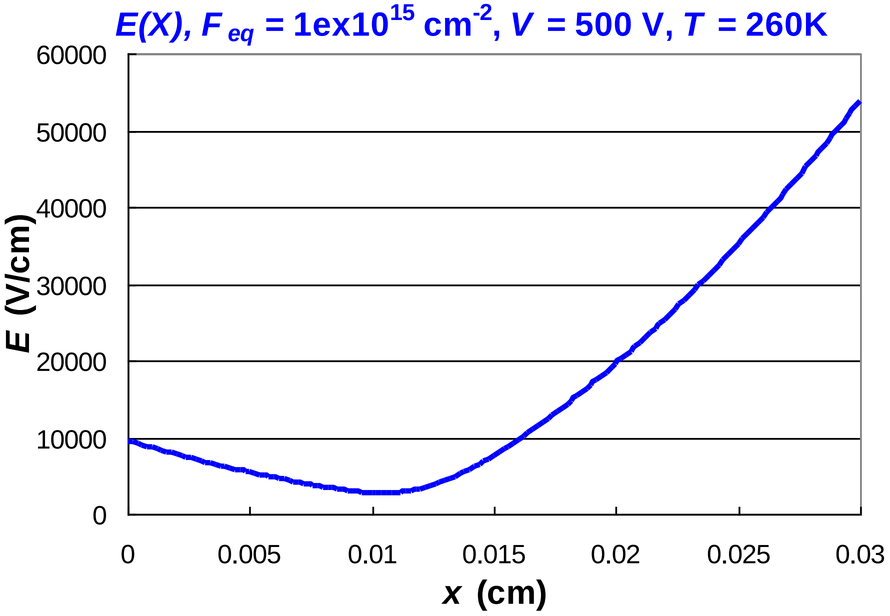
No contribution of DDs and DAs to generation current!

Then Poisson equation:

$$dE/dx = -eN_{eff}/\varepsilon\varepsilon_o \rightarrow \mathbf{E(x)}$$

Method: Numerical simulation (EXCEL)

p-on-n



Double Peak (DP) $E(x)$ profile

E. Verbitskaya, V. Eremin, 21 RD50 workshop, Nov 14-16, 2012, CERN

Alternative issues: comments

Recently: Simulation of detector characteristic using standard simulating software (ISE-TCAD, Atlas (Silvaco), etc.)

Pres. at 20 RD50 workshop, Bari: R. Eber, Karsruhe, KIT;
M. Miñano, IFIC, Valencia; also results from Deli University group

Main features

♦DDs and DAs are implemented (the same levels as in PTI model) which are considered as traps and generation levels

♦ **Disagreement in current when calculating with standard simulator, no DP E(x)**

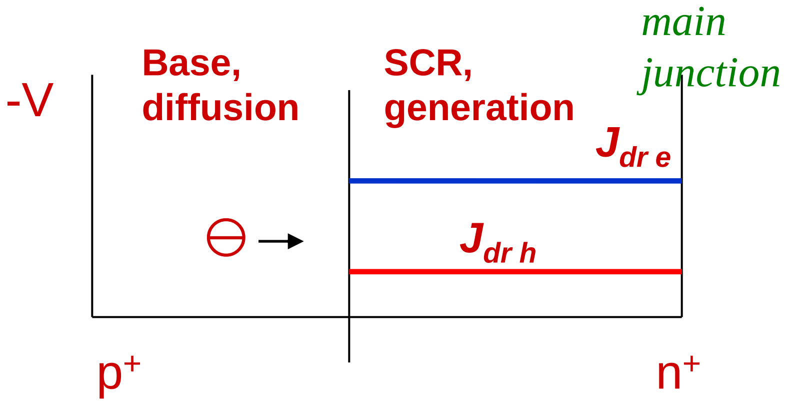
♦To agree with expected current calculated from α and *F*, tuning of initial parameters is done

(suggested: cross-sections, reduced lifetime, introduction rate)

Question: lifetime – is it recombination lifetime as in Simulator Standard physics model for a sensor with no radiation damage? Value?

Alternative issues: comments

If recombination is considered: →



At *F* beyond SCSI → p-Si in base region, electrons are minor carriers which diffuse towards SCR

I_{dif} depends on $L_{dif} = (D\tau_{\rho ec})^{0.5}$ to $(d\text{-}W)$ ratio

In SCR $DivJ_{dr\ e,h} = 0$

$J_{e\_dr} = env_{e\_dr} = J_{e\_dif} = \text{const}$

If so, no DP *E(x)* arises!

Also, generation and diffusion have different dependences on *V* and *T*

$I_{gen}(V) \sim V^{0.5}$ $(w \sim V^{0.5})$

$I_{dif}(V) = I_s$ at $V > 2kT/e$

$I_{gen}(T) \sim \exp(-E_g/2kT)$ - plot I-V in log-log scale

$I_{dif}(T) \sim \exp(-E_g/kT)$

This may be the most probable reason for necessity to make tuning/tailoring/ /adjustment of initial parameters for simulation (e.g., σ, *K)* in standard software

(see presentations on Simulation mentioned above and at 21 RD50 workshop)

Relationship between different lifetimes

Generation-recombination currents are described by Sah-Noyce-Shockley model
When *pn*<n_i^2, *generation rate U:*

$$U = -\frac{\sigma_p \sigma_n v_{th} N_t n_i}{\sigma_p[1+(p/n_i)] + \sigma_n[1+(n/n_i)]} \equiv -\frac{n_i}{\tau_g} \quad (98)$$

where the generation carrier lifetime τ_g is equal to

$$\begin{aligned} \tau_g &= \frac{1+(n/n_i)}{\sigma_p v_{th} N_t} + \frac{1+(p/n_i)}{\sigma_n v_{th} N_t} \\ &= \left(1+\frac{n}{n_i}\right)\tau_p + \left(1+\frac{p}{n_i}\right)\tau_n . \end{aligned} \quad (99)$$

S. M. Sze. Physics of Semiconductor Devices

Depending on the electron and hole concentrations, the generation lifetime can be much longer than the recombination lifetime and has a minimum value of roughly twice that of the recombination lifetime, when both n and p are much smaller than n_i.

Generation: If $n=p=n_i$ $\tau_{gen\_min} \approx 2\tau_{rec}$

Trapping – controls CCE; all levels contribute to τ since pulse signal is measured within θ = 25 ns that is far less than detrapping time constant for larger energy gap (at RT)

Uncertainty in lifetime may be the most probable reason for necessity to make tuning/tailoring/adjustment of initial parameters for simulation in standard software

(see presentations on Simulation mentioned above and at 21 RD50 workshop)

Generation lifetime vs. F

$I_{bgen} = en_i Vol/\tau_{gen}$; $I_{bgen} = \alpha F Vol$

$\tau_{gen} = (en_i/\alpha)F^{-1}$

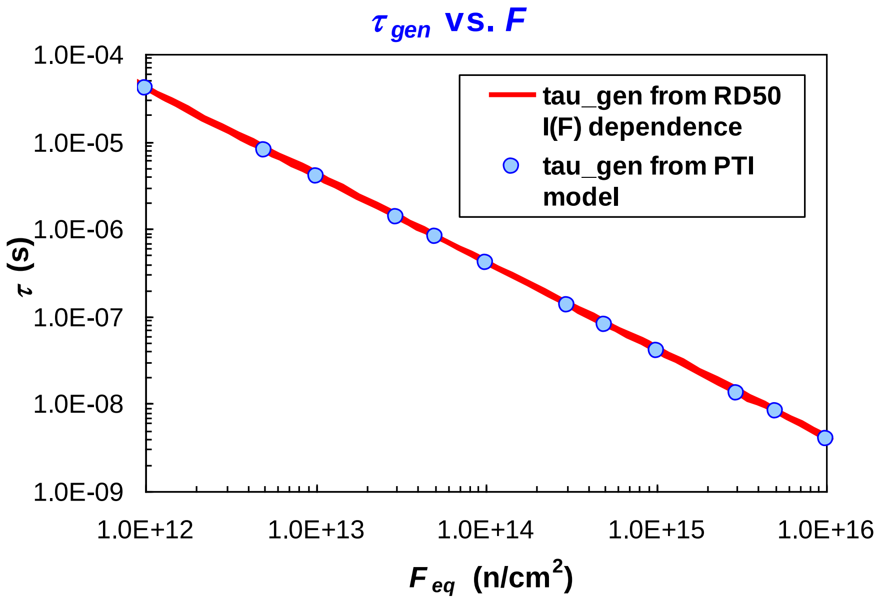
$\boldsymbol{\tau_{gen} = 4.32\mathrm{x}10^{7}/F_{eq}}$

<u>For trapping</u>: $1/\tau_{tr} = \beta F_{eq}$

$\beta_e = 3.2\mathrm{x}10^{-16}\ \mathrm{cm^2ns^{-1}}$; $\beta_e = 3.5\mathrm{x}10^{-16}\ \mathrm{cm^2ns^{-1}}$

$\tau_{tr\_e} = 3.1\mathrm{x}10^{6}/F_{eq}$
$\tau_{tr\_h} = 2.9\mathrm{x}10^{6}/F_{eq}$

I. Mandić, et al.,
NIM A 612 2010) 474



$\boldsymbol{\tau_{gen} \approx 15\tau_{tr}}$

For $F_{eq} = 1\mathrm{x}10^{14}\ \mathrm{cm^{-2}}$

$\boldsymbol{\tau_{gen} = 4.3\mathrm{x}10^{-7}\ \mathrm{s}}$

whereas lifetime used in Silvaco

$\tau \approx 1\mathrm{x}10^{-7}$ s – recombination lifetime?

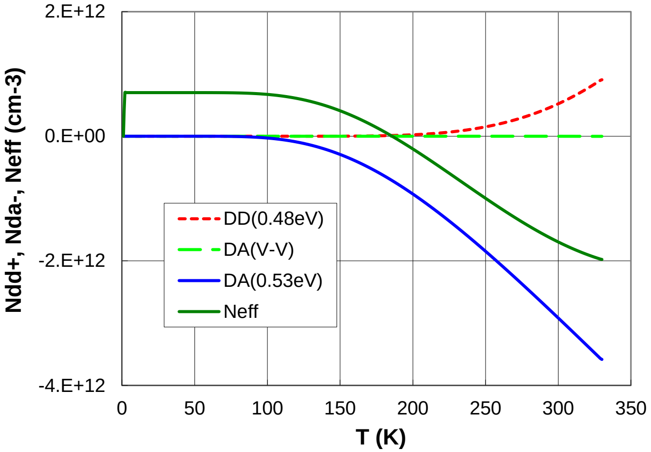
How to insert *τ(F) in standard software?*

Another trend in alternative issues: implementation of multiple traps

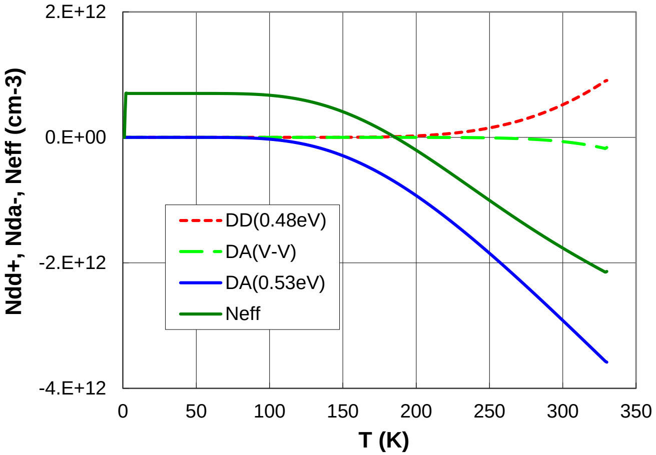
F_{eq} ~ 10^{14} cm^{-2} DLs: DD, DA, VV^-

In plots: concentration of charged DLs and total N_{eff}

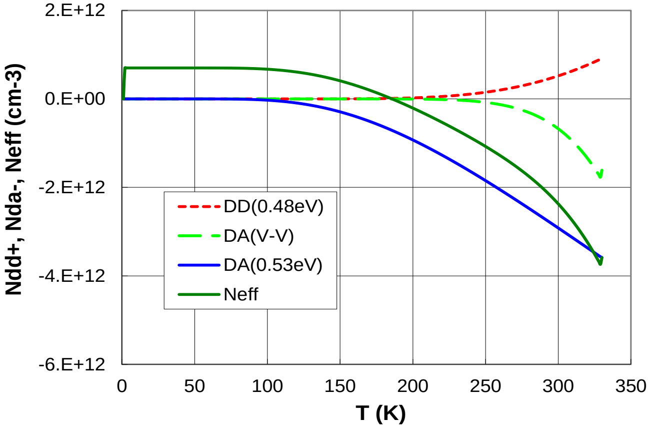
N_{VV} = $1x10^{14}$ cm^{-3}



N_{VV} = $1x10^{16}$ cm^{-3}



N_{VV} = $1x10^{17}$ cm^{-3}



DLs with E_a ~ 0.4 eV affect:

♦ space charge region depth (at very high *F*);

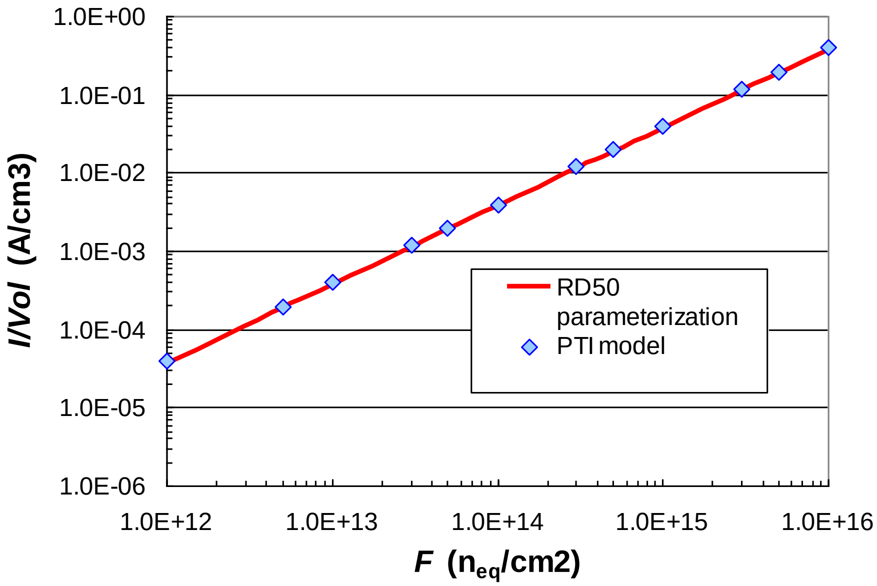
♦ trapping time constant

Deep levels with E_a ~ 0.4 eV (VV, C_i-O_i) hardly affect current

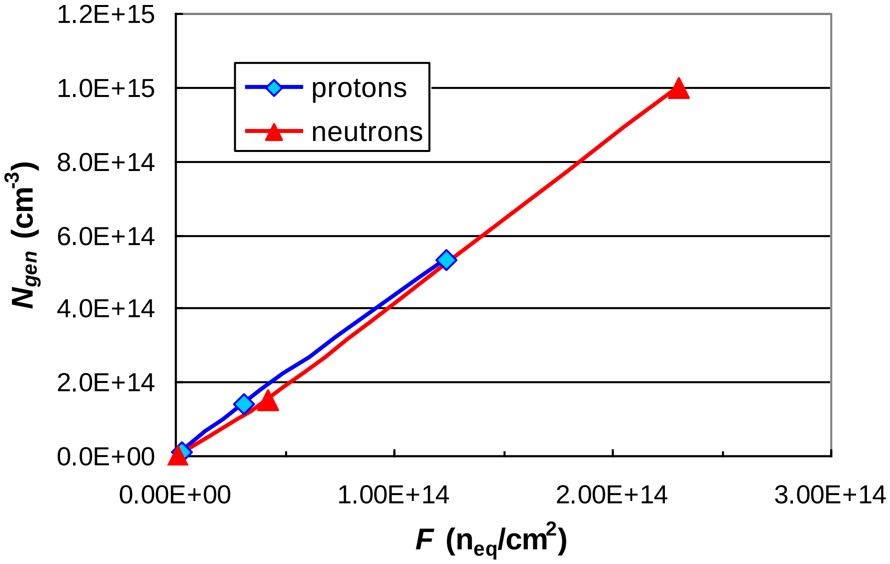
E. Verbitskaya, V. Eremin, 21 RD50 workshop, Nov 14-16, 2012, CERN

Reverse current simulation using PTI model

Carrier generation via single effective level 0.65 eV



N_{gen} vs. fluence dependence



RD50 parameterization: $\alpha = 3.7\text{x}10^{-17}$ A/cm
PTI model gives $\alpha = 4\text{x}10^{-17}$ A/cm

No adjustment of parameters
Is required

Linear dependence of N_{gen} vs. F agrees with data on $I(F)$

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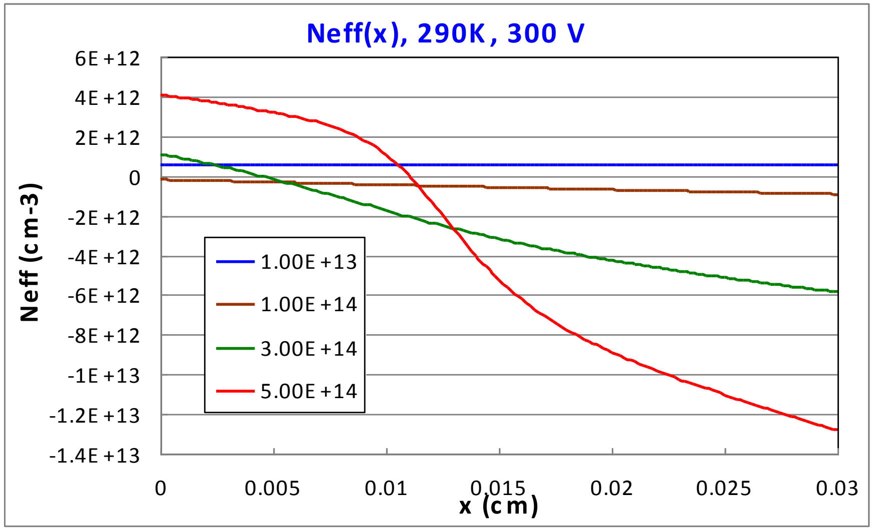
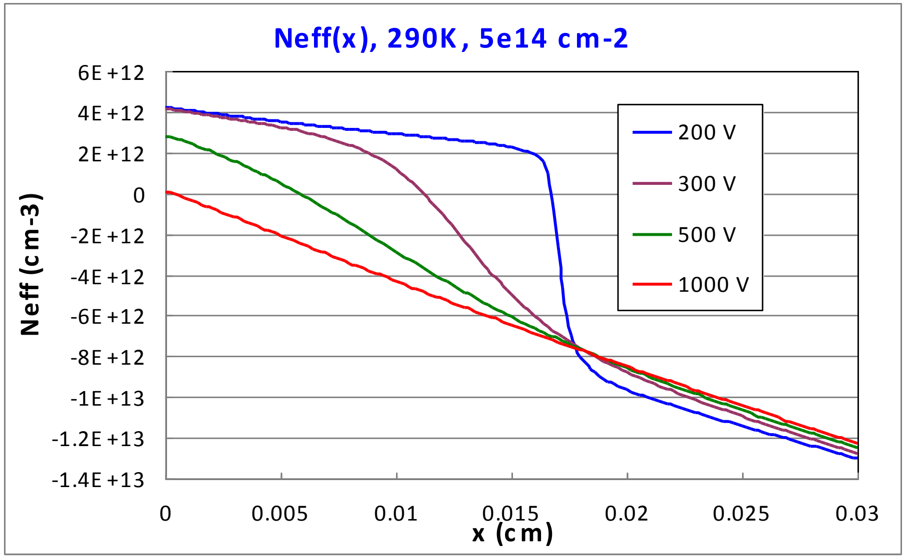
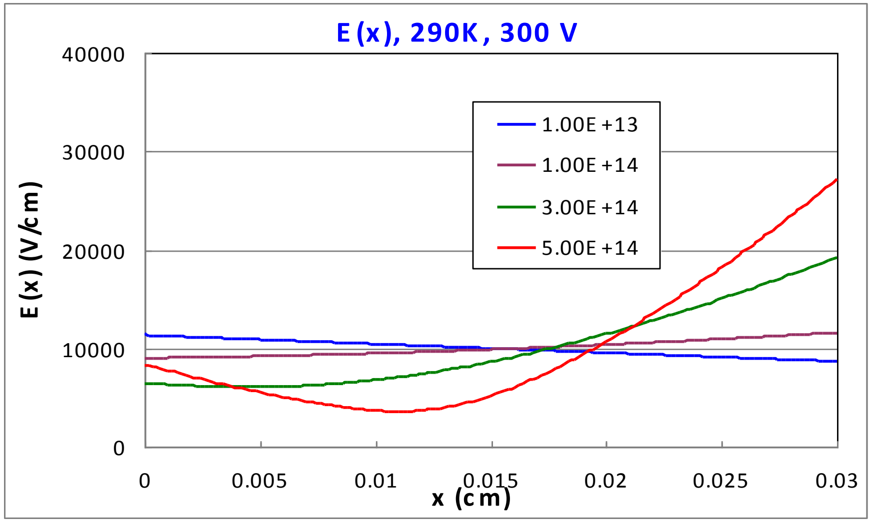
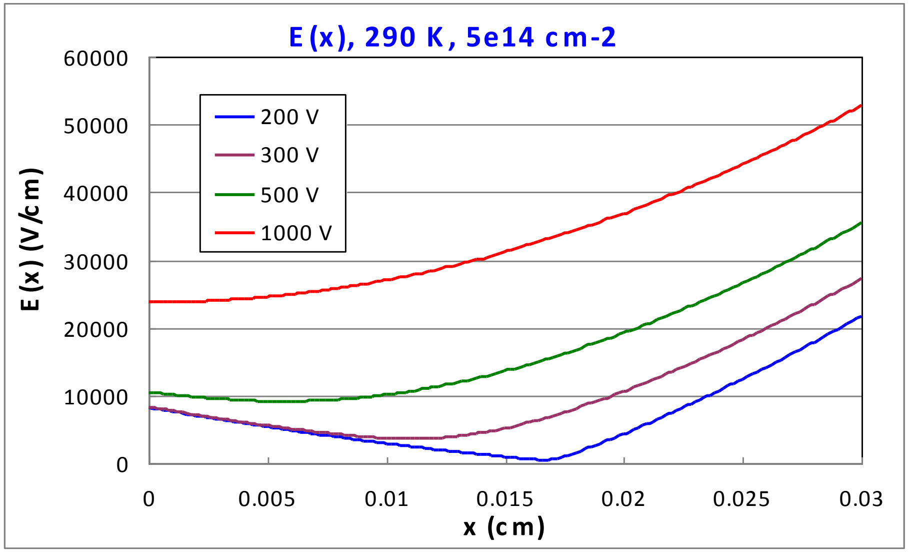
Results on simulated N_{eff}(x) and E(x)


Neff(x), 290K, 300 V


Neff(x), 290K, 5e14 cm-2


E(x), 290K, 300 V


E(x), 290 K, 5e14 cm-2

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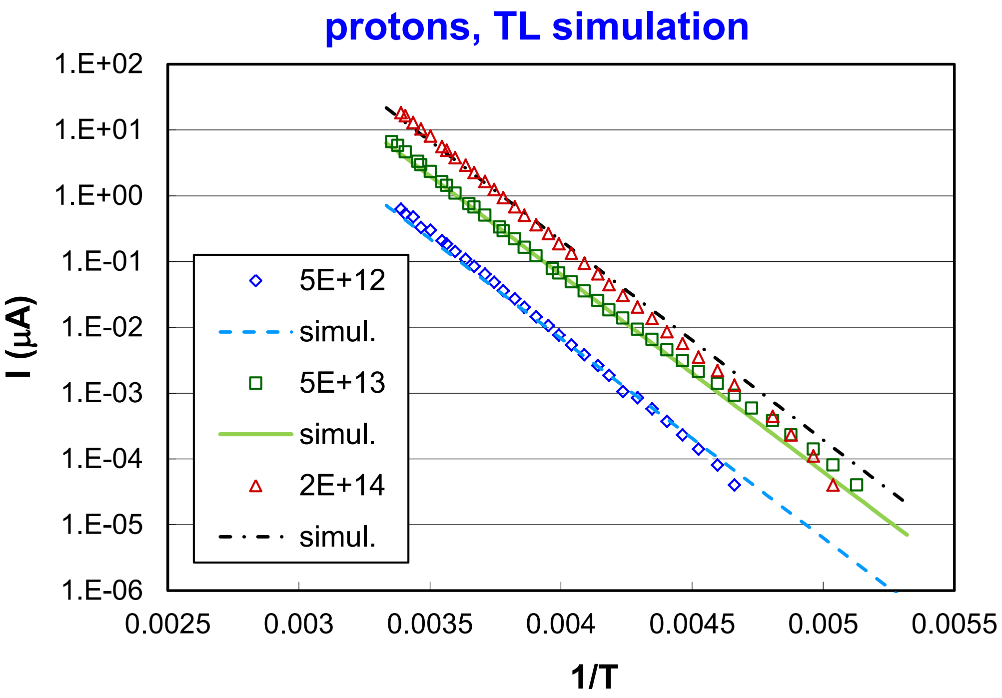
Simulation of I_{gen} using two levels

E. Verbitskaya, et al., presented at 20 RD50 workshop, Bari, May 30 – June 1, 2012

Bulk generation current may be simulated using two levels (TL):
– two independent processes
DDs: E_v + 0.48 eV; DAs: E_c – (0.525±0.005) eV

$N_{DA}/N_{DD} = 1.2$; $k_{DD} = 1$



♦ k_{DD} and k_{DA} are different for neutrons and 23 GeV protons;
♦ cross-sections should be tuned

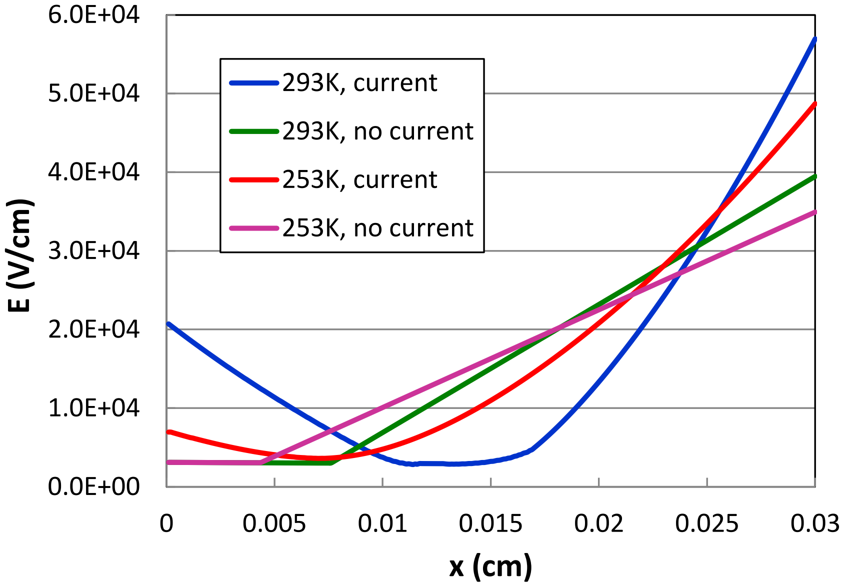
→ Using a single generation level for I_{gen} calculation is more simple and unambiguous

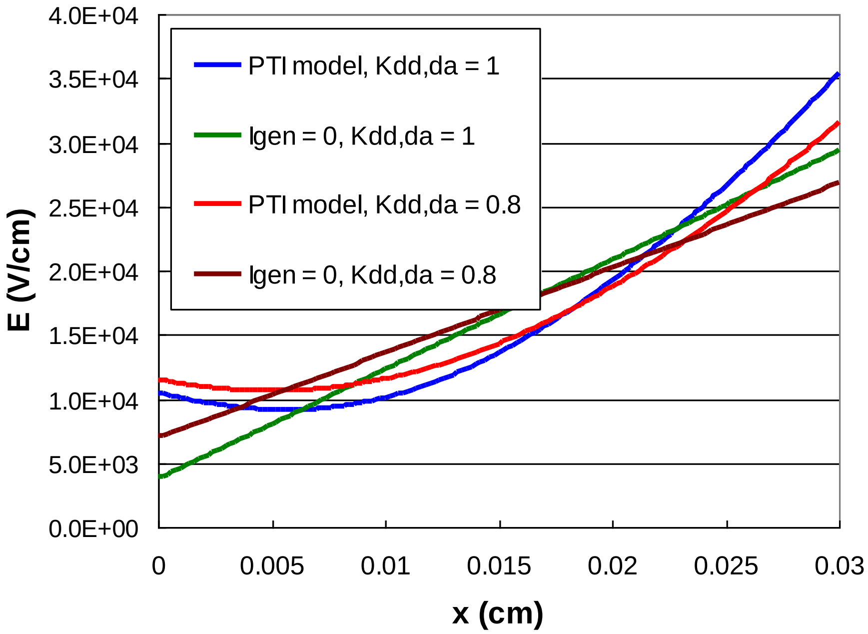
Impact of I_{bgen} on E(x) profile

Key parameters for adequate *E(x)* description: bulk generation current and deep traps

Impact of I_{gen} – double peak *E(x)*

Simulation without current – no DP *E(x)*





I_{gen} is important parameter
since it gives correct *E(x)* reference to other characteristics (*CCE, t_{dr}*)

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Conclusions

- PTI model considers *E(x)* profile formation in irradiated Si detectors caused by two independent processes: carrier generation via effective level with E_a = 0.65 eV and carrier trapping to midgap DDs and DAs.

- This model gives nice agreement of the current with *I(F)* dependence

  Therefore,

Consideration on contribution of bulk generation current gives adequate description of irradiated detector characteristics

- The nature of lifetime used in standard simulation software should be clarified

Acknowledgments

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Thank you for attention!