

Temperature dependence of reverse current of irradiated Si detectors

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Outline

Motivation

- ◆ Model of bulk generation current based on Shockley-Read-Hall statistics
- ◆ Parameters of investigated detectors and experimental procedure
- ◆ Simulation of generation current of detectors irradiated by 23 GeV protons and neutrons:
 - single level model
 - two level model (PTI model with midgap levels)
 - alternative versions
- ◆ Lifetime vs. fluence dependence
- ◆ Impact of bulk generation on $E(x)$ profile

Conclusions

Motivation

Goal:

Analysis of bulk generation current of irradiated detectors, impact on characteristics of irradiated detectors

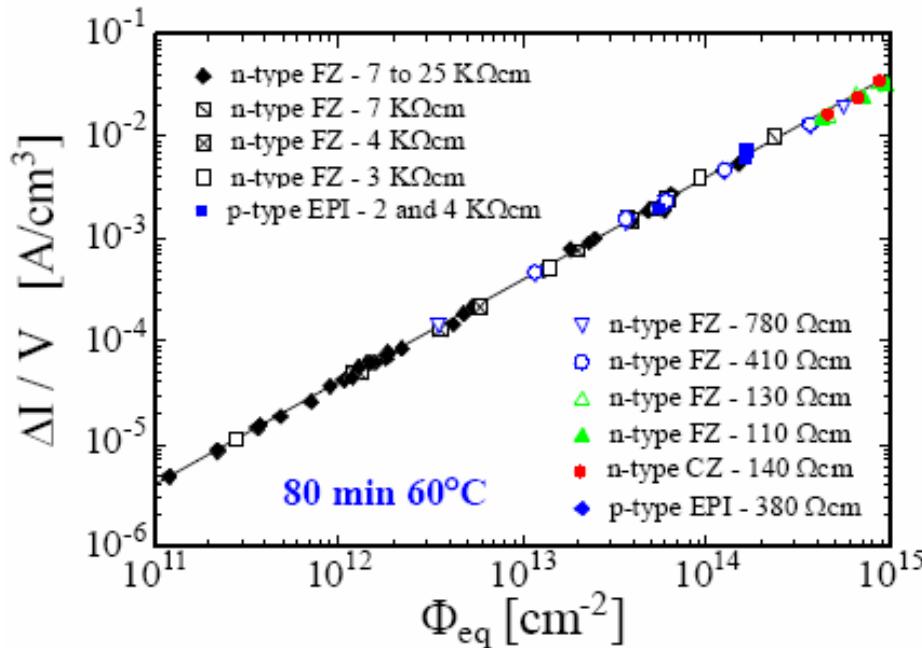
Importance:

bias voltage applied to p⁺-n or n⁺-p junction,
power dissipation

Earlier results:

- ✓ Low neutron fluence ($10^{10} \div 10^{12} \text{ cm}^{-2}$): E-center gives the main contribution to the reverse current [E. Borchi and M. Bruzzi, NIM A 310 (1991) 273]. Agreement between calculated and measured damage coefficient was obtained.
- ✓ Activation energy of generation current of neutron irradiated detectors was estimated as 0.6 – 0.65 eV (our earlier data)
- ✓ Recent results on $I(T)$ scaling; simulation and experiment; A. Chilingarov, RD50 notes and presentation at 18 RD50 workshop, May 2011, Liverpool

Earlier results of RD50 collaboration



G. Lindström, NIM A 512 (2003) 30

Linear fit of I/F is a strong argument to use linear dependence of the concentration of radiation induced defects which act as generation centers on F

$$\alpha = 3.7 \times 10^{-17} \text{ A/cm}$$

Modeling of bulk generation current

Modeling is based on Shockley-Read-Hall statistics

Emission rates $e_{e,h}$:

$$e_e = \sigma_e v_{eth} N_c \exp\left(\frac{E_t - E_c}{kT}\right); \quad e_h = \sigma_h v_{hth} N_v \exp\left(\frac{E_v - E_t}{kT}\right)$$

Generation rate:

$$G = \frac{\sigma_e \sigma_h v_{th} n_i N_t}{\sigma_e \exp\left(\frac{E_t - E_i}{kT}\right) + \sigma_h \exp\left(\frac{E_i - E_t}{kT}\right)}$$

$E_t = E_t - E_v$; σ - carrier capture cross section, N_t – deep level concentration

G is determined by a larger energy gap

Assumption for $\sigma(T)$:

$$\sigma(T) = \sigma_0 (T/T_0)^{-m} \quad m = 0 \div 2$$

(V. Abakumov, et. al., Sov. Phys. Semicond. 12 (1978) 1)

Experimental

Irradiated detectors

#	radiation	F, cm-2	ρ , kOhm.cm	processing	d, μm
923-D26	p	5.00E+12	1,2-3	stand. oxyd.	188
923-D35	p	5.00E+13		stand. oxyd.	188
923-D39	p	2.00E+14		stand. oxyd.	188
921-D12	p	5.00E+12		prol.oxyd.+TD	188
899-82	n	1.00E+12	1,2-3	stand. oxyd.	200
899-97	n	4.20E+13		stand. oxyd.	200
899-112	n	2.30E+14		stand. oxyd.	200

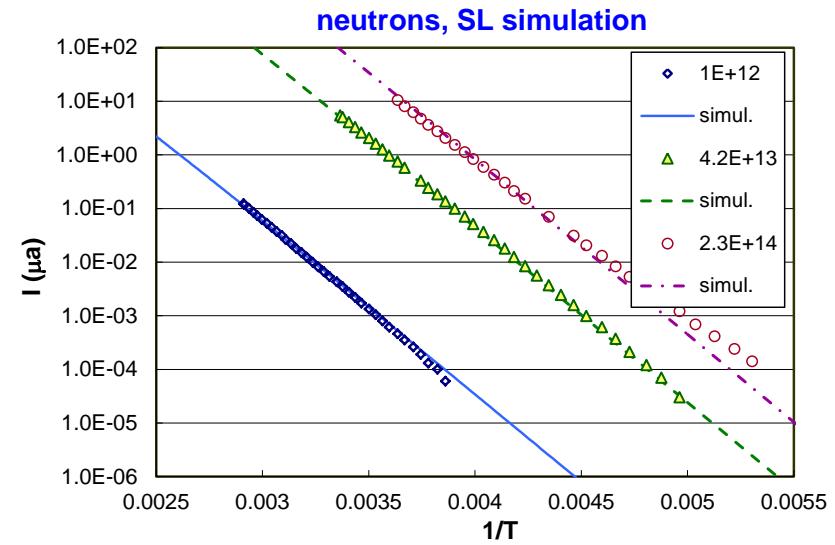
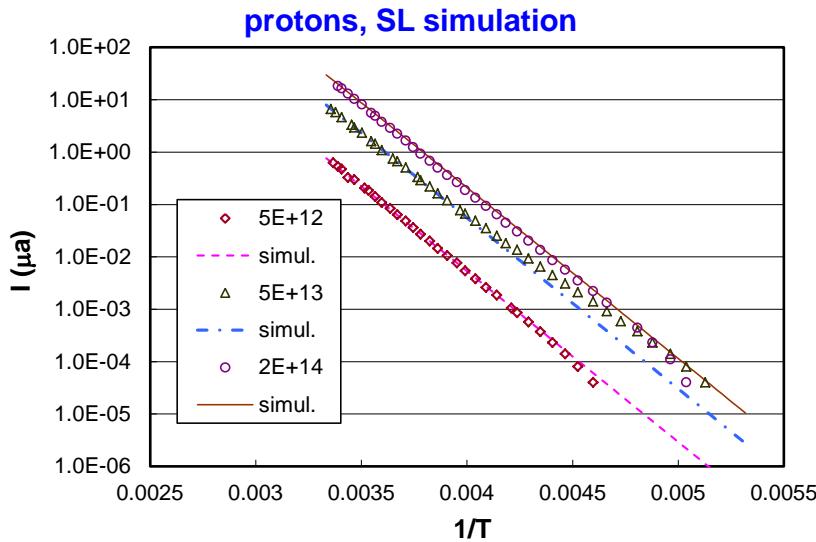
- ◆ T = 200÷400 K
- ◆ Full depletion – bulk generation current is measured
- ◆ Guard ring grounded

Reverse current simulation

1. Carrier generation via single level (SL) simulation)

$$I = e\sigma v_{th} n_i N_{gen} S d \exp(-E_a/kT)$$

$$\sigma(T) = \sigma_0 (T/T_0)^{-2}$$



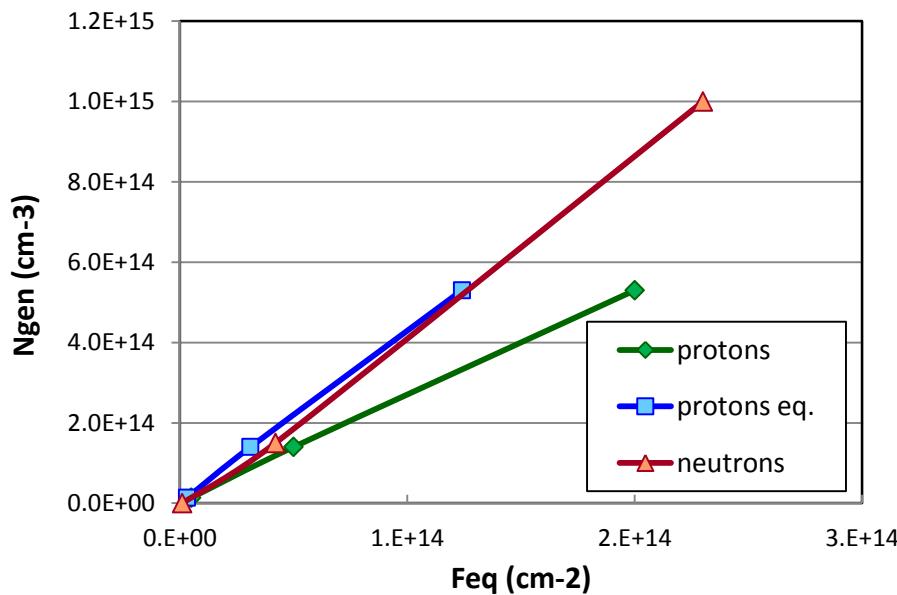
$F_p (\text{cm}^{-2})$	5×10^{12}	5×10^{13}	2×10^{14}
$F_{eq} (\text{cm}^{-2})$	3.1×10^{12}	3.1×10^{13}	1.24×10^{14}
$E_c - E_t (\text{eV})$	0.65	0.65	0.65
$\sigma_e (\text{cm}^2)$	1×10^{-13}	1×10^{-13}	1×10^{-13}
$N_{gen} (\text{cm}^{-3})$	1.35×10^{13}	1.4×10^{14}	5.3×10^{14}

$F (\text{cm}^{-2})$	1×10^{12}	4.2×10^{13}	2.3×10^{14}
$E_c - E_t (\text{eV})$	0.65	0.65	0.65
$\sigma_e (\text{cm}^2)$	5×10^{-14}	7×10^{-14}	1×10^{-13}
$N_{gen} (\text{cm}^{-3})$	1.6×10^{11}	1.5×10^{14}	1×10^{15}

Reverse current simulation

1. Carrier generation via single level (SL simulation)

N_{gen} vs. fluence dependence



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

Reverse current simulation

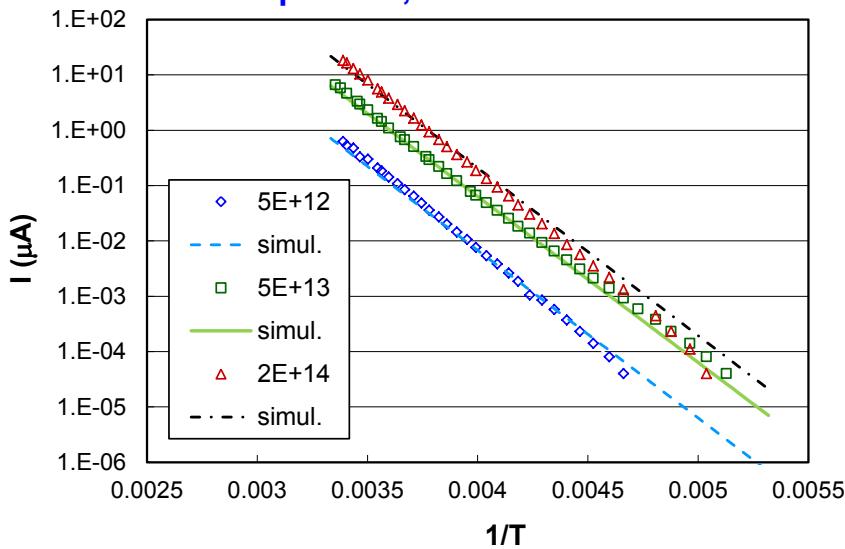
2. Carrier generation via two levels (TL simulation) – two independent processes

DD: $E_v + 0.48$ eV; DA: $E_c - (0.525 \pm 0.005)$ eV

– midgap levels used in all PTI simulations and fits

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

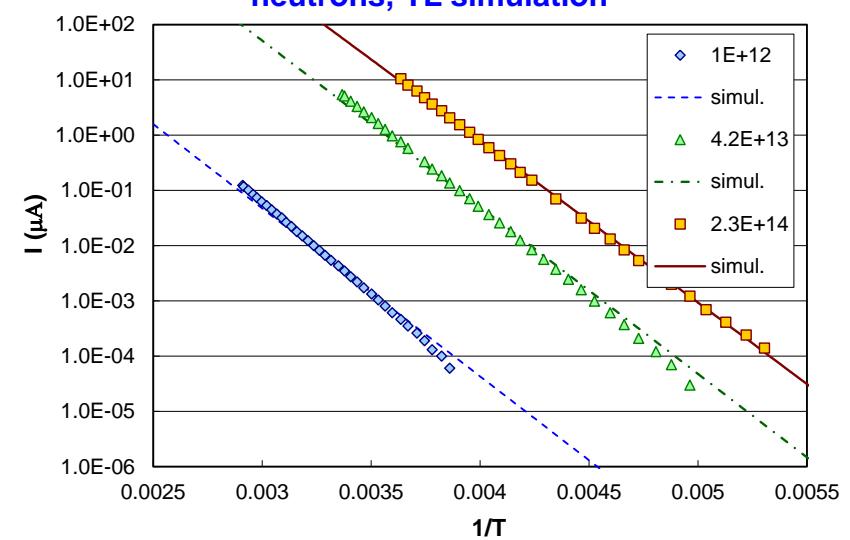
protons, TL simulation



Contributions to current from DD and DA are close

$$N_{DA}/N_{DD} = 2; k_{DD} = 0.5$$

neutrons, TL simulation



Contribution from DA prevails
(at $F \geq 10^{13} \text{ cm}^{-2}$)

Parameters of two level simulation

protons

F_p (cm $^{-2}$)	5x10 12		5x10 13		2x10 14	
F_{eq} (cm $^{-2}$)	3.1x10 12		3.1x10 13		1.24x10 14	
	DD	DA	DD	DA	DD	DA
E_r-E_v (eV)	0.48	0.6	0.48	0.595	0.48	0.595
E_c-E_t (eV)	0.64	0.52	0.64	0.525	0.64	0.525
σ_e (cm 2)	1x10 $^{-14}$	1.5x10 $^{-14}$	1x10 $^{-14}$	1x10 $^{-14}$	1x10 $^{-14}$	1x10 $^{-14}$
σ_h (cm 2)	1.4x10 $^{-14}$	1x10 $^{-14}$	1.4x10 $^{-14}$	1x10 $^{-14}$	1.4x10 $^{-14}$	1x10 $^{-14}$
N_t (cm $^{-3}$)	5x10 12	6x10 12	5x10 13	6x10 13	2x10 14	2.4x10 14

neutrons

F (cm $^{-2}$)	1x10 12		4.2x10 13		2.3x10 14	
	DD	DA	DD	DA	DD	DA
E_r-E_v (eV)	0.48	0.6	0.48	0.59	0.48	0.59
E_c-E_t (eV)	0.64	0.52	0.64	0.53	0.64	0.53
σ_e (cm 2)	1x10 $^{-15}$	1x10 $^{-14}$	1x10 $^{-14}$	1x10 $^{-14}$	1.4x10 $^{-14}$	1x10 $^{-14}$
σ_h (cm 2)	1x10 $^{-14}$	4x10 $^{-16}$	1x10 $^{-14}$	1.2x10 $^{-14}$	1x10 $^{-14}$	3x10 $^{-14}$
N_t (cm $^{-3}$)	5x10 11	1x10 12	8.4x10 12	4.2x10 13	1.15x10 14	2.3x10 14

Generation rate is determined by a larger energy gap

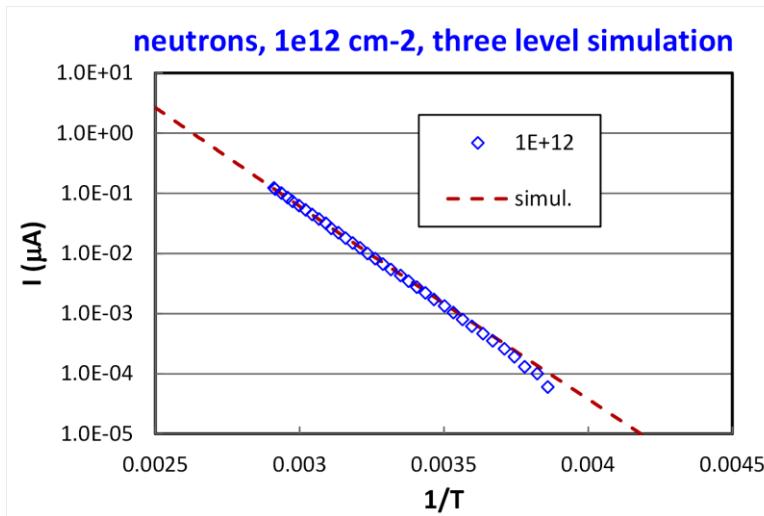
σ_e – sensitive for DD

σ_h – sensitive for DA

Generation via two midgap levels, DDs and DAs, adequately describes temperature dependence of reverse current

Reverse current simulation

3. Neutrons, $F = 1 \times 10^{12} \text{ cm}^{-2}$ → Additional generation level?



3rd level: DA2, $E_c - 0.43 \text{ eV}$

$$k_{DD} = 0.5$$

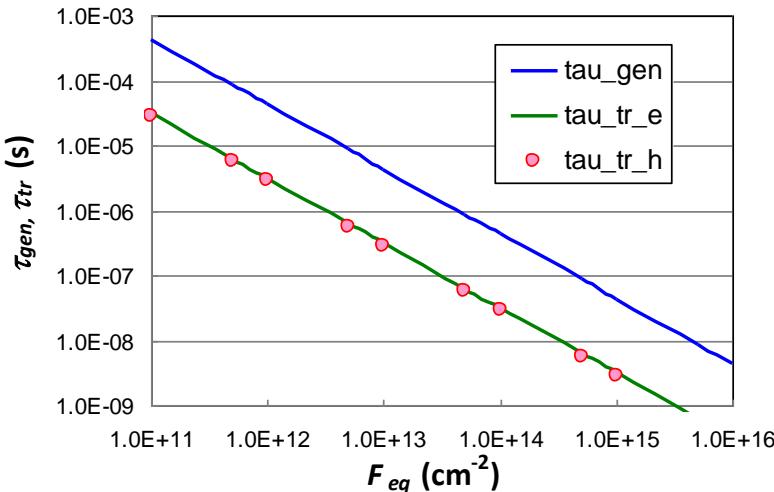
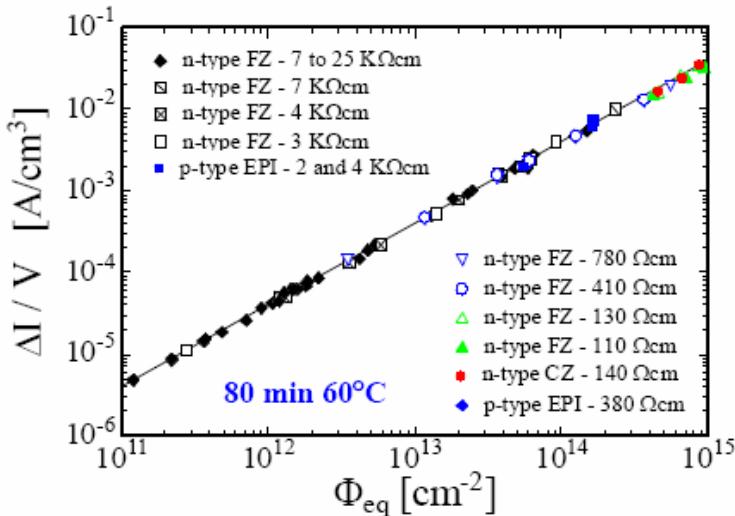
$$N_{DA1}/N_{DD} = 1$$

$$N_{DA2}/N_{DA1} = 5$$

	DD	DA1	DA2
$E_t - E_v$ (eV)	0.48	0.6	0.69
$E_c - E_t$ (eV)	0.64	0.52	0.43
σ_e (cm^2)	1.2×10^{-15}	1×10^{-15}	1×10^{-15}
σ_h (cm^2)	1×10^{-15}	1.1×10^{-15}	3×10^{-15}
N_t (cm^{-3})	5×10^{11}	5×10^{11}	5×10^{12}

Contribution from DA2 prevails
 - agrees with [E. Borchi and M. Bruzzi, NIM A 310 (1991) 273]

Generation lifetime vs. F



$$I_{bgen} = e n_i \text{Vol} / \tau_{gen}; \quad I_{bgen} = \alpha F \text{Vol}$$

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

$$\tau_{gen} = 4.32 \times 10^7 / F_{eq}$$

$$\beta_e = 3.2 \times 10^{-16} \text{ cm}^2 \text{s}^{-1}; \quad \beta_h = 3.5 \times 10^{-16} \text{ cm}^2 \text{s}^{-1}$$

$$\tau_{tr_e} = 3.1 \times 10^6 / F_{eq}$$

$$\tau_{tr_h} = 2.9 \times 10^6 / F_{eq}$$

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

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

$$F_{eq} = 1 \times 10^{15} \text{ cm}^{-2}$$

$$\tau_{gen} = 40 \text{ ns}$$

$$\tau_{tr_e,h} \approx 3 \text{ ns}$$

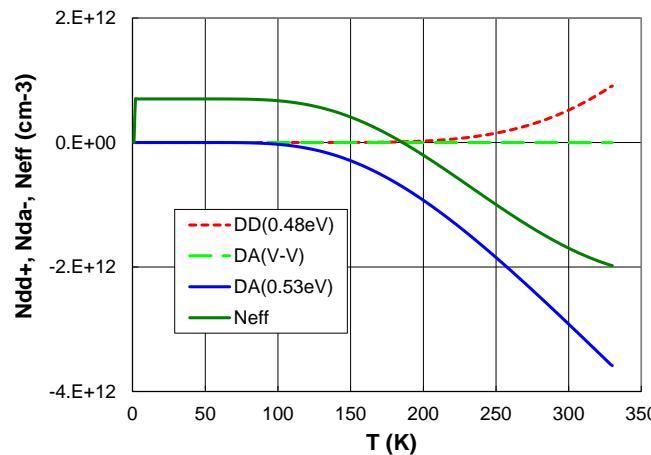
Trapping: all levels contribute to τ since pulse signal is measured within $\theta = 25$ ns that is far less than detrapping time constant for larger energy gap (at RT)

Generation: only midgap levels contribute

Whether DLs with $E_a \sim 0.4$ eV can affect I_{gen} (occupancy of DLs vs. T)

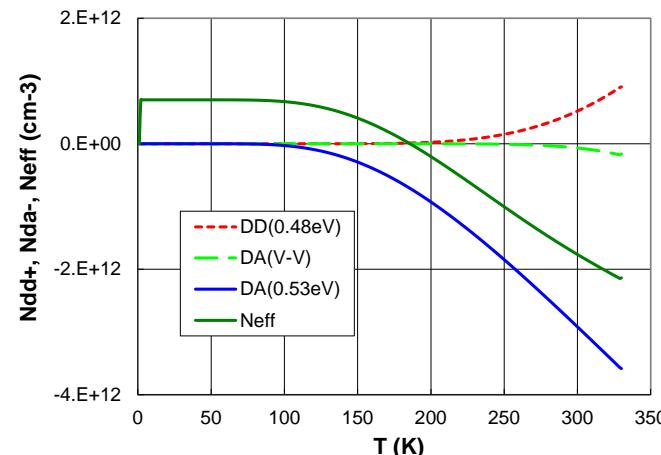
$F_{eq} \sim 10^{14} \text{ cm}^{-2}$ DLs: DD, DA, VV-

$$N_{VV} = 1 \times 10^{14} \text{ cm}^{-3}$$

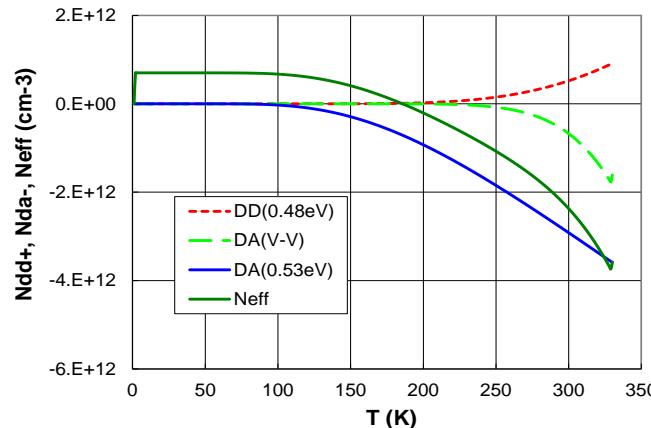


In plots: concentration of charged DLs
and total N_{eff}

$$N_{VV} = 1 \times 10^{16} \text{ cm}^{-3}$$



$$N_{VV} = 1 \times 10^{17} \text{ cm}^{-3}$$



DLs with $E_a \sim 0.4$ eV affect:

- ◆ space charge region depth (at very high F);
- ◆ trapping time constant

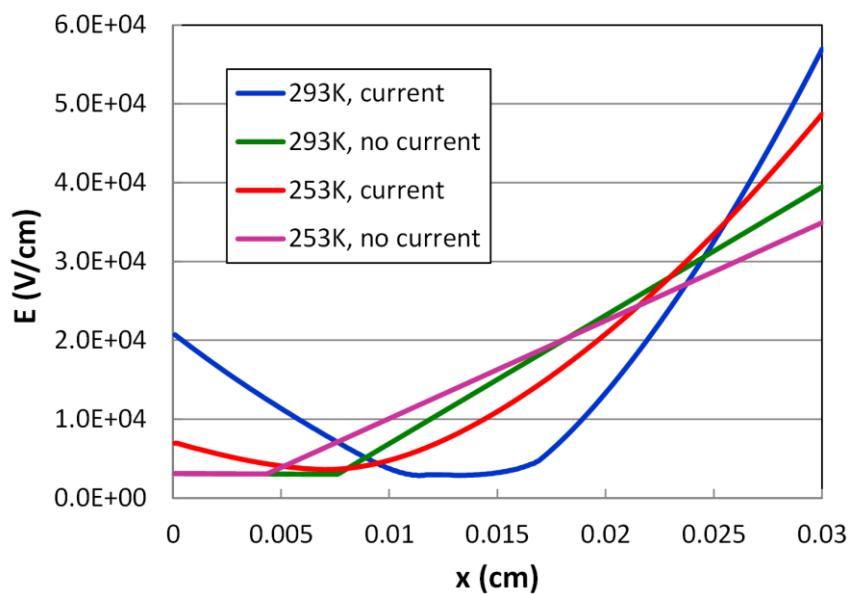
Deep levels with $E_a \sim 0.4$ eV (VV, C_i-O_i)
hardly affect $I(T)$ dependence

Impact of I_{gen} on $E(x)$ profile

Key parameters for adequate $E(x)$ description: deep levels and generation current

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

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})

Alternative approach:
Generation may be considered via lifetime – suggested by Delhi University group

Conclusions

Single level model of $I(T)$:

- Activation energy of bulk generation current E_a is 0.65 eV independent on proton/neutron fluence
- Concentration of effective generation level is proportional to F_{eq}

Two level model of $I(T)$:

- Two midgap levels, DDs and DAs, describe $I(T)$ dependence of generation current
- Contribution of DAs to the generation current prevails in neutron irradiated detectors whereas in proton irradiated detectors both constituents are close

Generation lifetime is significantly larger than trapping lifetime

Bulk generation current gives adequate description of irradiated detector characteristics

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Thank you for attention!