Contribution from $E_g(T)$ dependence into parameterization of the bulk generation current of irradiated Si detectors

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Motivation

1. I(T) parameterization is important for the research in the frame of SWG of RD50 collaboration.

2. Generation of the bulk current in irradiated detectors is a critical process for the electric field distribution in the detector sensitive volume.

1. Physically correct I(T) parameterization is a basis for T-scaling of the reverse current in irradiated detectors .

Energy band gap in semiconductors

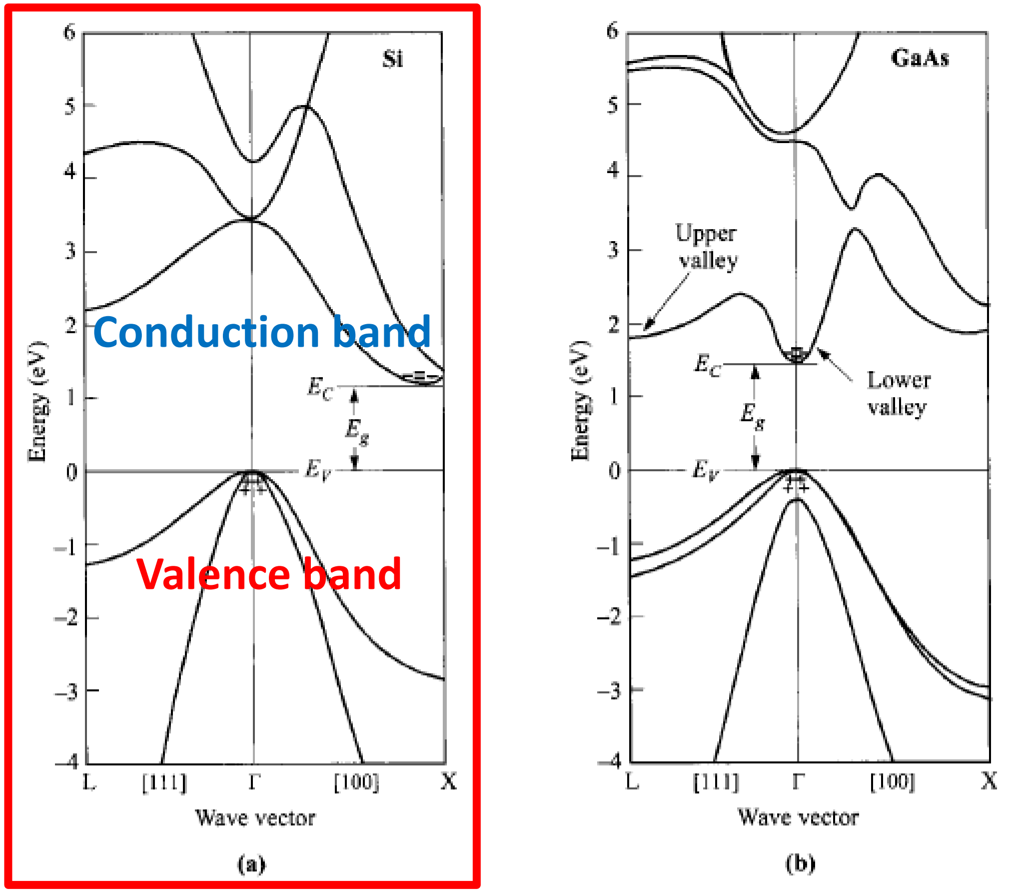
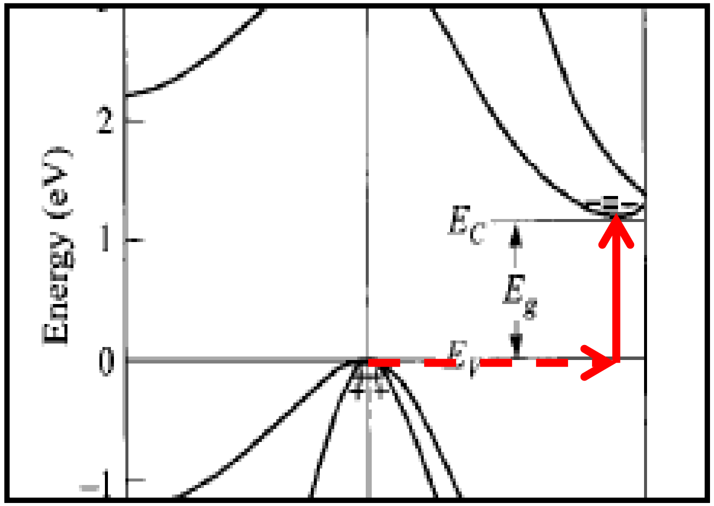
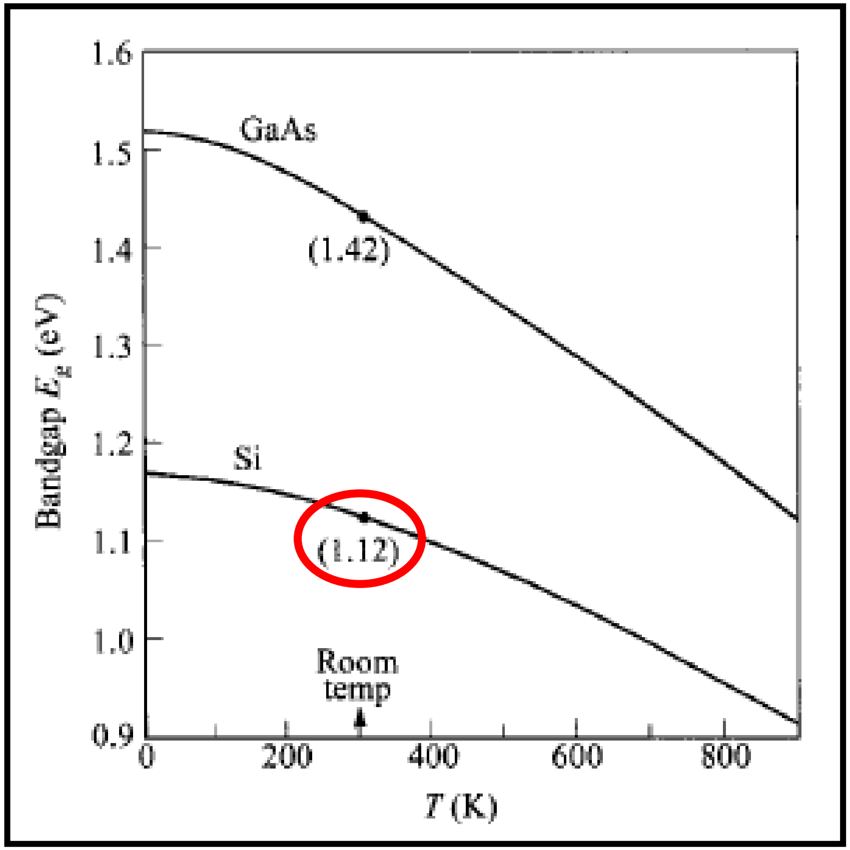


Fig. 4 Energy-band structures of (a) Si and (b) GaAs, where E_g is the energy bandgap. Plus signs (+) indicate holes in the valence bands and minus signs (–) indicate electrons in the conduction bands. (After Ref. 20.)

Energy band gap in Silicon





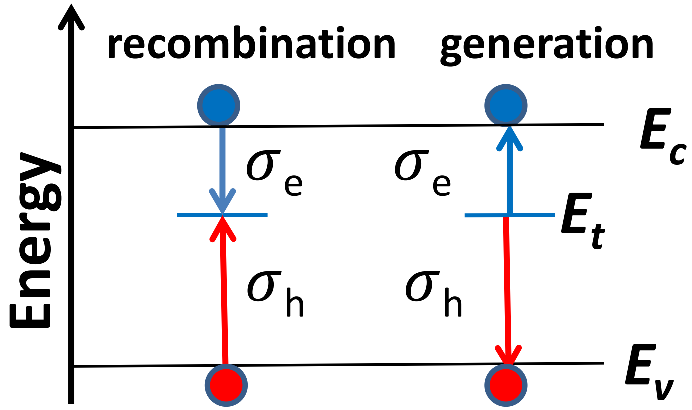
Eg(T=0K) = 1.169 eV

$$E_g(T) \approx E_g(0) - \frac{\alpha T^2}{T + \beta}$$

	$E_g(0)$ (eV)	α (eV/K)	β (K)
GaAs	1.519	5.4×10^{-4}	204
Si	1.169	4.9×10^{-4}	655

Eg(T = +20C) = 1.125eV
Eg(T = -20C) = 1.134eV

Generation/recombination in a real Si p-n junction



$G_e = e_e n_t$ $G_h = e_h(N_t - n_t)$

$R_e = c_e(N - n_t)n$ $R_h = c_h n_t p$

$U = G - R$

$$c_e = v_{th}^{e}\sigma_e \qquad e_n = v_{th}^{e}\sigma_e \cdot \exp\left(-\frac{E_c - E_t}{kT}\right)$$

$$c_h = v_{th}^{h}\sigma_h \qquad e_h = v_{th}^{h}\sigma_h \cdot \exp\left(-\frac{E_t - E_v}{kT}\right)$$

Solution for the current generation rate

$$U = \frac{\sigma_e \sigma_h v_{th}^e v_{th}^h N_t (pn - n_i^2)}{\sigma_e v_{th}^e [n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)] + \sigma_h v_{th}^h [p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)]}$$

Simplification for the depleted region:

p = 0 and n = 0 **…………….since generation in SCR**

$n_i = (N_c N_v)^{0.5} \exp(-E_g/2kT)$

$E_i = E_g/2 + kT/2 \ln(N_V/N_C)$

Simplification for Si:

$E_i = E_g/2$

N_c=2.8e19 cm^{-3}, N_V=2.65e19 cm^{-3} (S.Sze, PSD-3rt edition, 2007)

$E_i = E_g/2$ + 0.0E26/2x0.055 = 1.12 + 0.0007 eV (~0.05% difference)

Activation form of equitation for the generation rate

$$U = \frac{\sigma_e \sigma_h v_{th}^e v_{th}^h N_t (n_i^2)}{\sigma_e v_{th}^e [n_i \exp\left(\frac{E_t - E_i}{kT}\right)] + \sigma_h v_{th}^h [n_i \exp\left(\frac{E_i - E_t}{kT}\right)]}$$

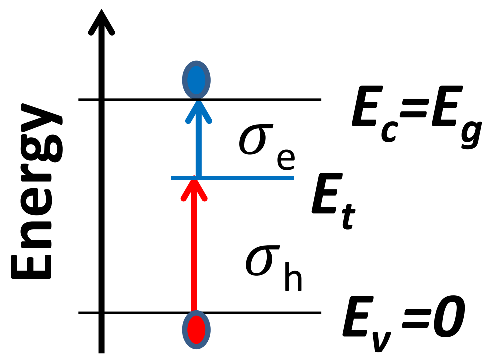
$$U = \frac{\sigma_e \sigma_h v_{th}^e v_{th}^h N_t n_i^2}{\sqrt{N_c N_v}\left[\sigma_e v_{th}^e \exp\left(-\frac{E_g - E_t}{kT}\right) + \sigma_h v_{th}^h \exp\left(-\frac{E_t}{kT}\right)\right]}$$

$$U = \frac{\sigma_e \sigma_h v_{th}^e v_{th}^h N_t \sqrt{N_c N_v}}{\sigma_e v_{th}^e \exp\left(\frac{E_t}{kT}\right) + \sigma_h v_{th}^h \exp\left(\frac{E_g - E_t}{kT}\right)}$$

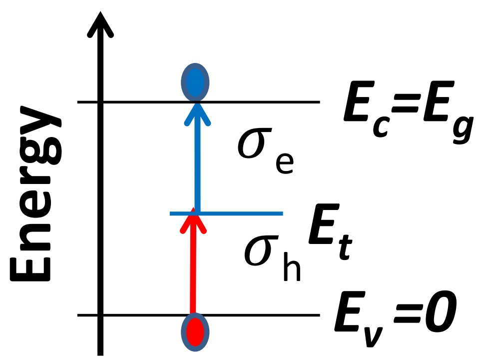
Single level model

$$U = \frac{\sigma_e \sigma_h v_{th}^e v_{th}^h N_t \sqrt{N_c N_v}}{\sigma_e v_{th}^e \exp\left(\frac{E_t}{kT}\right) + \sigma_h v_{th}^h \exp\left(\frac{E_g - E_t}{kT}\right)}$$

$$I_{bgen} = UAw$$



$$U_{up} = \frac{\sigma_h v_{th}^h N_t \sqrt{N_c N_v}}{\left[\exp\left(\frac{E_t}{kT}\right)\right]}$$



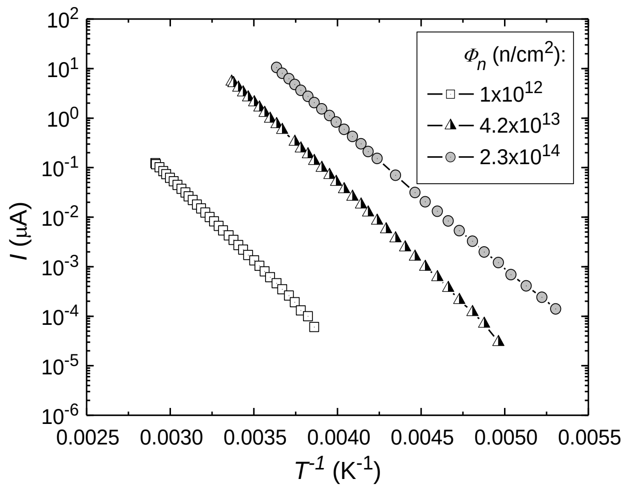
$$U_{low} = \frac{\sigma_e v_{th}^e N_t \sqrt{N_c N_v}}{\left[\exp\left(\frac{E_g - E_t}{kT}\right)\right]}$$

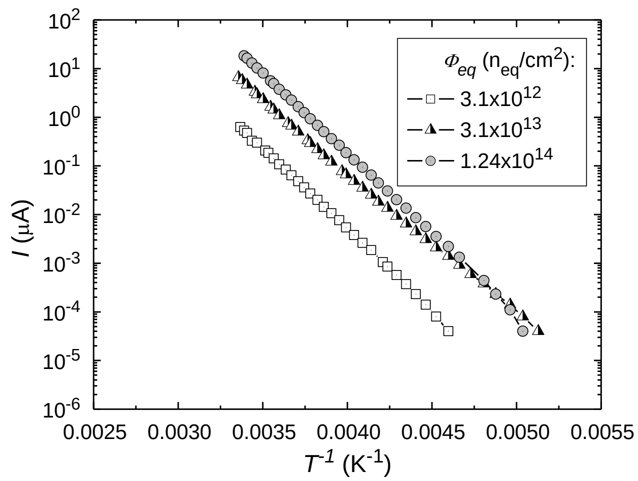
Sub-conclusions

1. Transformation of "statistical" form of equitation for the current generation rate into the "activation" form eliminates parameters which exploit Eg.
2. The temperature dependence of Eg now is substituted by temperature dependence of the position of generation center level in forbidden gap.
3. The temperature shift of the generation center level is not defined theoretically or experimentally and the universal dependence is unknown up to now .
4. The argument against this conclusion can be picked up from any experiment which covers a wide range of temperatures in which the effect dominates.
5. The I_{bulk} (T) analysis is a proper experiment which can show evidence of Eg (T).

Samples and I(T) characteristics

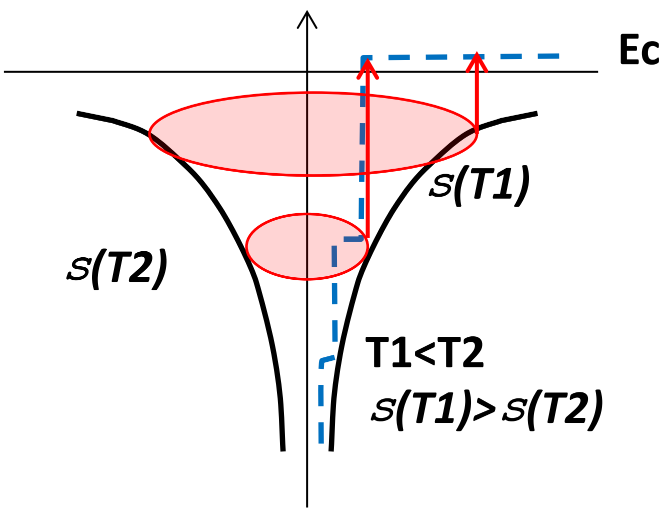
#	radiation	F (cm^{-2})	F (n_{eq}/cm^2)	d (mm)	SCSI	V_{fd}	V_{op} (V)
899-82	neutrons	$1x10^{12}$		200	no	120	140
899-97	neutrons	$4.2x10^{13}$		200	yes	65	75
899-112	neutrons	$2.3x10^{14}$		200	yes	200	240
921-D26	protons	$5x10^{12}$	$3.1x10^{12}$	188	no	95	110
923-D35	protons	$5x10^{13}$	$3.1x10^{13}$	188	yes	50	60
923-D39	protons	$2x10^{14}$	$1.24x10^{14}$	188	yes	130	160





$s(T)$ dependence

$$U = \frac{\sigma_h v_{th}^h N_t \sqrt{N_c N_v}}{\left[\exp\left(\frac{E_t}{kT}\right)\right]}$$



SQR(N_c N_v) ~ $T^{3/2}$

V_{th} ~ $T^{1/2}$

s(T) = $s_o(T/T_o)^m$

with 0 > m > -3.

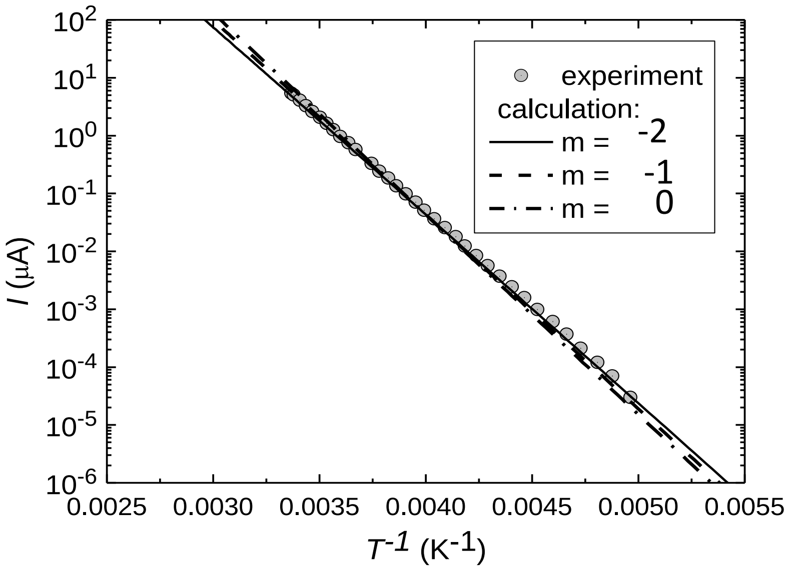
s(T) ~ T^{-2}

$E_t(T) - ?$

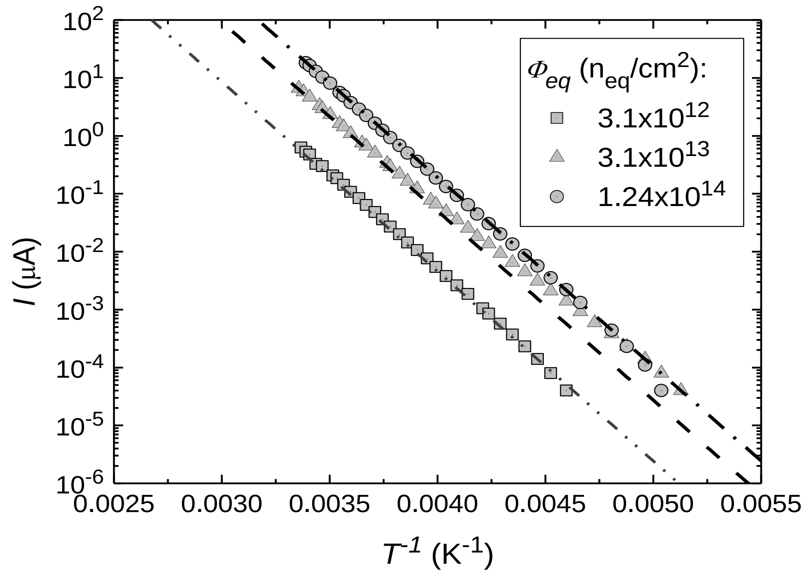
Activation energy of reverse current in the frame of SL model

Goal: bulk generation current temperature scaling

Neutrons, 4.2e13 cm^{-2}



Protons



The activation energy E_t *for the current generation :*

in neutron irradiated detector .... 0.645 eV

in proton irradiated detector .... 0.65 eV

Two level (TL) approximation for reverse current in irradiated detectors

Goal: bulk generated current scaling + electric field simulation

PTI DL model:

Deep acceptor (DA) $E_c - 0.525$ eV (E$_{DAact}$ = 1.12 – 0.525 = 0.595 eV)

Deep donor (DD) $E_v + 0.48$ eV (E$_{DDact}$ = 1.12 – 0.48 = 0.64 eV)

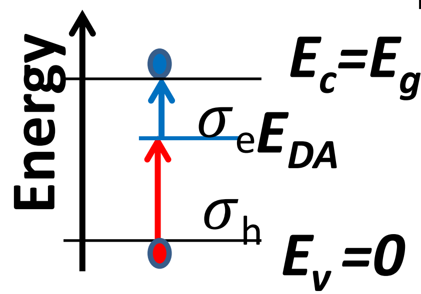
Proved by : simulation of CCE recovery at low T (Lazarus effect),
simulation of DP electric field distribution,
simulation of multiplication gain in irradiated detectors.

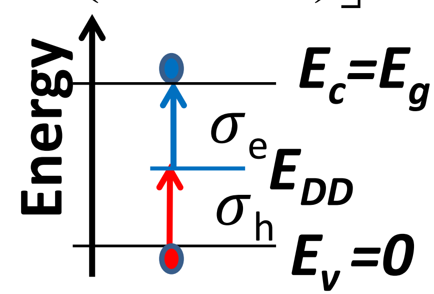
$$U = U_{DA} + U_{DD} = \frac{\sigma_h v_{th}^h N_{DA}\sqrt{N_c N_v}}{\left[\exp\left(\frac{E_{DA}}{kT}\right)\right]} + \frac{\sigma_e v_{th}^e N_{DD}\sqrt{N_c N_v}}{\left[\exp\left(\frac{E_g - E_{DD}}{kT}\right)\right]}$$

Additional parameter is required:

ratio: N_{DD}/N_{DA} or

introduction rates : K_{DD} and K_{DA}





Bulk generated current parameterization with TL model

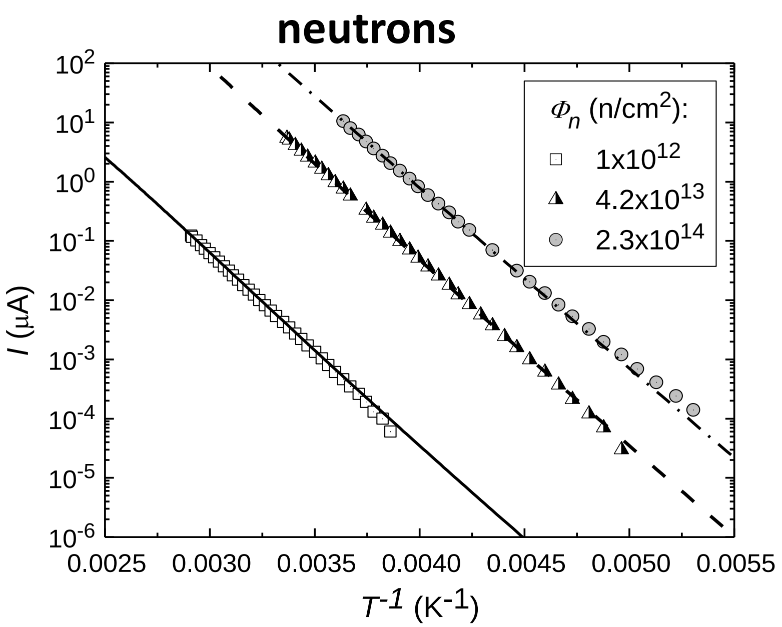
Neutrons, K_{DD} = 1 cm^{-1}, K_{DA} = 1.5 cm^{-1}.

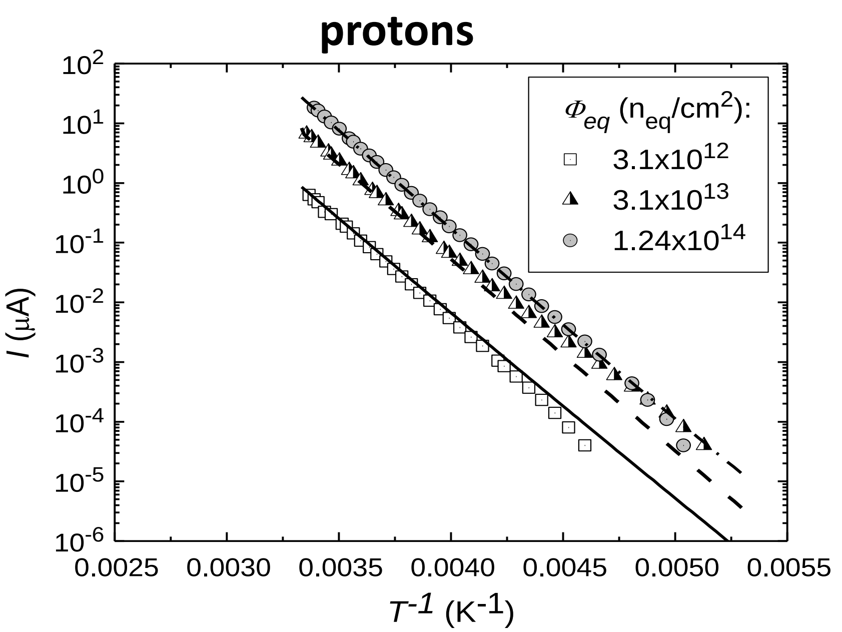
F (n/cm^2)	$1x10^{12}$		$4.2x10^{13}$		$2.3x10^{14}$	
Deep level	DD	DA	DD	DA	DD	DA
E_t (eV)	0.47	0.6	0.48	0.6	0.47	0.6
s_e (cm^2)	$8x10^{-14}$	$1x10^{-15}$	$8x10^{-14}$	$1x10^{-15}$	$8x10^{-14}$	$3x10^{-15}$
s_h (cm^2)	$1x10^{-15}$	$5.5x10^{-15}$	$1x10^{-15}$	$5.5x10^{-15}$	$1x10^{-15}$	$2.5x10^{-14}$
N_t (cm^{-3})	$3.5x10^{10}$	$5.25x10^{10}$	$4.2x10^{13}$	$6.3x10^{13}$	$2.3x10^{14}$	$3.45x10^{14}$

Protons, K_{DD} = 1 cm^{-1}, K_{DA} = 1.1 cm^{-1}.

F (n_{eq}/cm^2)	$3.1x10^{12}$		$3.1x10^{13}$		$1.24x10^{14}$	
Deep level	DD	DA	DD	DA	DD	DA
E_t (eV)	0.478	0.6	0.48	0.6	0.48	0.6
s_e (cm^2)	$8x10^{-14}$	$1x10^{-15}$	$8x10^{-14}$	$1x10^{-15}$	$8x10^{-14}$	$1x10^{-15}$
s_h (cm^2)	$1x10^{-15}$	$1.2x10^{-14}$	$1x10^{-15}$	$1x10^{-14}$	$1x10^{-15}$	$5x10^{-15}$
N_t (cm^{-3})	$5x10^{12}$	$5.5x10^{12}$	$5x10^{13}$	$5.5x10^{13}$	$2x10^{14}$	$2.2x10^{14}$

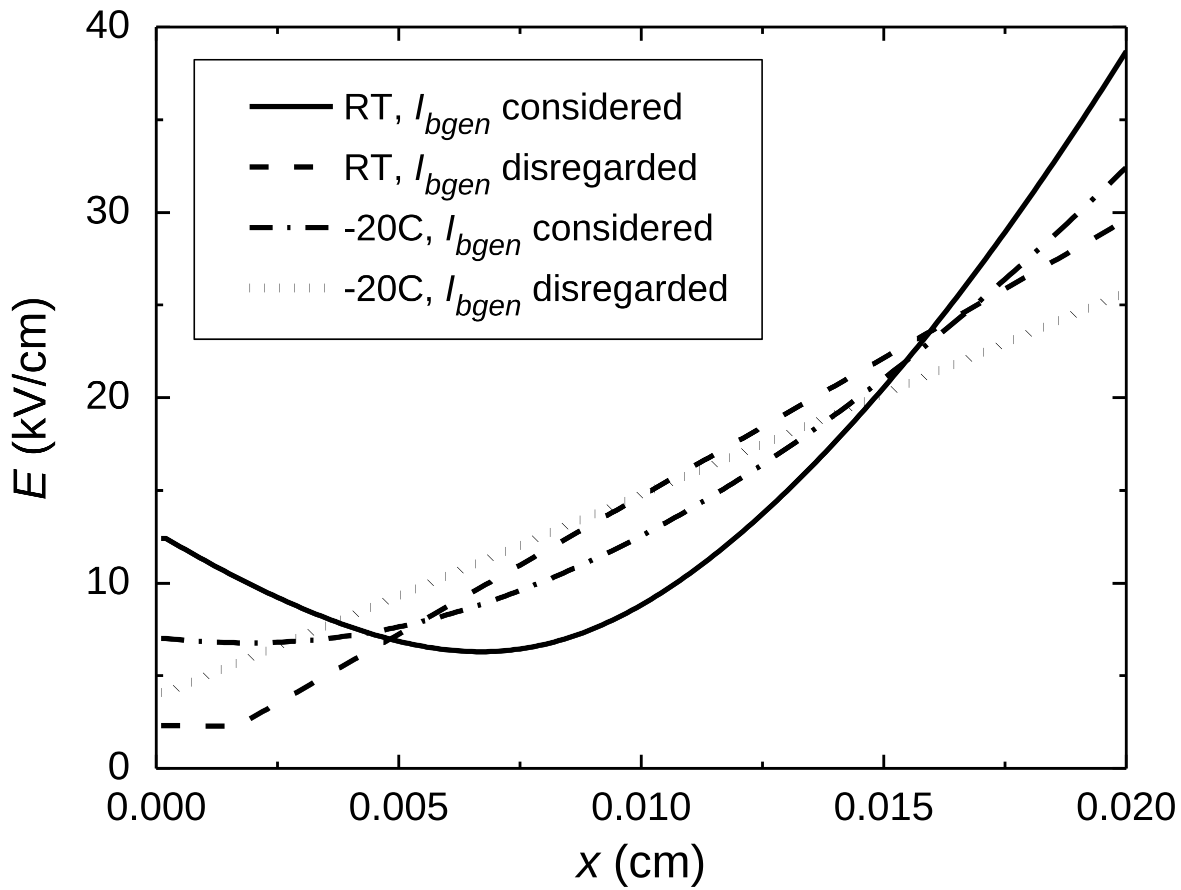
Fit of I(T) curves for detectors irradiated by different fluences with TL model





DP electric field distribution modeling with the TL model

***Proton irradiated detector at V* = 300 V, *F*$_{eq}$ = 1x10^{15} n$_{eq}$/cm^2.**



Conclusions

1. E_g (T) is not important for the temperature scaling of the bulk generated reverse current
2. The influence of T on the position of DL in semiconductor forbidden gap is not predictable and unknown up to now.
3. Simulation / modeling society should agree the SIG(T) dependence which is not clarified yet due to experimental difficulties. SIG ~ T^{-2} is proposed.
4. One exponential fit of the I(T) curves can be applied as usually abs(E_i – E_t) > kT. This gives a simple and effective way for T-scaling of the current.

Thank you for your attention

Generation/recombination in semiconductors

Recombination coefficient

Recombination rate $$R = R_{rec} * p * n$$

Generation rate $$G = R_{gen} * p * n$$

Principe of detailed equilibrium $$G_n = R_n$$ $$G_p = R_p$$

$$G = R_{rec} * n_i^2$$

Transition rate $$U = R - G = R_{rec}(p*n - n^2)$$

Bulk generation current

$$I_{bgen} = UAw$$

Due to: $I_{bgen} = en_i Aw/\tau_{gen}$

$$\tau_{bgen} = \frac{\sqrt{N_c N_v}\left[\sigma_e \exp\left(-\frac{E_g - E_t}{kT}\right) + \sigma_h \exp\left(-\frac{E_t}{kT}\right)\right]}{e\sigma_e\sigma_h v_{th}^e v_{th}^h n_i N_t}$$

$$\tau_{up} = \frac{\left[\exp\left(\frac{E_t}{kT}\right)\right]}{\sigma_h v_{th}^h N_t n_i \sqrt{N_c N_v}} \qquad \tau_{low} = \frac{\left[\exp\left(\frac{E_g - E_t}{kT}\right)\right]}{\sigma_e v_{th}^e N_t \sqrt{N_c N_v}}$$