Annealing of effective trapping times in irradiated silicon detectors

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Motivation

Trapping of drifting carriers sets the ultimate limit for use of position sensitive Si-detectors; depletion depth (defect engineering, 3D) and leakage current (cooling) can be controlled !

The carriers get trapped during their drift – the rate is determined by effective trapping times! Why study them?

- An input to simulations of operation of irradiated silicon detectors!
  - prediction of charge collection efficiency (LHC, SLHC, etc.)
  - optimization of operating conditions
  - optimization of detector design (*p*+ or *n*+ strips, thickness, charge sharing)
- Characterization of different silicon materials in terms of charge trapping!
- Defect characterization?

The goal is to get as much charge out the detectors as possible!

As the defects responsible for trapping change after the irradiation so do the trapping times! Unlike N_{eff} or I_{leak} there are no systematic studies of $\tau_{eff,e,h}$ annealing performed so far!

equivalent fluence

introduction rate of defect *k*

occupation probability

capture cross-section

thermal velocity

$$\frac{1}{\tau_{eff,e,h}} = \Phi_{eq} \underbrace{\left[\sum_k g_k \, (1 - P_k^{e,h}) \, \sigma_{k,e,h}(T) \, v_{th,e,h}(T) \right]}$$

assuming only first order kinetics $g_k \neq g_k(\Phi_{eq})$ of defects formed by irradiation at given temperature and time after irradiation

$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t) \, \Phi_{eq}$$

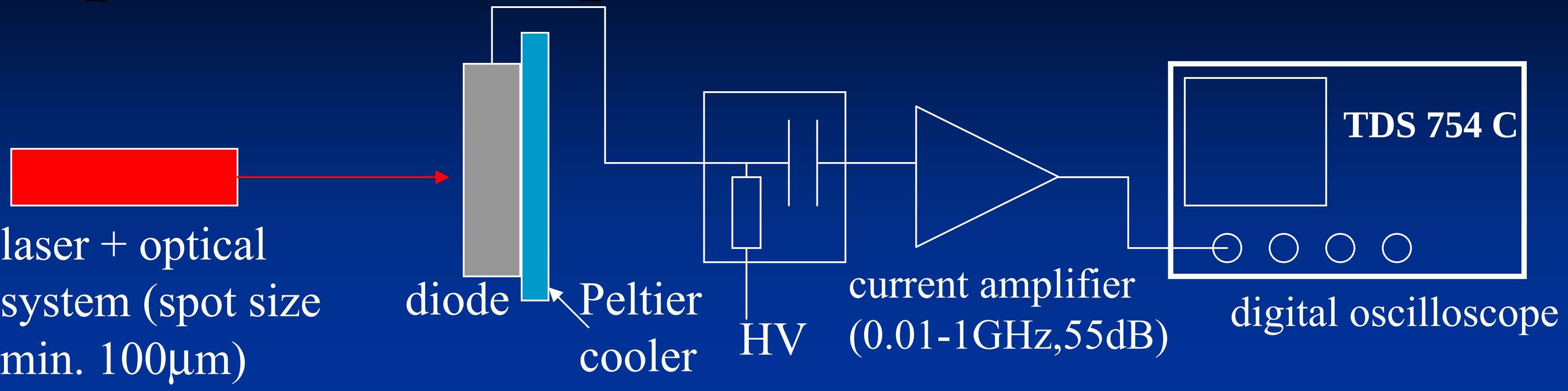
β(-10°C, *t=min Vfd*) [10^{-16} cm^2/ns]	24 GeV protons (average)	reactor neutrons
Electrons	**5.6±0.2**	**4.1±0.2**
Holes	**6.6±0.3**	**6.0±0.3**

The β was so far found independent on material;

- resistivity
- [O], [C]
- type (p,n)
- wafer production (FZ, Cz, epitaxial)
- **$\beta_{e,h} \sim 0$ for ^{60}Co irradiated samples**

The goal of this presentation is to determine $\beta_{e,h}(20^{o}C,t)$ at different annealing temperatures!

Experimental setup - TCT



laser + optical system (spot size min. 100µm)

diode

Peltier cooler

HV

current amplifier (0.01-1GHz,55dB)

digital oscilloscope

- light pulse (λ=660 nm) repetition rate (50 Hz)
- about $5\ 10^5$ electron-hole pairs/pulse (neutral density filter)
- samples have hole in metalization (p^+ contact) or mesh metalization (n^+ contact)

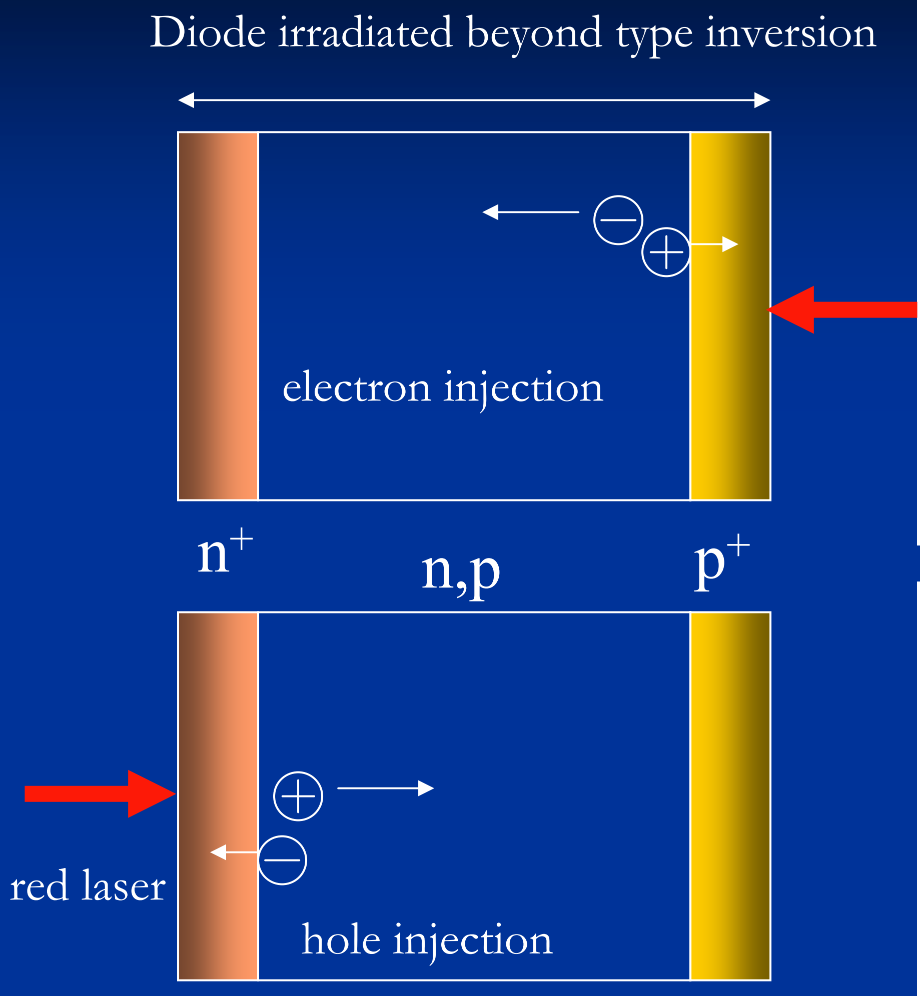
Samples

- 300 µm thick p^+-n-n^+ pad detectors (0.5x0.5 cm^2, single guard ring),

from same wafer 15 kΩ cm; V_{fd}~15V, <111>, standard float zone material.

- 3 samples for each T (40,60,80^{o}C),
  - two irradiated to $\Phi_{eq}=7.5 \cdot 10^{13}$ cm^{-2}
  - one irradiated to $\Phi_{eq}=1.5 \cdot 10^{14}$ cm^{-2}

Determination of $\tau_{eff,e,h}$ – Charge correction method (I)



Diode irradiated beyond type inversion

electron injection

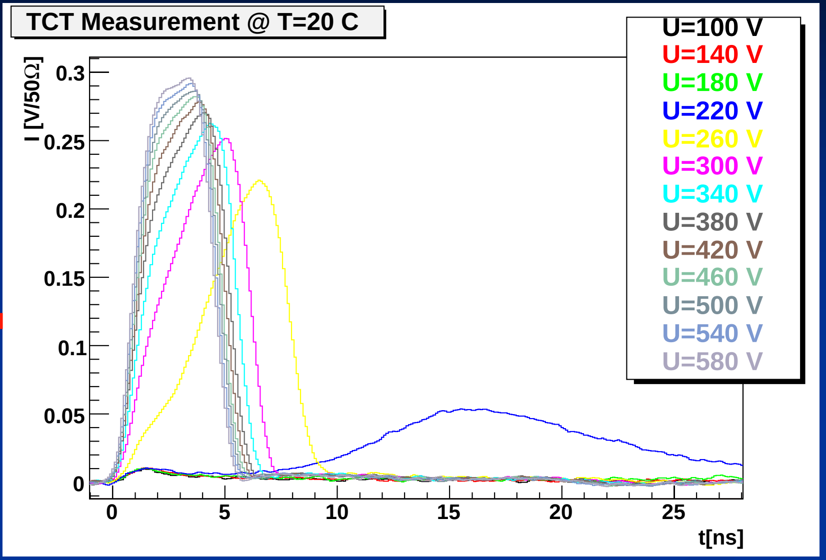
n^+

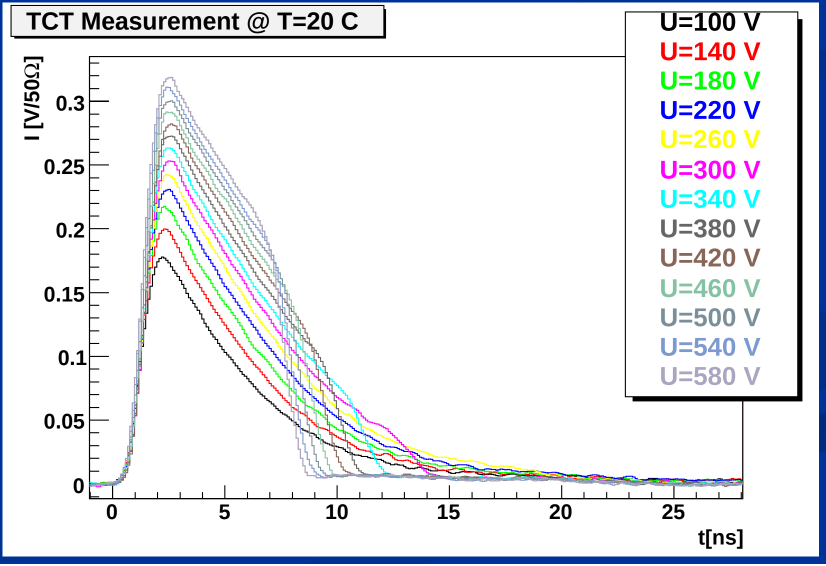
n,p

p^+

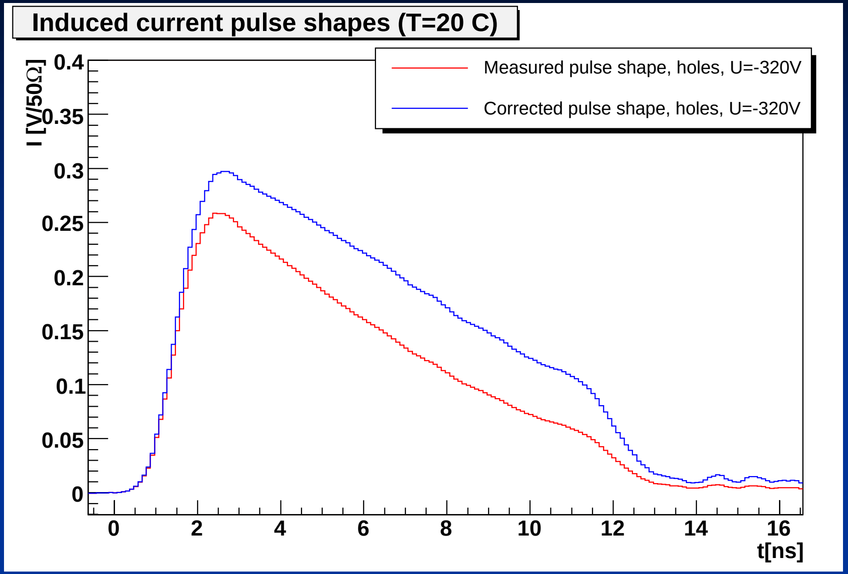
red laser

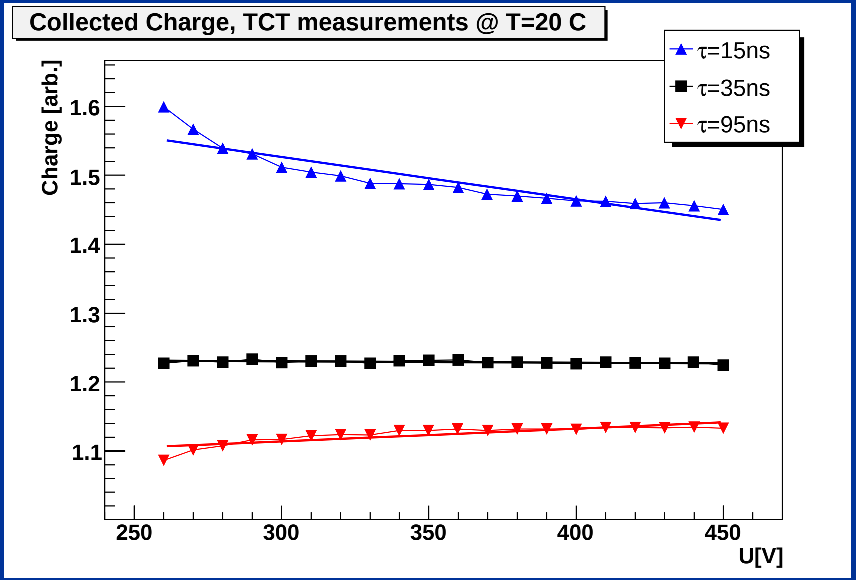
hole injection





Determination of $\tau_{eff,e,h}$ (II) – Charge correction method (II)





Charge increases with *V* for *V*>*V*$_{fd}$!

Measured

$$I_m(t) = I_{e,h}(t) = \left[e_0 \; N_{e,h} \frac{1}{D} v_{e,h}(t) \right] \exp\left(\frac{-t}{\tau_{eff,e,h}}\right)$$

Corrected

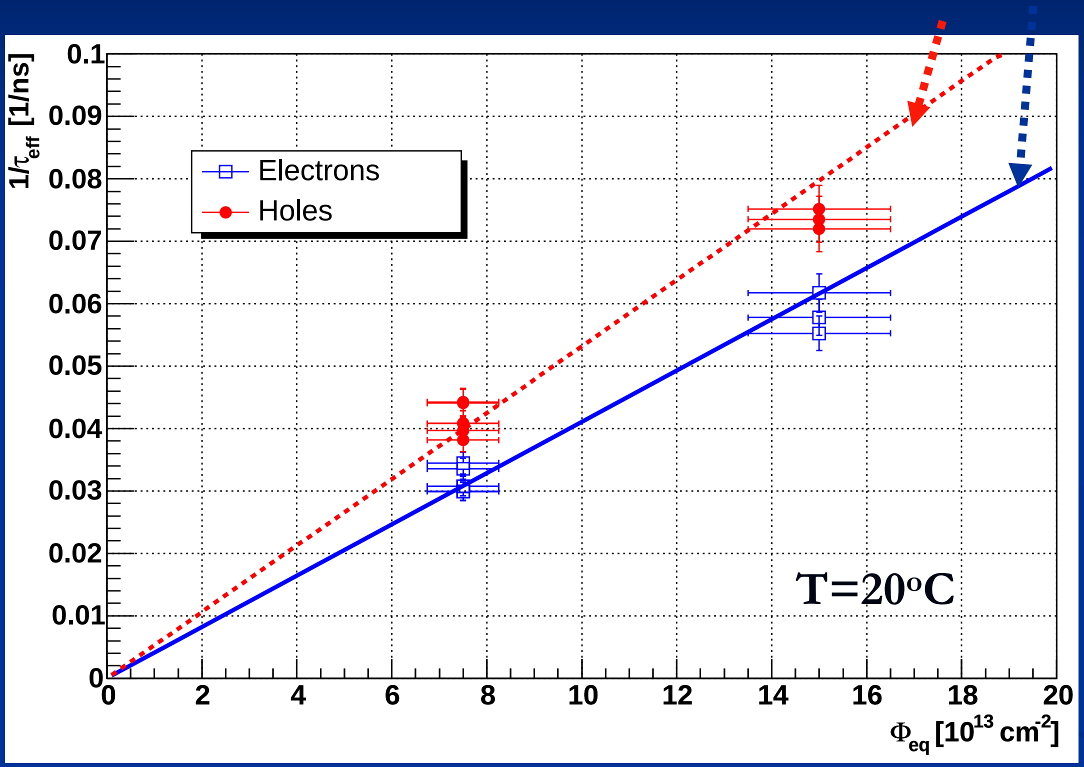
$$I_c(t) = I_m(t) \exp\left(\frac{t-t_0}{\tau_{tr}}\right)$$

***Q_c*=constant for *V>VFD* ⟶ $\tau_{tr}=\tau_{eff}$**

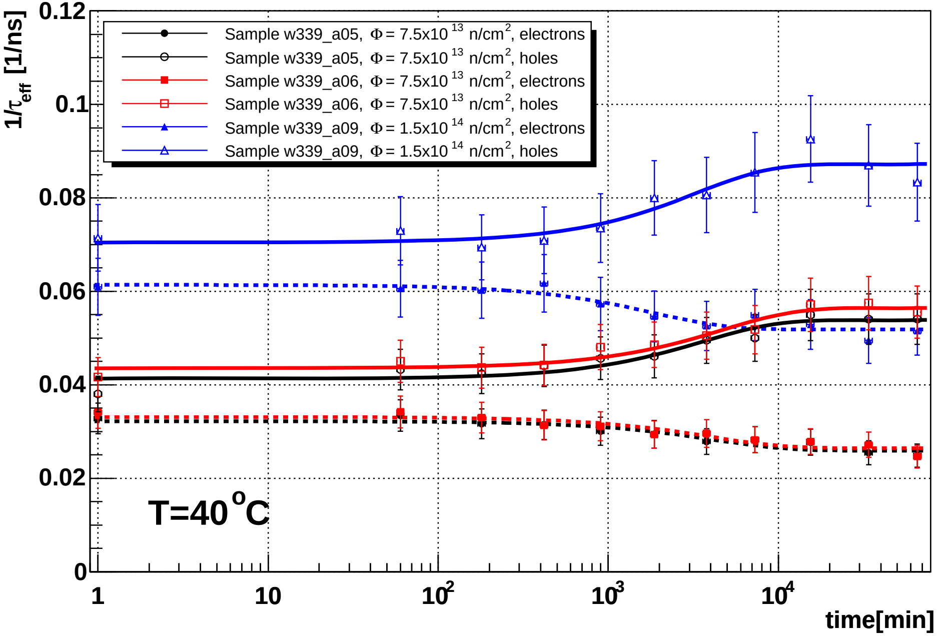
(without trapping the signal of fully depleted detector doesn't depend on voltage)

Effective trapping times at *t*=min V_{fd}

“world” average



Annealing plots (I)



annealing $\beta_{e,h}(20^oC,t)$ performed at elevated temperatures of 40,60,80°C:

- increase of β_h during annealing
- decrease of β_e during annealing
- evolution of defects responsible for annealing of trapping times seems to obey 1st order dynamics ($\tau_{an} \neq \tau_{an}(\phi)$) for all annealing temperatures

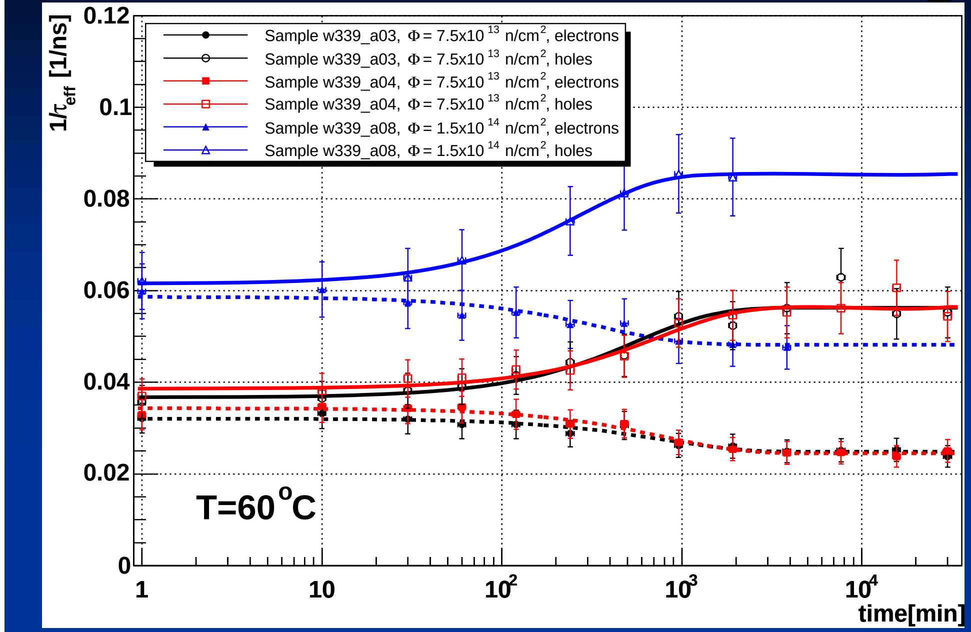
A → **B**
A → B , **C** stable
1st order

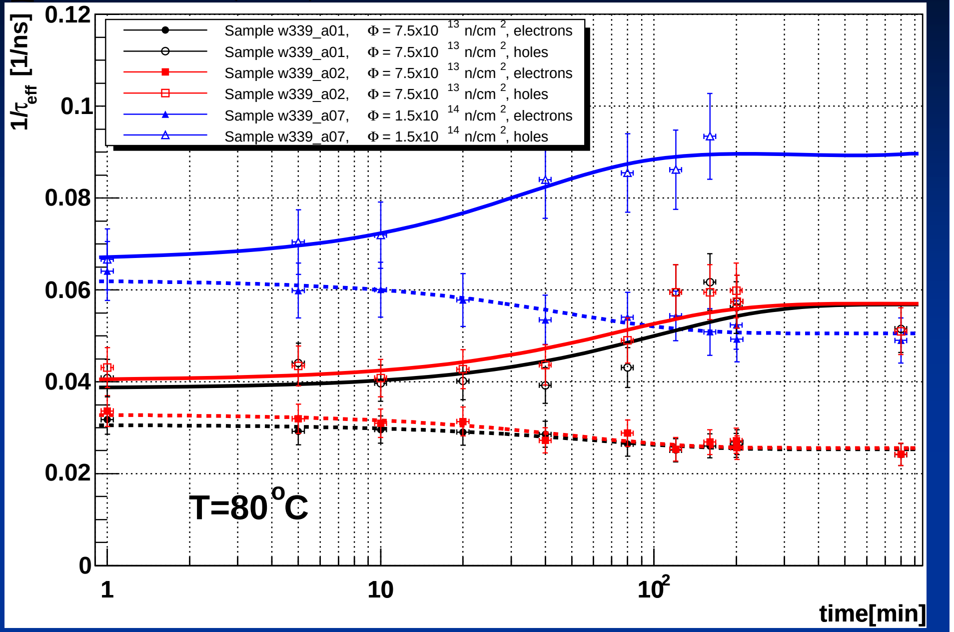
A+B → C, **D** stable
A+B → **C**
A+B → **C, D** stable
1st order for [B]<<[A]

$$\beta = \beta_0 \exp(-\frac{t}{\tau_{ta}}) + \beta_\infty \left[1-\exp(-\frac{t}{\tau_{ta}})\right] = (\beta_0-\beta_\infty)\exp(-\frac{t}{\tau_{ta}})+\beta_\infty$$

bold red – active
black – inactive

Annealing plots (II)





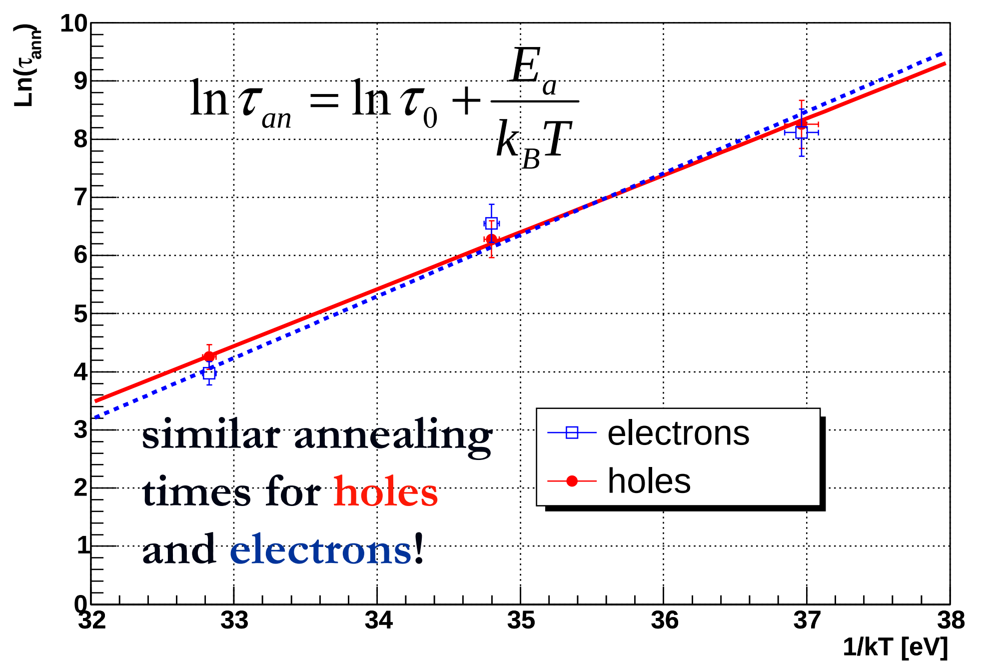
electrons	40°C	60°C	80°C
$\frac{\beta_0-\beta_\infty}{\beta 0}$	0.20 ± .03	0.23 ± 0.05	0.20 ± 0.03
τ_{ta}[min]	3347 ± 1290	648 ± 250	53 ± 10

holes	40°C	60°C	80°C
$\frac{\beta_0-\beta_\infty}{\beta 0}$	−0.29 ± .04	-0.46 ± 0.07	−0.40 ± 0.06
τ_{ta}[min]	3852 ± 720	534 ± 240	70 ± 35

- ~20 % change for electrons
- ~30-40 % change for holes

There is an ongoing systematic study for **charged hadron** irradiated samples!

Arrhenious relation – extrapolation



$$\ln \tau_{an} = \ln \tau_0 + \frac{E_a}{k_B T}$$

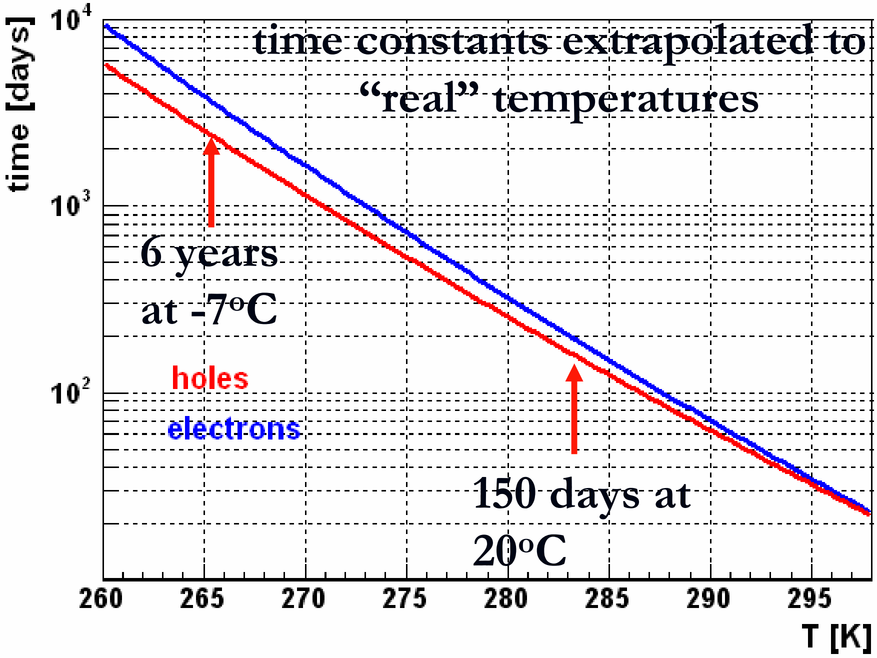
similar annealing times for holes and electrons!

	$\tau_0[min]$	E_{ta} [eV]
electrons	$3.88 \cdot 10^{-14}$	1.06 ± 0.1 eV
holes	$8.44 \cdot 10^{-13}$	0.98 ± 0.1 eV

Activation energies different from that of reverse annealing of N_{eff}

Have we overestimated the CCE at the end of LHC for p^+-n detectors ?

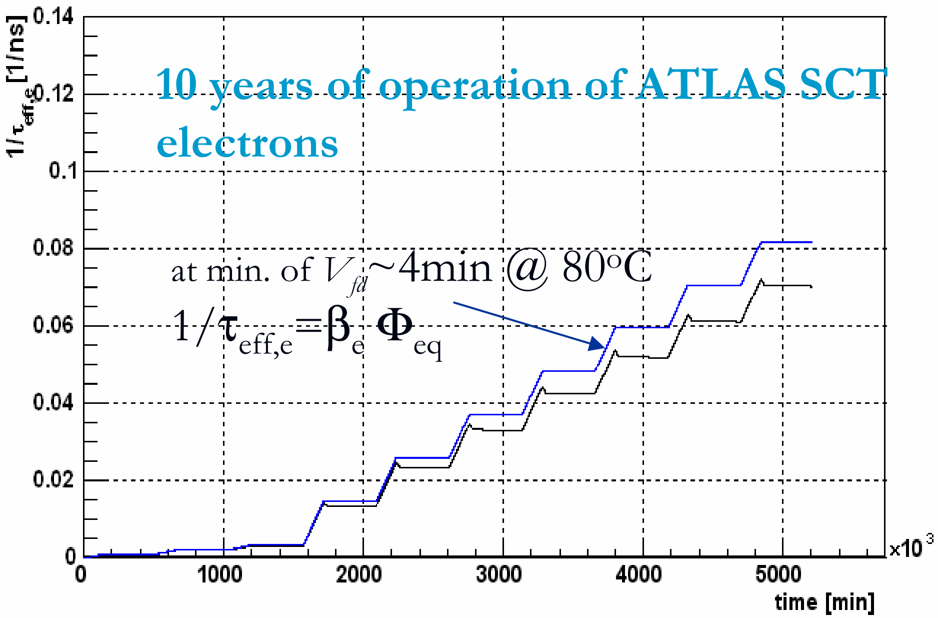
$\tau_{an,h}$ ~ 6 years at -7°C – at the end of operation large part of the initial damage will be “reverse annealed”

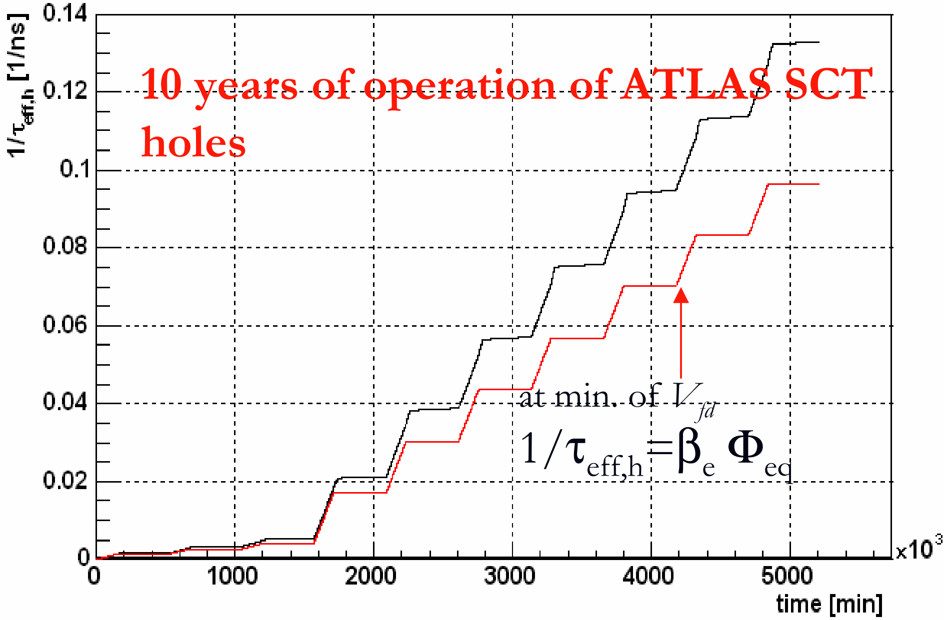


time constants extrapolated to “real” temperatures

6 years at -7°C

150 days at 20°C



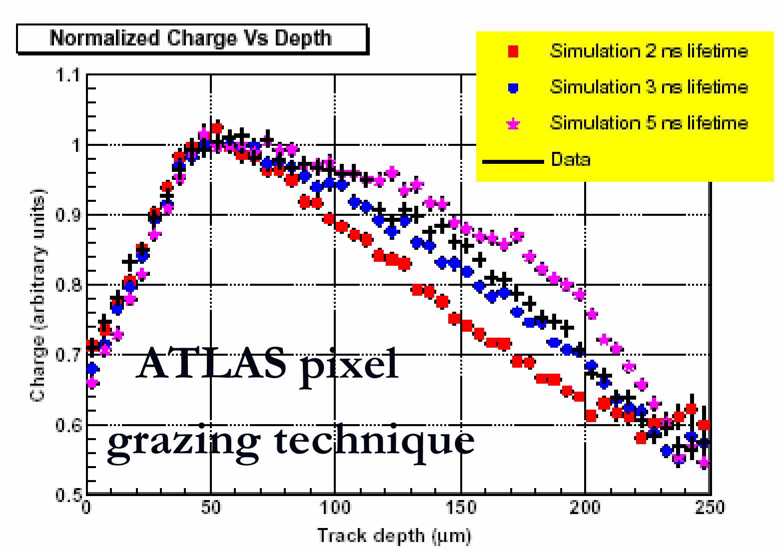


- ~30% larger trapping at the end of ATLAS-SCT for p^+n detectors as measured after annealing for 4 min at 80°C
- Few percent lower CCE than measured with accelerated annealing at the end of operation

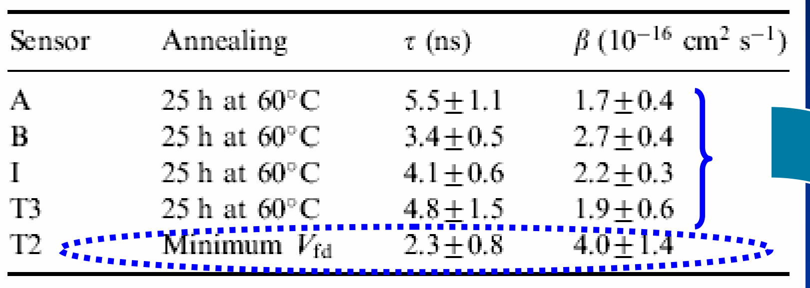
ATLAS detector ("hole coll.")
19% of the signal – e drift
81% of the signal – h drift

Do we see beneficial effect for electrons – pixel detector (n^+-n) will receive an order of magnitude higher fluence!

Impact of annealing on performance (I)



T. Lari, *Nucl. Inst. Meth.* A518 (2004) 349.



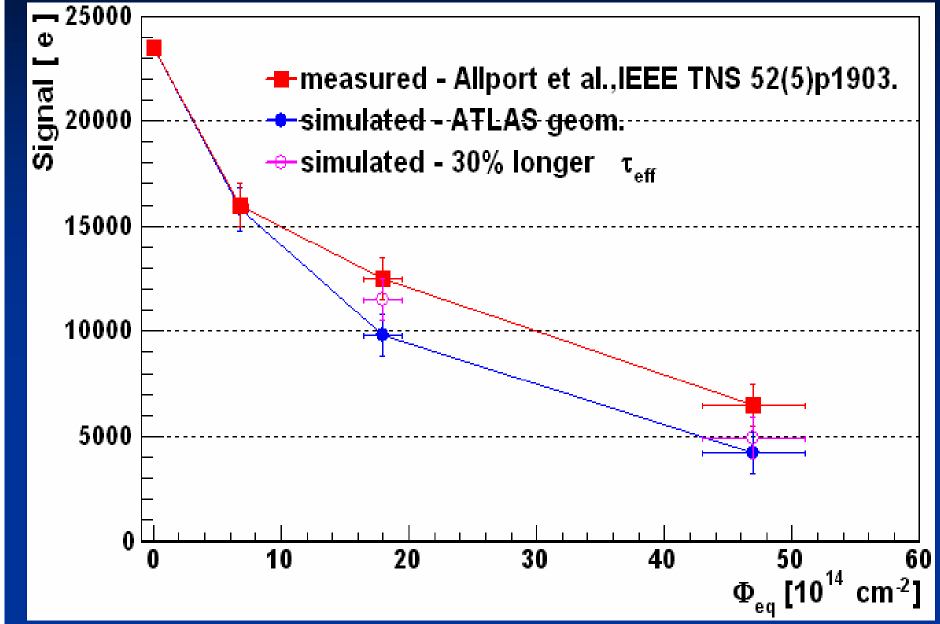
Sensor	Annealing	τ (ns)	β (10^{-16} cm^2 s^{-1})
A	25 h at 60°C	5.5±1.1	1.7±0.4
B	25 h at 60°C	3.4±0.5	2.7±0.4
I	25 h at 60°C	4.1±0.6	2.2±0.3
T3	25 h at 60°C	4.8±1.5	1.9±0.6
T2	Minimum V_{fd}	2.3±0.8	4.0±1.4

Larger effect than measured with TCT and n irradiated samples!

Annealing (long term) is **BENEFICIAL** for detectors "collecting electrons" especially if increase of N_{eff} reverse is not a problem (epi-Si, MCz detectors)

- increase of CCE with annealing (if the increase of V_{fd} can be kept at least moderate)
- compensate loss of depletion depth (V_{fd} increase) by larger signal from depleted part

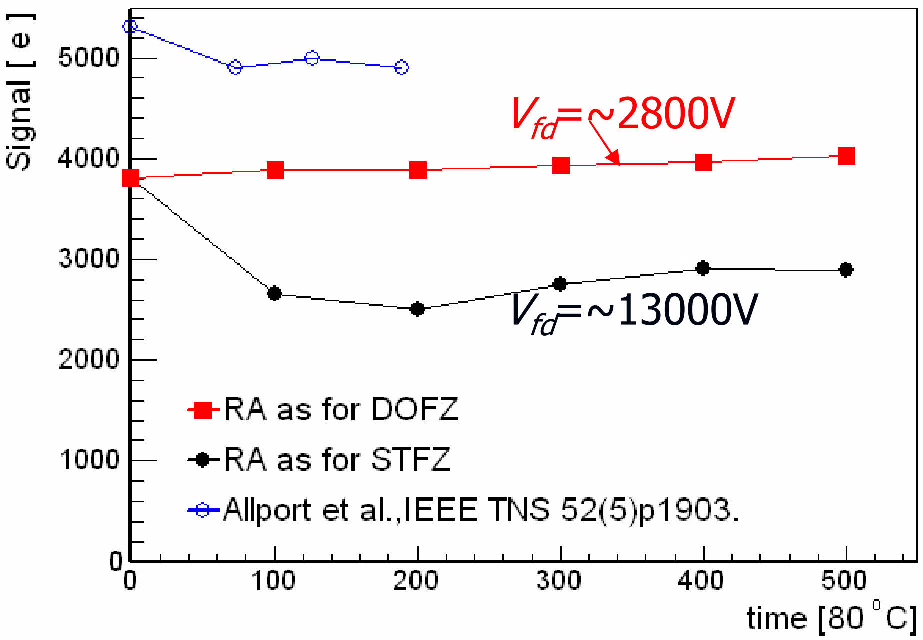
Impact of annealing on performance (II)



Sensor irradiated to 7.5x10^{15} p cm^{-2}
U=750 V, T=-10°C

During the reverse annealing the signal can even increase for highly irradiated detectors!

The loss due to smaller depletion depth is (over) compensated by smaller trapping!



Conclusions

Annealing of trapping times at different temperatures (40,60,80^{o}C) has been studied in neutron irradiated high resistivity STFZ detectors:

- increase of trapping probability by around 40% for holes ☹
- decrease of trapping probability by around 20% for electrons ☺
- the annealing seem to be governed by first order process
- time constants are around 600 min at 60^{o}C
- extrapolation of annealing time constants to lower temperatures can be done by using

$E_{a,h}$=0.98 eV $E_{a,e}$=1.06 eV

↓

The use of **n+** read-out is beneficial !

- can results in higher signal
- compensation of smaller depletion depth by smaller trapping

The use of **p+** read-out has an additional disadvantage!

(Charge collection efficiency at the end of operation of ATLAS-SCT might be overestimated!)