Annealing of Heavily Irradiated n-on-p Diodes at Temperatures 20°, 40°, 60° and 80°C

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Introduction

- Silicon sensors in upgraded LHC experiments will be exposed to radiation fluences up to 2×10^{16} n_{eq}/cm^2 which will substantively affect their properties: leakage current **(I)**, depletion voltage **(V_{fd})** and charge collection efficiency **(CCE).**

- Evolution of these properties highly depends on temperature and time spent after irradiation and can be slowed down or accelerated by temperature regulation.

- Previous studies in **RD48** with n-type silicon sensors irradiated up to $3 \times 10^{14} n_{eq}/cm^2$ found annealing acceleration factors with respect to 20°C:

40°C f=30

60°C f=550

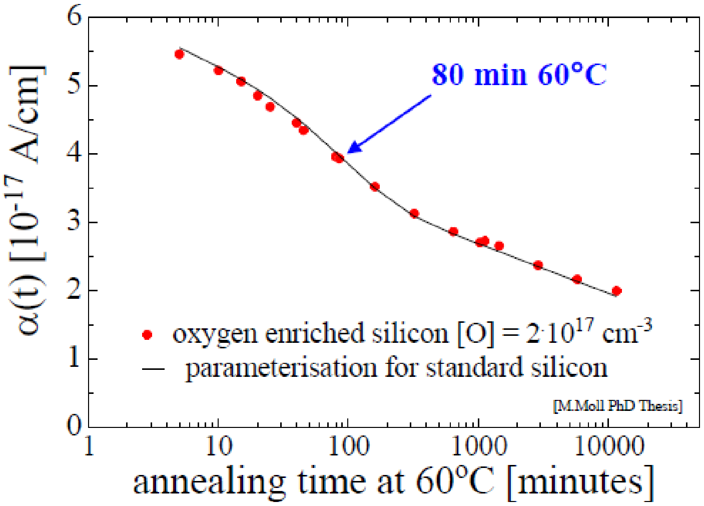
80°C f= 7400

- **Liverpool** group found discrepancies in the acceleration factors when applying to **CCE .** They suggested reduction by 2.1.

- **Prague** measurement provides further analysis of acceleration factors by annealing studies of **I** and **V_{fd}** from **CV** and **CC (V)** of diodes irradiated by neutrons to fluences 1×10^{15}, 2×10^{15} and 1×10^{16} at annealing temperatures 20°, 40°, 60° and 80°C.

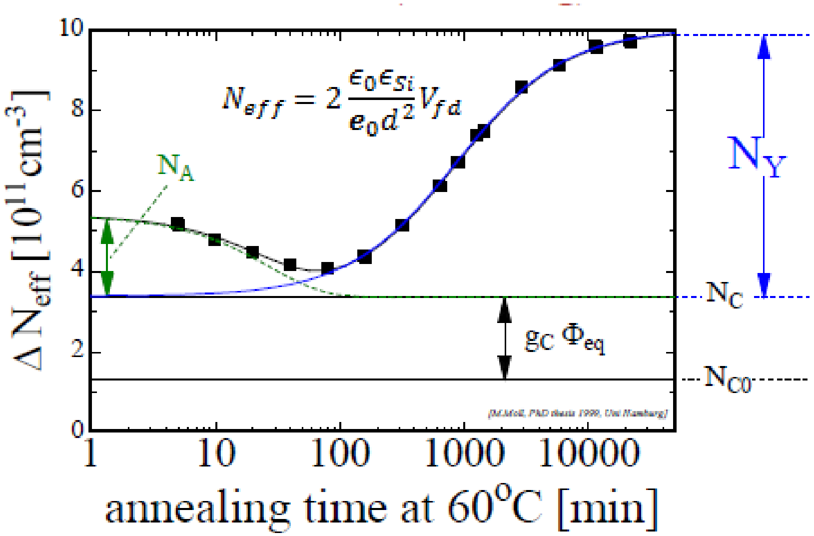
Evolution of leakage current and full depletion voltage after irradiation – Hamburg parameterizations

- Annealing behaviour of I/(VØ)



Leakage current decreases in time

Annealing behaviour of Neff



Short term: Beneficial annealing

Long term: Reverse annealing

- time constant depends on temperature

From M. Moll

How do these parameterizations fit to heavily irradiated silicon?

Samples and Annealing steps

Samples

- Diodes: Micron, n-on-p, FZ, approx. 0.4x0.4cm^2
- 12 diodes were irradiated with neutrons at Triga Research reactor in Ljubljana

Diodes	thickness	$\emptyset_{eq}$ [n/cm^2]
4 x 2328-6	300µm	1×10^{15}
4 x 2437-3	140µm	2×10^{15}
4 x 2437-3	140µm	1×10^{16}

Annealing steps

1. Annealing (at 20°C or heating in owen to 40°C, 60°C or 80°C)
2. Cooling to -20°C in frigo
3. CV and IV measurement
4. CC (V) measurement with infrared laser
5. Heating in Nitrogen environment

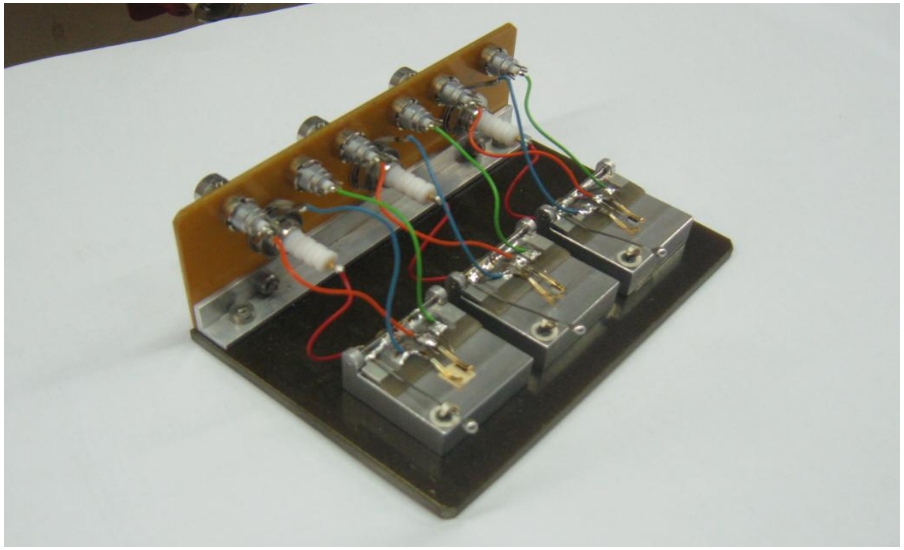
Many repeatings

Set Up

- Lab measurement set-up upgraded for HV measurements
- HV Power supply K248
- Signal generated by infrared laser (1060nm) in whole depth of silicon diode
- Trigger by pulse generator
- Digital scope Tektronix for automatic

data acquisition

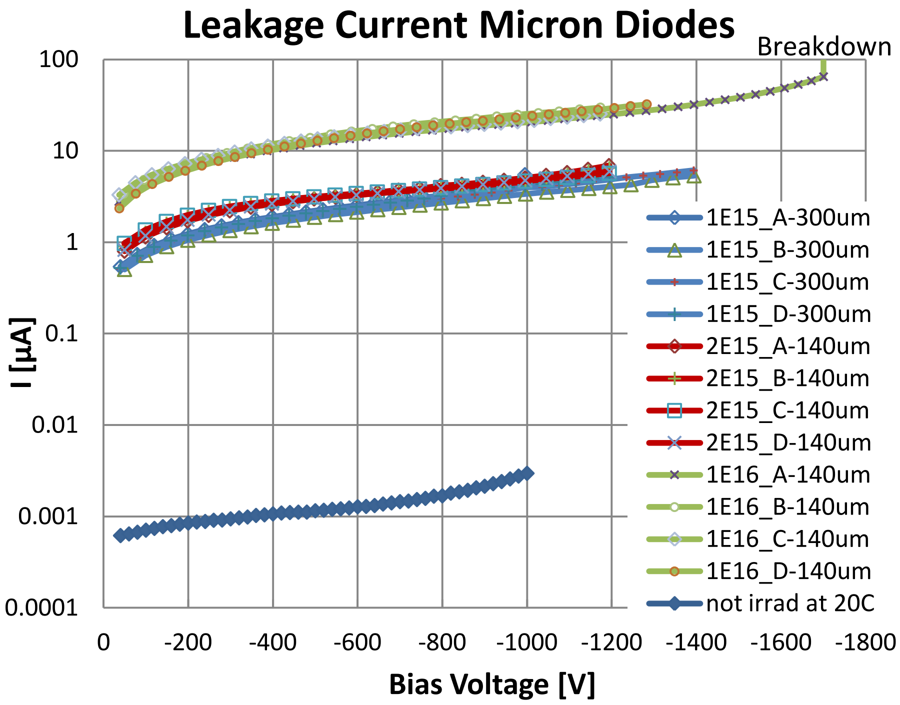
- Preamplifier (designed by Jan Šťastný)
- Temperature is read out at each step of measurement by PT100 directly connected to diode

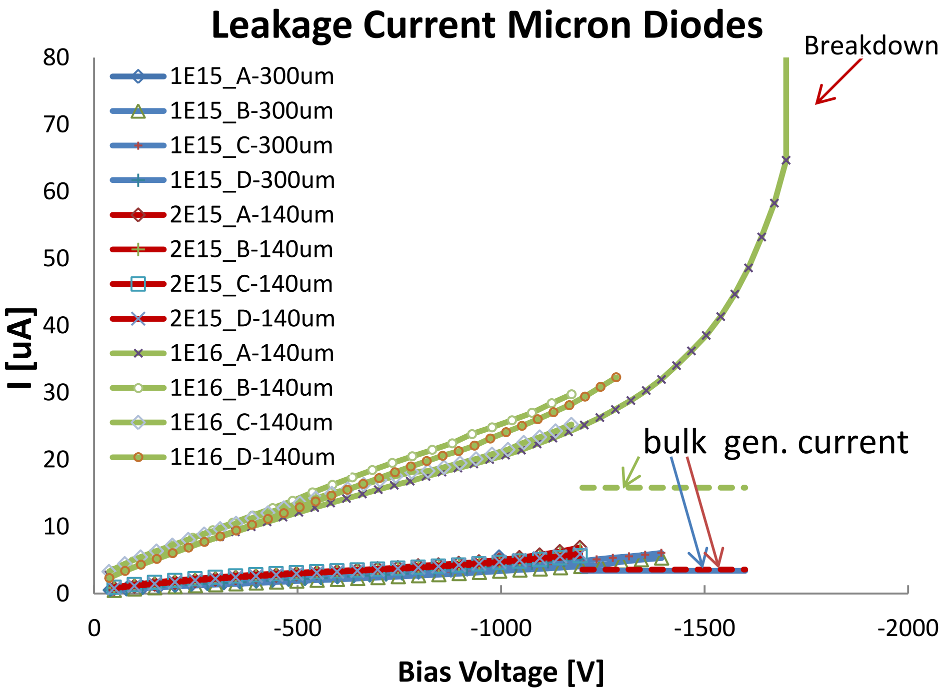


Probe box design by Zdenek Kotek

Leakage Current before controlled annealing steps

at -20°C, annealed approx. 10 days at RT



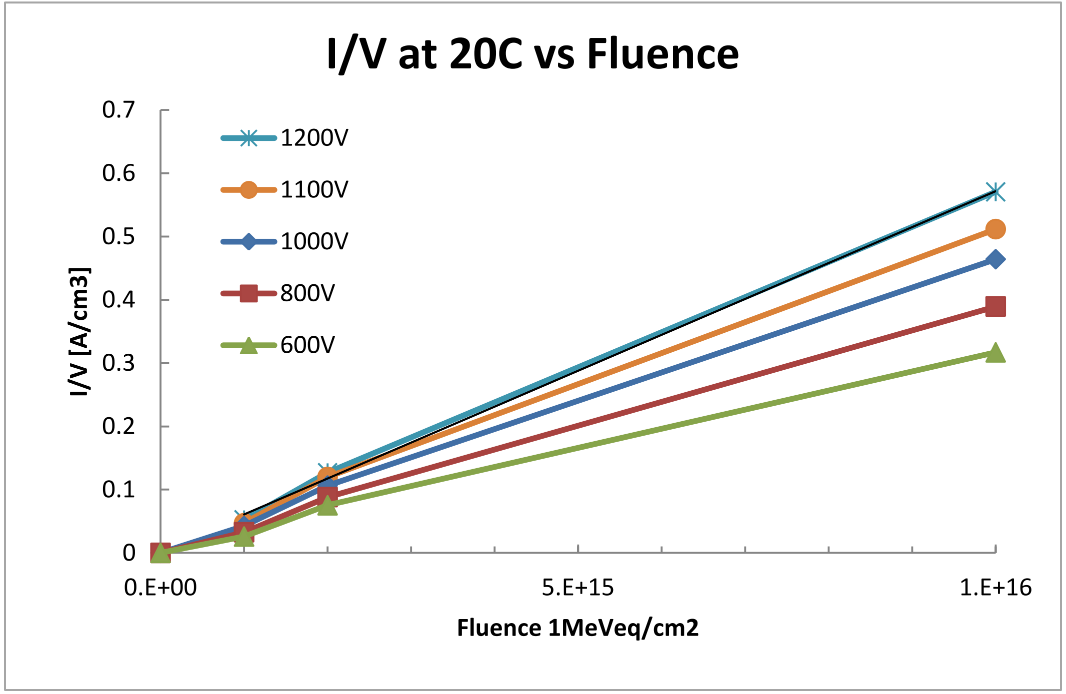


$$I_{meas}(V) = I_{gen}(V) + I_{av}(V)$$

Leakage Current before controled annealing steps

Leakage current vs Fluence measured after about 10 days annealing at RT

I/V normalized to +20°C,



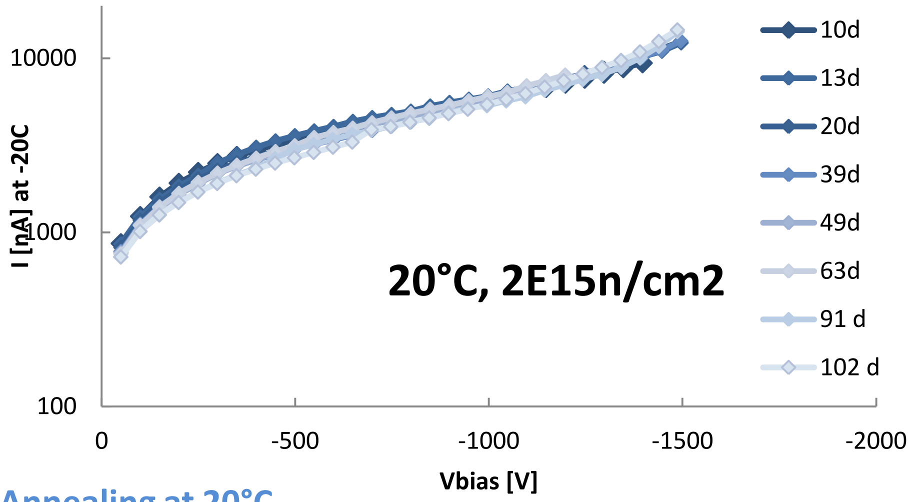
Damage parameter

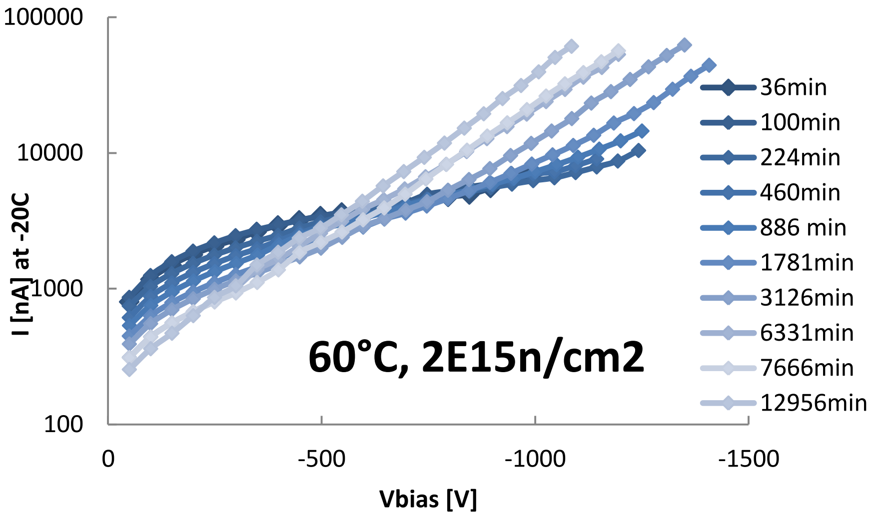
$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

at 1200V: alfa= $5.6*10^{-17}$ A/cm , V – whole volume
V_{fd} > 1200V for diodes irradiated to $1*10^{16}$n/cm^2

Alfa = (3.99 ± 0.03)10^{-17} A/cm at 80min at 60°C
M. Moll

Annealing of Leakage current at 20°C, 60°C and 80°C: $2*10^{15}$n/cm^2 140μm





Annealing at 20°C

- no change in IV up to 100 days

Accelerated annealing

- At low bias voltages current decreases in time as expected from Hamburg parameterization for leakage current
- At high voltages current increases with annealing due to multiplication effect
- with increasing annealing time multiplication starts at lower voltages

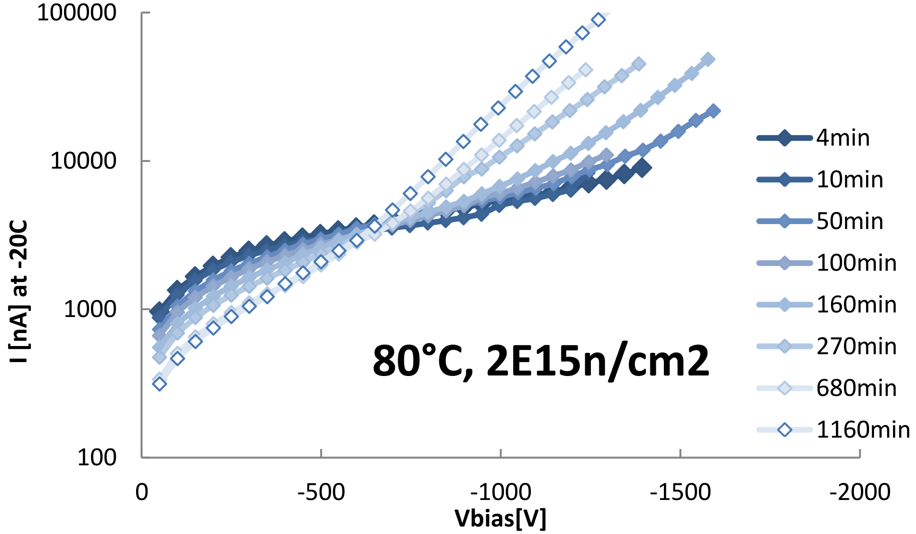
Accelerated Annealing at 60°C

At 1000V multiplication indication appears after 800min

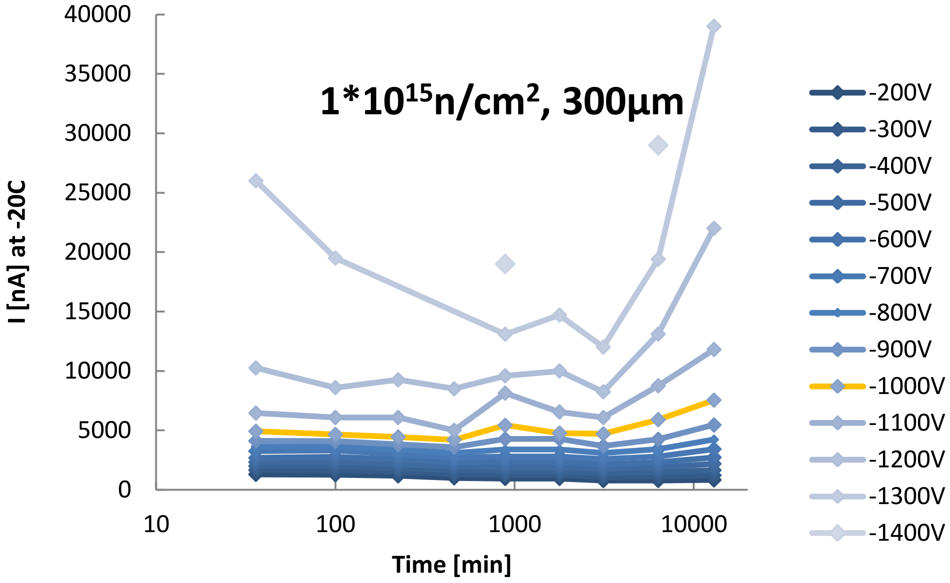
Accelerated Annealing at 80°C

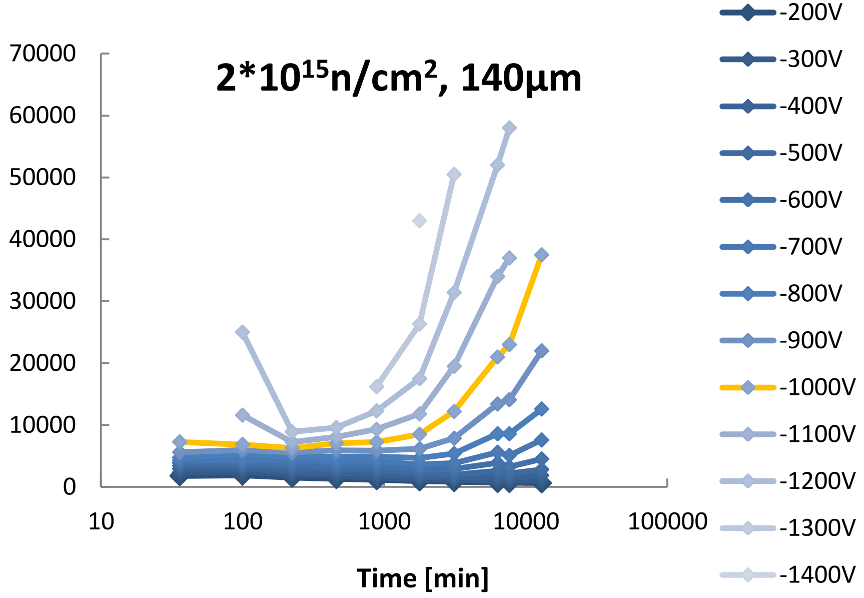
At 1000V multiplication indication appears after 50min

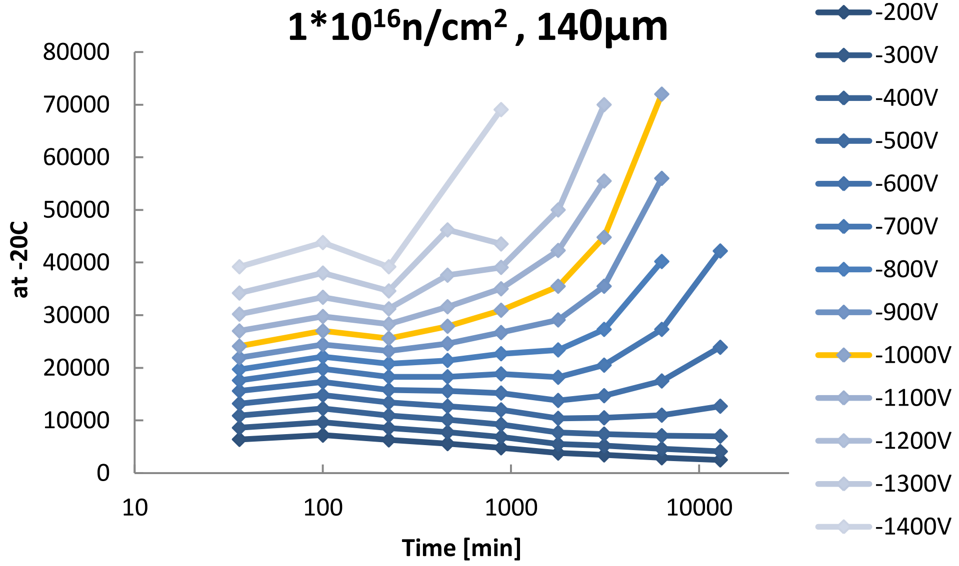
More measurements at 20°C and 40°C need to be done for longer annealing times to evaluate accelerating factors to 20 ° C



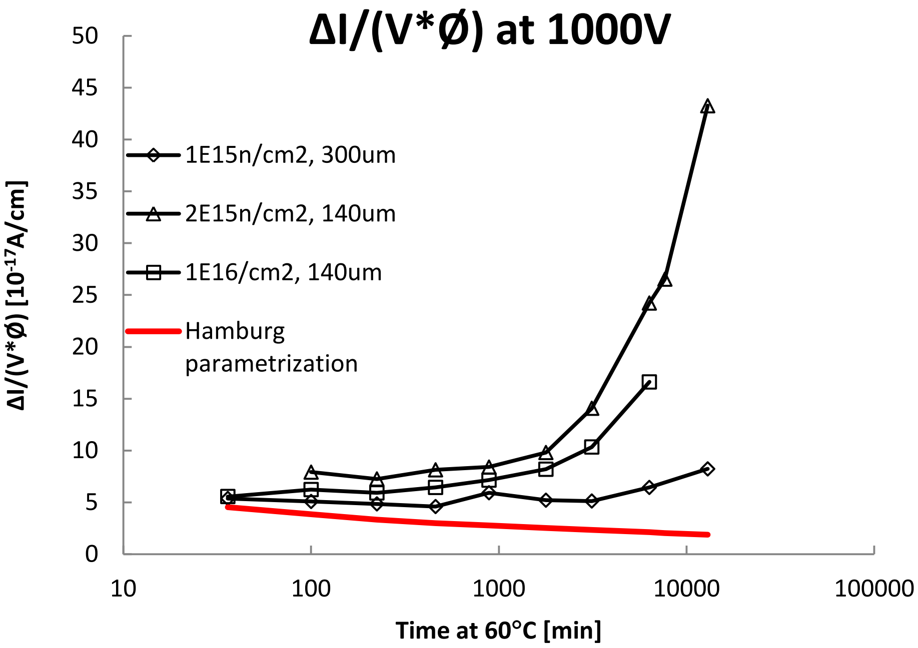
Leakage current vs Annealing time at 60°C for different fluences







Comparison with parameterization for low fluences
- annealing at 60°C

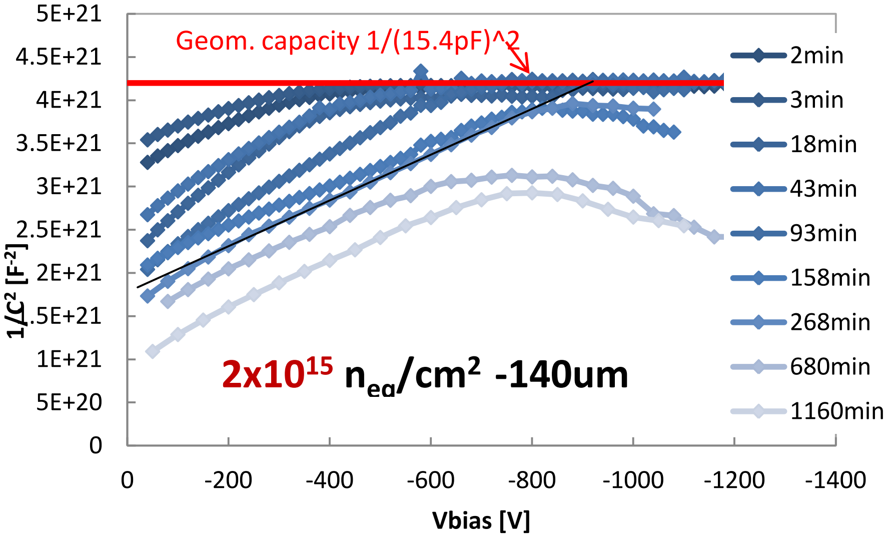


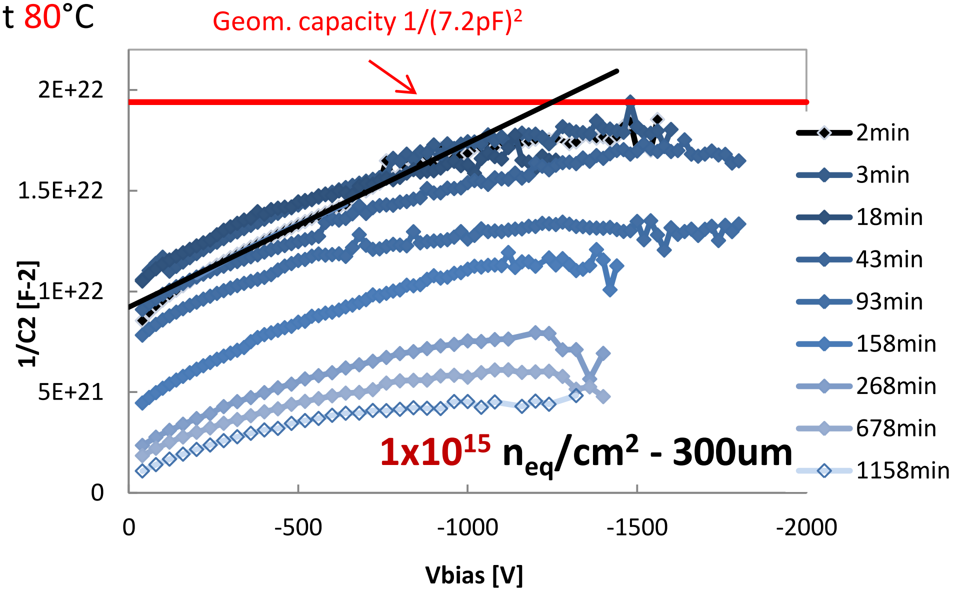
- Leakage current higher then expected due to charge multiplication
- **Presence of multiplication and the effect of thickness should be considered in parameterization for high fluences**

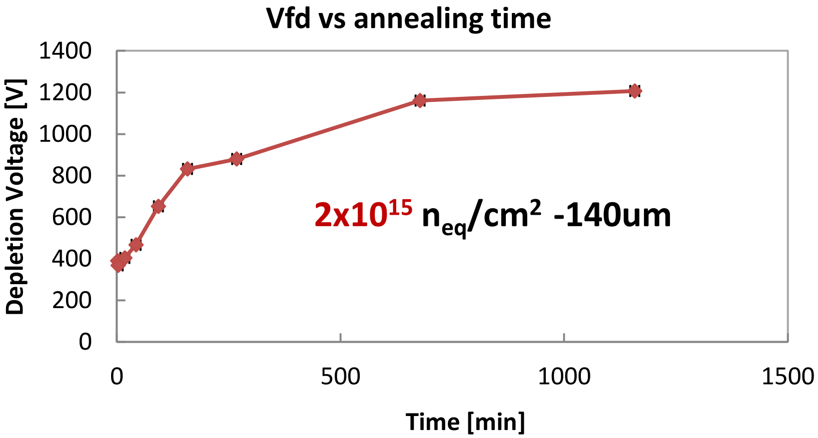
I normaliyed to +20C
V- whole volume
V_{fd} > 1000V
2*10^{15} 140um diode fully depleted until 3000min at 60C

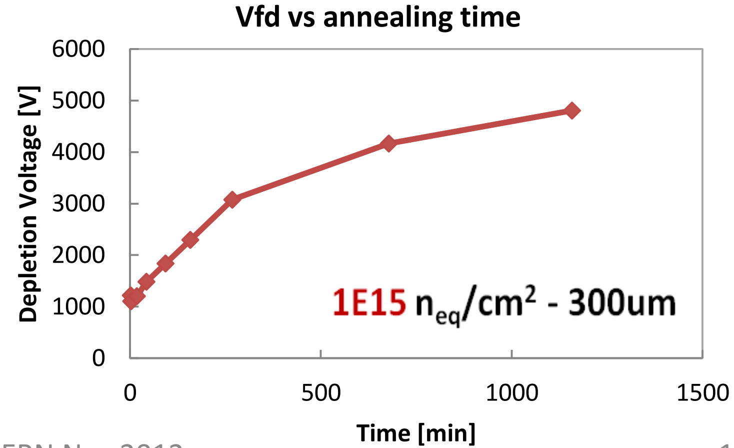
Evaluation of Full Depletion Voltage from CV measurements

10kHz (most stable measurements at -20°C)
Vfd defined as the cross section of linear fit before the kick and geometrical bulk capacity $1/(C_{bulk})^2$ because the plateau is not obvious at highest fluence or thicker sensor
Examples of CV at different annealing times at 80°C



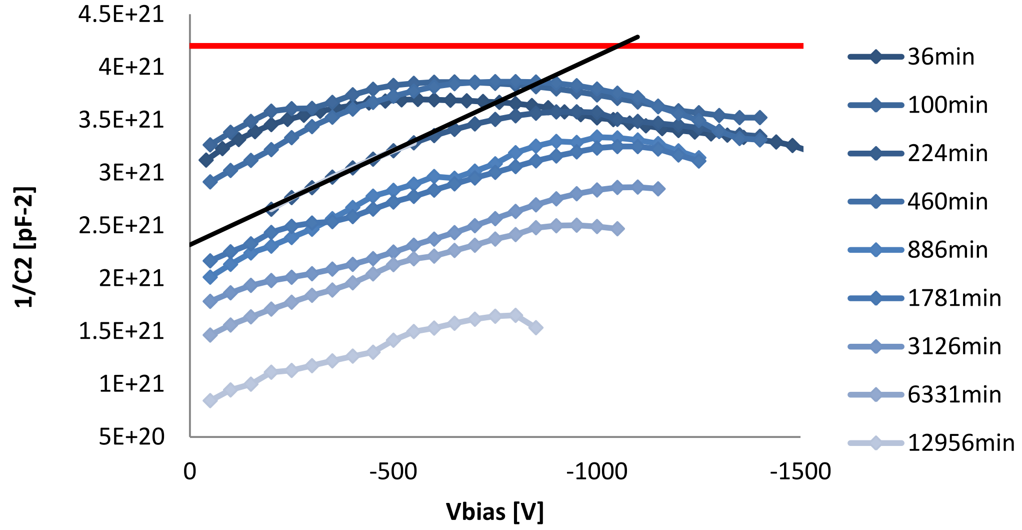




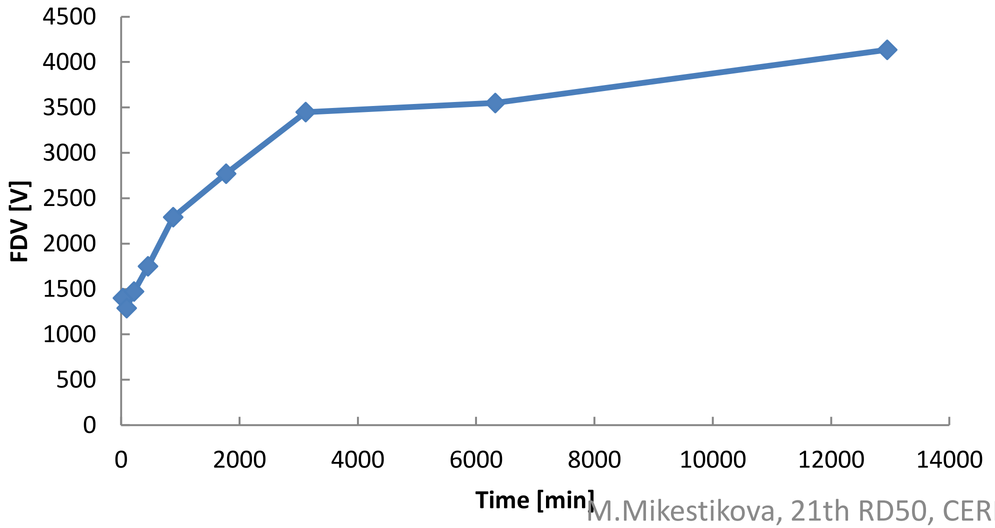


Evaluation of Full Depletion Voltage from CV measurements

CV at different annealing time at 60°C – 1x10^{16} neq/cm2 - 140um



Vfd vs time at 60°C: 1E16n_{eq}/cm^2



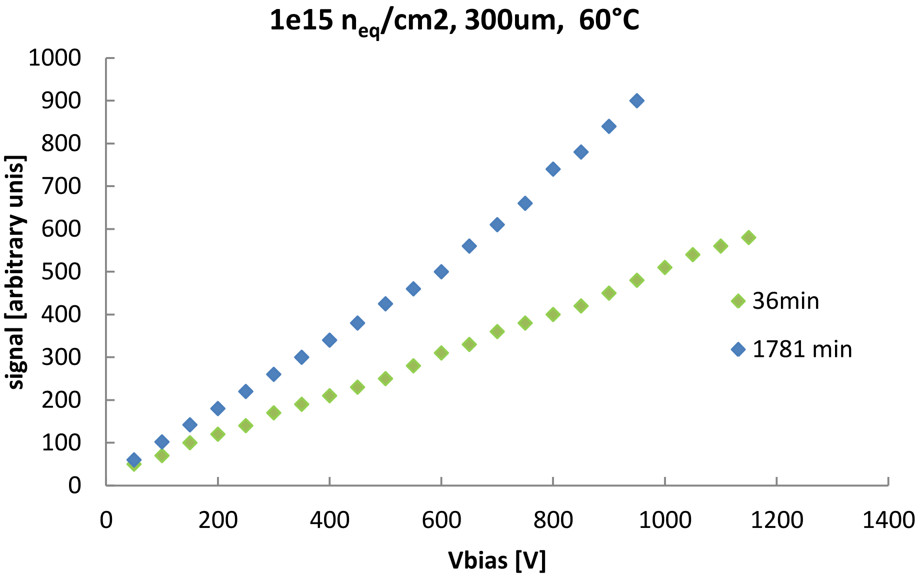
Evaluation of Full Depletion Voltage from CC(V) measurements with infrared laser

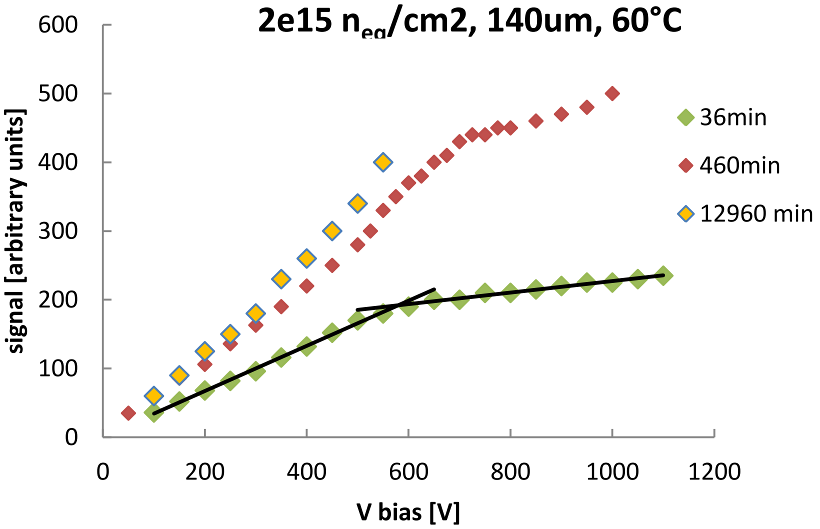
- V_{FD} evaluated as a kick in CC(V) curves

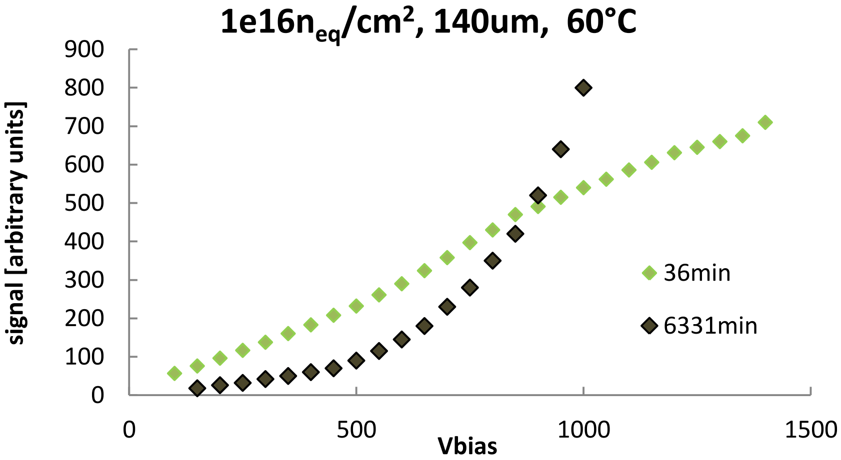
- The kick observed only at thin diodes irradiated to $2*10^{15}n_{eq}/cm2$

- At longer annealing times observed avalanche effect – charge multiplication

- at long annealing times high voltage measurement are not possible due to high noise caused by multiplication







Comparison of the absolute signal amplitude not possible just comparison of the position of the kick

Comparison of Predicted V_{fd} from Hamburg model and Measured Vfd at minimum

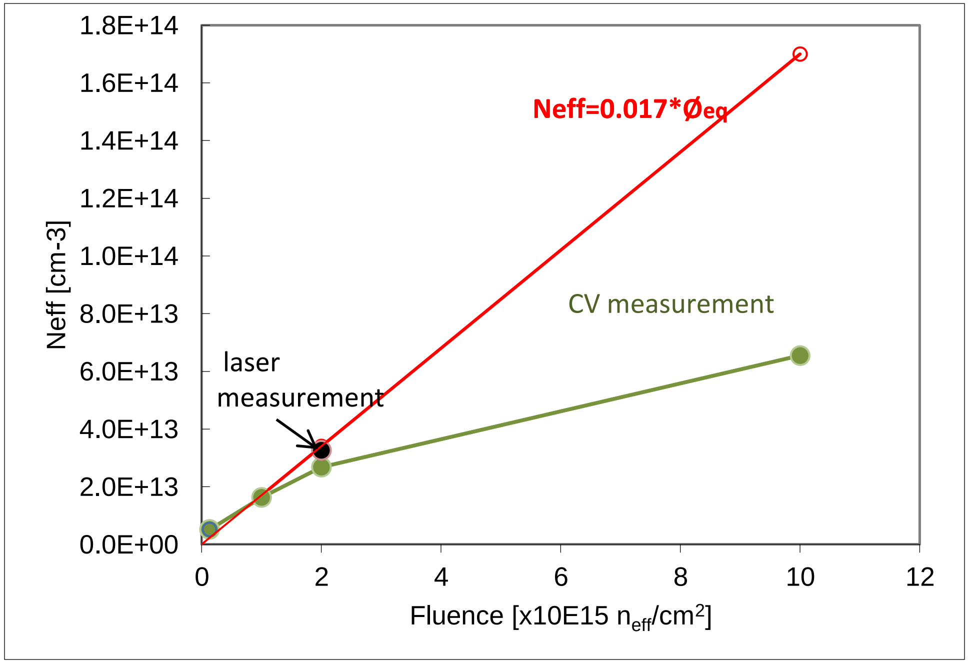
Stable space charge concentration can be estimated using the minimum of time dependence plot and is parameterized by $\Delta N_{eff} = g_c \cdot \emptyset_{eq}$

Expected V_{fd} values were evaluated using $g_c = 0.017 cm^{-1}$ for neutron irradiated FZ silicon up to $\emptyset_{eq} = 6*10^{14} n_{eq}/cm^2$

[G. Kramberger et al. ,A612 (2010)]

	Expected V_{fd}	**Measured V_{fd} in minimum**
300um $1*10^{15}$	1150 V	1150 V
140um $2*10^{15}$	500 V	400 V (CV) 490V (CCV)
140um $1*10^{16}$	2500 V	980 V

stable space charge concentration vs fluence

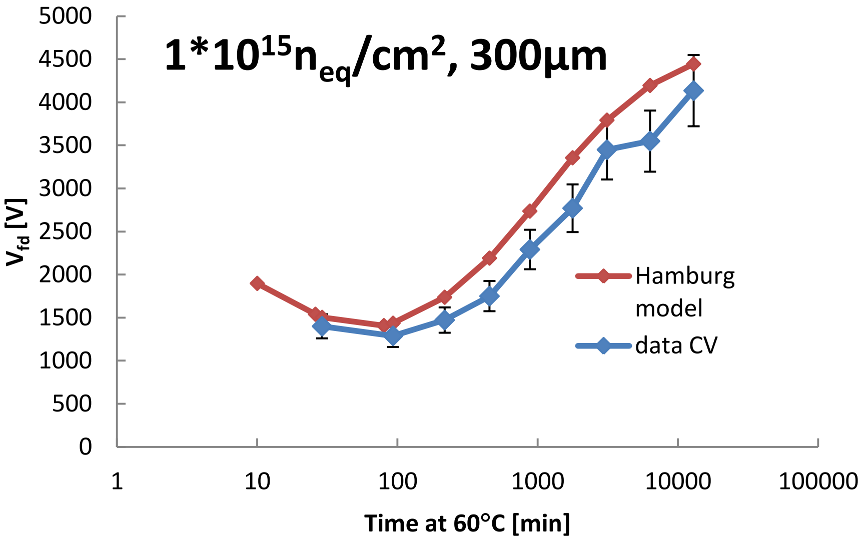


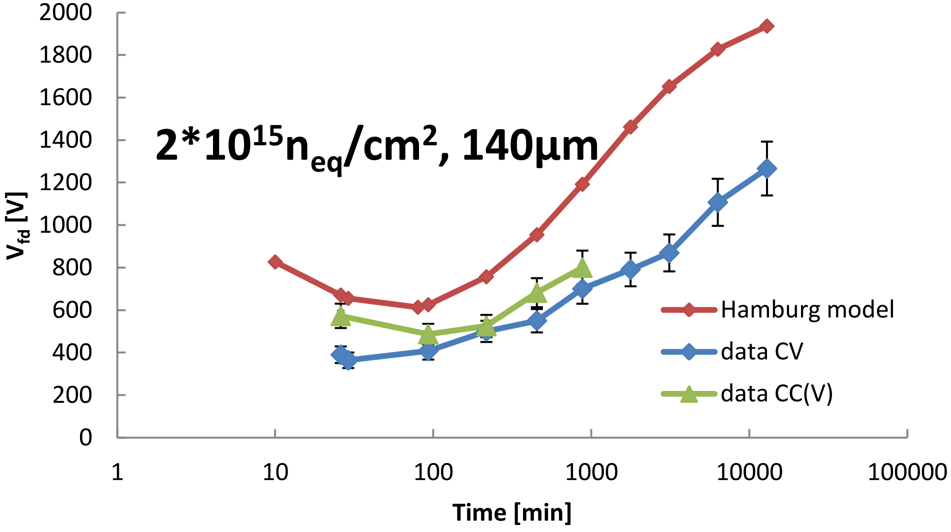
Q: At heavy irradiation

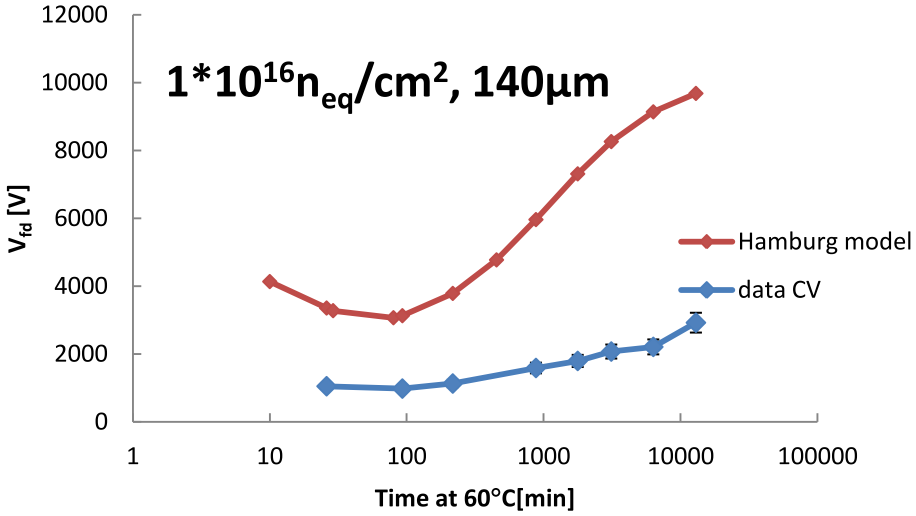
a) stable space charge concentration doesn't have linear behavior or

b) V_{fd} from CV has no meaning

Comparison of Predicted evolution of V_{fd} from Hamburg model and Measured V_{fd} at 60°C







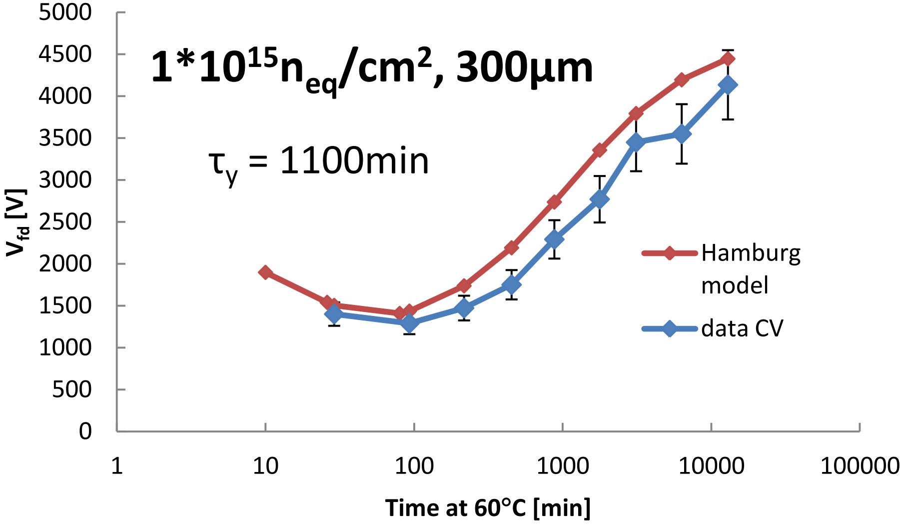
- Predicted V_{fd} calculated using Hamburg model with following parametrs:
  Stable: g_c=0.017 cm^{-1}
  Short term: g_a = 0.018 cm^{-1}, τ_a = 19min
  Long term: g_y = 0.053 cm^{-1}, τ_y = 1100min

- evolution of V_{fd} corresponds to Hamburg model only with diodes irradiated to fluence $1*10^{15}$ n/cm^2

- V_{fd} from CV 100 -150V lower then from CC(V)

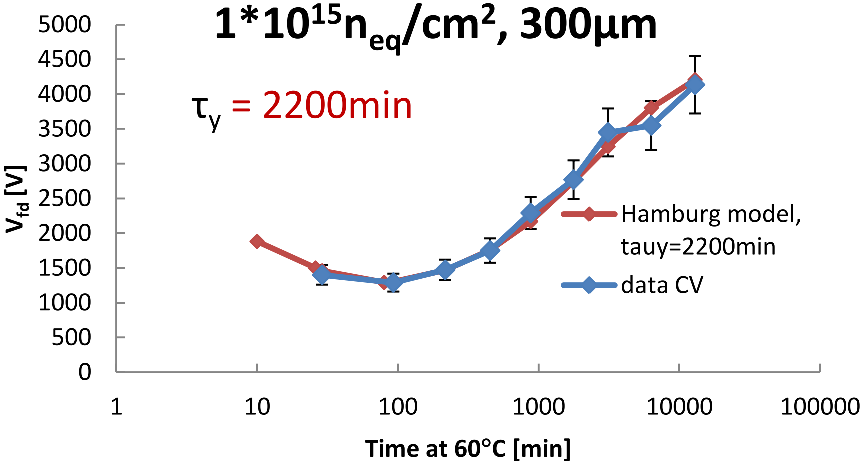
Comparison of Predicted evolution of V_{fd} from Hamburg model and Measured V_{fd} at 60°C with different time constant τ_y of reverse annealing at 60°C

Reverse annealing seems to be 2x slower than predicted



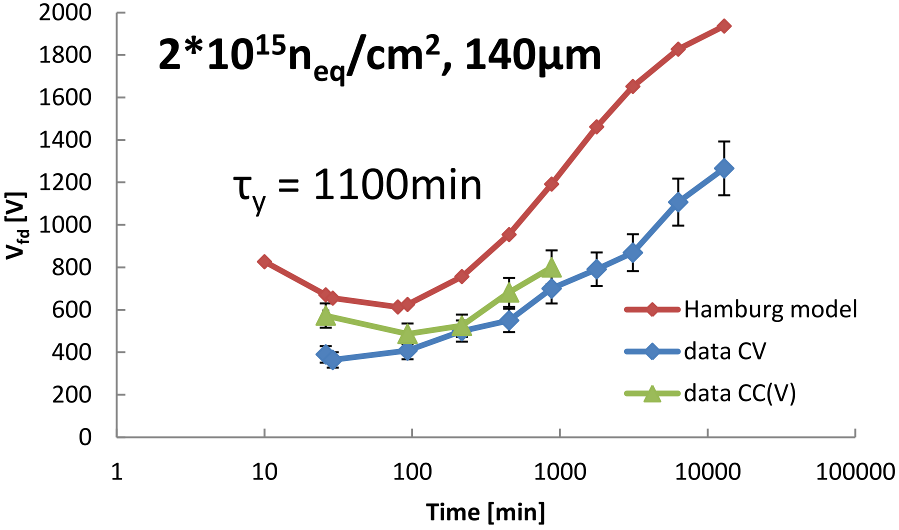
$1*10^{15} n_{eq}/cm^2$, 300µm

τ_y = 1100min



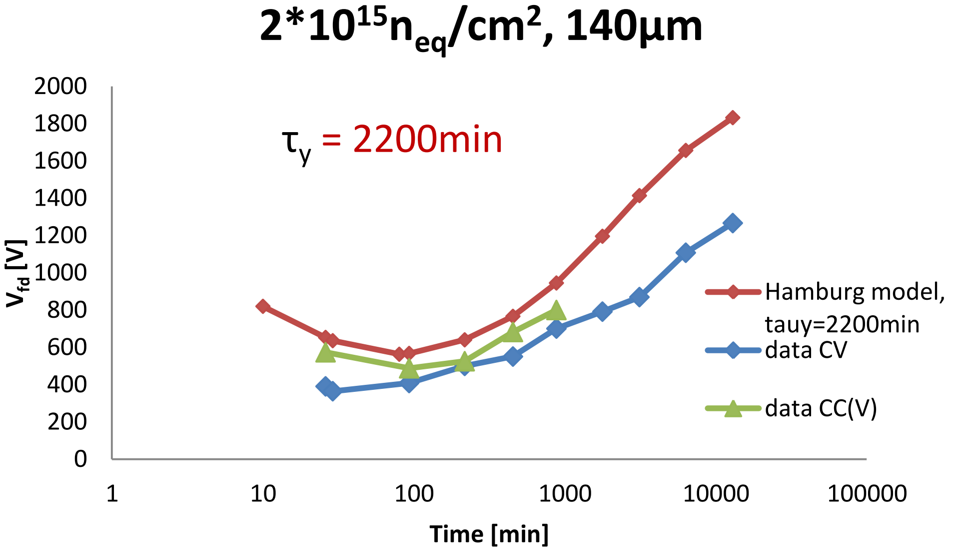
$1*10^{15} n_{eq}/cm^2$, 300µm

τ_y = 2200min



$2*10^{15} n_{eq}/cm^2$, 140µm

τ_y = 1100min

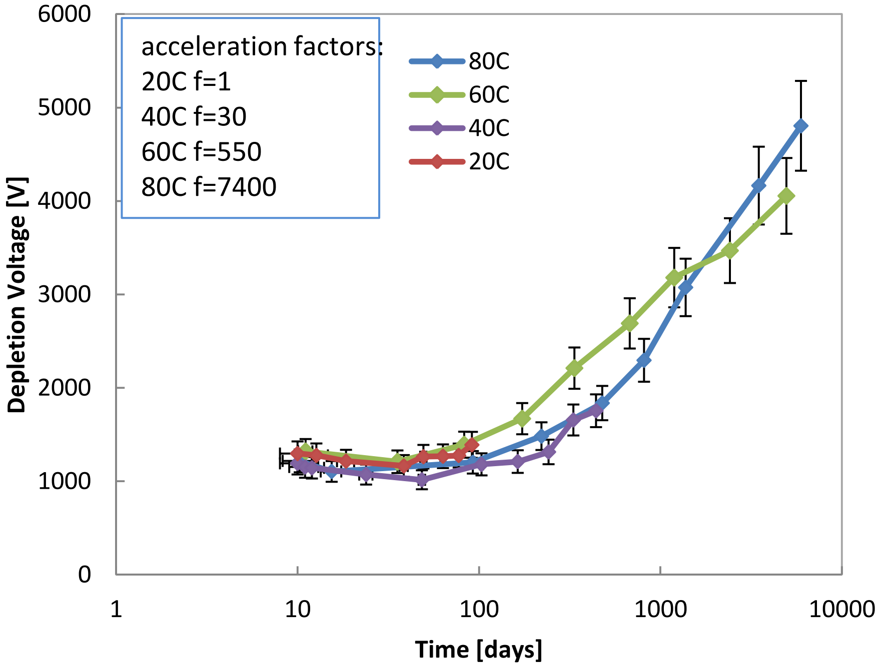


$2*10^{15} n_{eq}/cm^2$, 140µm

τ_y = 2200min

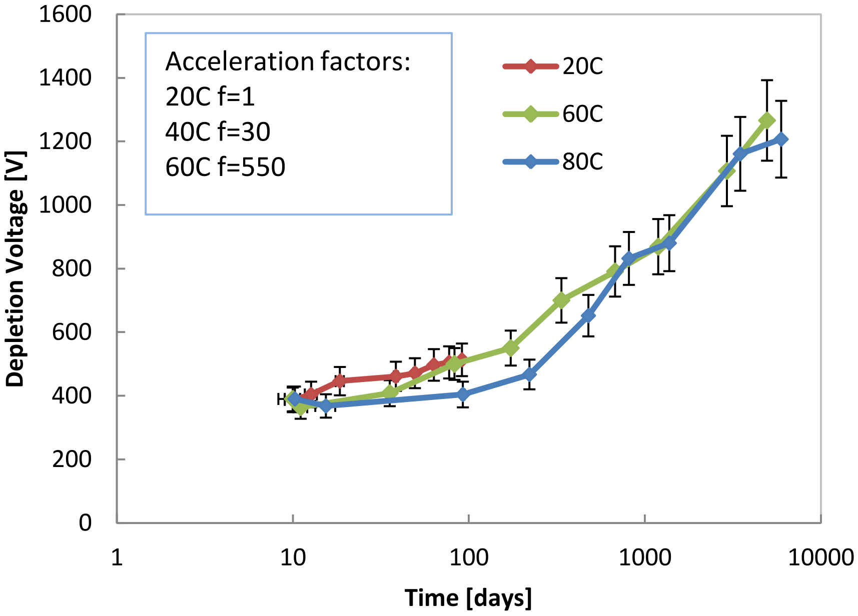
Compararison of annealing of V_{fd} from CV at different temperatures, $1*10^{15}n/cm^2$ 300µm

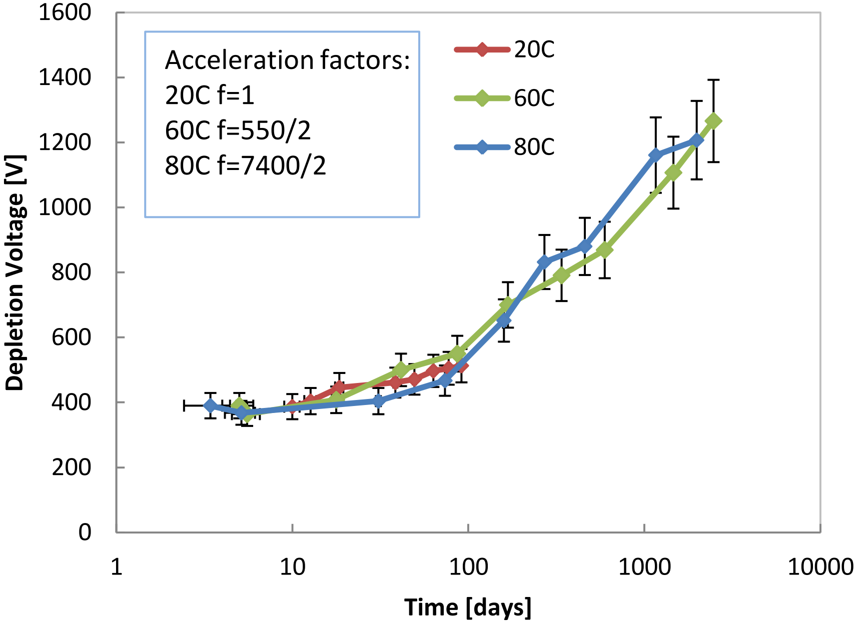
Accelerated annealing at 40°, 60° and 80°C scaled to 20°C by RD48 acceleration factors



- Accelerated Annnealing of Vfd scales quite well to 20°C in measured interval of time.
- Need longer 20°C annealing to compare reverse annealing data.

Comparison of annealing of V_{fd} from CV at different temperatures, $2*10^{15} n_{eq}/cm^2$ **140µm**


Acceleration factors:
20C f=1
40C f=30
60C f=550

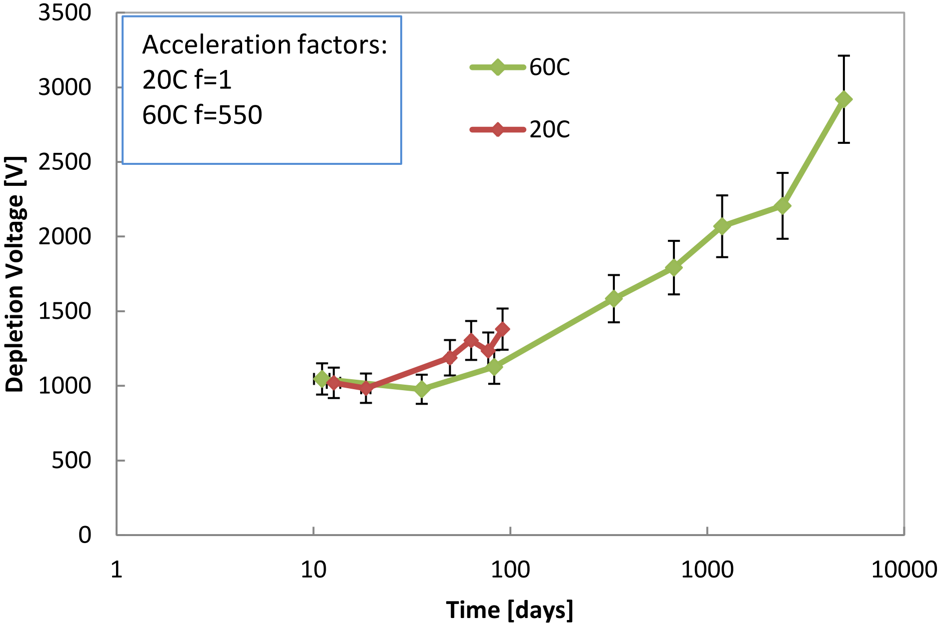

Acceleration factors:
20C f=1
60C f=550/2
80C f=7400/2

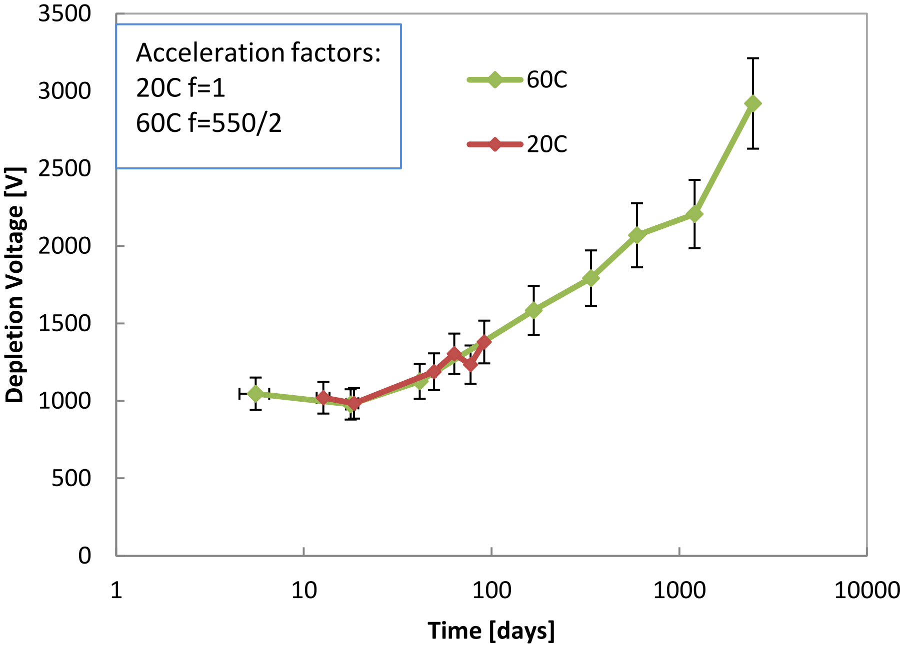
RD48 acceleration factors

Acceleration factors reduced by 2 better fit the 20°C annealing

Need longer 20°C annealing to compare reverse annealing data

Comparation of annealing of V_{fd} from CV at 20°C and 60°C, $1*10^{16} n_{eq}/cm^2$ **140µm**





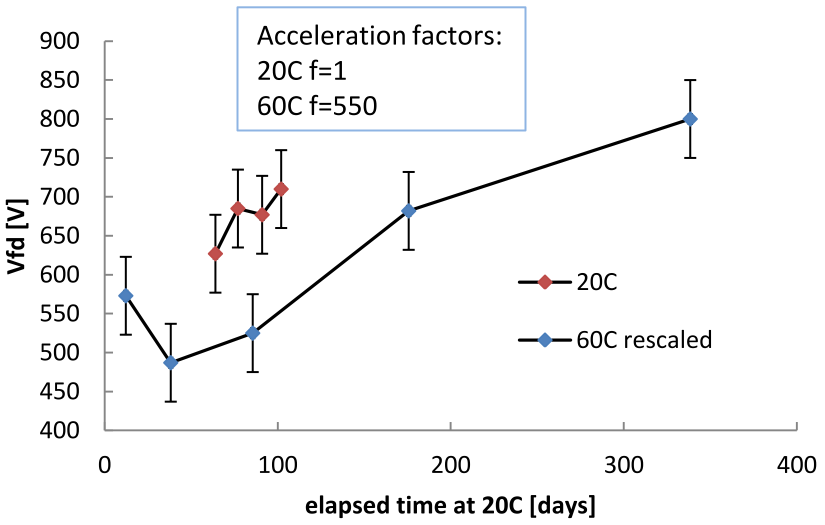
RD 48 acceleration factors

Acceleration factor reduced by 2 better fit the 20°C annealing

Need longer 20°C annealing to compare reverse annealing data

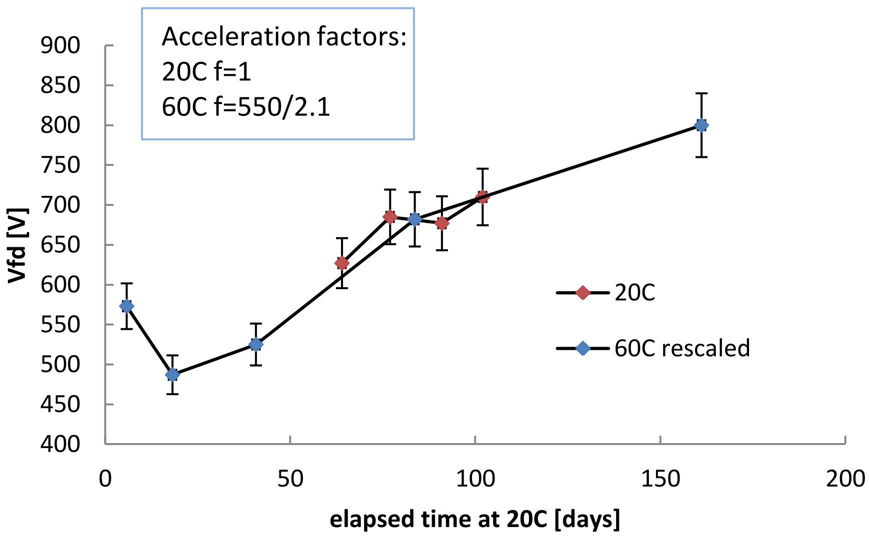
Comparison of 20°C and 60°C annealing of V_{fd} from Laser measurement

$2*10^{15}$ n/cm2, f=550



RD 48 acceleration factor 550

$2*10^{15}$ n/cm2 f=550/2.1



Acceleration factor reduced by 2.1 as suggested by G.Casse

Conclusion

Annealing of leakage current and full depletion voltage was performed on p-type diodes irradiated with neutrons with high fluences: $1*10^{15}$, $2*10^{15}$ and $1*10^{16}$n/cm^2 at 20°, 40°, 60° and 80°C to verify Hamburg parameterizations deduced from low fluences measurements.

Measurements done with diodes irradiated to fluence **$1*10^{15}$ n_{eq}/cm^2** correspond to prediction of low fluence parameterization

- Evoluation of full depletion voltage fit to Hamburg model but the Reverse annealing seems to be 2x slower than predicted
- Leakage current behavior follows the expectation until multiplication appears at high voltages and at long annealing times

For diodes irradiated **to $2*10^{15}$** and **$1*10^{16}$ n_{eq}/cm^2** :

- Stable space charge concentration from CV measurements is no more linear function of fluence, the values of V_{fd} are 3 times lower then expected for $1*10^{16}$.
- Accelerating factors of reverse annealing divided by 2 better fit the RT annealing
- Leakage current is strongly influenced by charge multiplication

Measurement done with higly irradiated samples showed that low fluence parameterization must be modified. Parameterization for high fluences requires more parameters than for low fluences. It would have to include also parameters like thickness and presence of charge multiplication

Such a parameterization might be difficult or not possible, and in this case a series of tables or experimental current curves for the various thicknesses and voltages has to be used as reference.