Annealing effects on operation of thin Low Gain Avalanche Detectors

G. KRAMBERGER, V. CINDRO, A. HOWARD, Ž. KLJUN, I. MANDIĆ, M. MIKUŽ

JOŽEF STEFAN INSTITUTE, LJUBLJANA

A BROAD COLLABORATION WITH ATLAS-HGTD GROUPS

Motivation

- LGADs will be used at ATLAS-HGTD and CMS-ETL as timing detectors
- Lots of studies have been done, but a very large majority of those after 80 min@60°C annealing (corresponds roughly to the time of yearly maintenance period at close to room temperatures)
- Annealing studies are needed:
  - to predict a long term operation and plan an operation scenario
  - to know the limits/dangers of possible unplanned events/situations
- Annealing is important in detector operation
  - almost all detector bulk properties change with annealing (trapping, leakage, effective doping)
  - annealing can influence initial acceptor removal

This presentation will concentrate on gain layer depletions voltage, effective doping concentration, leakage current, charge collection and timing measurements.

studies submitted for publication and available at http://arxiv.org/abs/2005.14556

Effective doping concentration

Hamburg model

$$N_{gl}(t) = N_B\left(1-\eta\left(1-\exp(-c\cdot\Phi_{eq})\right)\right) + N_{deep}(t)$$ ← initial acceptor removal $c(N_B, \Phi_{eq}, t)$

$$N_{deep}(t) = N_a \exp(-t/\tau_a) + N_c + N_y\left(1-\exp(-t/\tau_Y)\right)$$ ← deep defects behaviour with time

$N_a = g_a \cdot \Phi_{eq}$ $N_c = g_c \cdot \Phi_{eq}$ $Ny = g_y \cdot \Phi_{eq}$

deactivation of effective acceptors

defects constant in time

activation of effective acceptors

The above equation is valid for both gain layer and bulk:

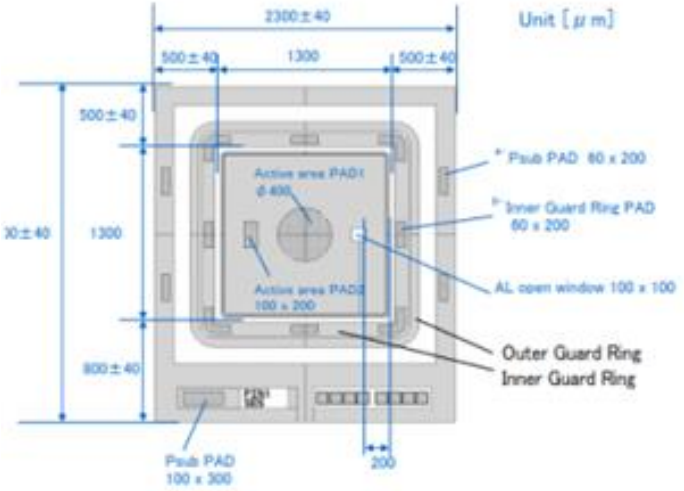
- bulk layer dominated by deep defects (max. N_{deep}~10^{14} cm^{-3})
- gain layer dominated by initial acceptor term (N_B~10^{16} cm^{-3})
- The study concentrated to annealing of initial doping concentration $c(N_B, \Phi_{eq}, t)$ as well as on the bulk
  - Are these equations still valid in the presence of enhanced hole concentration?
  - Are they valid in very high electric fields?

Samples, setup and procedures

- HPK (LGAD run 4) samples of different gain layer doses, bulk resistivity and thickness

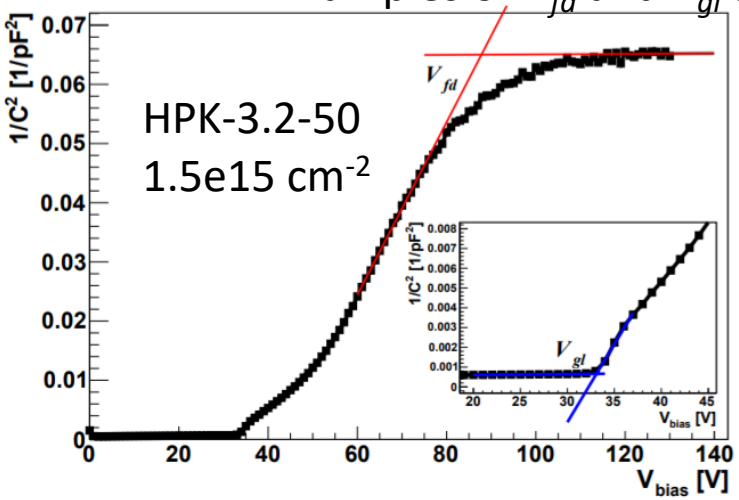
Sample	Thickness	V_{gl}	V_{fd}	Φ_{eq} $[10^{14}\ \mathrm{cm}^{-2}]$
HPK-1.1-35	35 μm	31 V	195 V	8, 15, 30
HPK-1.2-35	35 μm	33 V	36 V	8, 15, 30
HPK-3.1-50	50 μm	42 V	49 V	8, 15, 30
HPK-3.2-50	50 μm	56 V	64 V	4, 6, 8, 15, 22.5, 30

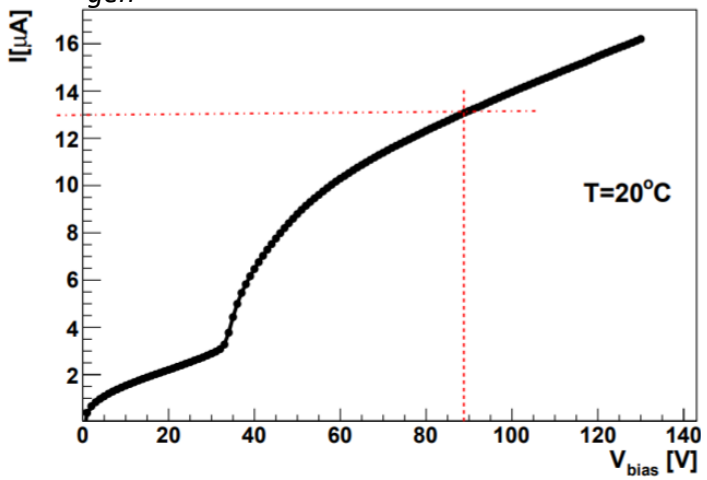
1.3x1.3 mm^2
single pad devices



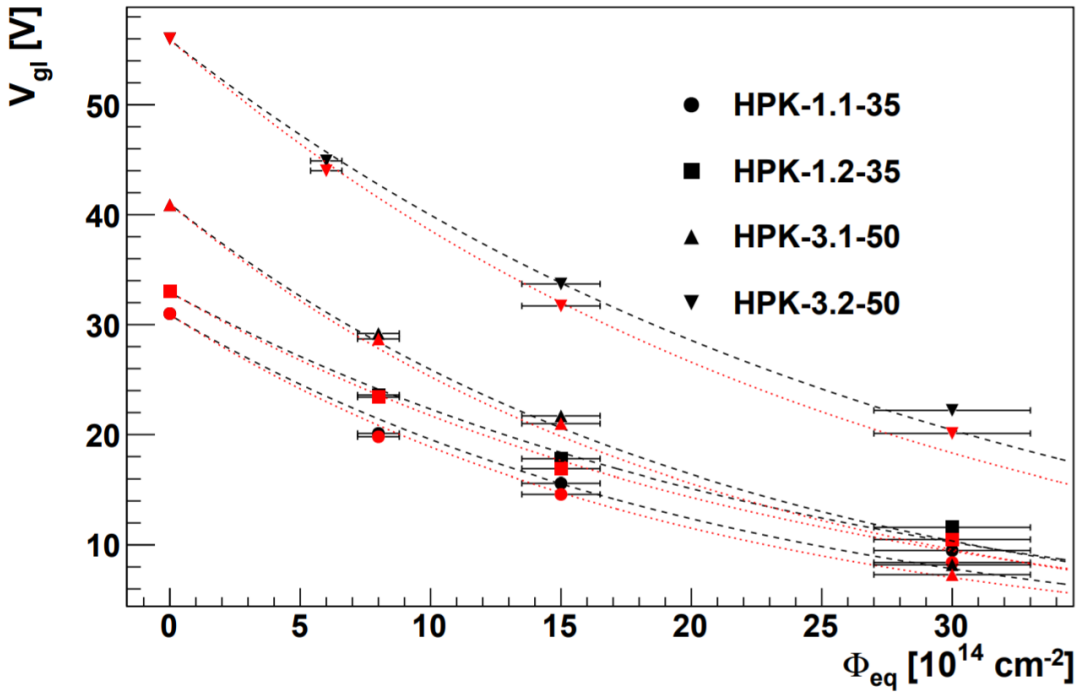
- Irradiated with neutrons at JSI reactor
- Measurements were done with two different setups:
  - probe station for CV (20°C, 500 mV, 10 kHz) and measurements
  - timing measurements with ^{90}Sr setup

Examples of V_{fd} and V_{gl} and I_{gen} determination





Annealing of V_{gl} (I)

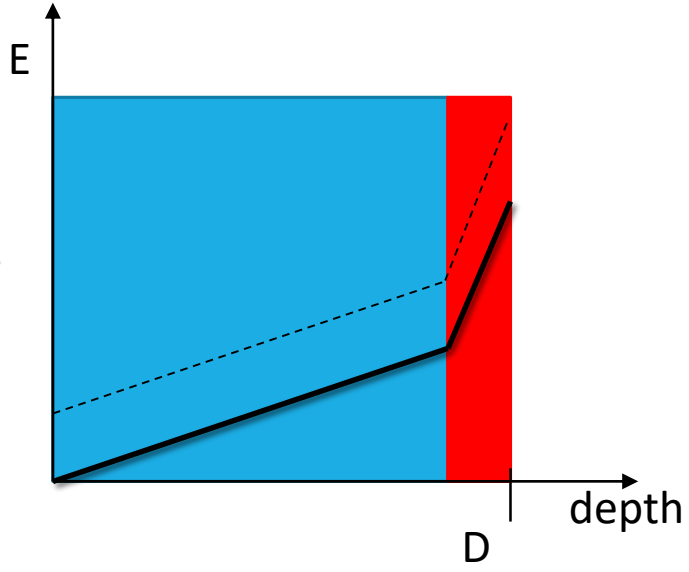


$$V_{gl}(\Phi_{eq},t) = V_{gl}(0)\cdot\exp(-c(t)\cdot\Phi_{eq})$$

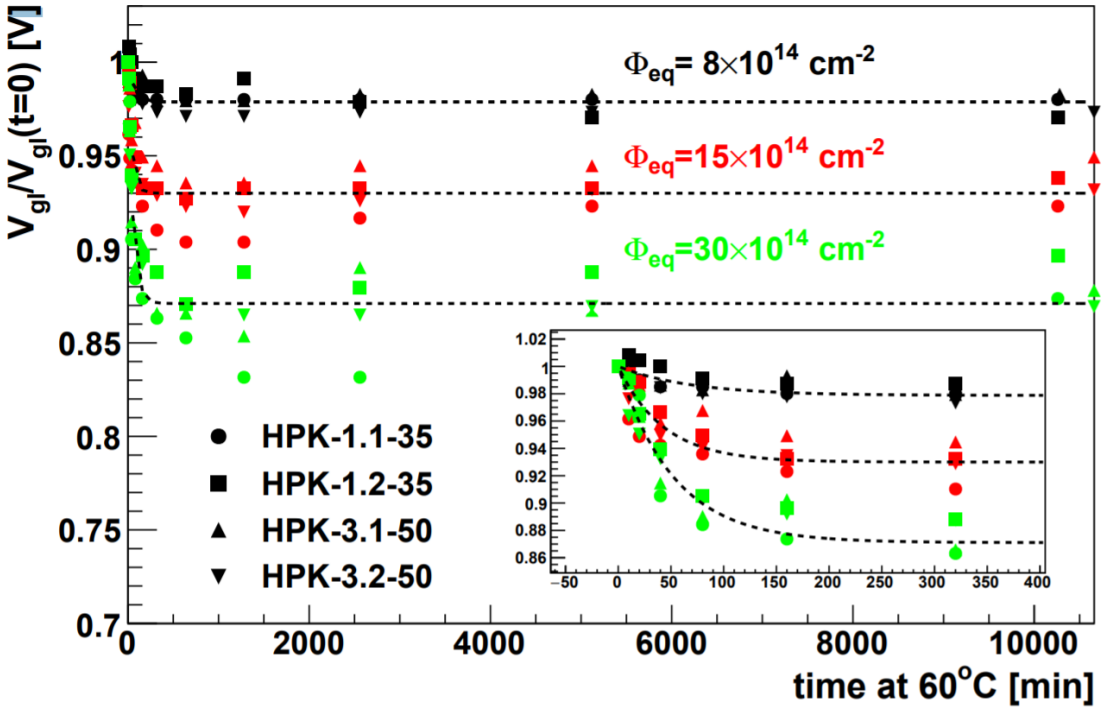
	HPK-1.1-35	HPK-1.2-35	HPK-3.1-35	HPK-3.2-35
$c(t=0)[10^{-16}\ \mathrm{cm}^2]$	4.5±0.3	3.9±0.3	4.5±0.3	3.3±0.2
$c(t=80\ \mathrm{min})[10^{-16}\ \mathrm{cm}^2]$	4.9±0.3	4.2±0.3	4.8±0.3	3.7±0.3

- V_{gl} is directly related to gain – the higher the V_{gl} for a given sample the higher the gain at given bias voltage
- All sensors show approximately same behaviour (not material related)
- The change due to annealing is not large, but can have significant impact on device performance "every volt counts in gain layer"

To increase the field by 1 V/µm ($V>V_{fd}$) in gain layer you need D·V/µm (50 V for D=50 µm)



Annealing of V_{gl} (II)



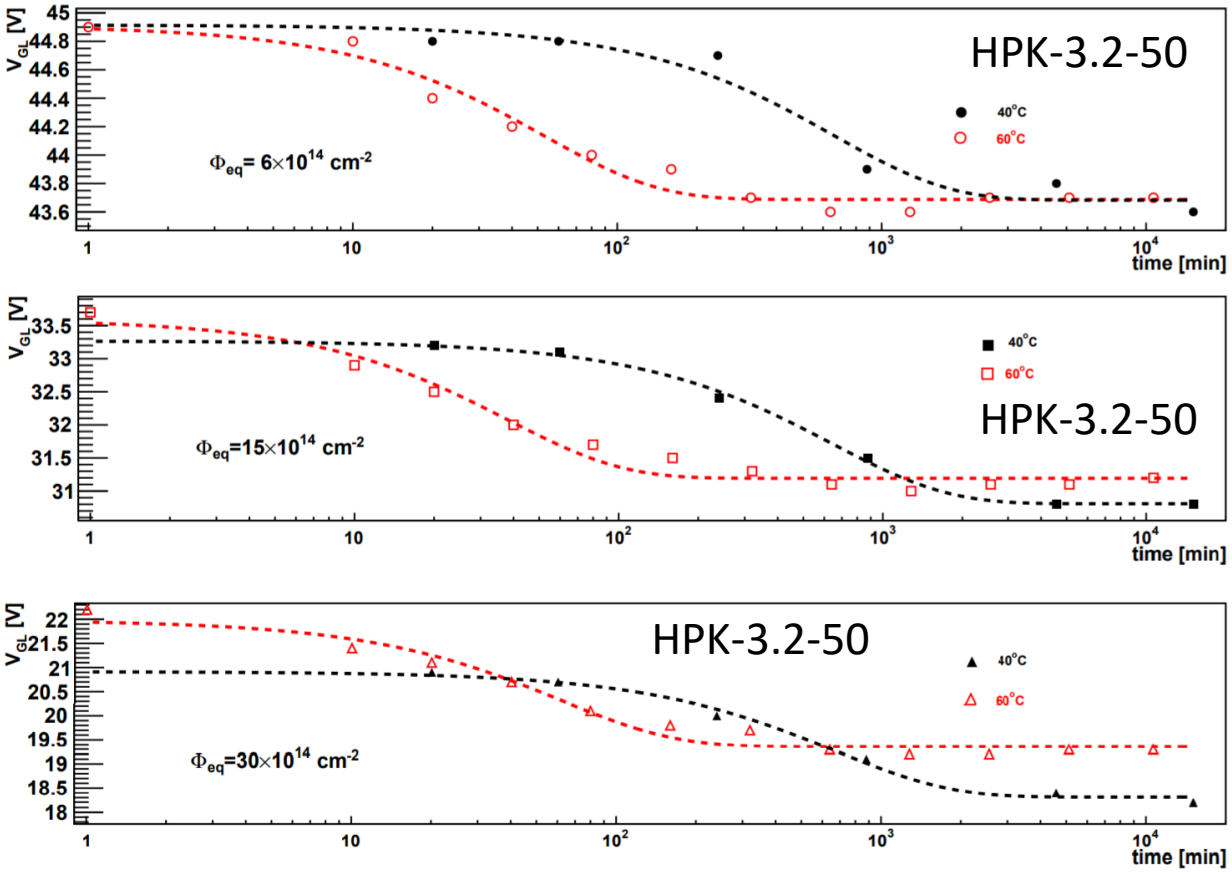
$$\frac{V_{gl}}{V_{gl}(t=0)} = F \cdot \exp(-t/\tau_{gl}) + (1-F)$$

$\Phi_{eq}[10^{14}\ \mathrm{cm}^{-2}]$	8	15	30
F	0.021 ± 002	0.07 ± 0.003	0.13 ± 0.003
τ_{gl} [min]	68 ± 19	43 ± 8	53 ± 6

- The relative amplitude of change *F* :
  - depends on fluence
  - doesn't depend on material
- At 1.5e15 cm^{-2} HPK-3.2-50 the change in $V_{gl}(0)-V_{gl}(\infty)$=2 V – significant and has a clear impact on charge collection – will be shown later
- The time constants are comparable to short term annealing
- At our standard annealing point 80min @ 60°C we get a conservative estimate on the required operation voltage

average $\tau_{gl} = 50 \pm 5$ min

Annealing of V_{gl} (III)



Need for studies at more temperatures!

- Measurements of annealing were done also at 40°C for HPK-3.2-50
- Possible determination of activation energy and scaling to lower temperatures
- Annealing amplitude (*F*) agrees with the one measured at 60°C
- Activation energy and scaling to lower *T*

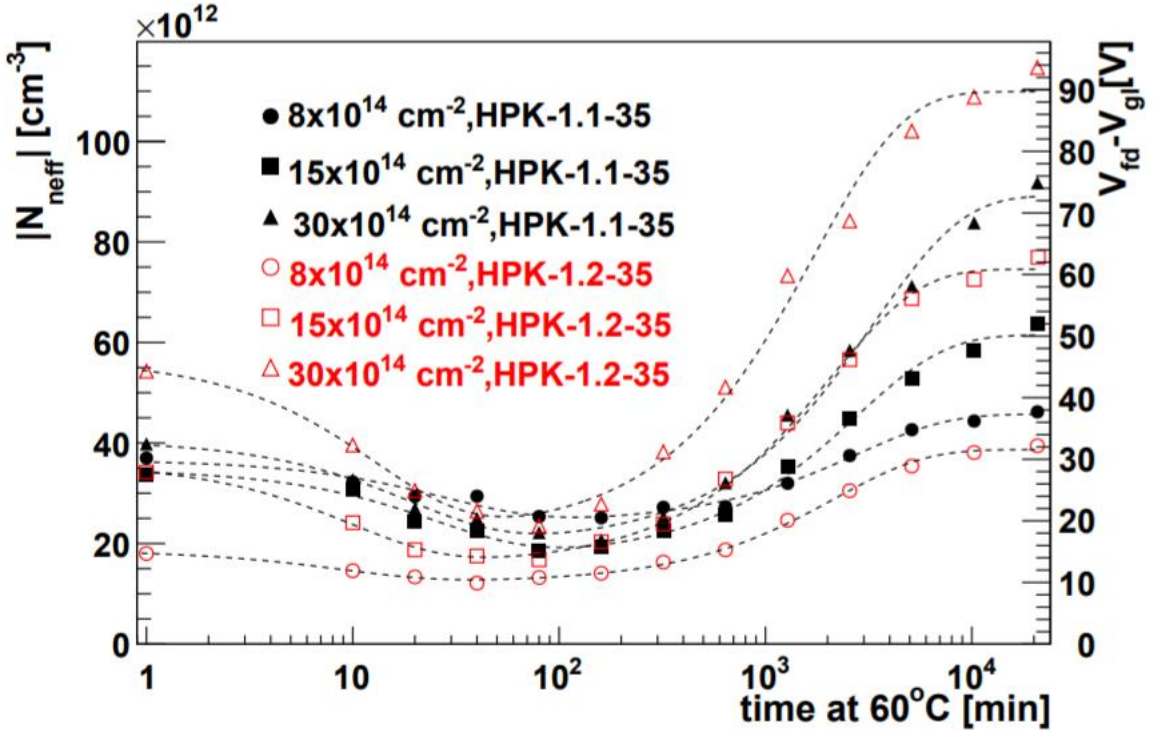
$$\tau_{gl}(60°\mathrm{C}) = 47 \pm 6 \text{ min} \qquad \tau_{gl}(40°\mathrm{C}) = 652 \pm 50 \text{ min}$$

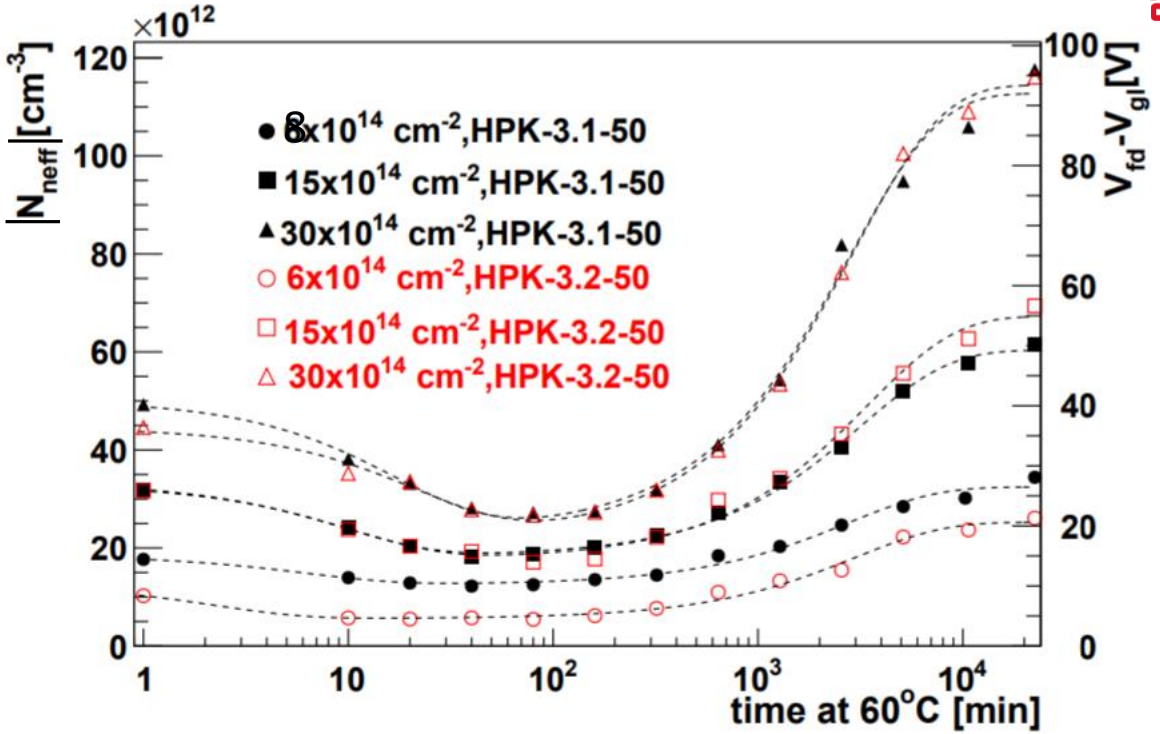
$$\frac{\tau_{gl}(T_1)}{\tau_{gl}(T_2)} = \frac{\exp(\frac{E_a}{k_B T_1})}{\exp(\frac{E_a}{k_B T_2})} \rightarrow E_a = \frac{k_B T_1 T_2}{T_2 - T_1} \ln(\frac{\tau_{gl}(T_1)}{\tau_{gl}(T_2)})$$

$$E_a = 1.15 \pm 0.07 \text{ eV}$$

- The time constant at -30°C would be 5.3 years – so effectively no annealing during running!

Annealing of space charge in the bulk (I)



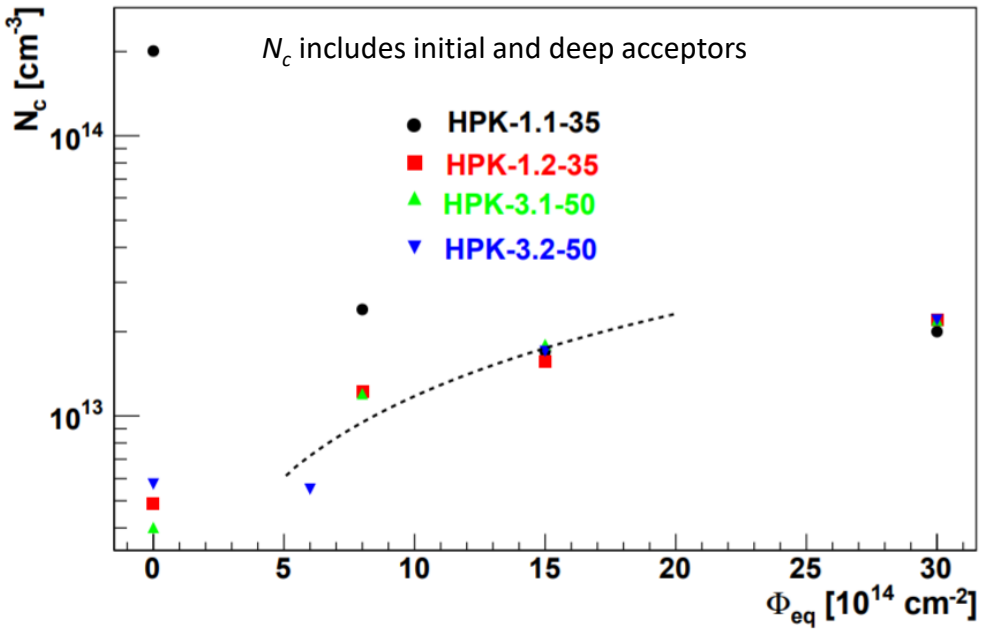


$$N_{eff} = \frac{2\varepsilon\varepsilon_0(V_{fd} - V_{gl})}{e_0\,(D - x_{gl})^2}$$

- x_{gl} taken to be 2.5 μm – not disclosed, but has marginal effect on results
- Hamburg model fits the data well
- N_{eff} for 50 μm sensors (3.1 and 3.2) show same type of bulk for both
- N_{eff} for 35 μm sensor (1.1 and 1.2) differ due to difference initial bulk resistivities

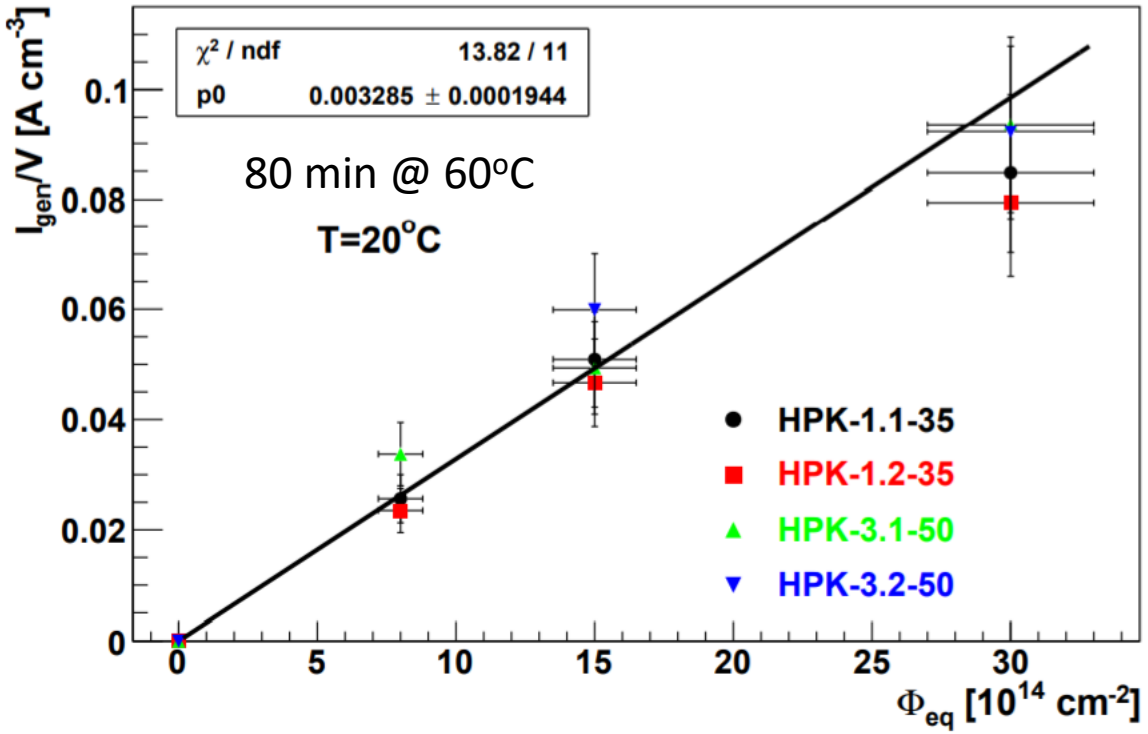
Annealing of space charge in the bulk (II)

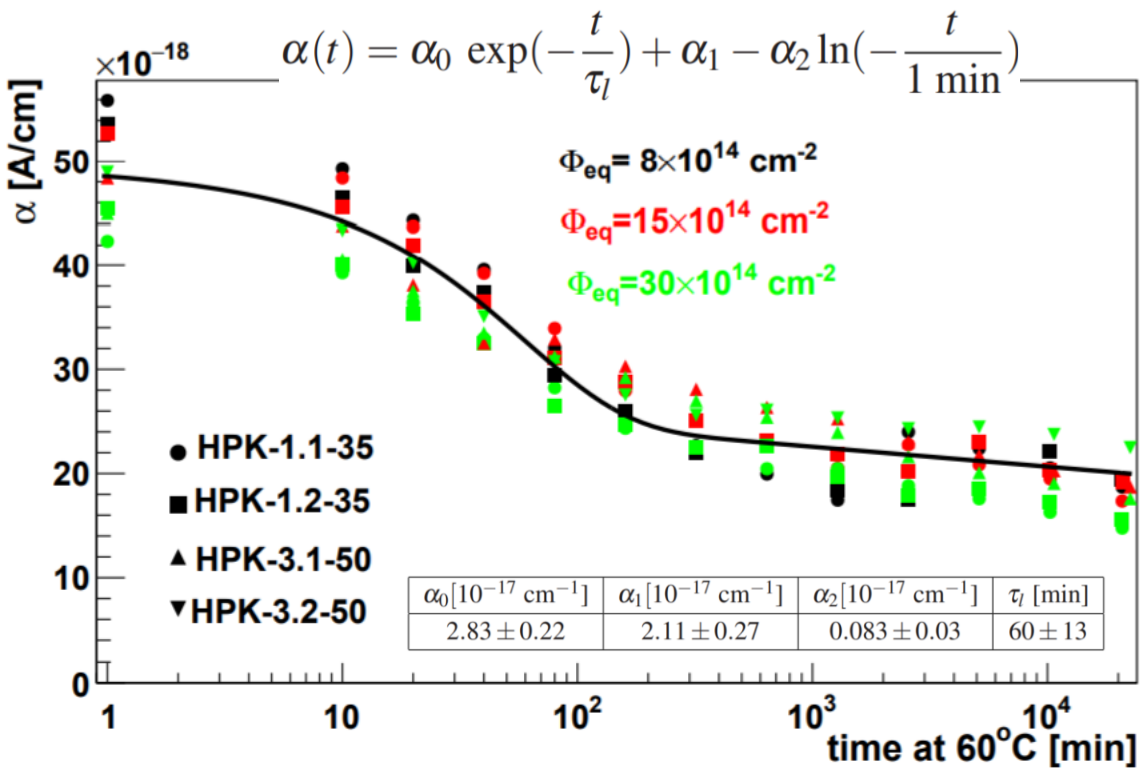
	Φ_{eq}[cm^{-2}]	N_C [10^{13} cm^{-3}]	g_a[10^{-2} cm^{-1}]	τ_a [min]	g_Y[10^{-2} cm^{-1}]	τ_{ra} [min]
HPK-1.1-35	$8\cdot10^{14}$	2.41 ± 0.1	1.57 ± 0.2	29 ± 8	2.4 ± 0.2	2780 ± 400
HPK-1.1-35	$15\cdot10^{14}$	1.72 ± 0.2	1.17 ± 0.2	27 ± 7	2.9 ± 0.2	2740 ± 310
HPK-1.1-35	$30\cdot10^{14}$	2.00 ± 0.2	0.7 ± 0.2	21 ± 7	2.3 ± 0.2	3330 ± 370
HPK-1.2-35	$8\cdot10^{14}$	1.22 ± 0.1	0.81 ± 0.2	9.4 ± 3	3.3 ± 0.1	2170 ± 120
HPK-1.2-35	$15\cdot10^{14}$	1.57 ± 0.1	1.36 ± 0.2	10.4 ± 2	3.9 ± 0.2	2060 ± 130
HPK-1.2-35	$30\cdot10^{14}$	2.2 ± 0.2	1.16 ± 0.2	13.7 ± 5	2.9 ± 0.2	1740 ± 220
HPK-3.1-50	$8\cdot10^{14}$	1.25 ± 0.2	0.75 ± 0.1	6.5 ± 3	2.5 ± 0.1	2750 ± 520
HPK-3.1-50	$15\cdot10^{14}$	1.82 ± 0.1	0.93 ± 0.1	10 ± 2	2.8 ± 0.2	3180 ± 220
HPK-3.1-50	$30\cdot10^{14}$	2.35 ± 0.1	0.89 ± 0.1	18 ± 6	3.0 ± 0.2	2840 ± 320
HPK-3.2-50	$6\cdot10^{14}$	0.55 ± 0.05	1.1 ± 0.2	3 ± 5	3.1 ± 0.33	2967 ± 400
HPK-3.2-50	$15\cdot10^{14}$	1.77 ± 0.01	1.05 ± 0.1	12 ± 4	3.1 ± 0.33	3415 ± 420
HPK-3.2-50	$30\cdot10^{14}$	2.25 ± 0.01	0.8 ± 0.1	24 ± 6	3.0 ± 0.31	2940 ± 180



- Long term annealing constant τ_Y~2500-3500 min at 60°C, longer than those for FZ, but compatible with those in oxygen rich material e.g. DOFZ, MCz.
- Same holds for introduction rate of reverse annealing defects around g_Y~0.03 cm^{-1}
- Difficult to precisely determine short term annealing constants of few tens min at 60°C
- Introduction of "stable damage" is around g_c~0.012 cm^{-1}
  - full removal of acceptors in the bulk assumed
  - the point at maximum fluence excluded – possible saturation of the damage

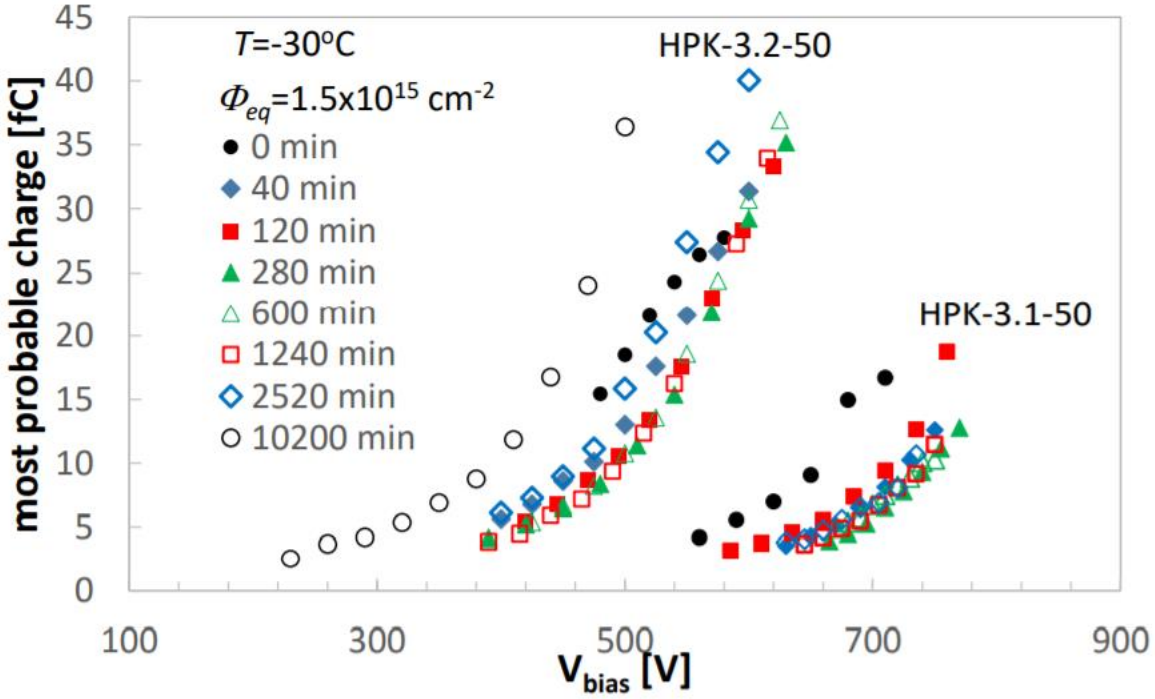
Generation current

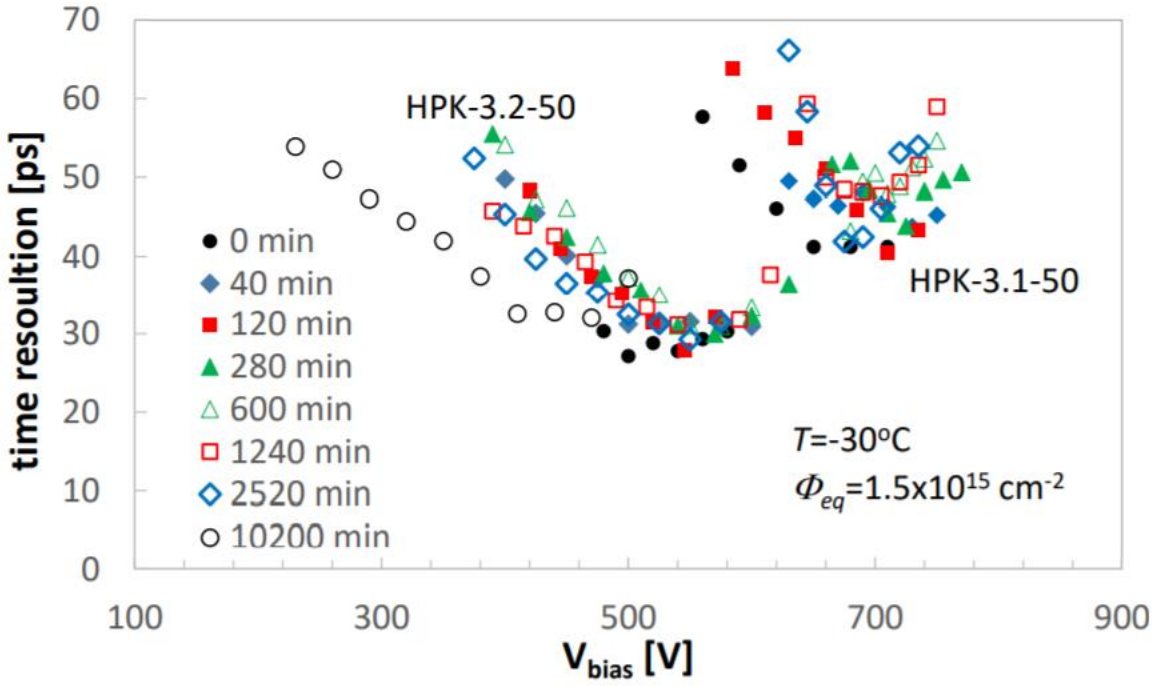




- Generation current was obtained from leakage current measurements $I_{leak}=G\cdot I_{gen}$
  - except for the HPK-3.2-50 at lowest fluence the *Gain(V_{fd})~1*
  - leakage current damage constant obtained from the fit was lower $\alpha=3.3\cdot10^{-17}$ A cm^{-1} than standard (temperature, fluence and determination uncertainty can be the reason)
- Long term behaviour of α(20°C) is universal for all can be fit with standard ansatz.

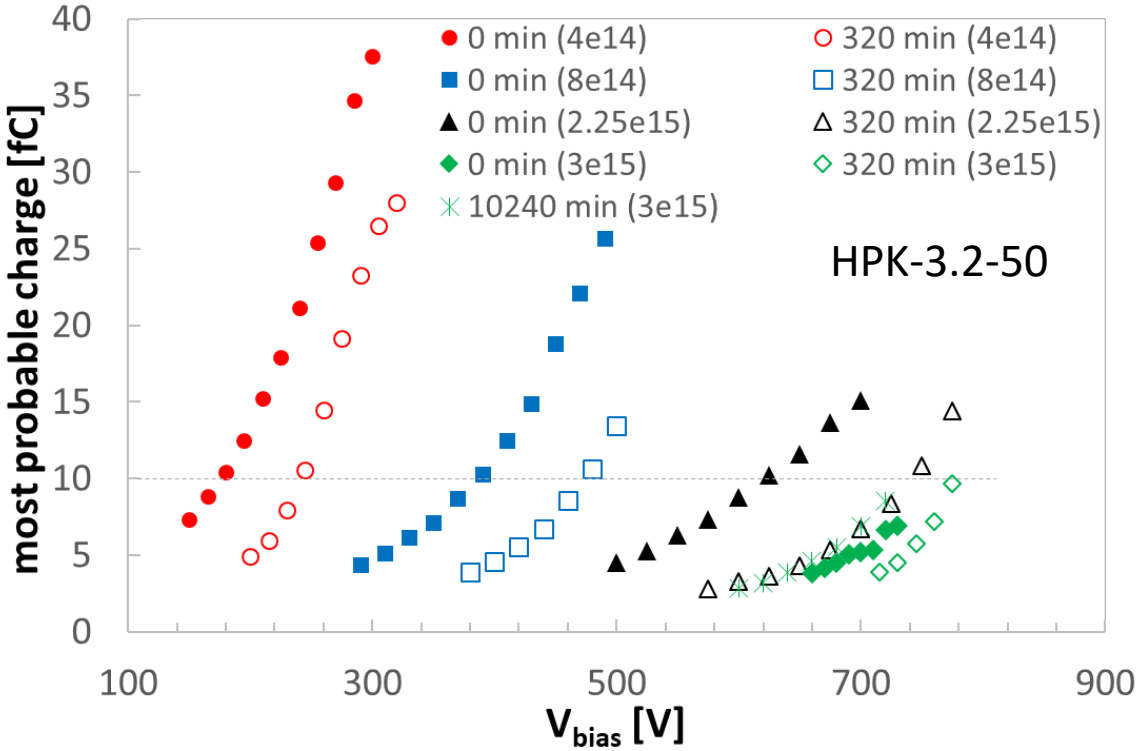
Charge and time measurements (I)

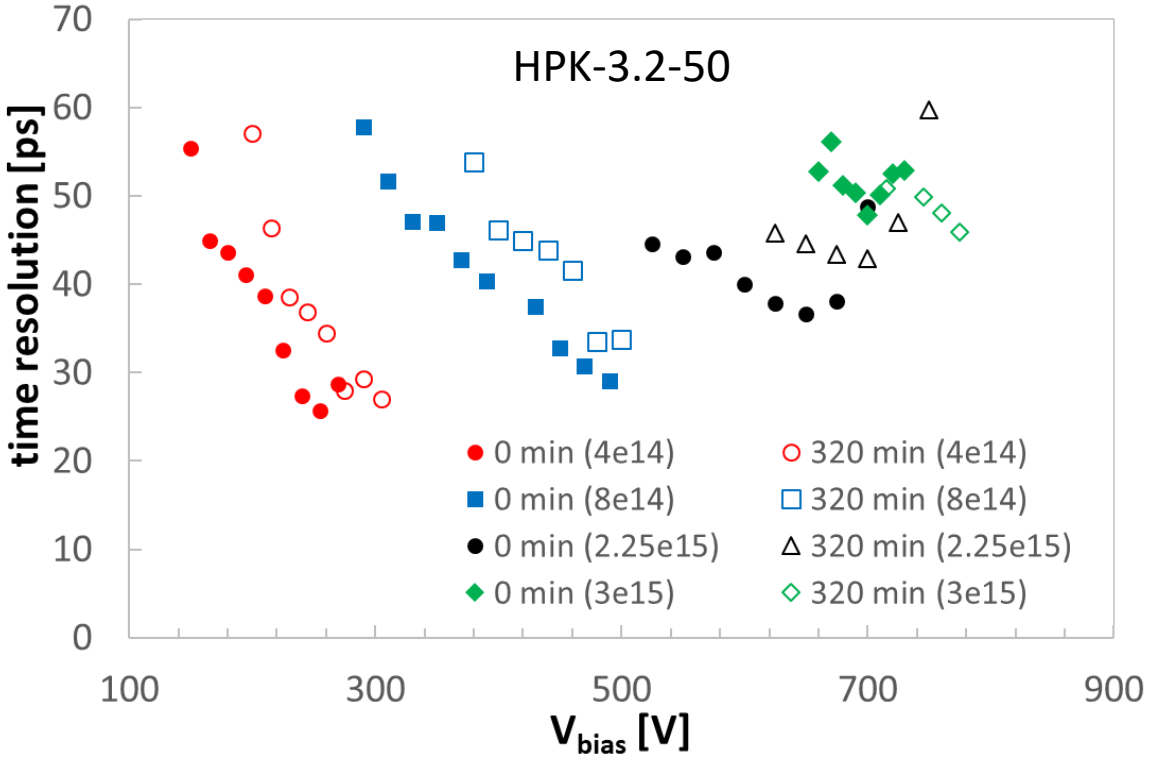




- Charge collection measurements for both show better charge collection at t=0 min
- Up to ~2000 min annealing there is not much change in charge collection (CC)
- For very high annealing times the CC improves significantly (verified on two samples HPK-3.2-50 samples)
- Time resolution follows the observations from CC measurements - better CC means lower voltage for reaching given time resolution

Charge and time measurements (II)

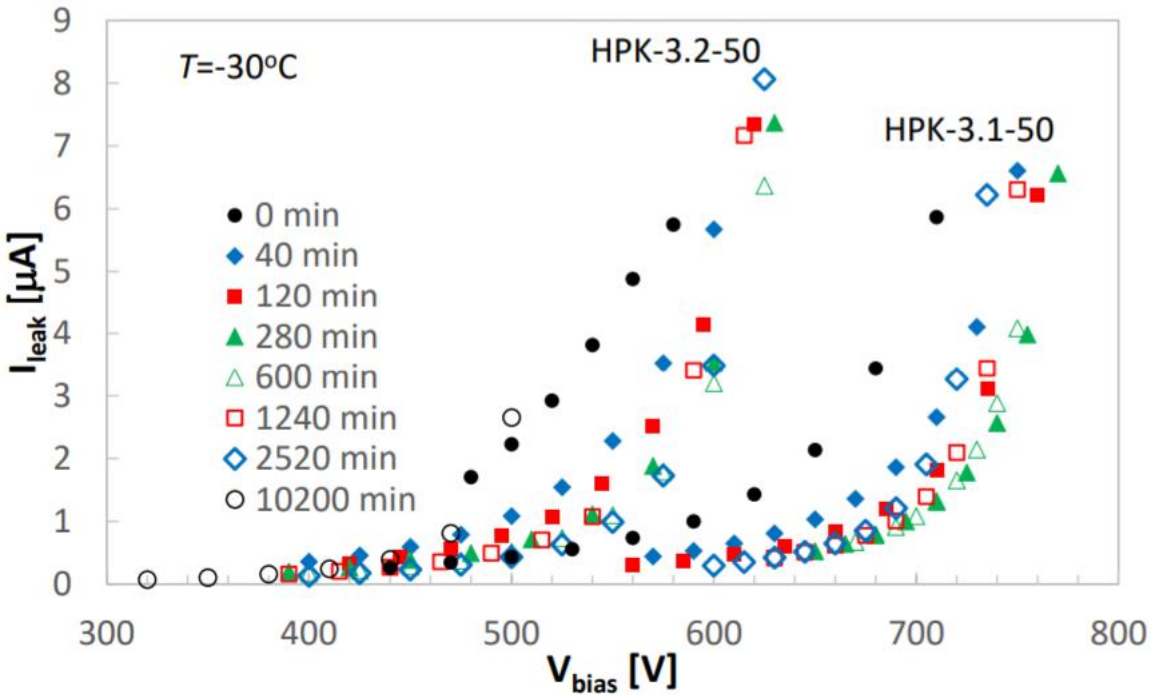




- Same annealing behaviour was observed also at other fluences
- Changes in V_{gl} offset the required bias voltage by 50-100 V and the difference slightly increases with fluence for most of the interested fluence range (not at the highest fluences)
- The offset in voltage required for given charge translates to lower voltage required for given time resolutions
- The time resolution degrades from 27 ps for 4e14 cm^{-2} to ~50 ps for 3e15 cm^{-2}

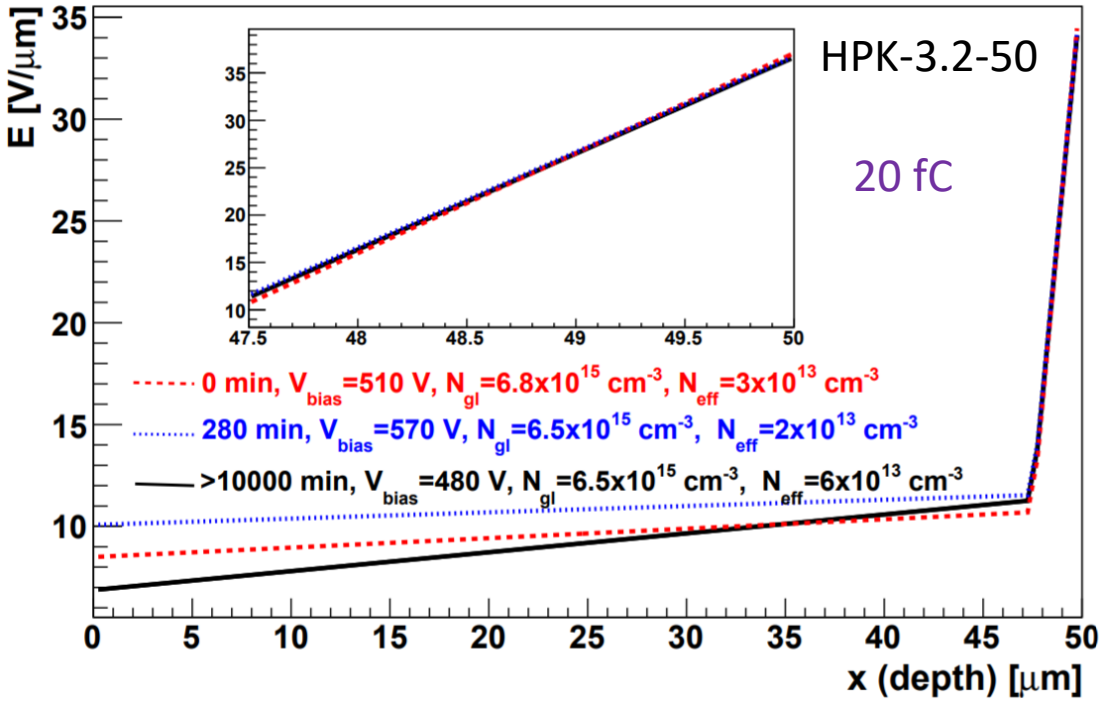
Leakage current annealing

$I_{leak}=Gain(V_{bias})\cdot I_{gen}(t_{an})$

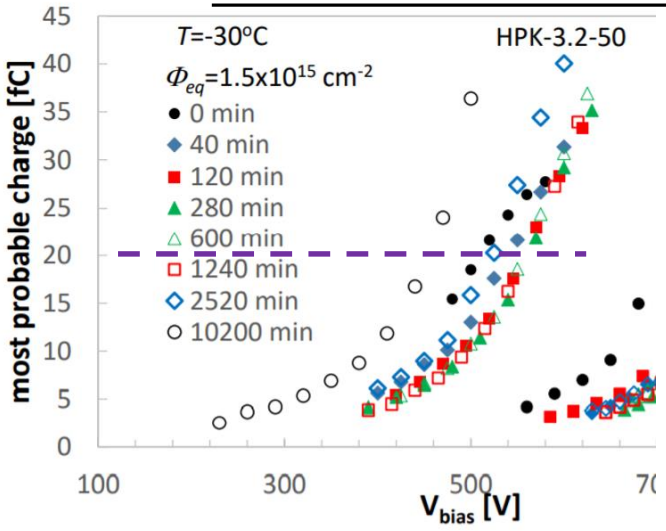


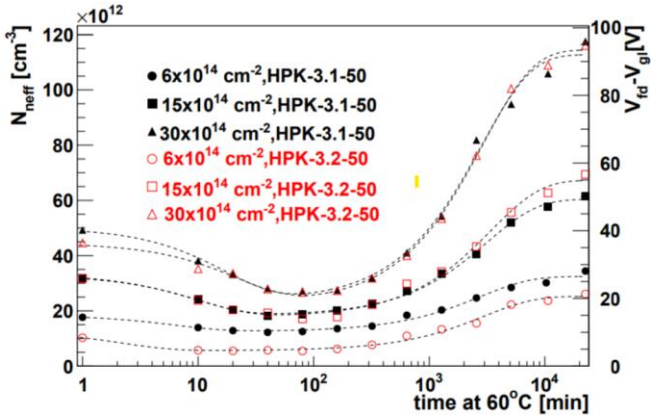
- Leakage current decreases with annealing time, but the difference at given bias is larger than implied by generation current, due to $Gain(V_{bias})$
- The gain at larger bias prevails after >10000 min and the leakage current is larger than at lower times
- For most interested annealing times ~tens min<t_{an}<2000 min the leakage current decreases as $Gain(V_{bias})$ is almost constant

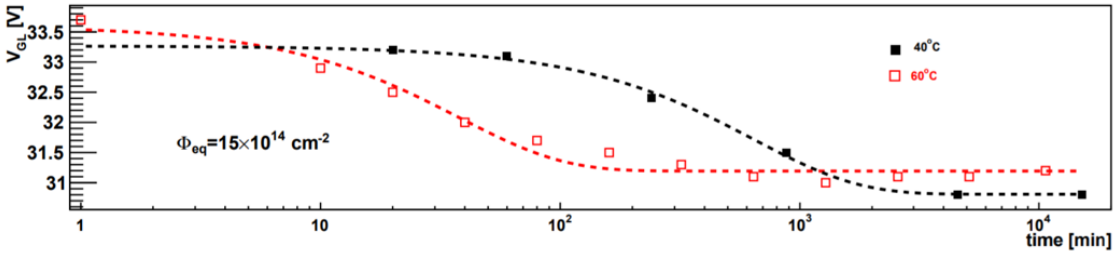
Qualitative explanation



A reminder of the three plots used for calculation







- Calculation of electric field in abrupt junction approximation:
  - V_{bias}(20 fC) at different annealing times (dashed magenta line)
  - N_{gl} from V_{gl} measurements at those annealing times (x_{gl}~2.5 μm)
  - N_{eff} from V_{gl} and V_{fd} measurements at those annealing times
- There is a large difference in bulk electric field, between all three points, but almost difference in the gain layer, **hence same charge**
- Bulk doping can have an effect on the electric field in the gain layer even though it is much smaller ($E(x) \propto \int_0^x N_{eff}(x')dx'$)

Conclusions and future work

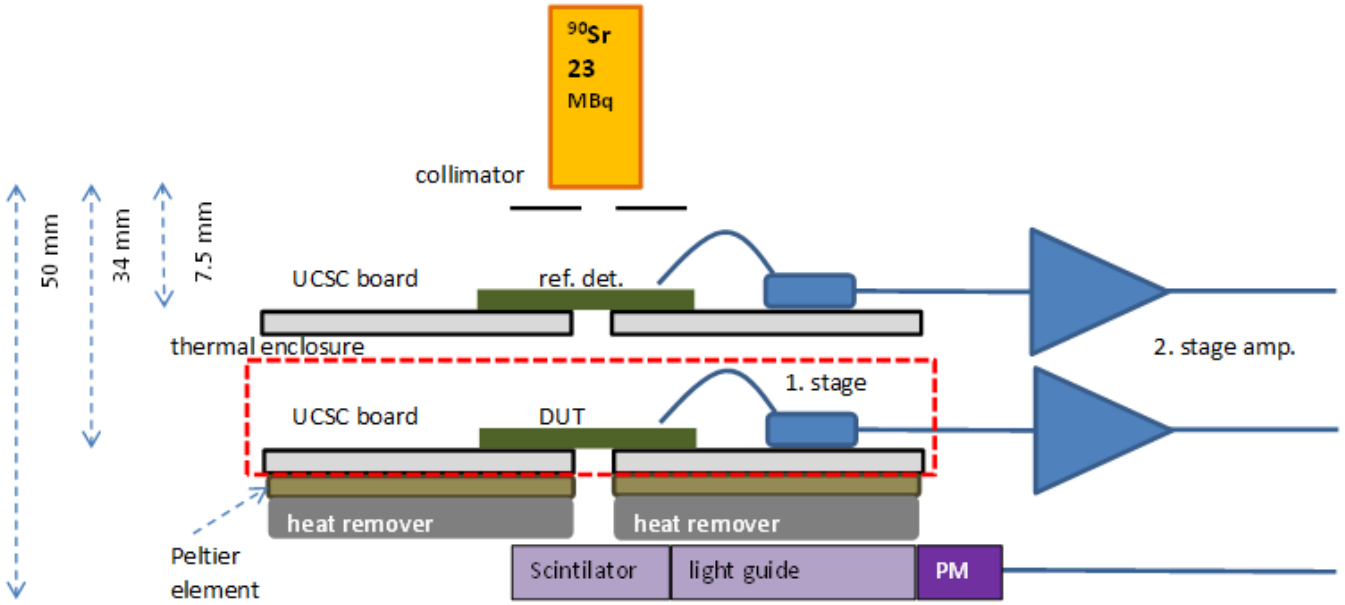
- Performance and properties of HPK LGAD detectors were investigated
- Gain layer depletion voltage was found to change during annealing by
  - 1-2% for 8e14 cm^{-2}, ~7% at 1.5e15 cm^{-2} and ~13% at 3e15 cm^{-2} - independently on detector type
  - τ_{gl}(60°C)~50 min and τ_{gl} (40°C)~650 min -> activation energy E_a=1.15±0.07 eV -> V_{gl} annealing will be frozen during yearly operation at HL-LHC
- N_{eff} behaves as expected with annealing parameters (Hamburg model) similar to those of oxygen rich silicon
- Generation current shows universal behaviour and in agreement with previous measurements
- Charge collection measurements showed better performance in terms of *Gain(V)*:
  - immediately after annealing
  - at very long annealing times >10000 min
  - practically unchanged for other annealing times in-between
  - this is also reflected in time measurements (required time resolution is reached at lower bias voltages)
- Calculation of electric field in abrupt junction approximation qualitatively explained the measurements

^{90}Sr Measurement System and analysis

- Triggering without DUT (no analysis bias introduced by that):

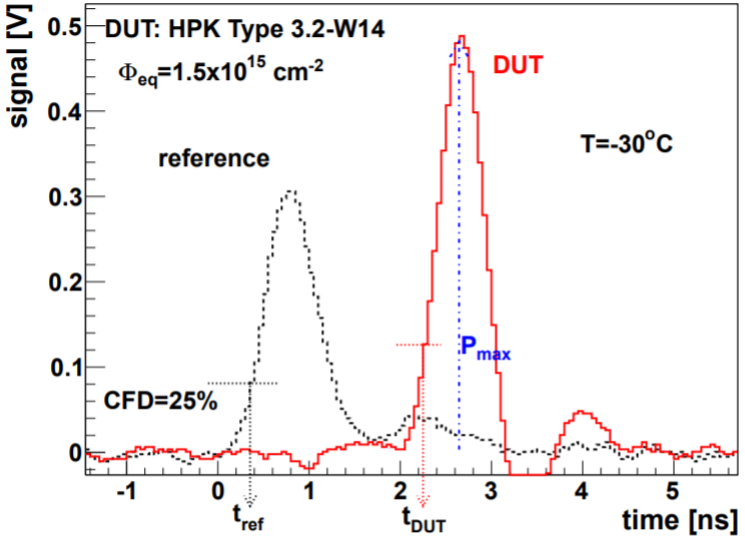
Trigger = (Sci+PM) AND (Ref.Det)

- Small devices - not perfect alignment (30-40% of trigger have signal in DUT
- CFD with 25% is used



The humidity was monitored and the dew point was always well below the operation temperature (dry air ventilation)

Typical event



Charge & time spectrum