High temperature annealing of heavily irradiated LGADs

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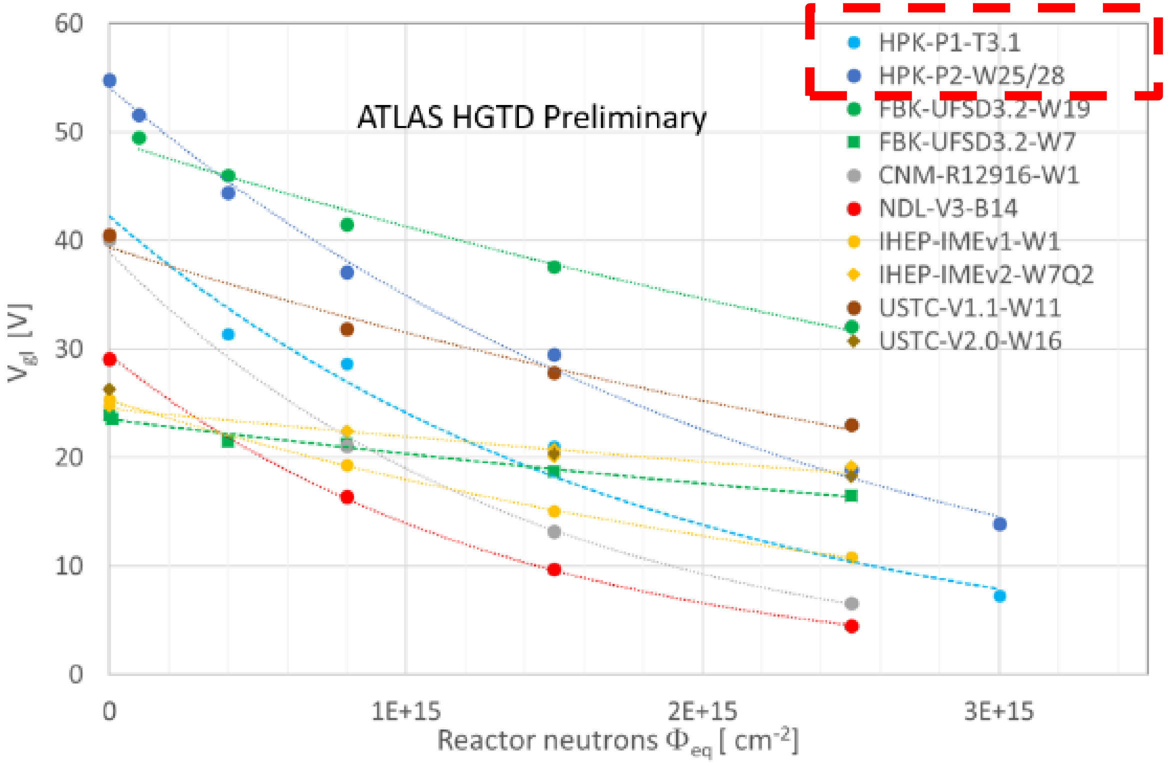
Motivation (I)

- ➢LGADs as timing detectors have a major problem with radiation hardness – “effective acceptor removal”
- ➢The problem was addressed by defect engineering (carbon enrichment), but we are still limited to <3e15 cm^{-2}



Reduction of V_{gl} requires increase of operation bias!

Interstitial channel : I + Bs → Bi (dominant channel)
(electrically inactive Bi can form different defect complexes)

$$dN_B = -\sum_i c_i \cdot N_B d\Phi \quad , \quad c = \sum_i c_i\,([\mathrm{O}],[\mathrm{C}],[\mathrm{B}])$$

$$N_B = N_{B,0} \exp(-c\,\Phi_{eq})$$

Assuming linear relation between N_B and V_{GL}:

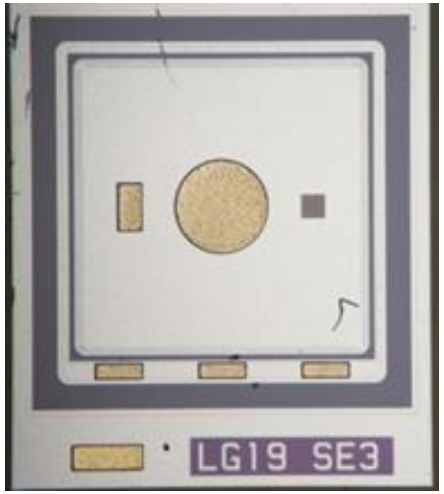
$$V_{GL} = V_{GL,0} \cdot \exp(-c \cdot \Phi_{eq})$$

Are the defect complexes formed with B after annealing stable or can we recover performance by elevated temperatures?

Similar to **DRIVE** (Detector Recovery/Improvement Via Elevated-temperature-annealing) from 2005 (BNL/Ioffee/HIP)

Sensors studied

- There is also a practical element to the study:
  - During RD phase of ATLAS-HGTD there is a need to test irradiated assemblies (ASIC+LGAD)
  - Bump bond activation after neutron irradiations (Ag) is a serious difficulty for handling assemblies and being able to do bump bonding after irradiation with functional sensors is a major advantage
- We have chosen the sensors that are most widely studied/understood from LGAD productions:
  - HPK-P1 T3.1, T3.2 – exploration of high temperature annealing for detector recovery
  - HPK-P2 W28 – ATLAS irradiated assembly feasibility studies

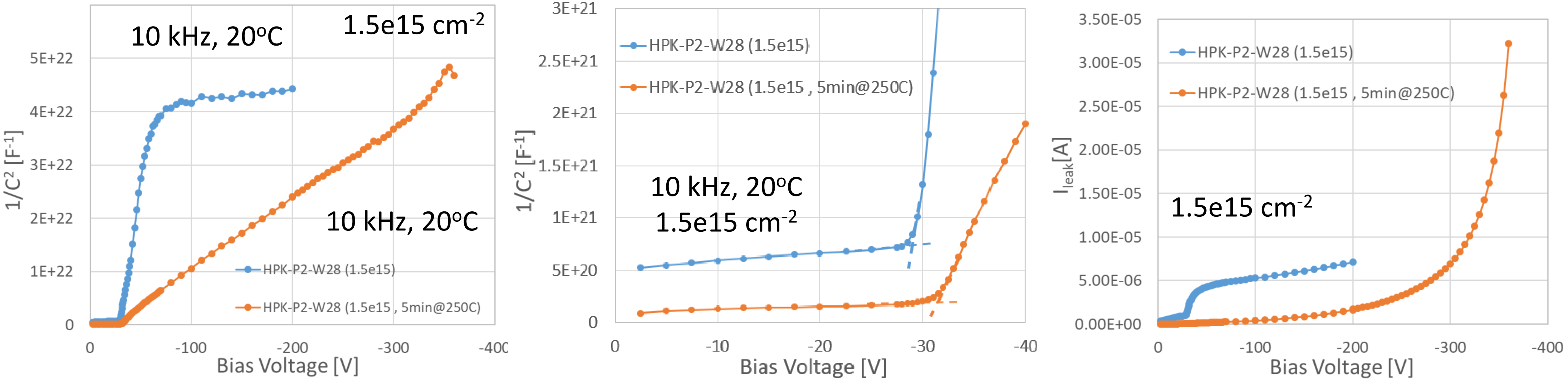


HPK-P1-T3.1:
1.3x1.3 mm^2, 50 μm, V_{gl}~41 V
(reactor neutrons to 8e14, 3e15, 6e15 cm^{-2})

HPK-P1-T3.2:
1.3x1.3 mm^2, 50 μm, V_{gl}~55.5 V
(reactor neutrons to 1.5e15, 4e15, 6e15 cm^{-2})

HPK-P2-W28:
1.3x1.3 mm^2, 50 μm, V_{gl}~54.5 V
(reactor neutrons to 1.5e15 cm^{-2})

5 min at 250°C annealing - results



- annealing done in air atmosphere
- huge changes in performance – improvements –> unlike standard sensors large N_{eff} is beneficial
  - ΔV_{fd}~300 V
  - ΔV_{gl}~3 V
  - ΔI_{leak} - difficult to tell, due to different depletion, but looks like an order of difference
- How does that reflect in the performance?

5 min at 250°C annealing - results

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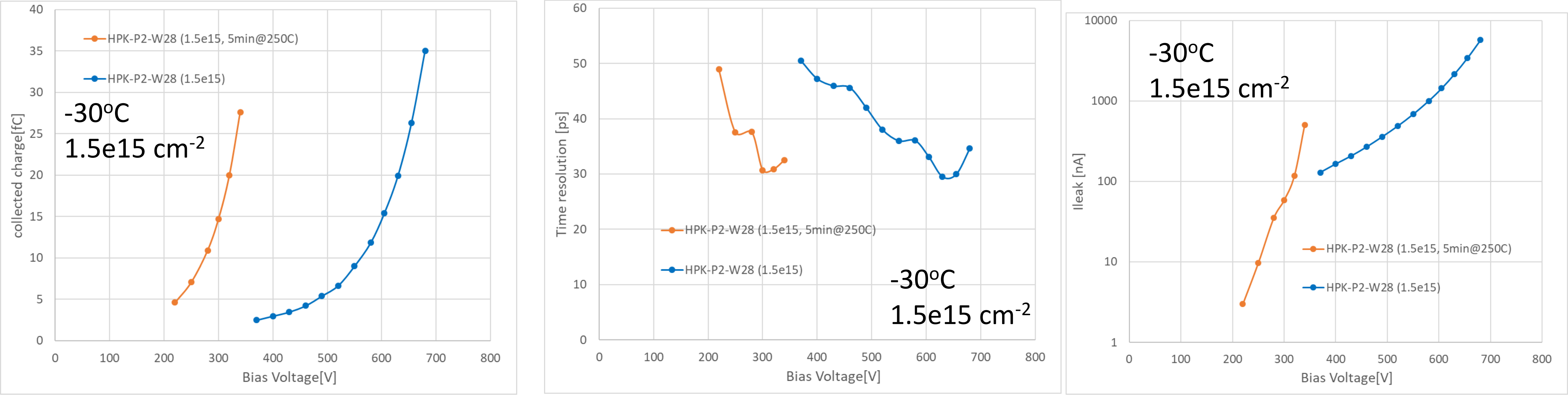


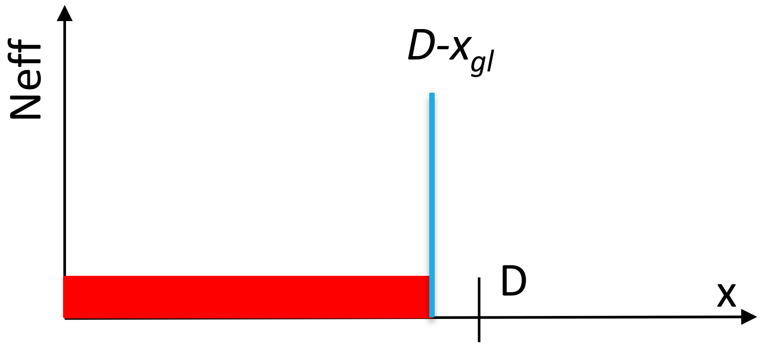
- Huge **improvement in performance** in all respects - even more than predicted from ΔV_{gl}
  - V_{10fC} is reduced to ~300 V
  - same timing resolution is reached at much lower voltages
  - approximately an order of magnitude smaller leakage current

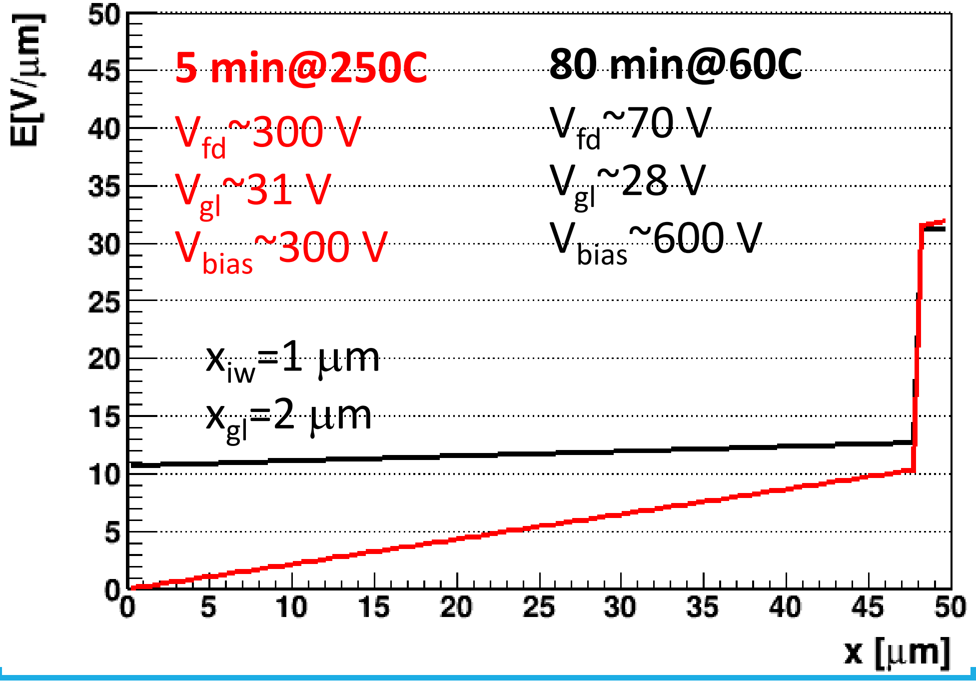
5 min at 250°C annealing - results

Electric field in LGAD

$$\mathrm{E}(x) = \frac{N_{deep}}{\varepsilon\varepsilon_0}x + \frac{N_B}{\varepsilon\varepsilon_0}x_{iw}H(x - D + x_{gl}) + E_0$$

derived from: $V_{fd\text{-}}V_{gl}$ V_{gl} $\frac{V-Vfd}{D}$

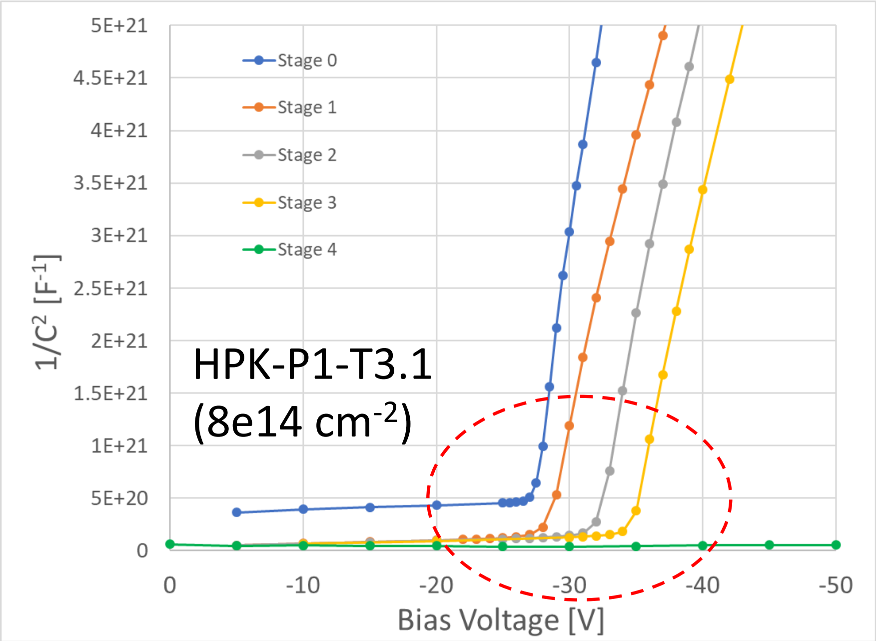


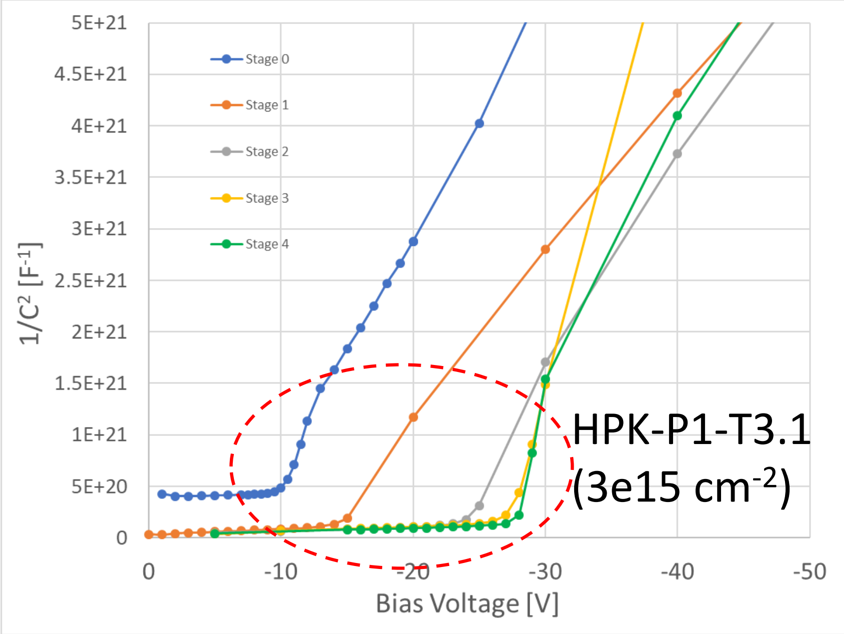


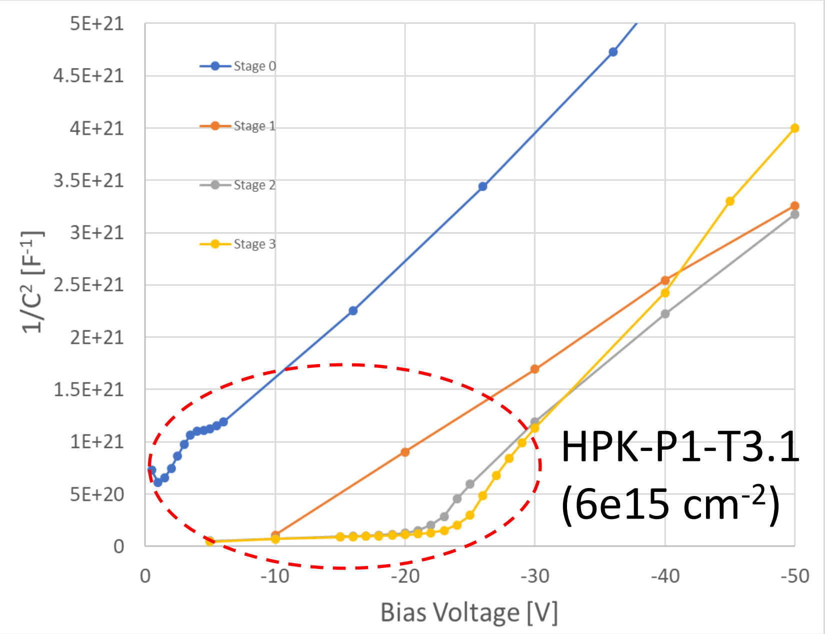
- Large N_{eff} reduces the voltage drop in the bulk and keeps the operation voltage safely away from SEB
- Note that what $N_{deep}\cdot D$ can become important also for the electric field in the gain layer
- **ΔV_{gl} is less important for the observed improvement in performance.**

Performance of HPK-P1-T3.1 sensors after HT annealing

- Isochronal annealing in **Ar athmosphere** at the elevated temperatures were performed with 30 min steps at : 300^{o}C (Stage1), 350^{o}C (Stage2), 400^{o}C (Stage3), 450^{o}C(Stage4). Stage0 – no annealing at all.
- measurements were performed 20oC (CV-IV) and -30oC (CC/timing)



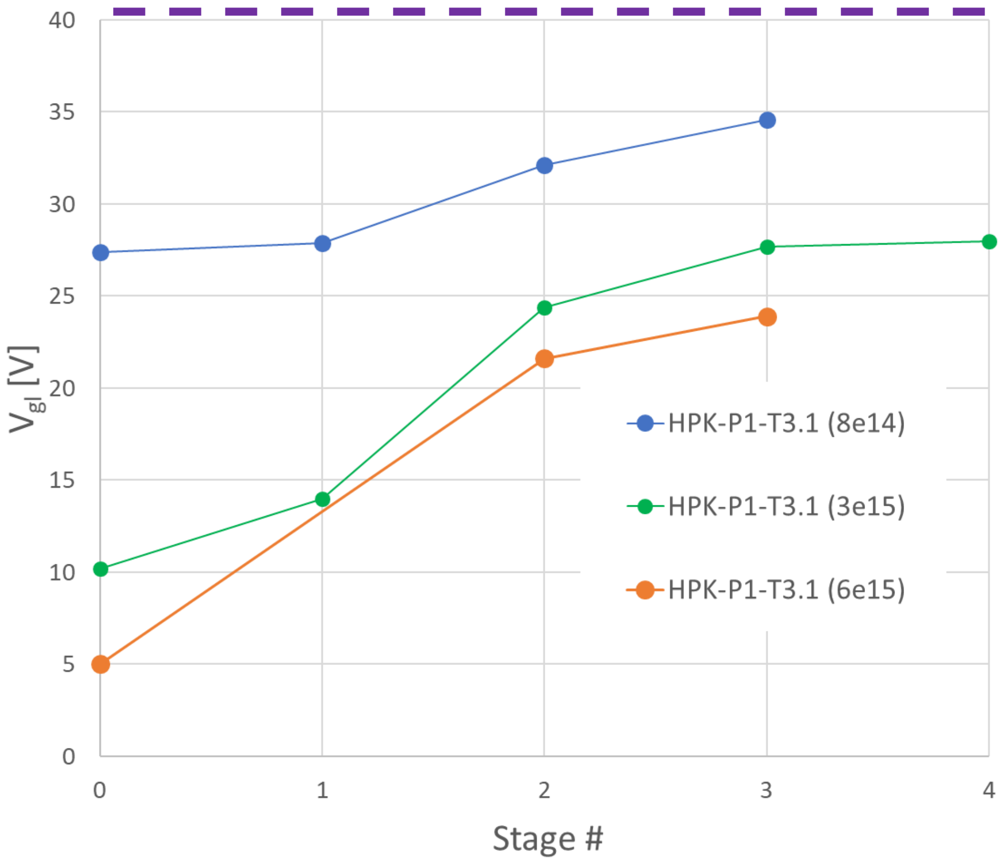




A clear shift of V_{gl} to higher values can be observed with increased annealing temperature!

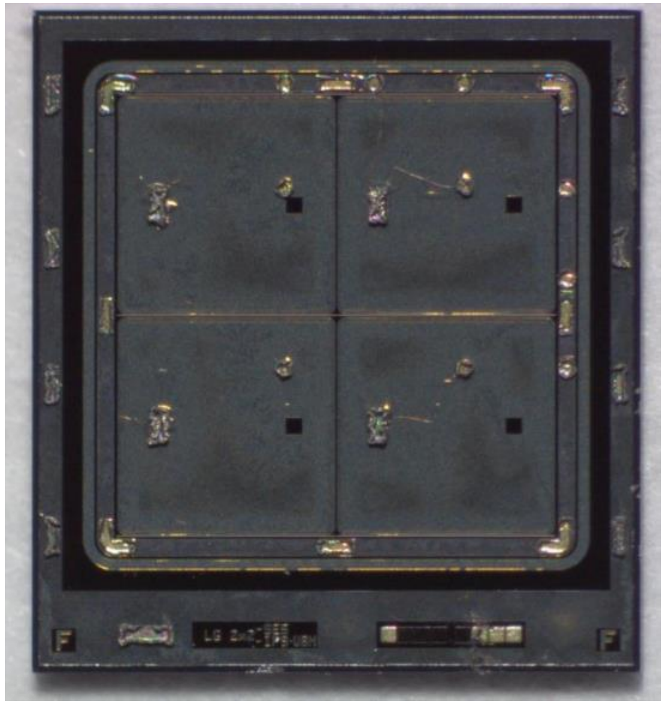
Performance of HPK-P1-T3.1 sensors after HT annealing

Stage0 – no annealing
300^{o}C (Stage1)
350^{o}C (Stage2)
400^{o}C (Stage3)
450^{o}C (Stage4)



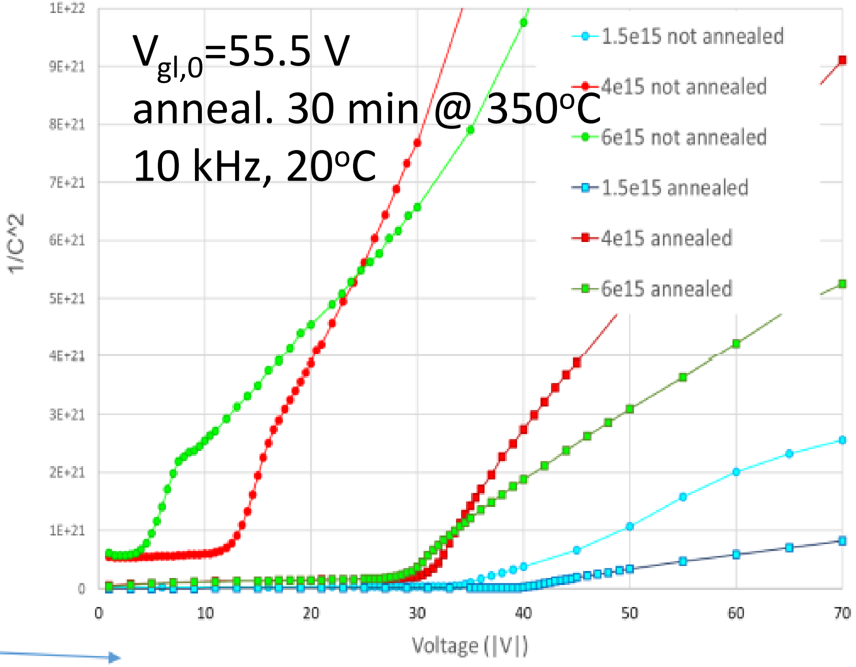
V_{gl} (before irr.)=41 V
Type 3.1 sensors

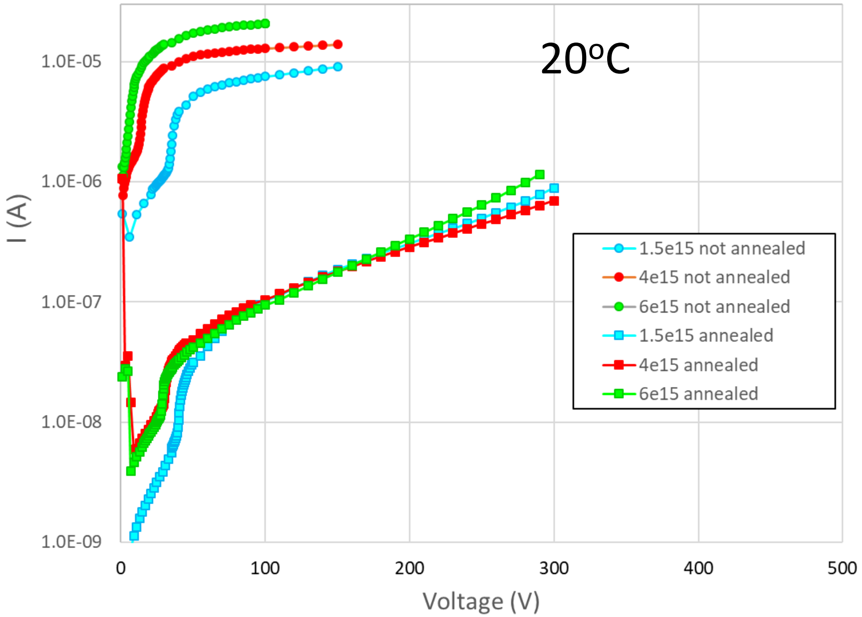
An attempt to heat to 600^{o}C failed - melted aluminium

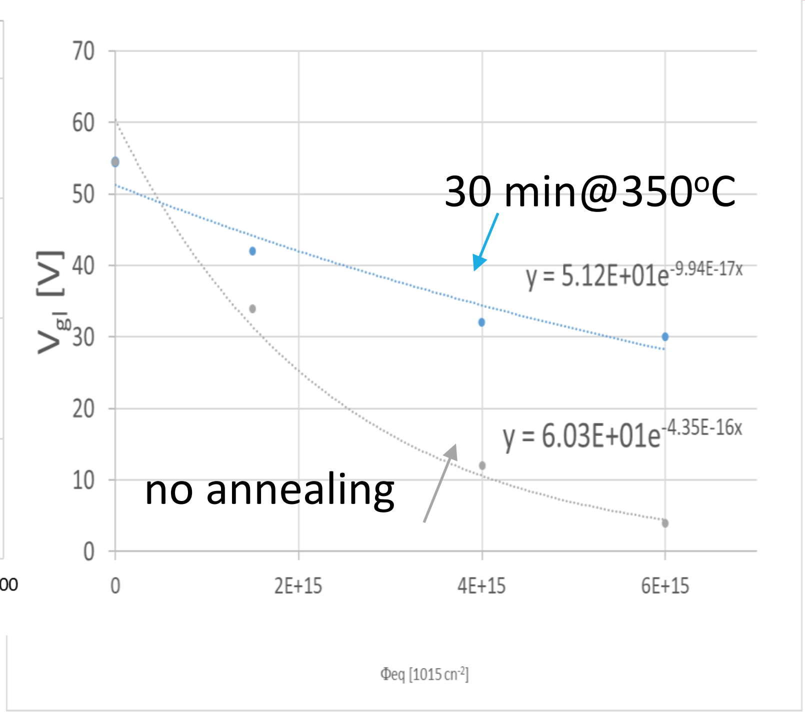


The largest change is seen between 300^{o}C and 350^{o}C.

Performance of HPK-P1-T3.2 sensors after HT annealing


$V_{gl,0}$=55.5 V
anneal. 30 min @ 350°C
10 kHz, 20°C

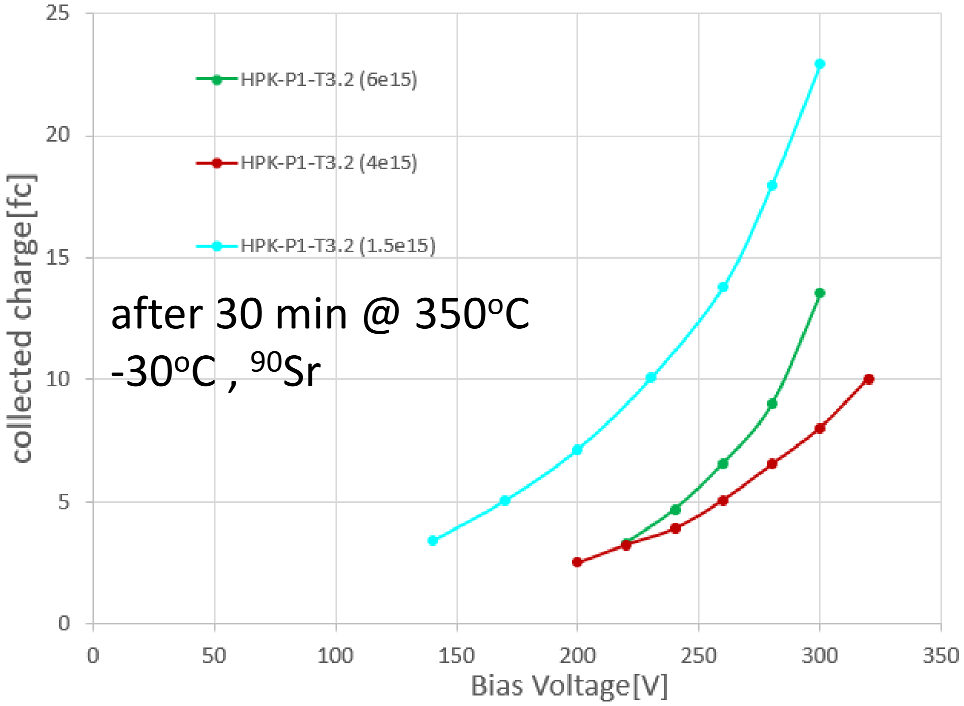

20°C


30 min@350°C

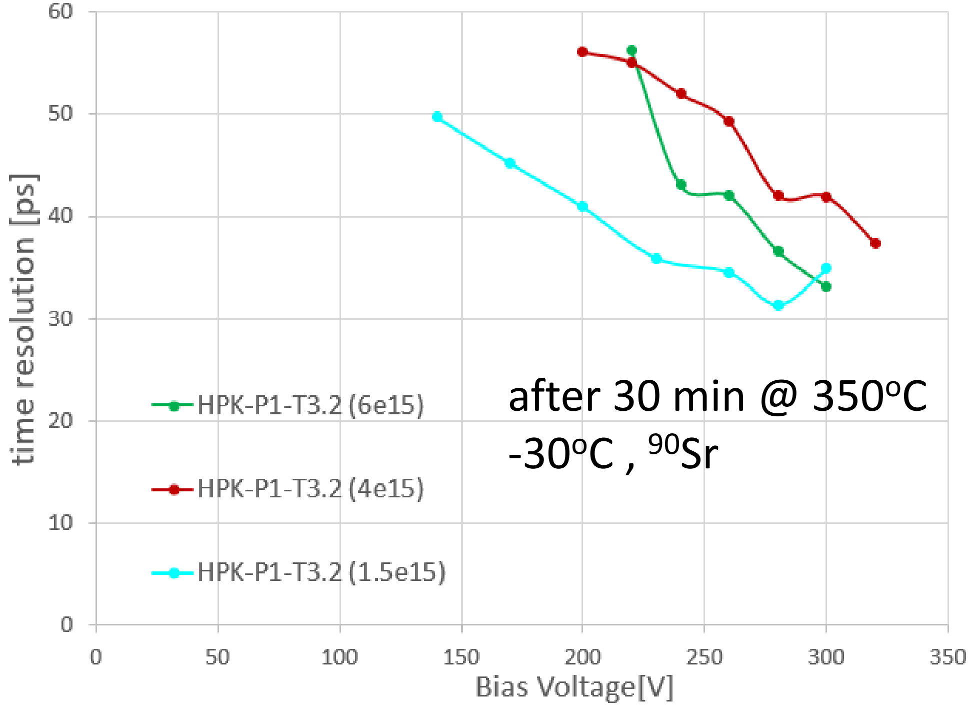
no annealing

- ➢large increase of V_{gl} with annealing step (30 min @ 350°C) particularly for high fluence **- this becomes the dominant recovery mechanism at high temperatures.**
- ➢effectively the acceptor removal constant is reduced by factor of ~4-5.
- ➢huge improvement in leakage current – reduced by almost two orders of magnitude

Performance of HT annealed sensor



after 30 min @ 350°C
-30°C , ^{90}Sr



after 30 min @ 350°C
-30°C , ^{90}Sr

- Good timing resolution comparable to non-irradiated device
- The combination of bulk N_{eff} increase and V_{gl} increase reduces the radiation damage effects significantly and almost restores the performance of LGADs to that before irradiations

Conclusions

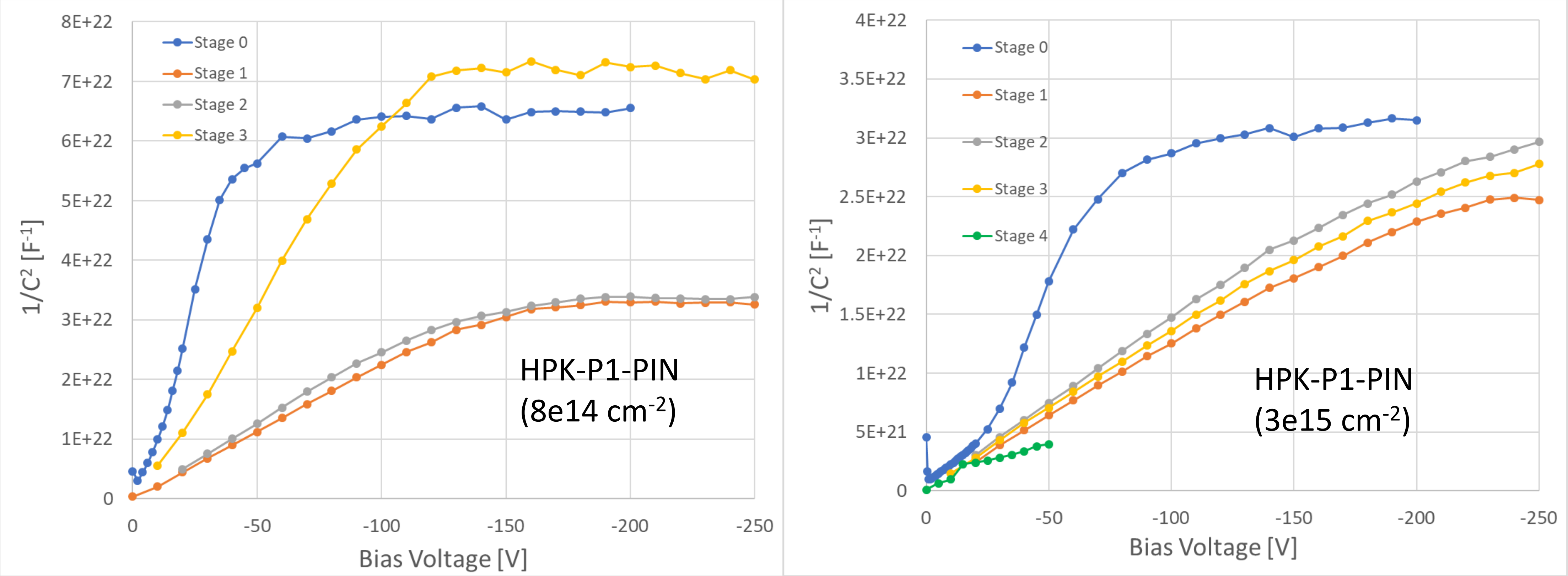
- High temperature annealing improves the performance of LGADs dramatically
  - V_{gl} increases significantly – becomes the dominant improvement mechanism at around ~350°C
  - V_{fd} increases and by that reduces the voltage drop in the bulk and pushes the required voltages to much lower levels – the dominant improvement mechanism at around ~250°C.
  - Leakage current shows the expected annealing behaviour and reduces for almost tow order of magnitudes after 350°C annealing – power dissipation becomes a non important.
  - Charge collection/Timing measurements confirm the large improvement seen in CV/IV with good performance at >6e15 cm^{-2}

Could HT annealing be used to cure sensors/modules?

  - for installed this is very difficult/impossible and it depends on the module design and components – electronics is a "powerfull" heater
  - for unmounted modules in special conditions it may work, depending on the interconnections and components – nevertheless huge saving and performance improvements possible.

- Would that work also for C-enriched gain layer?

Performance of HPK-P1 sensors after HT annealing



- The increase of Vfd is clearly visible, but mostly after the first step (Stage2) – and indication of a process/changes at 350°C
- The increase of Vfd also improves the performance – the larger the Neff in the bulk, the more the loss of Vgl is compensated!