Characterisation of silicon sensors for the CMS HGCAL project

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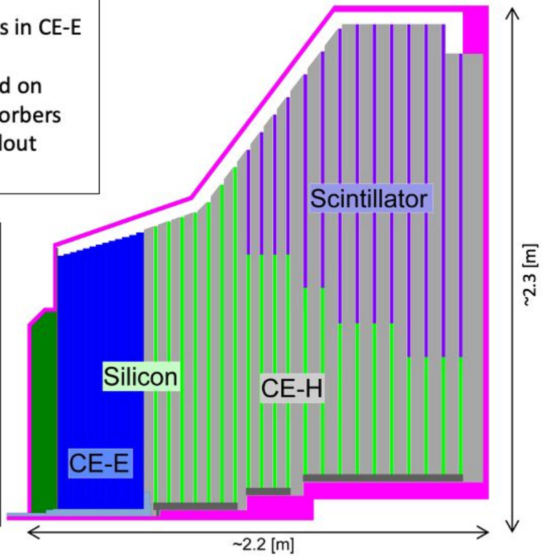
What is HGCAL?

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:

Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -30ºC
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap

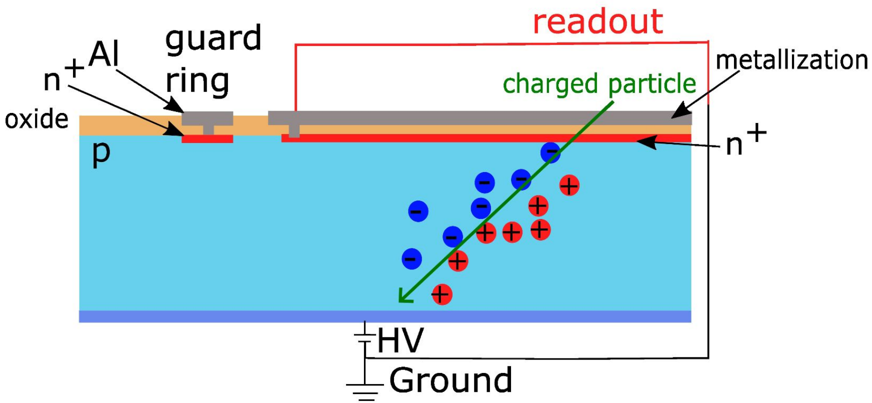


- CMS Endcap Calorimeter will be replaced by HGCAL (High Granularity Calorimeter)
- HGCAL will use ~620 m² silicon sensors produced on 8-inch wafers
- Three different thicknesses: 300 µm, 200 µm (Float zone) and 120 µm (Epitaxial)
- Fluences of up to 1e16 n_{eq}/cm^2

Motivation for the study →

It is needed to know the annealing behavior of silicon sensors at various temperatures to be able to extrapolate to 0°C, which will most likely be the temperature in the detector during shutdowns

Irradiation and Annealing effects on silicon sensors



Main concept:

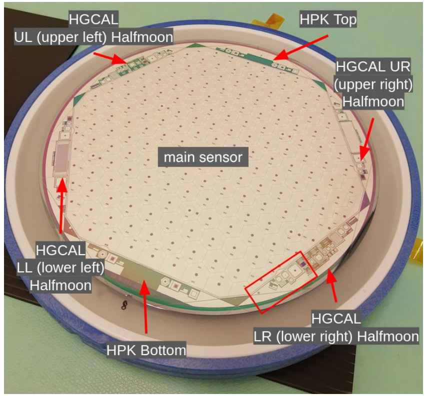
- Charged particles traversing the detector create electron-hole pairs. Then electron-hole pairs are separated by an electric field and drift to the electrodes. This is the signal we are looking for

- Radiation damages silicon detectors by creating defects
- Annealing can change effects from damage through different mechanisms

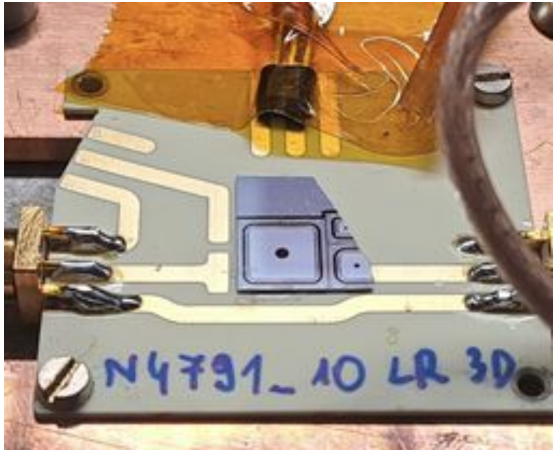
Effect/Measurement	Leakage current	Depletion voltage	Charge collection
Irradiation	Increase	Increase	Decrease
Short-term annealing	Decrease	Decrease	Increase
Long-term annealing	Decrease	Increase	Decrease

Irradiated single pad diodes overview

- Neutron irradiation at JSI (Jozef Stefan Institute), Ljubljana, Slovenia
- 4 batches of sensors
- Annealing steps performed at temperatures: 6.5℃, 20℃, 60℃ - all ongoing
- Recently was added : 40℃ - my work



Single pad diode on PCB



Thickness/Fluence	2e15 n_{eq}/cm^2	4e15 n_{eq}/cm^2	6e15 n_{eq}/cm^2	15e15 n_{eq}/cm^2
120 um			✔	✔
200 um		✔	✔	
300 um	✔	✔		

Experimental setup

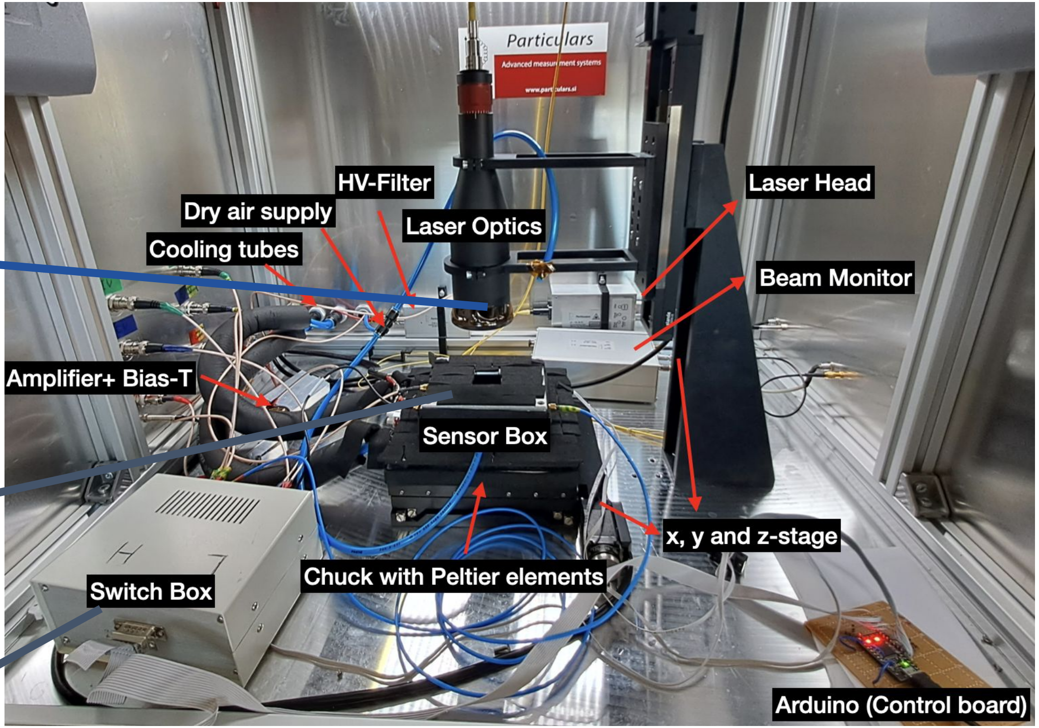
Setup is used to measure IV, CV, CC

Particulars Setup

- IR-laser (1064 nm) creates electron-hole pairs (with an IR-laser electron–hole pairs are created in the whole volume)
- These charge carriers drift under the influence of the electric field and induce current in the readout circuit

Sensor placed on a cooled copper holder, connected via SMA connectors

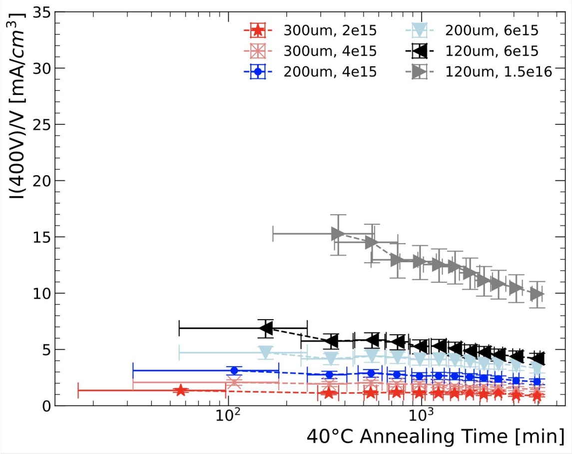
Switch Box to change measurement type



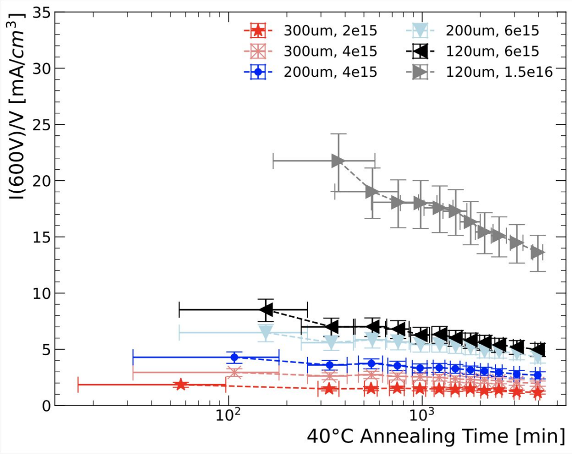
Leakage current

- Volume-normalised leakage current at 400V, 600V, 800V
- Expected continuous decrease for all voltages with some fluctuations
- This data will be used to extract leakage current annealing time constant and temperature scaling factors

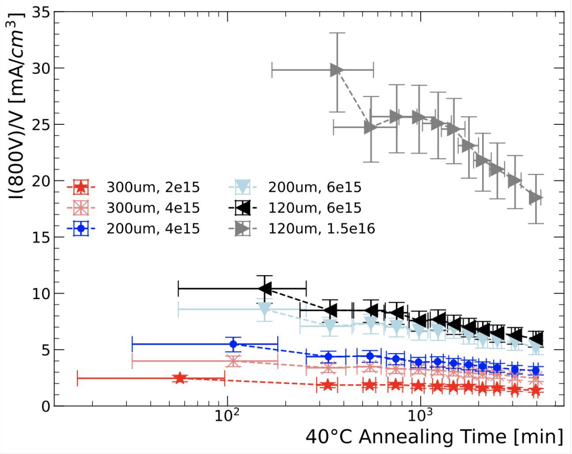
400 V



600 V

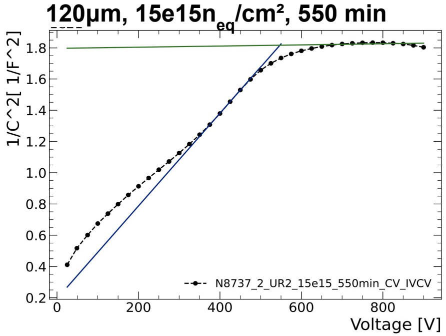


800 V

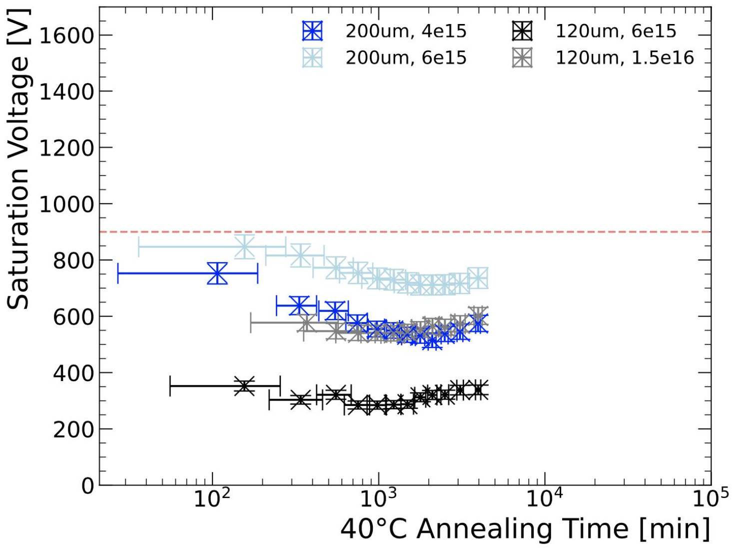


Saturation voltage-Annealing

- Only excractable for thin sensors (120um,200um) due to the Voltage limit of 900V in the measurements, while saturation voltage exceeds that for 300um sensors
- All measurements at 2 kHz frequency



Saturation Voltage vs Annealing time

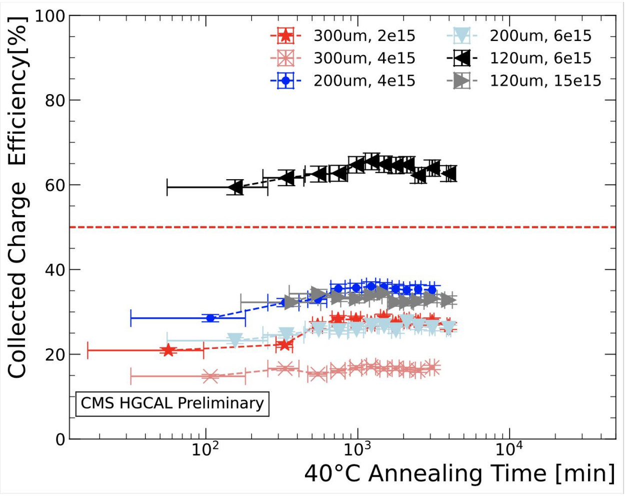


- It is can be seen that Saturation voltage decreases with annealing time during beneficial annealing
- It seems that measurements reached the minimum for all sensors
- More data is needed

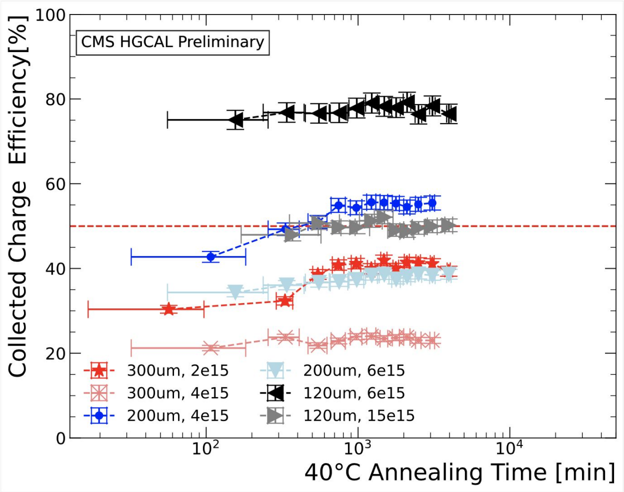
Charge collection-Annealing

- Increase in Charge collection during beneficial annealing
- The decrease can already be seen (reverse annealing)
- More data is needed

400 V



600 V



Conclusion

- Annealing studies are performed on six diodes of different thicknesses and fluences.
- Observed behavior (in agreement with studies on 6.5℃, 20℃, 60℃ annealing):
  - Leakage current decrease with annealing time
  - Beneficial annealing: Charge increase, saturation voltage decrease
  - Reverse annealing: Increase in saturation voltage, decrease in charge collection

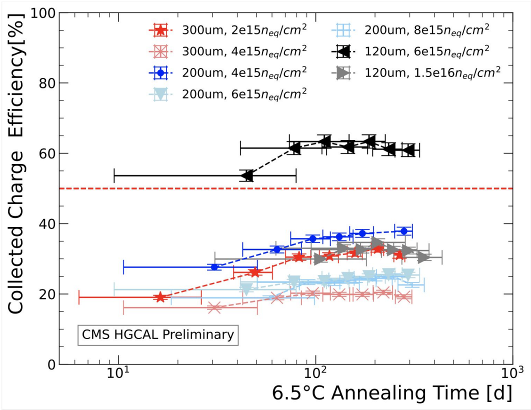
Ongoing work

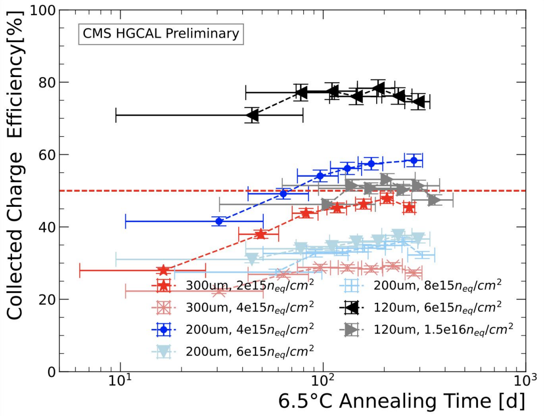
- Further measurements for longer annealing times
- Comparison of results between all annealing temperatures
- Extraction of annealing time parameters at various temperatures to extrapolate to the actual shutdown temperatures planned for HGCAL

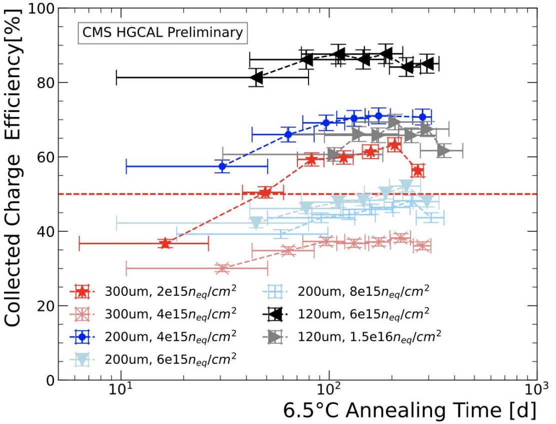
Thank you for listening!

Backup

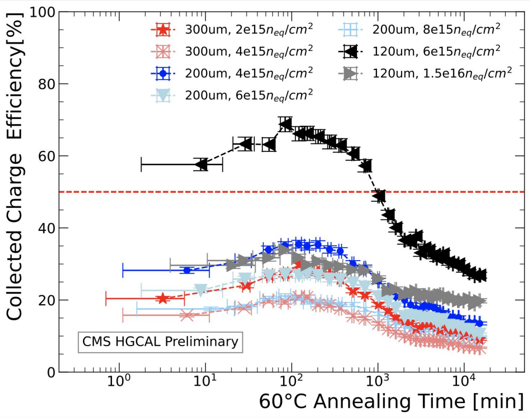
Charge collection-Annealing (6.5℃ and 60℃)

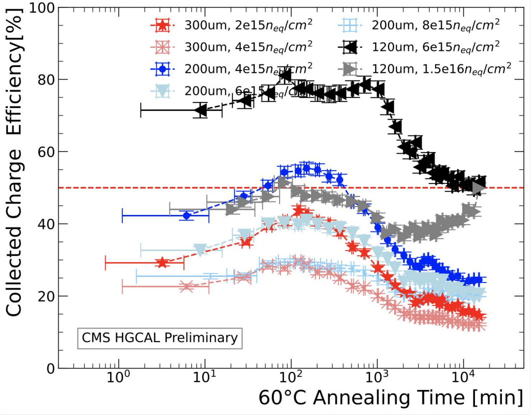


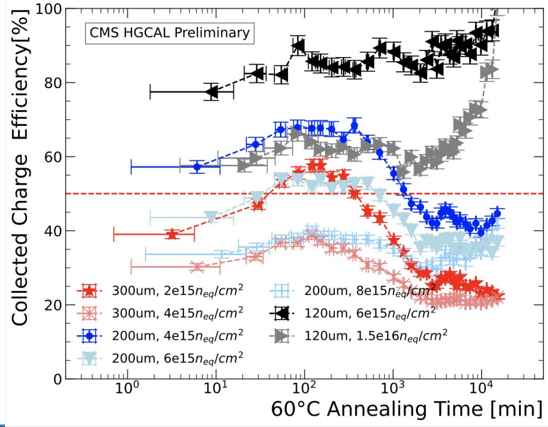




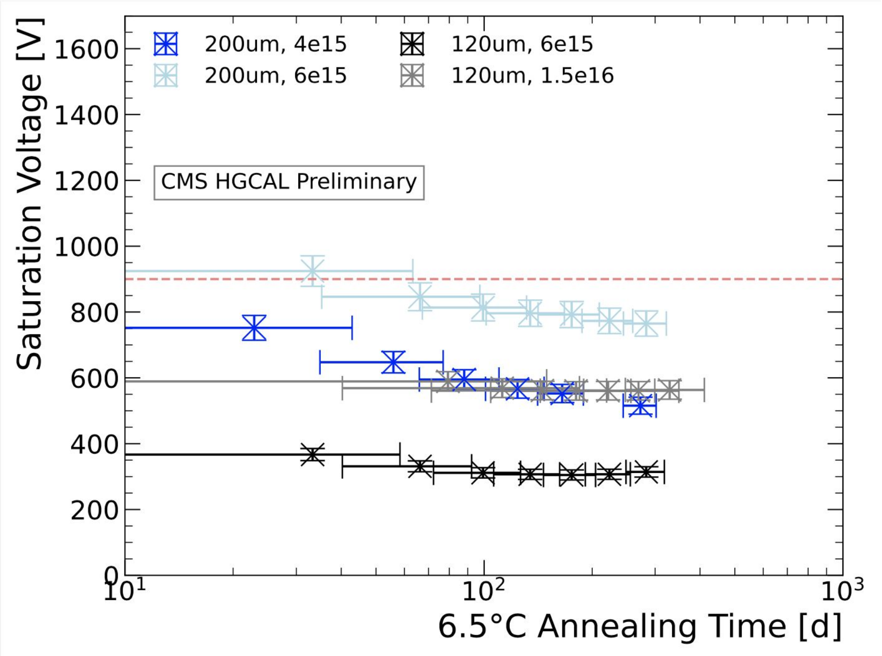
400 V | 600 V | 800 V

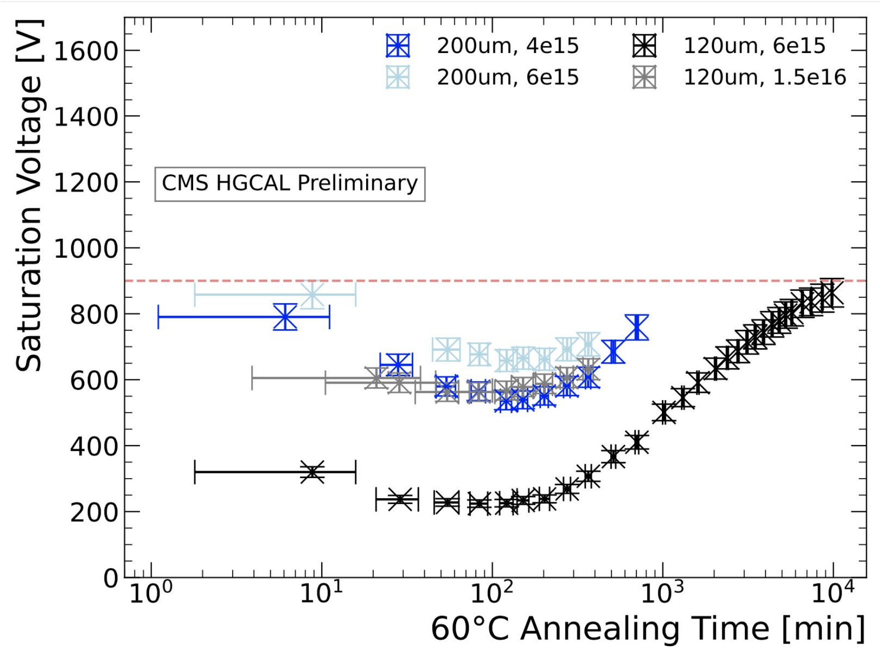




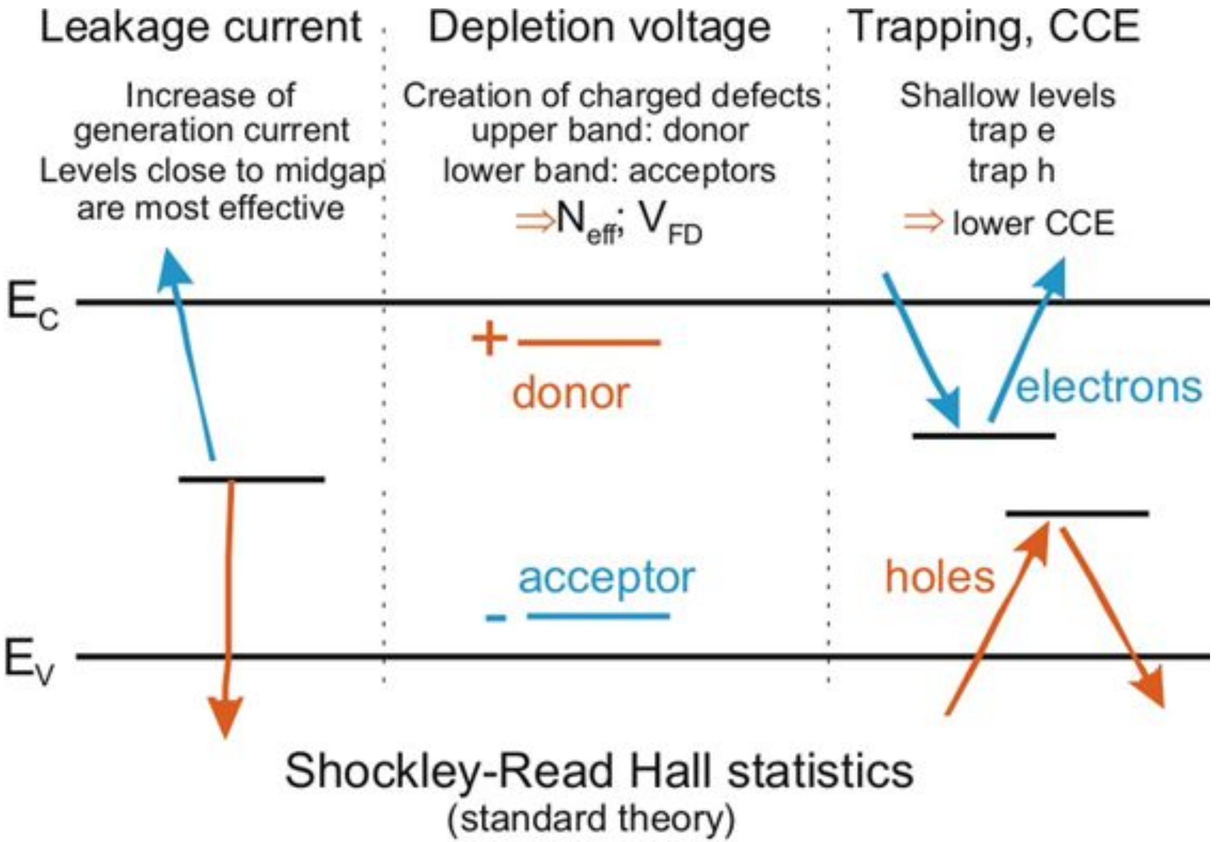


Saturation voltage-Annealing (6.5℃ and 60℃)





Defects impact on detector properties

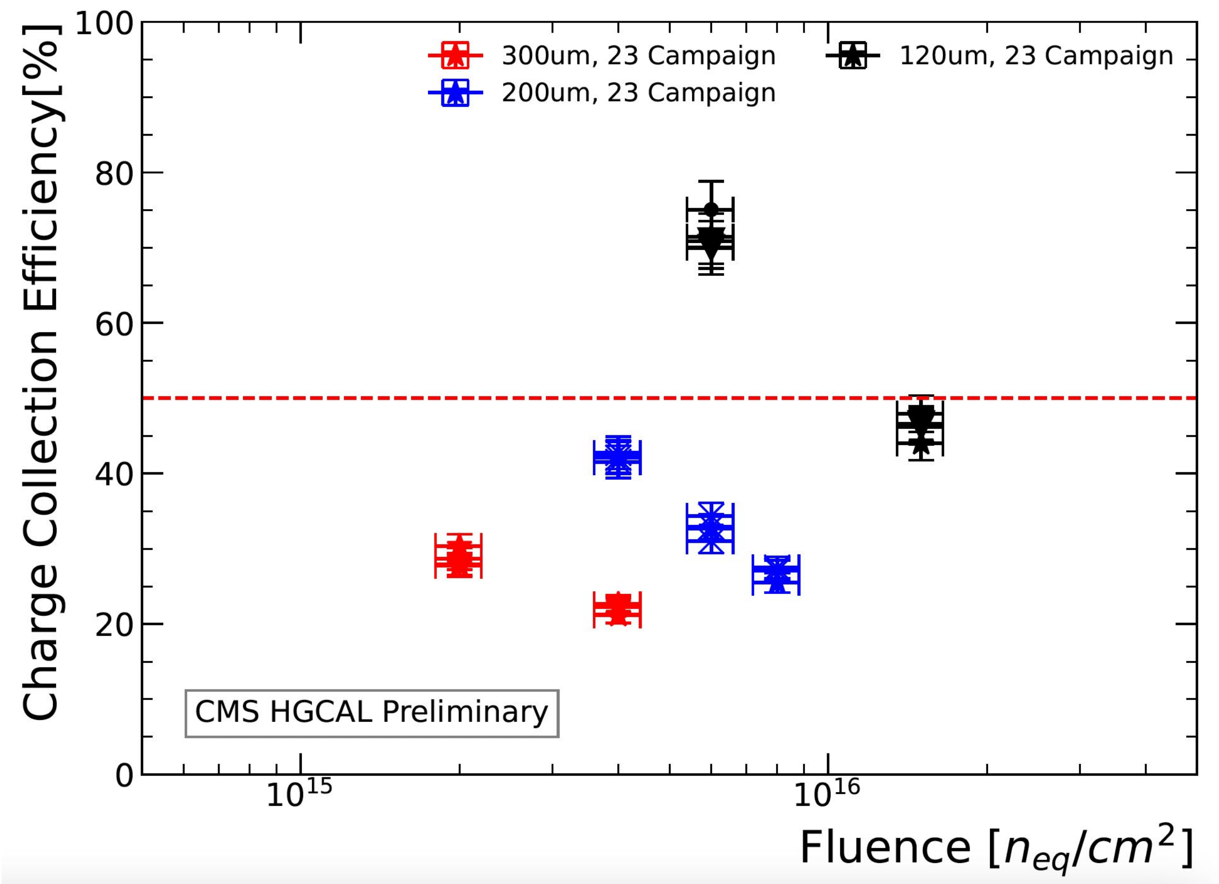


Annealing mechanisms

- **Migration and complex formation**
  - Defects become mobile at a certain temperature and can migrate through the silicon lattice
  - Migrating defects can for example recombine with their counterparts or form new defect complexes, e.g. $V + O_i \rightarrow VO_i$
- **Dissociation**
  - A defect complex can decay into its components if the vibrational energy of the lattice is high enough
  - One or more of the constituents can migrate until forming another defect or disappearing into a sink

- All mechanisms need to overcome an energetic barrier: Activation energy
- All processes are temperature dependent

Charge efficiency vs fluence



- no additional annealing
- 4 batches measured
- well in agreement