Radiation tolerance study using test-structure diodes from 8-inch silicon sensors for CMS HGCAL

Oliwia Kałuzińska (CERN)
on behalf of the CMS Collaboration

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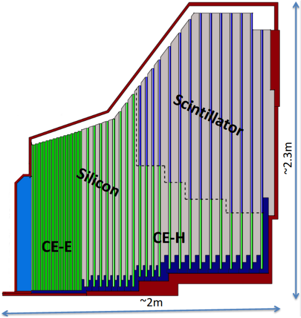
Short reminder of HGCAL

- CMS Endcap Calorimeter will be replaced by the High Granularity Calorimeter (HGCAL) for the HL-LHC
- HGCAL will use ∼620 m^2 silicon sensors produced on 8-inch wafers
- Three different thicknesses: 300 μm, 200 μm (Float zone) and 120 μm (Epitaxial)
- Full sensor results in the previous talk
  - Radiation tolerance study using 8-inch full-wafer silicon sensors for CMS HGCAL
- Results from test-structure diodes will be presented in this talk

Key Parameters:

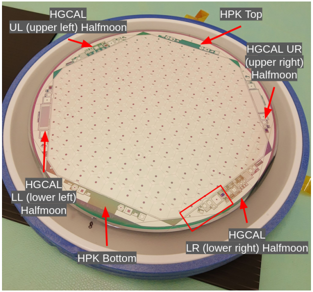
Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -35ºC
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap



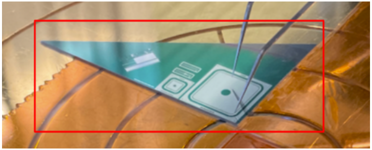
Small sized test structures on the full wafer

- Hexagonal full sensor from circular wafer
- Remaining space used for small sized test structures, e.g. diodes
- Neutron irradiation at two institutes: JSI (Jozef Stefan Institute) and RINSC (Rhode Island Nuclear Science Center)
- Fluence ranging from $6.5 \cdot 10^{14}$ n_{eq}/cm^2 to 10^{16} n_{eq}/cm^2
- Electrical characterization (IV/CV) results in this talk
  - Isothermal annealing of radiation defects in bulk material of the diodes
- Charge collection measurements ongoing

Full wafer silicon sensor



Test-structure diode contacted using two needles (pad and guardring)

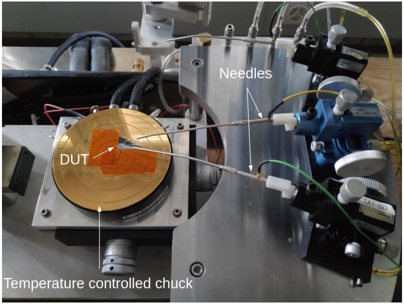


- Master Thesis on Si sensor characterisation

Electrical characterization procedure

- IV and CV measurements on temperature-controlled chuck connected with the needles
- Temperature: -20 °C
- Frequency for CV: 10 kHz, measurements with other frequencies ongoing
- 15 samples, 5 fluences, 9 annealing steps
- The results shown are from the JSI irradiation unless otherwise mentioned

CERN EP-DT-DD SSD group
IVCV probestation

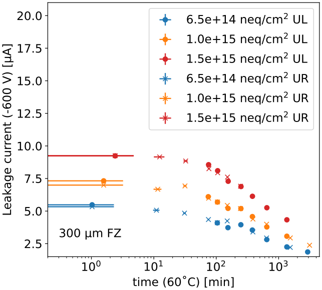


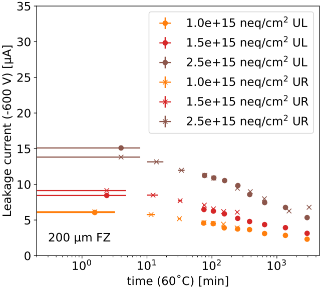
Nominal annealing steps

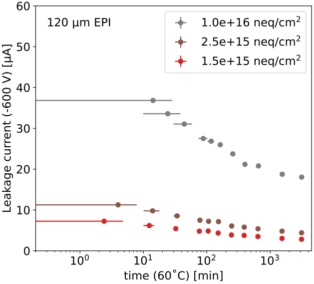
Total time at 60 °C [min]	Annealing step [min]	Temperature [°C]
10	10	60
30	20	60
70	40	60
150	80	60
250	100	60
390	140	60
740	25	80
1500	57	80
3000	120	80

Expected behaviour of the leakage current

Leakage current as a function of annealing time at -600 V





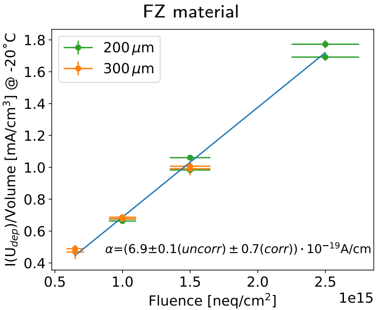


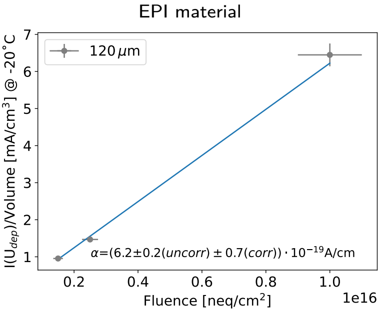
- The leakage current increases with fluence
- The current decreases with annealing time
- Compatible results for the same fluence and thickness across different halfmoons and irradiation batches, including 10% JSI fluence uncertainty

Extracting current related damage rate

$$\frac{I}{V} = \alpha \cdot \phi$$

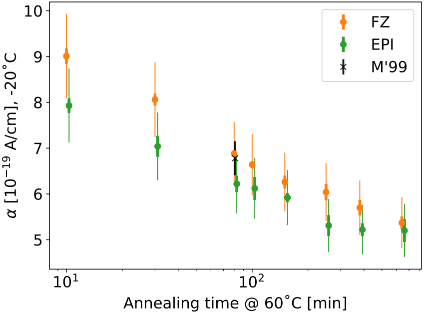
Leakage current at depletion voltage vs. fluence (ϕ) after 80 min of annealing at 60°C





- α determined for the FZ and EPI samples individually
- Leakage current at 80 min at 60°C (and U_{dep}) interpolated due to different time offsets (see backup)
- α slightly lower for EPI material
- In agreement with the value extracted for the full sensors
  - Radiation tolerance study using 8-inch full-wafer silicon sensors for CMS HGCAL

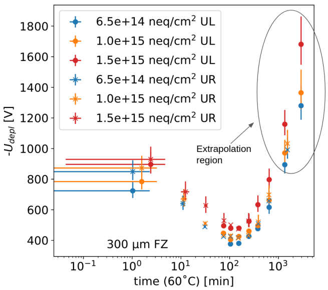
α vs. annealing time

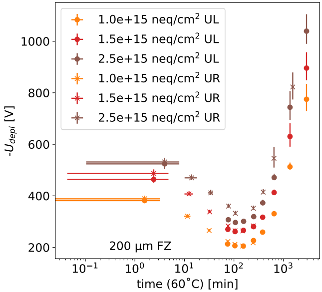


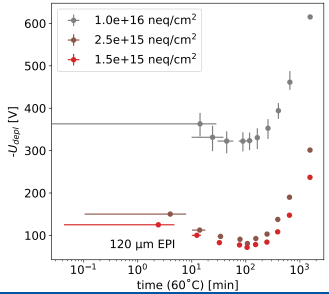
- α for both materials falls logarithmically off as expected
- FZ and EPI results compatible with each other
- Good agreement with reference value (M'99) ▸ PhD Thesis of M. Moll

Depletion voltage dependency

Depletion voltage vs. annealing time

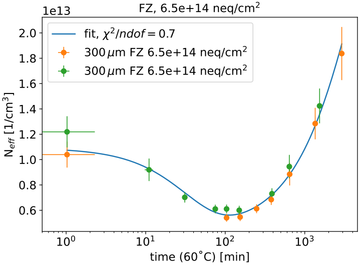


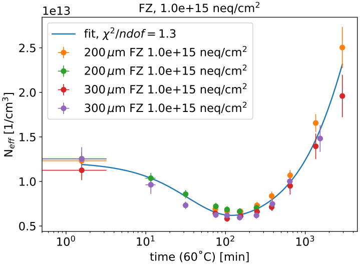


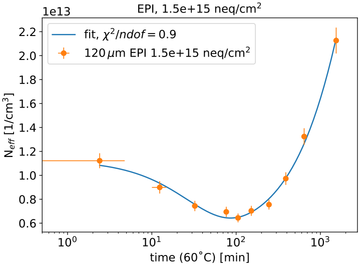


- Extracted from CV measurements
- Beneficial and reverse annealing regimes clearly visible
- Results from samples with same fluence and thickness are compatible, also including 10% JSI fluence uncertainty

Effective doping concentration estimation



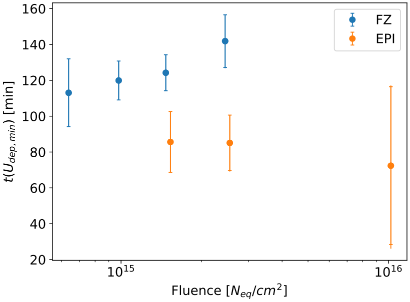




- Depletion voltage expressed in terms of the effective doping concentration (N_{eff})
- Samples of different fluence and material fitted separately using the Hamburg model
- Good description for each fluence by the Hamburg model
- Plateau not reached within the studied annealing time range

Estimation of the optimal annealing time

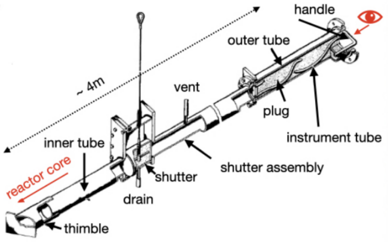
Annealing time at which the minimum depletion voltage is reached

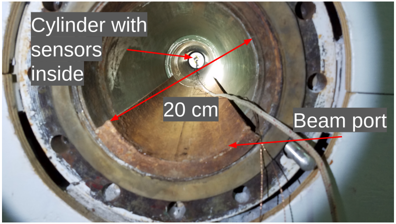


- $\sim(130 \pm 20)$ min at 60 °C for FZ material with slight increase with the fluence
- $\sim(80 \pm 20)$ min at 60 °C for EPI material
- Minimum at 80 min was expected for all materials based on literature
  ▸ PhD Thesis of M. Moll
- Compatible with results of p-type sensors tested for ▸ ATLAS tracker upgrade

RINSC large-area neutron irradiation facility

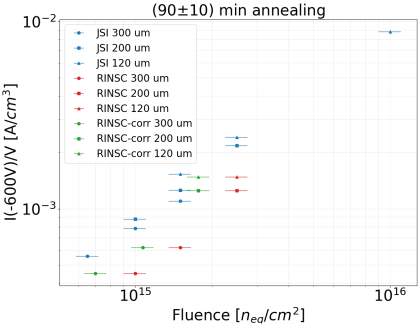
- Test structure diodes irradiated at well established irradiation facility JSI
- Full 8-inch wafers impossible to irradiate at JSI, due to irradiation slot limitation (max. 6-inch)
- Evaluate RINSC for irradiation of full 8-inch sensors:
  - Test structure diodes irradiated at RINSC were compared to the ones irradiated at JSI

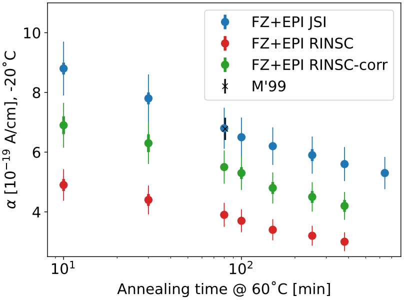




▸ Rhode Island Nuclear Science Center ▸ Neutron Irradiation and Electrical Characterisation of the Silicon Sensors

Leakage current: JSI vs. RINSC





- Based on leakage current measurements, it was found that the delivered fluence was overestimated
- Correction of delivered fluence values by 40% brings JSI and RINSC results closer
- Results agree within large fluence uncertainties (10% JSI, 10% RINSC), but systematic offset visible
- Study ongoing if additional fluence correction is needed

Summary and take-home messages

- Electrical characterization of the test-structure silicon diodes from 8-inch full wafer of the HGCAL prototype phase presented
- Leakage current is proportional to the fluence and decreasing with the annealing time
- Current related damage rate is compatible between the different materials and is in agreement with expectation
- Depletion voltage (effective doping concentration) changes with annealing time show clearly the beneficial and reverse annealing regimes
- For the FZ material, the minimum depletion voltage is reached after $\sim(130 \pm 20)$ min of annealing at 60 $^{\circ}$C and for EPI material – after $\sim(80 \pm 20)$ min at 60 $^{\circ}$C
- A discrepancy of fluence estimation between JSI and RINSC was found and corrected. Further studies ongoing.
- Temperature operation scenarios can be defined that ensure HGCAL operation without entering a reverse annealing region towards the end of the HL-LHC

Thanks to CERN EP-DT-DD SSD group for providing the infrastructure for measurements and support.

CERN

CMS Compact Muon Solenoid

KIT Karlsruher Institut für Technologie

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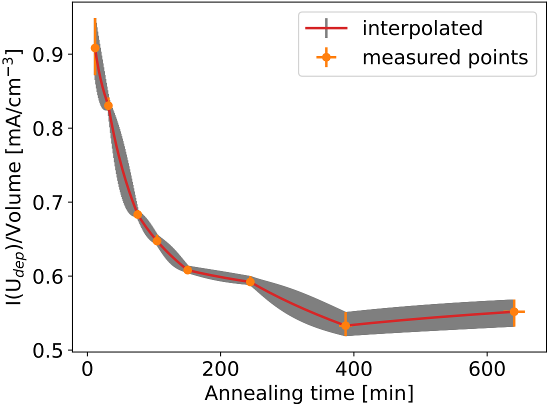
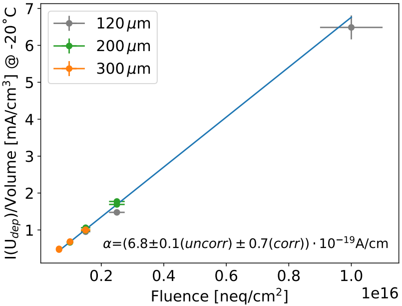
Backup

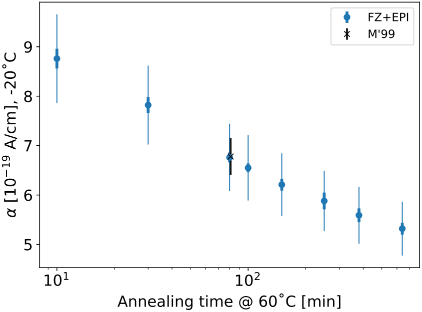
Leakage current interpolation

Interpolation of the leakage current per diode volume at depletion voltage for one exemplary diode

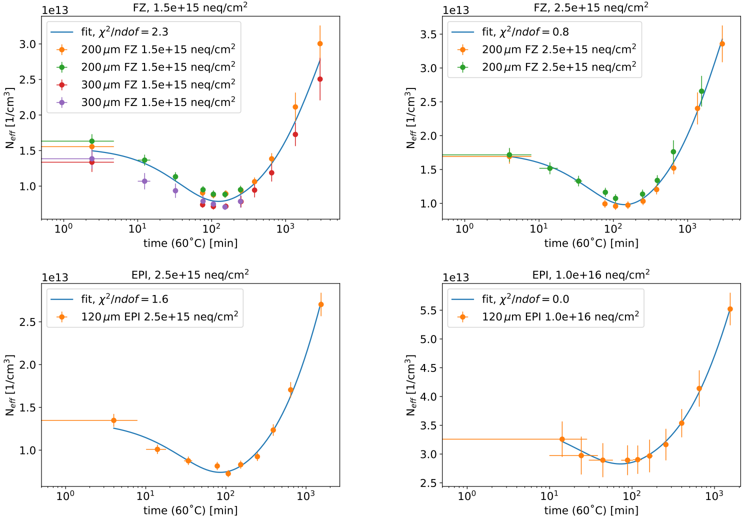


Extracting current related damage rate – all diodes combined

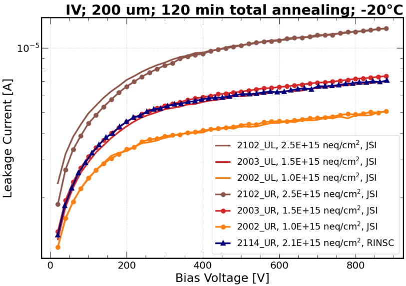


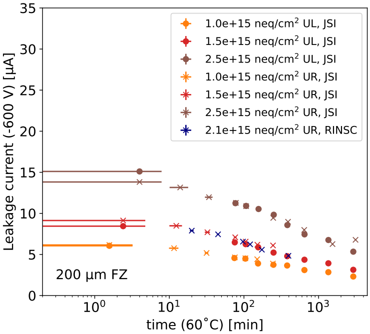


Effective doping concentration fits



Leakage current: JSI vs. RINSC





- Diodes irradiated at RINSC to smiliar fluence show lower current than the corresponding ones irradiated at JSI
- RINSC fluence appears lower than Ljubljana fluence