Radiation tolerance study using 8-inch full-wafer silicon sensors for CMS HGCAL

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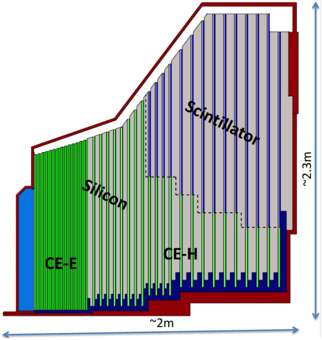
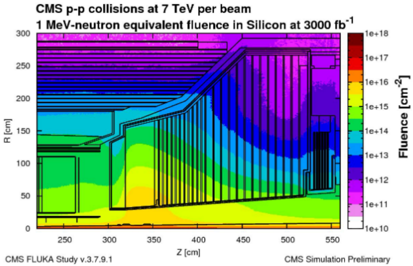
The 39th RD50 Workshop
Valencia, Spain
November 19, 2021

Upgrade for High - Luminosity LHC

- Increase in luminosity and radiation level at HL-LC
- CMS detector needs upgrade before the HL-LHC
- One of the upgrades is the replacement of the Endcap Calorimeter by a High Granularity Calorimeter (HGCAL)
- HGCAL will be based on silicon sensors in high radiation regions

CMS calorimeter endcap upgrade design



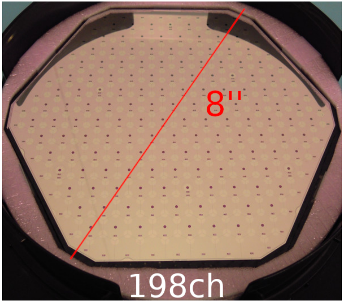


CMS HGCAL TDR

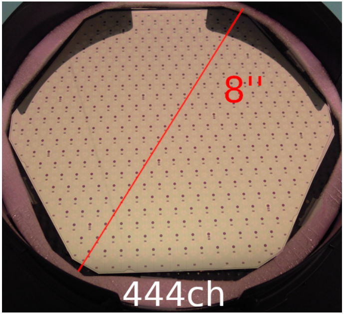
Silicon Sensors for CMS HGCAL

- Silicon pad sensors will cover a total area of 620 m^2
- Hexagonal shape for optimization of wafer usage
- Three different thicknesses adapted to radiation fluences
- Two geometries: Low-Density (LD) and High-Density (HD)
- Each sensor segmented into several hundred cells of hexagonal shape of 0.5 to 1.1 cm^2 in size
- Prototypes sensors (56 LD, 32 HD) have been delivered in Summer 2020 and partially sent to RINSC

Low-Density sensor



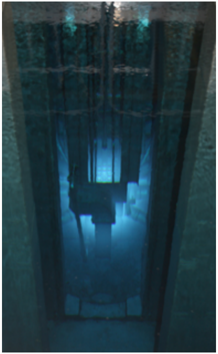
High-Density sensor



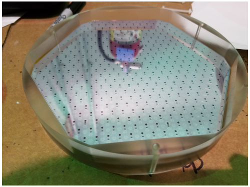
New irradiation facility: RINSC

- Rhode Island Nuclear Science Centre, US
- Neutron irradiation of the sensors up to 10^{16} 1MeV n_{eq}/cm^2 in 180 min
- Four sensors in a puck irradiated at a time
- Irradiation of the 8-inch wafers possible only at RINSC because of the beamport width

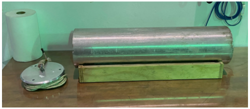
Reactor Core



Sensor in a puck



Cylinder

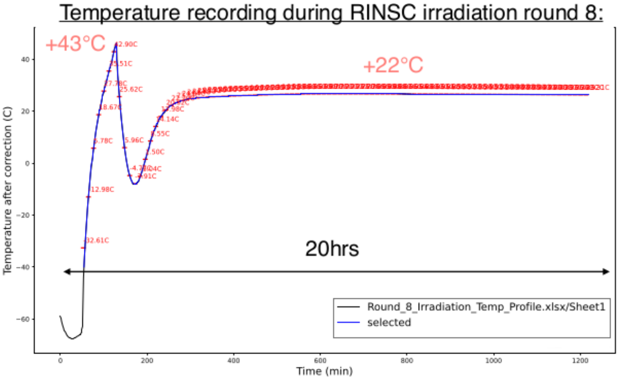


Beamport

RINSC webpage

Specifics of RINSC irradiation facility

- High temperatures during irradiation
- Temperature during the irradiation was recorded
- Annealing already during irradiation and after
- Additional annealing up to 80min at 60°C done at CERN

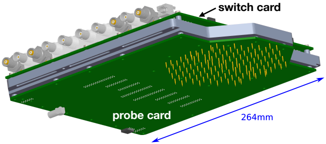


Target fluence: $5 \cdot 10^{15}$ 1MeV n_{eq}/cm^2, irradiation time: 76 min

Electrical characterisation at CERN

The probe station

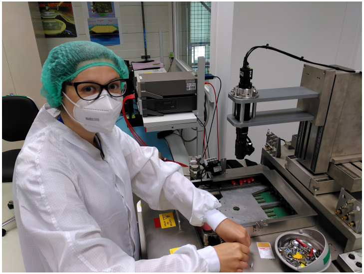
- Use custom-made "ARRAY system" - full wafer IV+CV probe card
- Simultaneously contact and bias all pads in a sensor
- Per-cell IV and CV of all cells before and after additional annealing
- Temperature controlled chuck, enables measurements at -40°C
- Temperature stable with time, less than 1°C inhomogeneity across the chuck at -40°C

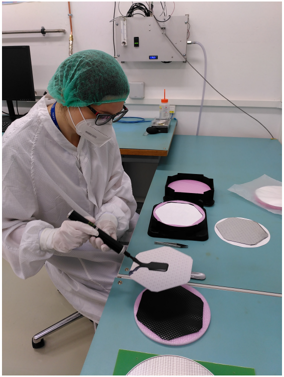


ARRAY system

Irradiation of HGCAL silicon sensor prototypes

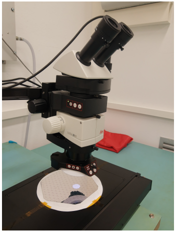
- Started in August 2020, finished in June 2021
- 26 sensors characterised at CERN
- 7 irradiation rounds
- 5 different target fluences



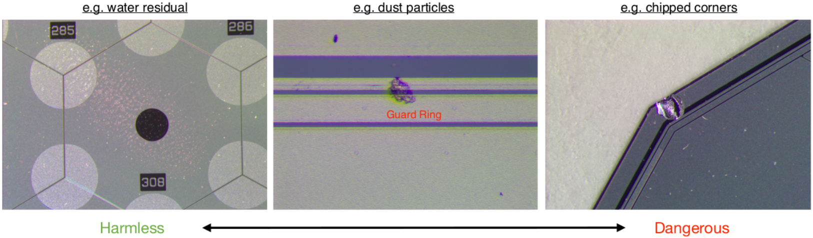


Visual inspection is important

- Identification of mechanical defects
- Removal of dust
  - Particular focus on guard ring (GR) area
- Fully manual inspection
  - Now partially automated; working on full automation with the use of ML

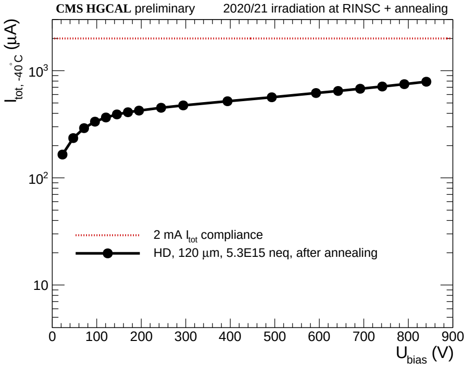


Examples of features observed on irradiated sensors:



IV test measurement at -40°C

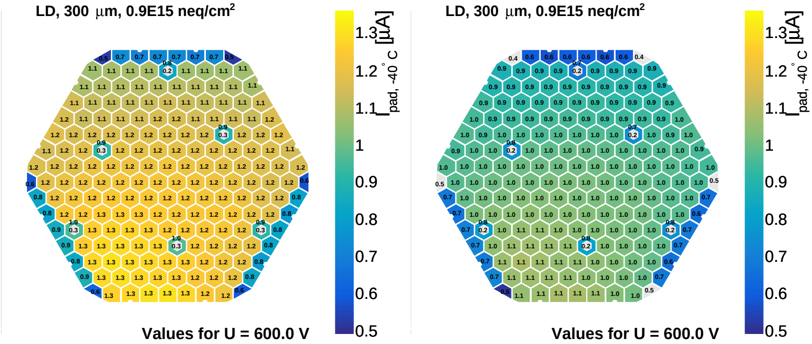
- Measure total leakage current by increasing bias voltage by 10V up to 850V or I_{tot}=2mA
- 2mA is a system-defined compliance limit to protect the ARRAY test system
- Total leakage current well below 2mA for most sensors
- Note log scale



IV measurement at -40°C

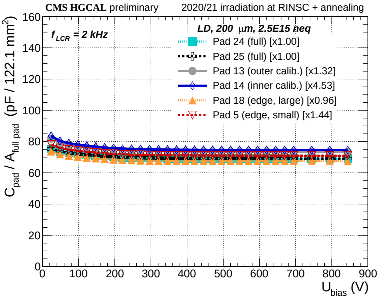
- Additional annealing lowers leakage current
- Assume leakage current as proxy for fluence
- Fluence profile visible

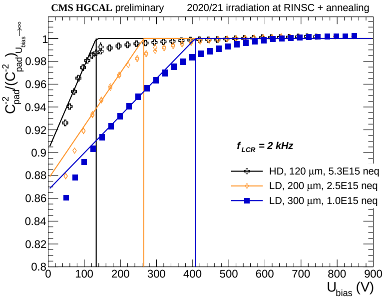
Per-pad leakage current before and after additional annealing



Capacitance and depletion voltage

- Capacitance of partial cells normalized to the full-cell area
- Obtained values in agreement within $\pm$ 5%
- Depletion voltage estimation based on squared-inverse of open-corrected serial capacitance
- Thicker sensors show higher depletion voltage at the same fluence

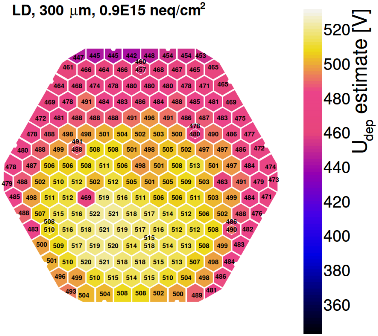


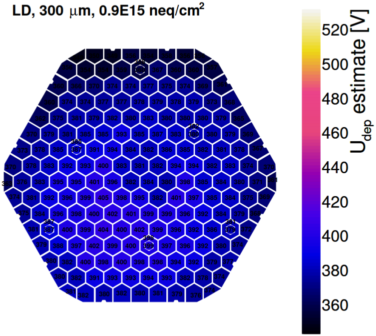


CV measurement at -40°C

- Additional annealing lowers the depletion voltage

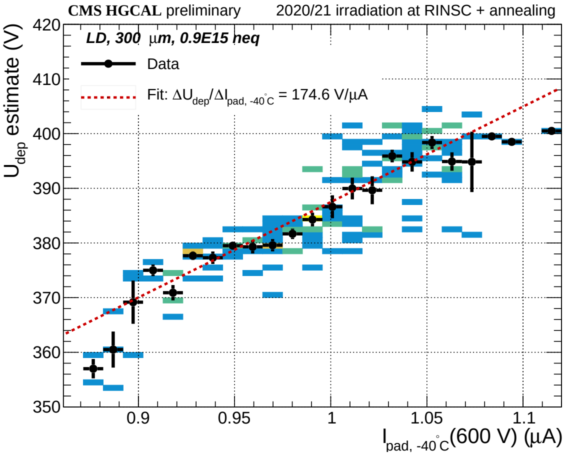
Per-pad depletion voltage estimation before and after additional annealing



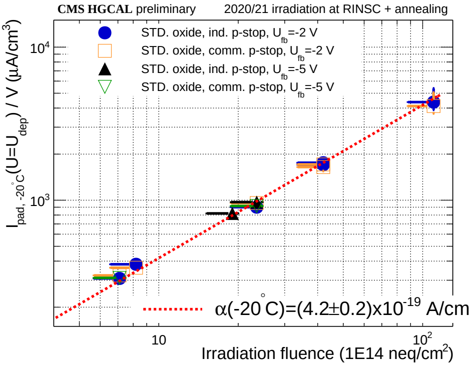


Correlation between fluence and depletion voltage

- Higher depletion voltage observed for higher leakage current (proxy for fluence)



Current related damage rate



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

- Systematic uncertainties: up to 20% for fluence and 7% for leakage current
- $\alpha_{-20^\circ C} = (4.2 \pm 0.2 - 0.8 + 0.2)x10^{-19}$ A/cm for current at U_{dep}
- $\alpha_{-20^\circ C} = (5.9 \pm 0.2 - 1.1 + 0.3)x10^{-19}$ A/cm for current at 600V
- $\alpha_{-20^\circ C} = (6.9 \pm 0.3 - 1.4 + 0.4)x10^{-19}$ A/cm for current at 800V

Take-home messages

- One of the upgrades in CMS experiment is the replacement of current endcap calorimeters with the High Granularity Calorimeter.
- Silicon sensor will cover an area of over 600m^2 in HGCAL
- 8-inch prototype silicon wafers were irradiated at RINSC and electrically characterised at CERN for the first time.
- Additional annealing reduces leakage current and depletion voltage
- Depletion voltage and leakage current (as proxy for the fluence) positively correlated
- Preliminary alpha-value (after annealing):
  $\alpha_{-20^\circ C} = (4.2 \pm 0.2 - 0.8 + 0.2) x 10^{-19}$ A/cm

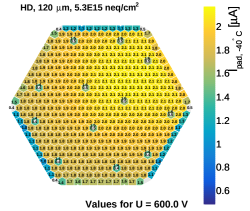
Backup

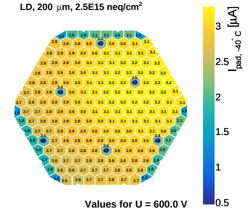
List of the sensors characterised at CERN

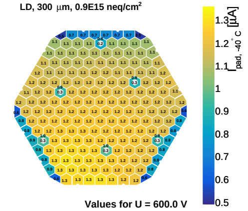
Round	ID	Temp [°C]	P-stop	Thickness [µm]	Geometry	Flat band voltage [V]	P-Stop conc.	Oxide quality	Material	Target fulence [neg/cm2]	RINSC irradiation
1	1004	-30 & -40	ind.	300	LD	-5	STD	STD	FZ	6.5E+14	26 Aug 2020
	1002					-2					
	1101		com.			-5					
	1102					-2					
3	3002	-40	ind.	120	HD	-2	0.5*STD	STD	epi	1.0E+16	20 Oct 2020
	3102		com.								
	3003		ind.				STD				
	3103		com.								
4	2109	-40	com.	200	LD	-5	STD	Type B	FZ	2.5E+15	21 Jan 2021
	2110							Type C			
	2111							Type D			
	2112							Type E			
5	2004	-40	ind.	200	LD	-5	STD	STD	FZ	2.5E+15	28 Jan 2021
	2002					-2					
	2105		com.			-5					
	2114					-2					
8	3009	-40	ind.	120	HD	-2	STD	STD	epi	5.0E+15	11 Mar 2021
	3010										
	3109		com.								
	3110										
10	1013	-40	ind.	300	LD	-2	STD	STD	FZ	1.0E+15	15 Apr 2021
	1114		com.								
	N0538 WNo.3		ind.			-5					
	N0538 WNo.25		com.			-2	Type C				
11	N0541 WNo.4	-40	ind.	200	LD	-5	STD	STD	FZ	2.5E+15	6 May 2021
	N0538 WNo.10					-2	Type C				

IV measurements at -40°C

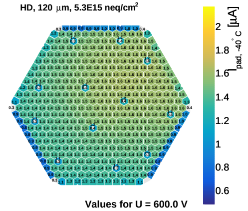
Per-pad leakage current before additional annealing

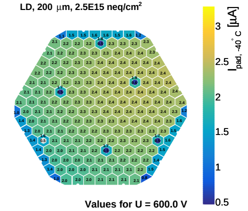


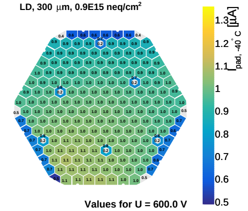




Per-pad leakage current after additional annealing

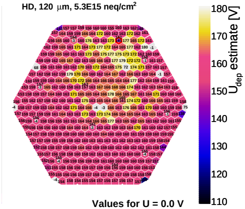


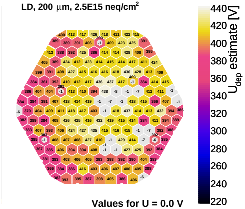


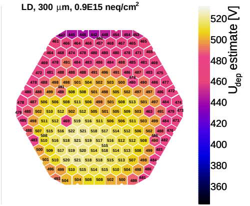


Backup
CV measurements at -40°C

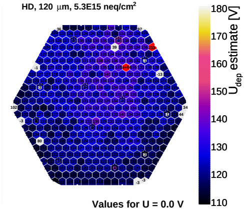
Per-pad depletion voltage estimation before additional annealing

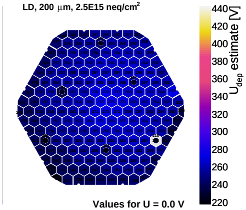


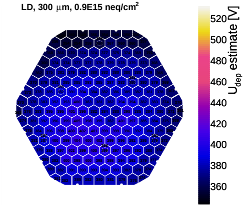




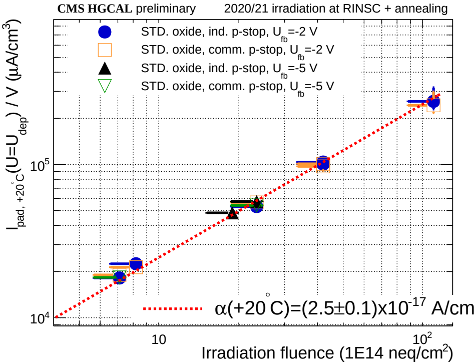
Per-pad depletion voltage estimation after additional annealing







Backup
Alpha-value at 20°C



- Systematic uncertainties: up to 20% for fluence and 7% for leakage current
- $\alpha_{20^\circ C} = (2.5 \pm 0.1 - 0.5 + 0.1) x10^{-17}$ A/cm for current at U_{dep}
- $\alpha_{20^\circ C} = (3.5 \pm 0.1 - 0.7 + 0.2) x10^{-17}$ A/cm for current at 600V
- $\alpha_{20^\circ C} = (4.1 \pm 0.2 - 0.8 + 0.2) x10^{-17}$ A/cm for current at 800V