Characterisation of Silicon Sensors for the High Luminosity Upgrade of the CMS Endcap Calorimeter

Report by:

Anthony Watt, Maynooth University, Ireland

Supervised by:

Philipp Zehetner, Ludwig Maximilian University of Munich, Germany

Thorben Quast, CERN, Geneva, Switzerland

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Abstract

CERN is currently in the process of testing silicon sensors produced by Hamamatsu photonics (HPK). These silicon sensors are planned to be used in the upgrade of the CMS detector for the HL-LHC upgrade. The testing of these sensors requires both an analysis software & a laboratory setting to examine the electrical characteristics of the silicon sensors. At CERN the priority was to contribute to the existing analysis software to allow HPK pre-series sensors to be analysed & characterised using both the manufacturers data & CERN's measurement data. Once this data is analysed it will give HGCAL feedback on whether the sensor design is suited for the acceptance parameters set for the High Luminosity upgrade or whether any changes will need to be made and communicated to the manufacturer. The analysis of the data at CERN will give an informative view of whether or not the current protocol for sensor measurement and analysis within HGCAL will need to be changed.

Contents

1 Introduction

During the long shutdown 3 from 2025 to 2027, the LHC is planned to be upgraded to the HL-LHC. For the CMS detector (Compact Muon Solenoid) the Endcap Calorimeter is to be upgraded and replaced by the High Granularity CALorimeter (HGCAL). This upgrade is necessary to be compatible with the increased luminosity and increased radiation exposure from the HL-LHC.

The HL-LHC is estimated to operate with:

- *Instantaneous Luminosity:* (5 - 7.5) x 10^{34} $s^{-1}cm^{-2}$
- *Integrated Luminosity:* 3000 fb^{-1}
- *Radiation Fluence*: 1×10^{16} n_{eq}/cm^2 *
- *Pile-Up Events:* 140-200 events. [1]

* *n_{eq}/cm^2 is equal to 1 MeV equivalent of neutrons per cm^2*

CERN is currently in the process of testing Silicon sensors produced by Hamamatsu photonics (HPK). These sensors are planned to be used on the HGCAL as a means of detection and analysis during beam collisions in the HL-LHC. The testing of these sensors requires both analysis software and a laboratory setting to examine the characteristics of the silicon sensors. At CERN the priority was to contribute to the existing analysis software for pre-series HPK sensors to be analysed and characterised using the manufacturers data. Once this data was analysed, HPK Sensors were measured in a clean room environment at CERN to see if the data is comparable with the manufacturer. This data then needed to be plotted using a visualisation software for visual comparisons to be made. Once the data was analysed, any recommendations to the silicon sensors which were deemed necessary were mentioned to the manufacturer and any changes in the measuring process at HGCAL were taken into consideration.

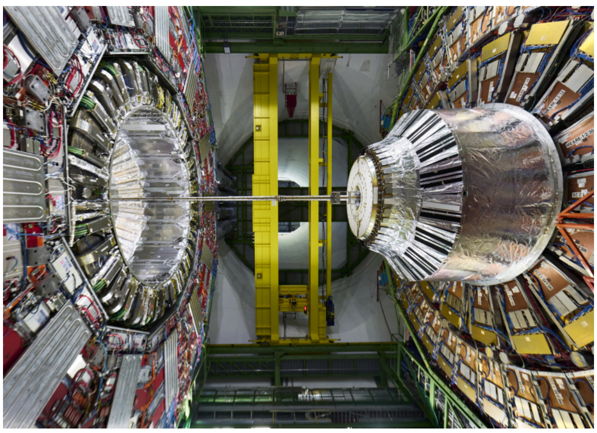


Figure 1: The Compact Muon Solenoid (CMS) in CERN 2021. [2]

1.1 HGCAL Upgrade Criteria

- *Precision Measurements* - Obtain precise timing from each cell and identification of vertex of which there is triggering interaction.
- *Fine Lateral Granularity* - S/N ratio allowing for MIP (Minimum Ionising Particle) calibration & to help with 2 shower separation & narrow jet observation.
- *Fine Longitudinal Granularity* - Fine sampling of longitudinal development of showers giving good EM energy resolution and pattern recognition.
- *Dense Calorimeter* - Preserves lateral compactness of showers.
- *Radiation Tolerance* - Preserves energy resolution after 3000 fb^{-1} with good inter-cell calibration ($\approx 3\%$).
- *Decision Making* - Contributes to level-1 triggering. [3]

1.2 Structure & Operational Requirements of HGCAL

HGCAL is planned to have:

- A psuedorapidity coverage of $1.5 < |\eta| < 3.0$
- Mass ≈ 215 Tonnes per end cap
- Full system maintained at - 30 °C
- ≈ 620 m^2 Si sensors in ≈ 26,000 modules
- 6 Million Si channels with ≈ 0.6 or 1.2 cm^2 cell size
- ≈ 370 m^2 of scintillators in approx. 3700 boards
- ≈ 240k scintillation channels with 4-30 cm^2 cell size
- Power at end of life of HL-LHC ≈ 125 kW per endcap

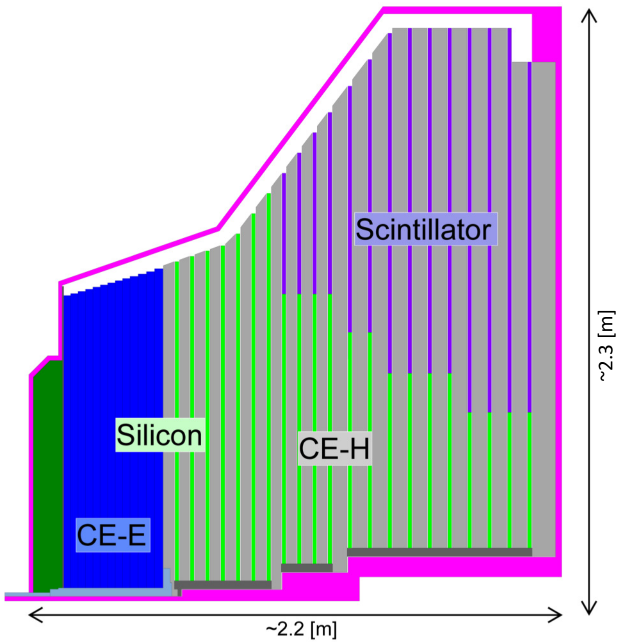
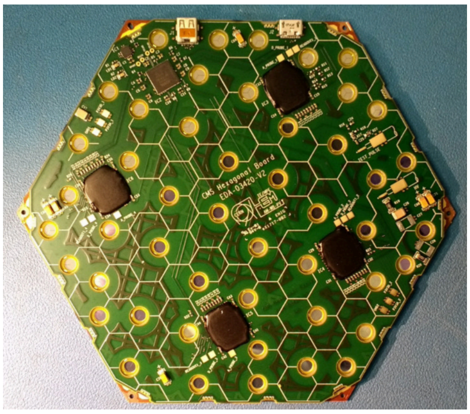
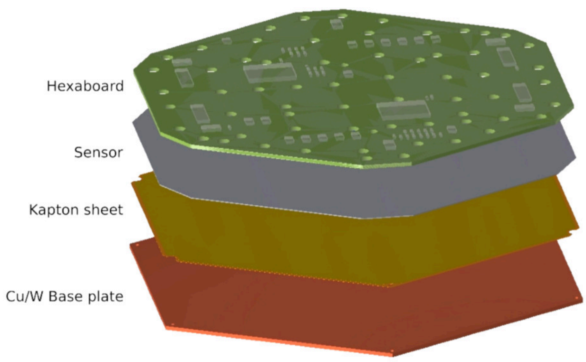


Figure 2: HGCAL structure (CMS 2022) [3]





Figures 3,4: Silicon Modules (CMS 2022) [4]

2 Characteristics of Silicon Sensors

2.1 Manufacturing Characteristics of Silicon Sensors

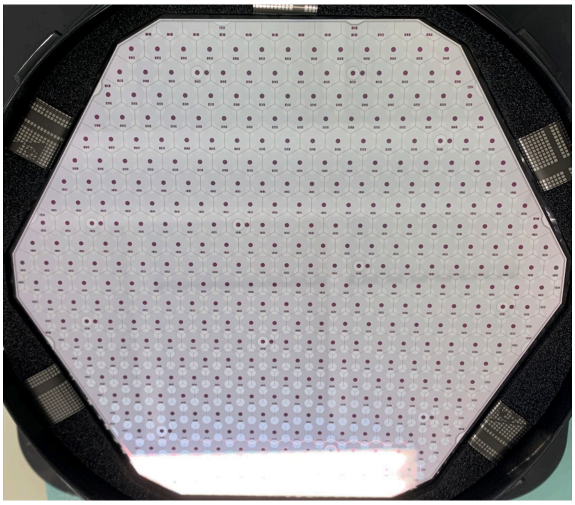
Hamamatsu Photonics (HPK) will manufacture the silicon sensors used by HGCAL. All sensors will:

- Have hexagonal geometry and cut from 8” circular silicon wafers.
- Either be Low Density (LD) or High Density (HD).
- Have p-type doping due to being more radiation tolerant than n-type.

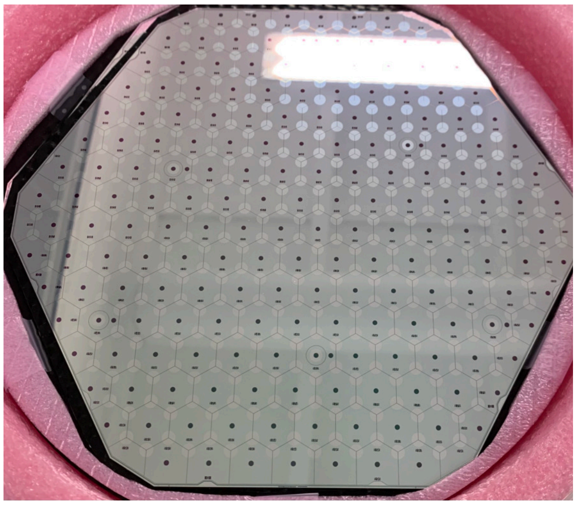
Manufacturing Characteristics	**LD**	**HD**
Active Thickness (µm)	200, 300	120
Number of Pads (Channels)	199	445
Cell Size (≈ cm^2)	1.2	0.6
Growth Type	Float-Zone	Epitaxial

Table 1: Manufacturing Characteristics of Silicon Sensors

Each sensor will have either 199 or 445 channels depending on its geometry.
The majority of these channels are fully hexagonal whereas around the edges of the sensor the channels are typically smaller in area and are not hexagonal. Each sensor will also have multiple calibration channels which have circular geometry and will be used for MIP (Minimum Ionising Particle) calibration until the end of life of the detector. A Guard Ring (GR) will surround all the channels shielding currents drawn at the sensors edge.



8” HD pre-series sensor



8” LD pre-series sensor

The layout of HGCAL will have HD sensors placed closest to the HL-LHC as they have more channels adding to the accuracy of the showers as well as an increased radiation tolerance over the LD sensors. The silicon sensors will be placed in the CE-E and the high radiation regions in CE-H sections of HGCAL *(See Figure 2).*

2.2 Acceptance Parameters of Silicon Sensors for HGCAL

The most important parameters measured by HGCAL are both IV (Current-Voltage) and CV (Capacitance-Voltage). Both measurements allow us to observe the electrical characterisations of silicon sensors.
HGCAL has placed acceptance criteria on both IV and CV measurements.
Global characteristics of a sensor are the criteria given to a full sensor and must be passed for a sensor to pass the criteria.
If any global characteristic fails, the sensor fails the grading criteria.
Per-pad characteristics are used to define any bad channels on a sensor.
A sensor can have a bad channel but still pass the overall grading as long as the global characteristics have passed.

IV - *Global (Full sensor) Characteristics:*

- Current at 600 V must be less than or equal to 100 µA
- Current at 800 V must be less than 2.5 times the current at 600 V
- Number of bad pads/channels must be less than or equal to 8.
- Allowed number of adjacent bad channels must be less than or equal to 2

Per-Pad Characteristics:

- Current at 600 V must be less than 100 nA per pad
- Current at 600 V must be greater than 10 nA and
  Current at 800 V must be greater than 2.5 times the current at 600 V
- Current at 600 V must be less than or equal to 10 nA and
  Current at 800 V must be greater than 25 nA

CV - *Global Characteristics (Using full size cells only):*

- Depletion voltage must be less than X V for sensor of Y thickness
- The maximum variation of depletion voltage must be no more than $\pm$ 10%
- Relative thickness variation across the sensor must be less than 10/Y

Where X = 70, 160, 370 V   Y = 120, 200, 300 µm

2.3 Naming scheme of Silicon Sensors

All silicon sensors at HGCAL have both sensor IDs and scratch-pad IDs. Sensor IDs are given by HPK to each sensor. Sensor IDs do not have any information about the sensors encoded in them. Scratch-pad IDs are etched onto the silicon sensors and are visible using a microscope. HGCAL has decided for pre-series and all future sensor campaigns to only use scratch-pad IDs when discussing sensors. The benefits of using scratch pad IDs are the sensor thickness and geometry is encoded within the IDs.

3 Analysis of Silicon Sensors

3.1 Analysis Framework for Silicon Sensor Data

The analysis of the silicon sensors for HGCAL is vital to understand whether the sensors can be used giving reputable results, mass produced, as well as understanding their behaviour when biased with high voltages and exposed to large doses of radiation. Sensors analysed for HGCAL will both be non-irradiated and irradiated sensors, which allows us to observe and understand how the sensors will operate within the environment of the HL-LHC.

An analysis framework *"HGC_Sensor_IVCV_Analysis"* is currently in use to [5] analyse measurement data for the silicon sensors. Using this framework, parameters such as total current in each channel, total current in the overall sensor and capacitance of each channel can be calculated and shown as the analysis software creates a PDF containing the data in numerical and graphical form.

HPK IV data for the pre-series sensors was in an alternate format than previously agreed with HPK resulting in an update for the analysis framework. The data by HPK contained measurement data such as leakage current at different bias voltages for each channel. In the new data format, the guard ring channel (GR) was saved as "GR" which differs from the old format which saved it as either "199" (LD) or "445" (HD) depending on the sensors geometry. The total current value for each voltage step was saved as channel "TOTAL" in the new IV format whereas before it was saved as channel "0". To keep the data format consistent, the analysis workflow now computes the geometry of the sensor being analysed & then assigns the "GR" current as either channel "199" or "445" and "TOTAL" current as channel "0". This change allows pre-series data to be consistent with previous generations of data.

3.2 Visualisation Software for Silicon Sensor Data

An external graphing software separate from the analysis software has been developed at CERN known as *"Automatic Silicon-Test Visualisation".* [6]
This software allows for more in depth detailed graphs of the data. This results in graphs which emphasise on any failure measured on the silicon sensors. This software is continuously being updated to include more graphing functions and more detailed graphs. Recent additions to the software are the inclusion of "Total IV" graphs which plot the total current of the sensor at each voltage step. This allows a much clear picture as to the increase of current in a sensor and if it increases too rapidly *(See Global Characteristics pg. 6)*. Another addition to the visualisation software is a box plot comparison script which allows us to compare CERN data vs HPK data side by side and see if any outlying channels are visible in each data set by colour coding any anomalous results.

4 Measurement and Analysis of Silicon Sensors

4.1 Measurement Procedure for Pre-Series Sensors

HGCAL has measurement procedures which all institutes involved in HGCAL [7] follow to ensure all results obtained have been measured in the same set up. Humidity must be recorded and measured. To ensure we have an appropriate environment, dry air is injected into the testing station to help decrease relative humidity. This humidity is read by the switch card connected to the measurement station. Temperature must be recorded to ensure temperature corrections are accurate. Once humidity and temperature are confirmed, the silicon sensor is taken out of a dry air cabinet and using a microscope its scratch-pad ID is checked to confirm which sensor is being measured. Using the microscope, the sensor is optically inspected to ensure no mechanical defects such as electrical discharge are visible. Any visible scratches are recorded and any removable foreign objects such as dust are removed. Extra caution is used when optically inspecting the guard ring due to currents typically being much higher there than any other channel. Currently at CERN our optical inspections are done by an AI system known as *"HexaScan AI"*. This AI system optically inspects the sensor and will alert the user to any visible defects on the sensor. The user then checks the photos taken by the AI and either confirms any dust/defects or removes any results with no visual issues. Once optical inspections are complete the sensors are placed under an ion blower for 5 minutes to reduce the potential charge build ups. After the 5 minutes are complete the sensor is then placed inside the measuring station and rotated and aligned to line up with the probe card. The sensor is then contacted with the probe cards and using HexDaQ a contact test is run to ensure proper contact between the probe card and sensor. Once a contact test confirms all channels are connected IV + CV measurements are started on the sensor.

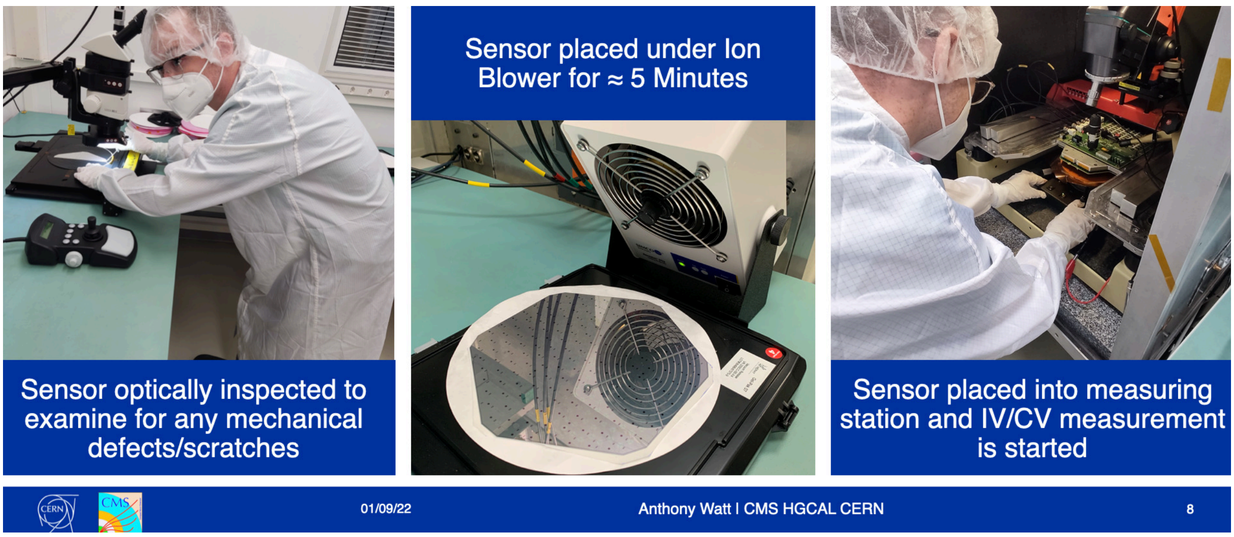


Figure 5: Measurement procedure at CERN

4.2 Measurements and Analysis of Pre-Series 120 µm HD Sensors

At CERN 9 pre-series 120 µm HD sensors were measured. All sensors were measured according to the procedures *(pg.8 - Measurement Procedure for Silicon Sensors)*. All 9 sensors were optically inspected with 8 out of 9 showing no visible defects of concern. Sensor 300050 showed structural damage at channel 332. This defect was most likely caused due to a stacking fault in the material during manufacturing.

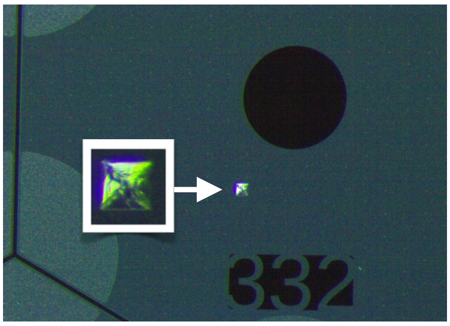


Figure 6: Sensor 300050

For IV measurements a voltage range of 100 - 900 V was applied to each sensor. Once IV measurements were completed the analysis software showed 8 out of 9 sensors passed IV criteria, except 300050 which failed. Using the plotting software which included the new pre-series changes, all IV data for the 9 sensors was plotted and compared with HPK data. Graphs of absolute current in the pads of each sensor at 600 & 800 V *(see figures 7,8)* and a separate graph of total current of each sensor at all voltage steps *(see figure 9)* were created.

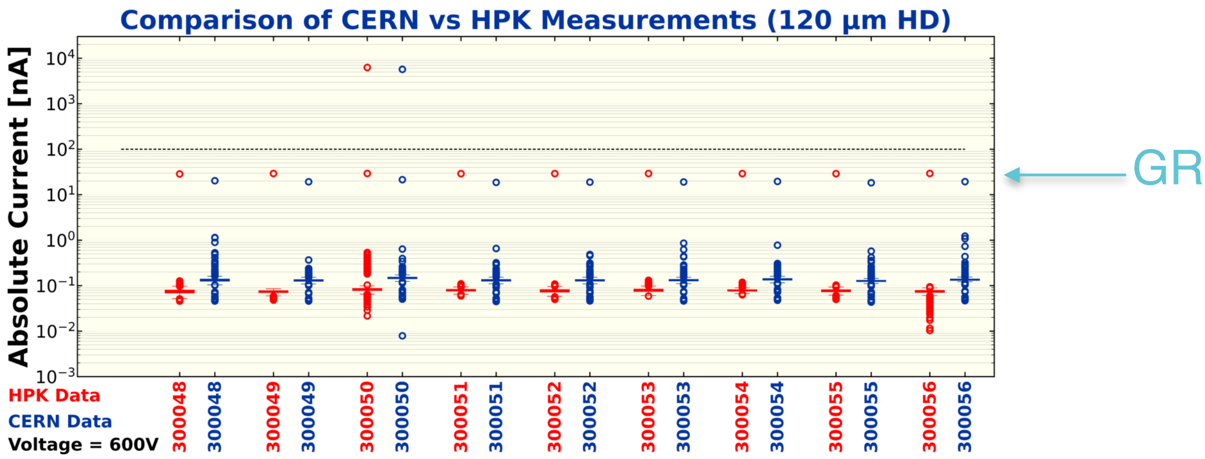


Figure 7: Box-plot of 9 120 µm HD sensors at 600 V measured by CERN vs HPK

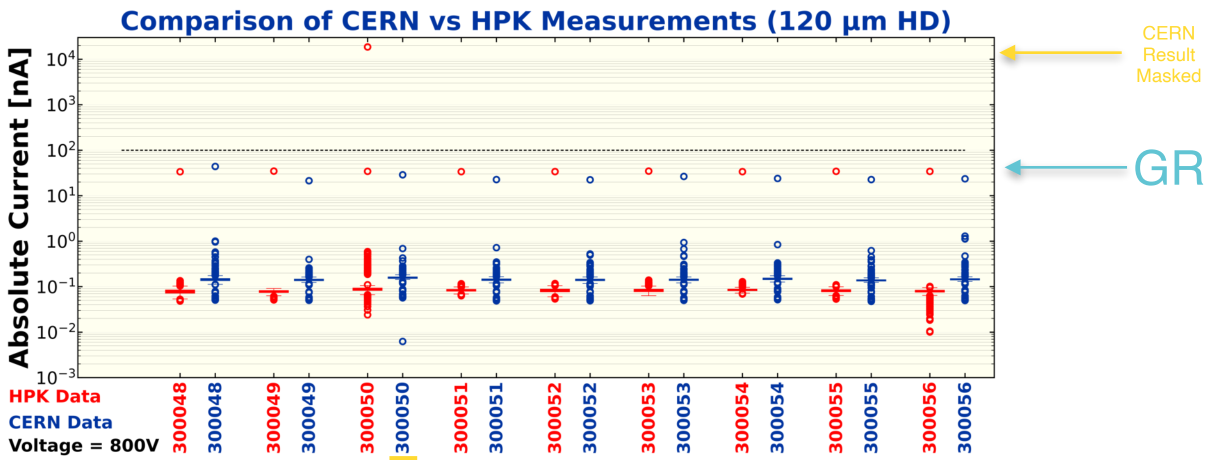


Figure 8: Box-plot of 9 120 µm HD sensors at 800 V measured by CERN vs HPK

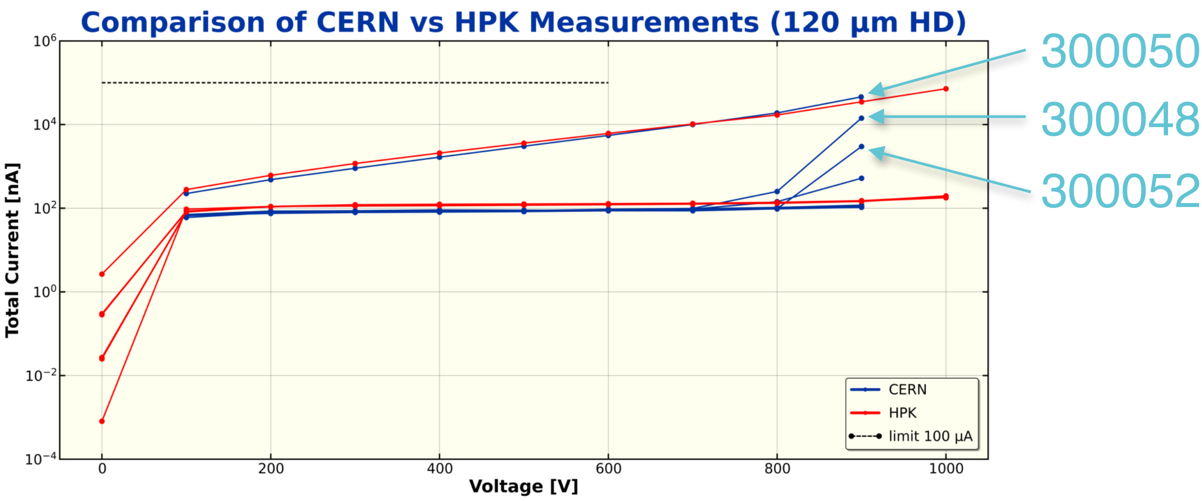


Figure 9: IV Total Graph of 9 120 µm HD sensors measured by CERN vs HPK

Sensors 300048 and 300052 are marked as they initially failed the first IV measurement. They were retested and passed the IV criteria. After passing, both sensors still exhibited higher currents than other sensors between 800 and 900 V but still passed the overall IV criteria. The failure in the first measurement resulted from both sensors guard ring currents increasing too rapidly between 600 & 800 V but there was no obvious signs of why this occurred. Sensor 300050 failed HPKs measurement and both CERN's initial measurement and re-measurement.

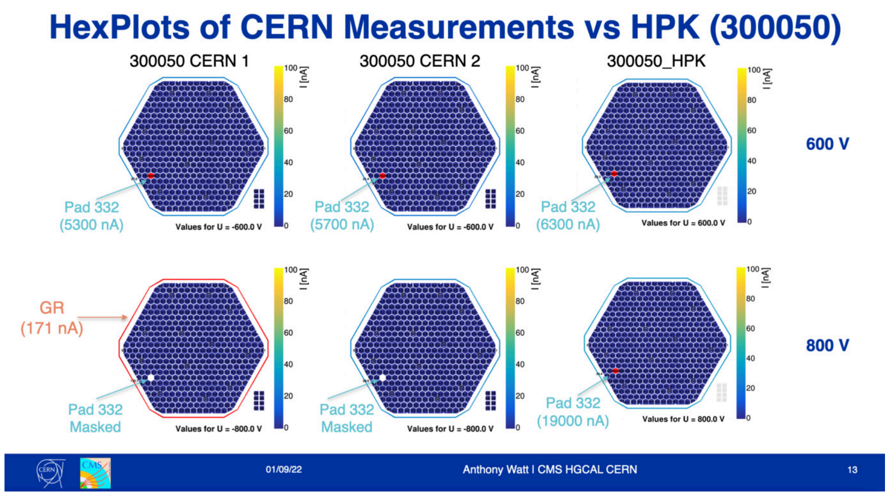


Figure 10: Hex-plots of failed sensor 300050 measured by CERN vs HPK

CERN measurement station has a fail-safe which masks any channel exceeding 5000 nA to prevent any damage to the probe/switch card and as a result sensor 300050 was masked before 800 V as current increased too rapidly (*See Figure 8*). HPK decided not to mask any channels in their measurements and as a result $\approx$ 20,000 nA total channel current was recorded at 800 V at pad 332.
All channels except damaged channel 332 performed well and as expected and no other channel showed any visible mechanical defects.

5 Conclusion

At CERN 9 High Density Pre-Series HPK sensors were measured and analysed. Results at CERN showed 8/9 sensors passed IV criteria except sensor 300050 which failed due to the total current increasing too rapidly between 600 and 800 V.
The cause of failure was most likely due to a fault in the stacking material at production which was visible on channel 332. All sensors passed CV criteria and performed as expected. CERN data was compared with HPK data and the results were reciprocated showing similar total current data for each sensor as well as current per channel performance.
Going forward CERN will analyse both 200 and 300 µm LD pre-series sensors as well as additional 120 µm HD sensors and will continue to analyse and see if any changes are needed to either the manufacturing or measuring process.
The analysis of the pre-series 120 µm HD sensors at CERN has led HGCAL to recommend the following to Hamamatsu:

- Any measurements take place after dicing has been completed.
- Ensure sensor back side layer is protected and not exposed to the bare chuck of the measuring station.
- Additional checks to their analysis files to ensure total current measured is equal to the sum of all the currents measured per channel.
- Formatting of the data files not to be changed and stick to the agreed formatting.

CERN has also recommended the following in the measuring process to HGCAL:

- All measurements to use 0 - 1000 V range.

Overall, the first phase of pre-series HD sensors has been a relative success in the sense that all sensors which passed performed well and as expected within the operation limits given by HGCAL.

6 Acknowledgements

I want to say thank you to the HGCAL team at CERN. I can't thank them enough for all the guidance and help they've offered me through my time working on this project and I would especially like to thank my supervisors Philipp Zehetner and Thorben Quast for giving me the opportunity to help with the CMS upgrade.
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