Study of Interpad-gap of HPK 3.1 LGADs with Transient Current Technique

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on behalf of the CMS Collaboration

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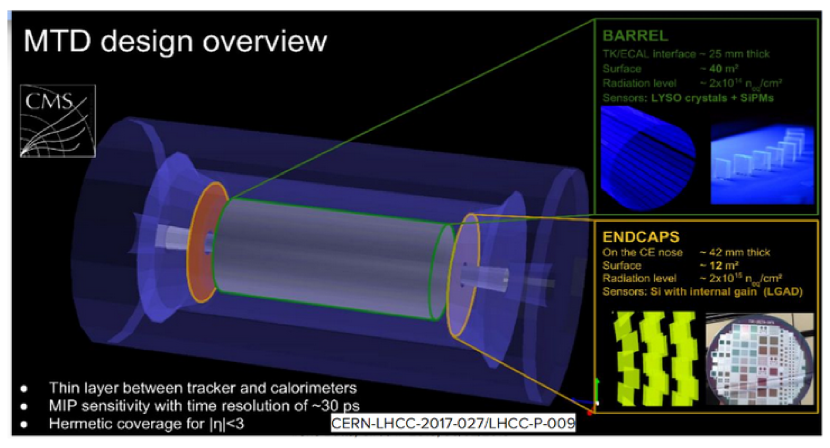
Introduction

- The Phase-II upgrade of LHC to HL-LHC by 2026 allows an increase in the operational luminosity value by a factor of 5-7, to collect data corresponding to an integrated luminosity of 3000 fb^{-1}.This concurs with an increase in the number of interactions per bunch crossings (pileup) up to a value of 140-200.
- This amount of data will increase in the precision of the Standard Model (SM) measurements and the sensitivity for Beyond Standard Model(BSM) searches.



- To cope with high pileup rates, the CMS experiment will install a precision MIP timing detector (MTD) to measure minimum ionizing particles (MIPs) with a time resolution of nearly 30-40 ps and hermetic coverage up to a pseudo-rapidity of $|\eta|$ = 3. [1]
- The endcap part (1.6 $<|\eta|<$ 3) of the MTD, known as the End-cap Timing Layer (ETL), will be based on silicon Low-Gain Avalanche Detector (LGAD) technology. The LGADs from one of the potential vendors, Hamamatsu Photonics K.K. (HPK), were measured. The measured LGADs include sensors with different design strategies. In particular, we focus on different values of narrower inactive region widths between the pads.

Samples Measured

The design of the HPK 3.1 test sensors has been taken from MTD TP-era. They consist of 2×2 pads wherein, each pad has an area of (1×3) mm^2. These sensors have a thickness of 50 μm. They have an interpad gaps of 30 μm, 50 μm, 70 μm and 95 μm.

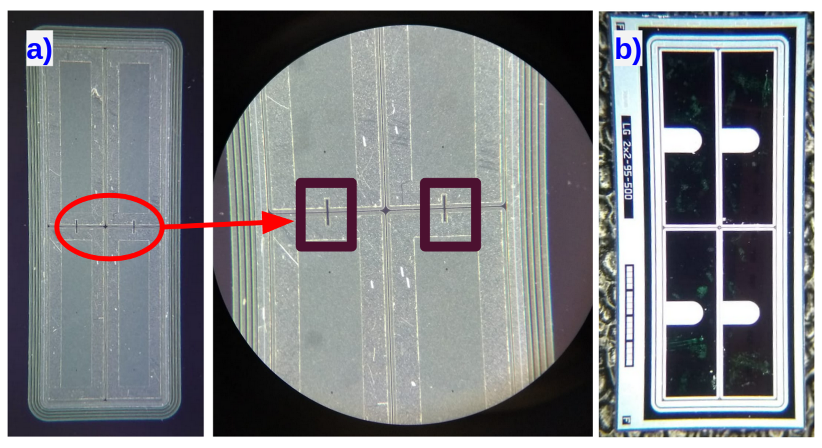


Figure 1: HPK 3.1 Type sample with 2×2 sensor showing sensors **a)** with broader metallisation region on pads and small optical opening running across adjacent pads (Type A) and **b)** individual pads with wider optical opening (Type B)

I-V and C-V Characterisation

- HPK 3.1 sensors with a thickness of 50 μm have a full depletion voltage of magnitude of 50 V.
- The sensors have a breakdown voltage of 220 V. The breakdown voltage is independent on the floating and/or grounding configuration of the remaining pads for sensors with 50 micron, 70 micron and 95 micron interpad-gap; but is not the same for the ones with 30 micron interpad-gap (shown in Figure 2 a) and b)).

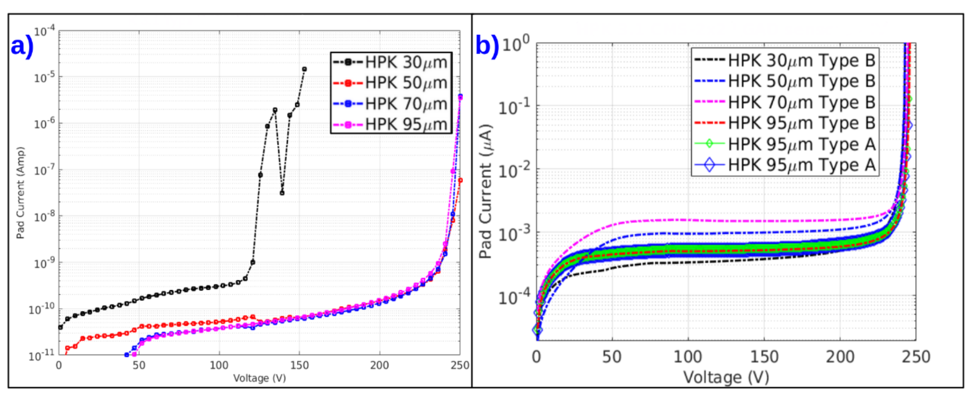


Figure 2. Current vs voltage plots of HPK 3.1 type sensors wherein: **a)** current is readout from one of the pads, while the other three pads are kept floating. Guard ring is grounded. **b)** current readout from one of the pads, while the other three pads as well as the guard ring are grounded. Note: All the plots are in logarithmic scale.

Study of Interpad-gap and Fill Factor

- The breakdown voltage depends on the design of the inactive region and interpad-gap between sensors.
- Fill Factor is the ratio of the area within the gain region to the total area.
- Measurements were performed by Particulars based Scanning TCT setup at a low IR laser intensity: 62.5% (equivalent to 4-5 MIPs).
- The interpad profile observed in TCT scan is a convolution of step function and the Gaussian beam of IR laser: S-curve.
- The curve fitting function is an error-function of the form :

$$f(x) = a + \left[\frac{b}{2} \times \mathrm{erf}\left\{\frac{\sqrt{2}(x-c)}{d}\right\}\right] \quad (1)$$

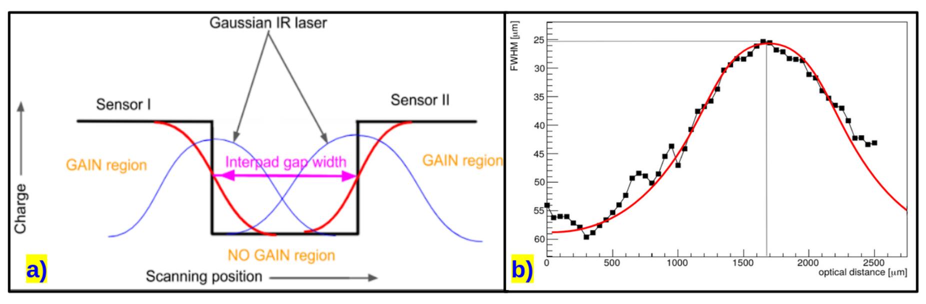


Figure 3: **a)** Measured interpad-gap is the distance between the mid-point of the S-curves of adjacent sensors. **b)** FWHM vs Optical distance of the IR laser from sensor. Gaussian shape IR spot with size: 25 µm. Focus position of the laser: ~ 1650 µm.

Results on Study of Interpad-gap with:

1) Variation in Temperature:

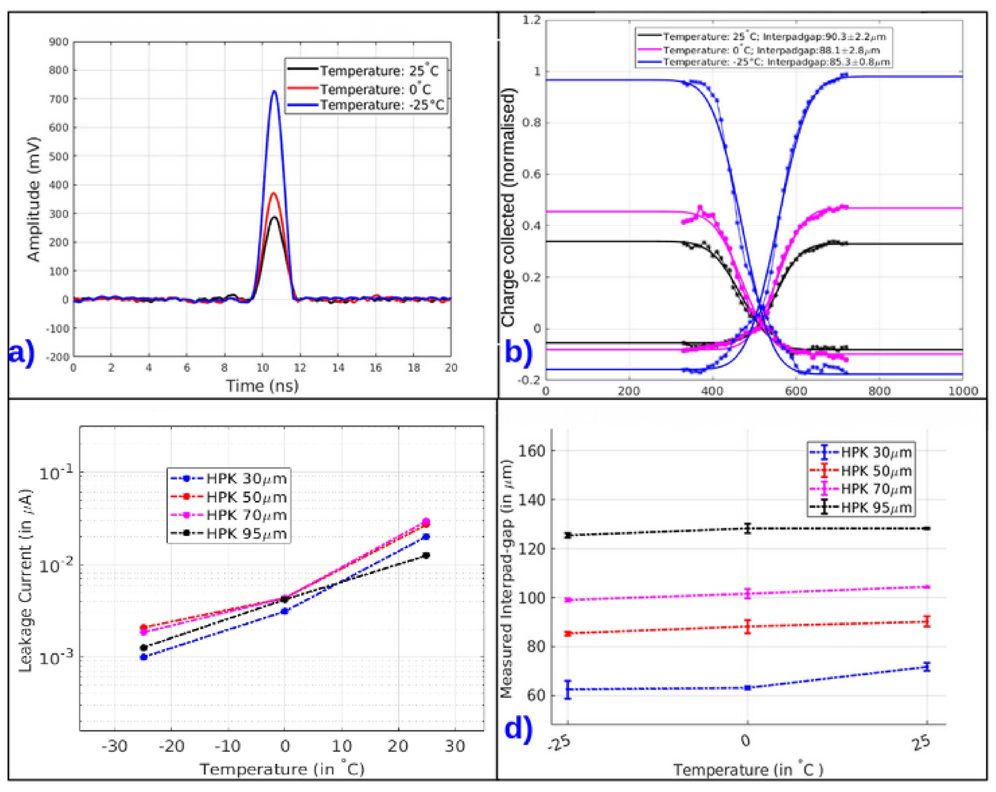


Figure 4: **a)** Pulse shapes, **b)** Charge Collected (normalised value) vs scanning distance for sensors (at 25°C, 0°C and -25°C) as the laser scans across two adjacent sensors with 50 µm interpad-gap, **c)** Leakage current with varying temperature and **d)** Variation in the measured interpad-gap with temperature. Measurements were performed at a voltage of 180 V.

Sample measured	Measured Interpad-gap @ 25°C (in µm)	Measured Interpad-gap @ 0°C (in µm)	Measured Interpad-gap @ -25°C (in µm)	Decrease in measured Interpad-gap from 25°C to -25°C (in %)
HPK Wafer-8 Set-P3 30µm	71.7	63.1	62.4	12.97
HPK Wafer-4 Set-P1 50µm	90.3	88.1	85.3	5.54
HPK Wafer-4 Set-P2 70µm	104.3	101.5	99.1	4.98
HPK Wafer-8 Set-P3 95µm	128.3	128.2	125.5	2.18

Table 1: Variation in the measured interpad-gap with temperature

- Decrease in measured interpad-gap (from 25°C to -25°C) lies in between 2-12 %. No significant variation in Fill-Factor.
- As expected, the leakage current measured from SMU at 180 V increases by an order of magnitude with rise in temperature from -25°C to 25°C.
- Charge collected value increases by a factor of 2 from 25°C to -25°C. (Inference: gain increases with decrease in temperature as also observed in [2])

2) Variation in Proton Fluence:

- Sensors irradiated with 10 MeV Protons @ IBA 10/5 cyclotron in the Department of Chemistry in University of Helsinki.
- Total integrated current : 0.42 µA-hr; such that sample in 1 & 3 (shown in **Figure 5**) get an integrated current of 0.15 µA/cm² while sensors in 2 & 4 (shown in **Figure 5**) receive an integrated current of 0.09 µA/cm². Four samples irradiated simultaneously over 1040 s such that samples in 1 & 3 are irradiated with a fluence of 10^{15} protons/cm² while 2 & 4 are irradiated with a fluence of 5×10^{14} protons/cm².

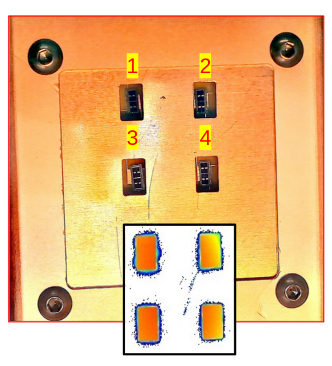


Figure 5: Collimator with sample holder showing the autoradiograph of the beam profiling across the four collimation slits.

Sample	Interpad-gap	Fluence (Protons/cm²)
HPK W4 P2	30 µm	10^{15}
HPK W8 P3	30 µm	5×10^{14}
HPK W4 P2	70 µm	10^{15}
HPK W8 P6	70 µm	5×10^{14}
HPK W4 P2	50 µm	10^{15}
HPK W8 P6	50 µm	5×10^{14}
HPK W4 P2	95 µm	10^{15} → No response!
HPK W8 P3	95 µm	5×10^{14}

Table 2: Samples from different wafers with varying interpad-gaps that were used for irradiation campaign and the proton fluences they were subjected to.

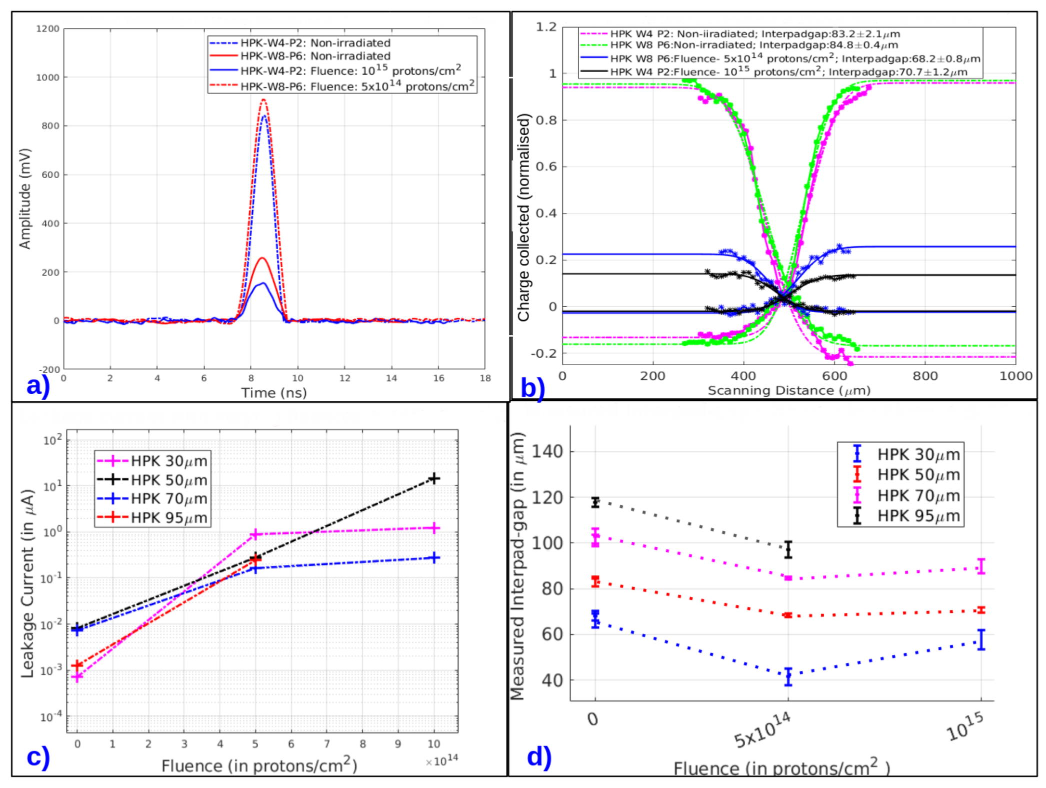


Figure 6: **a)** Pulse shape of non-irradiated and irradiated samples at different proton fluences and **b)** Charge Collected (normalised values) vs. scanning distance for sensors as the laser scans across two adjacent pads for sensors with 50 µm interpad-gap. **c)** Leakage current with varying fluences and **d)** Variation in the measured interpad-gap with proton fluence for sensors with 30 µm, 50 µm, 70 µm and 95 µm interpad-gap measured at 180 V and temp: -25°C. Measurements were performed at -25°C and 180 V.

HPK 3.1 Sensor	Measured Interpad-gap of sensor (@ 180V & -25 °C):					
	Non-irradiated (in µm)	Fluence: 10^{14} protons/cm²	% decrease	Non-irradiated (in µm)	Fluence: 10^{15} protons/cm²	% decrease
30 µm	68.1	41.4	39.21	66	57.6	12.73
50 µm	84.8	68.2	19.58	83.2	70.7	15.02
70 µm	103	84.5	17.96	101.1	89.8	11.18
95 µm	117.8	97	17.66	125	-	-

Table. 3: Variation in the measured interpad-gap with varying proton fluence

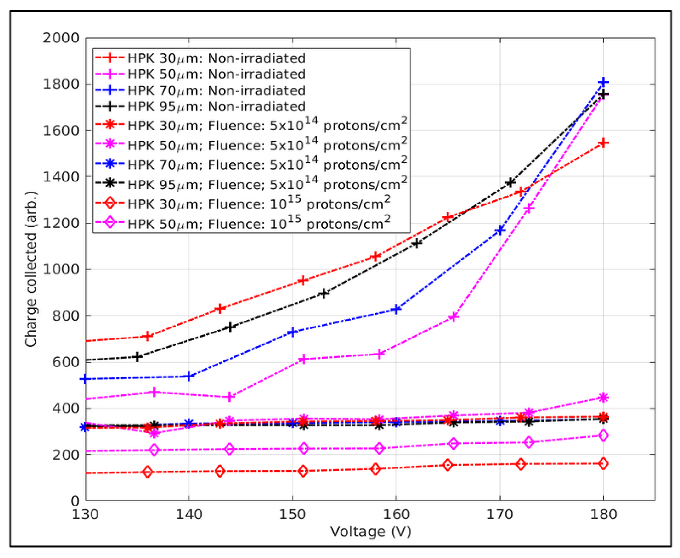


Figure 7: Voltage scans for the non-irradiated and irradiated samples with varying inter-pad gaps measured at -25°C.

- Measured interpad-gap decreases with irradiation.
- At a fluence of 5×10^{14} protons/cm^2, interpad-gap is reduced by 20-40% from its value before irradiation. CCE decreases by a factor of 3-4. However, on irradiating the sensors at 10^{15} protons/cm^2, interpad-gap increases in comparison to its value at 5×10^{14} protons/cm^2; since its CCE decreases by factor of 6. Therefore, on irradiating the sensors at 10^{15} protons/cm^2, the value of the measured interpad-gap decreases by 11-15% from its value before irradiation. Therefore, at high fluences we do not observe a significant change in Fill-Factor.
- The measured leakage current of the irradiated sensors from the SMU (at 180 V & -25°C) increases by 2 orders of magnitude.

Conclusion

- On studying the inter-pad gap with:
  1) Temperature variation: Gain is dependent on temperature and therefore CCE increases with decreasing temperature. The decrease in the interpad gap from 25°C to -25°C lies between 2-12 %. No significant change in Fill-Factor.
  2) Variation in proton fluence: The measured interpad gap decreases on irradiation. At 10^{15} protons/cm^2, the measured interpad-gap decreases by 11-15% $\longrightarrow$ This decrease is low. Therefore, the Fill Factor does not change significantly at higher fluence measurements.

References

[1] Collaboration CMS. A MIP Timing Detector for the CMS Phase-2 Upgrade. Technical Report CERN-LHCC-2019-003. CMS-TDR-020, CERN, Geneva, Mar 2019.

[2] G. Kramberger et. al. Radiation effects in low gain avalanche detectors after hadron irradiations. *Journal of Instrumentation*, 10:P07006–P07006, 07 2015.

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