Effect of thermal donors induced in bulk and variation in p-stop dose on the no-gain distance measurements of LGADs

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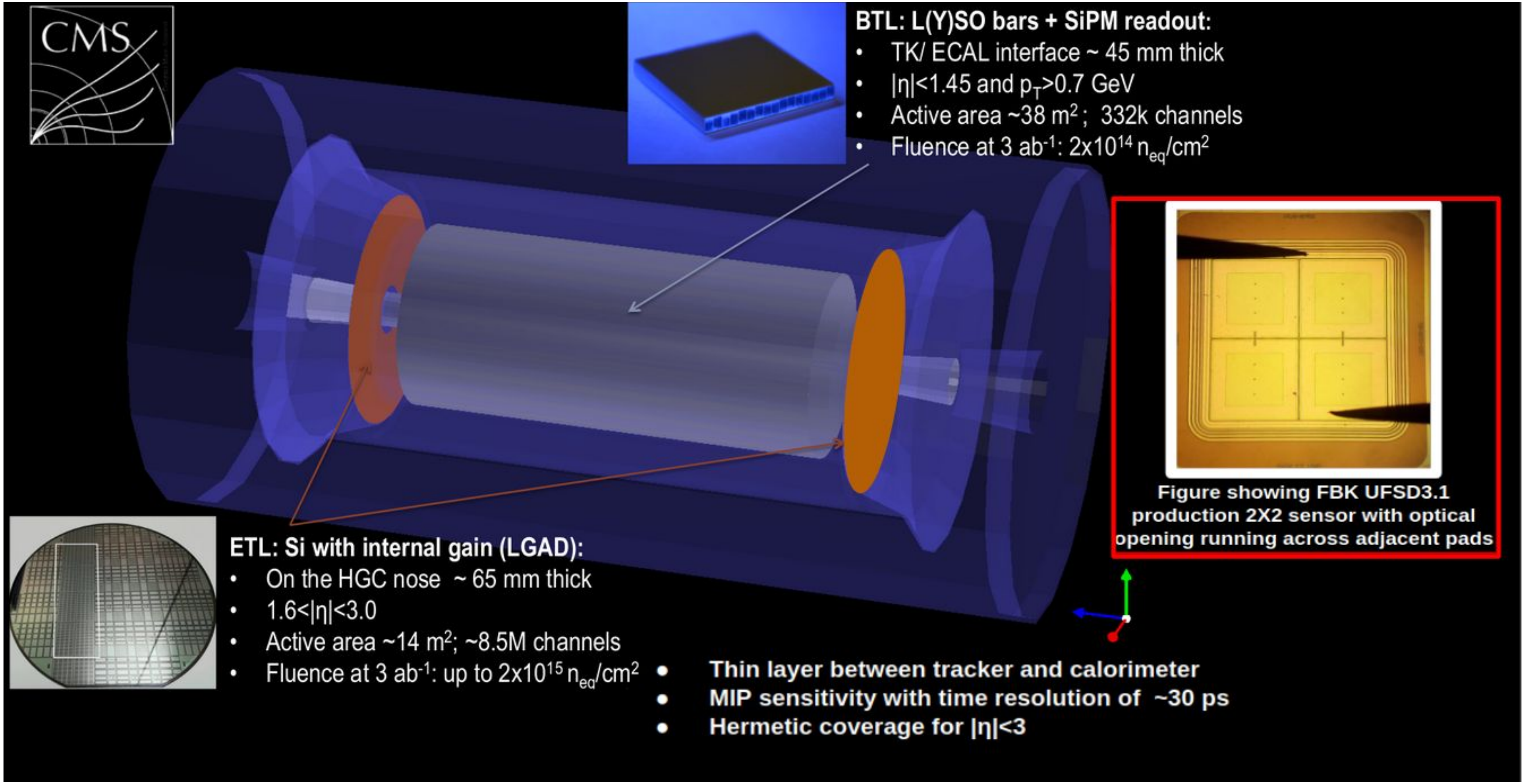
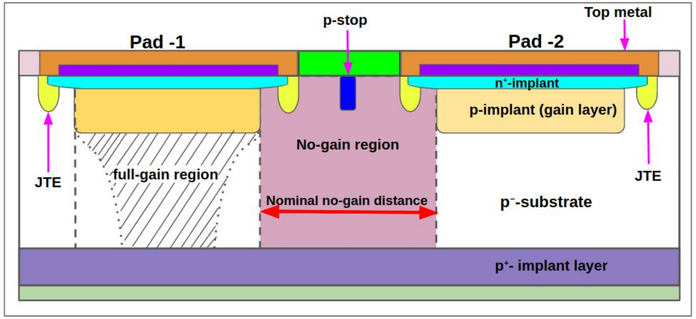
on behalf of the CMS collaboration

The 29th International Workshop on Vertex Detectors (Virtual) - October 5-8, 2020

Motivation :


CMS
BTL: L(Y)SO bars + SiPM readout:
• TK/ ECAL interface ~ 45 mm thick
• |η|<1.45 and p_T>0.7 GeV
• Active area ~38 m^2 ; 332k channels
• Fluence at 3 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2
Figure showing FBK UFSD3.1 production 2X2 sensor with optical opening running across adjacent pads
ETL: Si with internal gain (LGAD):
• On the HGC nose ~ 65 mm thick
• 1.6<|η|<3.0
• Active area ~14 m^2; ~8.5M channels
• Fluence at 3 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2
• Thin layer between tracker and calorimeter
• MIP sensitivity with time resolution of ~30 ps
• Hermetic coverage for |η|<3

Samples measured: FBK UFSD3.1 2x2 sensors



- Sensors with 11 different interpad termination strategies
- Identical gain layer dose : equivalent to FBK scale factor - 1.02
- Samples from 3 wafers:

- W13, W14 and W18 with 3 different p-stop dose such that :

p-stop dose W13 < p-stop dose W14 < p-stop dose W18

- **Objective behind this production :**

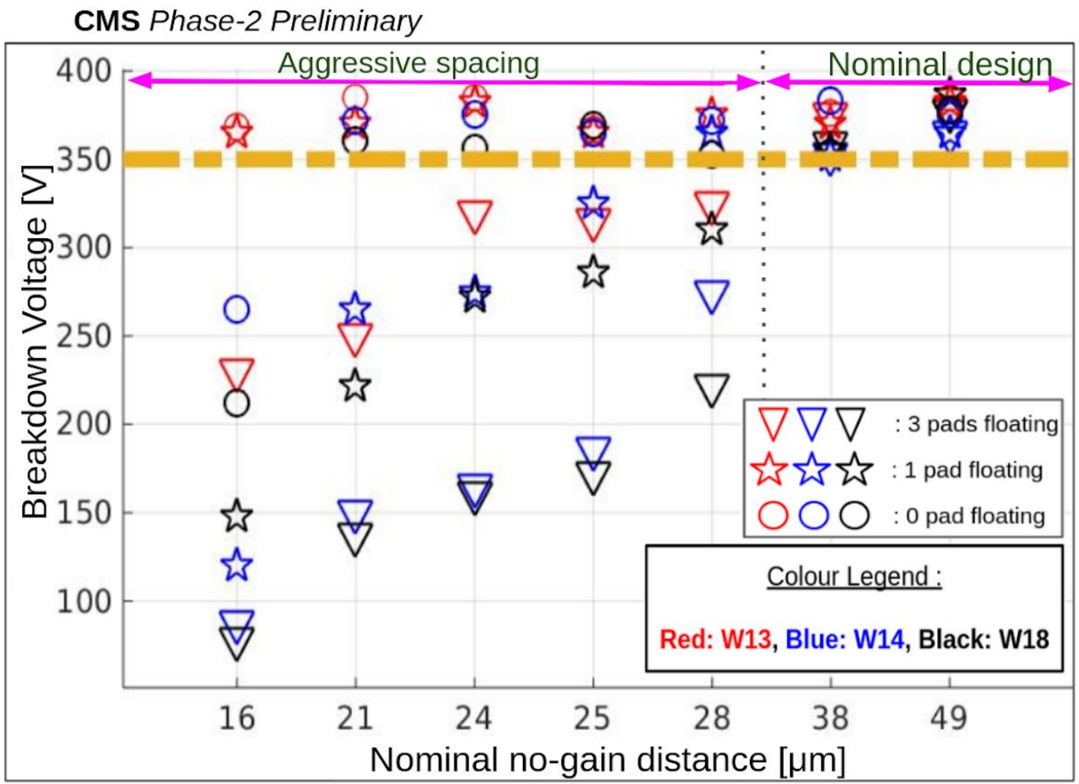
  Optimise the interplay between the no-gain region width and the p-stop doping dose

Type	Nominal width [µm]	Inter-pad design	Strategy
1	16	grid + extra grid	Aggressive
2	21	grid	Medium
3	21	grid	
4	24	grid	Safe
5	25	grid	
6	28	grid + extra grid	
7	28	grid + extra grid	
8	28	grid + extra grid	
9	38	2 p-stop	Super safe
10	49	2 p-stop + bias grid	
11	21	grid	Medium

IV measurements :

Breakdown voltage for sensors with varying nominal no-gain distance strategies:

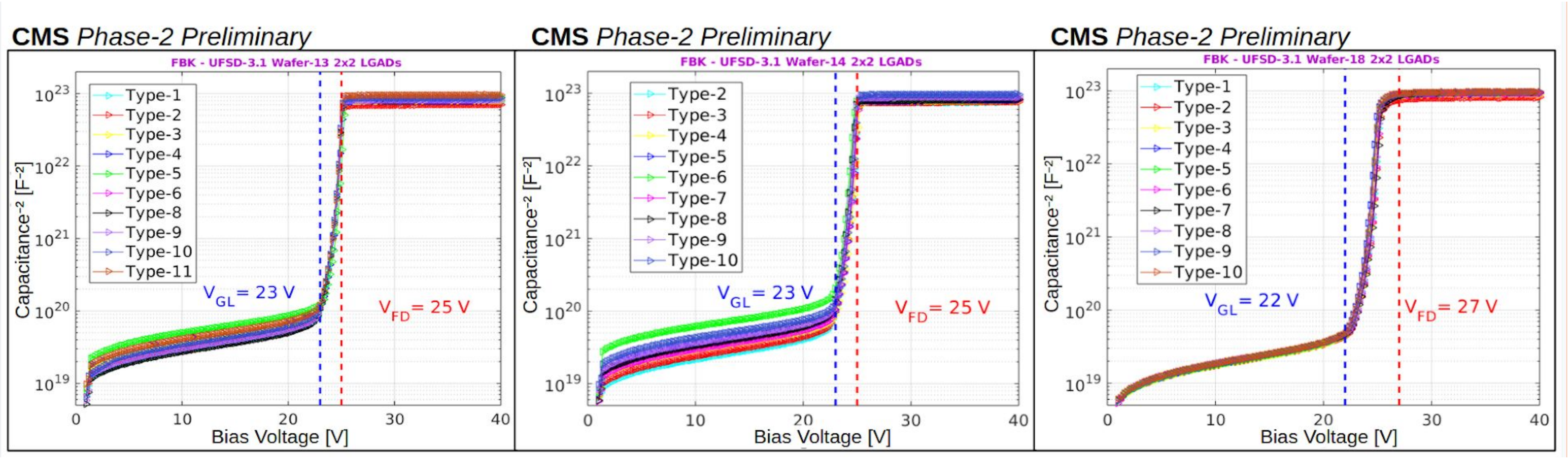
- For supersafe sensors: breakdown voltage does not depend on p-stop dose and electrical configuration of the pads.
- The inter-pad configuration does not affect the break-down voltage at low p-stop doses
- At increasing p-stop doses, the inter-pad terminal strategy affects the electrical behaviour of the sensor.
- Aggressive configuration: the p-stop dose plays a role in the breakdown voltage; even when the remaining pads are grounded.
- **Note:** the ETL plan is to use the conservative designs with larger interpad gaps, where the breakdown voltage is robust even with missing bump bonds.



CV measurements :

V vs 1/C² plots for sensors from W13, W14 and W18:

- Measured at 1 kHz.



- Uncertainties observed in the measured capacitance values for W13 and W14 sensors until the gain layer is depleted completely ---> shift in the capacitance value changes the slope in extrapolation of gain-layer depletion voltage as well as full-depletion voltage of the bulk (by ± 2V) -----> uncertainties in capacitance values measured for the sensors depends on the 'type' of the sensor.
- No such anomaly is observed when the gain layer begins to deplete for sensors from W18.

Reason for anomaly observed in CV measurements for W13 and W14:

Note: thermal donors in the bulk is an anomaly of this production due to unusually high purity silicon and not the nominal design.

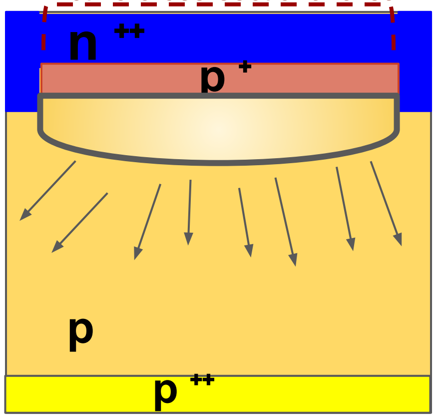
- UFSD3.1 : bulk is intrinsic (almost); very slightly p doped

In processing: due to thermal donors a small n^+ doping layer is created. So the bulk for UFSD3 & UFSD3.1 sensors from W13 and W14 is n^+.
Therefore, depletion starts from the bottom. As a result of which CV is different.

- Sort of ‘space charge inversion’ -----> polarity of bias does not change
- Since depletion begins from bottom -------> no interpad isolation. So active area is dependent on the nominal interpad-gap value and majorly on the area outside the sensor ---->both affecting the capacitance measurements.

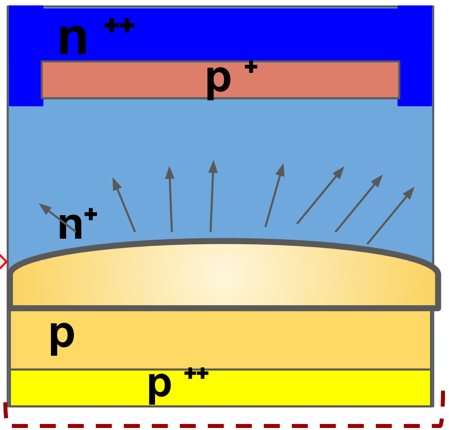
W18 (UFSD3.1)

Active cross-sectional area



Depletion begins from top

W13 and W14 (UFSD3.1)



Depletion begins from bottom

Active cross-sectional area

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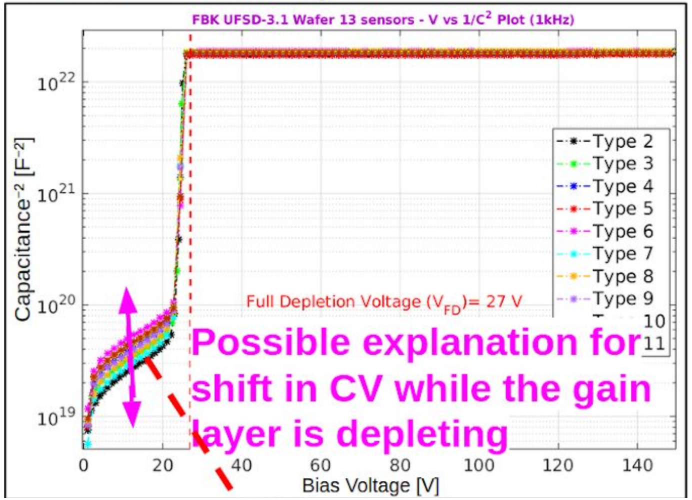

Observed as a significant shift in doping profile and is strongly dependent on the nominal interpad value!

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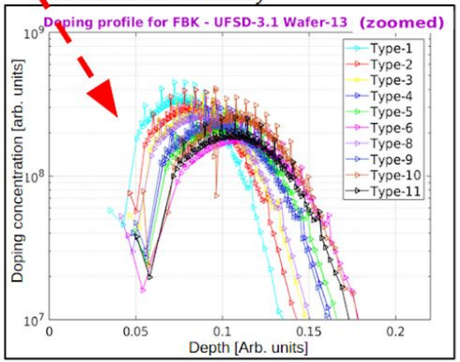

Type-6 (measured also for Type 9 & 10 - shown in back up slides)

- Offset observed in Measured no-gain distance and nominal interpad-gap value:
  ----> 10.65 ± 2.20 µm for W13 sensors
  ----> 6.27 ± 1.10 µm for W18 sensors
- Difference in measured no-gain distance between W13 and W18 : ~ 3-7 µm (with measured distance for W13 at a higher value)

Interpad profiles for : Nominal value - 28 µm

W13/W14 sensors (suspected n- bulk due to thermal donors) and W18 (p^+ implant in p-bulk)

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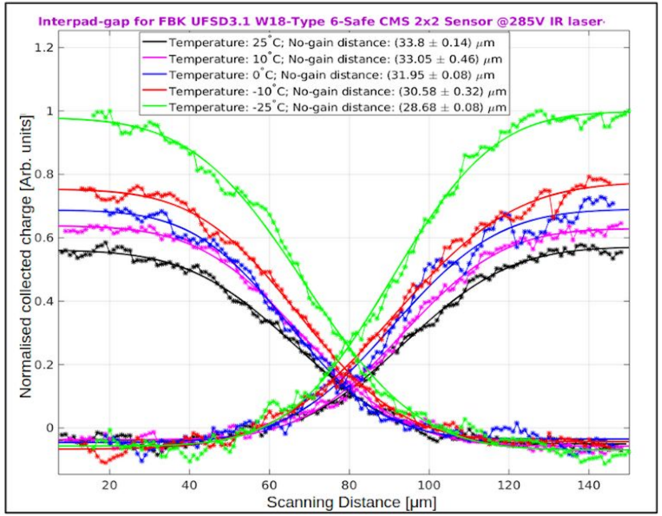

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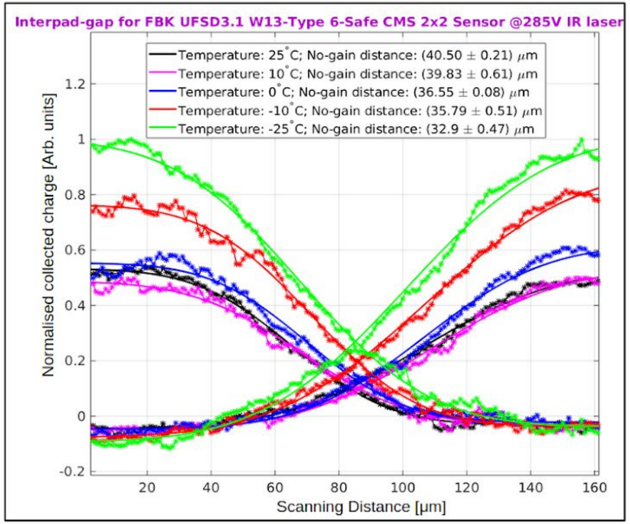

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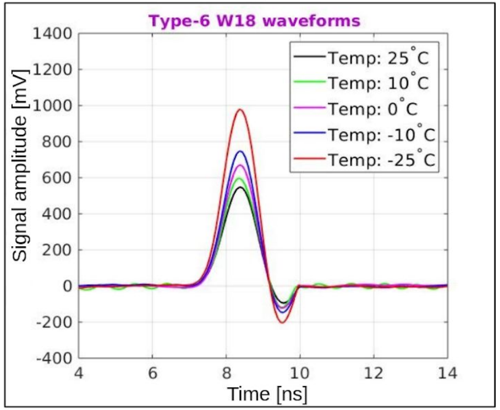

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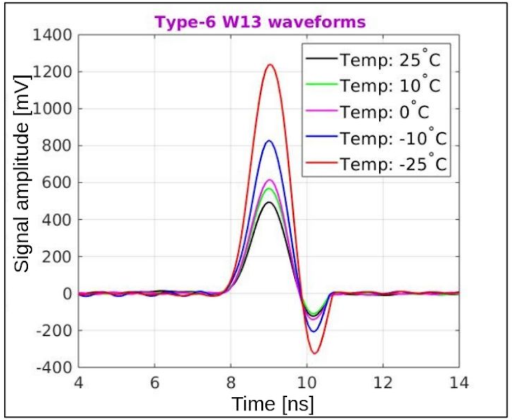

- Voltage scans show at RT (at same laser intensity) : behaviour is identical for sensors from W13 and W18. However, at 248K (-25⁰C) ----> the voltage scan plot for W13 gets steeper and Collected charge at 300V is ~2-3 higher for W13 sensors.
- With variation in temperature from 25⁰C to -25⁰C, The change in the measured no-gain distance decreases with an increase in the nominal interpad value.
- Change in the the measured no-gain distance with decreasing temperature is slightly higher for W13 sensors ----> even though the fill factor does not vary significantly with change in temperature for both W13 and W14 sensors.

Voltage scan comparison at different temperatures for W13 and W18 sensors

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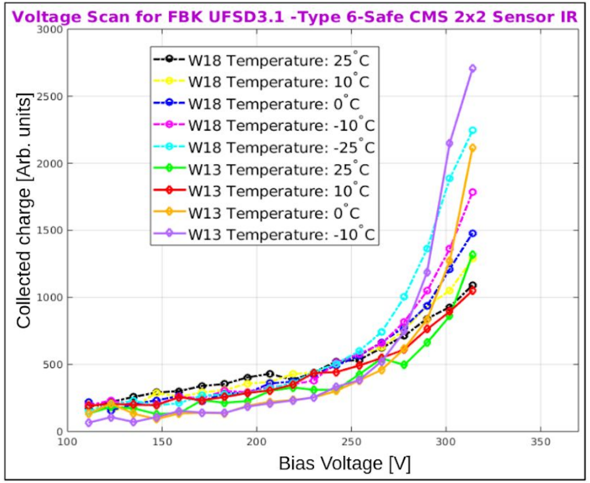


CMS *Phase-2 Preliminary*

Type	W13					W18			
	Nominal no-gain distance value	Measured no-gain distance @			% Decrease in Measured value (from 25⁰C to -25⁰ C)	Measured no-gain distance @			% Decrease in Measured value (from 25⁰C to -25⁰C)
		25⁰C	0⁰C	-25⁰C		25⁰C	0⁰C	-25⁰C	
Type 6 (285 V)	28	40.50 ± 0.21	36.55 ± 0.08	32.90 ± 0.47	18.77	33.80 ± 0.14	31.95 ± 0.08	28.68 ± 0.08	15.15
Type 9 (300 V)	38	46.38 ± 0.25	40.03 ± 0.06	37.91 ± 0.19	18.26	43.17 ± 0.31	38.39 ±0.67	38.84 ± 0.56	10.03
Type 10 (295 V)	49	60.90 ± 0.09	56.22 ± 0.43	51.90 ± 0.87	13.63	56.41 ± 1.09	55.27 ± 0.90	52.63 ± 0.88	6.70

Note*: Uncertainties are statistical only. The bias voltage is changed to keep the collected charge constant for measurements taken at different temperatures.*

Thank you !

Summary

- Decrease in the p-stop dose improves the breakdown behaviour of the sensors; independent of the interpad termination strategy ----> observed in IV measurements

- Uncertainties in capacitance values, until the depletion of the gain layer, is observed for sensors with thermal donors induced in the bulk. As a result of this space charge inversion of the bulk, the active cross-sectional area, majorly the area lying outside the sensors, affects the C-V measurements.
- Scanning TCT measurements performed with IR laser show no significant difference in the charge collection values when measured at RT.

- At lower temperatures: the voltage scan curves gets steeper for sensors with thermal donors induced in the bulk ---> collected charge increases by a value of ~2-3 @ high voltages (close to BDV)
- Decrease in the measured no-gain distance is slightly higher for sensors with thermal donors induced in the bulk (as well as measured value at a given temperature is higher in comparison to those without thermal donors in the bulk) ---> The % decrease does not affect the change in Fill factor significantly with variation in temperature.

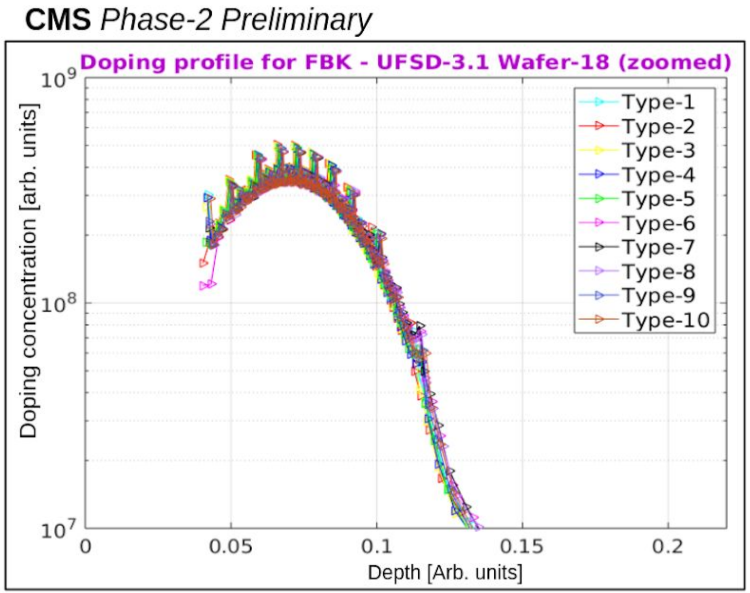
Back-up Slides

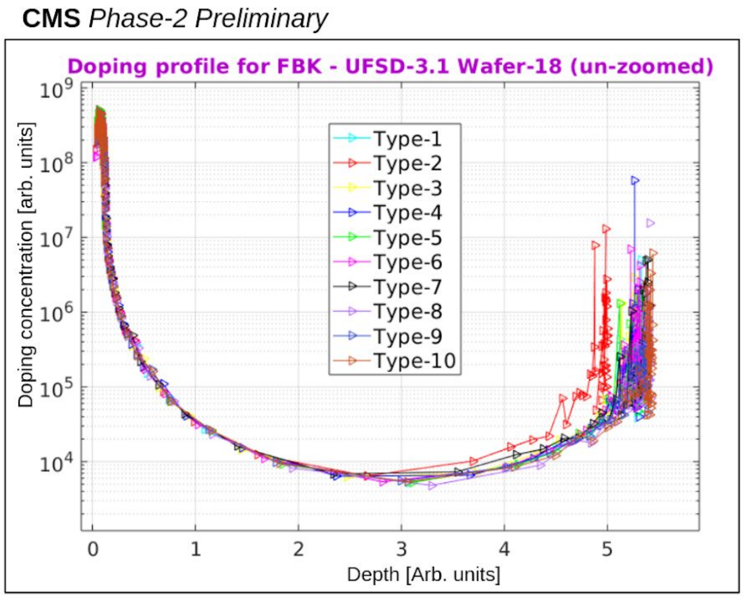
Doping profile extraction from CV measurements : **on W18 - as expected**

- No significant Shift in the depth of the gain-layer as well as of the thickness of the bulk for sensors without any thermal donors induced in the bulk.

Doping concentration, $$n(x) = -\frac{C^3}{q\varepsilon_{Si}A^2}\left(\frac{dC}{dV}\right)^{-1} = -\frac{2}{q\varepsilon_{Si}A^2}\left(\frac{d\,{}^{1}\!/_{C^2}}{dV}\right)^{-1}$$

Note:
In the doping profile extraction we consider the active cross-sectional area of each pad as a constant value ~ 1.3 x 1.3 mm²

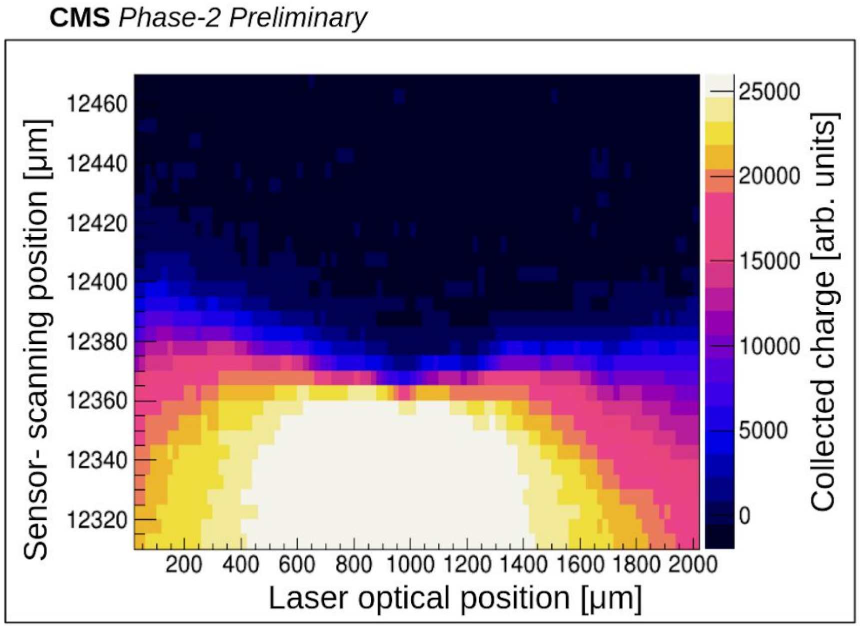


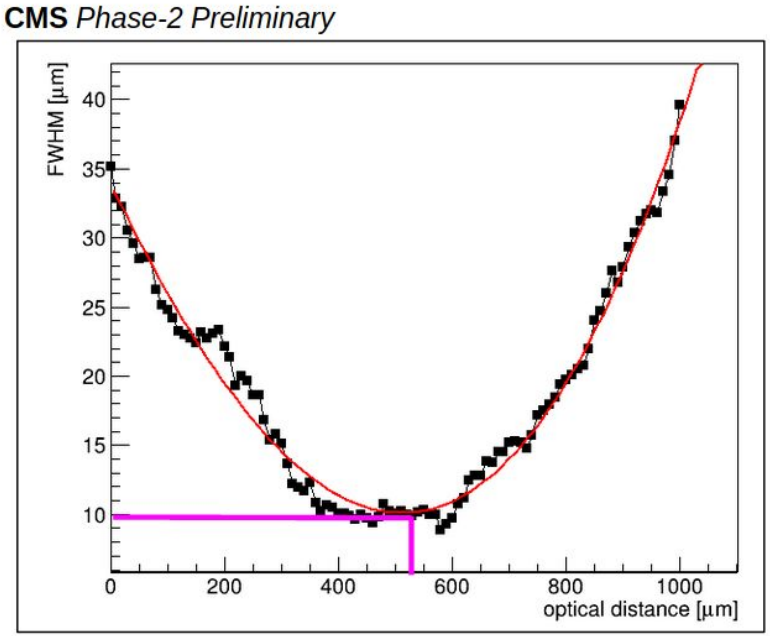


TCT scans : comparison study of **Type 6, 9 and 10 sensors** from **W13 and W18 sensors.**

* Based on : Voltage scans + interpad profiles (with varying temperature @ 285V, 295V and 300V for Type-6, Type-10 and Type-9 sensors, respectively)

Focus Scan- FBK UFSD3.1 W13 type-6 (Safe)



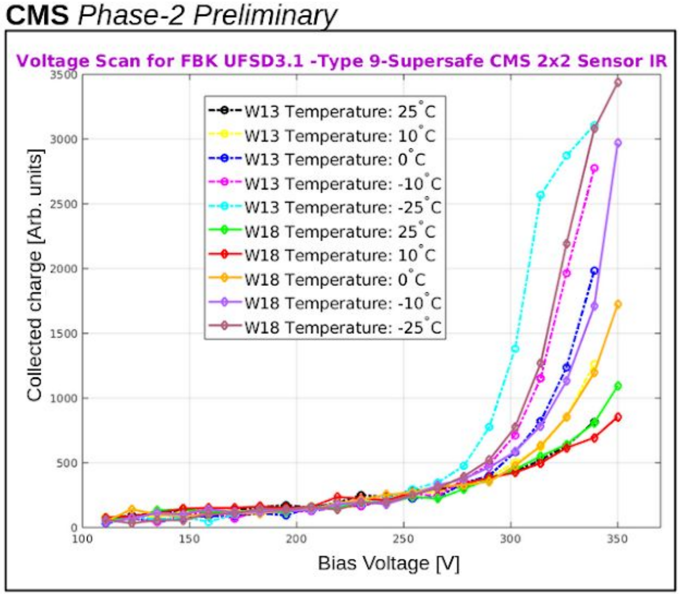


Measured with IR laser: low laser intensity (62.5 %, 1kHz) - equivalent to 5 MIPs

- Size of gaussian spot - 10 µm
- Focused optical positioning - 950 µm

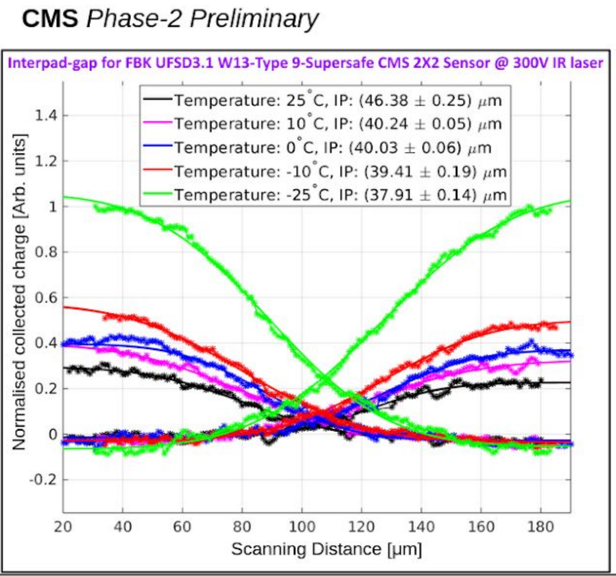
Type-9

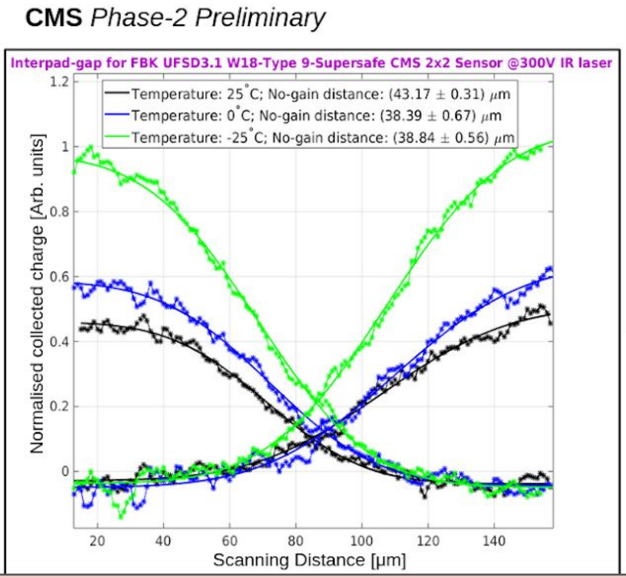
Voltage scan comparison at different temperatures for W13 and W18 sensors



<u>Interpad profiles for :</u>

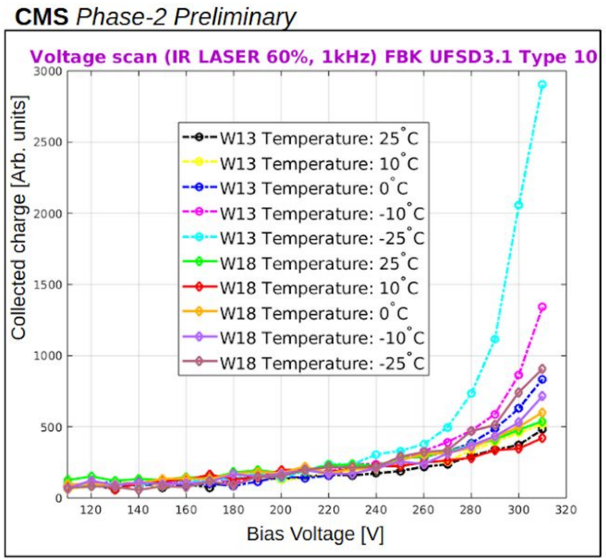
W13/W14 sensors (suspected n- bulk due to thermal donors) and W18 (p^+ implant in p-bulk)





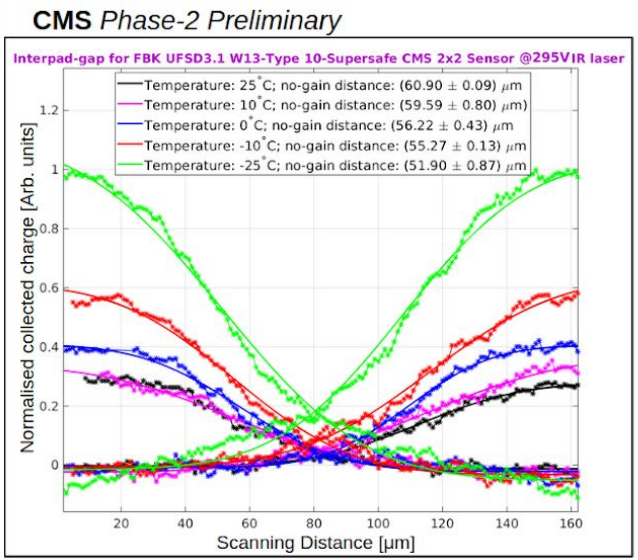
Type-10

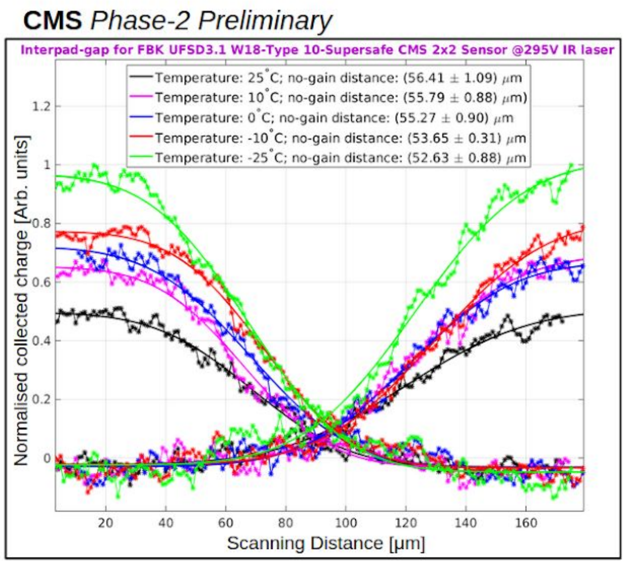
Voltage scan comparison at different temperatures for W13 and W18 sensors



Interpad profiles for :

W13/W14 sensors (suspected n- bulk due to thermal donors) and W18 (p^+ implant in p-bulk)





Effect of thermal donors induced in bulk and variation in p-stop dose on the no-gain distance measurements of LGADs

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Introduction

- The Phase-2 upgrade of LHC to HL-LHC by 2027, would increase the number of interactions per bunch crossings (pileup) up to a value of 140-200. 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. 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.

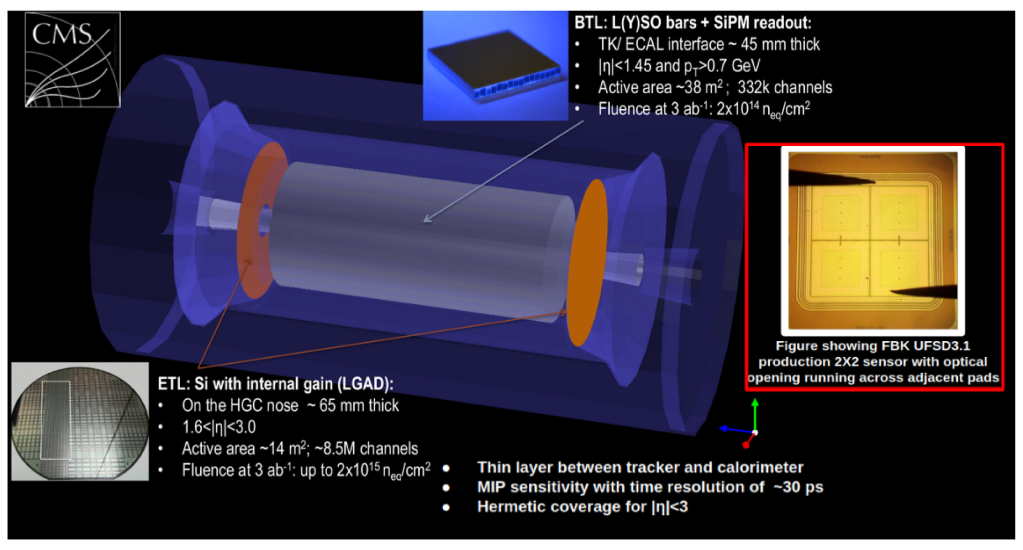


Figure 1: **CMS-MTD Design showing the positioning of the ETL and BTL.**

- The LGADs from one of the potential vendors, Fondazione Bruno Kessler (FBK), were measured. The measured LGADs from UFSD3.1 production include 2x2 pad sensors from 3 wafers (W13, W14 and W18), with an active thickness of 50 μm and identical gain layer with boron doping - equivalent to FBK scale factor of 1.02 (without any carbon co-doping), but have different p-stop dose such that:
p-stop dose W13 $<$ p-stop dose W14 $<$ p-stop dose W18
Within the individual wafers, the sensors vary in their inter-pad termination design strategies as shown below:

Type	Nominal Width	Inter-pad design	Strategy
1	16	grid + extra grid	Aggressive
2, 3, 11	21	grid	Medium
4	24	grid	Safe
5	25	grid	Safe
6, 7, 8	28	grid + extra grid	Safe
9	38	2 p-stop	Supersafe
10	49	2 p-stop + bias grid	Supersafe

Table 1: **showing different nominal widths and inter-pad terminal strategies of sensors from each wafer.**

Results on Electrical Characterisation

I-V measurements:

- The sensors have a breakdown voltage above $\sim$350 V.
- For Super-Safe sensors breakdown voltage does not depend on p-stop dose and electrical configuration of the pads.
- For Aggressive configuration: The p-stop dose plays a role in the breakdown voltage; even when the remaining pads are grounded
- The inter-pad configuration does not affect the breakdown voltage at low p-stop doses. At increasing p-stop doses, the inter-pad design strategy affects the electrical behaviour of the sensor.

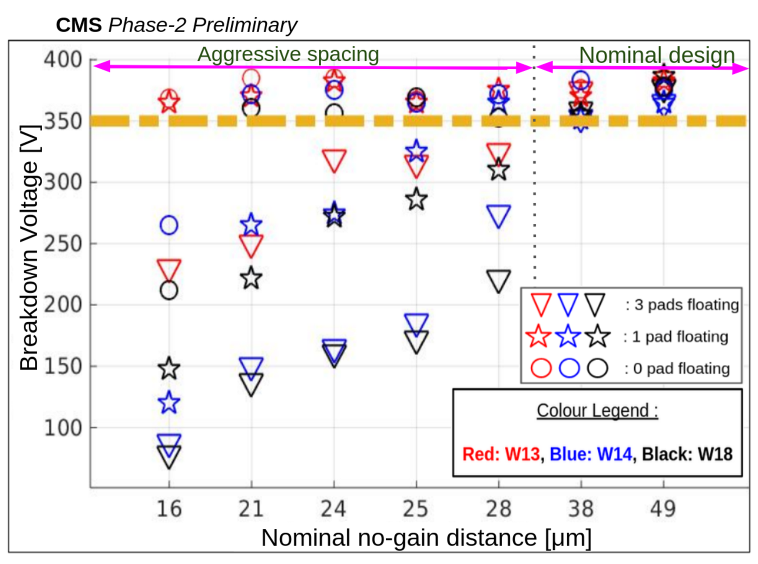


Figure 2: **I-V characterisation of sensors from three different wafers with varying p-stop dose and different nominal no-gain distance widths measured in three different electronic configurations.**

C-V measurements:

Gain-layer and bulk depletion voltage from C-V:

- For W13 and W14 sensors, the full depletion voltage of the bulk and gain-layer are 25 V and 23 V, respectively. Uncertainties observed in capacitance values, depending on the 'Type', until the gain layer is depleted. No such anomaly is observed in W18 sensors.

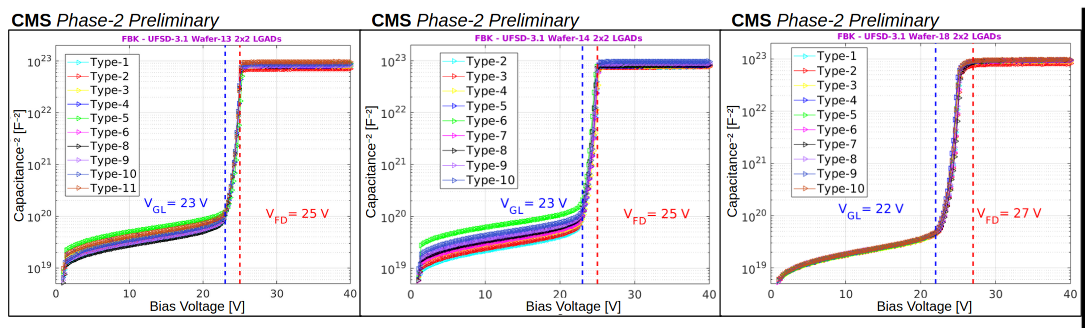
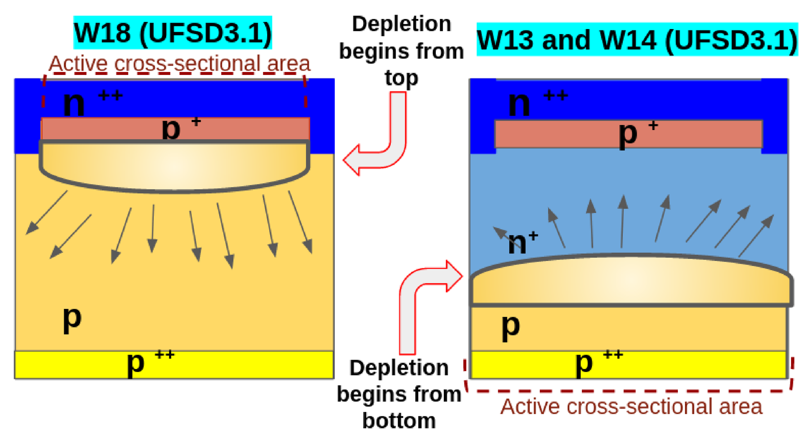


Figure 3: **Capacitance^{-2} vs bias voltage plot for sensors from the three wafers showing the gain-layer depletion voltage and the full depletion voltage of the bulk.**

Reason for anomaly observed in CV measurement:

- In general, UFSD3.1, like sensors in W18, bulk is intrinsic (almost); very slightly p-doped: depletion begins from the top.
- In processing: due to thermal donors induced in bulk, a small n-doping layer is created in the bulk for UFSD3.1 sensors from W13 and W14. Depletion begins from the bottom. As there is no inter-pad isolation at the bottom, active cross-sectional area is dependent on the nominal no-gain distance and majorly on the no-active region outside the sensor.



Note: **thermal donors in the bulk is an anomaly of this production due to unusually high purity silicon and not the nominal design. .**

Extraction of doping profile from C-V:

- Using the formula for doping concentration [$n(x)$], given by:

$$n(x) = -\frac{C^3}{q\epsilon_{Si}A^2}\left(\frac{dC}{dV}\right)^{-1} \quad (1)$$

where, active cross-sectional area(A) is taken as a constant value of 1.3$\times$1.3 mm^2.

- Uncertainties in the capacitance value until the depletion of gain layer (V_{GL}) gives rise to anomaly in doping profile extraction for W13 and W14 sensors. Consistency in C-V measurements, irrespective of the inter-pad strategy, can be observed in doping profile curves for W18 sensors.

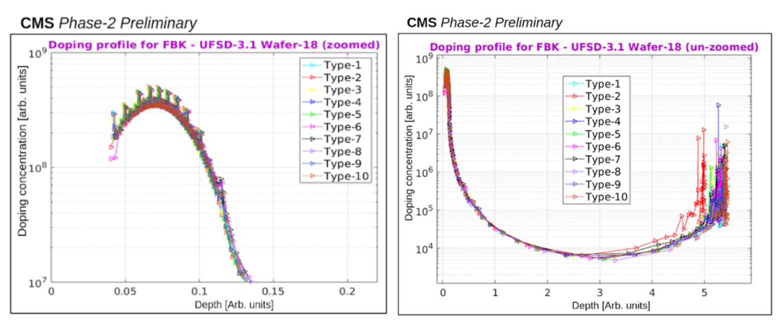


Figure 4: **Doping profile (doping concentration vs. depth) extracted from C-V measurements for sensors from W18 with different inter-pad strategies**

Scanning-TCT measurements:

- Measurements were performed by Particulars based Scanning TCT setup at a low IR laser intensity: 62.5% (equivalent to 5 MIPs), and at varying temperatures: 25°C to -25°C. The interpad profile observed in TCT scan is a convolution of step function and the Gaussian beam of IR laser (of beam spot size $\sim$10 μm): S-curve. The curve fitting function is an error-function of the form :

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

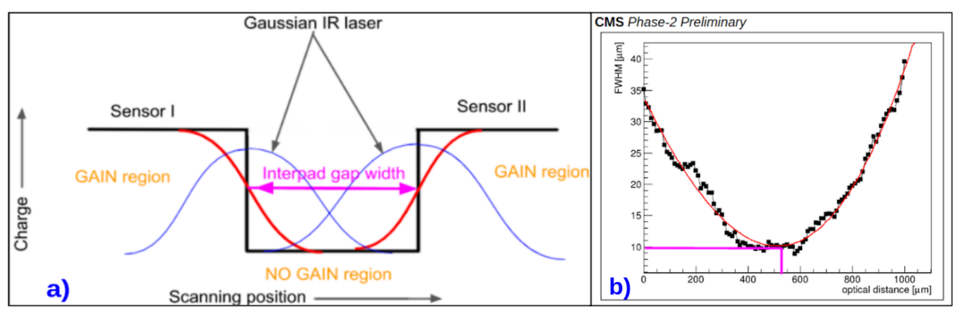


Figure 3: **a) Measured no-gain distance is the width between the mid-point of the S-curves corresponding to the adjacent pads. b) FWHM vs optical distance of IR laser from sensor.**

- Offset observed in Measured no-gain distance and nominal inter-pad gap value: 10.65 $\pm$ 2.20 μm for W13 sensors and 6.27 $\pm$ 1.10 μm for W18 sensors. Difference in measured no-gain distance between W13 and W18 : $\sim$ 3-7 μm (with measured distance for W13 at a higher value).
- Voltage scans at RT: behaviour is identical for sensors from W13 and W18. However, at -25°C,the voltage scan plot for W13 gets steeper and collected charge above 300V is 2-3 higher than for W18.

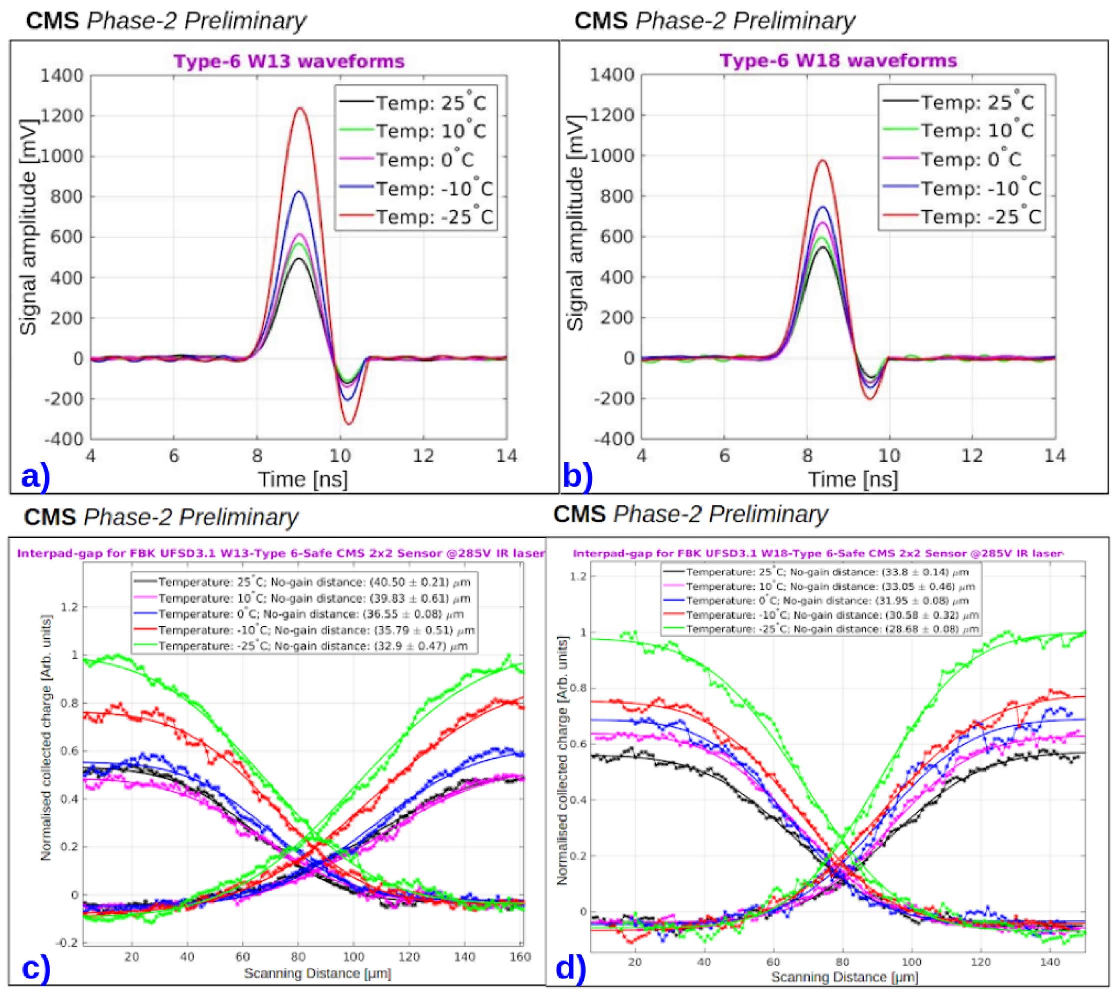


Figure 5: **showing comparison in: (i) current signals (a and b), and (ii) inter-pad profile measurements (c and d) with varying temperature for Type-6 sensors from W13 and W18, respectively.**

- With variation in temperature from 25°C to -25°C, the change in the measured no-gain distance decreases with an increase in the nominal interpad value; % decrease in measured no-gain distance value higher for W13 sensors.

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Type	Nominal no-gain distance value	Measured no-gain distance @ 25ºC	Measured no-gain distance @ 0ºC	Measured no-gain distance @ -25ºC	% Decrease in Measured value (from 25ºC to -25ºC)
W13					
Type 6 (285 V)	28	40.5 ± 0.21	36.55 ± 0.08	32.90 ± 0.47	18.77
Type 9 (300 V)	38	46.38 ± 0.25	40.03 ± 0.06	37.91 ± 0.19	18.26
Type 10 (295 V)	49	60.09 ± 0.09	56.22 ± 0.43	51.90 ± 0.87	13.63
W18					
Type 6 (285 V)	28	33.80 ± 0.14	31.95 ± 0.08	28.68 ± 0.08	15.15
Type 9 (300 V)	38	43.17 ± 0.31	38.39 ±0.67	38.84 ± 0.56	10.03
Type 10 (295 V)	49	56.41 ± 1.09	55.27 ± 0.90	52.63 ± 0.88	6.70

Table 2: **Measured no-gain distance with temperature variation for nominal design sensors from W13 and W18.Note: Uncertainties are statistical only. The bias voltage is changed to keep the collected charge constant for measurements taken at different temperatures.**

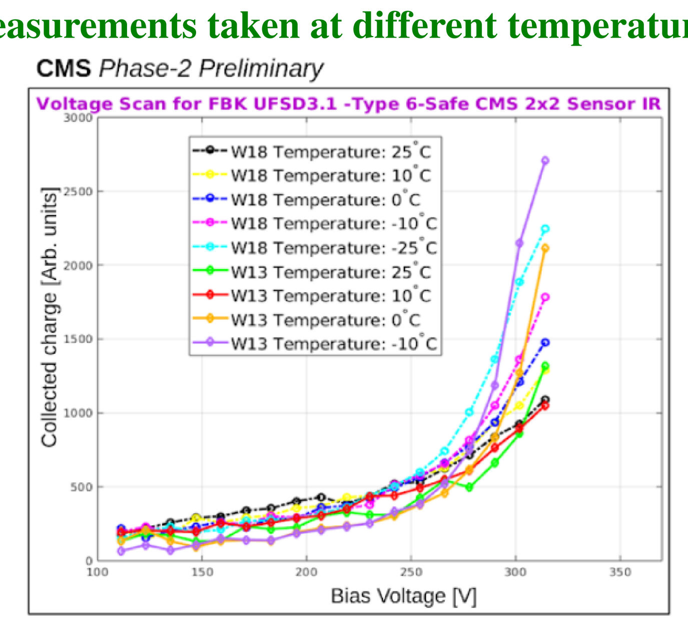

Figure 6: **Voltage scan on temperature variation for W13 and W18 sensors.**

Conclusion

- Decrease in the p-stop dose improves the breakdown behaviour of the sensors; independent of the interpad termination strategy.
- Thermal donors induced in the p-type bulk creates uncertainties corresponding to the capacitance values measured till the depletion of the gain layer. Due to space charge inversion of the bulk, the active cross-sectional area, majorly the area lying outside the sensors, affects their C-V measurements .
- Decrease in the measured no-gain distance with decreasing temperature is slightly higher for sensors with thermal donors induced in the bulk. The % decrease in no-gain distance value does not affect the fill factor significantly.

Special Acknowledgments

FONDAZIONE BRUNO KESSLER
INFN Istituto Nazionale di Fisica Nucleare
UNIVERSITÀ DEGLI STUDI DI TORINO