DESY Summer Student
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Measurements of Future Silicon Sensors for the Tracker Upgrade of the CMS Experiment at the LHC, CERN

The measurements were performed in the framework of the international tracker upgrade collaboration of the CMS experiment.

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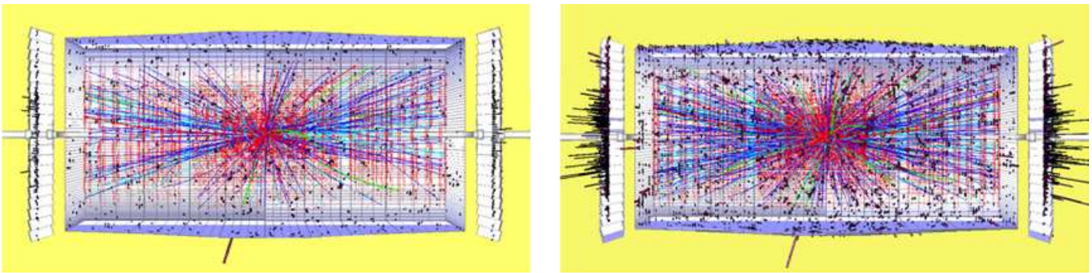
1 Introduction

In near future the LHC will be upgrade to sLHC. Its main goal is to increase the luminosity by an order of magnitude from 10^{34} to $10^{35} cm^{-2}s^{-1}$. But if luminosity gets increased the occupancy get increased at the same time.

1.1 CMS Upgrade Tracker

With higher luminosity in the CMS detector, the radiation dose increases as well. To measure under these circumstances, especially in the inner parts of the detector, we have to develop new radiation hard sensors. Also soft interactions superimposed on interesting events will increase from ≈20 to ≈200. Those actions combined cause increasing granularity of the detector. For this reason we need new sensor materials or we have to improve silicon sensors which is the better choice due to lower price.

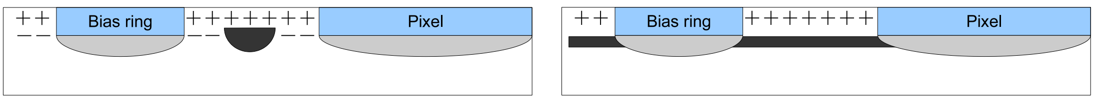


(a) $10^{34} cm^{-2}s^{-1}$ (b) $10^{35} cm^{-2}s^{-1}$

Figure 1: Single Event at different luminosities

2 Multi-Pixel sensor

Investigated sensors are delivered by one producer — Hamamatsu, with different methods of metal production, different substrates (P-in-N, N-in-P P-spray & N-in-P P-stop) and different thicknesses. The difference of P-stop and P-spray is shown in Figure 2. The designs of the test sensors is shown in Figure 3.



(a) P-stop (b) P-spray

Figure 2: Cross-section views of sensors N-in-P in different method of isolation[1]

The sensor consists of 12 regions constructed in different a way. Two different biasing methods are used to connect the single pixel with the bias ring. Regions with an odd region number has a punch through biasing which means that the pixels are connected over a MOS structure to the bias ring and regions with an even region number have poly silicon biasing where the biasing is made with a poly silicon resistor. Punch through isolation is easier to produce but is not radiation hard as a poly silicon resistor.

Each sensor:

- has metallization an backside,
- is covered with a SiO_2 layer on the top,
- has three different pitches with a distance of 80, 100 & 120 µm between the pixels,
- has two pixel lengths (1171µm & 2421µm).

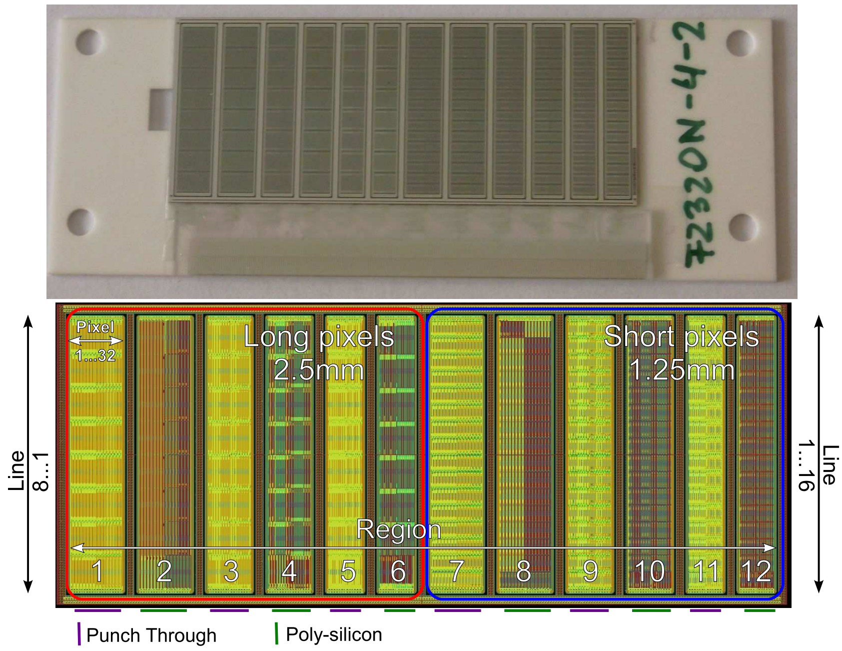


Figure 3: Multi-Pixel sensor

3 Measurements

The aim of the project was to investigate several samples of Multi-Pixel sensor:

- P-in-N type: M200N-05-Mpix-2, M200N-11-Mpix-2
- N-in-P p-spray type: M200Y-02-Mpix-2, M200Y-03-Mpix-1
- N-in-P p-stop type: M200P-04-Mpix-2, M200P-03-Mpix-1

Each sensor has a physical thickness of 320µm and an active thickness of 200µm. It has been produced on Magnetic Czochralski method grown silicon[2].

Each test was conducted in a clean room. For measuring purposes power suppliers Keithley 2410[3], ammeters Keithley 6485[4] and capacitance meter Agilent E4981A[5] were used.

The sensors were placed on the chuck of probe station (Fig. 4) and held by vacuum tweezers to reduce movements. The probe station has a constant temperature and humidity, it is necessary to obtain comparable results. The measuring temperature was 22°C. Below are described the measurements performed on the sensors. For safety reasons for each measurement the current limit of power supplier is set to 100µA.

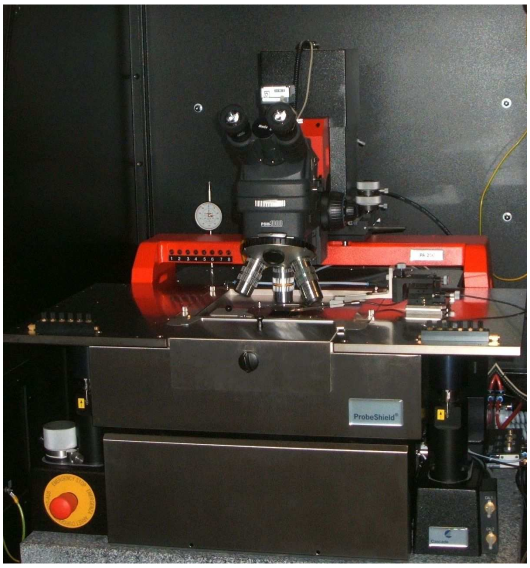
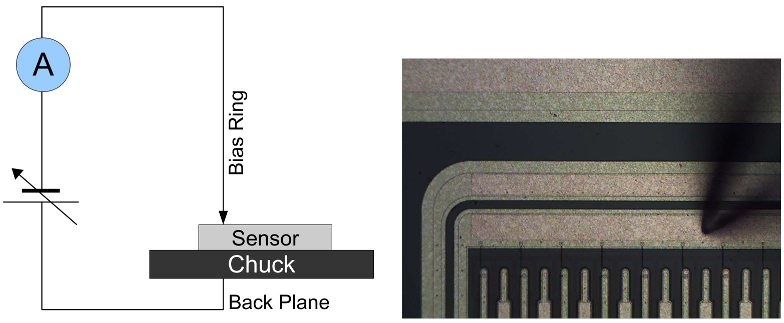


Figure 4: Probe station

3.1 I/V Bias Ring

The sensor is placed on the chuck of the probe station and the probe needle is connected to the bias ring as it is shown in Figure 5(b). The I/V characteristic is measured between the backside of the sensor called Backplane and bias ring in every regions of sensor. This measurement allows to select sensors with irregular I/V curve.

- Voltage 5V to 700V — in 10V steps in range 5 to 200V and in 25V steps in range 200 to 700V. For N-type sensors voltage is positive and for P-type sensors voltage is negative, that means that the sensor operates in reverse direction.



(a) Measurement setup (b) Needle contacting bias ring

Figure 5: I/V Bias Ring measurement

3.2 C/V Bias Ring

The sensor is placed on the chuck as well as the previous measurement. To measure the capacitance the setup is changed according to Figure 6. This measurement allows to determine the depletion voltage.

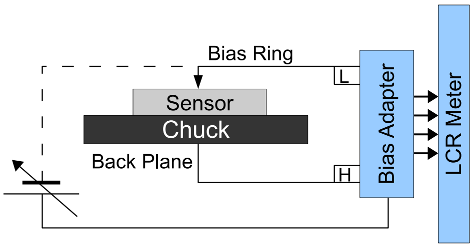


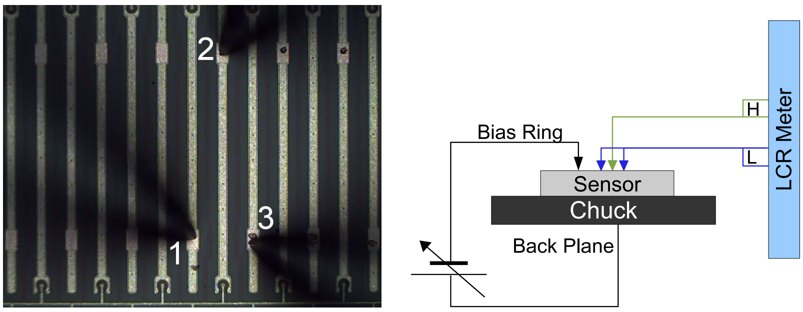
Figure 6: Setup of C/V Bias Ring measurement

- Voltage 5 to 450V — in 5V steps in range 5 to 200V and in 10V steps in range 200 to 450V. For N-type sensors voltage is positive and for P-type sensors voltage is negative.
- LCR: 1MHz at 1V amplitude

3.3 Pixel measurements

In these measurements the probe needles are connected to the pixels as is shown in Figure 7(a). Additionally the bias ring is connected to ground as well.

3.3.1 Interpixel capacitance (C_{int})

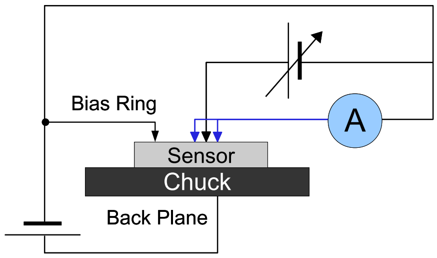


(a) Needles contacting pixels (b) Setup of C_{int} measurement

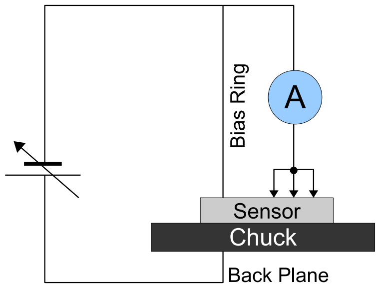
Figure 7: Example of connected needles and measurement setup

The setup for this measurement is shown in Figure 7(b). The measured value depends on the distance between the pixels. With longer pixels, the capacitance is higher than in shorter and with a smaller pitch, the capacitance is higher as well. This is expected because the capacitance should follow the equation $C \sim A/d$. This value should be low not to affect the read out electronics.

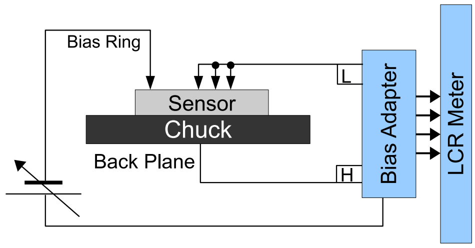
- Voltage 5 to 600V — in 5V steps in range 5 to 100V, in 10V steps in range 100 to 300V and in 20V steps in range 300 to 600V. For N-type sensors voltage is positive and for P-type sensors voltage is negative.
- LCR: 1MHz at 1V amplitude



(a) R_{int}



(b) I_{total}



(c) C_{total}

Figure 8: Measurement setups

3.3.2 Interpixel Resistance (R_{int})

R_{int} is the resistance between neighbour pixels. This resistance should be high, because one pixel should not affect others pixels and it is isolation of all individual pixels. The resistance should be greater than 1GΩ. The setup is shown in Figure 8(a)

- Voltage -2.5 to 2.5V in 0.2V steps.
- Bias voltage 600V — For N-type sensors voltage is positive and for P-type sensors voltage is negative.

3.3.3 I/V – DC-Pad (I_{total})

As it is shown in Figure 8(b) the total current of three pixels is measured. In this measurement a high current is a defect signature, because a high intrinsic dark current will make it impossible to see the signal and will also increase power consumption.

- Voltage 5 to 700V — in 5V steps in range 5 to 100V, in 10V steps in range 100 to 300V and in 20V steps in range 300 to 700V. For N-type sensors voltage is positive and for P-type sensors voltage is negative.

3.3.4 C/V – DC-Pad (C_{total})

The setup is shown in Figure 8(c). This measurement is a good tool to identify pixel defects, pixel breaks and short circuits between pixels, but the main reason is that this value should be low not to affect the read out of single pixels.

- Voltage 5 to 450V — in 5V steps in range 5 to 200V and in 10V steps in range 200 to 450V. For N-type sensors voltage is positive and for P-type sensors voltage is negative.
- LCR: 1MHz at 1V amplitude

3.3.5 Bias Resistance (R_{bias})

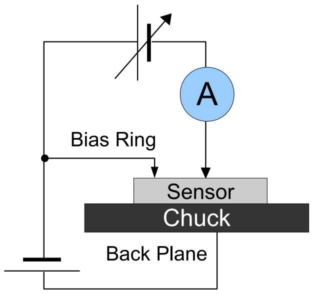


Figure 9: Setup of R_{bias} measurement

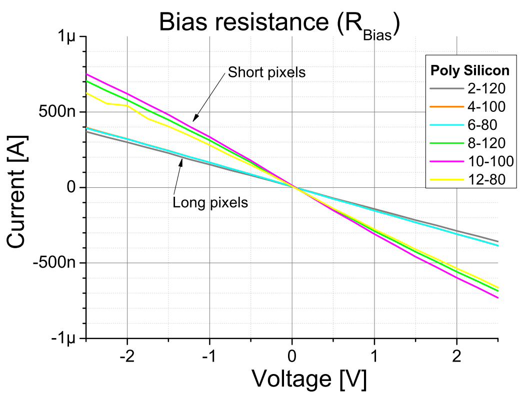
This measurement is only for poly silicon biased regions. The setup is shown in Figure 9. Bias resistance should be high enough (>1MΩ) so that signal current does not flow to bias ring.

- Voltage -2.5 to 2.5V in 0.2V steps.
- Bias voltage 600V — For N-type sensors voltage is positive and for P-type sensors voltage is negative.

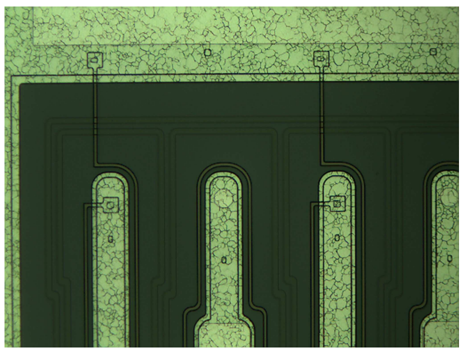
4 Results

4.1 R_{bias}

As a result of these measurements we obtain a plot of six curves per sensor (Fig. 10(a)). On the plot we see that for long pixels a smaller current flows than for short pixels. This is a consequence of the length of the resistor which is shown on Figure 10(b). So, for short pixels we have a smaller resistance than for long pixels because $R = \frac{U}{I}$. Long pixels are two times longer than short pixels and if we multiply values of short pixels by a factor of two, we should get similar values, what we obtained.



(a) I/V curves measured on the poly silicon bias resistor



(b) Picture of poly silicon resistor

Figure 10: R_{bias} measurement

In Figure 11, all the calculated resistance from all measurements is shown. As we see all values are above the 1MΩ limit. So all the bias resistors are good.

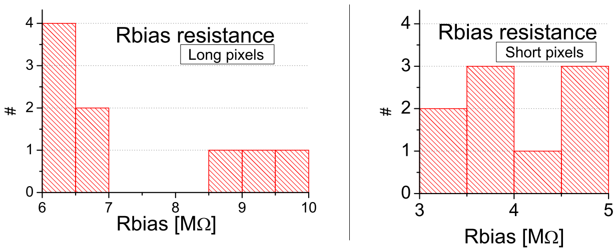
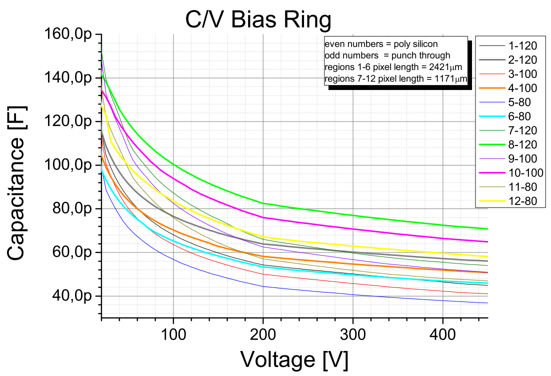
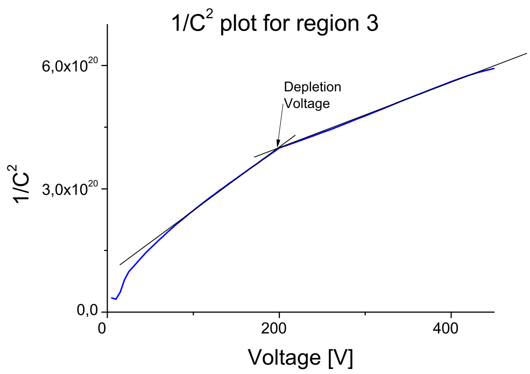


Figure 11: Histogram of calculated resistance of every region

4.2 C/V Bias Ring



(a) Result of C/V Bias Ring measurement



(b) Calculating depletion voltage

Figure 12: C/V Bias Ring

In the Figure 12(a) we see that poly silicon regions have higher values than punch through regions and the short pixels has higher values. From these measurements we determine the depletion voltage by make a $\frac{1}{C^2}$ plot and depletion voltage is voltage at the intersection of two lines like on Figure 12(b). This voltage ensure full charge collection efficiency in the CMS detector and this is a minimum voltage to supply sensors.

In Table 1 is shown depletion voltage of each sensor. In most cases depletion voltage is 200V, however all the regions are in a 200±25V band but in N-type sensor we have high fluctuation by the calculated values.

#	N-type	P-type	Y-type
1	193	195	200
2	222	195	200
3	201	198	199
4	198	197	198
5	194	200	200
6	200	200	200
7	196	200	200
8	224	200	200
9	214	200	198
10	227	199	199
11	210	201	202
12	214	200	200

Table 1: Calculated depletion voltage of each sensor, sorted by regions

4.3 I/V Bias Ring

In this measurements we determine the maximum voltage that could applied. In good samples this value is higher than 700V, but among the measured sensors 36% of all regions have lower maximum voltage. On the plot shown in Figure 13, the curves from regions 1, 6 & 7 are not good as others regions.

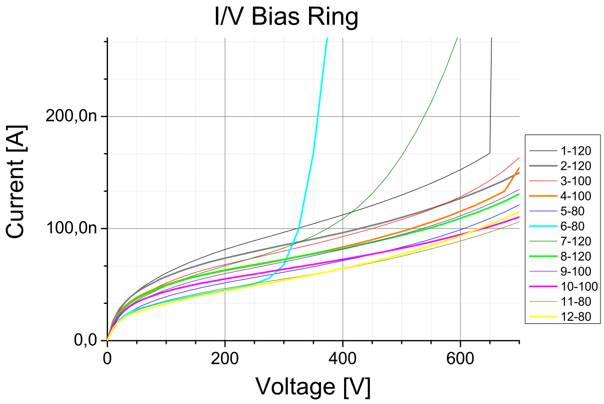
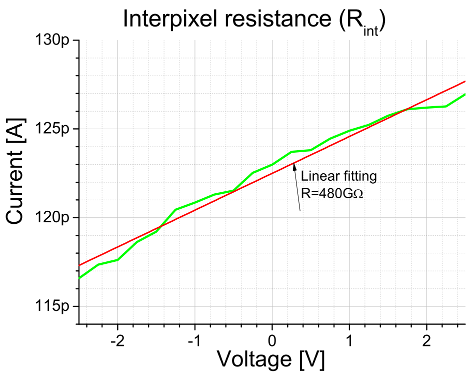
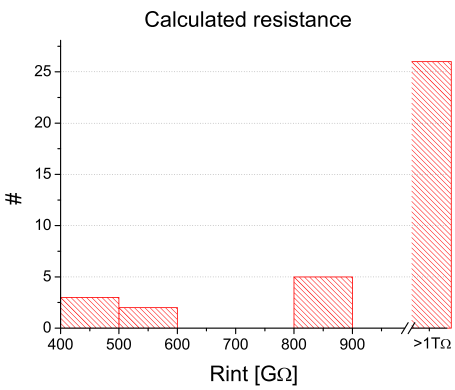


Figure 13: Result of I/V Bias Ring measurement

4.4 R_{int}



(a) Example of result from one region of sensor with linear fitting



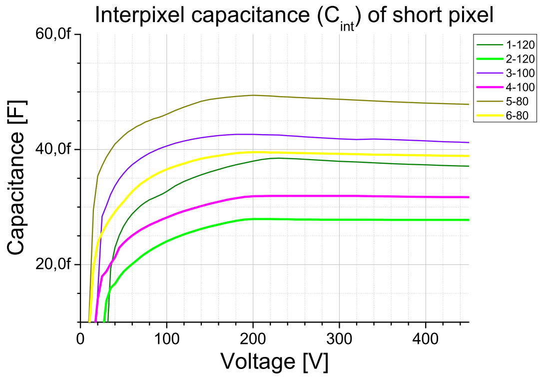
(b) Histogram of calculated resistance of every measured regions. Values above 1TΩ are summarized

Figure 14: R_{int} measurement

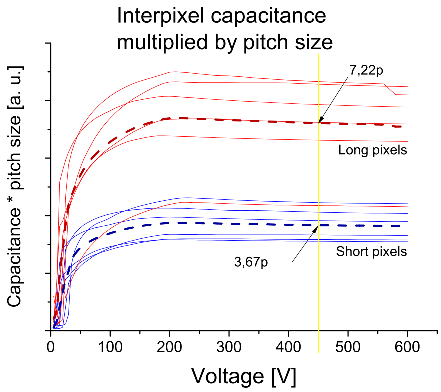
This measure determine resistance between pixels. Every regions has resistance higher than 1GΩ and more than 72% has resistance above 1TΩ (Fig. 14(b)) what is the measurement limit. The smallest value is 480GΩ so all measured samples are good.

4.5 C_{int}

Figure 15(a) shows curves of short pixels and we see that punch through regions has higher values than poly silicon. Also the regions with smaller pitch size has higher values than regions with greater pitch size. In Figure 15(b) a plot of capacitance multiplied by corresponding pitch sizes is shown. In ideal conditions these lines should overlap, but in real environment we see a trend in these lines. The dashed lines depict the average of each group (short and long pixels) and the point crossed by yellow line on average of short pixels should be two times smaller than average value of long pixels. What is good agreement with the measurement results.



(a) Example plot of measured regions with short pixels



(b) Values of capacitance multiplied by pitch size (120µm, 100µm and 80µm)

Figure 15: C_{int}

4.6 I_{total}

In the Figure 16 the resulting plot of this measurement is shown. Curves of the punch through regions have higher values than curves of the poly silicon regions. The current is proportional to the size of pitch as expected. On the third region the current sharply increase, that means that this region has some production error. Values are between 50pA and 350pA and average value is 150pA. So sensor of 256 pixels take 'dark power' of $150\text{pA} \cdot 200\text{V} \cdot 256\text{pixels} \approx 8\mu\text{W}$.

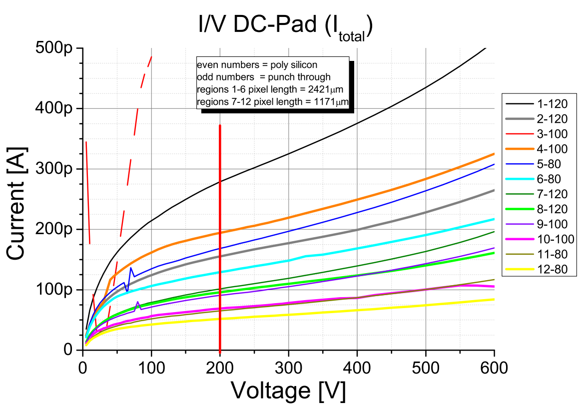


Figure 16: I_{total} measurement

4.7 C_{total}

In the plot shown in the Figure 17 we see that the capacity decreases to depletion voltage (about 200V) and then the values are constant and the values are between 150fF to 700fF.

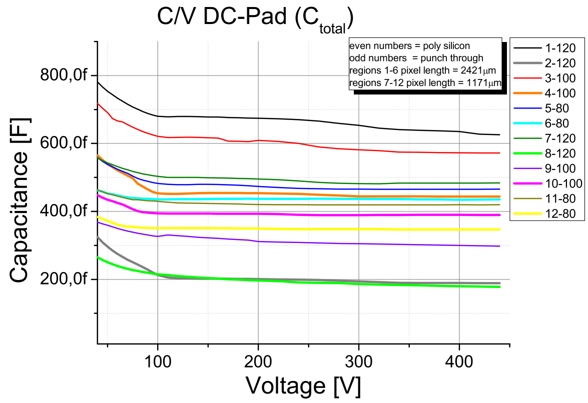


Figure 17: C_{total} measurement

5 Conclusions

The goal of the project was to perform various measurements of Mpix sensors. The main conclusion is that the different substrates N-type, P-type and Y-type are comparable. We expected that only 1% of regions has defects, but in these measurements were more than one third of defect regions what is the consequence of production errors. All requirements for R_{bias} and R_{int} was sufficiently fulfilled. One sensor of 256 pixels should take a 'dark power' of 8µW.

Acknowledgements

I would like to thank DESY for offering the summer students program, and to thank all the people who helped me with my work, with my measurements, giving timeless explanations to make me understand the details and for numerous helpful discussions: Thank you, Wolfgang Lange, Matthias Bergholz and all the CMS group. Furthermore I would like to thank my summer student colleagues and all people involved in the program.

References

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