Design of large scale sensors in a 180nm CMOS process modified for radiation tolerance

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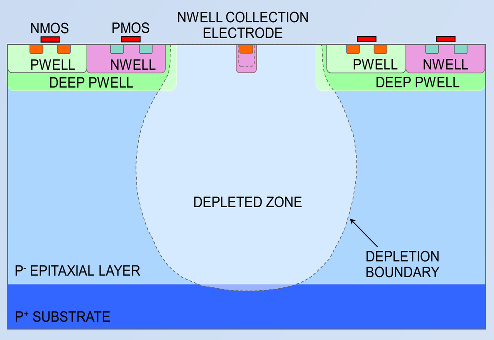
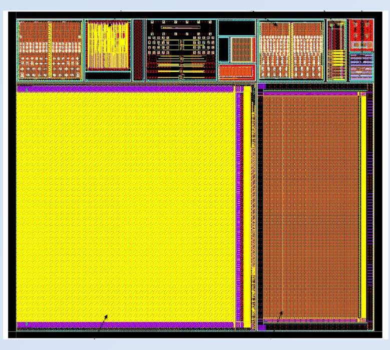
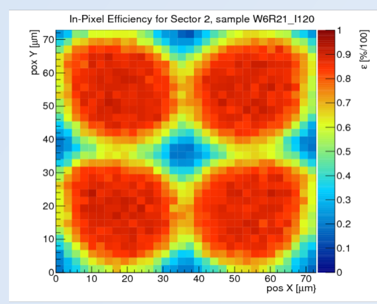
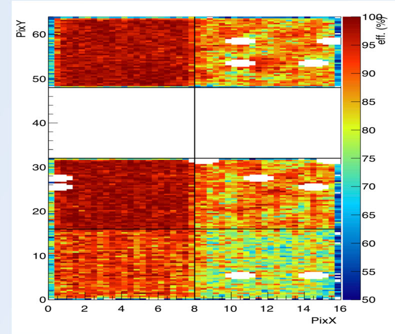
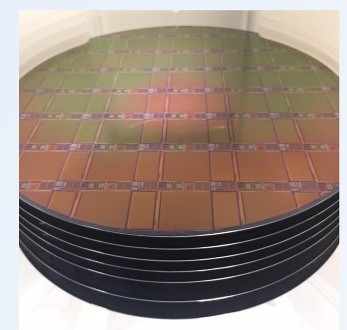
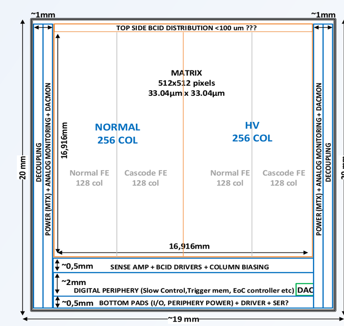
Two large scale Depleted Monolithic Active Pixel Sensors (DMAPS) have been fabricated with a process modification for increasing radiation tolerance: Monopix with a column drain synchronous readout, and Malta with a novel asynchronous architecture. After the first iteration for irradiated sensors, charge collection at the corner of the pixels had to be improved. In the following run, this aspect was corrected by some pixel and process modifications guided by extensive TCAD simulations. These were implemented in a small test chip miniMalta, for which cluster measurements are shown. In addition the digital architecture of both chips is analysed with simulations to demonstrate they can sustain average hit rates of 80 MHz/cm^2 if equipped with a trigger memory. Finally, the new engineering run in TJ 180nm technology foreseen for Q1 2020 is introduced.

DMAPS development evolution

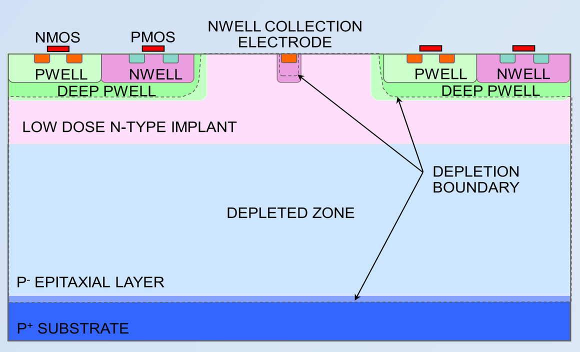
Standard Modified process [1]	Malta and Monopix designs	Sensor characterization	Further improvements MiniMalta MPW [2]	2nd submission with pixel improvements	Current developments
					
First promising measurements	First engineering run with large designs	Efficiency/charge loss at the corner of pixels	Pixel modifications and RTS improvements	New Czochralski substrate	
2014	07/2017	01/2018	09/2018	09/2019	Present

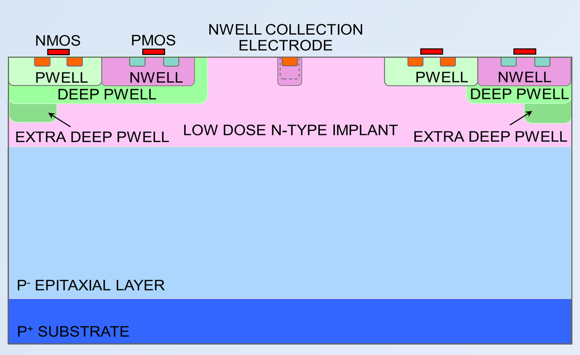
Pixel/Process modifications and FE improvement

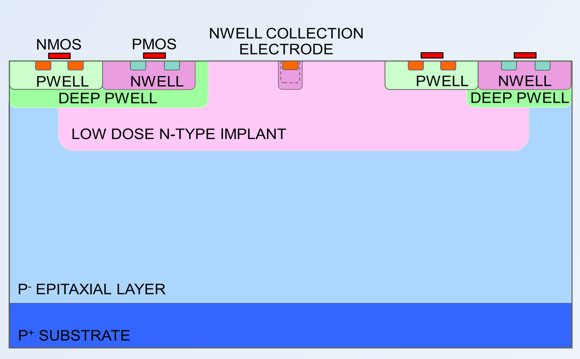
Two modifications were done after TCAD simulations to enlarge the lateral electrical field to accelerate charge collection from the pixel corners:

- Add an extra deep pwell implant (process modification)
- Include a gap in the n-layer (mask change)

Finally critical transistors were enlarged in the front end to reduce RTS noise



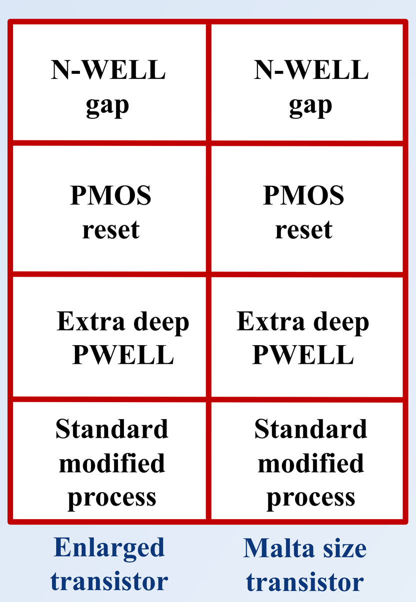


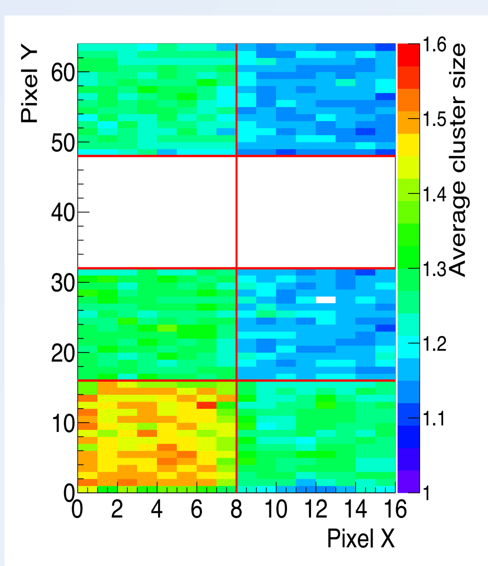


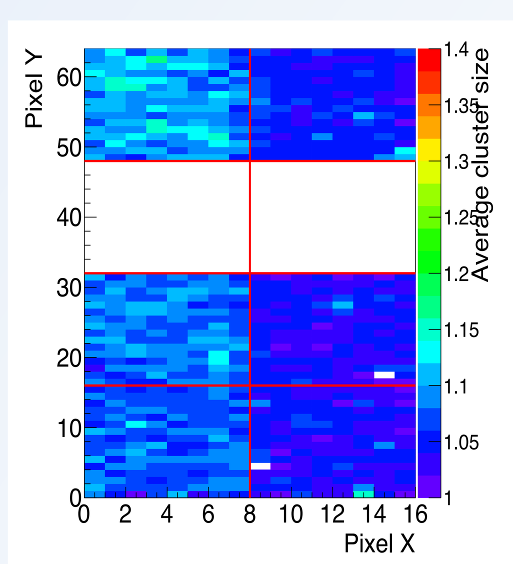
From left to right: standard modified process, extra deep p-well process modification and new mask with gap in the n-well

MiniMalta results :

- Sectors with **enlarged transistors** have less noise and allow operation at lower thresholds where they show larger cluster size
- **Un-irradiated sensors :** Additional modifications increase lateral field and therefore decrease cluster size
- **Irradiated sensors :** Modified sectors ensure charge collection after irradiation and hence have larger cluster sizes





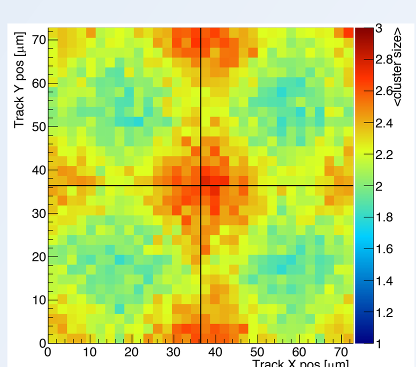
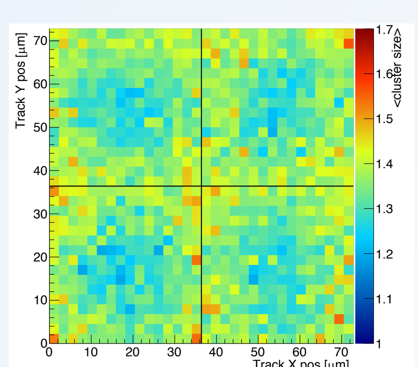
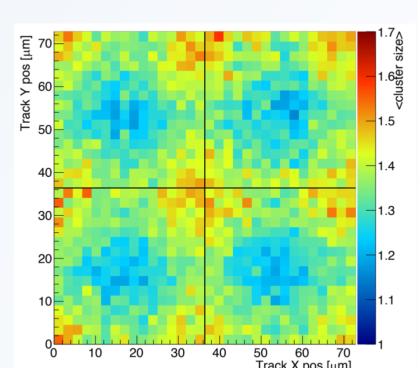
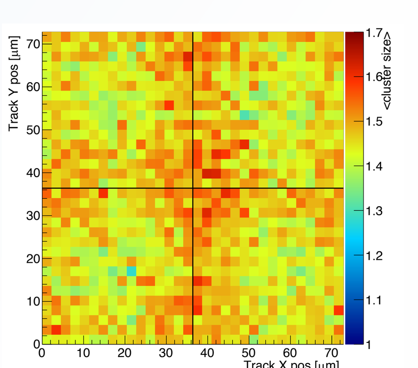


On the left the miniMalta sectors are described, in the middle the average cluster size for un-irradiated sensor and on the right the average cluster size for a 10^{15} N_{eq}/cm^2 irradiated sensor (data from ELSA test beam)

Czochralski is the standard method to grow single crystalline silicon and recently it has become available with higher resistivity. Contrary to epitaxial the high resistivity region extends over the full wafer thickness and hence allows to obtain larger signals

Cluster analysis shows:

- Much larger clusters with Czochralski substrate
- Sensors with n-gap blanket modification see larger clusters than those fabricated with the standard modified process in the pixel corners

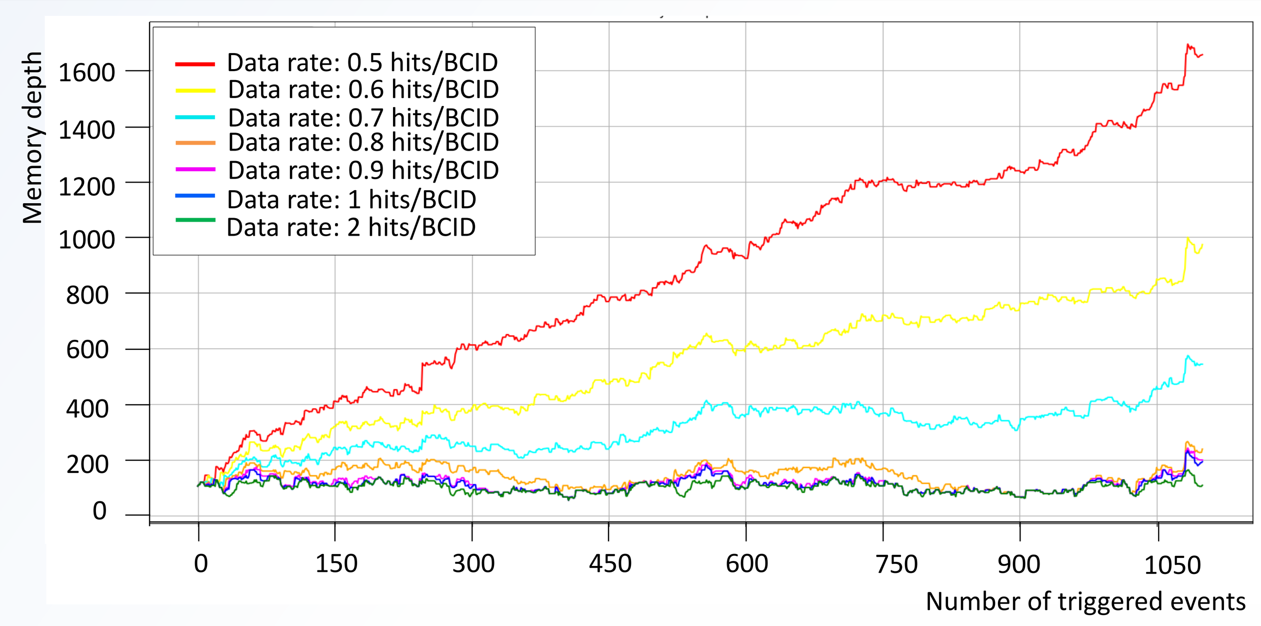
From left to right in pixel cluster size for Cz standard un-irradiated, Cz n-gap un-irradiated, Cz standard irradiated and CZ n-gap irradiated both to 10^{15} N_{eq}/cm^2

Data rate capability and memory simulations

The ATLAS experiment at CERN plans to upgrade its Inner Tracker System in order to go from $1x10^{34}$ $cm^{-2}s^{-1}$ to $7.5x10^{34}$ $cm^{-2}s^{-1}$. The Monolithic pixel detectors were proposed to be in the outer layer of the inner detector. The average hit rate for this layer according simulations is 80 MHz/cm^2 or a maximum of 8 hits per bunch crossing per chip.

Simulation parameters:

- 4 MHz trigger rate: generated with a Poisson Distribution
- Detector hits data from Athena with correct pixel dimensions
- For a 512 x 512 pixel matrix, there is a memory for every 32 columns
- The size of the word stored in the memory is 32 bits
- Variable readout capabilities of the chip explored



This graph shows that the minimum readout capability is 1 hit/BCID and considering the stated word length it is equivalent to 1.28 Gbps

Conclusions and current development

- There is a clear path on how to proceed to make the sensor more radiation tolerant and this will be followed in the upcoming submissions
- Pixel and process modifications reduce charge loss at the corner of pixels and therefore yield better efficiency (see H. Pernegger's presentation)
- New submission foreseen for Q1 of 2020 will include:
  - 10 new MiniMaltas: To study further FE, RTS and radiation tolerance
  - Malta v2 1 x 2 cm^2 (Half size): To explore timing applications
  - TJ-Monopix readout 2 x 1.9 cm^2: Pixel modifications and data rates capabilities
- Czochralski material generates more signal and therefore the cluster size is also larger than in epitaxial material
- Data rate simulations show very little margin in bandwidth and the need for readout at minimum 1.28 Gbps

References

[1] W. Snoeys et al. "A process modification for CMOS Monolithic Active Pixel Sensors for enhanced depletion, timing performance and radiation tolerance", Nucl. Instr. Meth. A Volume 765, 21 November 2014, https://doi.org/10.1016/j.nima.2017.07.046

[2] M. Dyndal et al, "Mini-MALTA: Radiation hard pixel designs for small-electrode monolithic CMOS sensors for the High Luminosity LHC", arXiv:1909.11987