International Conference on Technology and Instrumentation in Particle Physics IOP Publishing
Journal of Physics: Conference Series **2374** (2022) 012169 doi:10.1088/1742-6596/2374/1/012169

Latest developments and characterisation results of DMAPS in TowerJazz 180nm for High Luminosity LHC

L Flores Sanz de Acedo[1,2,*], P Allport[3], I Asensi Tortajada[4], D Bortoletto[5], C Buttar[2], R Cardella[1,6], F Dachs[1,7], V Dao[1], D Dobrijevic[1,8] M Dyndal[1], P Freeman[3], A Gabrielli[1] K Y Oyulmaz[9], H Pernegger[1], F Piro[1,10], P Riedler[1], H Sandaker[11], A Sharma[1,5], C Solans Sanchez[1], W Snoeys[1] and T Suligoj[8]

[1]CERN, Switzerland, [2]University of Glasgow, United Kingdom, [3]University of Birmingham, United Kingdom, [4]University of Valencia and Consejo Superior de Inv. Científicas (CSIC), Spain, [5]University of Oxford, United Kingdom, [6]Université de Genève, Switzerland, [7]Vienna University of Technology, Austria, [8]University of Zagreb, Croatia, [9]Bolu Abant Izzet Baysal University, Turkey [10]École Polytechnique Fédérale de Lausanne, Switzerland and [11]University of Oslo, Norway

E-mail: `leyre.flores.sanz.de.acedo@cern.ch`

Abstract.
The last couple of years have seen the development of Depleted Monolithic Active Pixel Sensors (DMAPS) fabricated in TowerJazz 180nm with a process modification to increase the radiation tolerance. While many of MAPS developments focus on low radiation environment, we have taken the development to high radiation environment like pp-experiments at High Luminosity LHC. DMAPS are a cost effective and lightweight alternative to state-of-the-art hybrid detectors if they can fulfil the given requirements for radiation hardness, signal response time and hit rate capability. The MALTA and Mini-MALTA sensors have shown excellent detection efficiency after irradiation to the life time dose expected at the outer layers of the ATLAS pixel tracker Upgrade. Our development focuses on providing large pixel matrixes with excellent time resolution (<2ns) and tracking. This publication will discuss characterisation results of the DMAPS devices with special focus on the new MALTA2 sensor and will show the path of future developments

1. Introduction

DMAPS are devices that integrate the readout electronics and the sensing volume in the same silicon die. They are fabricated in commercial CMOS technologies and offer high resolution, low material budget and a low cost.

At CERN in 2014 ALICE adopted the ALPIDE CMOS MAPS sensor [1] implemented in the Tower Jazz 180nm technology CMOS imaging sensor process for a renewed Pixel Inner Tracking System and since then several developments have continued in this technology. ATLAS ITk community created a collaboration to develop DMAPS sensor with radiation hardness constraints of 500 MRad TID and a NIEL fluence of $10^{15} MeV N_{eq}/cm^2$. This effort resulted in the submission of MALTA [3] and Monopix [2]. Both sensors included a process modification with respect to the ALPIDE to collect charge via drift instead of diffusion and to further extend the depletion region. A low dose n-implant layer was added to move the junction of the sensor away from the small collection electrode and create a fully planar junction. This is known as the standard modified process. The measurements of these detectors showed a loss in efficiency at the corner of pixels and the presence of Random Telegraph Noise that prevented operation at lower thresholds. To improve these results more modifications on the processing of the Tower Jazz 180nm technology as well as in the FE were introduced and tested in a prototype chip called mini-MALTA [4]. The extra deep p-well features a modification of the standard modified process with an additional deep p-type implant under the deep p-well. The n-well gap change consists of including a gap in the low dose n-blanket mask. The purpose of both changes is to improve charge collection for the charge generated near the pixel edges by creating a stronger lateral field. The FE changes target noise reduction by increasing the transistors size and larger gain. Mini-MALTA proved to be radiation hard up to $10^{15} MeV N_{eq}/cm^2$.

The signal generated in the sensor is proportional to the thickness of the sensitive layer. MALTA and Monopix had always been fabricated using a p-type substrate with a high resistivity epitaxial layer of 25-30 μm thickness. By moving to high resistivity Czochralski material the sensitive volume can be increased for higher reverse biases compensating at least in part the higher noise and higher charge threshold. This change was enough to compensate for the loss of efficiency in the pixels corners.

Bearing in mind all the things learnt during these years, MALTA2, was submitted at the end of 2020. Nowadays, design effort is in place to continue these developments with the MALTA3, a large device with high-granularity and few nanosecond time-resolution. Figure 1 is a timeline representation of the main mile stones for the DMAPS developments in TowerJazz 180 nm technology carried out at CERN that have been described above.

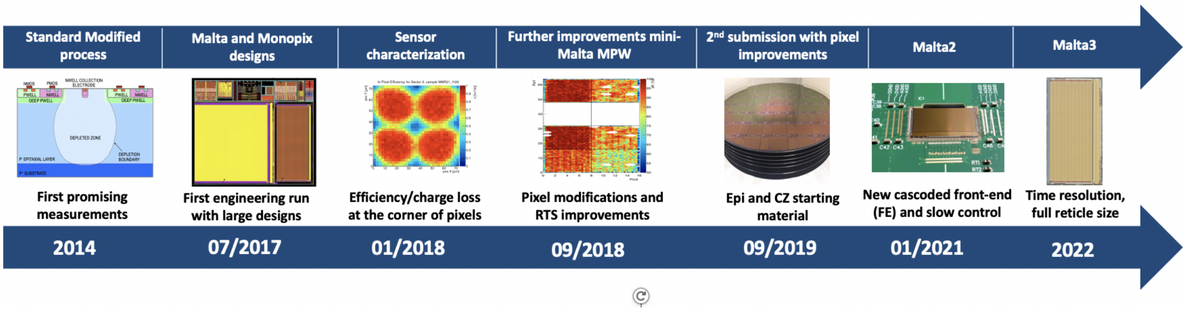


Figure 1. DMAPS timeline for the TowerJazz 180 nm developments at CERN

2. MALTA2 front-end, process modifications and expected time resolution

MALTA2 is a 20 x 10 mm^2 sensor, half the size with respect to the original MALTA. It has a pixel matrix of 512 x 224 rows and columns with a pixel pitch and size of 36.4 x 36.4 μm^2. The FE electronics are very similar to the ones described in [3] and [4]. The new schematic can be found in Figure 2.

The main difference between the old and this FE is that it has been cascoded with transistor M3 to have a higher gain and output impedance while preserving the band-width. Furthermore, transistor M4 has been increased in size, in Mini-MALTA it was 1.22 μm x 0.36 μm and in the new implementation it is 2.72 μm x 0.36 μm targeting to be less sensitive to RTS noise. Finally the capacitance CS has been incremented 2.7 times with the purpose of reducing noise and having a lower threshold dispersion per pixel. There are no regions in the pixel matrix. The

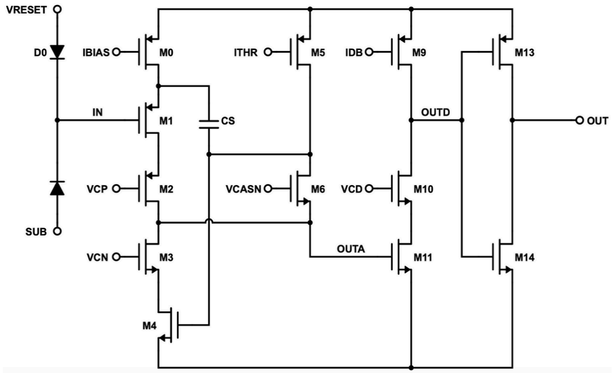


Figure 2. MALTA 2 front-end schematic with highlighted changes with respect to the old front-end design

only difference between one half and the other is that if required a mask change can be done to remove the new cascode from the FE and revert to the MALTA FE. Concerning the collection electrode it is 2 μm large and the separation to the rest of the electronics is 4 μm. The sensor has been fabricated in both Czochralski and epitaxial and with the extra deep p-well and the gap in the n-layer as process modifications. There are three different levels of doping in the n-blanket to study how the sensor is affected by it.

Figure 3 a) and b) show the threshold difference between the original FE and the new cascoded one. The plot is with respect to the DAC values ITHR that controls the length of the pulse into the discriminator and IDB in charge of setting the discriminator level. It can be observed that the lower ITHR and IDB the lower the threshold. However, the main difference is the minimum threshold achieved by the devices that is $\approx$ 200 electrons less for the new cascoded FE. The rms of the threshold improves for the new FE as well as the noise decreases.

The digital circuitry of MALTA2 has kept the same asynchronous architecture as in MALTA except from the slow control protocol which has now been implemented as a shift register. This change was done aiming to overcome the difficulties of the previous control block that made scans like measuring the threshold for the full matrix not possible.

Concerning time resolution, it has been characterised with a pico-TDC device for mini-MALTA [4] and MALTA2 should behave similarly. Time resolution is 2.6 ns for the sensor fabricated with epitaxial compared to 1.7 ns for the Czochralski samples above 10 V due to increased depletion voltage. This resolution is extracted from the linear combination of the time differences of reference MALTA signals between planes from test beam data. Figure 3 c) shows the time resolution distribution for a CZ Malta.

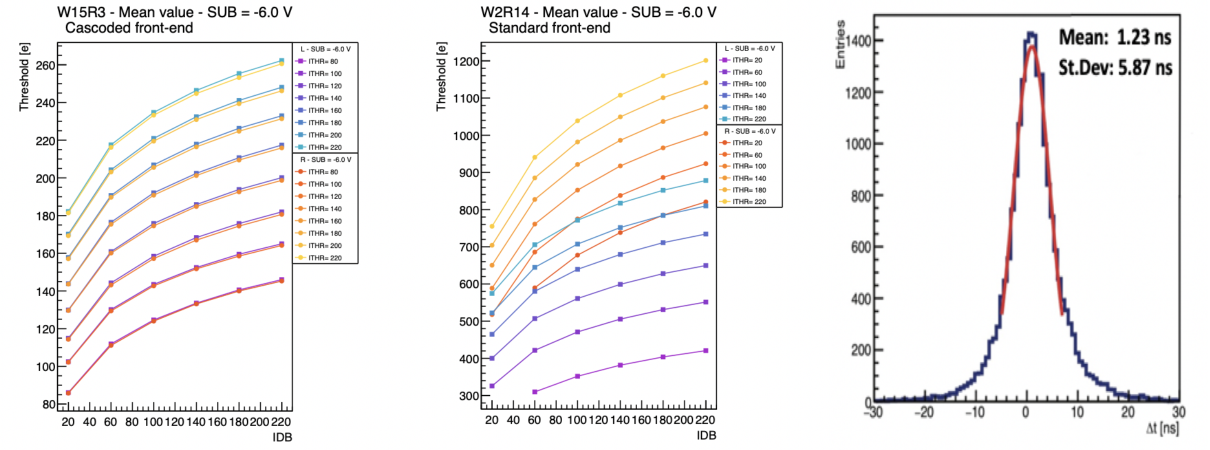
3. Malta2 initial characterisation results

MALTA2 has been characterised in the laboratory and it will be taken to test beam in the month of July, where radiation hardness and timing resolution will be checked. So far all the tests show full functionality of the device: source scans, threshold, dac linearity, noise etc. Figure 4 shows a dac linearity curve and a threshold and noise scan for the full matrix. It is worth pointing out that the DAC curve saturates at 1.8V as it is buffered and it covers the expected range of voltages from 0 to 1.8V.

4. Conclusions

The main conclusions can be summarised as follows:

- There is a clear path on how to make the sensor faster and more radiation tolerant.



a) b) c)

Figure 3. a) Mini-Malta threshold variation with respect to IDB and ITHR bias for the new cascoded FE available in Malta2. b) Mini-Malta threshold variation with respect to IDB and ITHR bias for the standard FE present in Malta. c) Malta time resolution plot

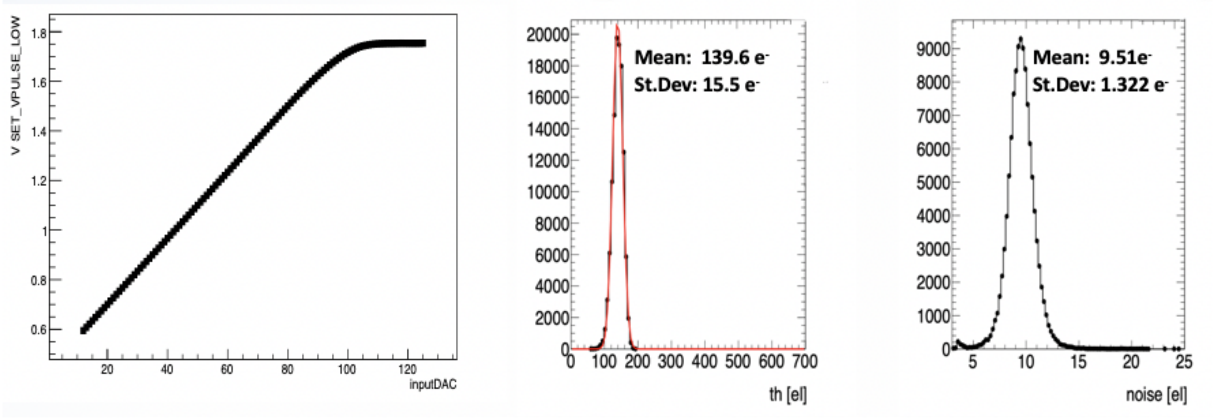


Figure 4. MALTA2 characterisation results.

- Malta2 should confirm radiation hardness $> 10^{15}\ MeV\ Neq/cm^2$ for TJ180nm technology and timing performance.
- Malta3 will merge latest process modifications and front-end design with improved time resolution and asynchronous readout in a large device.

References

[1] G. Aglieri et al., *The ALPIDE pixel sensor chip for the upgrade of the ALICE Inner Tracking System*, Volume 845, 11 February 2017, Pages 583-587

[2] K. Moustakas et al., *CMOS monolithic pixel sensors based on the column-drain architecture for the HL-LHC upgrade*, j.nima.2018.09.100

[3] I. Berdalovic et al, *Monolithic pixel development in TowerJazz 180 nm CMOS for the outer pixel layers in the ATLAS experiment*, 2018 JINST 13 C01023

[4] *Mini-MALTA: Radiation hard pixel designs for small- electrode monolithic CMOS sensors for the High Luminosity LHC* JINST, 15 (2020) P02005 [1909.11987]