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Radiation hardness and timing performance in MALTA monolithic pixel sensors in TowerJazz 180 nm

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ABSTRACT: The MALTA family of depleted monolithic pixel sensors produced in TowerJazz 180 nm CMOS technology target radiation hard applications for the HL-LHC and beyond. Several process modifications and front-end improvements have resulted in radiation hardness $>10^{15}$ 1 MeV n_{eq}/cm^2 and time resolution below 2 ns, with uniform charge collection and efficiency across the pixel of size $36.4 \times 36.4\ \mu m^2$ with small collection electrode. This contribution will

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present the comparison of samples produced on high-resistivity epitaxial silicon with Czochralski substrates, before and after neutron irradiation, and results from MALTA2 with a new cascoded front-end flavour that further reduces the RTS noise.

Keywords: Radiation-hard detectors; Materials for solid-state detectors

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Contents

1 Introduction

Future collider experiments demand their detector technologies to withstand the harsh environments they will operate in, such as large radiation dose, high hit rate with high granularity, and fast response time [1]. One of the most interesting detector technologies that can address these requirements is the monolithic pixel sensor with small collection electrode due to its large signal-over-noise ratio. Compared to the more largely used hybrid pixel sensors with bump-bonding technology, monolithic technologies offer advantages such as reduced production effort, reduced costs, and material usage due to the fact that readout electronics and sensor are integrated in the same silicon wafer [2, 3].

MALTA is a Depleted Monolithic Active Pixel Sensor (DMAPS) with small collection electrode, fabricated in TowerJazz 180 nm CMOS imaging technology. The MALTA matrix consists of 512 × 512 pixels with a pixel pitch of 36.4 µm and an octagonal shaped collection electrode with a diameter of 2 µm. The asynchronous readout avoids the distribution of high frequency clock signals across the matrix to reduce power consumption (10 mW/cm^2 digital and 70 mW/cm^2 analog power) and minimises analog-digital crosstalk [4]. The pixel design and sensor processing of MALTA have been developed such that it can withstand a large radiation dose while maintaining the advantages of using a small collection electrode with very low capacitance, i.e. minimising noise and low power dissipation. In order to achieve high detection efficiency after irradiation, the pixel design is optimised such that it can achieve excellent charge collection and electrical field configuration. This is done by using three different implant designs: the standard modified (STD) introduces a low-dose n-type blanket implant across the full pixel matrix, a design with a gap in this n-blanket implant (N-GAP), and a design with an additional deep p-well implant (XDPW) [5]. These pixel flavours are produced on high-resistivity epitaxial substrates (30 µm depletion layer) and on thick high-resistivity p-type Czochralski (Cz) substrates. Introducing the same sensor design on high-resistivity (3–4 kOhm) Cz substrates enables the combination of the advantages of small electrode CMOS sensors with those of a thick (100 µm) detection layer. Here, the low capacitance is maintained while the signal amplitude is increased due to the thicker depleted sensor layer.

2 MALTA-Czochralski

In the following sections results will be presented on MALTA sensors produced on epitaixal and Cz substrates before and after neutron irradiation. The data presented were recorded at the DESY test beam facility, using a 3–4 GeV electron beam with a telescope consisting of three MALTA epitaxial tracking planes. The non-irradiated devices under test (DUT) were operated at room temperature, whereas the irradiated DUTs were operated in a cold box at −14 °C.

2.1 Non-irradiated samples

Figure 1 illustrates the difference in efficiency response as a function of substrate bias for the non-irradiated epitaxial and Cz sensors. The hit detection efficiency is defined as the fraction of clusters on the DUT matched to telescope tracks over the total number of tracks. The DUT hit is matched to a track if the distance between the track interpolation position and the centre position of the cluster is smaller than 100 µm.

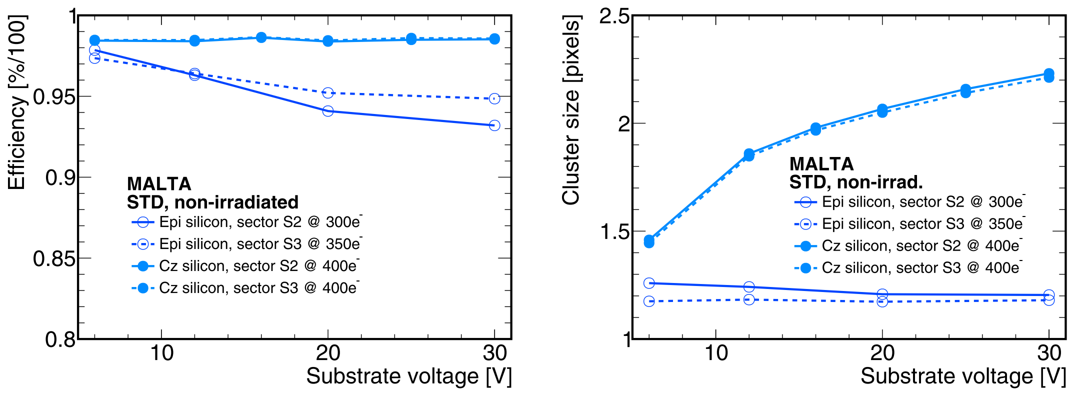

Figure 1. Left: efficiency of non-irradiated STD MALTA samples on epitaxial and Cz substrate versus substrate bias. Right: average cluster size of non-irradiated STD MALTA samples on epitaxial and Cz substrate versus substrate bias. Indicated are the respective discriminator thresholds (electrons) and the corresponding sector of the pixel matrix (S2 or S3). The sectors differ in the extension of the deep p-well, respectively for S2 and S3 medium and maximum [4].

Whereas the epitaxial sensors show decreasing efficiency at increasing bias voltage due to the increasing leakage current, the Cz samples show a flat dependency versus substrate voltage. Figure 1 also illustrates the relationship between cluster size and bias voltage. The cluster size, the number of adjacent pixels firing after a charged particle transverses the detector, for epitaxial sensors does not increase with substrate voltage. However, for a STD Cz sample the cluster size increases up to 2.2 pixels at 30 V due to the larger depletion depth in the thick substrate and therefore more charge is collected.

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2.2 Irradiated samples

Figure 2 shows the efficiency response of N-GAP epitaxial and Cz sensors as a function of substrate bias after neutron irradiation to 1×10^{15} 1 MeV n_{eq}/cm^2 and 2×10^{15} 1 MeV n_{eq}/cm^2. This figure illustrates the motivation to move to Czochralski sensors after irradiation, since the efficiency of Cz samples increases substantially with substrate voltage. As the bias voltage increases, the depleted region in the high resistivity substrate increases and with it its signal. After neutron irradiation the epitaxial sensors achieve a maximum efficiency at −12V, whereafter the efficiency declines.

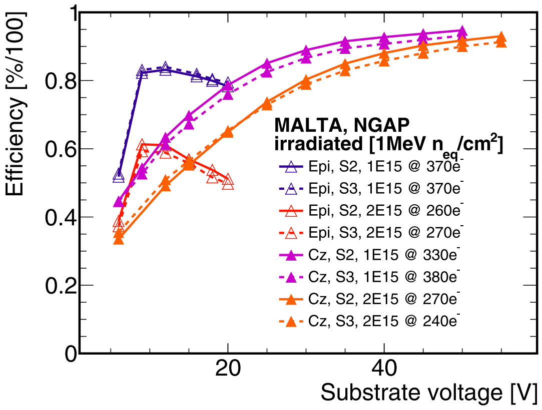

Figure 2. Efficiency of MALTA samples irradiated to 10^{15} 1 MeV n_{eq}/cm^2 and 2×10^{15} 1 MeV n_{eq}/cm^2 on NGAP epitaxial and Cz silicon versus substrate bias. Indicated are the respective discriminator thresholds (electrons) and the corresponding sector of the pixel matrix (S2 or S3). The sectors differ in the extension of the deep p-well, respectively for S2 and S3 medium and maximum [4].

2.3 Timing performance

With the bunch-crossing clock of the LHC being 25 ns, sensors and readout architecture have to be sufficiently fast in order to match the hits with the corresponding bunch-crossing. Furthermore, sub-nanosecond level resolution is required to contribute to jet sub-structure reconstruction [1]. Figure 3 illustrates that non-irradiated MALTA Cz STD is capable of fulfilling these requirements. Timing measurements were performed with a trigger scintillator for timing reference and a dedicated CERN developed ASIC, the Pico-TDC [6], to measure the difference in time between the fastest MALTA signal and the scintillator. The timing distribution is measured as a function of substrate voltage and the 50%-, 68%-, and 95%-integral of the time difference identify the core of the distribution and its tails. These results show that at higher substrate voltage, the signal is faster and has higher amplitude. From the integral of the timing distribution it can be concluded that there will be no pile-up of bunch-crossings, since all data can be read-out within 25 ns. Furthermore, figure 3 indicates that at a bias voltage >15 V 50% of the hits have arrived and are tagged within 2 ns for the full-size sensor. The ability to read out within 2 ns and preserve the timing information makes this technology interesting for physics analysis.

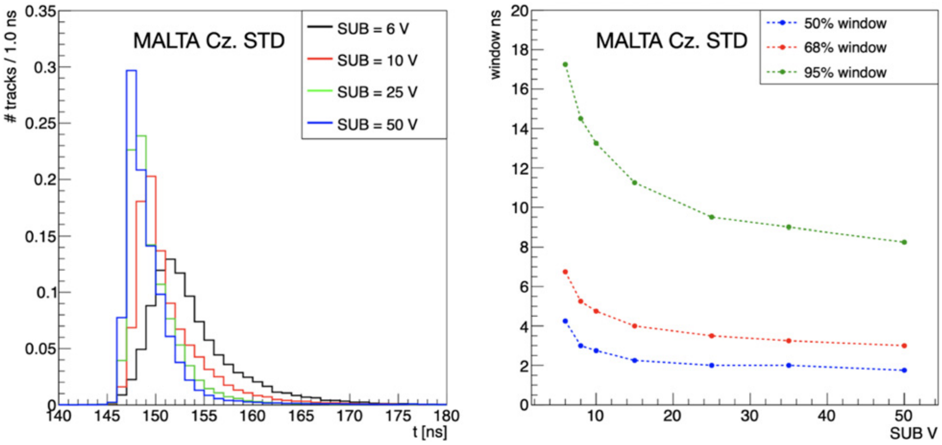

Figure 3. Left: difference in time of the fastest hit of the cluster (matched with the track in the DUT) and the time of the hit in the scintillator versus substrate bias. Right: integral of the difference in time distribution (left) versus substrate bias. Timing measurements were done for a non-irradiated MALTA Cz. STD sample and with low energy electrons from Sr-90 β-decay.

3 MALTA2

MALTA2 is the second prototype of the family of DMAPS in TowerJazz 180 nm technology. The matrix consists of 224 × 512 pixels, with a pixel size of 36.4 × 36.4 μm^2, and an active area of 18.33 mm^2. MALTA2 is fabricated on both epitaxial and Cz substrates and consists of the same pixel flavours as MALTA (STD, N-GAP and XDPW). MALTA2 has two front-end designs implemented: the standard MALTA and a cascode design as implemented for the MiniMALTA demonstrator [7]. Furthermore, the size of selected transistors are increased to reduce the Random Telegraph Signal (RTS) noise. This benefit was also shown in the MiniMALTA demonstrator, where the larger transistor size significantly decreased the RTS noise, both before and after irradiation [7]. Similar to the MALTA design, the readout of the MALTA2 chip is fully asynchronous. The benefit of the new front-end design for MALTA2 is illustrated by figure 4, which presents a threshold and a noise scan for a non-irradiated Epi N-GAP MALTA and MALTA2. Both designs show similar threshold dispersion, approximately 10% of the mean. However, the MALTA2 sensor shows significantly less RTS, indicated by the smaller tails in the noise scan, compared to the MALTA sensor at the same threshold (~350 electrons) and same bias voltage (−6 V). The reduction of the RTS from the front-end opens the possibility to operate at lower thresholds and therefore reach higher efficiencies.

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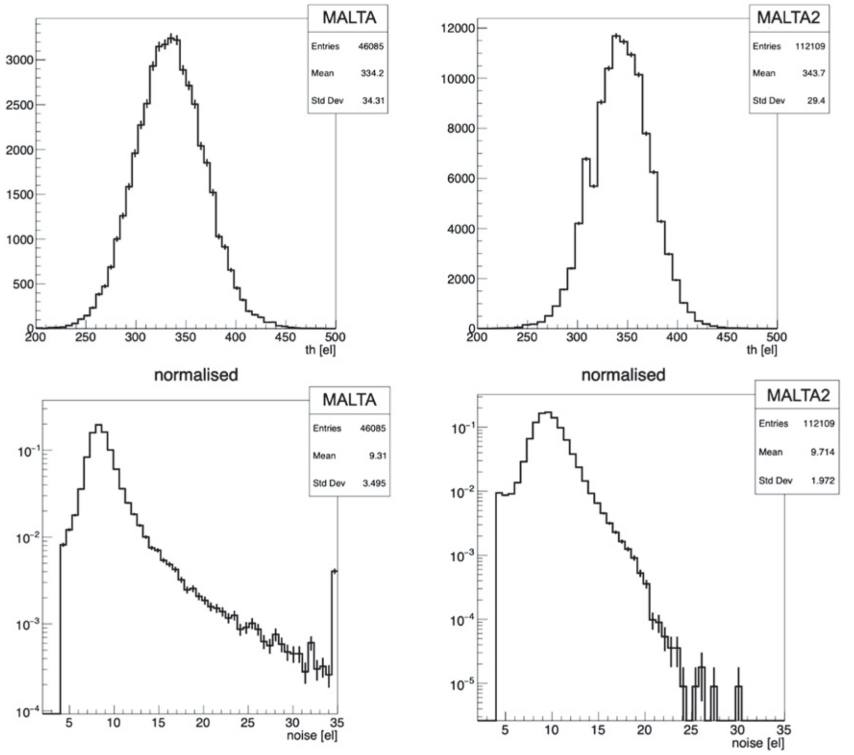

Figure 4. Threshold scan (top) and noise scan on logarithmic scale (bottom) of MALTA (left) and MALTA2 (right) (Epi, NGAP, 300 µm thick, high doping of n-blanket) for respectively 46085 and 112109 pixels, at −6 V SUB bias and −6 V PWELL bias.

Test beam at the Super Proton Synchrotron (SPS) at CERN is currently ongoing with the goal to demonstrate MALTA2 performance in terms of radiation hardness ($>10^{15}$ 1 MeV n_{eq}/cm^2) and timing performance. The custom telescope dedicated to demonstrate the performance of MALTA2 contains 6 MALTA tracking planes and a cold box which can host up to 2 DUTs. Preliminary results on new generation irradiated MALTA2 samples demonstrate uniform efficiency response over a wide range of threshold.

4 Conclusion

The combination of the pixel design and sensor processing of MALTA Cz. has provided excellent results for a full-size monolithic CMOS sensor with small collection electrode. MALTA2 should confirm radiation hardness $>10^{15}$ 1 MeV n_{eq}/cm^2 and excellent timing performance.

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