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Study of MALTA2, a Depleted Monolithic Active Pixel Sensor, with grazing angles at CERN SPS 180 GeV/c hadron beam

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Abstract: MALTA2 is a Depleted Monolithic Active Pixel Sensor designed to meet the challenging requirements of future collider experiments, in particularly extreme radiation tolerance and high hit rate. The sensor is fabricated in a modified Tower 180 nm CMOS imaging technology to mitigate performance degradation caused by 100 MRad of Total Ionising Dose and greater than 10^{15} 1 MeV n_{eq}/cm^2 of Non-Ionising Energy Loss. MALTA2 samples have been tested during the CERN SPS test beam campaign in 2023–2024, before and after irradiation at a fluence of 1×10^{15} 1 MeV n_{eq}/cm^2. The sensors were positioned at various inclinations relative to the beam, covering grazing angles from 0 to 60 degrees. This contribution presents measurements of detection efficiency and cluster size as functions of these angles, along with an estimation of the active depth of the depleted region based on the test beam results.

Keywords: Particle tracking detectors (Solid-state detectors); Radiation-hard detectors

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1 Introduction

Monolithic pixel detectors are widely considered for applications in high-energy physics experiments [1, 2], aiming to meet increasingly stringent requirements for vertexing and tracking detectors. Compared to hybrid pixel detectors, monolithic pixel detectors offer advantages in tracking applications due to their high granularity, low material budget, and low power consumption. Additionally, their fabrications using standard CMOS production processes from commercial foundries ensure lower costs and higher production yields. However, their radiation tolerance in dense collision environments remains a critical area of investigations.

The MALTA series of sensors, based on Depleted Monolithic Active Pixel Sensor (DMAPS), are designed to fulfill the requirements for the future collider experiments. They initially target radiation tolerance levels of 100 MRad for Total Ionizing Does (TID) and $> 10^{15}$ 1 MeV n_{eq}/cm^2 for Non-Ionising Energy Loss (NIEL), which are required by the outer pixel barrel of ATLAS ITk [3]. A critical challenge for these sensors is mitigating signal degradation caused by a reduced active region and charge trapping under such high fluence conditions. To investigate these radiation-induced effects on DMAPS pixels, a grazing angle technique [4] was performed on MALTA2 samples both before and after irradiation at a fluence of 1×10^{15} 1 MeV n_{eq}/cm^2, using the CERN Super Proton Synchrotron (SPS) 180 GeV/c hadron beam. The detection efficiency and cluster size as functions of the inclined angles are presented, along with an estimation of the active depth of the depleted region for an irradiated MALTA2 sensor.

2 MALTA2

MALTA2 is the second-generation sensor of the MALTA series, featuring optimizations to reduce Random Telegraph Signal (RTS) noise, thereby enabling an operational threshold of approximately 100 e^- [5, 6]. The sensor is fabricated using a Tower 180 nm CMOS imaging process, modified with an additional low dose N-type implant [7]. It features a matrix of 512×224 pixels within a total area of $1.8 \times 0.9\,cm^2$. The pixel pitch is $36.4 \times 36.4\,\mu m^2$, and the sensor thickness is available in 50 µm, 100 µm and 300 µm. The sensors are produced on two types of high-resistivity (> 1 kΩcm) p-type substrate: an epitaxial layer (EPI) and a Czochralski (Cz) bulk. The latter is optional for larger reverse substrate voltages (V_{sub}), yielding a larger depleted region and better radiation tolerance [8].

MALTA2 employs a small collection electrode design measuring $3 \times 3\ \mu\text{m}^2$, resulting in minimal capacitance (< 5 fF), low noise level (< $5\,e^-$) and low power consumption (~ 1 µW/pixel). To enhance the charge collection when the signal charge is generated at the pixel corners, two additional process modifications have been introduced in MALTA2: a gap in the low dose N-type implant (NGAP) at the pixel edge or an extra P-type implant at the same location (XDPW). Both modifications improve the charge collection and thus the detection efficiency [9]. The chip features an asynchronous read-out scheme that avoids propagating a clock signal throughout the pixel matrix, further reducing the power consumption from the digital part. The hit information is transmitted from the in-pixel circuit to the periphery, according to a sequence of short pulses, when a particle transverses the sensor. In this work, Cz sensors with a thickness of 100 µm and XDPW modification were characterized with test beam for performance analysis.

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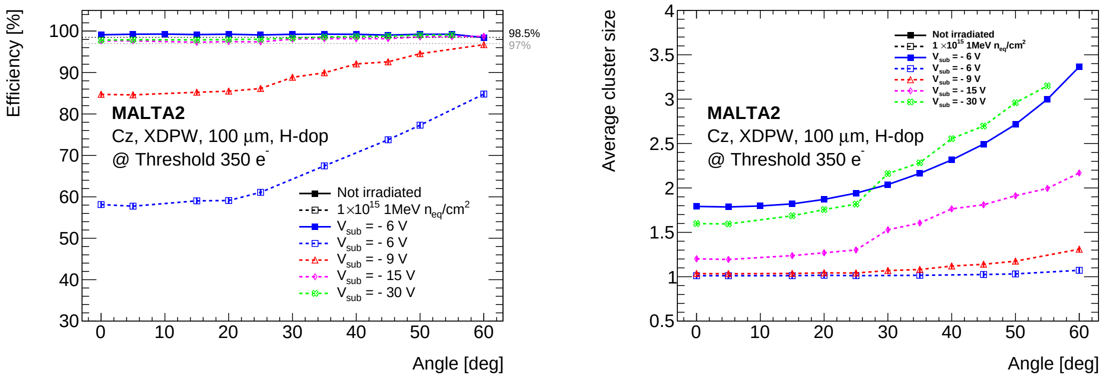
3 The MALTA telescope

The MALTA telescope [10], developed for characterizing pixel detector prototypes, is permanently installed at H6 beam line in the North Area of SPS at CERN. During the MALTA2 test beam campaign in 2023–2024, mixed hadron beams with a momentum of approximately 180 GeV/c were delivered.

The telescope comprises six reference planes employing MALTA chips. A scintillator, placed behind reference planes, provides a precise time reference. The trigger system is fully configurable, which enables triggering on coincidence between the scintillator and the telescope planes. A cold box, which can contain up to two Devices Under Test (DUT), is positioned between the innermost reference planes. The corresponding cooling system provides a temperature down to -15 °C and keeps relative humidity below 1%. In addition, a rotational stage is responsible for the inclination of the DUT from -60° to 60° along the vertical axis with respect to the beam line. The spatial resolution of the telescope, extracted from the residual between the tracking intercept and the fastest hit of the closest cluster reconstructed of a DUT, is better than 5 µm.

4 Grazing angle study

Two MALTA2 chips, one unirradiated and the other irradiated to a fluence of 1×10^{15} 1 MeV $\text{n}_{\text{eq}}/\text{cm}^2$, underwent the grazing angle technique. In the measurement, DUTs were rotated from 0° to 60° in 5° steps, relative to the particle track. The average detection efficiency and the average cluster size, before and after irradiation, as functions of rotational angles are depicted in figure 1. Before irradiation, a full efficiency greater than 98.5% was achieved, at V_{sub} of 6 V and with an operating threshold around $350\,e^-$, regardless of the angles, indicating a sufficient active region and effective charge collection. For the irradiated sample, a marked reduction in efficiency is observed at 0°, indicating charge collection loss due to a reduced active region and charge trapping. As the rotational angle exceeds 30°, the detection efficiency significantly recovers, attributed to the extended charge trajectory within the active region, enabling the collection of more signal charge. The average cluster size remains 1 across various rotational angles, showing suppressed charge sharing due to the reduced electric field at the pixel corners. To mitigate these degradations, the irradiated sensor is operated at larger V_{sub} (up to 30 V). As shown in figure 1(a), the average efficiency significantly recovers with increasing V_{sub}, approaching a level comparable to that before irradiation when the voltage exceeds 15 V. Similarly,



(a) (b)

Figure 1. (a) Average efficiency and (b) average cluster size of irradiated and unirradiated MALTA2 samples as a function of incidence angle between the beam and the sensor. V_{sub} is set at 6 V (6, 9, 15 and 30 V for irradiated sample) and the p-well is reversely biasd at 6 V. The operating threshold is around 350 e^-.

the recovery of the average cluster size, shown in figure 1(b), suggests an expanded active region and enhanced charge sharing due to an improved electric field at the pixel corners at larger V_{sub}.

Additionally, the active depth, taking the irradiated sensor as an example, is estimated according to the grazing angle measurement results. As illustrated in figure 2, the geometrical relationship between the active depth and the cluster size can be described as

$$\text{Cluster size}_{\perp}(\alpha) = \frac{D}{P}\tan(\alpha) + \text{Cluster size}_{\perp}(0), \text{[1]} \tag{4.1}$$

where P is the pixel pitch, α is the rotational angle, Cluster $\text{size}_{\perp}(0)$ and Cluster $\text{size}_{\perp}(\alpha)$ are the cluster sizes in the direction perpendicular to the rotational axis at angles of 0 and α respectively, and D is the assumed active depth. This method has been applied to measurements of unirradiated MALTA2 EPI sensors [11], yielding an active depth comparable to that obtained from Edge Transient Current Technique (E-TCT) measurements.

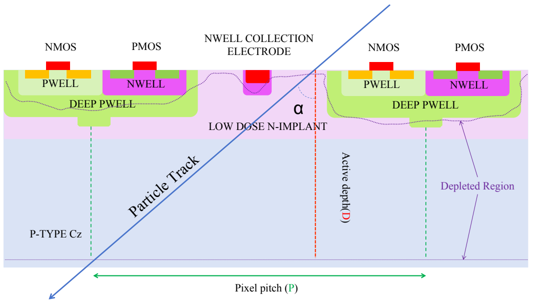


Figure 2. Illustration of the cross section of MALTA2 sensor and the grazing angle measurement method.

Shown in figure 3 are the residuals of the cluster size projected in the direction perpendicular to the rotational axis[2] at angles α and 0 degrees, plotted as functions of the tangent of α. Excellent

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[1] This formula is purely geometrical, assuming ideal efficiency within the depleted region and no contribution from external regions.

[2] Cluster size in the direction parallel to the rotational axis stays constant.

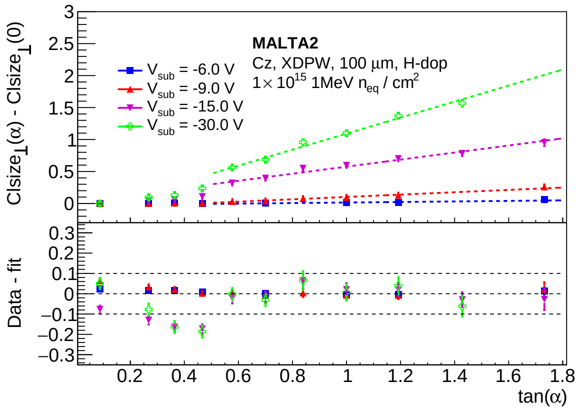

Figure 3. The linear fit of cluster $\text{size}_\perp$ residuals as a function of the tangent of the grazing angles. The sample is irradiated to 1×10^{15} 1MeV $\text{n}_\text{eq}/\text{cm}^2$ with V_sub set at 6 V, 9 V, 15 V and 30 V, and an operating threshold around $350\,\text{e}^-$.

linearities are observed when $\tan(\alpha)$ exceeds 0.5. However, they break down at lower angular regions where charge diffusion dominates the cluster formation process. Thus, a linar fit is performed on each data set, and the active depth *D* is extracted from the slope of the fitting function according to eq. (4.1). This technique becomes ineffective at V_sub of 6 V due to significant suppression of charge sharing between pixels. The estimated active depth increases with V_sub, and an approximation of 40 μm is obtained at V_sub of 30 V. The estimation is highly dependent on the threshold configuration, which significantly impacts the clustering process. Therefore, direct investigations via E-TCT are needed for further varifications.

5 Conclusion

MALTA2 is a full-scale DMAPS prototype of the MALTA project. Its detection performance, including detection efficiency and cluster size, before and after irradiation to a fluence of 1×10^{15} 1 MeV $\text{n}_\text{eq}/\text{cm}^2$, has been characterized with the grazing angle technique. Significant performance degradations were observed after irradiation, indicating a reduced active region and decreased electric field at the pixel corners. To mitigate these effects, the irradiated sensor is operated under larger V_sub, achieving an average detection efficiency of 97%, comparable to that obtained before irradiation. In addition, an approxmation of 40 μm for the active depth is obtained at V_sub of 30 V, with a threshold of around $350\,\text{e}^-$.

The conducted study provides important insights into sensor performance and radiation hardness, demonstrating the potential of MALTA2 for future collider experiment applications. Further investigations, through E-TCT, are planned to measure the active depth and verify the estimations made using the grazing angle technique.

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