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Test beam results of a depleted monolithic active pixel sensor using an HV-SOI process for the LH-LHC upgrade

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ABSTRACT: A Depleted Monolithic Active Pixel Sensor (DMAPS) on thick film SOI technology is being extensively investigated as a possible candidate for the outer layers of the ATLAS Inner Tracker in the HL-LHC upgrade. Its radiation hardness to TID (Total Ionizing Dose) and the absence of back gate effect for a dose of up to 700 Mrad was proven. Its charge collection properties have been characterized with radioactive sources and with eTCT (edge Transient Current Technique) measurements for both, unirradiated and irradiated devices. This article presents the first test beam results on this DMAPS on thick film SOI technology. The charge collection properties, charge sharing between pixel cells, spatial resolution and tracking efficiency are presented as a function of the applied bias voltage and different selection criteria.

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

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1 Introduction

The Large Hadron Collider (LHC) plans to operate with an instantaneous luminosity five times higher than its original design value reaching up to \( L = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) during the High Luminosity LHC (HL-LHC) [1]. To cope with the expected high hit occupancies, increased data rates, and the harsh radiation environment, the ATLAS detector plans to fully replace its Inner Detector [2]. The ATLAS CMOS collaboration is seeking new detector concepts based on commercial high voltage and/or high resistivity CMOS processes [3] as an option for the Inner Tracker (ITk) pixel layers. Depleted Monolithic Active Pixel Sensors (DMAPS) [4, 5] have also been investigated in the last years.

The DMAPS prototype on thick film Silicon-On-Insulator (SOI) technology presented in this article is an attractive detector concept to address the needs for the outer pixel layers. Accomplishing the ATLAS requirements by a monolithic detector would lead to a new era of the HEP detectors. A full validation programme of the technology and the fabricated monolithic pixel sensors is being carried out to evaluate its performance. Its radiation hardness to Total Ionizing Dose (TID) and the absence of back gate effect for a dose up to 700 Mrad has been measured and published [6]. Its charge collection properties have been characterized with radioactive sources and with edge Transient Current Technique (eTCT) measurements for both, un-irradiated and irradiated devices [7]. Test beam measurements have been performed for the first time with the additional challenge that a single 50\( \mu \text{m} \times 50\mu \text{m} \) pixel was readout. Charge collection properties, charge sharing, spatial resolution and tracking efficiency results are presented in this article.
2 DMAPS HV-SOI: XTB01 prototype

The Device Under Test (DUT) is a DMAPS built on a thick film SOI CMOS technology using the XFAB 180 nm process [8]. The Buried Oxide (BOX) isolates the full CMOS electronics technology from the substrate, which is reversely biased and used as a sensor diode. In contrast to other SOI technologies, XFAB provides a double well structure to shield the thin gate oxide transistors from the BOX. The transistor’s bulk silicon is partially depleted (PD). This makes the technology promising against the radiation effects on the transistors and against the back gate effect observed in other SOI technologies [9, 10]. The process makes it possible to apply high bias voltages (up to 300 V), which are used to partially deplete the substrate. It is possible to fabricate devices in higher resistivity material (1 kΩ · cm). Therefore, a fully depleted substrate could be achieved after thinning. Currently, no backside processing is used, so the HV is applied from the top using a $p^+$ implant ring. Additional grids surrounding each pixel to bias the sensor are also included.

The first prototype fabricated, called XTB01, is 300 µm thick with a size of 5 mm × 2 mm. The substrate is p-type silicon with 100 Ω cm resistivity. The HV is applied from an outer guard ring, and in addition the chip includes additional grids surrounding each pixel. The HV can be applied through these grids, too. All measurements presented in this paper were performed on a 50 µm × 50 µm pixel. The charge is collected in a small deep n-well with a size of 10.5 µm × 14 µm, which reduces the capacitance with respect to other high voltage CMOS approaches, where a large n-well is used as charge collecting electrode [11]. The deep n-well for the XTB01 is connected to the readout circuitry as illustrated in the pixel cross section shown in figure 1. For a first prototype, a standard 3T pixel readout circuit [4] is implemented in each pixel. A detailed description of the chip has been described in several publications [6, 7, 12].

3 Test beam instrumentation

Beam tests are crucial for performance characterization and optimization of any particle detector. XTB01 (unirradiated device) was placed in a test beam for the first time during 2014 and 2015, where a single 50 µm × 50 µm pixel was monitored and readout. The data presented in this article were recorded in 2015 at the CERN SPS North Area beam line H6 with a beam energy of 120 GeV $\pi^+$. The high momentum of the beam particles minimizes the effect of multiple scattering, which is a prerequisite for high-precision tracking measurements. The trajectories of the beam particles were reconstructed using the AIDA SBM FE-I4 telescope.
Figure 2. (a) Photo of the AIDA SBM FE-I4 Telescope. (b) Schematic top view of the AIDA SBM FE-I4 testbeam setup.

Figure 3. AIDA SBM FE-I4 (a) external trigger through the PMTs (b) internal trigger through the Hitbus chip.

3.1 AIDA SBM FE-I4 telescope

The AIDA SBM FE-I4 telescope mechanics are rather compact with a size of 60 cm × 20 cm × 20 cm and a weight of 4 kg. It is composed of two telescope arms, which are movable along the $z$ and $y$ axes as shown in figure 2(a). The space between the arms is used to place the DUT and the maximum space between the arms is 400 mm. The telescope is equipped with six single-chip FE-I4B silicon planar sensors [13], three per telescope arm, with a 250 × 50 µm pitch in the $x$ and $y$ directions respectively, and an active area of ~ 2 × 2 cm$^2$. Every second plane is rotated by 90° along the $z$ axis in order to achieve ~ 8 µm resolution in both directions. In addition, every plane can be tilted by 0°, 15° and 30° along the $y$ axis in order to increase the cluster size, and therefore the hit efficiency and position resolution. Figure 2(b) shows a sketch of the configuration of the telescope planes during data taking, where the indicated planes were tilted by 15°.

The AIDA SBM FE-I4 telescope triggering block diagram is sketched in figure 3. The telescope trigger can be applied externally as in other telescopes through external Photo Multipliers (PMTs), or internally, as a novel technique, through the Hitbus chip which provides online track Region-of-Interest (ROI) triggering. The Hitbus chip handles the HitOr trigger functionality of the FE-I4 planes. There are two Hitbus chips, one per arm, so that simultaneously hits can be requested in all six telescope planes.

The AIDA SBM FE-I4 telescope readout consists of two Reconfigurable Cluster Element (RCE) systems, and one High Speed Input Output (HSIO) board. The RCE software was modified to incorporate the Hitbus triggering. Currently the analysis is performed using the Judith software but
converters to the EUTelescope [14] file format are available.

The DUT readout system is explained in detail in section 3.2. A DUT with digital output can be considered as an extra plane of the telescope and be readout using the RCE system, which would internally synchronize the telescope and DUT data. On the other hand, a DUT with analogue output is readout by an additional analogue readout system. In this case, a combination of the one directional online synchronization shown in figure 3(b) and offline synchronization is used to synchronize the data, typically using timestamps.

3.2 XTB01 analogue readout

The analogue output of the 50\(\mu\)m \(\times\) 50\(\mu\)m single pixel was sent to the DRS4 board [15] which provides basically the same functionalities as a high speed oscilloscope. The DRS4 interface during data taking is illustrated in figure 4 where the coincidence between signal hit and telescope trigger indicates that a Minimum Ionizing Particle (MIP) has been detected. Only the Hitbus chip corresponding to telescope arm 1 was operative, requiring a hit to be detected in all three planes. The reset periods, which clear accumulated charge from the DUT to avoid saturation, are vetoed because the DUT cannot be readout. As a consequence, only a particle detected in all three planes outside the reset periods generates a trigger to be sent to the DRS4. If the DRS4 is not busy, an acknowledge signal is sent back to the telescope and both, telescope and DRS4 record the event. The data saved by the DRS4 for each event are waveform, reset waveform, event number and timestamp. An offline analysis was developed in order to distinguish the waveforms containing a DUT hit and the waveforms without a DUT hit. Additionally, the collected charge, hit detection time and charge collection time are extracted. First the algorithm smooths the raw data without reducing the number of points. Then, it checks for resets within the output signal as shown in figure 5(a) (in such a case the reset is deleted). At that point, the analyser proceeds and a selection on the slew rate needs to be passed in order to be processed further. In case a hit is detected as shown in figure 5(b), the collected charge, its collection time, and hit detection time are obtained from the fit parameters of the following fit function:

\[
\begin{align*}
    t \leq t_0 & \quad f = a + m \cdot (t - t_0) \\
    t > t_0 & \quad f = a + m \cdot (t - t_0) + b \cdot \left( e^{\frac{t-t_0}{\tau}} - 1 \right)
\end{align*}
\] (3.1)
where $b$ is the collected charge, $c$ is the charge collection time and $t_0$ is the hit detection time. If the slew rate cut is not passed, the waveform just contains the charge accumulated due to the leakage current. Those cases are used to calculate the electronic noise, which is given by the RMS of the Gaussian distribution of the leakage current centred at zero. The unirradiated device was characterized for a bias voltage of 60 V, 90 V and 120 V.

4 Charge collection and charge sharing

The collected charge and the noise during the beam tests have been measured. Figure 6(a) shows the signal and noise distribution for a single run with 150,000 events at a bias voltage of 120 V. The Landau distributed signal is very well separated from the Gaussian noise, leading to a Signal-to-Noise Ratio (SNR) of 22, which is comparable to the SNR of other HV/HR CMOS devices [11]. The signal size threshold used to define a DUT hit was 0.0012 V. Figure 6(b) shows the Most Probable Value (MPV) for the collected signal size as a function of the applied bias voltage. The DRS4 functionality did not allow the sample calibration with an $^{55}$Fe source, thus all results regarding charge are given in signal size, and expressed in units of volts as shown in both figures. The signal size grows linearly with the square root of the bias voltage, in agreement with previous laboratory measurements [7] and theoretical expectations.

Charge sharing is another important feature of pixel detectors as it is directly related to tracking resolution and radiation hardness. The generated electron cloud of a track going through the sensor increases its volume due to diffusion while drifting to the collecting electrode in an electrical field. As a consequence, the electron cloud can be collected by two or more pixel cells, leading to the charge sharing effect. On the one hand, high charge sharing results in better tracking resolution as the track position can be interpolated between the pixels using charge weighting if the signal size information is available per pixel. On the other hand, less signal will be available to each pixel cell, which may become a problem especially for irradiated devices where the signal decreases due to trapping effects. The charge sharing effect is observed in the XTB01 prototype as shown in figure 7. Figure 7(a) shows a 2D map of the MPV signal of the DUT at different positions within the pixel with a bias voltage of 120 V. The inner part of the pixel ($-20 \mu m \leq xy \leq 20 \mu m$) collects signals

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Figure 5. Offline waveform analysis on a $50 \mu m \times 50 \mu m$ pixel at a bias voltage of 120 V (a) Signal Size [V] of the DUT hit before smoothing (b) hit fitted to the function described in equation 3.1 to extract the collected charge, hit detection time and charge collection time.
Figure 6. (a) Signal over noise at an applied bias voltage of 120 V taken on a single run. The SNR is 22 for the threshold of 0.0012 V used during the measurement. (b) Most Probable Signal as a function of the different bias voltages applied during the test beam measurements with the width of the distributions shown in the vertical bars.

Figure 7. The (a) 2D map showing the MPV signal size as a function of the xy position within the pixel for an applied bias voltage of 120 V. The (b) MPV as a function of the x position within the pixel for 60 V, 90 V and 120 V.

above 0.006 V, whereas the outer part of the pixel collects signals below 0.005 V due to the charge sharing effect. Figure 7(b) shows the MPV as a function of the x position for all bias voltages, where the same conclusion is underlined for all the applied voltages.

5 Spatial resolution

The spatial resolution is a fundamental feature of pixel detectors, which is determined by the pixel pitch. However, the choice of the readout mode, the reconstruction algorithm, and the amount of charge sharing also play a role [16]. For a single pixel the spatial resolution is expected to be equal to the pixel pitch divided by the square root of twelve. The spatial resolution in a test beam is obtained through the hit track residuals.

Two different selection criteria are investigated to obtain the hit track residuals. These are the charge collection time (CCT) over the collected charge and the hit detection time ($t_0$). These parameters are obtained during the reconstruction and provide two possible selection criteria to
Figure 8. (a) Selection on the slew rate, which only considers hits collected fast for the analysis (b) Selection on the $t_0$, which only considers hits detected within 500-700 ns interval.

Figure 9. Track Residual for a bias voltage of 120 V with and without applying the $T_0$ cut (a) in the $x$ direction (b) in the $y$ direction.

improve the purity of real DUT hits. Figure 8(a) shows the CCT distribution versus the collected charge for all collected hits. The applied selection consists of selecting on the CCT over collected charge, considering only the hits below the black line for the analysis, with the aim to select the charges collected by drift and not those collected by diffusion. This selection was also applied for the analysis of the radioactive source measurements with the details given in [7]. Figure 8(b) shows the $t_0$ distribution for all collected hits. The applied selection consists of excluding from the analysis the hits collected outside the 500-700 ns interval as depicted in figure 8(b). As the trigger is applied externally, $t_0$ should be constant at around a certain value, set to 600 ns. Both selections produce the same effect on the analysis result, implying that the hits collected slower due to the diffusion component, are related with a delay in the hit detection time. Therefore, all results shown later in this article include the $t_0$ cut on the DUT hits.

Figure 9 shows the track residuals at a bias voltage of 120 V in the $x$ and $y$ planes with and without applying the $T_0$ cut. It is observed that the $T_0$ cut removes almost all hits with a residual larger than 100 $\mu$m. The spatial resolution after the cut is around 17 $\mu$m in comparison with the 14.4 $\mu$m expected using the pixel pitch calculation. The measured value is limited by the telescope resolution ($\sim 8 \, \mu$m), which adds in quadrature with the pixel resolution. Taking that into account, the spatial pixel resolution is around 15 $\mu$m.
6 Tracking efficiency

The hit detection efficiency is another fundamental characteristic of pixel detectors. The tracking efficiency is computed as the ratio of the reconstructed telescope tracks extrapolated to within the DUT pixel pitch and the DUT hits. Figure 10(a), 10(b), and 10(c) show the computed efficiency of the tested XTB01 with the \( t_0 \) cut applied, at a bias voltage of 60 V, 90 V and 120 V, respectively. By assuming that the XTB01 pixel is symmetric in square frames, one can add the hits over a larger area to reduce statistical variations on the XTB01 hit efficiency. It is observed that the inner and outer pixel efficiencies grow with the bias voltage, approximating the pixel size for the highest voltage. A simulation was used to compute corrections to the efficiency coming from the finite position resolution of the telescope tracks. Systematic uncertainties on these corrections are computed by varying the telescope resolution up and down by 1 µm. As a consequence, a correction factor was applied to all further results presented here. In addition, the track efficiency as a function of the bias voltage has been computed for the central 20% and central 80% of the pixel with the \( t_0 \) cut applied in figure 10(d). The tracking efficiency at the central 80% of the pixel is \( 99.6^{\pm 0.6}\% \) (tot) at a bias voltage of 120 V. The efficiency results were calculated together with its total error calculated as the quadratic sum of systematic and statistical error. The statistical error is negligible in comparison with the alignment uncertainty computed in the systematic error.

To investigate the tracking efficiency as a function of the direction, the tracking efficiency was projected for the \( x \) and \( y \) directions with \( t_0 \) cut applied and for a bias of 120 V as shown in figure 11. Figure 11(a) shows the track efficiency projected in the \( x \) direction at with \( -10 \mu m \leq y \leq 10 \mu m \), whereas figure 11(b) shows the projection in the \( y \) direction with \( -10 \mu m \leq x \leq 10 \mu m \). The width of the efficiency plateau corresponds to \( \sim 14 \mu m \) and \( \sim 20 \mu m \) in the \( x \) and \( y \) direction, respectively. The given absolute numbers are not so important but rather the difference between the \( x \) and \( y \) directions. This fits with the fact that the n-well electrode is not square, and one would expect a higher efficiency in the longer n-well size direction as observed here.

7 Summary

The XFAB thick film SOI technology is extensively investigated on fully monolithic prototype for the HL-LHC. The first test beam results on unirradiated devices have brought out interesting results. Regarding the collected charge, the measured SNR=22 is comparable to other HV/HR-CMOS devices, and the signal size MPV grows linearly as a function of the square root of the voltage, as expected. At the edge of the pixel, about 30% of the deposited charge is shared with the neighbouring pixels. The measured spatial resolution is about 15 µm in comparison with the 14 µm one would expect from the pixel pitch formula. Simulations were carried out to correct the DUT efficiency for telescope tracks not intersecting the DUT due to finite telescope resolution. The computed efficiency at the central 80% of the pixel taking into account those corrections is \( 99.6^{\pm 0.6}\% \) (tot) at a bias voltage of 120 V.

In conclusion, the presented test beam results confirm excellent charge collection properties observed with radioactive sources and eTCT. The device is 99.6% efficient at the central 80% of the pixel before irradiation, and test beam campaigns with irradiated devices will be performed in the coming months.
**Figure 10.** Tracking efficiency in a 50µm × 50µm pixel with no cuts on the DUT hits. The DUT efficiency is computed in rings to increase the statistics for bias voltages of (a) 60 V (b) 90 V and (c) 120 V. The DUT hit efficiency (d) is shown as a function of the bias voltage for different pixel regions with the $t_0$ cut applied.

**Figure 11.** Projected efficiency at a bias voltage of 120 V with cut $t_0$ applied (a) in the x direction (b) in the y direction. The fitted Gaussian resolution ($\sigma$) of the telescope is shown for both the x and y directions.

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