Performance of Edgeless Silicon Pixel Sensors on p-type substrate for the ATLAS High-Luminosity Upgrade

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Abstract—In view of the LHC upgrade phases towards the High Luminosity LHC (HL-LHC), the ATLAS experiment plans to upgrade the Inner Detector with an all-silicon system. The n-on-p silicon technology is a promising candidate to achieve a large area instrumented with pixel sensors, since it is radiation hard and cost effective.

The paper reports on the performance of novel n-on-p edgeless planar pixel sensors produced by FBK-CMM, making use of the active trench for the reduction of the dead area at the periphery of the device. After discussing the sensor technology an overview of the first beam test results will be given.

Index Terms—Silicon pixel sensors, edgeless sensors, radiation detectors, HL-LHC tracker

I. INTRODUCTION

THE ATLAS collaboration will upgrade the current Pixel Detector [1] in two phases. A first upgrade has already been realised during the shut-down in 2013-14, by inserting a fourth detection layer (Insertable B-Layer - IBL [2]) at a radius of 3.2 cm from the beam line. Beyond 2023, the Phase-II luminosity upgrade for the LHC, aims to increase the instantaneous luminosity to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, posing a serious challenge to the technology for the ATLAS tracker in the High Luminosity era (HL-LHC): the lifetime fluence for the innermost layer, including safety factors, is estimated to be on the order of $2 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ [3]. Hence, in view of a possible pixel system replacement after 2023, new pixel sensors are under study. Within the Planar Pixel Sensor collaboration (PPS) [4] several optimizations of the well-known silicon planar technology are under investigation.

The new pixel sensors will not only have to sustain the harsher environment, but also have to show high geometrical acceptance without overlapping adjacent modules. Hence the inactive area has to be reduced significantly. One way to reduce or even eliminate the insensitive region along the device periphery is offered by the “active edge” technique [5], in which a deep vertical trench is etched along the device periphery throughout the entire wafer thickness, thus performing a damage free cut (this requires using a support wafer, to prevent the individual chips from getting loose). The trench is then heavily doped, extending the ohmic back-contact to the lateral sides of the device: the depletion region can then extend to the edge without causing a large current increase.

The active edge technology has been chosen for a first production of n-on-p planar sensors at FBK. Studies performed with TCAD simulation tools helped in defining the layout and making a first estimation of the charge collection efficiency expected after irradiation [6].

In this paper an overview of the performance of novel edgeless silicon n-on-p planar pixel sensors fabricated at FBK-CMM [6] is presented. The sensors have been produced on 4” wafer of high resistivity Float zone (Fz) material, with a thickness of 200 $\mu\text{m}$, by making use of the active trench concept [5]. This technology requires a single-sided process, featuring a doped trench, extending all the way through the wafer, and completely surrounding the sensor (see Fig. 1). The presence of a support wafer was then required.

Fig. 1. Sketch of the pixel sensor (edge region).

The wafer layout contains nine ATLAS FE-I4 [7] compatible...
pixel sensors with different number of guard-rings - GRs - (0, 1, 2, 3, 5 and 10) and different pixel-to-trench distances (100, 200, 300 and 400 $\mu$m) in order to evaluate the best sensor configuration (see Table I). In addition, several test-structures have been also implemented to study the electrical behaviour of an even larger number of GRs and pixel to trench distances combination.

| # of GRs | pixel-to-trench distance ($\mu$m) |
|----------|----------------------------------|
| 0        | 100                              |
| 1        | 100                              |
| 2        | 100                              |
| 3        | 200                              |
| 5        | 300                              |
| 10       | 400                              |

In Figure 2 the edge area of a test structure is reported; this test structure featured FE-I4-like pixels. The black line surrounding the pixels’ electrodes is the doped trench; the distance between the trench and the pixels’ electrodes is 100 $\mu$m, and, as it can be seen, there are no guard-rings.

Since some sensors were to be bump-bonded to FE-I4 readout chips, it was necessary to select good sensors at the wafer level, by measuring their I-V characteristics. For this purpose, an additional layer of metal was deposited over the passivation and patterned into stripes, each of them shorting together a row of pixels, contacted through the small passivation openings foreseen for the bump bonding. This solution has already been adopted for the selection of good 3D FE-I4 sensors for the ATLAS IBL [8]. After the automatic current-voltage measurement on each FE-I4 sensor, the metal was removed by wet etching, which does not affect the electrical characteristics of the devices.

In Figure 3 a sensor before and after the temporary metal removal is reported.

II. 2015 DESY TESTBEAM RESULTS

In March 2015 one FE-I4 pixel module was tested on beam at DESY [9]. The module has been realized by bump-bonding one FE-I4B [7] readout chip and one active edge pixel sensor from our n-on-p production; the sensor had 100 $\mu$m pixel-to-trench distance and no GRs; it can be said that for what concerns the edge region this sensors looked as the one in Figure 2. In what follows this pixel module under test will be referred to as LPNHE5.

In DESY the measurements were performed on beamline 21 [9]. Electrons of 4 GeV/c momentum where impinging normally to our LPNHE5 module surface. The LPNHE5 device under test (DUT) was placed between the two arms of the DATURA beam telescope [10].

Several configurations were tested, including different bias voltage values for the DUT and different threshold values for the FEI4 readout chip; data were recorded too when the normal to the DUT was making an angle of 15° with respect to the beam axis. All measurements were performed at room temperature.

In Figure 4 a picture of the setup.

A trigger signal was generated by the coincidence of 2 scintillators pairs, one upstream and one downstream of the telescope. The data acquisition rate was limited to $\sim$ 250 Hz by some data acquisition problems.

Data were reconstructed using the eutelescope/eudaq software [11] and analysed with the tbmon2 package [12]. Tracks were built from clusters of hits in the telescope planes. An iterative alignment fit procedure, followed by a tracks fit step allowed to obtain a pointing resolution of about 3 $\mu$m, thanks also to the telescope planes pixel sensor small pitch.
Fig. 4. DESY testbeam setup. Two FE-I4 pixel modules (on the right) were put between the two EUDET/Aida telescope arms; the first two planes of the downstream arm can be seen on the left. Beam was coming from the right.

Fig. 5. Charge in clusters as a function of different threshold and bias voltage. Once a set of good tracks was defined, the clusters properties, the hit-efficiency and the spatial resolution of the LPNHE5 DUT were studied.

A. Cluster properties

Clusters were formed by grouping neighboring pixels that fired in time with tracks registered by telescope. For tracks at normal incidence about 20% of the clusters were composed by more than one pixel; for tracks at 15° more than 60% of the clusters were composed by two or more pixels. In Figure 5 the cluster charge, measured as Time-over-Threshold (ToT), is shown. As expected, lower threshold and higher bias voltage gives the cluster more charge.

\[ \sim 18\mu\text{m} \] \[1\]

Once a set of good tracks was defined, the clusters properties, the hit-efficiency and the spatial resolution of the LPNHE5 DUT were studied.

B. Hit-efficiency

The LPNHE5 hit-efficiency performance has been studied by looking at hits on the DUT close to the extrapolated track impact position. Table II reports the hit efficiency for the different tested configuration.

| bias (V) | threshold (ke) | efficiency (%) |
|---------|---------------|----------------|
| 30      | 2.0           | 98.4           |
| 40      | 2.0           | 98.7           |
| 40      | 1.6           | 99.1           |

TABLE II

Hit-efficiency for LPNHE5 as a function of bias voltage and threshold.

The hit efficiency is always above 98%; it is better than 99% for the best configuration (40 V bias voltage and 1.6 ke threshold). This is a remarkable result: even at moderate bias voltage the detector is full efficient.

In Figure 6 the so-called “in-pixel” hit efficiency is shown for 40 V bias voltage and 1.6 ke threshold. All the pixels have been superimposed in order to study the hit-efficiency as a function of the track impact point.

As it can be seen the efficiency is very uniform across the pixel cell, above 95% everywhere. The fact that after the temporary metal removal there were no biasing structures left made the cell very effective everywhere. A small less efficient region is visible at the corners of the cell; this is due to charge sharing with the neighbouring cells.

To completely validate the active edge approach the hit-efficiency at the sensor edge had to be measured. The results

\[ ^1 \text{The depletion voltage was 20 V.} \]

\[ ^2 \text{hit efficiency errors are negligible} \]
are shown in Figure 8. The efficiency is measured as a function of the track impact point for the row of pixels closest to the trench. Points with abscissa lower than 0 correspond to tracks passing in the volume within the pixels and the trench. It can be seen that the hit-efficiency is still above 90% for all configurations even 40 µm away from the last pixel implant 3. This result represents the validation of the active edge approach: the un-instrumented volume is active and highly efficient.

### C. Spatial resolution

To evaluate the spatial resolution of the LPNHE5 module the hit-residuals, defined as the reconstructed hit position minus the track impact position, were studied. The hit-residual distributions for the long (250 µm) and short (50 µm) pixel directions are presented in Figure 9. The analysis is strongly limited by the multiple scattering effect, estimated to be of the order of 30 µm. The RMS values of the hit-residual distributions for the long and short pixel directions are ∼ 80µm and ∼ 34µm, respectively; the results are consistent with the expectations.

### III. CONCLUSIONS

In this paper we reported the performance of thin n-on-p pixels aimed at the HL-LHC phase of ATLAS. These pixels are characterized by their reduced un-instrumented area at the detector periphery. This was possible thanks to the active edge technology.

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3 there are no usable tracks beyond -50 µm

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