Characterization and Beam Tests
Results of Non-Uniformly Irradiated 3D Pixel Sensors for HEP Experiments

Lopez, I (IFAE) et al

23 June 2013

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025.

This work is part of AIDA Work Package 9: Advanced infrastructures for detector R&D.

The electronic version of this AIDA Publication is available via the AIDA web site <http://cern.ch/aida> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=AIDA-CONF-2015-005>
Characterization and Beam Tests Results of Non-Uniformly Irradiated 3D Pixel Sensors for HEP Experiments

I. Lopez, S. Grinstein, A. Micelli and S. Tsiskaridze

Abstract—3D Pixel detectors, with cylindrical electrodes that penetrate the silicon substrate, offer advantages over standard planar sensors in terms of radiation hardness, since the charge collection distance can be reduced independently of the bulk thickness. In the framework of the ATLAS Forward Physics (AFP) program, work has been carried out to study the suitability of 3D pixel devices for forward proton tracking.

The AFP tracker unit will consist of an array of five pixel sensors placed at 2-3 mm from the Large Hadron Collider (LHC) proton beam. The proximity to the beam is essential for the AFP physics program as it directly increases the sensitivity of the experiment. Thus, there are two critical requirements for the AFP pixel detector. First, the dead region of the sensor has to be minimized. Second, the device has to be able to cope with a very inhomogeneous radiation distribution. Recent results of the characterization and beam test studies of in-homogeneously irradiated 3D pixel sensors produced at CNM-Barcelona will be presented.

Index Terms—pixel detectors, 3D pixels, radiation hardness, high energy physics.

I. INTRODUCTION

ATLAS [1] plans to install a Forward Physics detector (AFP) during the second shut-down of the Large Hadron Collider in 2018. The new AFP detector will be located at ≃210 m from the ATLAS interaction point. Its tracker will consist of five silicon pixel sensors placed at 2-3 mm from the proton beam [2]. This upgrade will allow the measurement of pp diffractive events at very small scattering angles which will enable QCD measurements (like double pomeron exchange in jet, Z and W channels) and searches for anomalous couplings (between γ, W or Z bosons) which include predictions beyond the Standard Model.

The proximity to the beam requires sensors able to operate after a very inhomogeneous radiation distribution, and the need to reduce the dead region in the sensor. Indeed, it has been estimated that the most radiated region of the sensors will receive doses of the order of $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$, while in the opposite side, the estimated dose is orders of magnitude lower [3].

During the current LHC shutdown (2013-2014), ATLAS is installing a new layer of pixel sensors at the innermost part of the ATLAS’ Inner Detector, called Insrtatable B-Layer (IBL), consisting of 14 staves of silicon detectors mounted on a new beam pipe. However, the IBL will include planar and 3D sensors [4]. Given the excellent radiation hardness performance of the 3D sensor and their moderate requirements in terms of operational bias voltage ($\sim 160$ V) and cooling after irradiation, AFP selected the 3D technology for the tracker detector. The IBL sensors have a large non-operational area on the opposite side of the wirebonding region. Therefore, different dicing techniques were investigated in order to reduce the dead region of the 3D sensors. As already mentioned, the damage due to radiation in the tracker sensors is expected to be very inhomogeneous over the sensor’s area. Since the bias voltage needed to deplete the silicon increases with the radiation dose, after a large non uniform radiation dose the depletion voltage of the irradiated area may be higher than the breakdown voltage of the un-irradiated area. In this case, the device performance, in terms of hit reconstruction efficiency, will be compromised: a high bias voltage will be needed in order to increase the charge collected in the irradiated area, but this will lead to high leakage currents in the non-irradiated zone, which introduces noise that may affect the operation of the device. The case discussed above is less likely to happen for sensors with a high initial $V_{bd}$. This paper presents the results of the electrical characterization of CNM 3D devices with a slim edge for AFP, and the results of the beam test studies of non-uniformly irradiated sensors.

II. THE AFP PIXEL MODULE

The current ATLAS Pixel Detector uses the FE-I3 [5] pixel readout electronics, but due to the necessity of a higher tolerance to radiation, the FE-I4 [6] was developed for the IBL, which, for the same reason, is chosen to be the front end for the AFP. The FE-I4 integrated circuit was designed in 130 nm technology and features an array of $80 \times 336$ pixels of $50 \times 250$ $\mu$m$^2$, with a total size of $20.2 \times 19.0$ mm$^2$ and with an active fraction of 89%.

The CNM IBL 3D sensors, were produced on a $230$ $\mu$m thick wafer with a double sided process, i.e. the n- and p-type columns are etched from the opposite sides of the substrate. The pixel configuration consists of two n-type readout electrodes connected at the wafer surface along the $250$ $\mu$m long pixel direction, surrounded by six p-type electrodes which are shared with the neighbouring pixels. The sensor design features $210$ $\mu$m long columns which are isolated on the n$^+$
side with p-stop implants. The edge isolation is accomplished with a combination of a \( n^+ \) 3D guard ring, which is grounded, and fences which are at the bias voltage potential from the ohmic side. In one direction, the inactive edge region is about 200 \( \mu \text{m} \) long, however, the dead area at the opposite side of the wirebonding is about 1 mm. This is the critical sensor side for AFP, which needs to be as close as possible to the beam. Therefore a new technique to adapt the IBL 3D sensors for AFP has been investigated. Detectors were post-processed using the scribe-cleave-passivate (SCP) technology to reduce the dead area. The details of such a method are described in other publications [7].

### III. Electrical Characterization of 3D Sensors for AFP

A good electrical behaviour of the AFP sensors is very important to obtain a high charge collection efficiency after a highly in-homogeneous radiation dose, so it is fundamental to maintain a high breakdown voltage after the dead area reduction. In order to test the effect of the dicing, two CNM 3D bare sensors (before the flip-chip) were sent to NRL to reduce the dead region using the SCP technology from the original 1 mm to 50-100 \( \mu \text{m} \) and bump-bonded to the FE-I4 chips on VTT (Finland) [8]. The devices were returned to Barcelona for their characterization.

Fig. 1 shows the electrical performance of the two sensors, the bias voltage versus the leakage current (IV curves), measured at room temperature before and after reducing the area with the SCP method. In this plot one can see that the dicing of the sensors affected to the electrical behaviour, increasing the leakage current and, in one case, decreasing the breakdown voltage.

A 90-Sr source was used to test the charge collection of the samples, with a scintillator providing an external trigger. The charge collection was could not be verified for either AFP prototype due to problems with the bump-bonding.

While the program to reduce the dead area was carried out, two IBL devices (not slim-edged for AFP) were irradiated non-uniformly: CNM-57 and CNM-83.

### IV. Non-uniform Irradiation of 3D Sensors

Once installed the AFP sensors will have to sustain radiation doses of about \( 5 \times 10^{15} \text{n}_{eq}/\text{cm}^2 \) during their lifetime only in a section of their operative area. Since the bias voltage needed to deplete the sensor increases with radiation dose, the non-irradiated area will need to sustain a high voltage keeping the leakage current at a low value to reduce the noise and be able to operate the device.

FE-I4 devices CNM-57 and CNM-83 were irradiated with protons at the CERN irradiation facility IRRAD1 with a non-uniform profile (see Fig. 2) in order to study the implications of such radiation doses. CNM-57 was irradiated with a maximum dose of \( 4.0 \times 10^{15} \text{n}_{eq}/\text{cm}^2 \), while CNM-83 was irradiated with more than twice the maximum value of the previous one, \( 9.4 \times 10^{15} \text{n}_{eq}/\text{cm}^2 \).

The bias voltage versus the leakage current of these devices are shown in Fig. 3. Notice that the breakdown voltages of CNM-57 and CNM-83 before irradiation are 75 V and 10 V respectively: since the operative bias voltage will need to be increased after irradiation to ensure a high charge collection, one can suspect (and will be verified in the following sections) that the later sensor will show large noise levels that will affect to the sensor’s efficiency. In fact, CNM-83 should have been irradiated to a lower fluency than CNM-57. As can be seen in Fig. 3, the leakage current of CNM-83 after irradiation at voltages around 130 V is greater than 100 \( \mu \text{A} \), with the frontend off. Due to this large leakage current CNM-83 was difficult to operate after irradiation.
Fig. 3. Leakage current versus bias voltage of the CNM FE-I4 3D sensors with slim edges before and after non-uniform irradiation with the readout chip off at $-20\,^\circ\text{C}$.

V. BEAM TEST STUDIES OF NON-UNIFORMLY IRRADIATED 3D SENSORS

After being irradiated, test beam studies were done to CNM-57 and CNM-83 devices, together with an un-irradiated sensor for reference, at the CERN SPS H6 beam line using 120 GeV pions in August 2012. From these studies the hit reconstruction efficiency on the irradiated and non-irradiated area of the sensors was calculated.

The track reconstruction of the beam particles was performed using the high resolution EUDET telescope [10], which consists in six Mimosa tracking planes, the trigger hardware and the readout data acquisition system. The EUDET set-up provides a resolution of $\sim 3\,\mu\text{m}$. The sensors were placed in between the telescopes planes at perpendicular incident angle with a temperature of $-15\,^\circ\text{C}$. The hit efficiency is determined by extrapolating tracks from the telescope on the devices, were a hit is searched in a $3\times3$ pixel area around the extrapolated track, after applying quality cuts.

The Mimosa sensors of the EUDET telescope has a smaller active area than the FE-I4 devices, so separate data samples were taken to cover the irradiated and non-irradiated areas on the sensors. The efficiency results obtained for the irradiated devices are shown in Fig. 4. The average efficiency obtained for sensor CNM-57 was of 98.9% in the non-irradiated region, while a 98.0% of efficiency was observed in the irradiated area after removing dead digital pixels. On the other hand, the efficiency of CNM-83 on the irradiated side was found to be about 60%, due to the large leakage current which caused noise that prevented the depletion of the irradiated region. Fig. 4 also shows the efficiencies of both devices in a $2\times2$ pixel region in order to highlight the pixel structure: notice that the areas with lower efficiency correspond to the columns of the p$^+\,3\text{D}$ silicon sensors.

VI. CONCLUSIONS

This paper presented studies of two characteristic features of the AFP pixel detector: the electrical characterization of the slim edge sensors, and the hit reconstruction efficiency of non-uniformly irradiated sensors.

The dead area of two FE-I4 sensors was reduced using the SCP method before flip-chip. The electrical characterization showed that the effect of such technique are the slight reduction of the breakdown voltage and the small increase of the leakage current. These effects may compromise the performance of the sensors for AFP, but further investigation is ongoing.

Two FE-I4 CNM 3D sensors were irradiated at CERN with a non-uniform radiation dose profile. For device with low breakdown before irradiation, the depletion of the irradiated area was not reached and the efficiency is poor. The device with high breakdown before irradiation was able to maintain the voltage needed to achieve excellent hit reconstruction efficiency.

ACKNOWLEDGEMENT

This work was partially funded by the MINECO, Spanish Government, under the Grant FPA2010-22060-C02-01/02, and the European Commission under the FP7 Research Infrastructures project AIDA, Grant agreement no. 262025.

REFERENCES


