Beam Test Studies of 3D Pixel Sensors Irradiated Non-Uniformly for the ATLAS Forward Physics Detector

S. Grinstein¹,a, M. Baselga¹, M. Boscardin², M. Christophersen³, C. Da Via³, G.-F. Dalla Betta³, G. Darbo⁵, V. Fadeyev⁶, C. Fleta⁷, C. Gemme⁸, P. Grenier⁹, A. Jimenezⁱ, I. Lopez⁹, A. Micelli⁶, C. Nellist⁷, S. Parker⁹, G. Pellegrini⁵, B. Philips⁴, D.-L. Pohl⁶, H. F.-W. Sadrozinski⁶, P. Sicho¹, S. Tsiskaridzeª

¹ICREA and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain
²Centro Nacional de Microelectronic, CNM-IMB (CSIC), Barcelona, Spain
³Fundazione Bruno Kessler, FBK-CMM, Trento, Italy
⁴School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
⁵Universita degli Studi di Trento and INFN, Trento, Italy
⁶INFN Sezione di Genova, Genova, Italy
⁷Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, USA
⁸SLAC National Accelerator Laboratory, Menlo Park, USA
⁹University of Hawaii, Lawrence Berkeley Laboratory, Berkeley, USA
¹°University of Bonn, Bonn, Germany
¹¹Instıtute of Physics ASCR v.v.i., Prague, Czech Republic

Abstract

Pixel detectors with cylindrical electrodes that penetrate the silicon substrate (so called 3D detectors) offer advantages over standard planar sensors in terms of radiation hardness, since the electrode distance is decoupled from the bulk thickness. In recent years significant progress has been made in the development of 3D sensors, which culminated in the sensor production for the ATLAS Insertable B-Layer (IBL) upgrade carried out at CNM (Barcelona, Spain) and FBK (Trento, Italy). Based on this success, the ATLAS Forward Physics (AFP) experiment has selected the 3D pixel sensor technology for the tracking detector. The AFP project presents a new challenge due to the need for a reduced dead area with respect to IBL, and the in-homogeneous nature of the radiation distribution in the sensor. Electrical characterization of the first AFP prototypes and beam test studies of 3D pixel devices irradiated non-uniformly are presented in this paper.

1. Introduction

ATLAS [1] plans to install a Forward Physics detector (AFP) in order to identify diffracted protons at ≈210 m from the interaction point [2]. The current AFP design foresees a high resolution pixelated silicon tracking system combined with a timing detector for the removal of pile up protons. The AFP tracker unit will consist of an array of six 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 [2]. Thus, there are two critical requirements for the AFP pixel detector: first, the active area of the detector has to be as close as possible to the LHC beam, which means that 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. Preliminary estimations indicate that the side of the sensors close to the beam will have to sustain doses on the order of \(5 \times 10^{15} \text{ n}_{eq}/\text{cm}^2\), while the opposite site is expected to receive several orders of magnitude less radiation [3].

Based on the successful performance of CNM [4] and FBK [5] 3D sensors productions [6] for the ATLAS Insertable B-Layer (IBL) [7], the 3D technology was chosen for the AFP tracking detector. However, the IBL sensors have a large inactive edge on the side which will be closest to the beam in the AFP configuration. To meet the AFP requirements, different aging techniques have been investigated to reduce the dead area of the IBL 3D sensors. Section 2 of this paper presents the results of electrical tests performed on slim-edge prototypes for AFP.

The bias voltage needed to deplete a silicon sensor increases with radiation dose. Since the radiation distribution of the AFP silicon sensors will be highly non-uniform, there can be a scenario where the breakdown voltage of the non-irradiated zone is lower than the depletion voltage of the irradiated one. This will degrade the device performance: a high bias voltage will increase the leakage current leading to noise (to a point where the device may not longer be operated), while an intermediate voltage will reduce the amount of charge collected in the irradiated area, degrading the hit reconstruction efficiency. Thus sensors with high initial breakdown voltage will be ideal for AFP. Section 3 of this paper presents the first beam test results of 3D sensors irradiated non-uniformly up to fluencies of...
2. The AFP Pixel Module

The pixel readout electronics of AFP will be the FE-I4 chip, which was developed for IBL. Built in the 130 nm CMOS process, the FE-I4 offers an increased tolerance to radiation with respect to the current ATLAS pixel readout chip, the FE-I3. The IBL chip features an array of 80 × 336 pixels with a pixel size of 50 × 250 µm². The total size of the FE-I4 chip is 20.2 × 19.0 mm² and the active fraction is 89%. The sensors are DC coupled to the chip with negative charge collection. Each readout channel contains an independent amplification stage with adjustable shaping, followed by a discriminator with independently adjustable threshold. The chip operates with a 40 MHz externally supplied clock. The time over threshold (ToT) with 4-bit resolution together with the firing time are stored for a latency interval until a trigger decision is taken.

The selected sensor for AFP is the IBL 3D sensor, since it provides high radiation tolerance at low bias voltage. The IBL 3D sensor is 230 µm thick with the n- and p-type columns etched from the opposite sides of the p-type substrate. The pixel configuration consists of two n-type readout electrodes connected at the wafer surface along the 250 µm long pixel direction, surrounded by six p-type electrodes which are shared with the neighboring pixels. The CNM 3D sensor design features 210 µm 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.

The IBL sensor design has a large (=1 mm) dead region in the side opposite to the wirebonds, see Fig. 1. This dead region was added to accommodate the bias stab needed for the active edge technology which was finally not incorporated into the IBL (the side opposite to the wirebonds is not critical for the IBL, since the sensors overlap in the r–φ direction). However, for the AFP project, it is critical to substantially reduce the mentioned dead area, since it will be closest to the beam.

In order to adapt the 3D IBL sensors for AFP, different techniques have been investigated. Detectors were post-processed using the scribe-crease-passivate (SCP) technology to reduce the dead area. Details of SCP method have been described in other publications. Very briefly, the method relies on passivating the sidewall with low defect density. A low defect density is obtained in a two-step process. First, the surface of the sensor is scribed at the desired edge location in the direction that coincides with one of the silicon crystal planes. Then the peripheral region is mechanically cleaved off. The resulting sidewall follows the crystal plane. The passivation step uses a dielectric material that depends on the bulk type of the silicon.

For p-type wafers used in this study, a dielectric with negative interface charge on the border with silicon is needed. This is accomplished by depositing an atomic layer (ALD) of Al₂O₃. Standard diamond-saw cuts were also investigated, but are not presented here.

3. Electrical Tests of the First 3D Sensors Prototypes for AFP

The SCP technology has been used to reduce the inactive area of the IBL sensors for AFP. Since a limited number of sensors were available at the time, the technique was first tested on 3D sensors designed for the FE-I3 readout chip. Though the pixel geometry is different, the results are expected to be relevant for the FE-I4 sensors, since the slim edge performance mostly depends on characteristics of the sensor periphery: sensor thickness, slim edge distance, and sidewall treatment.

Seven CNM 3D FE-I3 devices which presented breakdown voltages above 40 V were sent to NRL to reduce the dead area by applying the SCP technology, from the original 1 mm to 50–100 µm. The devices were returned to Barcelona to be bump-bonded to FE-I3 readout chips and characterized. Figure 2 shows the current versus bias voltage (“IV”) measurements at room temperature. Two assemblies show a resistive behavior. This is probably due to the slim-edge being too close to the 3D guard-ring, which effectively connects the ohmic side to ground. The charge collection was verified in all devices with good breakdown voltage using a 90-Sr source and an external trigger provided by a scintillator. Since the CNM 3D sensors were available at the time, the technique was first tested on 3D sensors designed for the FE-I3 readout chip. Though the pixel geometry is different, two FE-I4 IBL prototypes (CNM-57 and CNM-83) were irradiated with protons non-uniformly at the IRRAD1 facility at CERN-PS. The irradiation levels are listed in Table 1.
Figure 2: Current versus bias voltage for CNM FE-I3 3D sensors with slim edges (top). Two devices have resistive behavior. The rest has expected low leakage currents and high breakdown voltage. The MPV of the Landau fit to the ToT spectrum obtained with a Sr-90 source is shown below for the AFPs2 device.

Figure 3: Dose distribution on the CNM-57 sample. A similar profile was obtained for CNM-83, but with a maximum dose of $9.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$, see also Table 1.

Figure 4: Measurement of the leakage current as a function of the bias voltage for the two irradiated CNM devices at $-20^\circ \text{C}$ with the front-end chip not powered.

Table 1: Samples irradiated non-uniformly for AFP. The breakdown voltages shown are before irradiation.

| Sample  | Max. Dose $(10^{15} \text{ n}_{eq}/\text{cm}^2)$ | Breakdown Voltage (V) | Bias Voltage at Beam Test (V) |
|---------|---------------------------------|------------------------|-----------------------------|
| CNM-57  | 4.0                             | 75                     | 130                         |
| CNM-83  | 9.4                             | 10                     | 130                         |

Figure 5: Threshold (top) and noise (bottom) distribution of the FE-I4 CNM AFP prototype irradiated devices.

tests, it is necessary to verify that the front-end electronics was not damaged as a result of the proton irradiation. The operational threshold was set to 1700 electrons based on previous experience with the IBL devices. The threshold distributions of the two irradiated devices, shown in Fig. 5, present good uniformity, while the ENC (Equivalent Noise Charge) is below 200 electrons.

5. Beam Test Studies of Non-uniformly Irradiated 3D Sensors

Test beam studies of non-uniformly irradiated devices are essential to understand the AFP pixel detector module performance. Critical parameters, such as hit efficiency and position resolution, can only be determined at beam tests. Both CNM-83 and CNM-57, together with an un-irradiated reference device, have been characterized using 120 GeV pions at the CERN SPS H6 beam line in August 2012.
Beam particle trajectories were reconstructed using the high resolution EUDET telescope \[16\]. The telescope consists of six Mimosa tracking planes, the readout data acquisition system and the trigger hardware, and provides a $\approx 3\,\mu m$ track pointing resolution. The devices under test were placed between the telescope planes. Data presented here were recorded at perpendicular incident angle. The devices under test were cooled to $-15^\circ\,\text{C}$. The hit efficiency is determined from extrapolated tracks on the devices, after track quality cuts have been applied. A hit on the device under test is searched for in a $3 \times 3$ pixel window around the track position.

Since the active area of the FE-I4 devices is larger than the Mimosa sensors of the telescope, separate sets of data were taken to cover the irradiated and non-irradiated regions of the sensors. Fig. 6 shows the efficiency map for sensor CNM-57. The non-irradiated region has an average efficiency of 98.9%, while the efficiency for the irradiated side is 92.7%. If the dead and noise pixel cells (due to front-end issues) are removed, the average efficiency for “a” (“b”) is 99.2% (98.0%). The efficiency for “a” folded into a two by two pixel area is shown below.

6. Conclusions

The AFP project presents a new challenge for pixel detectors: reduced dead areas are needed to maximize the physics potential of the experiment, and the sensors have to be able to sustain a highly non-uniform irradiation distribution. The scribe-cleave-passivate technology used to reduce the inactive edge of 3D sensors showed promising results with FE-I3 devices. The first FE-I4 prototypes have already been produced and will be tested shortly. The first beam test studies of non-uniformly irradiated 3D pixel sensors for AFP have been presented. For devices with low initial breakdown, the performance is poor due to the large leakage current caused by the bias voltage needed to deplete the irradiated area. Devices that show good electrical behavior before irradiation are able to sustain the voltage needed to achieve excellent efficiency (> 98% at perpendicular incidence) throughout the sensor.

Acknowledgment

This work was partially funded by the MINECO, Spanish Government, under the grant FPA2010-22060-C02-01, and the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025. We would like to thank the Institute for Nanoscience (NSI) at the U.S. Naval Research Laboratory (NRL) and the NSI staff. The work done at NRL was sponsored by the Office of Naval Research (ONR). The work at SCIPP was supported by Department of Energy, grant DE-FG02-04ER41286.

References

[1] The ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider”, JINST 3 S08003 (2008).
[2] The ATLAS Collaboration, “Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment”, CERN-LHCC-2011-012, 2011.
[3] L. Adameczyk EST al., “AFP: A proposal to install proton detectors at 220 m around ATLAS to complement the ATLAS high luminosity physics program”, ATL-COM-LUM-2011-006, CERN (2011), AFP technical proposal.
[4] Centro Nacional de Microelectronic (CNM), Barcelona (Spain), http://www.mmb-cnm.cnm.csic.es/
[5] Fondazione Bruno Kessler (FBK), Trento (Italy), http://www.fbk.eu/
[6] C. Da Via EST al., Nucl. Instrum. and Methods in Phys. Res. A 694 (2012) 321330
[7] The ATLAS IBL Collaboration, “Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip”, submitted to JINST, http://arxiv.org/abs/1207.1906
[8] M. Garcia-Sciveres EST al., Nucl. Instrum. Methods Phys. Res. A 636, S155 (2011).
[9] I. Peric, EST al., Nucl. Instrum. Methods in Phys. Res. A 565, 178 (2006).
[10] S. Grinstein, The ATLAS Collaboration, Nucl. Instrum. Methods Phys. Res. A 699, 61 (2013).
[11] M. Christophersen, V. Fadeyev, B.F. Philips, H. F.-W. Sadrozinski, C. Parker, S. Eli, J.G. Wright, Nucl. Instrum. Meth. in Phys. Res. A 699 (2013) 14.
[12] M. Povoli EST al., iWoRID2011 Zurich 2011 (to be fixed!).
[13] U.S. Naval Research Laboratory, Washington, USA.
[14] M. Glaser, M. Huhtinen, F. Lemineur, C. Leroy, P. Roy, M. Tavlet, “Radiation Test Facilities in the New PS East Hall at CERN”, in Proc. 5th Eur. Conf. Radiation and its Effects Components and Systems, Fontevraud, France, 2000, pp. 136-141.
[15] M. Glaser, F. Ravotti, M. Moll, “Dosimetry Assessments in the Irradiation Facilities at the CERN-PS Accelerator”, IEEE Trans. Nucl. Sci, vol. 53 (4), pp. 2016-2022, 2006.
[16] E. Corrin, Nuclear Science Symposium Conference Record (NSS/MIC), 2009 IEEE, 816 (2009).