Available on CMS information server CMS CR -2017/190

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

01 July 2017 (v2, 24 July 2017)

Pixel Detector Developments for Tracker Upgrades of the High Luminosity LHC

M. Meschini, M. Boscardin, G. F. Dalla Betta, M. Dinardo, G. Giacomini, D. Menasce, R. Mendicino, A. Messineo, L. Moroni, S. Ronchin, D.M.S. Sultan, L. Uplegger, L. Viliani, I. Zoi, D. Zuolo

Abstract

This paper reports on the INFN (Istituto Nazionale di Fisica Nucleare, Italy) research activity in collaboration with FBK foundry, which is aiming at the development of new pixel detectors for the LHC Phase-2 upgrades. The R&D covers both planar pixel devices and 3D detectors built using columnar technology. All sensors are low thickness n-in-p type, as this is the general direction envisaged for the High Luminosity LHC pixel detector upgrades. Hybrid modules with 100μm and 130μm active thickness, connected to the PSI46dig readout chip, have been tested on beam test experiments. Selected preliminary results from test beams are described for both planar and 3D devices. The results on the 3D pixel sensors before irradiation are very satisfactory and support the conclusion that columnar devices are very good candidates for the inner layers of the upgrade pixel detectors.

Presented at *TIPP2017 International Conference on Technology and Instrumentation in Particle Physics 2017*

Pixel Detector Developments for Tracker Upgrades of the High Luminosity LHC

M. Meschini*[1], M. Boscardin[2], G. F. Dalla Betta[3], M. Dinardo[4], G. Giacomini[2], D. Menasce[5], R. Mendicino[3], A. Messineo[6], L. Moroni[5], S. Ronchin[2], D.M.S. Sultan[3], L. Uplegger[7], L. Viliani[1], I. Zoi[8,9], D. Zuolo[4]

[1] INFN, Firenze, Italy
marco.meschini@cern.ch,
[2] Fondazione Bruno Kessler, Trento, Italy
[3] Università di Trento and TIFPA INFN, Italy
[4] Università di Milano Bicocca and INFN, Italy
[5] INFN Milano Bicocca, Italy
[6] Università di Pisa and INFN, Italy
[7] Fermi National Accelerator Laboratory, Batavia, IL, USA
[8] Università di Firenze and INFN, Italy
[9] Hamburg University, Germany

Abstract. This paper reports on the INFN (Istituto Nazionale di Fisica Nucleare, Italy) research activity in collaboration with FBK foundry, which is aiming at the development of new pixel detectors for the LHC Phase-2 upgrades. The R&D covers both planar pixel devices and 3D detectors built using columnar technology. All sensors are low thickness n-in-p type, as this is the general direction envisaged for the High Luminosity LHC pixel detector upgrades. Hybrid modules with 100μm and 130μm active thickness, connected to the PSI46dig readout chip, have been tested on beam test experiments. Selected preliminary results from test beams are described for both planar and 3D devices. The results on the 3D pixel sensors before irradiation are very satisfactory and support the conclusion that columnar devices are very good candidates for the inner layers of the upgrade pixel detectors.

Keywords: Silicon Pixel Sensors, Silicon Detectors, 3D Pixel, Planar Pixel, Irradiations, High Luminosity LHC, Charge Collection

1 Introduction

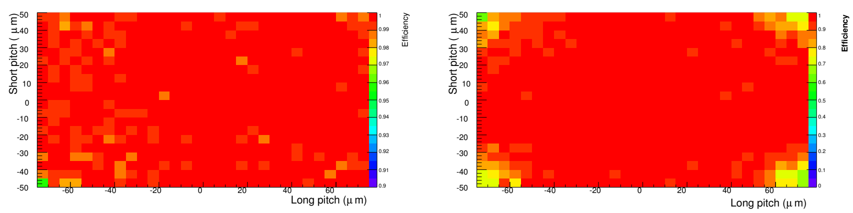
The Large Hadron Collider (LHC) at CERN will undergo major improvements during what is called Long Shutdown 3 (LS3), presently foreseen for years 2024-2026. The accelerator upgrade will enable to reach instantaneous peak luminosities in excess of $5\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the High Luminosity Phase (HL-LHC) [1]. As a consequence, experiments like ATLAS and CMS will need to be upgraded, and a complete redesign and replacement of inner trackers will be mandatory.

* Corresponding author

New tracker detectors have to be designed for an integrated luminosity up to $3000\,\mathrm{fb}^{-1}$ with a pile-up figure which is foreseen to average $\sim$140 events per bunch crossing and could rise up to $\sim$200 pileup events in the ultimate luminosity scenario. Pixel detectors in the innermost layers of the HL-LHC experiments will have to survive with high tracking efficiency up to a fluence which can exceed $2\times10^{16}\,\mathrm{n_{eq}}\,\mathrm{cm}^{-2}$ (1 MeV neutron equivalent) and a total dose estimated to be slightly above 10MGy. To reach these goals the pixel size must be adequately small, targeting an area of about 2500 $\mu\mathrm{m}^2$ with an active thickness between $100\,\mu$m and $150\,\mu$m, possibly keeping the capacitance below 100 fF. The total active sensor thickness should be small enough to keep both the bias voltage and the power dissipation after irradiation at a manageable level. The full sensor thickness, including the handle wafer where needed, should be kept compatible with the low material budget allowance for inner tracking systems, so it should possibly remain within 200 μm of silicon. The pixel sensors in the INFN R&D have been designed following the above requirements, for both planar and 3D columnar devices, going through different steps and production batches at FBK foundry to optimize the various production processes in order to identify the best candidates for the HL-LHC pixel detector upgrades. The sensors have been produced on 6" wafers in different sizes and pitches in order to be individually bump bonded to different ROCs (Read Out Chip). We made designs compatible with the present ROCs like FE-I4 for ATLAS and PSI46dig [2] for CMS, or with different prototype ROCs like the new RD53A developed in 65 nm technology, which should become available by the end of 2017 [3]. In the following we will show results on planar and 3D single-chip module pixel sensors tested in 2015-17 at the Fermilab Test Beam Facility (FTBF) with a 120GeV proton beam. The facility, described in [4], houses a tracking telescope with a resolution of about $8\,\mu$m on the Detector Under Test (DUT) which can be operated in a humidity and temperature controlled environment down to about -25 °C.

2 Planar Pixel Sensor

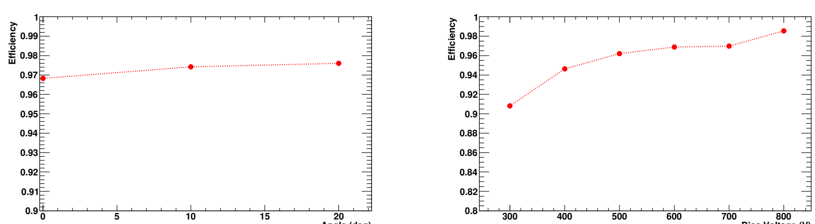
The results presented in this section refer to the hybrid modules corresponding to the first FBK planar batch. A detailed description of the various available layouts is given in Ref. [5]. In this section we report on the measurements performed on a planar pixel sensor belonging to wafer W30 (100 μm active thickness) and bump-bonded to the PSI46dig readout chip at Fraunhofer IZM (Germany). The sensor has a 100×150 $\mu\mathrm{m}^2$ pitch; it is characterised by a rather large gap of 50 μm between the n^+ pixel implants surrounded by C-shaped p-stop implants and no punch-through structure. A frame-shaped BCB (Benzo-cyclo-butene) layer has been deposited on wafers at IZM on both sensor and ROC periphery to help reducing discharges due to the high electric field between sensor and ROC. The device has been characterised in terms of detection efficiency, which is computed as the ratio of the number of tracks reconstructed by the telescope having a correspondent hit in the detector, and the total number of tracks reconstructed by the telescope and traversing the detector. Before calculating the efficiency the reconstructed tracks have been corrected for misalignments. This procedure for the evaluation of the efficiency has been used for all pixel sensors tested at FTBF. The same device has been tested before and after an irradiation campaign with 24 GeV/c protons performed at IRRAD (CERN) in 2016. The device has been irradiated with an average fluence of $3 \cdot 10^{15}$ n_{eq}/cm^2. The detection efficiency as a function of the track impact coordinate, obtained averaging on all the cells, is shown in Fig. 1, comparing the results before and after the irradiation campaign. Before irradiation the device is operated at a bias voltage of 40 V and at room temperature. After irradiation the detector is biased at 600 V and cooled down to -20 °C. The overall detection efficiency of the irradiated



(a) Before irradiation (b) After irradiation

Fig. 1. Detection cell efficiency as a function of the track impact position for the same planar device before (a) and after (b) the irradiation at $3 \cdot 10^{15}$ n_{eq}/cm^2. The efficiency is computed using tracks orthogonal to the detector surface.

detector has been measured at different bias voltages and also at different tilting angles with respect to the beam direction, as shown in Fig. 2. Before irradiation



(a) (b)

Fig. 2. Irradiated sensor at $3 \cdot 10^{15}$ n_{eq}/cm^2: (a) overall detection efficiency as a function of tilting angle at a bias voltage of 600 V, (b) overall efficiency as a function of bias voltage using orthogonal tracks.

the detection efficiency has been measured to be always above 99%, while the efficiency after irradiation reaches values greater than 97% for bias voltages of 600 V and above.

3 3D Columnar Pixel Sensors

The first INFN R&D batch of columnar pixel sensors was produced at FBK foundry in 2015. FBK developed for the 3D sensors a new single-sided process [6] on 6" Silicon-Silicon Direct Wafer Bonded wafers with active thickness 100 μm and 130 μm, using the DRIE technique (Deep Reactive Ion Etching). An artist's view, not to scale, illustrating the structure of a 3D sensor is shown in Fig. 3. The p+ (ohmic) columns pass through the high resistivity ($\gtrsim$3k Ohm·cm) active

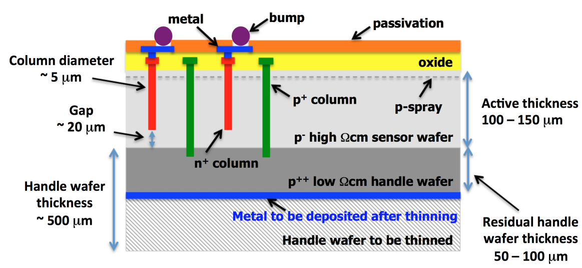


Fig. 3. Artist's view of the cross section of a 3D single-sided sensor.

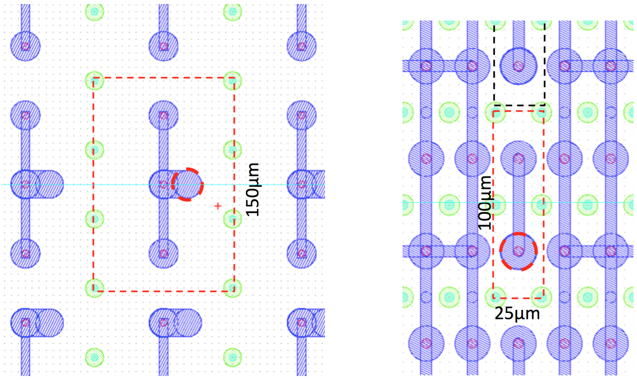
layer and reach the low resistivity handle wafer, where the bias voltage is applied from the back-side. The n+ (junction) columns are stopped at a distance of about 15-20μm from the handle wafer in order to avoid early breakdown [7].

3.1 3D Pixel Design

In order to study different pixel cell configurations we implemented cells with one, two or three junction columns (1E, 2E, 3E) where possible, with the option to have the bump pad just on top of a ohmic column (BO) as an alternative to the standard off-column position. We also included in the 3D layout sensors with pixel cell structures of 50×50 μm^2 or 25×100 μm^2 which have a dedicated adaptation metal network to allow a fraction of small pitch pixels to be read out with present ROCs with larger readout pitches as the PSI46dig (100 μm$\times$150 μm pitch). In the small pitch case only one pixel out of six is read out, all the others being shorted together by the metal grid. Two examples of different pixel cell designs and options are shown in Fig. 4.

3.2 Test Beam Results

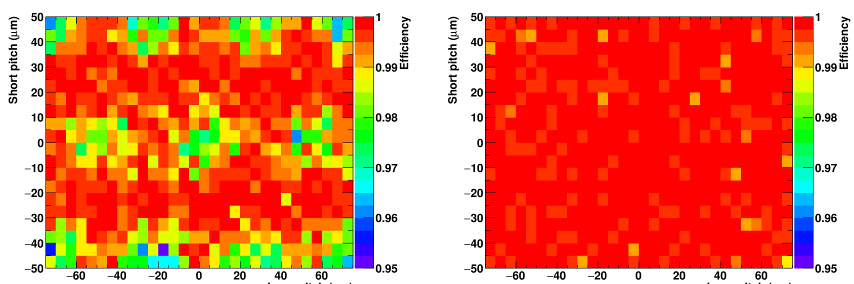
Many different measurements were performed to study the behaviour of the 3D pixel sensors, which in our case were bump bonded to the PSI46dig chip. The results presented here refer to sensors belonging to two non-thinned wafers (W76,



(a) (b)

Fig. 4. 3D pixel with 100μm×150μm cell size with three electrodes (a) and 3D pixel with 25μm×100μm cell size with two electrodes and BO (Bump On column) option (b). The metal layer is in blue, ohmic columns are in green, collecting electrodes circled in red.

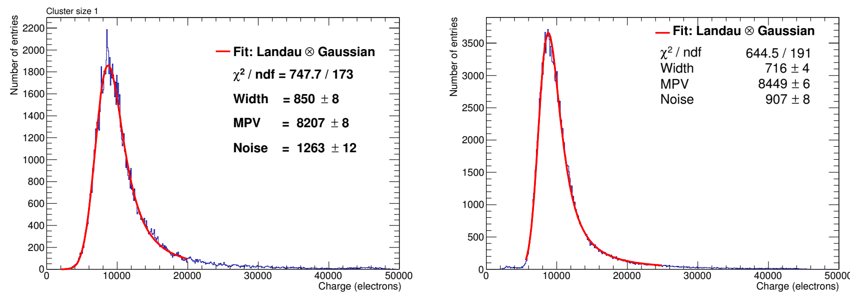
W78) with 130μm active thickness which were processed for Indium bump-bonding at Leonardo Company (Italy). We have measured the detection efficiency as a function of the bias voltage, which resulted in an efficiency above 98% for the 3E 100μm×150μm pixels already at 5V bias; this value increases with applied bias voltage and it reaches the geometric efficiency for orthogonal incident tracks around 20V where the measured efficiency is greater than 99.4% for both 2E and 3E pixels. The column positions are still visible in case of orthogonal tracks on the efficiency map (Fig. 5(a)) where all sensor cells are superimposed. For 10 degrees incident tracks, the 3D pixels recover full efficiency, as shown in Fig. 5(b). The collected charge distributions are reported in Fig. 6



(a) Orthogonal tracks (b) 10 deg tracks

Fig. 5. 3D pixel (100μm×150μm with three electrodes) two-dimensional efficiency maps for orthogonal (a) and 10 degrees inclined tracks (b).

for a 3D and a planar pixel sensor: the red line represents a fit to a Landau distribution convolved with a Gaussian. The most probable value of the Landau (denoted as "MPV") and the σ of the Gaussian (denoted as "Noise") are given. As can be seen both sensors collect the same charge for the same thickness (130 μm).



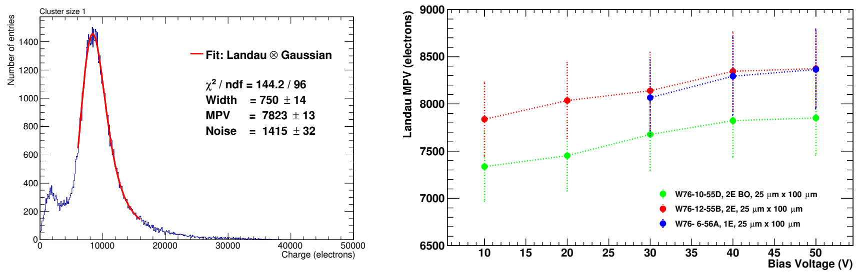
(a) Planar (b) 3D

Fig. 6. Collected charge for 100μm×150μm pixels: Planar, 100V bias (a) and 3D-2E, 40V bias (b).

We also tested small pitch 3D pixel sensors. As a representative example, we report the measurements of the charge collected by 25 × 100 μm^2 pitch sensors (wafer W76). The collected charge of three sensors with different layouts has been measured as a function of the bias voltage. The three configurations differ for the number of charge collecting electrodes (1E or 2E) and for the position of the bump, which can be either on top of the junction column (BO) or displaced from it. The distribution of the charge collected by the sensor with 2E BO configuration operated at a bias voltage of 40 V is shown in Fig. 7(a), where the secondary peak at low charge values is due to the contribution of not read out adjacent pixels. In Fig. 7(b) we report the most probable value of the Landau distribution as a function of the bias voltage for the three configurations. All three sensors are found to collect a comparable amount of charge within the systematic uncertainty, which we have evaluated to be around 5%, mainly due to the readout chip calibration procedures.

4 Conclusions

The first results on planar and "single side process" 3D pixels produced in INFN-FBK R&D show excellent sensor performance. The planar irradiated modules reach a detection efficiency of 97% at 600 V bias at $3 \cdot 10^{15}$ n_{eq}/cm^2; new irradiations of both planar and 3D pixels are underway to study their behaviour at higher fluences. Novel 3D BO pixel sensors with the bump pad on the junction column have been produced and tested on beam for the first time and they are



(a) (b)

Fig. 7. (a) Collected charge for $25 \times 100\ \mu\mathrm{m}^2$ 3D BO pixel sensor operated at a bias voltage of 40 V. (b) Most probable value of the Landau distribution as a function of the bias voltage for three $25 \times 100\ \mu\mathrm{m}^2$ 3D sensors with different layouts.

working according to our expectations. The intrinsic radiation tolerance properties of 3D sensors together with the results we obtained in beam test experiments before irradiation confirm they are very good candidates for the innermost pixel detector layers of the HL-LHC experiments.

Acknowledgments

I wish to warmly thank Mirko Brianzi for his invaluable help in the construction and in the characterisation of the pixel modules.

This work was supported by the Italian National Institute for Nuclear Physics (INFN), Projects ATLAS, CMS, RD-FASE2 (CSN1).

Irradiation at IRRAD (CERN, Switzerland) were supported by the H2020 project AIDA-2020, GA no. 654168.

References

1. G. Apollinari et al., "High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report", CERN-2015-005, doi:10.5170/CERN-2015-005.
2. H.C. Kästli, "Frontend electronics development for the CMS pixel detector upgrade", Nucl. Instrum. Meth. A731 (2013) 88.
3. RD53 Collaboration, "RD Collaboration Proposal: Development of pixel readout integrated circuits for extreme rate and radiation", Scientific Committee Paper CERN-LHCC-2013-008, LHCC-P-006, 2013.
4. M. Dinardo et al., "The pixel tracking telescope at the Fermilab Test Beam Facility" Nucl. Instrum. Meth. A811 (2016) 162-169. doi 10.1016/j.nima.2015.12.003
5. M. Meschini et al., "The INFN-FBK pixel R&D program for HL-LHC" Nucl. Instrum. Meth. A831 (2016) 116-121. doi 10.1016/j.nima.2016.05.009
6. G. F. Dalla Betta et al., "Development of a new generation of 3D pixel sensors for HL-LHC" Nucl. Instrum. Meth. A824 (2016) 386-387. doi 10.1016/j.nima.2015.08.032
7. G. F. Dalla Betta et al., "The INFN-FBK "Phase-2" R&D program" Nucl. Instrum. Meth. A824 (2016) 388-391. doi 10.1016/j.nima.2015.08.074