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First Results on 3D Pixel Sensors Interconnected to the RD53A Readout Chip after Irradiation to $1{\times}10^{16}$ neq cm^{-2}

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Abstract

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Abstract: Results obtained with 3D columnar pixel sensors bump-bonded to the RD53A prototype readout chip are reported. The interconnected modules have been tested in a hadron beam before and after irradiation to a fluence of about $1{\times}10^{16}$ neq cm^{-2} (1 MeV equivalent neutrons). All presented results are part of the CMS R&D activities in view of the pixel detector upgrade for the High Luminosity phase of the LHC at CERN (HL-LHC). A preliminary analysis of the collected data shows hit detection efficiencies around 97% measured after proton irradiation.

Keywords: Performance of High Energy Physics Detectors, Pixelated detectors and associated VLSI electronics, Radiation-hard electronics, Detector design and construction technologies and materials, Radiation damage to detector materials (solid state), Radiation-hard detectors.

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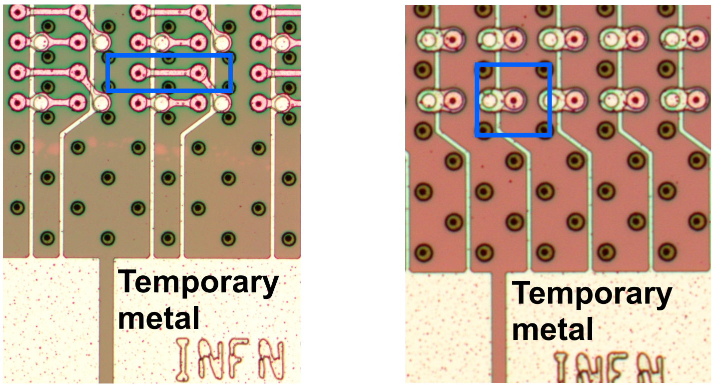
Contents

1 HL-LHC Requirements and 3D Pixels

Pixel detectors in the innermost layers of the HL-LHC experiments will have to withstand up to a fluence which can exceed 2×10^{16} neq cm^{-2}, while preserving high tracking efficiency [1]. The total active sensor thickness should be about 100 to 150 μm in order to keep both the bias voltage and the power dissipation after irradiation to a manageable level, while at the same time allowing for a reasonable amount of collected charge to reach full hit detection efficiency. Moreover, the radiation damage reduces the effective drift distance of charge carriers because of charge trapping, so it is not useful, in the case of planar sensors, to increase the thickness beyond the above limits. The 3D pixels, where charge carriers have to travel distances much shorter than the sensor thickness (only 35μm for a 50×50 μm^2 pixel pitch independently of the sensor thickness which is the driving parameter for planar pixels), are hence very good candidates to satisfy all of the above requirements.

2 The 3D Columnar Pixel Sensors

The 3D sensors [2] were fabricated at the FBK foundry in Trento; they were developed in a collaboration program with INFN (Istituto Nazionale di Fisica Nucleare, Italy). The substrates selected are p-type Si-Si Direct Wafer Bond (DWB) or SOI (Silicon On Insulator). The handle wafer is 500 μm thick low resistivity Czochralski (CZ). FBK active devices are implanted on a Float Zone (FZ), high resistivity (>3000 Ohm cm), 130 μm thick wafer. Columnar electrodes of both p^+ and n^+ type are etched by Deep Reactive Ion Etching (DRIE) in the wafer using a top-side only process. There are two different pixel cell pitches: 50×50 μm^2 and 25×100 μm^2; the latter may have one or two collecting electrodes per cell (2E). The 2E design has a more complex metal routing, with respect to 1E pixel cell, to connect readout electrodes to the square matrix RD53A bumping pads, but it may give advantage in hit detection efficiency. Two examples of pixel cells are shown in figure 1. A temporary metal layer is used for sensor testing at FBK premises and is subsequently removed. Both cell sizes are presently under evaluation in CMS for the inner layers of the upgrade pixel detectors for HL-LHC. After fabrication pixel sensor wafers were processed



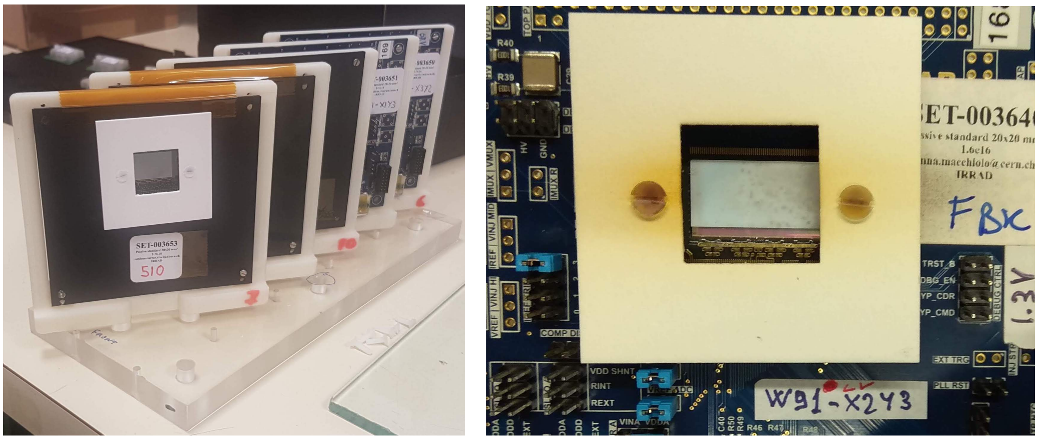
(a) $25 \times 100\,\mu m^2$ 2E sensor (b) $50 \times 50\,\mu m^2$ sensor

Figure 1. 3D sensor pictures taken with microscope. The contact pad for the probe and the vertical metal lines connecting all pixels are visible in the pictures by the 'Temporary metal' label. A 3D single pixel cell on each sensor is highlighted with the blue frames. Rectangular cell 2E design is shown in (a), and square cell design in (b).

for UBM (Under Bump Metalization), thinned down to 200 μm total thickness, diced and bump-bonded to RD53A prototype chips [3] at IZM (Berlin, Germany). The RD53A chip has 76800 readout channels (400 rows and 192 columns with a bump pad pitch of $50 \times 50\,\mu m^2$) and measures $20.1 \times 11.6\,mm^2$. RD53A contains three front ends, named Synchronous, Linear and Differential, to allow performance comparisons between different analog designs. All results presented here were obtained with the Linear Front-End in the central zone of RD53A (136 columns wide, from 128 to 263). The pixel sensor bonded to the readout chip needs to be glued and wirebonded onto an adapter card in order to be tested; these units will be referred to as modules in the following.

3 Irradiations

Irradiations were performed at the CERN IRRAD facility in 2018 in a high intensity 24 GeV/c proton beam, which has a FWHM of 12 mm in x and y directions. The target fluence was $1{\times}10^{16}$ neq cm^{-2}. Modules were tilted on the IRRAD beam at an angle of 55° in order to homogeneously irradiate the $20 \times 12\,mm^2$ sensor and readout chip area; the corresponding total ionizing dose was 6 MGy for $1.65{\times}10^{16}$ protons cm^{-2}. Cross checks were performed in order to establish the effective fluence integrated on the modules; visual inspections after irradiation and data analysis show that the modules were displaced with respect to the irradiation beam axis by a few millimeters. We estimated that the nominal fluence was reached in about one third of the linear FE. We measured hit efficiencies at different bias voltages in sub-sets of pixels to identify the irradiated regions; we could finally find for each sensor a bias voltage value above which all the pixels, independently of the received fluence, reach the same hit efficiency. In figure 2, the modules mounted on the adapter cards are shown. The two CMS modules were labeled w3x3y2 and w91x1y3 to identify the production wafer and the sensor position on the wafer itself.

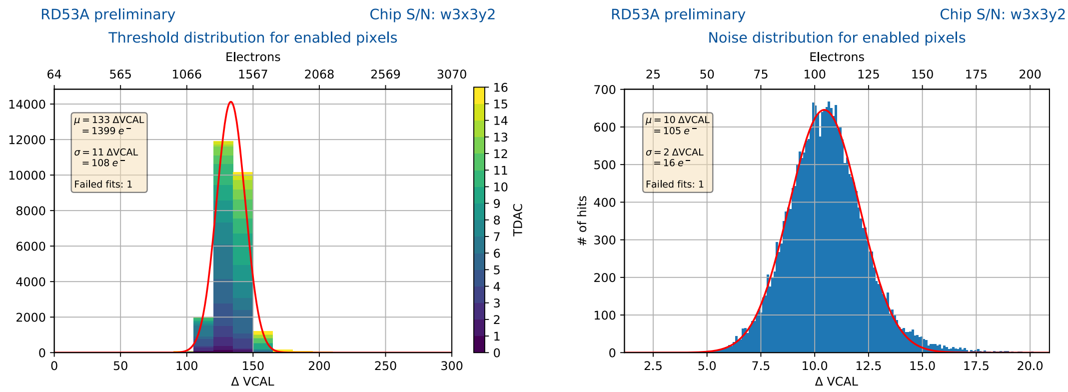


(a) Modules mounted on the irradiation trays (b) A module after irradiation

Figure 2. Tilted modules mounted on the irradiation tray: the two FBK 3D modules are the last ones in the stack (a). A module after irradiation (b); the dark brown band on the cardboard frame and on the nylon screw heads is due to the irradiation proton beam passing through the tilted module.

4 Data Taking and Results

Hybridized modules were tested in two test beam experiments in CERN's North Area H6B (120 GeV/c hadron beam) before and after irradiation in July and October 2018. H6B is equipped with a EUDET type telescope providing a track pointing resolution of about 2 μm [4]. Irradiated modules were kept cold at temperatures between −20°C and −30°C using dry ice bricks. The temperature was monitored via PT1000 sensors located close to the backside of the module and via NTC resistors soldered on the adapter card; these sensors gave consistent measurements. The tuning of the readout chip parameters was done on the beam-line for all the tested modules, targeting low thresholds and noise, having at most 1.5% masked pixels because of noisy channels. For the irradiated modules the average signal threshold was set to about 1400 electrons, with a noise value of 105 electrons for non-masked pixels, as shown in figure 3 for a $25 \times 100\ \mu m^2$ pixel size 3D module. For comparison we report that, in laboratory conditions, we measured a threshold of 1000 electrons with a noise of about 95 electrons on the linear front-end of the 3D modules before irradiation. The number on noisy channels to be masked before/after irradiations depends mainly on the readout chip itself, it can be affected by the irradiation and we did not yet investigate it. The color scale for the threshold distribution represents the 4-bit DAC value used for the trimming of each individual pixel response. The 3D modules before irradiation reached hit detection efficiencies above 98.5%, for perpendicular incident tracks, already at moderate HV bias. In our analysis dead pixels are excluded from the hit efficiency calculation. After irradiation, a bias voltage of at least 120V is needed to reach high hit efficiency. Leakage currents in the Test Beam environment, at nominal operation voltage, were in the order of few hundreds nA before irradiation. After irradiation current increased to ~100μA for normally working, non-defective, modules. Since the total number of available modules was pretty small, both before and after irradiation, we were obliged to use also less than perfect quality modules which had, regardless of the irradiation fluence, very high currents (up to ~800μA in one case). This fact did not prevent the collection of good data samples, but

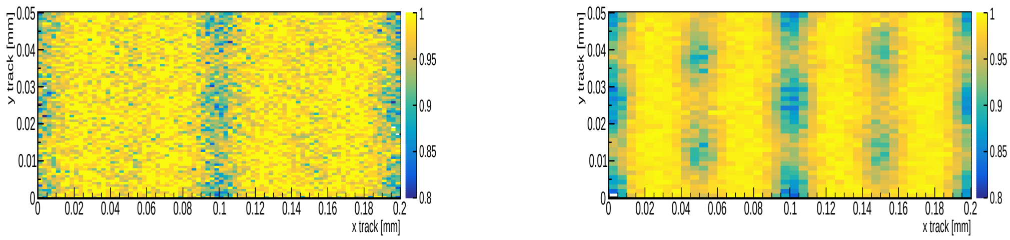


(a) Module Threshold

(b) Module noise

Figure 3. Signal threshold (a) and noise (b) distributions for module w3x3y2 after irradiation.

somewhat limited the maximum reachable bias voltage. All the bias voltages shown in this paper are effective voltages, evaluated after having taken into account the voltage drop on the limiting resistors in series to the High Voltage bias circuit. A comparison of hit efficiency before and after irradiation is shown in figure 4 for $25 \times 100\ \mu\text{m}^2$ and figure 5 for $50 \times 50\ \mu\text{m}^2$ pixel size modules, for perpendicular incident tracks. In the efficiency plots the hits reconstructed over the whole module are projected on a 2×2 pixel cell window to show the sensor geometry and the possible effects of the columnar electrodes. The geometrical inefficiency due to the columnar electrode diameter

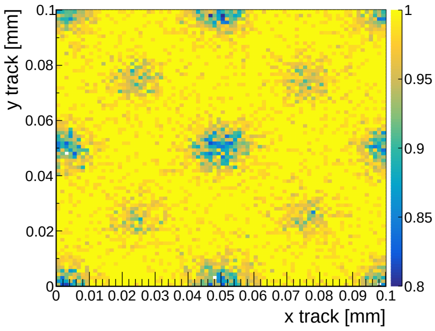


(a) Efficiency before irradiation at 3V bias

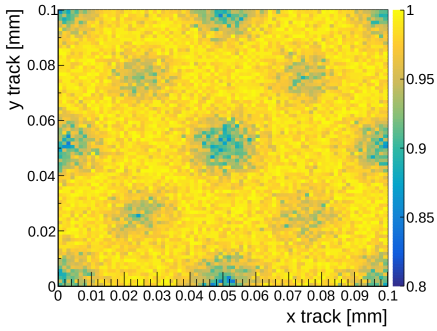
(b) Efficiency after irradiation at 120V bias

Figure 4. Hit detection efficiencies before (a) and after irradiation (b) for the $25 \times 100\ \mu\text{m}^2$ module w3x3y2.

(5 μm) was estimated to be around 1.5%. This effect can be greatly reduced by tilting the module on the beam. In non irradiated modules at 34° tilt angle, the hit efficiency detection reaches 99.3% for all sensors. The hit detection efficiencies as calculated in our data analysis for different runs are reported in Table 1. The differences between the two modules are given by the maximum reachable bias voltage in the test beam setup. In some selected runs it was possible to take data with a different bias voltage in order to verify if the depletion region reaches the p^+ electrodes delimiting the cell perimeter. The hit efficiency as a function of the applied bias voltage is reported in figure 6 for the available different bias points.



(a) Efficiency before irradiation at 15V bias



(b) Efficiency after irradiation at 150V bias

Figure 5. Hit detection efficiencies before (a) and after irradiation (b) for the $50 \times 50\,\mu\text{m}^2$ module w91x1y3.

Table 1. Hit detection efficiency summary table, for the highest recorded bias voltages.

3D Pixel-RD53A Linear FE	$25 \times 100\,\mu\text{m}^2$	$50 \times 50\,\mu\text{m}^2$
Before irradiation	97.3%	98.6%
After irradiation	96.6%	97.5%

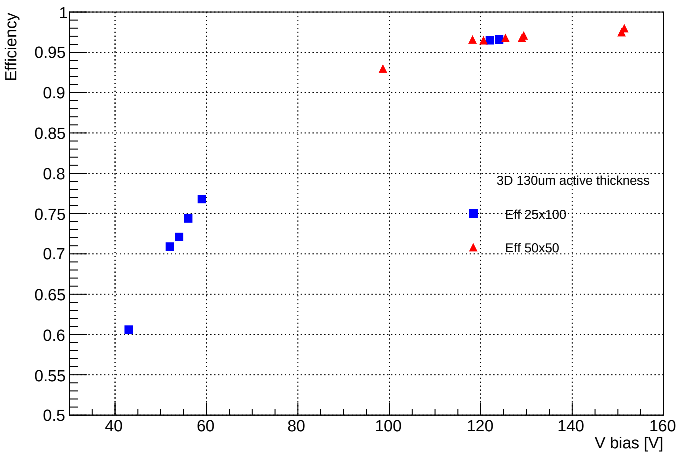


Figure 6. Hit detection efficiency vs applied bias voltage after irradiation

5 Conclusions

The upgrade of the CMS tracker for the HL-LHC will require radiation hard pixel sensors because of the expected extreme fluences. Thanks to their intrinsic characteristics, 3D pixels are to be considered as a possible option for the inner layers of the future trackers. Test beam results obtained with FBK 3D pixel sensors bump-bonded to the RD53A readout chip show high hit efficiencies before irradiation already at moderate bias voltages. After irradiation to $1{\times}10^{16}$ neq cm^{-2} the efficiency is greater than 96.6% at bias voltage of 150V or less. Although we made use of modules with irradiated RD53A chips, the results presented here aimed at sensor performance and not at chip performance. A new batch of 3D pixels exploring a different production technology is in progress at FBK foundry since December 2018; it will provide very useful data for a deeper study of 3D sensors and their applications in large quantity. More irradiations and beam tests are planned to verify at larger scale the performance of these innovative detectors for their use in the upgrade trackers.

Acknowledgments

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References

[1] K. Klein, *The Phase-2 Upgrade of the CMS Tracker*, *CERN-LHCC* (2017) 009, CMS-TDR-014

[2] G. F. Dalla Betta, *Small pitch 3D devices*, *PoS Vertex2016* (2017) 028

[3] M. Garcia-Sciveres, *The RD53A Integrated Circuit*, *CERN-RD53-PUB* 17-001

[4] I. Rubinskiy, *An EUDET/AIDA Pixel Beam Telescope for Detector Development*, *Physics Procedia* 37 (2012) 923