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The INFN R&D: New pixel detector for the High Luminosity upgrade of the LHC

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Summary. — The High Luminosity upgrade of the CERN-LHC (HL-LHC) demands for a new high-radiation tolerant solid-state pixel sensor capable of surviving fluencies up to a few 10^{16} particles/cm^2 at $\sim$3 cm from the interaction point. To this extent the INFN ATLAS-CMS joint research activity, in collaboration with Fondazione Bruno Kessler-FBK, is aiming at the development of thin n-in-p type pixel sensors for the HL-LHC. The R&D covers both planar and single-sided 3D columnar pixel devices made with the Si-Si Direct Wafer Bonding technique, which allows for the production of sensors with 100 μm and 130 μm active thickness for planar sensors, and 130 μm for 3D sensors, the thinnest ones ever produced so far. The first prototypes of hybrid modules bump-bonded to the present CMS and ATLAS readout chips have been tested in beam tests. The preliminary results on their performance before and after irradiation are presented.

1. – Introduction

The High Luminosity upgrade of the CERN-LHC (HL-LHC) demands for a new high-radiation tolerant solid-state pixel sensor capable of surviving fluencies up to a

(*) On behalf of the INFN (ATLAS-CMS) FBK Pixel R&D Collaboration.

few 10^{16} particles/cm^2 at $\sim$3 cm from the interaction point. This is required to replace the current planar technology silicon detectors which, no matter of the way they are operated, are ultimately limited by the degradation of the signal to noise ratio and, therefore, can be reliably employed up to few 10^{15} particles/cm^2 in the best case. Indeed after 3000 fb^{-1}, *i.e.* after 10 years of operation, the innermost layer of the pixel detector will be exposed to a fluence of 2×10^{16} n$_{eq}$/cm^2. The carriers lifetime will be reduced to $\sim$0.3 ns, corresponding to a mean free path of $\sim$30 μm for electrons at saturation velocity. Candidate technologies which can withstand these very high fluences are thin planar or 3D columnar silicon pixel sensors. In order to increase the signal by increasing the electric field, keeping the bias voltage within normal operation conditions (*i.e.* at most a few hundreds of volts) together, the distance between electrodes is reduced.

A joint ATLAS-CMS group within INFN, which is collaborating with the foundry at Fondazione Bruno Kessler-FBK (Trento, Italy), is developing thin planar and 3D columnar silicon pixel sensors on n-in-p 6$''$ Float Zone (FZ) wafers directly bonded to a low resistivity substrate [1]. In this work, we will present preliminary testbeam results on their performance before and after irradiation.

2. – CMS measurements of thin planar sensors

Testbeam studies both of thin planar and 3D devices have been performed by the CMS Collaboration at the Fermilab MTest area using the Captan based DAQ, together with the pixel telescope based on the PSI46 analog chip ($100 \times 150 \mu$m^2 cell size, 80 rows and 52 columns) [2]. The telescope has 8 pixel planes with $\sim$8 μm resolution on each coordinate. Prototype sensors were bump-bonded to the PSI46 digital chip, $100 \times 150 \mu$m^2 cell size, which is fully integrated into the Captan DAQ system.

The thin planar sensors are produced with two nominal thicknesses, 100 and 130 μm. The measured thickness is about 10% smaller than the nominal one due to boron diffusion from the wafer carrier. We expect to measure a Landau Most Probable Value (MPV) of about 6300 e^- and 8400 e^- for 100 and 130 μm thick sensors, respectively.

Figure 1 shows the trend of the Landau MPV as a function of the bias voltage for non-irradiated sensors. The measurement is performed by selecting 1-pixel clusters with impinging track impact point within 20 μm from the cell periphery. The charge distribution is fit with a Landau convolved with a Gaussian. The charge collection behavior is as expected. The sensors were then irradiated up to $\sim$10^{15} n$_{eq}$/cm^2 at Los Alamos laboratory with 800 MeV protons and re-tested at the testbeam. The Landau MPV as a function of the bias voltage for two sensors thicknesses, 100 and 130 μm, is reported in fig. 2. The
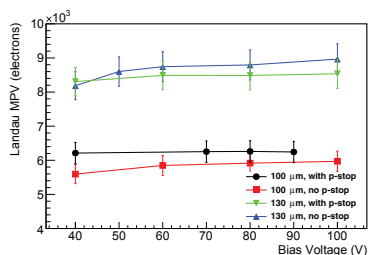

Fig. 1. – Landau Most Probable Value (MPV) *vs.* bias voltage for non-irradiated thin planar sensors. The cell size is $100 \times 150 \mu$m^2.
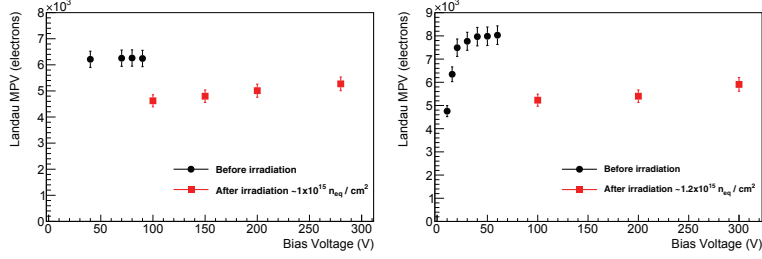
Fig. 2. – Landau Most Probable Value (MPV) *vs.* bias voltage for non-irradiated (black circles) and irradiated (red squares) thin planar sensors 100 (left) and $130\,\mu$m (right) thick. The irradiation fluence is $\sim 10^{15}\,\mathrm{n_{eq}/cm^2}$. The cell size is $100 \times 150\,\mu\mathrm{m}^2$.

charge loss is 20–24%, mainly due to a low bias voltage applied since no spark protection was used for this first batch of sensors.

3. – CMS measurements of thin 3D sensors

The 3D silicon sensors are made with a single-sided process optimized by FBK. The sensors have a support wafer made of silicon. The Ohmic columns have a depth greater than the active layer thickness (for bias), while the junction columns have a depth smaller than the active layer thickness (for higher voltage breakdown). The column diameter is $\sim 5\,\mu$m.

Sensor modules are made with three different cell sizes and with a different number of junction columns: $100 \times 150\,\mu\mathrm{m}^2$ pitch for full compatibility with the available readout chip are made with two (2E) and three (3E) junction columns; sensors with $100 \times 25\,\mu\mathrm{m}^2$ pitch are made with one (1E) and two (2E) junction columns (for the latter we also tested the configuration with bump pads on top of the junction columns in order to clear space between junction and Ohmic columns); sensors with $50 \times 50\,\mu\mathrm{m}^2$ pitch are made with one (1E) junction column. In fig. 3 the Landau MPV is shown as a function of the bias voltage for the different types of sensors. The collected charge is compatible with planar sensors.
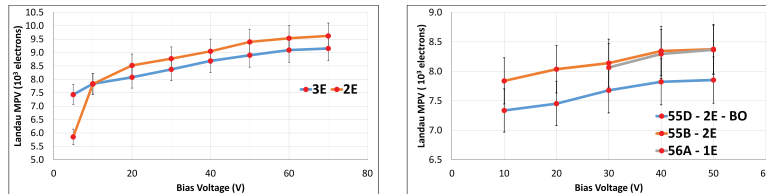

Fig. 3. – Landau Most Probable Value (MPV) *vs.* bias voltage for non-irradiated 3D sensors. The cell size is $100 \times 150\,\mu\mathrm{m}^2$ and $100 \times 25\,\mu\mathrm{m}^2$ for the left and right plot, respectively. Data are reported for different numbers of junction columns (2E and 3E electrodes for the $100 \times 150\,\mu\mathrm{m}^2$ pitch, and 1E and 2E electrodes for the $100 \times 25\,\mu\mathrm{m}^2$ pitch). We also made $100 \times 25\,\mu\mathrm{m}^2$ 2E pitch sensors with bump pads on top of the junction columns (BO).
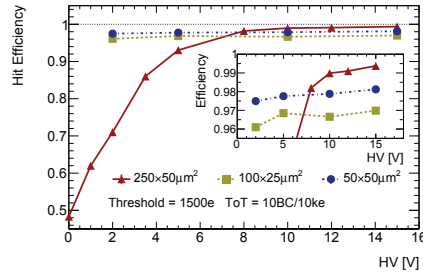
Fig. 4. – Average efficiency *vs.* bias voltage (HV) for three different 3D sensors: $50 \times 50\,\mu\mathrm{m}^2$, $100 \times 25\,\mu\mathrm{m}^2$, and $50 \times 250\,\mu\mathrm{m}^2$ pitch. In the inset a zoom on the efficiency axis is shown. The charge is measured with the Time-over-Threshold (ToT) technique, and the time is measured in terms of bunch crossings (BC).

4. – ATLAS measurements on thin 3D sensors

Testbeam studies on 3D devices bump-bonded to the ATLAS FE-I4 readout chip, $25 \times 250\,\mu\mathrm{m}^2$ cell size, have been performed with the "Aconite" [3] telescope at the CERN SPS H6A beam line with $120\,\mathrm{GeV}$ pions. The telescope has 6 pixel planes based on the Mimosa26 readout chip ($18.4\,\mu\mathrm{m}$ pitch, square pixel cells, 576 rows and 1152 columns) with $\sim 2\,\mu\mathrm{m}$ resolution on each coordinate. Three modules, $130\,\mu\mathrm{m}$ thick, with pitch $50 \times 50\,\mu\mathrm{m}^2$ 1E, $25 \times 100\,\mu\mathrm{m}^2$ 1E, and $50 \times 250\,\mu\mathrm{m}^2$ 2E, were tested, together with a planar $150\,\mu\mathrm{m}$ thick sensor used as a reference.

In fig. 4 the average efficiencies are shown as a function of the bias voltage for all 3D modules: $50 \times 50\,\mu\mathrm{m}^2$ pitch sensors have an efficiency almost flat at $\sim 98\%$ for a bias voltage between 2 and $10\,\mathrm{V}$, with a slight increase of $\sim 1\%$; $100 \times 25\,\mu\mathrm{m}^2$ pitch sensors have a qualitatively similar trend as sensors with $50 \times 50\,\mu\mathrm{m}^2$ cell size; $50 \times 250\,\mu\mathrm{m}^2$ pitch sensors have an efficiency greater than 99% above $\sim 10\,\mathrm{V}$ (ramping up to $\sim 10\,\mathrm{V}$).

5. – Conclusions

The first prototype sensors, both thin planar and 3D columnar, developed within the INFN Pixel R&D Collaboration with the partnership of FBK, show good data quality and the performances are as expected.

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