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Performance of new radiation tolerant thin n-in-p Silicon pixel sensors for the CMS experiment at High Luminosity LHC

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Abstract

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/cm² at ~ 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 and 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 planars, and 130 μm for 3D sensors, the thinnest ones ever produced so far. First prototypes of hybrid modules bump-bonded to the present CMS readout chip have been tested in beam tests. Preliminary results on their performance before and after irradiation are presented.

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Index Terms—pixel, silicon, sensor, planar, 3D, radiation hard, HL-LHC

I. 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 few 10^{16} particles/cm² at ~ 3 cm from the interaction point. This is required to replace the current planar technology silicon detectors which, no matter which 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/cm² in the best case. Indeed after 3000 fb^{-1} , i.e. after ten years of operation, the innermost layer of the pixel detector will be exposed to a fluence of 2.3×10^{16} 1 MeV equivalent neutrons (n_{eq})/cm². The carriers lifetime will be reduced to ~ 0.3 ns, corresponding to a mean free path of $\sim 30 \mu\text{m}$ for electrons at saturation velocity. Candidate technologies which can withstand these very high fluences are thin planar or 3D columnar silicon pixel sensors. To the extent of increasing the signal by increasing the electric field, together keeping the bias voltage within normal operation

conditions (i.e. at most a few hundreds of volts), the distance between electrodes is reduced. Moreover, at the foreseen peak luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ there will be up to 200 interactions/25 ns bunch crossing. In order to maintain the occupancy at $\text{\textperthousand}$ level and to the extent of increasing the spatial resolution, the pixel cell size is foreseen to be $25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$ (the current one is $100 \times 150 \mu\text{m}^2$ and $50 \times 250 \mu\text{m}^2$ for CMS and ATLAS, respectively).

A joint ATLAS-CMS group within INFN, which is collaborating with the foundry 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 proceeding, we will present preliminary testbeam results on their performance before and after irradiation.

II. 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 ($100 \times 150 \mu\text{m}^2$ cell size, 80 rows and 52 columns) [2]. The telescope has 8 pixel planes with $\sim 8 \mu\text{m}$ resolution on each coordinate. Prototype sensors were bump-bonded to the PSI46 digital chip [3], $100 \times 150 \mu\text{m}^2$ cell size, which is fully integrated into the Captan DAQ system.

Fig. 1. Landau Most Probable Value (MPV) vs bias voltage for non-irradiated thin planar sensors. The cell size is $100 \times 150 \mu\text{m}^2$.

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Fig. 2. Landau Most Probable Value (MPV) vs bias voltage for non-irradiated (black circles) and irradiated (red squares) thin planar sensors 100 (upper plot) and 130 μm (lower plot) thick. The irradiation fluence is $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. The cell size is $100 \times 150 \mu\text{m}^2$.

The thin planar sensors are produced with two nominal thicknesses, 100 and 130 μm . The measured thickness is about 10% smaller than nominal due to Boron diffusion from the wafer carrier [4]. 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 distribution convolved with a Gaussian. The charge collection behavior is as expected. The sensors were then irradiated to $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at Los Alamos laboratory with 800 MeV protons and re-tested at the testbeam. The Landau MPV as a function of bias voltage for two sensors thicknesses, 100 and 130 μm , are reported in Fig. 2. The 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.

The auxiliary punch-through structures, crucial for an easy preliminary selection of the sensors prior to their coupling with the chips, cause significant local efficiency losses, see Fig. 3, especially at high bias voltages required for an efficient use of

Fig. 3. Average efficiency map on cell. The efficiency is affected by the punch-through structure (some modules are affected before irradiation, all modules are affected after irradiation). Even and odd columns are shown separately on the upper and on the lower plot, respectively. The cell size is $100 \times 150 \mu\text{m}^2$. The z axis, color scale, represents the efficiency.

the irradiated sensors. This would advise against their use or, at least, would suggest their strong miniaturization in order to confine their effects within smaller area of the sensor.

III. THIN 3D COLUMNAR SENSORS

The 3D silicon sensors are made with a single-sided process optimized by FBK [5]. 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 $\sim 5 \mu\text{m}$.

Sensor modules are made with three different cell sizes and with a different number of junction columns [6]: $100 \times 150 \mu\text{m}^2$ pitch sensors for full compatibility with the available readout chip are made with two (2E) and three (3E) junction columns; sensors with $100 \times 25 \mu\text{m}^2$ 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 $50 \times 50 \mu\text{m}^2$ pitch are made with one (1E) junction column. In Fig. 5 the Landau MPV is shown as a function of the bias voltage for the different types

Fig. 4. Scketh of the production of 3D silicon pixel sensors by Fondazione Bruno Kessler (Trento, Italy) [5].

Fig. 5. Landau Most Probable Value (MPV) vs bias voltage for non-irradiated 3D sensors. In the upper plot the pixels have a cell size of $100 \times 150 \mu\text{m}^2$ while in the bottom plot both $100 \times 25 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$ cell size are shown [6]. Data are reported for different numbers of junction columns (2E and 3E electrodes for the $100 \times 150 \mu\text{m}^2$ pitch, 1E and 2E electrodes for the $100 \times 25 \mu\text{m}^2$ pitch, and 1E electrode for the $50 \times 50 \mu\text{m}^2$ pitch). We also made $100 \times 25 \mu\text{m}^2$ 2E pitch sensors with bump pads on top of the junction columns (BO).

of sensors. The collected charge is compatible with planar sensors. The overall efficiency is greater than 99% for orthogonally impinging particles, even though in correspondence to the junction and Ohmic columns an unavoidable degradation of the efficiency is seen. Complete efficiency uniformity can be recovered with a 10° tilt of the sensors with respect to the impinging particles.

IV. CONCLUSION

First prototype sensors, both thin planar and 3D columnar, developed within the INFN Pixel R&D collaboration with partnership of FBK, show good data quality and the performance is as expected. The radiation campaigns of prototype sensors were limited by the radiation tolerance of the PSI46 digital chip (~ 250 Mrad). In order to push forward our R&D, we need to exploit more radiation-hard readout chips. The first prototype of the RD53 chip (joint ATLAS-CMS collaboration to develop a high-radiation tolerant readout chip in 65 nm CMOS technology for the HL-LHC) will become available by winter 2018. This chip will allow to submit our sensors to the target radiation fluence and to fully exploit the small sensor pitch.

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