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R&D for new silicon pixel sensors for the High Luminosity phase of the CMS experiment at LHC

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Summary. — The High Luminosity upgrade of the CERN LHC collider (HL-LHC) demands a new high-radiation–tolerant solid-state pixel sensor capable of surviving fluencies up to a few 10^{16} n_{eq}/cm^2 at $\sim 3\,\mathrm{cm}$ 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 readout chip, have been tested on beam. The first results on their performance before and after irradiation are presented.

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1. – Introduction

During its High Luminosity phase, the CERN LHC collider (HL-LHC) will deliver an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. After ten years of operation the integrated luminosity will be $\sim$3000 fb^{-1}. The innermost layer of the pixel detector of the CMS experiment, located at $\sim$3 cm from the interaction point, will be exposed to a fluence of $2 \times 10^{16}\, n_{eq}/\mathrm{cm}^2$. In order to properly operate in such harsh environment new pixel sensors must be developed.

One of the most critical design parameter in the development of these sensors is the distance between the electrodes that generate the electric field inside the cells of the sensor. In fact, a kind of golden rule for operating these sensors at high irradiation doses is to collect electrons (the faster carriers) and set the electrode distance at a few electron mean free paths at saturated velocity. This allows for an optimization of the signal while keeping the bias voltage as low as possible. In our case, at a fluence of $2 \times 10^{16}\, n_{eq}/\mathrm{cm}^2$, the electrons lifetime becomes $\sim$0.3 ns and the mean free path at saturated velocity $\sim 30\,\mu$m. The mean free path of the holes will be even lower together with their contribution to the signal. These considerations primarily led to the choice of n-in-p sensors to avoid type inversion in the bulk.

Two different technological solution were available: planar sensors, where the electrodes are parallel to the sensor surface, and 3D sensors, where the electrodes are orthogonal to the sensor surface. In the first case the distance between the electrodes is fixed by the sensor thickness, in the second case it is limited by the technological process used to build the sensor.

The INFN ATLAS-CMS joint research activity, in collaboration with Fondazione Bruno Kessler (FBK), developed new thin n-in-p silicon pixel sensors, employing a recent technology called Direct Wafer Bonding (DWB). Wafers produced using this technology are composed by an underlying p^+-type layer with low resistivity and an upper p-type layer with high resistitivity, which constitutes the active layer of the sensor [1]. The lower layer provides mechanical support and Ohmic contact for the upper layer. Planar sensors are built implanting $n+$ electrodes on the external surface of the upper layer. In the case of 3D sensors, two types of columnar electrodes are implanted: $p+$, which go into the lower layer in order to be polarized, and $n+$, which end $\sim 20\,\mu$m before the low-resistivity layer as shown in fig. 1. The typical elementary structure has a rectangular cross-section with an $n+$ electrode at the center and a $p+$ electrode at each corner. A single pixel cell can be composed by 1 (1E), 2 (2E) or 3 (3E) of these structures. Sensors presented here have $150 \times 100\,\mu\mathrm{m}^2$ pixel cells and are 2E or 3E.

Both 3D and planar sensors fabrication processes take place only on one side of the sensor with a consequent reduction of the costs.

Test-beam studies of both planar and 3D devices have been performed at the Fermilab MTest facility using 120 GeV protons. A telescope of 8 pixel detectors readout by the

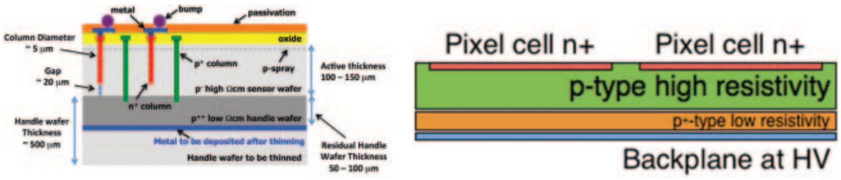

Fig. 1. – Artistic view of 3D (left) and planar (right) sensors.

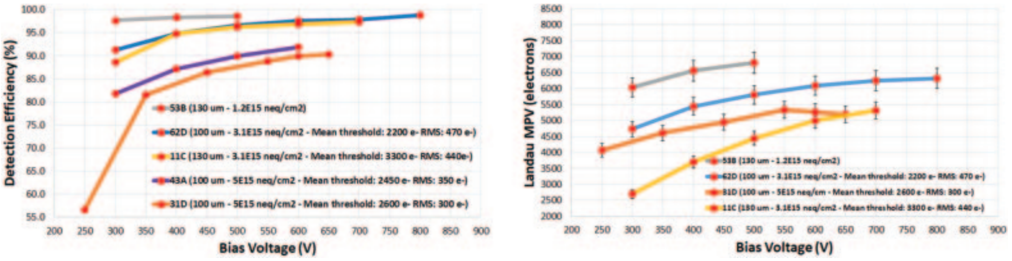

Fig. 2. – Detection efficiency (left) and collected charge MPV (right) as a function of the applied bias voltage for planar irradiated sensors. Active thickness, irradiation fluence and applied threshold are shown for each sensor.

PSI46 analog chip ($100 \times 150\,\mu\text{m}^2$ cell size, 80 rows and 52 columns) is used to reconstruct the proton tracks. The track extrapolation errors on the transverse coordinates at the position of the detector under test were $\sim 9\,\mu\text{m}$. Prototype sensors were bump-bonded to the PSI46 digital chip, $100 \times 150\,\mu\text{m}^2$ cell size. The data acquisition is based on the CAPTAN system developed at Fermilab [2].

The first results from test-beam campaigns of planar and 3D sensors, both before and after irradiation with protons up to a fluence of $\sim 5 \times 10^{15}\, n_{eq}/\text{cm}^2$, will be presented.

2. – Planar sensors

Planar sensors with $150 \times 100\,\mu\text{m}^2$ pixel cells and two different active thicknesses ($100\,\mu$m and $130\,\mu$m) have been tested.

The measured Most Probable Values (MPV) of the collected charge before irradiation are ∼6000 and ∼8000 for $100\,\mu$m and $130\,\mu$m active thickness sensors, respectively, and are consistent with the expectations. Detection efficiency is greater than 99.8% in all the sensors without punch through structures and around 97% for sensors with punch through structure(1).

The measured collected charge and detection efficiency of detectors irradiated at different fluences are shown in fig. 2. As expected, the performance is compromised by the reduced charge collection efficiency. Nevertheless, up to a fluence of $\sim 3 \times 10^{15}\, n_{eq}/\text{cm}^2$, sensors with $100\,\mu$m active thickness and without punch through structure can still reach, at higher bias voltages, their original (before irradiation) performance. At higher fluences, the combined effect of the threshold and an even lower charge collection efficiency further reduces the performance. However, the measurements at $5 \times 10^{15}\, n_{eq}/\text{cm}^2$ demonstrate that much of the performance could be recovered by using a readout chip with a lower threshold (∼1000 electrons) and reducing the dimensions of the punch through structures as much as possible.

3. – 3D sensors

All 3D sensors have an active thickness of $130\,\mu$m. The measurements before irradiation clearly demonstrate that these sensors can reach full performance at bias voltages

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(1) Punch through structures are useful to test the sensor before the bonding to the readout chip.

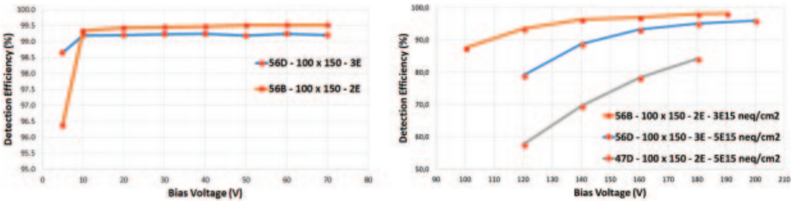

Fig. 3. – Detection efficiency before (left) and after (right) irradiation of 3D sensors with 2 (2E) and 3 (3E) $n+$ electrodes as a function of the applied bias voltage. Irradiation fluence is shown for each sensor.

much lower than the planar sensors of the same active thickness. This is obviously due to the much smaller distance between the electrodes ($62.5\,\mu$m in the worst case). The MPV of the collected charge is comparable with that of planar sensors with the same active thickness. The detection efficiency is intrinsically limited to ~99.2% (worst case) by the presence of the electrodes (see fig. 3). Full detection efficiency is recovered once the sensors are tilted by a small angle: a rotation of five degrees was sufficient to obtain 99.9% efficiency.

Unfortunately, it was impossible to perform any pulse height calibrations of irradiated detectors because the linear outputs of the readout chip became practically digital at these irradiation levels. Detection efficiency measurements on irradiated sensors confirms that a larger number of $n+$ electrodes per cell determines a higher efficiency, as shown in fig. 3. These results are very promising since the 3E sensor can reach a higher than 95% efficiency at a threshold of the order of 3000 electrons.

4. – Conclusions

A full characterization of planar and 3D sensors produced with single-sided technology on wafers obtained via Direct Wafer Bonding has been carried out. Measurements after irradiation with protons at different fluences up to $\sim 5 \times 10^{15}\, n_{eq}/\text{cm}^2$ show that these sensors are promising candidates for the High Luminosity upgrade of the inner tracker of the CMS experiment. We look forward to perform a new campaign of measurements using the new readout chip with higher radiation tolerance and lower threshold which is being developed by the CERN RD53 Collaboration.

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