New radiation tolerant thin planar and 3D columnar $n$–$in$–$p$ Silicon pixel sensors


Abstract—The High Luminosity upgrade of the CERN Large Hadron Collider (HL–LHC) calls for a new high–radiation tolerant solid–state pixel sensor, capable of surviving irradiation fluences up to a few $10^{16} \text{n}_{eq}/\text{cm}^2$ at $\sim$3 cm from the interaction point. To this extent, the INFN ATLAS–CMS joint research activity, in collaboration with Fondazione Bruno Kessler, is aiming at the development of thin $n$–$in$–$p$ type pixel sensors to be operated at the HL–LHC. The R&D covers both planar and 3D pixel devices made with the Si–Si Direct Wafer Bonding technique, which allows for the production of sensors with $100 \ \mu\text{m}$ and $130 \ \mu\text{m}$ active thickness, for planar sensors, and $130 \ \mu\text{m}$ for 3D sensors. First prototypes of hybrid modules, bump–bonded to the present CMS readout chips, have been characterized in beam tests. First results on their performance before and after irradiation are reported in this article.

Index Terms—pixel, Silicon, sensor, planar, 3D, radiation hard, HL–LHC

I. INTRODUCTION

The two general purpose experiments at the CERN Large Hadron Collider (LHC) $^{11}$, ATLAS $^2$ and CMS $^3$, will undergo a major upgrade in order to cope with the High Luminosity program of the LHC (HL–LHC). In particular, the pixel detector of the CMS experiment is designed to be located at $\sim$3 cm from the interaction point. At such a close distance, the 1-MeV neutron equivalent fluence, after 3000 fb$^{-1}$ of collected data, i.e. after ten years of operation, is expected to reach $2.3 \times 10^{16} \ \text{n}_{eq}/\text{cm}^2$. The design of planar silicon sensors currently used in CMS is ultimately limited by the degradation of the signal–to–noise ratio and it can be reliably employed up to few $10^{15} \ \text{n}_{eq}/\text{cm}^2$. Therefore, a new high–radiation tolerant solid–state pixel sensor design, capable to withstand ten times such a fluence, needs to be developed. One of the most critical geometrical parameters in the development of these sensors, is the distance between the electrodes that generate the electric field for charge collection. It is well known, in fact, that in order to operate these sensors at higher irradiation fluences, the input of the pre–amplifier should be connected to the electrode which collects electrons (the faster carriers). Furthermore, in order to keep the bias voltage as low as possible while preserving the largest part of the signal, the distance between opposite sign electrodes should not exceed few times the electrons mean-free-path at saturated velocity.

The best choice is a $n$–$in$–$p$ sensor which avoids type–inversion of the bulk and is less expensive since it allows for a single–sided process $^{12}$. In the considered HL–LHC scenario, the expected electron lifetime becomes $\sim 0.3 \ \text{ns}$ and the mean–free–path, at saturated velocity, $\sim 30 \ \mu\text{m}$ (the mean–free–path of the holes is shorter, hence their contribution to the signal is even smaller).

Two different technological solutions are 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’s active layer thickness, in the second case it is limited by the layout and the technological process used to build the sensor.

To keep the pixel occupancy at per mil level at the expected HL–LHC peak luminosity of $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, and to improve the spatial resolution, the foreseen pixel cell size is of $25 \times 100 \ \mu\text{m}^2$ or $50 \times 50 \ \mu\text{m}^2$. ATLAS–CMS INFN $^{11}$ is collaborating with the Fondazione Bruno Kessler–FBK foundry (Trento, Italy), to develop thin planar and 3D Silicon pixel sensors on $n$–$in$–$p$ 6” Float Zone (FZ) wafers, 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 $n$–type layer with high resistivity. The latter constitutes the active part of the sensor, while the former provides mechanical support and Ohmic contact for the upper layer $^{13}$.

In this article, we will present test-beam results on the performance of such sensors before and after irradiation, up to a fluence of $\sim 5 \times 10^{15} \ \text{n}_{eq}/\text{cm}^2$.

II. SENSOR DESCRIPTION

The dimensions and granularity of the present prototype sensors are designed to be compatible with the readout chip we used for tests, namely, the PSI46 digital chip $^{12}$, currently

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$^6$Fond. Bruno Kessler, Povo - Italy
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$^1$In this case, indeed, both the pixel implants and the guard–ring structure are on the same side.

$^2$The current one is $100 \times 150 \ \mu\text{m}^2$ and $50 \times 250 \ \mu\text{m}^2$ for CMS and ATLAS, respectively.
employed in CMS and consisting of a matrix of 80 rows and 52 columns of $100 \times 150 \, \mu m^2$ pixels.

![Pixel cell n+ Pixel cell n+](image)

**Fig. 1.** Sketch showing the cross section of a thin planar $n$--in--$p$ sensor. The thickness of the high resistivity layer (i.e. active layer) can be 100 or 130 $\mu$m, while that of the low resistivity layer can range from 185 to 50 $\mu$m. The two layers are bonded together with the Direct Wafer Bonding technique [4].

The thin planar sensors (see Fig. 1) are produced with two nominal active layer thicknesses, 100 and 130 $\mu$m. The measured thickness is about 10 $\mu$m smaller than nominal due to Boron diffusion from the underlying $p$--type layer [10]. Therefore the expected Most Probable Value (MPV) for the signal released by an orthogonally incident Minimum Ionizing Particle (MIP) should be about 6300 $e^-$ and 8600 $e^-$ for 100 and 130 $\mu$m thick sensors respectively. The pixel cell dimensions are $100 \times 150 \, \mu m^2$ as those of the readout chip. On some particular sensors, the pixels can also be equipped with bias punch–through structures, as shown in Fig. 2, to investigate their impact on performance.

![Fig. 2. The drawing of the bias punch–through structure. The bias line runs between couples of adjacent pixel columns and biases the punch–through dots of the nearby pixel cells.](image)

Several variants of pixel isolation techniques are implemented. They can be $p$--spray only or $p$--spray with $p$–stop. In addition, $p$–spray implants can be Low, Medium and High, while the $p$–stop rings can be Open or Close. It is worth noting that to properly characterize the isolation performance of these structures, the sensors should be irradiated at much higher fluence than those quoted in this paper. In fact, we can anticipate that in our tests of irradiated sensors we do not observe any anomaly, which can be attributed to lack of pixel isolation, even in the case of $p$–spray only at our maximum irradiation fluence (see Fig. 6).

The 3D Silicon sensors are made with a single–sided process, optimized by FBK [11] and sketched in Fig. 3. Two types of columnar electrodes are implemented: $p^+$ Ohmic columns, which terminate into the underlying layer (i.e. the low resistivity one) in order to be biased, and $n$+ junction columns, which end $\sim 20 \, \mu$m before the low resistivity layer. The nominal column diameter is, for both junction and Ohmic columns, $\sim 5 \, \mu$m.

![Fig. 3. The top figure provides the sketch of the production process of the 3D Silicon pixel sensors by Fondazione Bruno Kessler (Trento, Italy) [11]. Sensor modules are produced with a high resistivity layer (i.e. active layer) thickness of 130 $\mu$m, and with a low resistivity layer thickness of $\sim 500 \, \mu$m. The two layers are bonded together with the Direct Wafer Bonding technique [4]. At the bottom it is reported the layout of the $100 \times 150 \, \mu m^2$ pixel cell with two (2E) and three (3E) junction columns respectively. The Ohmic columns are shown in light green at the periphery of the pixel cells.](image)

Sensor modules are produced with three different pixel sizes and different number of junction/Ohmic columns [12]. Standard sensors, i.e. those with $100 \times 150 \, \mu m^2$ pixel size and therefore fully compatible with the readout chip, come in two flavors: with three (3E) and two (2E) junction columns, see Fig. 3. The non–standard sensors, instead, can have a $50 \times 50 \, \mu m^2$ or $25 \times 100 \, \mu m^2$ pixel size and their cell structure is, respectively, of type 1E and 2E. In each cell the bump pad is typically located next to one of the junction columns except for a variant of the $25 \times 100 \, \mu m^2$ sensor for which it is on the top of a junction column. This is to free space between the junction and Ohmic columns thus reducing the risk of short circuits. While standard sensors can be fully read out, only one sixth of the pixels of the other sensors can be read out. In addition this requires a pitch adapter to match the readout–chip input pad and a special circuit to bias the other pixels that are not read out (see Fig. 4).

### III. Test-Beam Setup, Readout Electronics, and Data Analysis

Test-beam studies, both of thin planar and 3D devices, have been performed at the Fermilab Test Beam Facility with a 120 GeV proton beam. The beam–particle trajectories are reconstructed by means of a telescope of 8 planes of the same pixel detectors employed in the first running phase of CMS (PSI46 analog chip [4]), with $100 \times 150 \, \mu m^2$ pixel cell size, 80 rows and 52 columns. The track extrapolation error at the center of the telescope, where the detectors under test (DUTs) are placed, is $\sim 8 \, \mu$m on both transverse coordinates. The Data Acquisition system (DAQ) is based on CAPTAN [8] boards which read out all telescope planes together with the DUTs.

The DUTs are kept at a constant temperature by means of a cooling system, based on a water–glycol chiller and an
The Landau function (hereafter referred to as MIP-MPV) is a Landau and a Gaussian function. The returned MPV of the charge signals is then fitted with a convolution of sizes, namely boundaries. No fiducial area cut is applied for finer pixel sensor is within a fiducial area of the pixel, 20\( \mu m \) \( ^2 \). The distribution of the charge signals is then fitted with a convolution of a Landau and a Gaussian function. The returned MPV of the Landau function (hereafter referred to as MIP-MPV) is affected by a systematic error of about 5% due to charge calibration circuitry of the readout chip. This error is evaluated demanding statistical consistency (\( \chi^2 = 1 \)) of a sample of MIP-MPVs as measured in each quadrant of a sensor and for several sensors.

The detection efficiency of the DUTs is measured by requiring that the pixel pointed to by the track, or at least one of its eight neighboring cells, be above threshold.

The irradiation of the sensor modules was performed at two facilities: at Los Alamos with 800 MeV protons \([6]\), up to \( \sim 1.2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \), and at CERN IRRAD with 24 GeV protons \([7]\), up to \( \sim 5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \). The irradiation was performed without any cooling and with sensors bump bonded to the readout chip and unpowered. Due to the limited radiation resistance of the PSI46 chip (\( \sim 5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \)), the sensors couldn’t be exposed to higher irradiation fluences. To test the sensors up to the expected fluence at HL–LHC we will use, once available, the first prototype of the RD53 chip \([5]\) (joint ATLAS–CMS collaboration to develop a highly radiation–tolerant readout chip, in 65 nm CMOS technology, for the HL–LHC) which will feature a 50 \( \times \) 50 \( \mu m \) \( ^2 \) granularity.

IV. PERFORMANCE OF THIN PLANAR SENSORS

Figure \([5]\) shows the trend of the MIP-MPV as a function of the bias voltage for two pairs of non–irradiated sensors of different thickness. The charge collected by the non–irradiated sensors matches the expectations. The measured particle detection efficiency is typically around 98% for sensors with a bias punch–through structure and 99.8% for the others.

By contrast, the MIP-MPV trends for three sensors irradiated up to three different values of fluence are shown at the top of Fig. \([8]\). At the maximum fluence of \( \sim 5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \) and 650 V bias voltage, the thin (100 \( \mu m \) thickness) sensor reaches an higher than 90% charge collection efficiency. At the intermediate fluence of \( \sim 3 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2 \), the other thin sensor reaches full charge collection efficiency at about 500 V, while, at the same bias voltage and a fluence more than twice as small, the thicker sensor is still loosing an important fraction.
of the charge. This means that, at the extreme fluence expected at HL–LHC, the thick sensor should be biased at much higher voltages than a thin sensor to deliver the same signal. This well explains the advantage of using thinner detectors for high–radiation applications.

The measured signal spectra, at the highest bias–voltages applied to each sensor, are shown in Figure 7. They are corrected to account for the main factors affecting the calibration circuit of the readout chip when operated at high radiation doses, and, namely, the variation of the bandgap reference–voltage and the change of the amplifier gain at high sensor leakage–current of the order of hundreds of μA.

The measured particle detection efficiency for the same irradiated sensors is shown at the bottom of Fig. 6. For what follows it is important to recall that the sensors have bias punch–through structures except the one at the intermediate fluence. The detection efficiency of the sensor irradiated up to \(5 \times 10^{15} \text{ cm}^{-2}\), doesn’t exceed \(\approx 90\%\) for two reasons: the relatively high threshold set in the readout chip (in order to mitigate the noise hit–rate, we have to set the threshold at around 2800 electrons) and the bias punch–through structure, which can cause a loss of efficiency from 2% up to 6% depending on the bias voltage and irradiation. Indeed, if

![Figure 6: MIP-MPV (top plot) and detection efficiency (bottom plot) as a function of the bias voltage for irradiated thin planar sensors. The sensors have bias punch–through structures except the one at the intermediate fluence. The shaded bands in the top plot reflect the uncertainty of the measurements and of their expected values (dashed lines).](image)

![Figure 7: MIP signal spectra at the highest bias–voltages applied to each sensor of Fig. 6. The applied bias voltages are 500 V, 800 V, and 650 V, respectively. Superimposed on each spectrum is its best fit performed with a convolution of a Landau and a Gaussian function. The main parameters returned by the fit are reported on the plot: Width: Landau natural width; MPV: Landau Most Probable Value; Noise: Gaussian rms.](image)
we limit the calculation of the efficiency only to the half–cells without punch–through structures, we obtain a detection efficiency of $\sim 96.4\%$. To better illustrate this effect, we report in Fig. 8 the maps of the detection efficiency within the pixel cells of the same sensor before the irradiation, at two bias voltages, 40 V (top plot) and 150 V (center plot), and, once irradiated, at a bias of 650 V (bottom plot). The inefficiency, initially limited only to the punch–through dot region, at higher bias voltage starts to affect also the region of the bias grid and, finally, at much higher bias voltage and after the irradiation, it extends to the whole area of the bias grid. The observed loss of efficiency is practically independent from either the active layer thickness, or the $p$–spray and $p$–stop isolation structure. This would advise against the use of punch–through structures or, at least, it would suggest their strong miniaturization in order to confine their effects within the smallest possible area of the sensor.

V. PERFORMANCE OF THIN 3D SENSORS

The MIP-MPV as a function of the bias voltage, measured before irradiation, is shown in Fig. 9 for the standard 3D sensors ($100 \times 150 \mu m^2$ pixel size), and in Fig. 10 for small pitch 3D sensors ($25 \times 100 \mu m^2$ and $50 \times 50 \mu m^2$ pixel sizes).

The collected charge is compatible, within the uncertainties, with that of planar sensors with the same active layer thickness.

The corresponding MIP signal spectra measured before irradiation are reported in Fig. 11 for the standard pitch 3D sensors at a bias voltage of 40 V and in Fig. 12 for the small pitch 3D sensors at a bias voltage of 50 V. The small ridge on the left–hand side of the two Landau function peaks of Fig. 12 is mainly due to the charge–sharing effects with the surrounding pixel cells which are not read out.

The measured particle detection efficiency at a threshold of about 2000 electrons is greater than 99% for orthogonally incident particles (see Table I), even though an unavoidable degradation of the efficiency is observed in correspondence to the junction and Ohmic columns. The complete uniformity of the efficiency can be recovered tilting the sensors by $5^\circ$ with respect to the incident particles.

TABLE I

<table>
<thead>
<tr>
<th>Angle (degree)</th>
<th>Efficiency 3E</th>
<th>Efficiency 2E</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>99.45</td>
<td>99.55</td>
</tr>
<tr>
<td>5</td>
<td>99.75</td>
<td>99.85</td>
</tr>
<tr>
<td>10</td>
<td>99.85</td>
<td>99.87</td>
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Unfortunately, we are not able to show the MIP-MPV as a function of the bias voltage for irradiated 3D sensors because of unreliable calibration of the readout chip due to radiation damage. We believe that during the irradiation campaign of these 3D detectors, the center of the proton beam was slightly offset with respect to the center of the sensor, hence damaging the periphery of the readout chip which is responsible for the digitization of the pulse height. Nevertheless, we measured their detection efficiency as a function of the bias voltage as...
the employed readout chips, excellent up to the maximal irradiation fluence tolerated by use in CMS, PSI46 digital. Their measured performance is has been carried out using the readout chip presently in 3D sensors. A first round of tests on beam of these prototypes fluences expected in HL–LHC. They are both thin planar and silicon pixel sensors capable to resist to the very high radiation developed in collaboration with FBK the first prototypes of new 3D sensors. A first round of tests on beam of these prototypes fluences expected in HL–LHC. They are both thin planar and silicon pixel sensors capable to resist to the very high radiation performance is certainly excellent given the rather high threshold efficiency at a threshold of about 300 V the most irradiated sensor reaches 96% reported in Fig. 13 for orthogonally incident particles. At a bias voltage of 200 V the most irradiated sensor reaches 96% efficiency at a threshold of about ~ 3000 electrons. This performance is certainly excellent given the rather high threshold set. By lowering the threshold to about ~ 2000 electrons we should indeed recover the full detection efficiency.

VI. CONCLUSION

The INFN joint ATLAS–CMS Pixel R&D group has developed in collaboration with FBK the first prototypes of new silicon pixel sensors capable to resist to the very high radiation fluences expected in HL–LHC. They are both thin planar and 3D sensors. A first round of tests on beam of these prototypes has been carried out using the readout chip presently in use in CMS, PSI46 digital. Their measured performance is excellent up to the maximal irradiation fluence tolerated by the employed readout chips, $\sim 5 \times 10^{15}$ n$_{eq}$/cm$^2$. To finally qualify these prototypes for HL–LHC a much more radiation resistant readout chip is required. Nevertheless, on the basis of the present results one can reasonably expect that, operating at a threshold close to 1000 electrons and exploiting the smaller distance between the electrodes of the finer pitch 3D sensors, as in case of 25 x 100 $\mu$m$^2$ and 50 x 50 $\mu$m$^2$ pixel size, full detection efficiency should be achieved at the target irradiation fluence with a bias voltage lower than 300 V. The first prototype of the RD53 readout chip will be available soon and will allow us to verify our expectations.

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REFERENCES
[4] IceMos Technology (Belfast, Ireland) web site: http://www.icemostech.com
Fig. 12. The MIP signal spectra measured, before the irradiation, with a 50×50 μm² 3D, type 1E, sensor (top plot) and with a 25×100 μm² 3D, type 2E, sensor (bottom plot). The spectra correspond to the two measurements reported in Fig. 10 at 50 V bias voltage.

Fig. 13. Efficiency as a function of the bias voltage for irradiated 3D sensors. The threshold of the most irradiated sensor is ~3000 electrons, while the other is ~2000 electrons.


