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LPNHE-FBK Thin n-on-p Pixel Sensors for HL-LHC Upgrade and Beyond

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In view of the LHC upgrade phase towards the High Luminosity LHC (HL-LHC), the ATLAS experiment plans to upgrade the Inner Detector with an all-silicon system. The n-on-p silicon technology is a promising candidate to achieve a large area instrumented with pixel sensors, since it is radiation hard and cost effective. This paper reports on the last n-on-p pixel productions made by a collaboration between the FBK-CMM and the LPNHE in Paris, with some focus on the latest designs of thin sensors bump-bonded to the RD53A prototype chip, featuring a 100×25 and 50×50 μm^2 pixel cells. An overview of 2019-2020 test-beam results for the produced devices will be given, with a special perspective to the sensor design for the ATLAS ITk pixel construction. Preliminary results for new 50 μm thick n-on-p pixel sensors, still produced by LPNHE at FBK-CMM will be also presented.

KEYWORDS: Fabrication technology, Planar silicon radiation detectors, Tracking detectors

1. Introduction

The ATLAS group of the Laboratoire de Physique Nucleaire et de Hautes Energies (LPNHE) of Paris, in collaboration with INFN, has developed a number of pixel sensor productions with Fondazione Bruno Kessler (FBK [1]) of Trento, Italy, in recent years. This paper reports the results of the most recent ones, designed after 2018 and oriented to small-pitch thin sensors aiming in particular to the upgrade of the trackers of the LHC experiments for the HL-LHC phase and beyond.

2. Active edge in thin pixel sensors

In 2018 we designed a thin n-on-p sensor production with FBK to test the concept of active edge based on deep trench. This technology is based on a trench, excavated with ion etching, running all around the sensor and reaching the back implant. It is filled with doped polysilicon, thus extending the back region to the edge wall and creating an equi-potential field-free region preventing the edge current generation from defects due to the dicing [2]. As in the case of some of our previous productions [3, 4] with FBK, it was a collaboration with other groups and it featured many different sensor designs compatible with a number of experiments (see fig. 1, left). With respect to earlier active-edge productions designed by our group, we have implemented here a few innovative features. The most evident one is that instead of using a linear trench, following a continuous line, the trench is

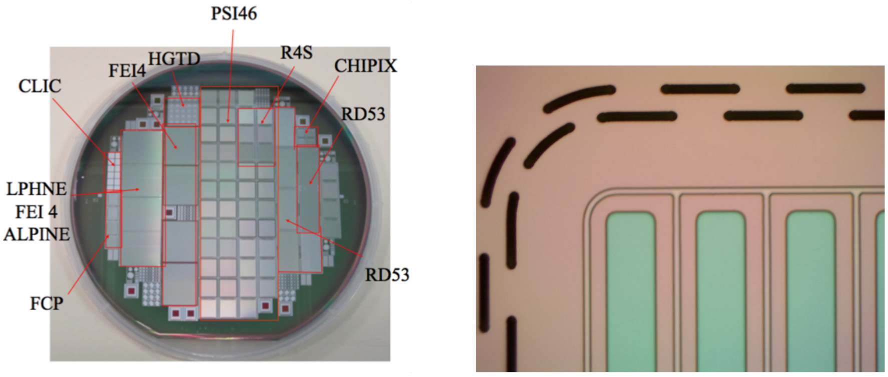

Fig. 1. (Left) Wafer layout of the LPNHE-FBK 2018 active edge production: different sensors aimed to different experiments are outlined; (Right) Detail of the staggered deep trench surrounding the pixel region and enforcing the active edge.

based now on a dashed pattern (see Fig. 1, right). The main reason for this was to ensure improved mechanical stability needed during the wafer post-processing, in particular during the support-wafer removal. In the design, two staggered trench lines are running parallel to each other. The production featured 130 and 100 μm thick 6” wafers bonded to 500 μm mechanical support wafers through a SiSi or SOI process and the trench depth is about 10 μm deeper with respect to the active thickness of the wafers, reaching the support wafer. In many of the devices, small-pitch pixels are featured, designed to be compatible with the RD53A readout chip [5]. They are subdivided into two pixel geometries, the 50 × 50 and the 25 × 100 μm^2. Different biasing schemes are used to allow the characterisation of the sensors before the connection to a readout chip: they include a temporary metal, which is the preferred solution at FBK, and different design of biasing networks based on punch-through [6]. The electrical quality of the sensors turned out to be very good, with typical breakdown voltage before irradiation larger than 200V (see fig.2). The depletion voltage was found to be typically in the range 20-30V depending on the wafer thickness.

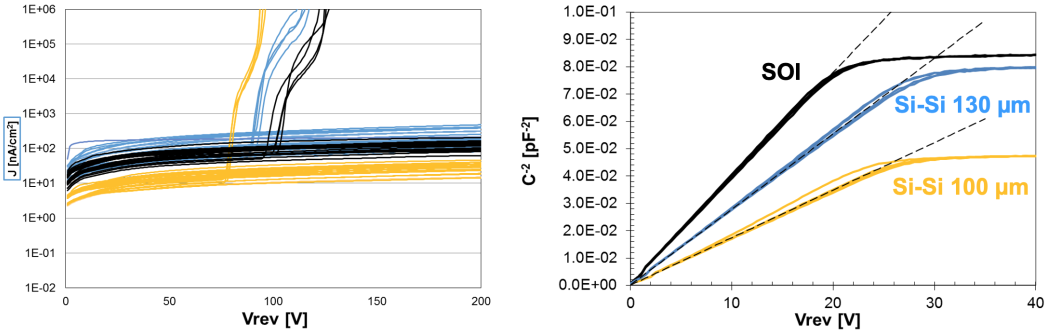

Fig. 2. IV and CV curves measured respectively on sensors and test structures. The typical breakdown voltage before irradiation of the devices is larger than 200V with the wafer depletion voltage between 20 and 30V depending on the thickness. The depletion voltage is smaller for the SOI wafers due to the different resistivity of this batch.

The sensors wafers were then processed at IZM Fraunhofer [7], Germany, in order to perform the under-bump metalization and remove the support wafers, before the dicing of the individual devices and the flip-chip to the readout electronics. The produced modules were characterized at testbeams at CERN with 120 GeV pions and at DESY with 4 GeV electrons before and after irradiation steps up to a maximum integrated fluence of $5 \times 10^{15} n_{eq}/cm^2$. The irradiation were performed with 24 GeV proton beam at CERN PS IRRAD and using a 26 MeV proton beam at KIT, in Karlsruhe [8]. Different features were analysed with testbeam data. The first is the behaviour of the active edge in assuring a significant hit efficiency even in the region close to the border of the device. Sensors with the most aggressive design, in which no traditional guard rings had been introduced between the pixels and the trench were characterised. In these devices the trench is at about 50 μm from the pixel edge. The hit efficiency in the region between the last pixel column and the trench was characterised with 4 GeV electrons at the DESY testbeam before and after the module irradiation to a fluence of $2.7 \times 10^{15} n_{eq}/cm^2$ and the comparison of hit efficiency as a function of the distance from the last pixel column is plotted in fig 3. The x axis represents the distance from the first column of pixels and consequently the last pixel column ends at 20000 μm, marked with the vertical line. The trench is about 50 μm distant from the last pixel and is located at a position around 20050 μm in the plot. Data show that the efficiency is still high in this region, with a benchmark of over 80% up to 25 μm from the last pixel, and this behavior is present also after irradiation. At the same time, the analysis of the plateau indicates a loss of efficiency of about 2% after the irradiation, which is consistent with data from other sensors of the same production. The hit efficiency was studied up to a fluence of $5 \times 10^{15} n_{eq}/cm^2$, which is the benchmark for the planar sensors which will be used in the ATLAS Inner Tracker upgrade. Measurements at the DESY testbeam indicate that the hit efficiency is still larger than 97% at that fluence, thus satisfying the ITk specifications (see Fig. 4).

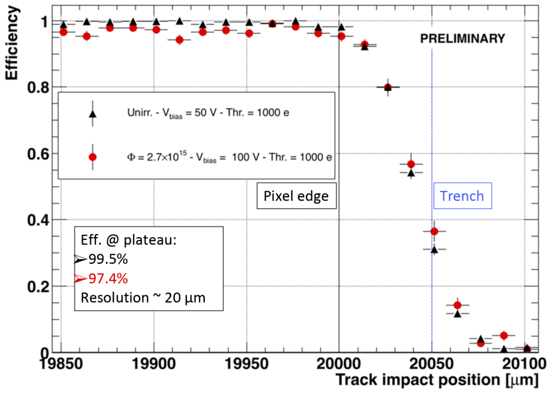

Fig. 3. Hit efficiency as a function of the reconstructed impact position of the track across the sensor before (circles) and after irradiation (triangles) for 4 GeV electrons. The multiple scattering which is present at this energy determines a smear in the reconstructed impact position. For this reason the efficiency is falling smoothly at the edge, with non-zero values even beyond the trench position.

3. Thin small-pitch pixel sensors in preparation for the ATLAS ITk upgrade

More recently another production of n-on-p pixel sensors has been designed by the LPNHE group in collaboration with FBK. This production was more closely related to the R&D for the upgrade of the ITk, but also in the perspective of future experiments. The effort to go in the direction of thin sensors led to three different thickness values, 150, 100 and 50 μm for the 6” wafers. The first two thicknesses are the standard values for the planar sensors used in the ITk, while the third was used for comparison and with the perspective of developing very thin sensors for future trackers used in

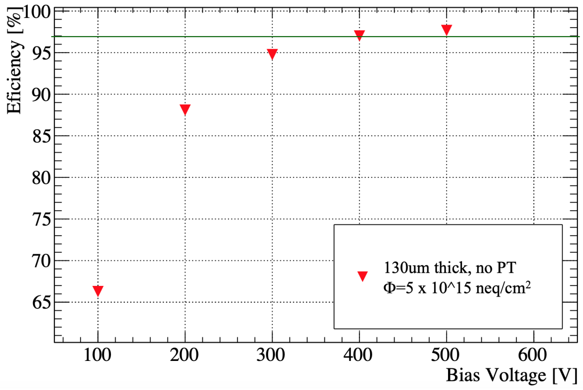

Fig. 4. Hit efficiency as a function of the voltage for 130 μm thick sensors irradiated at a fluence of $5 \times 10^{15} n_{eq}/cm^2$. Almost 98% efficiency is reached at 500V.

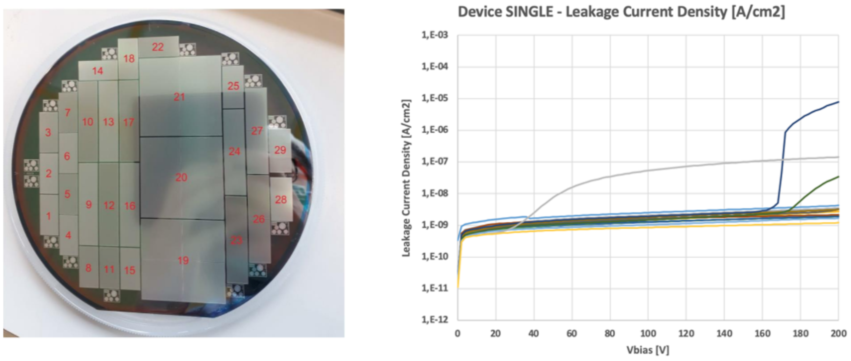

Fig. 5. (Left) Wafer layout of the LPNHE-FBK 2019 thin sensor production: single-chip, double-chip (with double length with respect to the single chips) and quad-chip (the three large structures) sensors are visible; (Right) Electrical behavior of the sensors shown through current-voltage characteristics. Typical breakdown voltage before irradiation is larger then 200V.

High Energy Physics. This has also been possible thanks to the low threshold achievable with the RD53A readout chip, for which the layout was designed through the use of single-, double- and quad-chip sensors (see Fig. 5). As in the previously described production, different biasing systems are implemented in different devices: a temporary metal and a punch-through network with different design options. The pixel geometry was implemented in the two 50×50 and 25×100 μm^2 options, which at the time of the design were the two possibilities foreseen in the planar pixel sensors of the ITk (the 25×100 option for the planar sensors has been recently dropped by the ITk community). No active edge is implemented here, but in agreement with the ITk specifications two different guard-ring systems were used, covering a region of 450 μm and 250 μm for the 150 μm and 100 μm sensor thickness respectively. The electrical behavior of the devices was very good, with typical breakdown voltage before irradiation exceeding 200 V (see Fig. 5, right). Depletion voltage was found in the range 10-15 V (for 100 μm) sensors increasing to 20-30 V for 150 μm devices. After flip-chip bonding at IZM Fraunhofer, a few devices were irradiated to a fluence of $2 \times 10^{15} n_{eq}/cm^2$ ("mid-fluence") and $5 \times 10^{15} n_{eq}/cm^2$ ("high-fluence") in order to study the hit efficiency after radiation damage at testbeams in DESY (see Fig. 6).

Due to the limited time window between the production and the first available testbeam opportunities, we were not able to apply parylene high-voltage protection to these modules, a circumstance

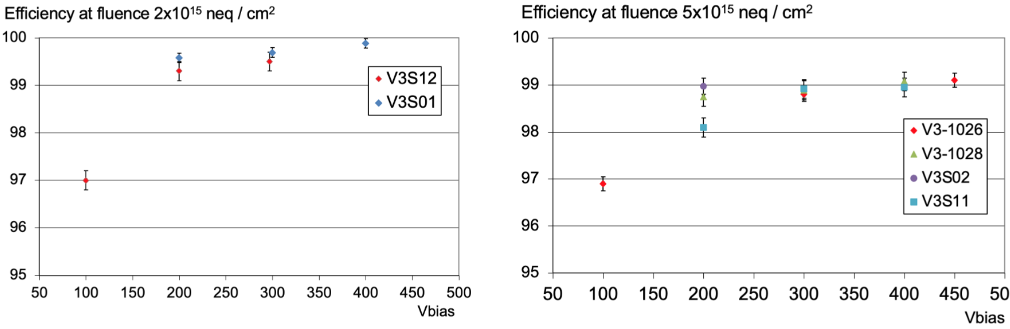

Fig. 6. Hit efficiency as a function of the bias voltage applied to the sensor after irradiation at a fluence of $2 \times 10^{15} n_{eq}/cm^2$ (left) and $5 \times 10^{15} n_{eq}/cm^2$ (right).

which limited their operation to 450 V after irradiation, in order to avoid risks of electrical discharge. Even at this reduced voltage tension, the hit efficiency was shown to be well above 99% for the mid-fluence and above 97% for the high fluence, which is the benchmark required for the ITk sensors. In particular for the high-fluence benchmark, the 97% limit is reached already below 200 V of effective bias voltage.

In the perspective of very thin sensors for future tracking systems, three 50 μm thick wafers have been added to this production and about five modules were built from those devices. In the choice of the sensors we have selected a mix of the biasing networking stuctures (temporary metal, punch-through) and guard ring regions (450 μm, 250 μm) in order to compare at best the different options. After the flip-chip one of the readout chips was found not to be responsive anymore, so we were able to test only the remaining four devices. As in the case of the 100 and 150 μm thick devices, the electrical behavior was found to be very good, with most of the devices not showing breakdown up to 200 V. The depletion voltage was found to be around 20 V with a couple of devices at around 40 V. These values are rather high for this thickness, the reason was not immediately clear and is still under investigation. The modules have been characterised before irradiation at a testbeam in DESY with 5 GeV electrons. While the device with temporary metal is showing a very uniform efficiency, well above 99%, even at very low bias voltage, the devices with punch-through networks lose a few percent of efficiency for perpendicular tracks due to the inefficient regions of the bias dots / rails (see Fig. 7). This effect seems to be more visible with respect to thicker devices and it is even more evident

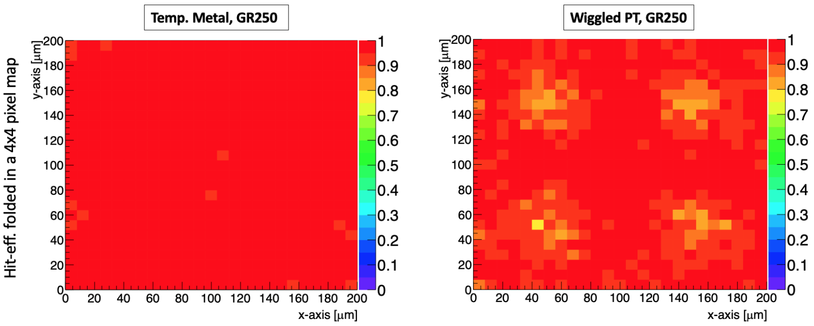

Fig. 7. Hit efficiency map for perpendicular tracks for a 50 μm thick sensor with temporary metal (left) and punch-thorugh biasing network (right). The regions corresponding to the bias dots, where the hit efficiency is penalised, are visible.

at low bias voltage. Measured hit efficiency at different values of bias voltage are summarised in Fig. 8. The modules have now been irradiated up to a fluence of $5 \times 10^{15} n_{eq}/cm^2$ and will be characterised at the next test-beam opportunities.

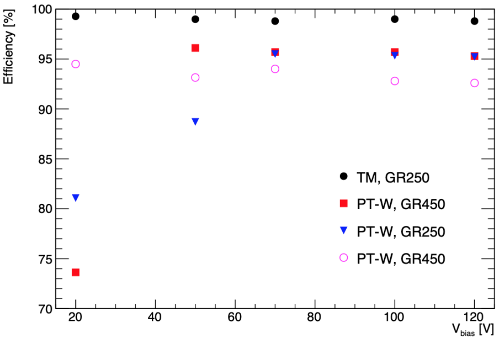

Fig. 8. Hit efficiency as a function of the applied bias voltage for the different 50 μm devices tested on beam. Here TM indicates the module with Temporary Metal, and PT-W the ones with punch-trough networks, with two options of guard-ring (GR) regions. The efficiency in all the devices with punch-through biasing structures is lower with respect to the device featuring a temporary metal and the effect is accentuated at low bias voltage.

4. Conclusion

Results of the most recent productions designed by the ATLAS LPNHE group in collaboration with FBK-CMM are presented. In particular, in the active edge production a novel design of the trench was implemented with staggered units instead of a continuous line, showing very promising results, with still significant hit efficiency in the region between the last pixel and the trench. A more recent production featuring small pitch sensors with device thickness going from 150 μm down to 50 μm has also been presented. The devices were characterised before and after irradiation and were shown to satisfy the benchmark performance required for the sensors in the ATLAS ITk specifications. In the 50 μm thick devices, the performance of sensors with temporary metal is better with respect to the sensors with punch-through structures.

Acknowledgments

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