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3D pixel modules characterization with RD53A readout for ATLAS ITk Upgrade

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Summary. — The High-Luminosity LHC (HL-LHC) with its large number of collisions per bunch crossing will present a very challenging environment to the particle detectors. To cope with these conditions, the current inner detector of the ATLAS experiment will be replaced with a new all-silicon Inner Tracker (ITk) during the Phase-II upgrade. Due to their superior radiation hardness, it has been chosen to instrument the ITk innermost layer with 3D pixel sensors. In this article the new pixel 3D sensor design and technology are reviewed, together with their characterisation before and after exposition to large radiation dose, close to the one expected for the innermost layer of ITk after 2000 fb^{-1} of integrated luminosity delivered by HL-LHC.

1. – Introduction

The Large Hadron Collider (LHC), located at CERN, is the world's largest and most powerful particle accelerator. ATLAS [1] is one of the two general-purpose detectors at the LHC. In order to advance our understanding of elementary particles and their interactions, the LHC accelerator will be upgraded to be able to reach about seven times its current nominal instantaneous luminosity. The so-called High Luminosity LHC (HL-LHC) is foreseen to start operations in 2027. To cope with the higher particle rate, detector occupancy and radiation damage associated to the HL-LHC period, and maintain the overall detector performance, several ATLAS sub-systems will have to be upgraded. In particular, the current ATLAS tracking system will be replaced by a full silicon detector, called ITk, composed by an inner pixel detector [2] surrounded by a micro-strip system [3]. Located in the immediate proximity of the proton-proton beam collision region, with a coverage up to $|\eta| = 4$ the silicon pixel system is critical for the reconstruction of charged particle tracks and vertices, as well as identification of c/b-jets. The HL-LHC presents an unprecedented challenge to the silicon pixel technologies: the detector has to provide excellent position resolution while sustaining radiation levels exceeding $1 \times 10^{16}\,\mathrm{n}_{eq}/\mathrm{cm}^2$ during its lifetime. The inner system, including the first two layers, is planned to be replaced after 2000 fb^{-1}, more than a factor of 10 of the integrated luminosity delivered to ATLAS since the LHC was turned on.

2. – Overview of pixel sensor for ITk detector

The baseline sensor technologies for the ITk Pixel system are 3D sensors for the innermost barrel and endcap layer (Layer 0) and thin planar sensors elsewhere (Layer 1 to Layer 4 in barrel and endcap).

2˙1. *3D pixel sensor*. – 3D silicon detectors are intrinsically more radiation tolerant than other available sensor technologies. The distance between the columnar electrodes, which penetrate the sensor bulk perpendicular to the surface, is decoupled from the device thickness and can be chosen to be significantly smaller than the thickness of the standard planar sensors where the electrodes are implanted in the surface of the device. The reduced electrode distance leads to less charge trapping from radiation-induced defects and lower operational voltages, which, in turn, translates into lower power dissipation after irradiation. The new 3D technology developed for ITk is characterized by an active thickness of 150 μm. The processing is carried out with the use of an handling wafer that is afterwards partially thinned, for a total thickness of 250 μm. The reduced thickness with respect to the 3D sensor generation installed and currently in use in the ATLAS Insertable B-Layer (IBL) [4] (with 230 μm active thickness) allows to decrease the electrode column diameter to a maximum value of 10 μm and to etch both n- and p-type columns from the same side. A lower thickness is also essential to decrease the hit cluster size, especially at large $|\eta|$, and hence the data rate.

During the R&D phase, two different technologies of 3D sensors were chosen: $25 \times 100\ \mu\mathrm{m}^2$ and $50 \times 50\ \mu\mathrm{m}^2$ pixel cell geometry with one electrode. These different sensors will be used in L0 and elsewhere, respectively. The different pixel designs are shown in fig. 1 compared with IBL pixel cell. Three founderies, the Centro Nacional de Microelectronica (CNM) [5], Fondazione Bruno Kessler (FBK) [6] and Sintef [7], have been selected to produce the 3D sensors for ATLAS ITk.

2˙2. *Planar pixel sensor*. – The n-in-p technology has been chosen because it is a single-sided process, simplifying the product flow with respect to the n-in-n technology presently used in the Pixel Detectors of the experiments at the LHC. The active sensor thickness is 100 μm in Layer 1 and 150 μm elsewhere, while the pixel cell sensor size is $50 \times 50\ \mu\mathrm{m}^2$ everywhere. The thickness choice is based on the requirements of radiation hardness and minimization of the material budget weighted against the cost implications of using thinner sensors.

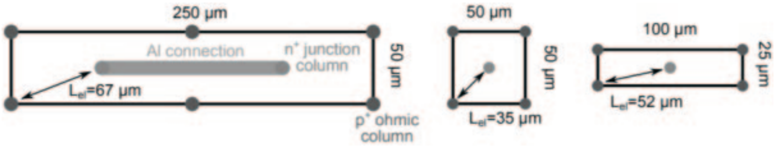

Fig. 1. – Different 3D pixel designs. From left to right: the pixel cell of the 3D pixel sensors employed in IBL, $50 \times 50\ \mu\mathrm{m}^2$ and $25 \times 100\ \mu\mathrm{m}^2$ pixel cells for the ITk innermost barrel layer and rings, respectively.

3. – ITk detector expected tracking performance

The tracking reconstruction efficiency has been evaluated using Monte Carlo sample of $t\bar{t}$ events with a pile-up $\langle\mu\rangle = 200$ [8]. For this sample which is dominated by low transverse momentum (low-p_T) pions, the inclusive efficiency of ITk is between 86% and 92%, depending on the detector region. This is below the single muon efficiency due to the larger interaction rate with the detector material for pions and electrons. In addition the fake rate, defined as the fraction of reconstructed tracks not matched to any single simulated particle traversing the detector, has been evaluated. The fake rate is expected to be reduced by a factor of 10 compared to its value in Run 2, despite an increase of almost a factor of 10 in the pile up. This is due to the higher number of hits per track, the reduced material budget and the better hermeticity of the detector.

Using single muon samples with a pile-up $\langle\mu\rangle = 200$, the expected impact parameters resolution *vs.* η has been studied, for two different energy values, 1 GeV and 100 GeV [8]. The transverse impact parameter resolution for $p_T = 100$ GeV for the $50 \times 50\ \mu\text{m}^2$ pixel pitch will be comparable to the current ATLAS detector. As expected, the intrinsic resolution is improved by a factor of 2 if the $25 \times 100\ \mu\text{m}^2$ pixel cell is used. The resolution in the longitudinal impact parameter for $p_T = 100$ GeV is improved with the ITk compared to the current ATLAS detector for both pixel pitch options, due to the much larger longitudinal pixel size of the IBL (250 μm). For $p_T = 1$ GeV, the resolution is dominated by material effects, and differences between the pixel pitches are relatively small. From the expected performance results, it was recently decided to use $25 \times 100\ \mu\text{m}^2$ pixel technology in the innermost pixel barrel layer of ITk and, to further improve performance, to reduce the innermost ITk layer from 39 mm to 34 (33) mm of the barrel (rings).

4. – RD53A pixel modules

Pixel modules are schematically built in two steps: the first is the hybridization, when one or more front-end ASICs are flip-chipped to a sensor tile, getting a so-called bare module, connecting chip and sensor via bump-bond interconnection; the second step is the module assembly, *i.e.*, the dressing of the bare module with a flex hybrid which connects the module to the on-detector services. By now RD53A front-end chip prototypes [9] developed by the RD53 Collaboration for both the ATLAS and CMS experiments are used for module building and sensor testing. This prototype is only half size the final one (approximately $1 \times 2\ \text{cm}^2$) and contains three different analog front-end designs which are called Synchronous, Linear and Differential. The differential front-end was chosen by the ATLAS Collaboration for the development of the final readout chip.

5. – Beam test measurements of 3D sensors

3D pixel sensors efficiency has been studied in several tests with beam [10]. Sensors are also tested after irradiation in order to study their performance at the end of life.

Pixel modules, assembled with RD53A chips, have been measured in two different beam test facilities: at Super Proton Synchrotron (SPS) of CERN using a 120 GeV pion beam and at the Deutches Electronen-Synchrotronen (DESY) in Hamburg with 5 GeV electron beam. In both cases the EUDET-type telescope [11] has been used to reconstruct the trajectories of the beam particles. At the SPS a custom designed cooling box allows to reach temperatures as low as -50 °C, suitable to study irradiated modules as well as to keep a constant temperature of 20 °C for the operation of non-irradiated modules. At DESY, cooling for operations with irradiated modules is provided by dry ice which allows to reach temperatures as low as the CERN chiller based box, although the control of the set temperature is less precise. The data acquisition systems used to tune and operate the RD53A chips was the YARR system developed at LBNL [12].

5˙1. *Before irradiation.* – Before irradiation 3D sensors with both 50×50 μm^2 and $25{\times}100$ μm^2 pixel cell geometries show a hit efficiency over 97% for perpendicular incident tracks even with a bias of 0 V. Inefficiencies are mainly located in correspondence of the fully passing p-type columns which are inactive. The hit efficiency increases over 99% when the sensors are tilted by 15 degrees. Moreover, the efficiency distribution over the pixel cell is uniform since the particles are not passing all the way through the p-columns.

5˙2. *After irradiation.* – The ITk requirement for the hit efficiency after end of life irradiation is greater than 97%. First results of RD53A modules with 3D sensor 50×50-1E have demonstrated the possibility of reaching the target efficiency of 97% after irradiation at 5×10^{15} n$_{eq}$/cm^2 with a bias voltage of about 40–60 V and after irradiation at 1×10^{16} n$_{eq}$/cm^2 in a bias voltage range of 80–150 V. Similar results are obtained for the 25×100 modules that operate with an efficiency close to 97%, operating modules at 120 V, after an irradiation at both 5×10^{15} n$_{eq}$/cm^2 and 1×10^{16} n$_{eq}$/cm^2.

6. – Conclusions

The ATLAS ITk upgrade is designed to work under the extreme conditions at the High-Luminosity LHC. ITk is designed to be an all-silicon detector, with high granularity, with extended coverage in η and increasing the inner tracker hermeticity.

ITk will bring important improvements on the performance front, allowing the track reconstruction in high luminosity condition, maintaining good reconstruction efficiencies with an important improvement on the fake rate, compared to Run-2 condition. Moreover, ITk will provide excellent impact parameter resolutions. To further improve performances, the ATLAS baseline for the barrel's Layer 0 has been updated by the reduction of its radius from 39 to 34 mm.

Results of the beam tests for 3D pixel modules prototypes are encouraging. The efficiency of 3D pixel modules before irradiation is higher than 97%, and after irradiation at 1×10^{16} n$_{eq}$/cm^2 the efficiency is maintained close to 97% for both 50×50 μm^2 and 25×100 μm^2 sensors operating modules at bias voltage between 80 V and 150 V.

REFERENCES

[1] ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[2] ATLAS Collaboration, CERN-LHCC-2017-021, ATLAS-TDR-030 (2018).
[3] ATLAS Collaboration, CERN-LHCC-2017-005, ATLAS-TDR-025 (2017).
[4] Abbott B. *et al.*, *JINST*, **13** (2018) T05008.
[5] Centro Nacional de Microelectrónica, `http://www.cnm.es/`.
[6] Fondazione Bruno Kessler, `https://www.fbk.eu/`.
[7] Stiftelsen for industriell og teknisk forskning, `https://www.sintef.no/en/`.
[8] ATLAS Collaboration, CERN, ATL-PHYS-PUB-2019-014 (2019).
[9] RD53 Collaboration, CERN, CERN-RD53-PUB-17-001 (2017).
[10] Terzo S. *et al.*, *Nucl. Instrum. Methods A*, **982** (2020) 164587.
[11] Rubinskiy I. *et al.*, *Phys. Proc.*, **37** (2012) 923.
[12] Heim T., *J. Phys. Conf. Ser.*, **898** (2017) 032053.