Overview of Silicon Pixel Sensor Development for the ATLAS Insertable B-Layer (IBL)

S. Grinstein*, on behalf of the ATLAS Collaboration
*Institut de Física d’Altes Energies (IFAE) and ICREA. Universitat Autònoma de Barcelona (UAB), E-08193 Bellaterra (Barcelona), Spain

Abstract—The ATLAS Pixel Detector is the innermost part of the ATLAS tracking system and is critical for track and vertex reconstruction. In order to preserve the tracking performance notwithstanding the increasing instantaneous luminosity delivered by the LHC, ATLAS plans to introduce a new pixel layer (IBL) mounted directly on a reduced diameter beam pipe. The IBL will have to sustain an estimated radiation dose, including safety factors, of $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$. Two sensor technologies are currently being considered for the IBL, planar n-on-n slim edge and 3D double sided designs. Results of the characterization, irradiation and beam test studies of IBL pixel devices are presented.

Index Terms—ATLAS upgrade, pixel detectors, 3D pixels, radiation hardness, high energy physics

I. INTRODUCTION

THE ATLAS [1] Inner Detector (ID) [2] provides charged particle tracking with high efficiency. With three cylindrical barrel layers between 50 and 120 mm around the beam axis (and three forward and backward endcap disks), the Pixel Detector [3] significantly enhances track impact parameter resolution, and therefore, vertex reconstruction and $b$-tagging. These in turn are critical for several ATLAS analyses like searches for the Higgs boson or super-symmetric particles. To further improve the performance of the silicon system and to compensate the possible deterioration that the innermost layer of the pixel detector may suffer after the first few years of operation, the ATLAS Collaboration will insert an additional pixel layer (Insertable B-Layer or IBL [4]) inside the current Pixel Detector during the LHC shutdown planned for 2013-2014. Until complete replacement of the entire inner detector for the high luminosity LHC, the IBL will have to sustain an estimated radiation dose of $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$, where $\text{n}_{eq}$ represents a particle with the non-ionizing energy loss of a 1 MeV neutron.

The baseline design of the IBL is a barrel layer consisting of 14 staves mounted directly on a new (smaller) beam pipe with a tilt angle of $14^\circ$ (see Fig. 1). The average radius of the sensitive area is 33 mm. Each stave is equipped with 16 to 32 modules depending on the final sensor layout. Two sensor technologies are currently under investigation for the IBL modules, planar and 3D sensors. Planar modules are interconnected to two front-end chips doubling their length in the $z$ direction with respect to the 3D modules, which are read out by a single chip. A stave layout being considered combines planar and 3D sensor technologies. Due to space restrictions the IBL modules will have no overlap in the $z$ direction, making imperative the need of very small inactive edges to minimize efficiency losses.

The IBL design assumes an integral luminosity of $550 \text{ fb}^{-1}$ and a peak luminosity of $3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ to determine the sensor requirements. Including conservative safety factors, this translates into a NIEL dose of $5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ and an ionization dose of 250 Mrad. Up to this fluency, IBL modules are required to provide a hit efficiency in the active area $> 97\%$ and a $r - \phi$ resolution better than 10$\mu$m for minimum ionization particles. Other constraints to achieve this efficiency are the operational temperature, set at $-15^\circ$ C, and the maximum bias voltage, set at 1000 V. The power dissipation should not exceed 200 mW/cm$^2$ at the nominal temperature. Finally, the sensor design has to minimize the dead regions, in order to achieve this both planar and 3D sensors target inactive edges of 200$\mu$m.
II. THE FRONT-END CHIP FOR THE IBL

To face the challenges of the radiation and high occupancy environment of the inner radii of the ATLAS ID, while also improving the physics performance of the current system, the front-end readout electronics and the sensor technology used in the present Pixel Detector have to be upgraded and the material budget subjected to tight requirements. The readout chip used in the present detector, the FE-I3 [5], was excluded from the IBL design because its active footprint is too small and its hit rate capability not high enough [4]. The IBL will utilize the FE-I4 integrated circuit [6], designed in 130 nm technology which features an array of 80 x 336 pixels with a pixel size of 50 x 250 μm². The large size of the chip, 20.2 x 19.0 mm², leads to a larger active fraction than its predecessor (89% vs 74%). The sensors will be DC coupled to the chip with negative charge collection. Each readout channel contains an independent amplification stage with adjustable shaping, followed by a discriminator with independently adjustable threshold. The chip operates with an externally supplied clock, nominally 40 MHz. The time over threshold (ToT) with 4-bit resolution together with the firing time are stored for a latency interval until a trigger decision is taken. The primary output rate is 160 Mb/s, four times faster than the output rate of the FE-I3 chip.

III. PIXEL SENSORS FOR THE IBL

Two sensor technologies are being considered for the IBL, planar and 3D sensors. Planar modules consist of 2-chip assemblies while 3D modules consist of a single chip. Both module designs offer similar nominal acceptance. However, the requirements of the two technologies in terms of temperature and bias voltage differ, being less restrictive for 3D sensors. Both technologies have to demonstrate that they satisfy the IBL requirements in terms of performance after irradiation to 5 x 10¹⁵ nₑ/μm². Planar and 3D sensors with the IBL design have been fabricated, and have been interconnected (bump-bonded) with the FE-I4 read out chip. These planar and 3D bare assemblies were wire-bonded to an electronic card to carry out the characterization and test-beam studies need to evaluate the technologies. The wire-bonded devices are also referred to as single chip assemblies.

A. Planar Sensors

The IBL planar sensors rely on the proven technology of the current ATLAS Pixel Detector [7] [8], n-on-n pixels on a diffusion oxygenated flat-zone silicon bulk. The chosen thickness for the substrate is 200 μm, a sizable reduction from the 256 μm featured in the current Pixel Detector. Isolation between the n⁺ implants is obtained through the moderated p-spray technique. A bias grid [7] is integrated into the design to determine the sensor electrical quality before bump-bonding. In order to reduce the inactive edges, the planar IBL design shifts the guard rings on the ohmic side beneath the outer pixels. To keep the sensor length constant, the edge pixels are extended to 500 μm (see Fig 2). A distortion on the electric field on the sensor edge will be introduced by this layout, but the charge collection after irradiation occurs primarily in the region directly beneath the n⁺ implant. The inactive edge of planar devices achieved with this design is around 200 μm (see Section VII).

The planar IBL sensors have been produced at CiS [9] (Germany) which also supplied ATLAS with sensors for the current Pixel Detector.

B. 3D Sensors

The 3D pixel sensor design exploits recent silicon technology advances to produce column-like electrodes that penetrate the substrate, instead of being implanted on the wafer surface [10]. The depletion region thus grows parallel to the wafer surface. The ~ 10 μm diameter columns are alternatively n- and p-type doped defining the pixel configuration. The 3D design is intrinsically radiation hard since it decouples the electrode distance from the bulk thickness, making possible the reduction of the charge collection path without reducing the amount of sensor material the charge particles traverse.

IBL 3D sensors have been manufactured in two production facilities, CNM [11] (Spain) and FBK [12] (Italy), with the same specifications (see also Section IV). The sensors are produced on a 230μm thick wafer with a double sided process, i.e. the n- and p-type columns are etched from the opposite sides of the substrate. The pixel configuration consists of two n-type readout electrodes connected at the wafer surface along the 250 μm long pixel direction, surrounded by six p-type electrodes which are shared with the neighboring pixels, see Fig. 3.

The CNM 3D sensor design features 210 μm long columns which are isolated on the n⁺ side with p-stop implants. The edge isolation is accomplished with a combination of a n⁺ 3D guard ring, which is grounded, and fences which are at the bias voltage potential from the ohmic side (see Fig. 3). The inactive edge region is about 200 μm long. The sensor quality before wafer dicing is evaluated on the 3D guard ring.

The FBK 3D sensor design presents pass-through columns isolated on the junction side with the p-spray technique. A 200 μm long ohmic fence isolates the pixel area from the edges in the z direction. The sensor quality is evaluated before dicing using a temporary metal line that connects 336 pixels into a strip, see Fig. 4. A total of 80 strips that are connected to a probing pad located outside the active region of the sensor, allow to evaluate the electrical characteristics of the device.
Fig. 3. Design of the CNM 3D sensors (top) [13]. The electrodes do not penetrate the full thickness of the sensor. Below a detail of the production mask is shown. The two electrode configuration is visible as well as the 3D guard fence.

Fig. 4. Detail of the FBK 3D design [14]. The temporary metal strips are used to evaluate the electrical characteristics of the device before bump-bonding. After the measurements are completed the temporary metal layer is removed.

IV. SELECTION OF SENSORS FOR THE IBL

Both planar and 3D sensors have to meet the IBL wafer quality and electrical specifications [4]. The most critical parameters to determine the sensor quality are the leakage current and the breakdown voltage. Planar sensors are expected to be fully depleted at 30 V, and required to have a breakdown voltage greater than 60 V. Fig. 5 shows the current versus bias voltage ("I-V") measurements at room temperature for several unirradiated planar sensors after dicing. The entire sensor is biased uniformly through the bias grid structure [7].

The depletion voltage for the IBL 3D sensors is \( \sim 5 - 10 \) V and the breakdown voltage is required to be greater than 25 V. The CNM sensors are evaluated by measuring the I-V behavior on the 3D guard ring. Fig. 6 shows the I-V characteristics of two sensors, before dicing and after bump-bonding. The breakdown voltage improves in the bump-bonded assemblies probably due to the reduction of the stress across the substrate after dicing. The I-V curves can not be directly compared since the measurement after bump-bonding is done on the full sensor. However, the measurement on the 3D guard ring is found to be very indicative of the behavior of the full sensor, since the current is largest on the edge region where the 3D guard ring is located. This has been verified by mapping the leakage current along the bump-bonded assemblies as shown in Fig. 6.

The devices produced at FBK are tested using 80 temporary metal lines that allow to detect fabrication defects on the full sensor before dicing. Fig. 7 shows the I-V characteristics of all the strips in an FBK sensor, the breakdown voltage for this device is above 50V.
Fig. 7. I-V curves measured at room temperature on the 80 temporary metal lines of an FBK device.

TABLE I

<table>
<thead>
<tr>
<th>Name</th>
<th>Technology, Thickness</th>
<th>Edge Design</th>
<th>Fluency ($n_{eq}$/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUB2</td>
<td>Planar, 250 µm</td>
<td>Slim</td>
<td>4E15 (n)</td>
</tr>
<tr>
<td>SCC60</td>
<td>Planar, 200 µm</td>
<td>Slim</td>
<td>5E15 (p)</td>
</tr>
<tr>
<td>SCC24</td>
<td>Planar, 200 µm</td>
<td>Conservative</td>
<td>6E15 (p)</td>
</tr>
<tr>
<td>CNM81</td>
<td>CNM 3D, 230 µm</td>
<td>GR+Fences</td>
<td>5E15 (n)</td>
</tr>
<tr>
<td>CNM34</td>
<td>CNM 3D, 230 µm</td>
<td>GR+Fences</td>
<td>5E15 (p)</td>
</tr>
<tr>
<td>FBK11</td>
<td>FBK 3D, 230 µm</td>
<td>Fences</td>
<td>5E15 (p)</td>
</tr>
<tr>
<td>FBK13</td>
<td>FBK 3D, 230 µm</td>
<td>Fences</td>
<td>Unirradiated</td>
</tr>
</tbody>
</table>

V. IRRADIATION OF IBL DEVICES

In order to investigate the behavior of the devices after the radiation doses required for the IBL, several planar and 3D assemblies were irradiated. The irradiation program was carried out at the Karlsruhe Institute of Technology (Germany) using a 23 GeV proton beam, and at the Jozef Stefan Institute (Slovenia) with reactor neutrons. Though the assemblies were exposed to different fluencies, only results with samples irradiated to fluencies close to the IBL target of $5 \times 10^{15}$ $n_{eq}$/cm$^2$ will be included below. All the samples were annealed for 2 hours at 60°C, accounting for different previous annealing history between the devices when possible. Table I summarizes the samples used in the results presented in the next sections.

VI. CHARACTERIZATION OF IBL DEVICES

Before the performance of the devices is studied in beam-tests, it is necessary to determine the operational parameters in terms of electronics threshold settings, bias voltage and noise. A low threshold setting is desirable to increase detection efficiency, however, the associated increase in noise could deteriorate the overall performance. Similarly, high bias voltages will increment the collected charge, but the increase on the leakage current could raise the device noise beyond acceptable levels.

A priori, each sensor technology has different characteristics, that may influence the operational parameters, for example the input capacitance presented to the electronics. However, both planar and 3D devices were found to be able to operate at thresholds as low as 1000 electrons with similar noise levels of around 150 electrons. Fig. 8 shows the device occupancy as a function of the electronic threshold for a planar device. A 1500 electron threshold was used for beam-test of both planar and 3D devices (see Section VII), allowing a 500 electron safety margin in order to ensure low noise levels.

In the case of the planar device the bias voltage limit is given by the electrical engineering constraints. In principle, it should be as high as possible to increase charge collection. Thus planar devices will be operated at 1000 V after being irradiated to the IBL fluency. In the case of 3D sensors, the electrical constraints of IBL are easily met. However, the operational voltage has to be optimized to ensure good charge collection while maintaining acceptable noise levels. Fig. 9 shows the charge collection and noise occupancy for a proton irradiated CNM device (CNM34) as a function of the bias voltage corrected for the voltage drop across the electronic high voltage filter. The optimal voltage setting of 160 V ensures high charge collection efficiency while maintaining the noise level low. Both CNM and FBK devices were operated at 140-160 V during the test beam studies presented in this article (see Section VII).

VII. TEST-BEAM STUDIES OF IBL DEVICES

Critical performance parameters, such as hit efficiency and position resolution, can only be determined at beam tests. Pla-
Planar and 3D IBL devices were studied in the CERN north area with a 120 GeV π-beam from the Super Proton Synchrotron during June and September 2011. The EUDET [15] beam telescope was used for tracking purposes. The telescope consists of six Mimosa tracking planes, the trigger hardware and the readout data acquisition system, and provides a $\sim 3\mu$m track pointing resolution. The devices under tests are placed between the telescope planes. Data at different incidence angles, $0^\circ$ and $15^\circ$, have been recorded to evaluate the device performance. The $15^\circ$ data, taken with the devices rotated in the long pixel direction, correspond to the approximate expected incidence angle for the IBL configuration. The devices under test were cooled down to the IBL operational temperature by means of dry ice and a heating system was used to regulate the temperature. Fig. 10 shows four devices mounted between the telescope planes and rotated by $15^\circ$ in the long pixel direction with respect to the incoming particle beam.

The hit efficiency is determined from extrapolated tracks on the devices, after track quality cuts have been applied. A hit on the device under test is searched for in a $3 \times 3$ pixel window around the track position.

The hit efficiency for a planar proton irradiated device (SCC60) is shown in Fig. 11 (top). The device was operated at 1000 V and the sensor temperature estimated at $-15^\circ$ C. The plot shows the efficiency as a function of the track hit position folded into a two by two pixel area in order to highlight the pixel structure. Noisy and dead pixels are not considered in the efficiency calculation. The overall efficiency was 97.6% at $15^\circ$ incidence angle. The apparent loss of efficiency in the left side of the pixel is associated to the bias grid structure. Also shown in Fig. 11 (bottom) is the efficiency of the bias grid structure. As expected for the planar device LUB2. The plot shows the efficiency along the long pixel direction, the length of the inactive edge region in this direction is of $\sim 200\mu$m while the overall efficiency is 99.0%. Again, the efficiency loss resulting from the punch through structure associated to the bias grid can be observed.

The hit efficiency for some 3D devices is shown in Fig. 12. The top plot shows the efficiency for a CNM neutron irradiated device (CNM81) operated at a bias voltage of 160 V. For perpendicular tracks the inefficient areas associated to the p$^+$ electrodes are clearly visible. This is not the case for the readout electrodes, which at this voltage, collect enough charge from the region that separates the electrode from the ohmic side to detect the passing particles. The overall efficiency for CNM81 under this configuration is 97.5%. The efficiency loss caused by the electrodes is expected to be larger at normal incidence. The middle plot of Fig. 12 shows the efficiency of a proton irradiated CNM device (CNM34) at $15^\circ$ track incidence angle, operated at 160 V. The associated efficiency for this device in this configuration is 98.7%. The effect of the pass-through electrodes can be seen in the bottom plot of Fig. 12, which shows the efficiency for an unirradiated FBK device (FBK13) at normal incidence and operated at 20 V. As expected for the FBK design, both electrodes show similar regions of lower efficiency. The overall hit efficiency for the device is 98.8%.

The position resolution of the IBL detector will be critical for the physics program. A preliminary estimation of the position resolution of the IBL devices has been carried out based on the residual distribution in two pixel clusters. The position resolution
Fig. 13. Two hit cluster resolution for a proton irradiated FBK device (FBK11). The data was taken with tracks with an incident angle of 15° and with the device operated at 140 V. The estimated resolution is of 9.5µm including the contribution from the track resolution and residual system misalignment.

VIII. CONCLUSIONS

The ATLAS Collaboration will install a fourth pixel layer in 2013-2014. The IBL will be mounted directly on a new beam-pipe at an average radius of 3.3 cm. Two pixel technologies are being evaluated for the IBL, planar and 3D sensors. A possible layout that combines both technologies is under consideration. Planar and 3D sensor pre-productions have been completed and the devices have been characterized and investigated with beam tests. Both technologies performed within the IBL requirements after irradiation to fluencies of $5 \times 10^{15}$ n$_{eq}$/cm$^2$.

REFERENCES