Detailed studies of Full-size ATLAS12 sensors

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The goal of the ITk strip sensor collaboration is to develop a Silicon Microstrip sensor that is suitable for use in the ATLAS Upgrade Inner Tracker (ITk), see earlier talks by S. McMahon and I-M Gregor.

The LoI tracker layout features 5 layers of barrel, and 7 layers of end-cap strip detectors, with a total area of about 200 m².

The main requirements for the sensors stem from the foreseen upgrade from the LHC to the HL-LHC, increasing the luminosity by 5x.

Consequently, the ITk will have to cope with 10x increased radiation levels, corresponding to $1.1 \times 10^{15} \text{n-equivalent/cm}^2$, including safety factor of 2.
Sensor Prototypes: Wafer Description

During the foreseen sensor lifetime, radiation damage will lead to changes in device properties. The voltages required for full depletion will rise, and the sensor is foreseen to operate in partial depletion towards the end of its life.

The sensor will need specifically designed structures to mitigate the risks of breakdown from increased surface charge whilst retaining a low inter-strip capacitance.

A single-sided $n$-in-$p$ sensor offers a trade-off between the above requirements and cost, allowing for operation in partial depletion mode towards the end of its life cycle, see the talk by N. Unno.

The ATLAS12A sensors were manufactured by Hamamatsu Photonics on a 6"/150mm wafer process, using Float-Zone p-type silicon.

The sensors described in this talk are the main sensors cut from the wafers. These are full size, fully functional prototypes for studying the sensor characteristics and uniformity and for the development of detector modules. 120 sensors were delivered in three batches:

- VPX12318: 33 sensors, W600-W650
- VPX12518: 32 sensors, W651-W699
- VPX12519: 35 sensors, W700-W750
- VPX14757: 20 sensors, W751-W785

Talks by K. Hara and M. Mikestikova will cover the studies performed on mini sensors cut from these wafers.
Sensor Prototypes: Sensor Description

- Largest sensor cut from the wafer is a square measuring 97.5mm x 97.5mm, denoted “Outer Cut”. Sensors with 450µm reduced edge metal, denoted “Inner Cut” were made available as well.
- With 1280 read-out strips, 2 field shaping strips and necessary bias rail and guard ring structures, the strip implant pitch becomes 74.5µm
- Strips are arranged in 4 columns with axial orientation, and have a length of 23.9mm
- Strip implants are biased through poly-Silicon bias resistors
- A p-stop trace is present between strips for increased strip isolation
- Strip implants are AC-coupled to readout strips in the top metal layer
- Sensor has a passivation layer with openings for bond pads etc.
Experimental Methods and Results: Mechanical Properties

Mechanical Specifications.

- 310±20 μm Nominal thickness
- Thickness uniformity: ±10μm
- Sensor flatness to be within 200μm when unstressed
- Outer cut: 97540±25 μm x 97540±25 μm size
- Inner cut: 95692±25 μm x 95692±25 μm size
- No chips or cracks at dicing line to extend inwards more than 50μm

Visual inspection and verification of specifications is performed by a non-contact optical Coordinate Measurement Machine, with a precision of <2 μm in X, Y, and ~4 μm in Z
Sensor Mechanical Properties

Mechanical Properties: Coordinate system
- (0,0,0) is fixed to centre of sensor, label & scratchpad are in the bottom right
- measurement grid is a 11x11 matrix with 9.440mm pitch

Mechanical Properties: Method and Results
- Flat plane is fitted to measured space points, and subtracted to obtain net bow
- The lower left plot contains plots of the raw data points, and an interpolated net bow profile (middle plot)
- The lower right plot contains a histogram of the difference between the highest and lowest net bow point for 97 sensors, showing an average of 51.4µm with 12µm RMS
Experimental Methods and Results: Bias Voltage and Frequency Dependence of Parameters

Leakage Current

- Sensors have proven to be very sensitive to environmental conditions during storage and measurement:
  - Measurements taken in cleanroom atmosphere: $T=19\pm2^\circ C$, Humidity = $40\pm10\%$ RH
  - Sensors stored in dry conditions: $T=21^\circ C$, RH<5%, in ESD safe containers
- Right plots contain overlaid IV curves, one plot per batch, running from 0 to -1000V
- Below is a histogram of the leakage current at -600V bias of 95 sensors. Average is almost 3 orders of magnitude below specification of 200 $\mu A$

![Histogram of leakage current at -600V bias]
**Sensor Bulk Capacitance**

- Very uniform behaviour across sensors. $V_{\text{depletion}} = 366 \, \text{V}$, $\text{RMS} = 8.3 \, \text{V}$, or 2%, for 92 sensors measured.
- Extracted active depth is $301 \, \mu\text{m}$ with a nominal wafer thickness of $310 \, \mu\text{m}$.
- Uniformity in results indicates very well controlled backplane implant depth.
- Doping concentration estimated from slope, flat region agree within 5%.
Frequency dependence of $C_{\text{bulk}}$

Bulk Capacitance – frequency and bias voltage dependence

- Very uniform and smooth behaviour. Steady values for most bias voltages between 1 and 6 kHz.
- Drop in capacitance at higher frequency probably due to bias resistance & strip implant impedance forming a lossy transmission line.
**Strip Coupling Capacitance**

Coupling Capacitance measured in isolation:

- Typical result shown for sample strip of wafer VPX12519-W746, measured between strip implant and metal strip directly
- Smooth behaviour in 600Hz-2kHz region, for bias voltages in -50 to -500V range
- Simultaneous measurement of implant resistance confirms measurement frequency should be between 600Hz-2kHz
- Nominal value 25.7 pF/cm – well within specification of >20 pF/cm. More results on the bulk of the sensors is included towards the end of this talk

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**Strip Coupling Capacitance vs Frequency and Bias Voltage**

- **Capacitance (pF)**
  - Frequency (Hz)
  - Bias (V) = {-50, -100, -150, -200, -250, -300, -350, -400, -450, -500}

**Strip Implant Resistance**

- **Resistance (MΩ)**
  - Frequency (Hz)
  - Bias (V) = {-50, -100, -150, -200, -250, -300, -350, -400, -450, -500}
The Punch-Through Protection circuit is incorporated to protect the sensor and front-end electronics to excessive charge liberated in the bulk, for example as the result of a beam splash.

The strip implants continue under the bias resistors, leaving a 8 μm gap to the bias rail, see the bottom left picture. Soft breakdown will occur across this gap above a certain potential threshold. The PTP structure on the ATLAS12 sensors is of the fully gated design, see the talk by M. Mikestikova later today.

A static measurement consists of performing an I-V scan across the bias resistor of a biased sensor. The maximum voltage, current are set to 50V, 50μA respectively.

As can be seen from the plot in the bottom right, the resistance across the gap changes from bias resistance to less than 100 kΩ at a distinct threshold. The result shown is typical for the sampled channels across the batches.
Inter-strip Capacitance

Inter-Strip Capacitance Measurements

- Measure the capacitance between strip metal and its direct neighbours using an LCR meter
- Value determined by strip metal geometry, and top surface layout
- Plots contain results typical for the strips sampled across sensors from 3 batches
- Frequency dependence measurement suggests LCR frequency should lie in 50-100 kHz interval (note: response below 10kHz depends largely on measurement setup details)
- Nominal value is 0.77 pF/cm, measured at 100kHz. This is within specification of <0.8pF/cm, and in good agreement with earlier results, confirming findings from collaborating institutes
- Measurements including the next neighbouring strips yield 10-15% higher values
Inter-strip Resistance

Inter-Strip Resistance is measured by imposing a voltage (-5...5V) on a strip implant, and measuring the current running through the bias resistor of the neighbouring strip implant, by measuring the imposed voltage with a high-impedance instrument.

- Typical result for the induced current on a sample strip for various bias voltages is plotted at the bottom left.
- The results are well within specification of >10xRbias (15 MΩ)
- Extracted Inter-Strip Resistance is plotted on the right, against bias voltage. The error bars stem from the statistics of this delicate measurement; the maximum resistance that can realistically be measured by the setup used is estimated around 30 GΩ.
Experimental Methods and Results: Strip Scans

For scanning the leakage current, Coupling Capacitance and Bias Resistance of all strips of a sensor, the following “full strip test” protocol is used for a single strip:

1. Connect the strip metal to the SMU set at 10V, and measure the leakage current. If the current is above a set threshold, the strip is marked as having a short and the measurement skips to the next strip

2. Increase the voltage to 100V and record the current

3. Connect the strip to GND

4. Connect the strip to the LCR meter, and measure the R-C series network of bias resistor and coupling capacitance. Record the results

5. Connect the strip to GND, and move to the next strip

The first batch, VPX12318, has been measured using a single needle setup, where the probestation chuck is moved to test every single channel individually. The z-height and contact overdrive of the needle is set once for the whole of the sensor.

For strip tests of the batches VPX12518 and VPX12519, a custom 32 channel low-leakage probecard with associated switching equipment is used.

Through the edge sense feature of the probecard, the z-height and probestation chuck overdrive is recalibrated (and recorded) upon every touchdown. This greatly increases the reliability and consistency of the contact quality between probecard needles and strip metal.
Strip Scan Results

The plots contain a typical result for a full strip measurement of a sensor showing no defects.

- The recorded current is probably SMU meter noise imposed on the probecard leakage current
- A repeating 32 channel pattern is visible in the coupling capacitance, bias resistance plots due to the non-uniformity of the probecard channels
- The trends in the coupling capacitance, and bias resistance plots are a sensor feature, not a measurement artefact
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Strip Scan Result Summary

Map of faulty strips of 81 sensors, grouped per batch.

- Strips marked **blue** have a high current due to a pinhole or a short, strips marked **red** have an out-of-range bias resistance
- Other faults are virtually absent
- Batch VPX12318 is probed with the single needle technique, which might result in false strip failures due to a bad needle contact
- In general, very low number of defects: 111 strips in 81 sensors probed.
- Faulty strips seem randomly distributed, no obvious geometrical correlation visible
- Fewer defects found than indicated by HPK
Strip Scan Result Summary

The plots on the left contain summary data of the coupling capacitance and bias resistance of 81 sensors (over 400'000 channels) probed across three batches

- The tail in Rbias values for the first batch might be due to the variability in contact quality when using a single needle at fixed z height.
- All sensors fall well within tolerance
- Very tight distributions: around 1 pF RMS spread on the capacitance, and around 50 kΩ RMS on the bias resistance indicate a good consistency of the processing, both across a sensor surface as well as across sensor batches
4. Summary and conclusion

Sensors as delivered have high yield: virtually all sensors delivered fall well within specifications.

The table below lists the properties that were measured in reasonable quantity across the batches.

Other properties listed in the specifications document, such as typical top metal resistance, implant resistance, were measured on a small sample basis. No discrepancies between the measurements and specifications were found.

From the measurement data, the conclusion must be that the sensors delivered by HPK are of consistent, high quality, satisfy the requirements and are suitable for our application.

<table>
<thead>
<tr>
<th>ATLAS12 property</th>
<th>specification</th>
<th>measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum bow</td>
<td>&lt;200 µm</td>
<td>&lt;100 µm (avg 51.4µm)</td>
</tr>
<tr>
<td>Leakage current @ 600V bias</td>
<td>&lt;200 µA</td>
<td>&lt;350 nA for 95% of sensors</td>
</tr>
<tr>
<td>Depletion Voltage</td>
<td>&lt;300V, wafer resistivity allowing</td>
<td>364±7.2V</td>
</tr>
<tr>
<td>Bias resistor value</td>
<td>1.5±0.5 MΩ</td>
<td>1.5±0.1 MΩ or better</td>
</tr>
<tr>
<td>Inter-strip Resistance</td>
<td>&gt;15±5 MΩ</td>
<td>&gt;30 GΩ</td>
</tr>
<tr>
<td>Inter-strip Capacitance</td>
<td>&lt;0.8 pF/cm</td>
<td>~0.77 pF/cm</td>
</tr>
<tr>
<td>Coupling Capacitance</td>
<td>&gt;20 pF/cm @ 300V</td>
<td>26.5 pF/cm</td>
</tr>
<tr>
<td>Percentage good strips</td>
<td>&gt;98% per segment</td>
<td>&gt;99.97%</td>
</tr>
</tbody>
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