The upgrades to the ATLAS and CMS experiments, in view of the HL-LHC program, require the supply of silicon sensors on a much larger scale than for previous projects in High Energy Physics. Following the Market Survey MS-4086/EP, this is one of a series of three Invitations to Tender for the supply of silicon sensors, one each for the ATLAS ITk Strips, CMS Outer Tracker and CMS HGCAL upgrade projects respectively.

This technical specification concerns the supply of silicon sensors for the CMS Outer Tracker project.

The provisions of this Technical Specification shall prevail on the General Conditions of CERN Contracts (CERN/FC/6211-II). The General Conditions of CERN Contracts shall apply insofar as they are neither countermanded nor expressly modified in this Technical Specification.
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<th>Definition</th>
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<tr>
<td>2S</td>
<td>10x10 cm strip sensor for modules with 2 Strip sensors</td>
</tr>
<tr>
<td>AC, DC</td>
<td>Alternating Current, Direct Current</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC Apparatus, a general-purpose detector at LHC</td>
</tr>
<tr>
<td>CERN</td>
<td>European Organization for Nuclear Research</td>
</tr>
<tr>
<td>CMS</td>
<td>Compact Muon Solenoid, a general-purpose detector at LHC</td>
</tr>
<tr>
<td>CV</td>
<td>Capacitance vs voltage</td>
</tr>
<tr>
<td>ENIG</td>
<td>Electroless Nickel Immersion Gold</td>
</tr>
<tr>
<td>ESD</td>
<td>Electro Static Discharge</td>
</tr>
<tr>
<td>FZ</td>
<td>Float zone, a silicon material being fabricated with float-zoning method</td>
</tr>
<tr>
<td>GDS</td>
<td>Graphic Data System</td>
</tr>
<tr>
<td>GeV</td>
<td>Giga electron Volt, a unit of energy, $10^9$ eV</td>
</tr>
<tr>
<td>HGCAL</td>
<td>High-Granularity Calorimeter for the endcaps of CMS at HL-LHC</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>High-Luminosity LHC, a upgraded LHC with 5 times larger collision rate and 10 times larger collected data</td>
</tr>
<tr>
<td>HPK</td>
<td>Hamamatsu Photonics Kabushiki kaisha</td>
</tr>
<tr>
<td>ITk</td>
<td>Inner Tracking detector, a detector system inside the solenoid magnet of ATLAS detector</td>
</tr>
<tr>
<td>IV</td>
<td>Current vs voltage</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider, an accelerator colliding protons at 7 TeV each</td>
</tr>
<tr>
<td>MS</td>
<td>Market Survey</td>
</tr>
<tr>
<td>OT</td>
<td>(CMS) Outer Tracker</td>
</tr>
<tr>
<td>PS</td>
<td>Proton Synchrotron, to accelerate protons to 25 GeV</td>
</tr>
<tr>
<td>PS-p</td>
<td>5x10 cm macro-pixel sensor for modules with one Pixel and one Strip sensor</td>
</tr>
<tr>
<td>PS-s</td>
<td>5x10 cm strip sensor for modules with one Pixel and one Strip sensor</td>
</tr>
<tr>
<td>QA</td>
<td>Quality Assurance</td>
</tr>
<tr>
<td>QC</td>
<td>Quality Control</td>
</tr>
<tr>
<td>QR code</td>
<td>Quick Response Code, a 2-dimensional bar code</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RT</td>
<td>Room Temperature</td>
</tr>
<tr>
<td>SPS</td>
<td>Super Proton Synchrotron, to accelerate protons to 450 GeV</td>
</tr>
<tr>
<td>TeV</td>
<td>Tera electron Volt, a unit of energy, $10^{12}$ eV</td>
</tr>
<tr>
<td>TTV</td>
<td>Total Thickness Variation</td>
</tr>
<tr>
<td>UBM</td>
<td>Under Bump Metallisation</td>
</tr>
<tr>
<td>Vfd</td>
<td>Full Depletion Voltage</td>
</tr>
<tr>
<td>Wirebonding</td>
<td>Ultrasonic aluminium-wire wedge bonding</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

1.1 Introduction to CERN

CERN, the European Organization for Nuclear Research, is an intergovernmental organization with over 20 Member States\(^1\). Its seat is in Geneva but its premises are located on both sides of the French-Swiss border (http://cern.ch/fplinks/map.html).

CERN’s mission is to enable international collaboration in the field of high-energy particle physics research and to this end it designs, builds and operates particle accelerators and the associated experimental areas. At present more than 11 000 scientific users from research institutes all over the world are using CERN’s installations for their experiments.

The accelerator complex at CERN is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. The flagship of this complex is the Large Hadron Collider (LHC) as presented below:

![CERN Accelerator Complex](http://home.web.cern.ch/about/member-states)

Further information is available on the CERN website: [http://cern.ch](http://cern.ch)

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\(^1\) [http://home.web.cern.ch/about/member-states](http://home.web.cern.ch/about/member-states)
1.2 Introduction to HL-LHC
The Large Hadron Collider (LHC) is the most recent accelerator constructed on the CERN site. The LHC machine accelerates and collides proton beams but also heavier ions up to lead. It is installed in a 27 km circumference tunnel, about 100 m underground. The LHC design is based on superconducting twin-aperture cryo-magnets which operate in a superfluid helium bath at 1.9 K.
High Luminosity LHC (HL-LHC) is a project aiming to upgrade the LHC collider after 2020-2025 in order to maintain scientific progress and exploit its full capacity. By increasing its peak luminosity by a factor five over nominal value it will be able to reach a higher level of integrated luminosity, nearly ten times the initial LHC design target. To this aim, HL-LHC is exploring new beam configurations and new advanced technologies in the domain of superconductivity, cryogenics, rad-hard materials, electronics and remote handling.

1.3 Introduction to CMS
The Compact Muon Solenoid, or CMS (http://cms.cern.ch), is a particle physics experiment at the Large Hadron Collider (LHC) at CERN. The CMS detector is designed to study particles produced in high-energy proton-proton and heavy ion collisions to seek answers to fundamental questions such as: “understanding why the world is the way it is, why some particles weigh more than others and what constitutes the dark matter in the Universe”. The CMS detector is located 100 m underground at the French village of Cessy near Geneva. The experiment is in operation and the data now being collected by CMS is distributed to institutes around the world to be analysed. The CMS collaboration\(^2\) (hereafter “the CMS collaboration”) involves 4300 particle physicists, engineers, technicians, students and support staff from 179 universities and institutes in 41 countries. As part of the future contract, CERN will delegate several activities to the CMS collaboration, including but not limited to technical project coordination and performance of acceptance tests.

1.4 Introduction to the Silicon Sensors for the CMS Tracker Phase-2 Upgrade Project
The CMS detector needs to be substantially upgraded in order to exploit the increase in luminosity provided by the HL-LHC. This upgrade is referred to as the CMS Phase-2 Upgrade. The increase in radiation levels requires improved radiation hardness, while the larger pileup and associated increase in particle density requires higher detector granularity to reduce occupancy, increased bandwidth to accommodate higher data rates, and improved trigger capability to keep the trigger rate at an acceptable level while not compromising physics potential.
To achieve that, the entire silicon tracking system, presently consisting of pixel and strip detectors, will be replaced. The new tracker will feature increased forward acceptance, increased radiation hardness, higher granularity, and compatibility with higher data rates and a longer trigger latency. In addition, the tracker will provide tracking information (on tracks above a configurable transverse momentum threshold) to the L1 trigger, information presently only available at the High-level Trigger stage. This will allow the trigger rates to be kept at a sustainable level without sacrificing physics potential.

The tracking system will consist of two distinct subsystems. The innermost part or Inner Tracker will be based on silicon pixel detector technology with small 2500 $\mu$m\(^2\) pixels. The radial region from...
200 mm to 1200 mm will be covered by the Outer Tracker and is based on silicon strip and macro-pixel technology.

To cope with the increased radiation levels during HL-LHC operation, a sufficiently radiation hard sensor technology is necessary. A comprehensive R&D campaign conducted over the past 10 years concluded that silicon strip and macro-pixel sensors made in n-on-p technology using high resistive float zone silicon are the best candidates for the Outer Tracker. Such sensors are able to provide sufficient signal-to-noise ratio for minimum ionising charged particles at manageable operating conditions (voltage and current requirements, power dissipation and cooling) while surviving the full projected lifetime of 10 years even at the highest fluences estimated for the new Outer Tracker.

For the Outer Tracker, two different sensor types will be used: DC coupled macro-pixel sensors called PS-p and AC coupled strip sensors in two different designs called PS-s and 2S sensors. These sensors will be operated at a temperature of -20°C as detectors for charged particles within a high radiation environment with fluences of up to $1\times10^{15}\text{n}_{\text{eq}}/\text{cm}^2$, a magnetic field of 4 T and a dry air or nitrogen atmosphere.
2 SCOPE OF THE SUPPLY

The successful bidder (hereinafter referred to as the “contractor”) shall supply all the silicon strip sensors, macro-pixel sensors and the corresponding test structures and documentation (hereinafter referred to, in whole or in part, as the “supply”) as defined in this technical specification and its annexes. The supply must originate from CERN Member States, ATLAS or CMS Member States (as specified in the tender form).

2.1 Deliverables Included in the Supply

The supply consists of silicon strip and macro-pixel sensors, the related documentation as well as test structures and other devices, as defined in the present technical specification in accordance with the quantities defined in the tender form.

- The first 5% of the supply are considered as the “Pre-Production” units (sensors);
- The remaining 95% of the supply are considered as the “Production” units (sensors);

CERN may order additional units as an option, in accordance with section 2.4 below.

2.2 Activities performed by the Contractor

The contractor shall perform the following activities:

- Adjust the designs delivered by CERN to the production process implemented by the contractor;
- Production of the lithography masks from the designs provided by CERN;
- Production of processed wafers;
- Dicing of the wafers into sensors with the required precision specified in section 3.2.3;
- Quality control, inspection, acceptance testing, as specified in section 3.6;
- Documentation, as specified in section 3.7;
- Packing;
- Shipping, if so requested by CERN;
- Storage of the lithography masks for at least three years after the production has finished to enable additional orders with the same design as defined for the options described in section 2.4 and in the tender form;
- Active participation in monitoring group providing feedback on possible acceptance test issues, as described in section 4.5.1.

The start of the Pre-Production must be contingent on completion of the Pre-Series (if this option has been ordered, see section 2.4) according to the delivery schedule, and conformity of the Pre-Series sensors with the requirements described in section 3.

The start of the Production must be contingent on completion of the Pre-Production according to the delivery schedule, and conformity of the Pre-Production sensors with the requirements described in section 3.

If the sensors delivered during Pre-Series or Pre-Production do not conform to the technical requirements defined in section 3, CERN reserves the right to:

1. review and optimize the production process together with the contractor to facilitate an increase of the production quality and yield;
2. adapt the technical requirements together with the contractor to ensure that the quality of the delivered sensors matches the requirements of the experiment;

3. terminate the entire contract without any compensation due to the contractor(s) for such termination if no acceptable mitigation can be found with the previous two actions.

Upon acceptance of Pre-Production by CERN, any changes to the manufacturing process shall be subject to CERN’s prior approval in writing.

2.3 Documents, files provided by CERN

CERN will provide the detailed GDS files for each of the three sensor designs and the accompanying test structures, including information on the layout of the wafer. The provided layout will not be camera ready but a representation of the structures on the sensor after processing. The contractor is expected to derive the final design of the sensors based on the GDS files provided. Effects like over-/under-etching or implant diffusion are not taken into account and shall be corrected for by the contractor. Final values of the spacing of p-stops, metal overhang, guard ring geometry and similar layout optimization details are the responsibility of the contractor. The wafer layouts will be optimized for 6” production technology. Any modification of the finished on-wafer values of more than 1 µm shall be agreed in writing with CERN.

2.4 Options

During the execution of the contract, CERN also reserves the right to order:

1. Up to 500 Pre-Series units to be delivered before production of Pre-Production units;

2. Up to 15% additional sensors of each type as specified in section 2.1, using the identical mask set. Any such additional orders will be communicated to the contractor in a timely manner and not later than six months prior to the last foreseen delivery date;

3. Application of UBM for PS-p wafers using electroless nickel immersion gold (ENIG) technology and subsequent dicing;

4. Any surplus of good Production sensors from the production run.
3 TECHNICAL REQUIREMENTS

3.1 General Description

The supply must consist of n-on-p type AC-coupled strip sensors in two different designs called 2S and PS-s sensors and of n-on-p type DC-coupled macro-pixel sensors called PS-p, fabricated on 6” processing lines. The wafer material must be either standard pre-thinned p-type float zone wafers of 320 µm thickness with a thick backside implant of 20-30 µm (hereinafter referred to as “FZ290”). Or thinned p-type wafers with a target thickness of 200 or 240 µm and only a thin backside implant of about 1 µm or more (hereinafter referred to as “thFZ200” and “thFZ240”).

The contact pads must be able to withstand probing with commonly-used probe needles during the quality assurance measurements. The connection to the readout chips will be done using standard ultrasonic aluminium wire wedge bonding (hereinafter referred to as “wirebonding”), therefore all pads on the front side and the full sensor backside must be compatible with this technology.

High voltage stability and low current operation of the sensors shall be ensured using guard ring(s) and an appropriate sensor periphery which must include a p+ edge implant to protect the active sensor area from damage at the cutting edge. Dicing with better than ±10 µm precision is essential since the sensor edges are used for precision alignment during module assembly.

The backside of the sensors must be covered by a uniform aluminium metallisation of wire bondable quality with a good ohmic contact to the bulk of the sensor using a p+ implant. The frontside shall be passivated with the exception of the contact and wirebonding pads of the implant and readout strips and parts of the bias and guard rings.

Each delivered sensor or sensor pair shall be accompanied by four halfmoon shaped cut-offs from the same wafer. These halfmoons must contain all the test structures and test sensors as defined in section 2.3.

Table 1 below summarises the estimated total number of sensors to be delivered:

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Sensor Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2S sensor</td>
<td>17050</td>
</tr>
<tr>
<td>PS-s sensor (2 per wafer)</td>
<td>6234</td>
</tr>
<tr>
<td>PS-p sensor (2 per wafer)</td>
<td>7525</td>
</tr>
</tbody>
</table>

Table 1 – Estimated total number of sensors to be delivered

The above estimated quantities shall be used for adjudication purposes only. The quantities shown are for a combined number of Pre-production and Production units needed by the CMS collaboration. These quantities include the estimate of yield for module assembly. No later than six months before delivery of the last Production units, CERN reserves the right to adjust the exact number of units according to the actual module assembly yield. Possible yield variations for strip sensors are in the range of -5% to +15%. For the macro-pixel PS-p sensors higher losses during flip chip assembly are assumed making higher yield variations in the range of -15% to +15% possible.

3.1.1 AC-coupled strip sensors: 2S and PS-s

Strips must be n-type implants capacitively coupled to a metal readout strip. The dielectric between implant and readout strip must be thin to enable a high capacitance while being electrically and mechanically stable. The capacitor formed between the implant and readout strips must provide a high breakdown voltage as specified later. Each implant strip must be connected to a common bias
line using a polysilicon resistor. Strip isolation shall be achieved using p-stop implants. The contact pads must be able to withstand probing with standard probe needles during the quality assurance measurements. The connection to the readout chips will be done using wirebonding, therefore all pads on the front side and the full sensor backside must be compatible with this technology as defined in section 3.2.3.

### 3.1.1.1 Main specifications for 2S sensors

**Sensor Type:** AC coupled strips with atoll p-stop isolation and polysilicon bias  
**Material:** p-type FZ290 or thFZ240  
**Physical dimensions:** 94183 x 102700 µm²  
**Strip pitch:** 90 µm  
**Width-to-pitch:** 0.25  
**Strip implant length:** 50205 µm  
**Number of strips:** 2 x 1016  
**Polysilicon bias resistor:** 1.5 MΩ  
**Periphery:** Single guard ring and ≥ 500 µm p+ edge implant  

Wirebonding pads on every strip and the bias ring

### 3.1.1.2 Main specifications for PS-s sensors

**Sensor Type:** AC coupled strips with atoll p-stop isolation and polysilicon bias  
**Material:** p-type FZ290 or thFZ240  
**Physical dimensions:** 98140 x 49160 µm²  
**Strip pitch:** 100 µm  
**Width-to-pitch:** 0.25  
**Strip length:** 23397 µm  
**Number of strips:** 2 x 960  
**Polysilicon bias resistor:** 1.5 MΩ  
**Periphery:** Single guard ring and ≥ 500 µm p+ edge implant  

Wirebonding pads on every strip and the bias ring

### 3.1.2 DC-coupled macro-pixel sensors: PS-p

Macro-pixels must be long, rectangular pixels with n-type implants as readout electrodes. The pixel implants must be directly read out without capacitive coupling. Each pixel shall be connected to a biasing grid using punch-through structures which are mainly foreseen for testing purposes. During normal operation, each pixel will be biased through the readout chip. The isolation of the pixels shall be done with p-stop implants.

These sensors will be flip-chip bonded to an ASIC of which 16 chips are needed to cover the full sensor. The contact pads must be compatible with the requirements of this process, which concerns mainly the application of an UBM. Optionally, the application of the UBM and the subsequent dicing shall be carried out by the contractor as specified in section 2.4.
3.1.2.1 Main specifications for PS-p sensors

Sensor Type: DC coupled macro-pixel with atoll p-stop isolation and punch-through bias
Material: p-type FZ290 or thFZ200 or thFZ240
Physical dimensions: 98740 x 49160 µm²
Pixel width: 100 µm (normal cells)
200 µm (wide edge cells)
Pixel cell length: 1467 µm
Number of pixels: 32 x 960
Periphery: Single guard ring and ≥ 500 µm p+ edge implant
Bump bond pads on every pixel and the bias ring

3.2 Sensor Properties and Requirements

The contractor shall ensure that each sensor delivered to CERN conforms to all the specifications and requirements listed below. The post-irradiation performance will be evaluated by CERN by irradiating miniature sensors, test chips, diodes, and large area sensors. Final acceptance will be given by CERN after conformity with these specifications and requirements is verified by CERN.

3.2.1 Substrate Material

The sensors must be produced on 6” (150mm) wafers. Substrates must be high resistive p-type wafers produced in FZ technology with a crystal orientation of <100>.

The wafers must be either standard wafers with a physical thickness of 320 µm and an active thickness of 290 µm (hereafter called FZ290) or thinned wafers with a physical thickness of 200 or 240 µm and a similar active thickness (hereafter called thFZ240 or thFZ200), as shown in table 2 below.

<table>
<thead>
<tr>
<th>Summary: Substrate Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Wafer size</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Crystal orientation</td>
</tr>
<tr>
<td>Thickness (physical)</td>
</tr>
<tr>
<td>Thickness (active)</td>
</tr>
<tr>
<td>Thickness tolerance</td>
</tr>
<tr>
<td>Resistivity</td>
</tr>
<tr>
<td>Oxygen concentration</td>
</tr>
</tbody>
</table>

Table 2 – Substrate material

3.2.2 Design and Lithography Mask Requirements

The design of the sensors including the full layout of the wafers will be provided by CERN in the form of GDSII files as stipulated in section 2.3. All dimensions mentioned in this technical specification document and in the GDS files refer to physical dimensions in the processed devices and not to dimensions in the lithography masks.
The contractor shall be responsible for the final mask designs and shall produce engineering drawings or mask designs to be submitted to CERN for approval in writing before the start of production. Any violations of design rules in the designs provided by CERN, where the violated design rules have not been communicated to CERN prior to the aforementioned approval, shall be solved by the contractor at the contractor’s expense.

Any modification of the finished, on-wafer values more than 1 µm, shall be agreed in writing with CERN. The responsibility to ensure the compatibility of the designs with the contractor’s process, and that the design of the sensors fulfills the technical requirements must remain with the contractor.

Each wafer must consist of one or two sensors covering most of the area of the wafer. The remaining free silicon areas (“halfmoons”) must include various test structures and test sensors designed by CERN, which will be used by CERN for quality assurance and process monitoring. The contractor may utilize these structures for in-house QC as well or reserve space to add its own test and monitoring structures. The area of the wafer reserved for such structures shall be communicated to CERN as part of the design rules mentioned above. The overall area reserved for these must not be larger than 2 cm² per wafer and must be located outside the area reserved for the sensors as defined by CERN.

### 3.2.3 Sensor Mechanical/Optical Properties

The supply must conform to the following mechanical/optical properties and tolerances:

- **Dicing precision:** < ±10 µm (deviation of physical edge from specification in GDS)
- **Physical thickness (average):** < ± 5%
- **Active thickness (average):** < ± 5%
- **Active thickness variation within a wafer:** < ± 10 µm
- **Sensor bow after process/dicing:** < 200 µm for FZ290  
  < 250 µm for thFZ240 and thFZ200

Readout wirebonding pads and the sensor backside must be compatible with standard wire bonding technology, without causing a degradation in sensor quality. Wirebonding is done with ultrasonic wedge wire bonding machines with wires of 25 µm diameter and medium hardness with a composition of 99% Al, 1% Si.

- **Pull test mean:** > 10 g (corrected for angle)
- **Pull test RMS:** < 10% of mean
- **Probability for lift off:** < 20%

**Passivation:** Sensors to be passivated on the pad side and un-passivated on the backplane. See the GDS files for the openings on the passivation.

**Sensors must be free from:**
- stains or residues from unspecified chemicals or reactions;
- scratches;
- cracks at the sensor edges;
- chips at the sensor edges larger than 40 µm.

**Termination structure of the edge:** Contractor’s choice with agreement with CERN;
Alignment marks are required for module optical metrology: these are included in the GDS files provided by CERN and shall be included in the final design. Additional alignment marks needed by the contractor must be outside the main sensor area unless locations are explicitly agreed with CERN.

**Overall Dimensions:** as provided in GDS design files ± 1 µm

**Mask misalignment:** ≤ 3 µm between any two masks

**Identification:** Identification scratch pads or the equivalent as agreed with CERN shall be used for sensor labelling. The sensor labelling shall be marked on the identification pads by the contractor.

### 3.3 Sensor Electrical Properties Before Irradiation

All electrical specifications in this section must assume the following measurement conditions except where otherwise noted:

- **Temperature:** Leakage current normalised to 20°C
- **Humidity:** < 60% rH
- **LCR settings:** amplitude < 1 V and frequency = 1 kHz

#### 3.3.1 Process Parameters

Test structures must be included on the halfmoon shaped cutaways on each wafer as specified by CERN. Measurements on these structures must show stability of the defined process parameters to be homogenous over each wafer and from wafer to wafer.

- **Strip implant R_{strip}:** < 250 Ω/square
- **Aluminium strip R_{alu}:** < 30 mΩ/square
- **Dielectric breakdown V_{die}:** > 150 V (I_{die} < 1 nA@150 V)
- **Flatband voltage |V_{fb}|:** < 5 V

#### 3.3.2 Global sensor characteristics

Extracted from I-V (0 V – 1000 V, 20V steps) and C-V (0 V – 400 V, 10V steps) curves on the full sensor (guard ring floating, bias ring grounded, backplane at high voltage bias). The specifications shall be respected regardless if the sensor is pushed flat onto a vacuum chuck or not.

- **Full depletion voltage V_{fd}:**
  - < 180 V @ 200 µm active thickness
  - < 250 V @ 240 µm active thickness
  - < 350 V @ 290 µm active thickness

- **Current @600V I_{600}:**
  - ≤ 2.5 nA/mm³ for FZ290 (eg. < 7.25 µA for 2S)
  - ≤ 5 nA/mm³ for thFZ240 (eg. < 6 µA for PS-s)
  - ≤ 5 nA/mm³ for thFZ200 (eg. < 5 µA for PS-p)

- **Breakdown voltage V_{break}**
  - > 800 V, I_{600} < 2.5 x I_{600}

- **Longterm stability:** |
  - |<ΔI_{600}>/<I_{600}>| < 20% in 48h@600 V and < 30% rH

- **Sensor robustness**
  - Sensors must withstand standard handing procedures such as placement on probe stations and lamination to support circuit boards without developing additional bad strips/pixels or reduced breakdown voltage.

If any of these requirements are not met, a sensor is considered as non-conforming.
3.3.3 Characteristics of each strip
This subsection only applies to strip sensors! All strip parameters shall be measured at 350V bias voltage.

**Strip current** $I_{\text{strip}}$: $< 2 \text{ nA/cm}$

**Onset voltage of microdischarge** ($V_{\text{MD}}$): $> 800 \text{ V, } I_{800} < 2.5 \times I_{600}$

Identification of onset voltage at the supplier is primarily done in the IV measurement. The onset of microdischarge will be finally validated by CMS based on the noise performance of the pads as described in section 3.5.

**Bias resistor** $R_{\text{poly}}$

- $\text{median}(R_{\text{poly}})$: $1.5 \pm 0.5 \Omega$ (calculated for each sensor)
- $R_{\text{poly}}$: $\text{median}(R_{\text{poly}}) \pm 5\%$ (for each strip with respect to the median of the corresponding sensor)

**Coupling capacitance** $C_{\text{ac}}$: $> 1.2 \text{ pF/cm } \mu\text{m}$

**Pinholes check** $I_{\text{diel}} < 100 \text{ pA@10 V}$

**Interstrip resistance** $R_{\text{int}}$: $> 10 \text{ G}\Omega \text{cm (strip to one nearest neighbour)}$

**Interstrip capacitance** $C_{\text{int,IN}}$: $< 0.5 \text{ pF/cm (strip to one nearest neighbour, LCR settings: < 1 V and 1 MHz)}$

**Metal and strip implant integrity**: Strips must be free of metal or implant breaks and / or shorts to neighbouring strips and / or P-stop implants

If any of these requirements are not met, a strip is considered as bad.

A sensor is rejected if:

- **Percentage of bad strips**: $> 1\%$ per sensor
- **Clustering of bad strips**: more than two bad strips in any set of 5 consecutive strips

3.3.4 Characteristics of each pixel
This subsection only applies to macro-pixel sensors! All pixel parameters shall be measured at 350V bias voltage.

**Pixel current** $I_{\text{pixel}}$: $< 300 \text{ pA/pixel}$

**Onset voltage of microdischarge** ($V_{\text{MD}}$): $> 800 \text{ V, } I_{800} < 2.5 \times I_{600}$

Identification of onset voltage at the supplier is primarily done in the IV measurement. The onset of microdischarge will be finally validated by CMS based on the noise performance of the pads as described in section 3.5.

**Interpixel resistance** $R_{\text{int}}$: $> 1 \text{ G}\Omega$ to each neighbouring pixel

Additionally, pixels must not be:
Shorts:       Pixel implant or aluminium readout is short-circuited with any of its neighbours

If any of these requirements are not met, a pixel is considered as bad.

A sensor is rejected if:

**Number of bad pixels:** > 0.5 % per sensor

**Clustering of bad pixels:** more than two bad pixels within any cluster of 4 x 4 pixels

### 3.4 Required Sensor Performance After Irradiation

Sensors must conform to the following requirements after being subjected to irradiation with ionizing and non-ionizing radiation of a fluence of $F = 1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ for PS-p and PS-s sensors or $F = 3 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ for 2S sensors.

The figures below assume an annealing period of 7 days at +25 °C (or 80 min. at +60 °C) after completion of the irradiation, and measured at -20 °C and low humidity of < 30% rH:

**Breakdown voltage $V_{\text{break}}$**

$> 800 \text{ V}$

**Onset voltage of microdischarge ($V_{\text{MD}}$):**

$> 800 \text{ V}, \quad I_{600} < 2.5 \times I_{600}$

Identification of onset voltage at the supplier is primarily done in the I-V measurement. The onset of microdischarge will be finally validated by CMS based on the noise performance of the pads as described in section 3.5.

**Maximum current at 800 V:**

$< 1 \text{ mA}$

**Interstrip resistance $R_{\text{int}}$:**

$> 100 \text{ M}\Omega \text{cm}$ (at 600 V bias voltage)

**Interstrip capacitance $C_{\text{int,IN}}$:**

$< 0.5 \text{ pF/cm}$ (strip to one nearest neighbour, LCR settings: < 1 V and 1 MHz)

**Minimum charge collected at 600 V:**

$> 12000$ electrons for 2S sensors

$> 9600$ electrons for PS-s and PS-p sensors

**Defective strips:**

After irradiation, the number of defective strips must remain within the pre-irradiation acceptance levels.

### 3.5 Micro-discharge

The IV requirements in these specifications are designed so as to ensure an acceptable rate of noisy channels due to micro-discharge. A channel shall be deemed noisy if the random probability of noise pulses above a 4000 e- threshold, when measured with a 25ns shaping time and at 600 V bias, is above 1% (nominal channel noise with the CMS Binary readout Chip is 1000 e-). The noise behaviour of the sensors will be monitored throughout the module assembly. The number of such noisy or otherwise inoperable channels (excluding defects resulting from sensor mishandling by CERN) must remain within the allowed limits on the fraction or number of defective channels: sensors found to be failing this criterion shall be rejected.

---

3 The collected charge is defined as the most probable value (MPV) extracted from the convoluted Landau-Gauss distribution of signals induced by minimum ionizing particles.
In order to ensure an acceptable module yield, the fraction of sensors found to fail the noise performance criteria after module assembly must remain below 3%.

As more experience is gained with sensor quality and performance during production, CERN reserves the right to modify and adapt the sensor acceptance tests and criteria at the contractor’s, should this be necessary to efficiently reject sensors affected by micro-discharge in order to meet the above requirements, or to avoid needlessly rejecting good sensors.

3.6 Minimum tests to be carried out by the contractor

The following measurements shall be carried out by the contractor and the results checked for conformity to the specifications defined in section 3.3. Only conforming sensors shall be sent to CERN. The results from these measurements shall be communicated to CERN using data base tools to be provided by CERN. Acceptance will be given by CERN after verification of conformity to specifications, in accordance with section 4.4.

3.6.1 Environmental conditions

Environmental conditions must be monitored and documented during measurements and must be within the following range:

- **Temperature:** 26°C ± 3°C
- **Humidity:** < 60% rH

3.6.2 Global measurements on each sensor

The contractor shall perform global measurements on each sensor in accordance with the below requirements:

- IV curve from 0…1000 V in steps 20 V
- CV curve from 0…400 V in steps of 10 V (LCR settings: < 1 V and 1 kHz)
- Full depletion voltage ($V_{fd}$) and currents at 600 V ($I_{600}$) and 800 V ($I_{800}$)

3.6.3 Checks on each strip

Measurements shall be performed by the contractor on each strip of each sensor. The specifications shall be respected regardless if the sensor is pushed flat onto a vacuum chuck or not. The strips must be free from:

- **Pinholes:** Readout strip not fully isolated from implant strip
- **Metal shorts:** Aluminium readout strip is short-circuited with any of its neighbours
- **Metal opens:** AC pad does not achieve contact to the full length of its readout strip
- **Implant shorts:** Strip implant is short-circuited with any of its neighbours
- **Implant opens:** DC pad does not achieve contact to the full length of its readout strip
- **Bias resistor out of spec:**
  - **median($R_{poly}$):** 1.5 ± 0.5 MΩ (calculated for each sensor)**
\[ R_{\text{poly}}: \quad \text{median}(R_{\text{poly}}) \pm 5\% \text{ (for each strip with respect to the median of the corresponding sensor)} \]

If any of these requirements are not met, a strip is considered as bad. A sensor is still accepted if all of the following is fulfilled:

- **Number of bad strips:** \( \leq 1\% \) per sensor
- **Clustering of bad strips:** not more than two bad strips within any cluster of five consecutive strips

### 3.7 Information and Documentation

#### 3.7.1 General

The contractor shall perform checks to ensure consistency of processing and to maintain all sensor characteristics, in particular, electrical parameters, within the present technical specification.

In particular, the properties of the polished silicon substrate material used shall be tightly controlled by the contractor to ensure uniformity over the production. Adequate evidence of this shall be provided prior to manufacturing, in the Production and Quality Plan, as defined below. Different sensors batches shall be easily identified with particular silicon substrate batches.

The contractor shall set up a Production and Quality Plan, to be submitted to CERN for approval as per section 4.2, specifically including:

- Definition, quantity, and identification of production batches and delivery lots as defined in section 4.1, and shipment date, ensuring traceability;
- Raw material control and traceability of ingot;
- Acceptance testing, measuring methods;
- Replacement procedures for sensors or production batches rejected, in case of rejections from CERN;
- Labelling;
- Format of data supplied with delivered sensors, including wafer batch information.

Any proposed change with respect to the approved Production and Quality Plan incurred during production must be subject to prior approval by CERN in writing.

#### 3.7.2 Labelling

##### 3.7.2.1 On silicon labelling

Each main sensor (2S, PS-s or PS-p) and each of the four halfmoons must carry a unique label at a location pre-determined by CERN in the GDS design files mentioned in section 2.3. The label must be at least readable by optical inspection using a microscope. The labelling must ensure that each main sensor and each halfmoon can be uniquely identified and traced back to the original wafer and its production batch.
3.7.2.2 Package labelling

Each sensor shall be packaged in a dedicated envelope mentioning the sensor type, version and serial number in human readable and machine readable (bar or QR code) format. The four halfmoons of one wafer shall be packaged in a dedicated envelope as well mentioning the sensor type, version and serial number of the sensor(s) they were processed with on the same wafer and serial numbers uniquely identifying each halfmoon.

3.7.3 CMS Tracker sensor naming convention

The CMS Tracker upgrade serial number scheme is made of 19 digits of alpha-numeric code as shown below:

HPK_VPXBBBBB_WWW_PPPPP

(Examples: HPK_VPX28442_2-S_MAIN0, HPK_VPX26591_PSP_MAINA)

<table>
<thead>
<tr>
<th>BBBBB</th>
<th>5-digit batch number</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWW</td>
<td>3-digit wafer type identifier:</td>
</tr>
<tr>
<td></td>
<td>2-S: for 2S strip sensor wafer</td>
</tr>
<tr>
<td></td>
<td>PSS: for PS-s strip sensor wafer</td>
</tr>
<tr>
<td></td>
<td>PSP: for PS-p macro-pixel sensor wafer</td>
</tr>
<tr>
<td>PPPPP</td>
<td>5-digit part identifier:</td>
</tr>
<tr>
<td></td>
<td>MAIN0: for 2S main sensor</td>
</tr>
<tr>
<td></td>
<td>MAINA: for upper sensor on PS-p or PS-s wafer</td>
</tr>
<tr>
<td></td>
<td>MAINB: for lower sensor on PS-p or PS-s wafer</td>
</tr>
<tr>
<td></td>
<td>TESTn: one of the four halfmoons with test-structures; n: 1-4</td>
</tr>
</tbody>
</table>

Table 3 – CMS Tracker sensor naming convention

3.7.4 Data Supplied by the Contractor

The contractor shall provide the following data for each main sensor:

- Sensor type: 2S, PS-s or PS-p;
- Sensor version to trace changes to masks or the production process;
  - Issuing of new versions shall be agreed with CERN
- Contractor’s serial number, which must allow full traceability to wafer, ingot and production batch;
- Temperature, humidity level, voltage step and delay time of IV and CV measurements;
- IV and CV curve measurements as defined in section 3.6.2;
- Full-depletion voltage ($V_{fd}$) extracted from CV curve of the sensor;
- Sensor leakage currents at 600 V ($I_{600}$) and 800V ($I_{800}$) extracted from IV curve of the sensor;
- List of bad strip numbers indicating the failure type as defined in section 3.3.3 and 3.6.3;
Substrate description (i.e., origin, orientation, approximate resistivity and any special comments, which must include information, coded if necessary, to ensure traceability of the substrate and polishing).

The contractor shall provide to CERN the electronic data in pre-agreed upon format for uploading into the CMS database, as well as upload the data directly into the database.

In addition, the contractor must enclose a hard copy of the above data, summarised in the form of a summary sheet, together with the supply.
4 PERFORMANCE OF THE CONTRACT

Unless specifically mentioned otherwise, the contractor shall apply the most restrictive clause in case of ambiguity between the clauses of the contract, including its annexes.

All deliverables and activities that are not explicitly mentioned in the technical specification but are essential for the execution of the contract shall be considered an integral part of the technical specification and therefore subject to clause 3.1 of General Conditions of CERN Contracts.

4.1 Definition of Production Batch and Delivery Lot

A production batch refers to all wafers that have been processed together or consecutively under identical conditions and sharing similar electrical properties.

Wafers from different ingots shall be introduced sequentially in the production line, so that wafers processed within a given production batch are derived from one or two ingots. The contractor shall identify the source ingot for each of the wafers in the production batch. The contractor shall clearly identify all sensors and halfmoons from the same production batch.

The number of conforming sensors delivered to CERN originating from a given production batch should not be lower than 30 (2S sensors) or 60 (PS-s or PS-p sensors) in average.

All sensors from the same production batch shall be organised in a single delivery lot. A “delivery lot” is defined as one or more production batches that are shipped at the same time by the contractor.

4.2 Delivery Requirements

The contractor shall deliver in delivery lots, according to a detailed delivery schedule defining at least the quantities and sensors types to be delivered quarterly. The deliveries shall typically be twice a month.

In this respect, as part of its bid, the bidder shall submit a detailed delivery schedule showing the quantities and sensors types delivered quarterly, in accordance with the below requirements.

The contractor shall:

- Complete the design and layout development of the sensors and structures as specified in section 3.2.2 resulting in final mask set and final design files (Engineering drawings, GDS design files, Production and Quality Plan (section 3.7)) for approval no later than six weeks following the contract notification (date when the contract is sent to the contractor by CERN for signature) or submission of the detailed layouts by CERN, whichever comes later.
- Deliver the Pre-Production units over a period of six months, starting no later than 20 weeks after approval of the Pre-production units’ design by CERN;
- Continue with delivery of Production units no later than 12 weeks after validation of the design and performance of the Pre-production units and approval to proceed by CERN;
- Deliver a quantity of at least 3'050 6” wafers per quarter for the ATLAS ITk Strips and CMS Outer Tracker (excluding the production of 8” wafers for CMS HGCAL, pixel sensors, etc.).

The detailed delivery schedule submitted by the bidder will be discussed and finalised before signature of the contract. Upon agreement between the parties, it shall become contractually binding. CERN reserves the right to require design adjustments and mask changes to be made after the Pre-Production and before the manufacturing of Production units is started, in which case the contractor
will be granted up to 12 extra weeks before the start of Production for the sensor types affected by the changes, in order to allow for the redesign and mask fabrication.

4.3 Packing and Shipping

Packing and the method of delivery must ensure adequate protection against damage (including theft, loss etc.) during handling and transportation. All necessary care shall be taken to protect sensors and test structures on halfmoons against ESD, humidity and contamination with dust or chemicals.

The sensors must be individually packed, with their surfaces protected, in envelopes, or as otherwise agreed. All (and only) sensors from the same production batch shall be packed into a single sealed box which can then be packed within larger transportation boxes. Each individual sensor envelope shall be clearly labelled as defined in section 3.7.2. Each sealed box of sensors from one production batch shall be clearly labelled indicating the type and quantity of sensors, the CMS serial numbers and the corresponding production batch number.

All halfmoons with test structures from the same wafer shall be packed, with their surfaces protected, into a single envelope. All (and only) halfmoon sets from the same production batch shall be packed into a single sealed box which can then be packed within larger transportation boxes. Each individual halfmoon envelope shall be clearly labelled as defined in section 3.7.2. Each sealed box of halfmoons from one production batch shall be clearly labelled indicating the sensor type on the wafers which the halfmoons come from, quantity of halfmoons, the CMS serial numbers and the production batch number, and must contain paper copies of the documentation defined in section 3.7.4.

All labelling must be in bar or QR code format and alphanumerical form.

The transportation boxes shall be externally labelled with the Packing List showing the content (sensor types, quantities, CMS serial numbers, and the production batch numbers), and clearly identified as fragile. Transportation boxes must always contain matching sets of sensors and halfmoons from the identical production batches.

The contractor is responsible for the packing and, if requested by CERN, for the transport to CERN. In all cases, it shall ensure that the supply is delivered to CERN without damage and any possible deterioration in performance due to transport conditions.

4.4 Acceptance and Warranty

4.4.1 Acceptance Process

Acceptance of the supply shall be given by CERN only after the delivered supply is deemed to be in conformity with the contract, including documentation and data referred to in this technical specification, all acceptance tests specified in section 4.4 have been successfully completed and all tests or other certificates have been submitted to CERN.

The warranty period shall be as defined in the tender form.

CERN shall be entitled to carry out detailed inspection (optical, electrical, functional and irradiation tests) to ensure that the delivered sensors conform to the specifications and that measurement results provided by the contractor are consistent with the measurement results obtained by CERN. Acceptance tests performed by CERN should last three to four months.
In case acceptance is denied, CERN will provide all relevant measurements and investigations concerning this decision to the contractor. Any impact on the subsequent production of the supply shall be discussed with the contractor and, if applicable, appropriate measures must be implemented to prevent subsequent parts of the supply to fail in a similar way.

4.4.2 Acceptance Tests carried out by CERN

Acceptance test will be carried out by CERN on a per batch basis by sample measurements of sensors and test structures. CERN will randomly select one or more sensors as well as test structures for a full optical and electrical characterisation, and irradiation tests.

Results must confirm that each tested sensor is fully conforming to the specifications described in section 3. Complementary measurement on test structures included on the halfmoons are performed and must be conforming to the specifications described in section 3. In case non-conforming results are found, CERN reserves the right to perform additional measurements and inspections on sensors and test structures to better understand the consequences and causes of the non-conformity.

4.4.3 Non-conforming sensors at CERN

Non-conforming sensors will be returned to the contractor at the contractor’s expense and replaced by conforming sensors not later than four months after CERN has notified the contractor of the non-conforming sensors.

CERN reserves the right to reject the full batch where three or more sensors of a batch are found to be non-conforming or if three or more halfmoons from different wafers of the same batch are found with at least two non-conforming measurements each.

If more than three consecutive production batches are rejected due to the above-mentioned reasons, CERN shall reserve the right to stop the production after consultation with the contractor. The contractor shall be responsible to investigate the cause for the repeated failures in their production process and shall find a remedy. Production shall only be resumed when the contractor is able to prove that the problems have been identified and corrected. CERN will cooperate in finding and correcting the problem by providing all measurement results extracted from affected sensors and test structures and conduct additional investigations after consultation with the contractor.

4.5 Contract Follow-up and Progress Monitoring

4.5.1 Monitoring Group

A monitoring group shall be set up, composed of representatives of CERN, the contractor’s contact persons and any other representatives deemed necessary by CERN. The monitoring group shall meet quarterly to:

- evaluate the progress of the contract execution;
- discuss any issues that may affect the quality or the delivery of the supply.

It shall immediately be informed of any difficulty encountered in the execution of the contract and shall assess any modification proposed. If required, it shall approve the change of sub-contractors.

In addition to the above quarterly meetings, CERN may call for Ad-hoc meetings at any time during the execution of the contract.
4.5.2 Contractor’s Contact Persons

The contractor shall assign a person responsible for the technical execution of the contract and its follow-up, as well as a person responsible for the commercial follow-up, throughout the duration of the contract. These persons shall be able to communicate in English.

4.5.3 Progress report

The contractor shall send a written progress report to CERN on a quarterly basis and no later than ten working days before the quarterly monitoring group meeting is held, until delivery of the last batch of the supply.

All communications and documents must be in English.

This report must include all the necessary information, in particular:

- Actual progress in comparison to scheduled progress;
- Any issue encountered during the production of the supply.

5 CERN CONTACT PERSONS

Persons to be contacted for technical matters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Telephone</th>
<th>Email</th>
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<tbody>
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<td><a href="mailto:Duccio.Abbaneo@cern.ch">Duccio.Abbaneo@cern.ch</a></td>
</tr>
</tbody>
</table>

Persons to be contacted for commercial matters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Telephone</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Mr Charles Carayon</td>
<td>+41 22 767 6338</td>
<td><a href="mailto:Charles.Carayon@cern.ch">Charles.Carayon@cern.ch</a></td>
</tr>
</tbody>
</table>

In case of absence:

<table>
<thead>
<tr>
<th>Name</th>
<th>Telephone</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrs Cristina Lara</td>
<td>+41 22 767 8486</td>
<td><a href="mailto:Cristina.Lara@cern.ch">Cristina.Lara@cern.ch</a></td>
</tr>
</tbody>
</table>