Specifications and Pre-Production of n^+-in-p Large-format Strip Sensors fabricated in 6-inch Silicon Wafers, ATLAS18, for Inner Tracker of ATLAS Detector for High-Luminosity Large Hadron Collider

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Abstract – The full volume of the inner tracker of the ATLAS experiment will be replaced with new all-Silicon detectors for HL-LHC. The strip detectors, in the radial extent of 40 to 100 cm, are made of four layers of cylindrical-structures in the barrel and six layers of disk-structures in the endcap section with 2 layers of strip sensors for stereo-viewing in each layer-structure. The corresponding area of strip sensors, at 165 m^2, will be covered with 10976 barrel and 6912 endcap sensors.

A new approach is adopted to use p-type material to be more radiation-tolerant, making the readout in n-strips, so-called n^+-in-p sensors, to cope with the fluence of 9.7×10^{14} (1.6×10^{15}) 1-MeV neutron-equivalent (n_{eq})/cm^2 and ionizing dose of 44 (66) Mrad at the maximum in the barrel (endcap in the parenthesis) section, for its lifetime including a safety factor of 1.5. The readout is AC-coupled and the strips are biased via Polysilicon resistors for all sensors.

In the barrel sensors, the geometry is square, 9.8×9.8 cm^2, to have the largest area of sensor possible from a 6-inch wafer. The strips are laid out in parallel with a strip pitch of 75.5 μm and 4 or 2 rows of strip segments in two types of sensors, "short strips (SS)" for the inner 2 layers and "long strips (LS)" for the outer 2, respectively. In the endcap, we have designed roughly trapezoidal sensors with built-in stereo angle, curved edges along the circumference, and in 6 unique shapes in each radial extent, R0 to R5. The strips are in fan geometry, with a mean pitch of approximately 75 μm and 4 or 2 rows of strip segments.

The sensors of this specification are labelled as "ATLAS18xx" where xx stands for SS, LS, Rx (x=0 to 5). With the specifications of mechanical features and electrical performance, CAD files for processing were laid out by following successful designs of ATLAS07, ATLAS12 and ATLAS17LS of the barrel sensors, and ATLAS12EC/R0 of the R0 endcap sensors, together with a number of optimizations.

"Pre-Production" amount of 1041 wafers were fabricated and delivered with the tests carried out by vendor. The quality of the sensors was reviewed through the data as provided by the vendor. These sensors were used for establishing and exercising acceptance procedures, and subsequently to be used for pre-production of strip modules and layer structures.

Silicon Strip sensor for HL-LHC

After the heavy radiation, all the Silicon sensors are expected to have significantly changed their device properties. Bulk damage will have altered the sensor's depletion characteristics, with the voltage needed for full depletion having risen to over one thousand volts for a 300 μm thick Silicon. Surface damage will have raised the oxide-silicon interface charge by an order of magnitude. Design of the strip sensor needs to balance the requirements of strip isolation, low strip capacitance, with those of avoiding high field regions and possible breakdown.

The strip sensor of ATLAS SCT for the LHC [1] were p-strips in n-bulk wafers, so-called p^+-in-n sensor, which requires full depletion as the n-type bulk mutates to a p-type material after the fluence over a few times 10^{13} neq/cm^2. We have chosen a new approach to use non-inverting p-type material and makes the readout in n-strips, so-called n^+-in-p sensor, which allows single-side processing, making the sensor affordable than double-side processing of n^+-in-n sensor, and to operate the sensor in partially depleted mode. We have developed and optimized the designs through the prototype sensors [2].

The sensors for the LHC were made on a 4-inch wafer process. Today, leading companies in fabricating Silicon strip sensors offer 6-in. (150 mm diameter) wafer processes. Processes of 8-in. wafers are the latest. We have chosen 6-in. for established reliability and cost.

The latest development of low-noise readout ASIC has allowed acceptable signal (collected charge)-to-noise ratio at 500 V at the end of life. The low voltage specification enables higher yield for sensors, easier power circuit design for high voltage, and matches the rating of the high voltage cables of the LHC to be re-used.

Typical sensor temperature at the end of operations will be in the range between -30 and -25 °C, with a temperature gradient of up to 12 °C across the sensor due to readout electronics on sensor. The sensors will be kept in dry nitrogen atmosphere.

Stave and Petal

A layer of the cylindrical structure in the barrel or a disk in the endcap is made of a unit of "stave" or "petal" of "Silicon strip modules" with single-side-readout Silicon strip sensors, glued on top and bottom side of a thermo-mechanical and electrical core [3]. A stave is made of 14 single-side modules, rotated 26 mrad each (Fig. 1(a)). A petal is made of 9 modules, with unique shape of sensors with built-in stereo angle of 20 mrad, in each radial extent from R0 to R5 (Fig. 1(b)).

With a requirement of maximum 1% channel occupancy to ensure efficient and stable pattern recognition, a strip in a sensor is sectioned into 4 or 2 segments, being approximately a strip length of 2.4 cm or 4.8 cm in the inner or the outer part of the radial extent, respectively. With a strip pitch of 75 μm, occupancies (occ) are estimated to be 0.92% and 0.57%, respectively, at a pile-up of 200 events of minimum-bias events [4].

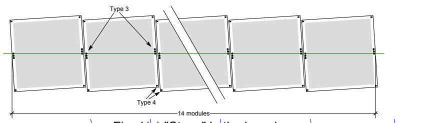

Fig. 1(a) "Stave" in the barral

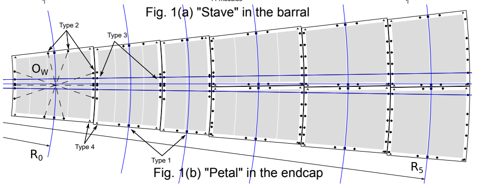

Fig. 1(b) "Petal" in the endcap

Barrel sensors: SS and LS

The barrel sensors with 4 or 2 strip segments are named as the "short strip (SS)" and the "long strip (LS)" sensors, respectively. We have laid out the sensors in 6 in. wafer by inheriting features of the ATLAS17LS sensor, including the outer dimensions with two dicing lines, with optimization of fiducial mark shapes and locations. The ATLAS18 SS and LS sensors are diced along the inner dicing line (slim edge design).

A schematic layout of the SS sensor is in Fig. 2. Mechanical features of the barrel sensor are summarized in Table 1. The outer dimensions and areas are in Table 2.

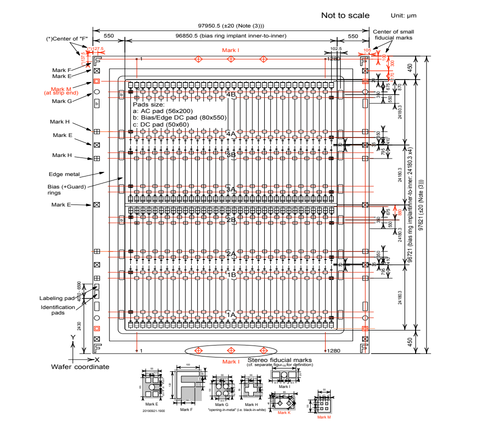

Fig. 2. Layout of ATLAS18SS sensor

Table 1. Mechanical features of the barrel sensors

Parameter	Specification
Dicing tolerance	± 20 μm
Edge distance (inner cut)	450 ± 20 μm and 550 ± 20 μm longitudinal and lateral to strips, respectively, measured as the distance from the inner edge of the bias ring to cut edge (after dicing).
Number of implanted strips per segment	1282 the outer-most strip, called "field-shaping strip", in each side works to shape the electric field to the last readout strip
Number read-out strips per segment	1280
Pitch of the strips	75.5 μm
Read-out implant strip width	16 μm highly doped n-implants
Read-out metal strip width	22 μm Aluminium (pure-Al), capacitively coupled (see below) over the n-implant strip, with an overhang of 3 μm per side
Polysilicon bias resistors	overlapping the implanted strips
Isolation structure	narrow p-implant trace, 6 to 8 μm wide in between and continuously surrounding the readout implant strips, with an implant surface dose of approximately 4x10^{12} ions/cm^2
Punch-through protection (PTP)	a narrow gap, ≤20 μm between the bias rail and the end of strip implant. The gap is covered with a conductive layer extended from the bias rail that is insulated from the bulk and the strip implant

Endcap sensors: R0 to R5

The endcap main sensor, the "stereo annulus" sensor, is defined according to Fig. 3, which fits in the "usable" area of 6-in. wafer. Each sensor is defined in its radial extent in the global cyclic coordinate system where its origin, O, is at the beamline of the ATLAS detector. The inner and the outer circles of the outer dimension and the centre circle of the sensor are defined by the radii, R_i, R_o, and R, respectively.

The strips are laid out in fan geometry with their focal point, F, being rotated by φs(20 milli-radian) with respect to the centre line in the global coordinate at the centre of the sensor (which is the centre of the wafer, Ow).

The boundary of "strip region", i.e. the inner edge of the implant of the bias ring, is defined by the inner and the outer circle, r_i and r_o, which is inside by the longitudinal (to the strips) edge space of 450 μm from the R_i and R_o, longitudinally. The lateral edge of the strip region is defined to have the gap between the implant edge of the bias ring to the implant edge of the last strip is the same for the gap between the strips.

The crossing corners of the implant edges of the bias ring are labeled as (a, b, c, d). The lateral outer edges are defined by the parallel lines to, and 550 μm outside from, the lateral implant edge of the bias ring. Thus, the focal point of the lateral outer edges, F', has an offset from the focal point of the strips, F.

Due to limitation in manufacturing, the circular dicing is made with an approximation of consecutive short straight lines ("flats"). In order to keep the required edge space, the inner circle of the outer dimension is made with the flats with the circle R_i being the circumscribed circle. The outer circle of the outer dimension is made with the circle R_o being the inscribed circle, thus, the vertexes of the flats are on the circumscribed circle, R_occ.

The crossing corners of the edges of the outer dimension are labeled as (A, B, C, D). By design, the corners of the inner edge, A and D, are on the circle R_i, and the corners of the outer edge, B and C, on the circle R_occ.

The basic parameters of the endcap sensors are summarized in Table 3. Their dimensions and areas are summarized in Table 2.

The "Stereo annulus" endcap sensors must follow the features in the SS barrel sensor. Besides the different shape of sensor edges, the features that are different from the SS sensor are:

- Number of strips per strip segment, as listed in Table 2 and 3
- Arrangement of the AC, DC and HV pads
- Arrangement of the fiducial marks.

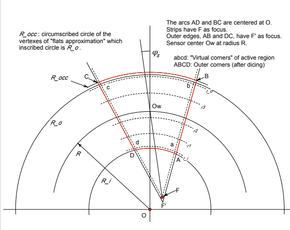

Fig. 3. Definition of endcap sensors

Table 3. Parameters of endcap sensors

Basic parameters (in wafer coordinate) Endcap sensor		R0	R1	R2	R3	R4	R5
a	x	39.0955	49.3763	36.7098	32.5878	38.4555	43.9394
	y	-56.1068	-47.3110	57.6942	-60.1220	-56.5475	-52.4005
b	x	47.3140	56.0569	-24.7238	36.0039	41.6635	46.9007
	y	47.5119	36.8121	62.5777	56.7436	52.5883	47.8989
c	x	-49.3826	-57.7362	-24.6016	-38.3392	-43.8444	-48.9050
	y	47.3061	36.6449	-63.8040	56.6286	52.4805	47.7996
d	x	-37.0270	-47.6970	36.5875	-30.2525	-36.2747	-41.9351
	y	-55.9010	-47.1438	-56.4678	-60.0070	-56.4397	-52.3012
A	x	39.6071	49.8880	37.2139	33.1240	38.9917	44.4755
	y	-56.6118	-47.8155	58.2059	-60.6002	-57.0256	-52.8785
B	x	47.8979	56.6409	-25.1307	36.5666	42.2263	47.4636
	y	47.9166	37.2181	63.1617	57.1708	53.0158	48.3267
C	x	-49.9845	-58.3384	-25.0056	-38.9200	-44.4253	-49.4860
	y	47.7066	37.0474	-64.4064	57.0531	52.9057	48.2253
D	x	-37.5210	-48.1909	37.0887	-30.7708	-36.7930	-42.4533
	y	-56.4013	-47.6446	-56.9616	-60.4823	-56.9153	-52.7770
R_i (mm)		384.0500	489.3730	575.1440	638.1590	756.4510	867.0120
R_o (mm)		488.8730	574.6440	637.6590	755.9510	866.5120	968.2350
R_occ (mm)		488.8826	574.6553	637.6715	755.9547	866.5162	968.2397
(dR_(occ-o))		0.0096	0.0113	0.0125	0.0037	0.0042	0.0047
R_Ow (mm)		438.6140	534.6390	609.4050	697.8990	812.4710	918.7490
r_i (mm)		384.5000	489.8230	575.5940	638.6090	756.9010	867.4620
r1 (mm)		403.4810	507.9160	606.4020	664.8320	811.4820	907.6230
r2 (mm)		427.4620	535.0090	---	697.0550	---	---
r3 (mm)		456.4420	559.1010	606.4020	729.2780	811.4820	907.6230
r_o (mm)		488.4230	574.1940	637.2090	755.5010	866.0620	967.7850
Strip parameters							
(*)No. Strips, Row0		1026	1282	1538	898	1026	1154
Row1		1026	1282	---	898	---	---
Row2		1154	1410	---	898	---	---
Row3		1154	1410	1538	898	1026	1154
Stereo angle φ_s (mrad)		20	20	20	20	20	20
Ang pitch φ_p (μrad), Row0		193.0863	154.7122	129.0774	109.5053	96.1753	85.7429
Row1		193.0863	154.7122	---	109.5053	---	---
Row2		171.6880	140.6774	---	109.5053	---	---
Row3		171.6880	140.6774	129.0774	109.5053	96.1753	85.7429
(**)Strip Pitch (μm), Row0		74.4	76.0	74.5	70.0	72.9	74.5
Row1		78.1	78.8	---	72.9	---	---
Row2		73.6	75.4	---	76.4	---	---
Row3		78.5	78.8	78.4	80.0	78.1	77.9
(***)Strip L (mm), Row0		19.0	18.1	30.8	26.2	54.6	40.2
Row1		24.0	27.1	---	32.2	---	---
Row2		29.0	24.1	---	32.2	---	---
Row3		32.0	15.1	30.8	26.2	54.6	60.2

Note:
R_o Inscribed circle of flats of outer edge
R_occ Circumscribed circle of flats of outer edge
r_x Boundaries of strip area
(*) "No. Strips" includes the field shaping strips. The 1st and the last "readout" strip are "1" and "No.Strips" - 2.
(**) Calculated at the inner radius of the boundaries of the row
(***) Calculated from the inner to the outer radius of the boundaries of the row

Table 2. Dimensions and areas of ATLAS18 sensors

	SS	LS	R0	R1	R2	R3	R4	R5
Dimension(*1)								
- Length(*2) (mm)	97.621	97.621	106.879	87.831	65.480	118.655	111.070	102.369
- Width(*2) (mm)	97.951	97.951	97.882	114.979	127.568	75.487	86.652	96.950
- Thickness(*3) (mm)	0.320	0.320	0.320	0.320	0.320	0.320	0.320	0.320
Sensor area(*1)								
- Area (mm^2)	9562	9562	9189	9100	7601	8213	8943	9311
- Perimeter (mm)	391	391	385	384	368	375	383	387
Strip area(*4)								
- Area (mm^2)	9368	9368	8996	8912	7424	8018	8744	9110
- Perimeter (mm)	387	387	381	380	364	371	379	383
- Strip segments	4	2	4	4	2	4	2	2

(*1) Outer dimension of sensor. The max. in the endcap sensors.
(*2) Length and Width are in longitudinal and perpendicular directions to strips, respectively
(*3) Nominal thickness
(*4) Inside of the bias ring

Fiducial markers of endcap sensors

The definition of the fiducial markers follows the barrel sensor in Fig. 2, in the circular coordinate in Fig. 3. The endcap sensors have four sets of fiducial markers each serving different purposes, in addition to the standard set of fiducial markers.

Type 1 fiducial markers: they are located along the straight sides of the sensor and are used to define, together with the sensor center, the sensor radius and origin or interaction point (O), shown as squares (⊞) in Fig. 1(b) where a blue arc centered at the origin with the corresponding sensor radius is drawn to guide the view.

Type 2 fiducial markers: to determine the sensor center (OW). These are located along the arcs defined by the outer and inner radius and on the straight sides of the sensor, shown in Fig. 1(b) as red, thick plus (✚) marks.

Type 3 fiducial markers: to help position the sensor on the petal face. These markers are determined by three lines crossing at the interaction point. The middle line defines the X axis of the "Petal" coordinate.

Type 4 fiducial markers: Mark F. They are located at the corners of the edge region to server for the vendor and the experiment.

Wafer layouts

Resulting wafer layouts of the 2 barrel (SS and LS) and 6 endcap sensor types (R0 to R5) are shown in Fig. 4. One large-format main sensor is laid out in the central region of wafer. In a main sensor, the strip region is divided by the virtual boundaries (dotted lines) of the row of strip segments in the sensor.

The endcap sensors, R0 to R5, are skewed-trapezoid with circular inner and outer edges, strips being laid out in fan geometry with their focal point being rotated by 20 milli-radian with respect to the radial centre of the sensor. The shape of the end cap sensors is called as "stereo annulus".

Acknowledgements

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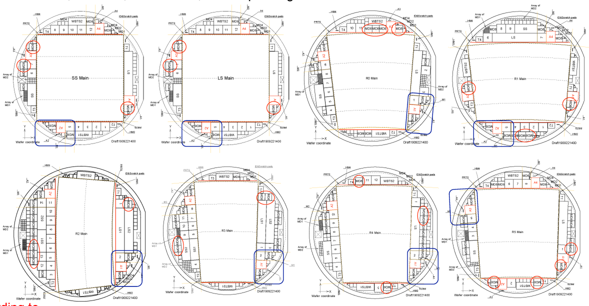


Fig. 4. Wafer layouts of ATLAS18 sensors

Miniature sensors and test structures

Miniature sensors and test structures are laid out in the halfmoons. They are miniature sensors (Mini(1×1 cm^2), SSmini(1×2.6 cm^2), LSmini(1×5 cm^2)), ATLAS test chips [5] (A1 to A4), monitor diodes (1×1 mm^2 (MD1), 2×2 mm^2 (MD2), 4×4 mm^2 (MD4), 8×8 mm^2 (MD8)), wirebonding test structures (WBTS, Fig. 5), Polysilicon Bias Resistor test structure (PRTS, Fig. 6), and contractor's test structures (T1 to T4).

For all wafers, one halfmoon has two additional cuts that segment one piece with ATLAS test chip and a MD8 diode (Testchip&MD8) and the other with a miniature sensor and a MD8 diode (Mini&MD8) for Quality Assurance. The locations of those QA pieces are encircled (in blue) in the corresponding halfmoons in Fig. 4.

In order to have a well-defined volume and the current flowing in the volume, several MD8 diodes (encircled in red, MD8pStop) are laid out with an extra p-stop ring between the diode and the guard ring, as shown Fig. 7. No MD8pStop are in the QA pieces. Extra p-stop ring may lower the breakdown voltage.

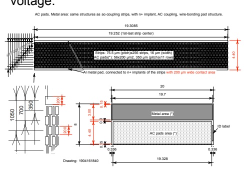


Fig. 5. Wirebonding test structure

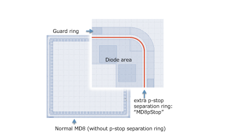


Fig. 7. MD8 diode with extra p-stop ring

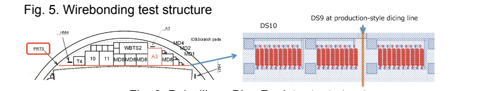


Fig. 6. Polysilicon Bias Resistor test structure

Tests Carried out by Vendor

Major electrical properties of the sensors are summarized in Table 4. Those properties are to be maintained initially and after full irradiation. The vendor performs the tests and provide the data to ensure the quality of the produced sensors/wafers. Those test items are summarized in Table 5.

Table 4. Major electrical properties

Parameters	Values
Wafer type	p-type FZ <100>
Wafer resistivity	>3.5 kΩcm
Full depletion voltage (*Vfd*)	<350 V
Maximum operating voltage	500 V
Polysilicon bias resistor (*Rb*)	1.5±0.5 MΩ(*)
Inter-strip resistance at 300V	>10×*Rb*
Inter-strip capacitance at 300V	<1pF/cm
Leakage current at 500V (@25°C, RH<10%)	<0.1 μA/cm^2
Breakdown voltage (*Vbd*)	>500 V
Bad strips	≤8 consective, <1% per segment, <1% per sensor
Minimum collected charge at 500V	6350 electrons

(*) 1.8±0.5 MΩ at -20 °C

Table 5. Tests by vendor

Test items	Data
Full depletion voltage	*Vfd*
Leakage currents up to 700 V	*I-V*
Leakage current	at *Vfd*+50V at 500V
Polysilicon bias resistance	upper, lower
Breakdown voltage	*Vbd*
List of bad strips	segment# - strip#

Pre-production of ATLAS18 sensors/wafers

According to the specification, the contracted vendor, Hamamatsu Photonics K.K. has laid out CAD drawings through more than 6 iterations with ATLAS to refine the designs. A set of drawings of selected layers [6] out of the production drawings are stored in the CERN EDMS file server.

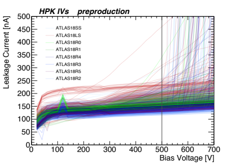
Prior to full production of the sensors, "Pre-Production" units(sensors), a total of 1041 sensors/wafers, are produced first in the amount of 5% of the quantity needed by the experiment including an anticipated loss of the sensors during the construction of ITk strip detector, through CERN and KEK. A small amount of SS sensors is produced additionally as "Prototype" sensors. The reception sites have subsequently distributed to ITk strip sensor testing sites. The Pre-Production quantity, the quantities distributed to the testing sites are summarized in Table 6.

The quality of the delivered sensors are reviewed through the data supplied by the vendor. The plots of leakage currents vs bias voltage, leakage currents at 500V, breakdown voltages, full depletion voltages, fraction of bad strips of all Pre-Productions sensors out of HPK data are shown in Fig. 8. The quality of the sensors is excellent. The testing sites will verify the quality separately and report elsewhere.

Table 6. Pre-Production summary

		Reception sites and testing clusters				
	Pre-Production	CERN			KEK	CERN(*)
Stype	Total/Stype	Cambridge + QMUL	Prague	Vancouver + Carleton	KEK + SCIPP	Cambridge + QMUL
18SS	318	159			159	60
18LS	318	159			159	
18R0	45		20	25		
18R1	45		25	20		
18R2	45		20	25		
18R3	90		40	50		
18R4	90		60	30		
18R5	90		40	50		
Total	1041	318	205	200	318	60

Stype: Sensor type
(*) Additional sensors as "Prototype" from simultaneous producton



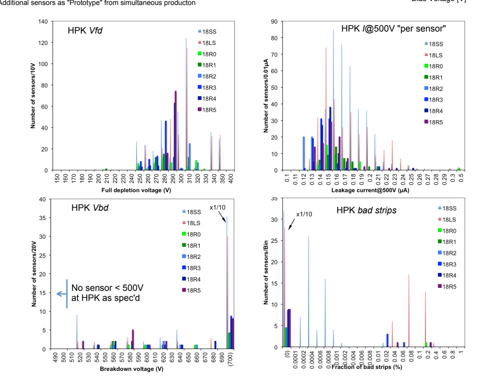


Fig. 8. Quality of Pre-Production sensors at HPK