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Establishing the Quality Assurance programme for the strip sensor production of the ATLAS tracker upgrade including irradiation with neutrons, photons and protons to HL-LHC fluences

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ABSTRACT: The successful pre-production delivery of strip sensors for the new Inner Tracker (ITk) for the upgraded ATLAS detector at the High Luminosity LHC (HL-LHC) at CERN was completed and based on their performance full production has commenced. The overall delivery period is anticipated to last 4 years to complete the approximately 22000 sensors required for the ITk. For Quality Assurance (QA), a number of test structures designed by the collaboration, along with a large area diode and miniature version of the main sensor, are produced in every wafer by the foundry Hamamatsu Photonics K.K (HPK). As well as Quality Control (QC) checks on every main sensor, samples of the QA pieces from each delivery batch are tested both before and after irradiation with results after exposure to neutrons, gammas or protons to fluences and doses corresponding to those anticipated after operation at the HL-LHC to roughly 1.5 times the ultimate integrated luminosity of $4000\,\mathrm{fb}^{-1}$. In this paper the procedures are presented and the studies carried out to establish that the seven ITk QA Strip Sensor irradiation and test sites meet all the requirements to support this very extensive programme throughout the strip sensor production phase for the ITk project.

Contents

1 Introduction

Since the Quality Control (QC) testing cannot reliably monitor all the possible variations in production parameters that may influence deterioration during operation at the HL-LHC, the Quality Assurance (QA) procedures including post-irradiation testing, are essential for guaranteeing adequate long term performance and are beyond the scope of what any manufacturer can reasonably check themselves. It is therefore vital that these procedures are as robust as possible and seen by the manufacturer to be fully reliable as they have the potential to lead to rejection of batches otherwise satisfying all the agreed QC tests. As a result ATLAS, with input from independent experts, has developed detailed sensor QA plans for the high-volume production. They included work sharing between several institutes and looking at the planned sampling rate; the proposed acceptance criterion; the measurement and irradiation procedures; along with the required standards of precision, consistency and reproducibility, among the participating irradiation facilities and QA institutes [1].

2 ATLAS18 wafer design

The strip detectors of the outer region of the ITk, at radii (r) 40<r<100 cm, consist of 4 layers of cylinders (two Short Strip and two Long Strip) and 6 layers of disks with 6 rings of detectors (R0 to R5) in each disk. The ATLAS18 wafer design is laid out and fabricated as the pre-production and production design for the strip sensors for the ITk project [7], as shown in figure 1(a). Large area strip sensors are fabricated in substrate wafers with a diameter of 6 inches in p-type silicon, according to the design rules of HPK. This design is the successor to the wafer prototype campaigns ATLAS07, ATLAS12, ATLAS12EC/R0 and ATLAS17LS. The strips are biased via polysilicon resistors and
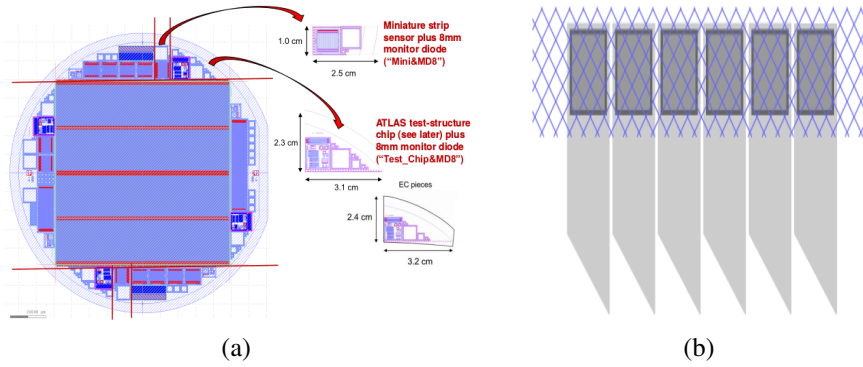
Figure 1. (a) ATLAS18SS design example (out of 8 different layouts) with QA "Mini&MD8" and "Testchip&MD8" wafer pieces. The QA pieces have "similar" geometries in the 8 different wafer layouts. (b) Scanning irradiation pattern of the QA pieces chosen from different batches at the Birmingham proton irradiation facility.

the readout is AC-coupled. The strip pitch is ≈75 µm in 4 or 2 rows of strip segments. At the peripheral wafer regions, known as "halfmoons" additional test structures are included, miniature sensors, monitor diodes (MD1, MD2, MD4 and MD8 of dimensions 1 mm, 2 mm, 4 mm and 8 mm square respectively) and ATLAS test chips. They are used to characterise and validate the sensor key parameters and to monitor the fabrication process of batches produced by HPK, figure 1(b). A pair of QA mini and QA test chip pieces is measured after irradiation for each batch to characterise its performance at the end of life of the experiment.

3 Measurement setups and qualification methods

3.1 Irradiations

For a total integrated luminosity of 4000 fb^{-1}, the strip sensors of the ITk detector [2] will be exposed to a large radiation fluence of up to $1.6{\times}10^{15}$ of 1 MeV n_{eq}/cm^2 and ionising dose of 0.66 MGy, including a safety factor of 1.5. The QA silicon pieces are exposed to proton, neutron and gamma irradiation up to the maximum fluences and radiation doses specified for the ITk Strip detector project. The irradiation programme consists of protons of 27 MeV energy at the Birmingham MC40 cyclotron, protons of 70 MeV energy at CYRIC in Tohokou University, neutrons at the Ljubljana JSI TRIGA reactor and gamma rays from the ^{60}Co source at UJP Praha [3]. The samples remain cold during the proton irradiations. For Birmingham the temperature inside the XY-axis robotic scanning chamber shown in figure 2(a), is −27°C and for CYRIC −15°C. At the timescale of the neutron irradiations at the TRIGA reactor, figure 2(b), no substantial annealing is expected and during the ^{60}Co irradiation at UJP Praha, figure 3, the samples are maintained at room temperature. The chamber and the reactor access tubes shown in figure 2 are much larger than the QA pieces, enabling multi-sample exposure. Same is true for the ^{60}Co exposure figure 3, where the holder geometry and material was chosen to verify the exposure uniformity to be lower than 5%.

The beam spot of the MC40 cyclotron configuration is 10×10 mm^2, and its position is controlled before each irradiation with gafchromic film [5]. Nitrogen gas flow in the chamber ensures the
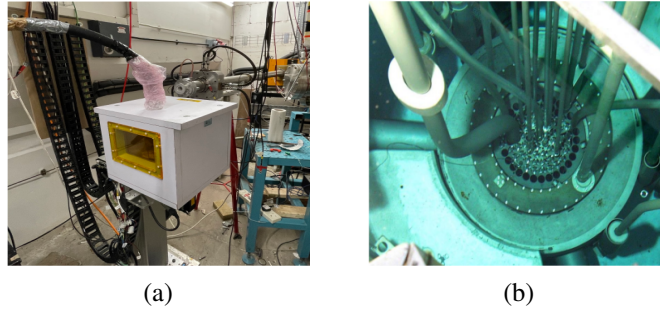
(a) (b)

Figure 2. (a) The high intensity proton irradiation area of the Birmingham MC40 cyclotron with the temperature controlled chamber and (b) The core of the TRIGA neutron reactor at JSI, Ljubljana.
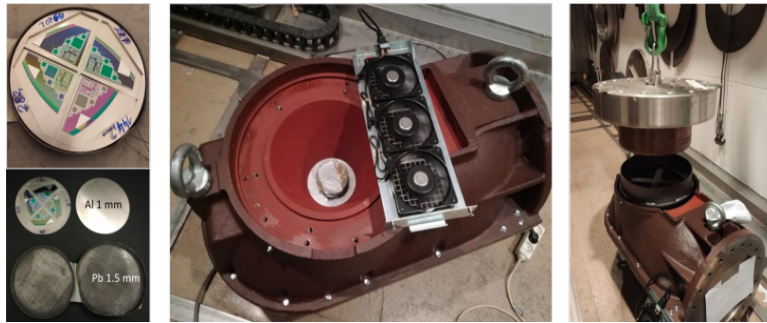

Figure 3. The sample holder for the ^{60}Co irradiation at UJP Praha, made with material thickness of 1.5 mm Pb and 1 mm Al to minimise the dose induced from scattered low energy charged particles and to achieve Charge Particle Equilibrium according to Total Ionising Dose Irradiation Standards [4].

relative humidity during irradiation is $\approx 10\%$. For the QA program during the irradiation site qualification, the scanning operation mode was preferred where the chamber follows a specified path, typically in horizontal rows with a vertical step of 5 mm. The beam current is chosen to be 200 nA. The QA silicon pieces are mounted on a 2 mm thick aluminium plate overlaid with nickel foil for dosimetry, all suspended within the cold box [6].

3.2 ALiBaVa setup

The Charge Collection Efficiency (CCE) measurements are performed using the ALiBaVa setup [8], designed to readout multi-channel silicon strip sensors using radiation-hard Beetle chips. The system consists of two hardware boards, a daughterboard on which the Beetle chips and the test mini-sensor are mounted and a motherboard which controls the triggering of signal readout from the sensor and communicates with a control PC, as shown in figure 4(a). The sensor under test is mounted on the daughterboard, biased at high voltage and placed in a freezer beneath a ^{90}Sr radioactive source. A schematic drawing of the KEK, Tsukuba setup is presented in figure 4(b). Two scintillators are placed below the sensor, which trigger the motherboard to readout from the Beetle chip when signal detected from the emitted electrons. The charge collected in each hit, with information of the cluster width and the noise of the strips, it is saved to a binary file. These files are analysed by a programme which extracts the most probable collected charge and saves histograms of the cluster width and noise.
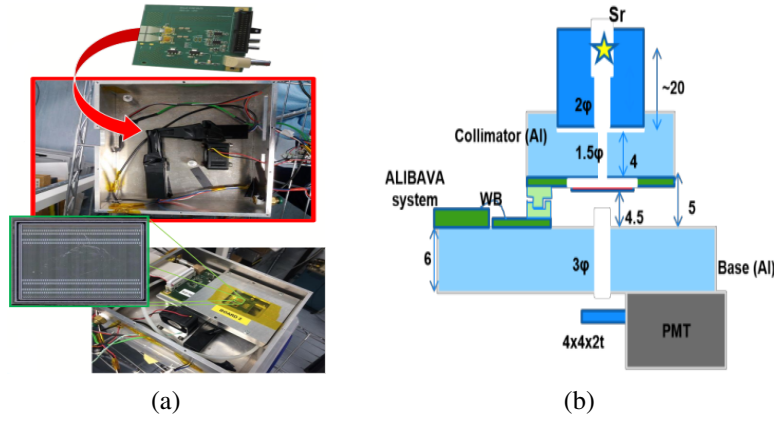
Figure 4. (a) The electronic readout components of the ALiBaVa setup with a mini-sensor mounted on the dautherboard both placed inside of an aluminium box with temperature and humidity control in Birmingham test site. (b) A cross section drawing of the boards below the collimator and the ^{90}Sr radioactive source on top of the equivalent setup in KEK, Tsukuba test site. The drawing outlines the geometry of the source, device under test, and triggering.

Then plots are created of the charge collection efficiency and cluster width as a function of bias voltage. The signal the software receives from the motherboard is measured in ADC counts which results from the Analogue to Digital Conversion of the signal from the Beetle chip. The signal is converted from ADC to a number of electrons. As the gain of the Beetle readout chip is temperature dependent, the signal size in ADC is also temperature dependent, so all signals must be scaled to a common temperature before converted to electrons, e^-. For a pre-irradiated ATLAS mini-strip sensor with 300 μm thickness, the signal produced by a minimum ionising particle traversing the sensor corresponds to 23.05 ke$^-$. After irradiation the performance of the sensor is degraded, so the collected charge is significantly lower. The QA specifications after irradiation at 1.6×10^{15} n$_{eq}$/cm^2 require a most probable collected charge of at least 6350 e$^-$ at V$_{bias}$ = -500 V [9, 10].

3.3 Test chip setup

The test chip is a 10×12 mm^2 wafer piece featuring numerous structures. Testing of these structures allows the extraction of key parameters of the sensors such as the interstrip resistance and capacitance, the coupling capacitance between implant and readout electrode and the bias resistance. A labelled diagram of the test chip is shown in figure 5(a) and the main structures of interest wire-bonded prepared for testing, figure 5(b). These are the bias resistors for the measurement of bias resistance, the coupling capacitor for the properties of the coupling oxide, the interdigitated structures for the interstrip properties, the field-oxide capacitor for the measurement of flatband voltage, the PTP structure for the characterisation of punch-through protection and the cross-bridge resistors for the measurement of implant and metal sheet resistances. The design of the test chip setup developed at Birmingham has been pioneered by collaborators at Toronto, to allow automatic testing of the test chip structures and MD8. A splitting box connects the measurement instruments to two switching matrices which in turn connect to various channels of the test chip, figure 6(a). The splitting box provides connections between the BNC cables delivering input and output to the instruments and the
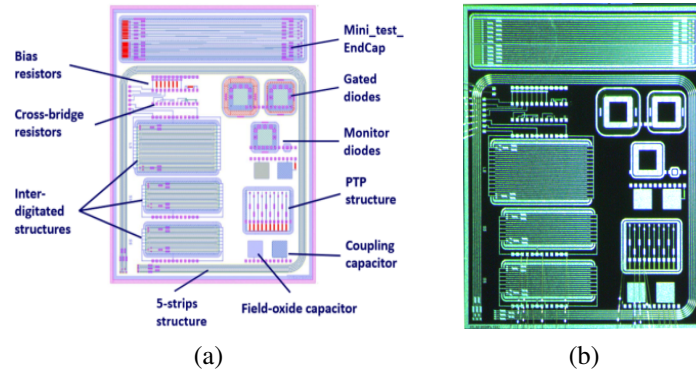
(a)   (b)

Figure 5. The ATLAS18 test chip (a) in the design file before fabrication and (b) in the diced wafer piece wire-bonded prepared for testing. The different test structures implemented in the chip are named out in part (a).
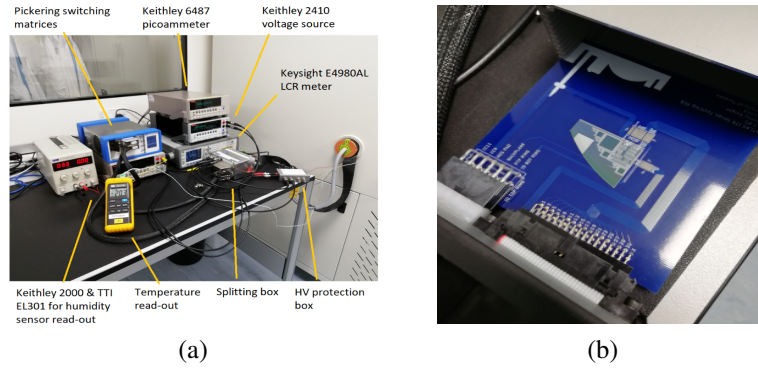

(a)   (b)

Figure 6. (a) Photo of the Birmingham test chip setup and (b) Test chip mounted on PCB.

D-sub connectors of the switching matrices. Also, it connects the D-sub connectors of the switching to the PCB via a Molex and a ribbon cable. Electrical connections to the test chip structures are provided by the available metal pads, which can be wire-bonded to a PCB. The switching matrices allow the connections between each measurement instrument and test chip pad to be switched on and off by a control PC. The wafer piece with the test chip and MD8 is mounted on a PCB which is secured inside a testing box, shown in figure 6(b). The testing box is placed inside a climate chamber which maintains stable temperature during measurements and allows for testing at −20°C. During the site qualification process, Python scripts were prepared to control through a PC, the measurement instruments along with the switching matrices and record the measured data.

4 Site qualification results

4.1 Charge collection efficiency

The most probable charge collected by the sensor, is extracted by a binned likelihood fit performed to the distribution of the collected charge per trigger event. In particular, the Landau distribution is convoluted with a Gaussian distribution and the convolution result is used to fit the charge collection
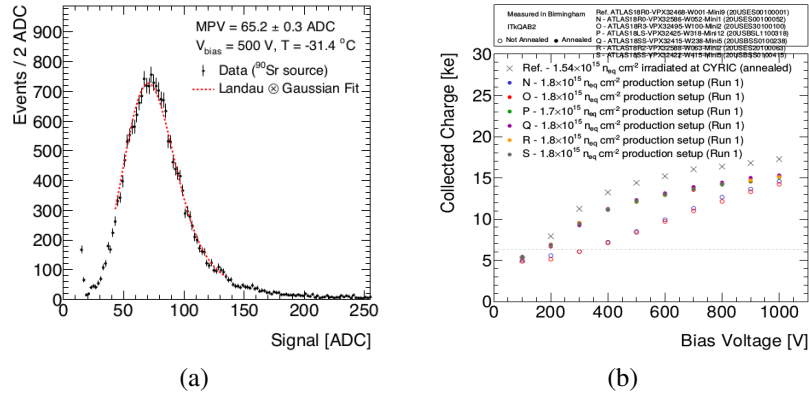
Figure 7. (a) Charge collection histogram for an ATLAS mini-sensor with Landau-Gaussian convolution fit and (b) Charge collection as a function of bias voltage after proton irradiation of six ATLAS18 pre-production mini-sensors pre- and post-annealing irradiated within the same irradiation slot at the Birmingham cyclotron facility.

histograms. The fit presented in figure 7(a), has three floating parameters, the most probable value (MPV), the width of the Landau distribution and the width of the Gaussian. The mean of the Gaussian is fixed to zero. The fitting range is carefully selected, so the signal peak can be separated from the noise tail which is present at low ADC counts.

The site qualification parameters of the QA groups on CCE measurements, are presented in table 1, after neutron irradiation at target fluence 1.6×10^{15} n_{eq}/cm². The MPV of the Landau component is used for the charge signal amplitude, as the difference with the MPV of the convolution has been investigated and found to be negligible. Good agreement is observed between the CCE values for the different sites. The samples shipped to the testing sites were irradiated at the same irradiation slot, so the usual fluence uncertainty of the order of 10%, associated with the irradiations did not contribute in this comparison. The collected charge as a function of voltage after proton irradiation at target fluence 1.6×10^{15} n_{eq}/cm² at CYRIC and Birmingham cyclotron facility is presented in figure 7(b). The comparison between pre- and post-annealing has been performed during the Birmingham irradiation site verification process and the post-annealing results are compared to CYRIC. The collected charge measured at 500 V negative bias voltage verifies the QA requirement of at least 6350 e⁻.

Table 1. Site qualification parameters for CCE measurements.

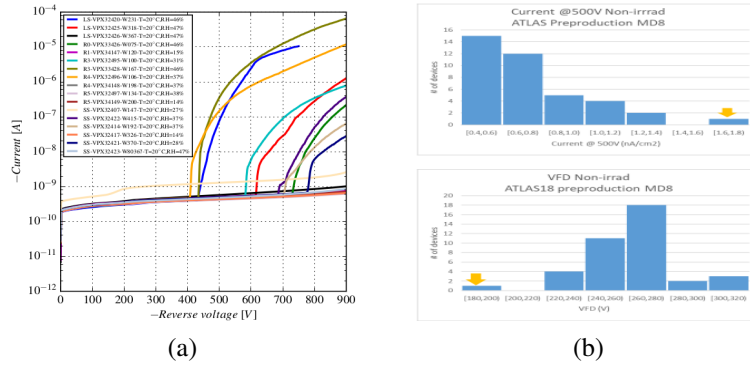|	Birmingham	Ljubljana	Toronto	Tsukuba	Valencia
Signal at 500 V [ke⁻]	7.18	7.48	7.46	7.71	7.63
Signal at 700 V [ke⁻]	9.68	10.14	10.37	10.11	10.55
Noise at 500 V [ke⁻] (irrad)	0.94	0.68	0.52	1.17	0.68
Noise at 700 V [ke⁻] (irrad)	0.94	0.70	0.55	1.18	0.70
Cluster width at 500 V (irrad)	1.32	1.38	1.30	1.11	1.89
Cluster width at 700 V (irrad)	1.42	1.50	1.40	1.25	2.14
Current at 500 V [μA] (scaled to −20°C)	17.80	16.20	13.30	16.70	16.60

Figure 8. ATLAS18 pre-production (a) MD8 current as a function of voltage and (b) Current value at 500 V and full depletion voltage V_{fd} results.

4.2 Test chip parameters and monitor diodes

For monitoring the wafer quality and process fabrication, current-voltage and capacitance-voltage measurements are performed on pre-irradiated MD8 monitor diodes part of the QA pieces ("Mini&MD8" and "Testchip&MD8"). In figure 8(a) is presented the current-voltage of MD8s measured on an automatic probe station in an ambient environment, relative humidity RH > 25% and temperature 20°C. The total current for all the cases is < 0.1 μA/cm². In the QA procedures, the breakdown voltage V_{bd} is specified to be above 500 V for dry environment RH < 10%. For devices tested in ambient environment, a few cases with V_{bd} < 500 V are observed. The full depletion voltage V_{fd}, extracted pre-irradiation for all the pre-production batches is presented in figure 8(b), according to the QA specifications below 350 V.

For verification purposes testing sites performed measurements in one pre-irradiated and one gamma irradiated at 0.66 MGy test chip, after annealing of 80 minutes at 60°C. The bias resistor R_{bias} structures, are identical to those on the main sensor which provide a high resistance electrical connection between the bias rail and the strip implants [11]. The R_{bias} is extracted from the current as a function of voltage measurement. For the pre-irradiated chips R_{bias} is extracted with average values of 1.55 MΩ. After gamma irradiation all of the three resistors tested with R_{bias} average of 2.16 MΩ, the measurements performed at −20°C [11]. In figure 9(a) the current as a function of voltage measurements of the bias resistor structures on the site verification test chips (one pre-irradiated, one gamma irradiated) is presented. The blue band shows the acceptance range R_{bias} = 1.5 ± 0.5 MΩ. The test chip features a punch-through protection (PTP) structure, consisting of the end of ten implants surrounded by a bias rail, to which they are connected at one end by a bias resistor, and a guard ring. Testing this structure involves applying a voltage to individual implants and measuring the current between the implant and the bias rail, while the backplane of the sensor is held at a high negative voltage to bias the Si bulk. From the gradient of the current as a function of voltage curve, the effective resistance is presented as a function of voltage, figure 9(b). The voltage at which the effective resistance is half of that of the bias resistor, is considered as the punch-through protection voltage, V_{ptp}. To ensure the protection of the readout electronics, the V_{ptp} is required to be significantly lower than the breakdown voltage of the coupling capacitor. The parametric test setup can be used to extract V_{ptp} for five of the ten channel ends on each test chip. For the
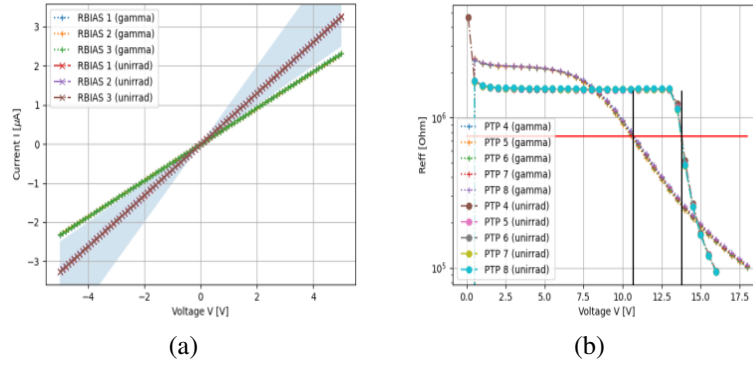
Figure 9. ATLAS18 pre-production (a) Polysilicon bias resistors current as a function of voltage. The blue band shows the specification of $R_{bias} = 1.5 \pm 0.5$ MΩ. (b) Punch-through-protection effective resistance as a function of voltage, before and after gamma irradiation.

pre-irradiated site verification test chip, an average value of $V_{ptp} = 13.81$ V is measured with a range of 0.05 V between individual implant ends. For the gamma irradiated sample, a lower average punch-through voltage of 10.66 V is measured with a range of 0.19 V. Both pre- and post-irradiation, V_{ptp} is measured below 100 V, the voltage limit to which the coupling capacitor is tested for dielectric breakdown. The interdigitated structures are designed to perform interstrip resistance R_{int}, and interstrip capacitance C_{int}, measurements. It consists of a series of n^+ implants of which every odd implant is connected at one side, and every even strip at the other so the total strip length is equal to that in the main sensors. The strips are surrounded by a bias ring, to which they are not connected and a guard ring [12]. There are three interdigitated structures on each test chip with different strip lengths and angles corresponding to main sensors for different parts of the strip detector. For the R_{int} measurement the bulk of the chip is fully depleted and the bias ring is grounded. A voltage sweep from -5 to 5 V is applied to one set of strips while the current is measured at the other set. The R_{int} is extracted from the inverse slope of the current-voltage curve. According to the QA specifications, the R_{int} is required to be a factor of 10 greater than the bias resistance to ensure good isolation between neighbouring implants. In figure 10(a) the current as a function of voltage measurements of interdigitated structures on the site verification test chips (one pre-irradiated, one gamma irradiated) is presented. The current value for the pre-irradiated structure is a few pA, as opposed to the few hundred nA after gamma irradiation due to decreased interstrip resistance. For the interstrip capacitance C_{int} measurement, figure 10(b), the Si-bulk is biased in full depletion and the bias ring is grounded. The same voltage sweep as in the R_{int} measurement, is applied to one set of strips with the low LCR meter probe to the second set. The C_{int} is defined as the capacitance contribution from both neighbouring strips $C_{int} = C_{meas}/l_{strip}$, where l_{strip} is the total strip length. The C_{int} is required to be measured less than 1 pF/cm, motivated by it's impact on the module readout noise, as well as prevention of signal loss due to charge division with C_{coupl}. The above QA requirement is satisfied for the gamma irradiated test chip. After completion of the site qualification procedures, proton irradiated pre-production test chips at target fluences 5×10^{14} and 1.6×10^{15} n$_{eq}$/cm^2 are measured. The extracted parameters are presented in table 2.
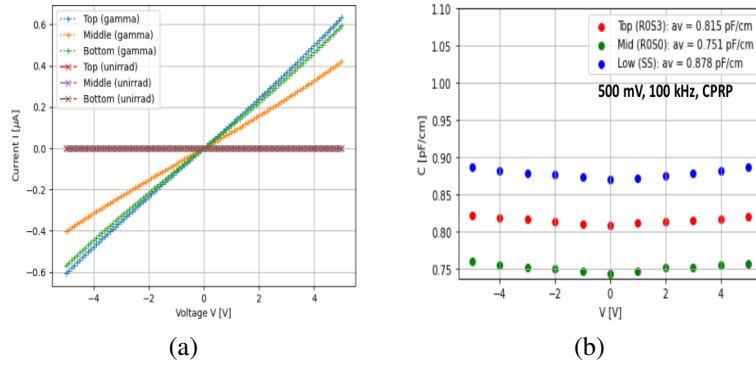
Figure 10. ATLAS18 pre-production (a) Interstrip resistance as a function of voltage, before and after gamma irradiation and (b) Interstrip capacitance as a function of voltage after gamma irradiation.

Table 2. Test chip parameters and monitor diode after proton irradiation at CYRIC.

Batch	VPX32469-W001	VPX32469-W095
Type	ATLAS18R1	ATLAS18LS
Serial Number	20USES11700001	20USBSL1700095
Irradiation	p4.68E14(CYRIC)	p1.54E15(CYRIC)
MD8		
Norm. Current [A/cm^2]	8.98×10^{-6}	2.51×10^{-5}
V_{bd} [V]	—	—
V_{fd} [V]	no meas	no meas
Bias Resistors		
Average R_{bias} [Ohm]	1.75×10^6	1.81×10^6
Range R_{bias} [Ohm]	5.39×10^3	6.71×10^3
Coupling Capacitor		
C_{coupl} [pF/cm]	20.8	21.1
I_{coupl} at 500 V [A]	1.50×10^{-9}	1.50×10^{-9}
Interdigitated Structure — Low		
R_{int} [Ohm]	6.07×10^7	1.54×10^7
C_{int} [pF/cm]	1.36	1.59
Interdigitated Structure — Mid		
R_{int} [Ohm]	2.91×10^7	no meas
C_{int} [pF/cm]	1.70	no meas
Interdigitated Structure — Up		
R_{int} [Ohm]	3.44×10^7	2.67×10^6
C_{int} [pF/cm]	1.25	0.89
PTP Structure		
Average V_{ptp} [V]	35.20	26.83
Range V_{ptp} [V]	0.87	0.42

5 Summary

A large throughput QA evaluation program has been designed for the large-volume sensor production. It includes post-irradiation assessment of the amount of signal and the technological parameters. To manage the workload, this testing program has been shared between several sites. The results from the seven QA test sites (Birmingham, Barcelona, Ljubljana, Prague, Toronto, Tsukuba and Valencia) have been verified. Agreement is observed between the test sites of the measured CCE at 500 V with samples from the same irradiation slot. In addition all sites confirm uniformity of the extracted test chip parameters after gamma irradiation. During pre-production, in total 39 batches were received and all qualified. Furthermore, the irradiation plan for the production sensors was established. The qualification of the Birmingham irradiation site required further investigation after the Production Readiness Review against intermittent mini-sensor low CCE performance. The site finally qualified after having established consistent results internally to the site and with other irradiation sites.

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