Development and Evaluation of ATLAS Inner Tracker Strip Sensors and Strip Detector Modules

by

Steven Juhyung Lee, B.Sc.

A thesis submitted to the
Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Science in Experimental Particle Physics

Ottawa-Carleton Institute for Physics
Department of Physics
Carleton University
Ottawa, Ontario
July, 2018

©Copyright
Steven Juhyung Lee, 2018

The undersigned hereby recommends to the
Faculty of Graduate and Postdoctoral Affairs
acceptance of the thesis

**Development and Evaluation of ATLAS Inner Tracker Strip
Sensors and Strip Detector Modules**

submitted by **Steven Juhyung Lee, B.Sc.**

in partial fulfillment of the requirements for the degree of

Master of Science in Experimental Particle Physics

Professor Thomas Koffas, Thesis Supervisor

Professor Dag Gillberg, Thesis Co-supervisor

Professor Alain Bellerive, Chair,
Department of Physics

Ottawa-Carleton Institute for Physics
Department of Physics
Carleton University
July, 2018

Abstract

The ATLAS Inner Tracker strip detector collaboration will be producing more than 20,000 silicon strip detector modules in anticipation of the high luminosity upgrade for the LHC (HL-LHC). The HL-LHC will achieve approximately 200 proton-proton collisions per 25 ns with the center of mass energy 14 TeV at the center of the ATLAS detector with the goal of improving the precision of physics measurements of known interactions and of potentially discovering unknown physics processes. To achieve this, the ATLAS collaboration aims to upgrade the ATLAS Inner Detector (ID) with the new all silicon radiation hard Inner Tracker (ITk) based on new technology developed since the installation of the ATLAS detector.

This M.Sc. thesis contains the details of the development and evaluation of the prototype silicon strip sensors for the ATLAS ITk. In addition, this thesis presents the development of the assembly technique for the silicon strip detector modules for the ATLAS ITk.

To my closest friend Tristan Kettles, for the old times.

Acknowledgments

I would like to first acknowledge my thesis supervisor Dr. Thomas Koffas for providing the insight, motivation and the opportunity to work with the world's largest experimental high energy particle physics collaboration. I would also like to acknowledge my technical supervisor Dr. Bart Hommels for the opportunity to partake in the research and development of the new sensors for the ATLAS ITk strip detectors. I would like to thank you for my advancement in knowledge, technical skills, insight and experience for the semiconductor strip sensors.

In addition, I would like to thank my co-supervisor Dr. Dag Gillberg, and my unofficial supervisor Dr. John Keller for the introduction to data analysis within the ATLAS collaboration.

Furthermore, I would like to thank the following members of the ATLAS ITk strip detector collaboration Robert Hunter, James Botte, Christoph Klein, Dr. Carlos Escobar, Dr. Mercedes Minano, Dr. Marcela Mikestikova, Dr. Jiri Kroll, Dr. Juergen Thomas, Laura Rehnisch, Martin Stegler and Martin Renzmann. The technical staff at the Department of Electrical engineering of Carleton University, Rob Vandusen and Angela McCormick and the technical staff in the Physics Department of Carleton University, Matt Bowcock, Philippe Graville, Rodney Schnarr and Vance Strickland.

The person I would like to dedicate my work to is my best friend Tristan Kettles (15 September 1991 to 7 September 2017). We spent the majority of our adult lives apart due to our career choices. My choice was the military then it became academia. His, the military then the police force. The last time I saw him alive he asked me to come home. He needed our lives to be just like the old times. I couldn't say yes. I was at the time retraining myself and procuring the apparatus needed for the Universal Quality Control Jig. I found myself at his funeral soon after and giving his eulogy. I cannot express how much I regret I couldn't come home and have one more day like the old times. The least I feel I can do is to dedicate my work to you. I am sorry I couldn't come home.

Statement of originality

Contributions made to the ATLAS ITk strip detector collaborations made by Steven J. Lee as part of this M.Sc. thesis

The majority of my contribution to the ATLAS ITk strip detector collaboration are displayed in Chapter 4, Chapter 5 and Chapter 6.

- ATLAS ITk strip sensor testing (Chapter 4).

Since early 2017, I have been probing and characterizing the prototype ATLAS ITk strip sensors at Carleton University. In addition, during my visits to the University of Cambridge, CERN and DESY Zeuthen I performed I-V curve, C-V curve, Interstrip Capacitance, Interstrip Resistance and full strip tests on the ATLAS07, ATLAS12 and ATLAS17LS prototype strip sensors (barrel, mini and endcap). I also presented the initial report of the first batch of ATLAS17LS prototype sensors to the ATLAS ITk strip sensor community. In addition to the sensor testing, I have also provided documentations, training, repairs and procurement of the existing apparatus at Carleton University.

- Designing, producing and inspecting the Universal Quality Control Jigs (UQCJs) also known as the TK Jig (Chapter 4).

For this task, I visited my technical supervisor Dr. Bart Hommels at the Cavendish Laboratory of the University of Cambridge for a total of 4 weeks. Constant improvements to the design and the product was made starting on 15 July 2017 until its acceptance on 30 June 2018. All of the designs were made using a student license for the Autodesk Inventor 2018 Computer Assisted Designing (CAD) software. I made constant interactions with the members of the ATLAS ITk strip detector collaboration to improve the design as well as

testing the performance of the jig at Carleton University and the visits to the University of Cambridge, CERN and DESY Zeuthen.

- Assembly of ATLAS12EC-R0-DESYHU-03 detector module at DESY Zeuthen (Chapter 5).

I participated in the construction of the detector module seen in Chapter 5. Within the timeframe of my visit, under supervision I attached eight ABC130 ASICs to the R0H0 hybrid board, and attached the R0H0 hybrid board onto the R0 sensor. In addition I provided feedback on the defective wirebonds. In addition, I've participated in the assembly of an R0H0 hybrid module at the university of Toronto in the summer of 2017.

- Analysis of the ATLAS ITk strip sensor characterization results (Chapter 6).

I developed several generalized analysis scripts written in linux bash, ROOT5 and ROOT6 which can be used for locating the sensor probing pads, identifying the leakage currents at different voltages, identifying full depletion voltage of the sensors and identifying the onset voltage for sensor junction breakdown. These scripts were used for extrapolating the data seen in Chapter 4 and Chapter 6.

- Testing traveling DAQ load.

Prior to my visit at CERN in 2017, I was trained on the ITSDAQ software using the traveling DAQLoad passing through Carleton University. This training was to be applied for the Irradiation Campaign seen in (Chapter 6).

- Irradiation Campaign 2017 (Chapter 6).

I worked with the staff at the IRRAD facility at CERN and also with the ATLAS ITk collaboration members to set up irradiation campaign seen in (Chapter 6). After the setup, I remained on a rotating shift at the IRRAD control zone until my visit to the University of Cambridge for a total of 51 days.

Contents

Abstract	iii
Acknowledgments	v
Statement of originality	vi
Table of Contents	viii
List of Tables	xi
List of Figures	xiii
List of Abbreviations	xviii
1 Introduction	1
1.1 A brief introduction to the fundamental experimental high energy physics	2
1.1.1 The Standard Model (SM)	4
1.2 The Large Hadron Collider (LHC)	6
1.3 A Toroidal LHC ApparatuS (ATLAS)	9
2 The ATLAS Inner Tracker (ITk) upgrade	12
2.1 A brief introduction to the inner tracking detector within ATLAS	13
2.1.1 Particle tracking performance	14
2.1.2 Radiation damage	16
2.2 The ATLAS Inner Detector (ATLAS ID)	18
2.3 The ATLAS Inner Tracker (ITk)	20
2.3.1 ITk layout	21
2.3.2 ITk performance requirements	21
2.4 The ATLAS ITk strip detector	24

2.4.1	Layout of the ITk strip detector	24
2.4.2	Radiation tolerance of the ATLAS ITk strip detector	26
2.4.3	Performance of the ATLAS ITk strip detector	27
3	ATLAS ITk strip sensors	30
3.1	A brief introduction to semiconductor silicon microstrip sensors	31
3.1.1	Semiconductors and p-n junctions	31
3.1.2	Semiconductor microstrip detector	39
3.2	ATLAS ITk strip sensor prototypes	41
3.2.1	General features of the ATLAS ITk strip sensors	42
3.2.2	ATLAS07	46
3.2.3	ATLAS12	47
3.2.4	ATLAS17LS	49
4	ATLAS ITk strip sensor characterization	50
4.1	Mechanical characterization	51
4.1.1	Visual inspection	51
4.1.2	Flatness test	52
4.2	Electrical characterization	54
4.2.1	Electrical characterization for the bulk material of the strip sensor	55
4.2.2	Full electrical characterization at the strip level	60
4.3	Apparatus for strip sensor testing: TK Jig	67
4.3.1	Design and prototypes	67
4.3.2	TK Jig	74
5	ATLAS ITk strip detector module assembly	76
5.1	A brief introduction to the principle of operations of the ATLAS ITk strip detector module	77
5.1.1	ABC and HCC	79
5.1.2	The hybrid boards	80
5.1.3	ABC130-HCC130 detector modules	81
5.2	ATLAS ITk strip detector assembly	83
5.2.1	The hybrid module	84
5.2.2	The strip detector module	91

6	The performance of the ATLAS ITk strip sensors	97
6.1	The performance of the ATLAS12, ATLAS12EC and ATLAS17LS strip sensors at the QC sites	98
6.1.1	The performance of the ATLAS12 strip sensors	99
6.1.2	The performance of the ATLAS17LS sensors	104
6.2	Irradiation damage to the ATLAS12EC strip sensor (Irradiation Campaign)	108
7	Summary and conclusion	113
	List of References	115
	Appendix A Mathematical derivations	119
A.1	The cross-sections of the proton-proton interactions	119
A.2	Depletion Depth in a p-n junction	120
A.3	Resistors in a semiconductor detector	122
	Appendix B ATLAS ITk Strip sensor Technical Specifications	124

List of Tables

1.1	Some of the predicted final states of the Higgs boson and their respective branching ratio with the relative uncertainty. [1]	4
2.1	The radiation hardness factors of the pions, protons and neutrons at the LHC. These values come from the metology of radiation damage during 10 years of operation at the LHC [2].	18
2.2	Summarized expected HL-LHC performance and the operational parameter of the current ATLAS ID [3]	20
2.3	The required tracking performance of the new ATLAS ITk [3]. From Left to right are the parameter resolution, unit, upper limit of this resolution, and the range. For example σ_{z_0} at $p_T=1$ GeV must be less than 100 μ m within the range of $ \eta $ less than 0.5. The (∞) symbol next to the σ represents very high transverse momentum (higher than 100 GeV).	22
2.4	The expected resulting maximal 1MeV neutron radiation fluence and dose at different sections of the ATLAS ITk [3].	22
2.5	The preliminary design parameters of the ATLAS ITk strip detectors [3]. The barrel layers are denoted with L and the identical endcap sections are divided in 6 different diameters denoted with D.	26
2.6	The glue requirement for th ATLAS ITk Strip detector modules [3]. .	27
2.7	The names and functionalities of the ASICs to be used on the ATLAS ITk strip detector [3].	28
3.1	The summarized table from [4] showing the comparison of measured parameter values with the technical specification	46
3.2	The summarized table from [5] showing the comparison of measured parameter values with the technical specification.	48
4.1	The ATLAS ITk strip sensor QC requirements as of 2017 [3].	66
4.2	Requirements for the Universal Quality Control Jig	67

5.1	Comparison of data flow of the ABC130 and HCC130 seen in the left and the ABCStar and HCCStar seen in the right [3].	79
6.1	The batches of the ATLAS ITk strip sensors tested at Carleton University	98
6.2	The batches of the ATLAS ITk strip sensors tested at the University of Cambridge	98
6.3	Comparison of the HPK made ATLAS17LS sensors batch VPX26244 to the technical specification.	107
B.1	ATLAS07 Technical Specification provided to HPK by ATLAS SCT collaboration [6].	125
B.2	ATLAS12 Technical Specification provided to HPK by ATLAS ITk collaboration [7].	126
B.3	ATLAS17LS Technical Specification provided to HPK by ATLAS ITk collaboration [8].	127

List of Figures

1.1	Diagram of two particles colliding and two particles outgoing [1]. . . .	3
1.2	A feynman diagram for the Double Higgs Production. The cross-section of this interaction is $\sigma_{HH}=33.4\text{fb}$ at $\sqrt{s}=13\text{TeV}$ proton-proton collision [1, 3, 9].	5
1.3	The invisible decay channel of Higgs boson production [1, 3, 9].	6
1.4	Schematic drawing of the LHC Complex. The four particle detectors ATLAS, CMS, LHCb and ALICE are highlighted in red [10–12]. . . .	7
1.5	The HL-LHC upgrade and the long shut down schedule for the LHC [3].	8
1.6	The reduction of relative uncertainty of the verified decay channels of Higgs boson seen in Tab. 1.1. The HL-LHC data has been simulated by the ATLAS collaboration [3]. At the current state, the processes where the Higgs boson decay into bottom quarks are most dominant.	9
1.7	Schematic drawing of the ATLAS detector [3, 13, 14]	10
2.1	Cylindrical coordinate system used for the ATLAS. The proton beam-line of the LHC is defined as the z axis of the coordinate system [15].	13
2.2	A schematic of a single particle track in the ATLAS detector. The detectors are drawn in green, the particle track in purple, the primary vertex in red and the distance of minimum approach between the particle track to the primary vertex are highlighted in orange.	14
2.3	Simulated 200 pile up events inside the ATLAS ITk [16]	16
2.4	Cross-sectional view of one of 4 quadrants of the ATLAS Inner Detector [13]	19
2.5	A 3D CAD drawing of the new ATLAS Inner Tracker [3].	21
2.6	The plots demonstrating the radiation lengths of components the current ATLAS ID and the material thickness requirement for the new ATLAS ITk [3].	23

2.7	Schematics of one barrel stave can be seen at the bottom and one endcap disk petal can be seen at the top of this figure. The schematics also show the basic outline of how a detector module is mounted onto the structural supports [3].	25
2.8	The assembly diagram of the ATLAS ITk Strip Detector [3]	29
3.1	A schematic representation of p-n junction with thickness w . X is the charge carrier depletion depth produced by an external bias voltage (V_b) [17]	33
3.2	A C-V curve of two detectors of 1cm^2 area. The detector in figure a) has resistivity of $8\text{ k}\Omega\text{ cm}$ and thickness $w=247\text{ }\mu\text{m}$ and the detector in figure b) has resistivity of $6\text{ k}\Omega\text{ cm}$ and thickness $w=300\text{ }\mu\text{m}$ [17]. . . .	35
3.3	The left shows a typical I-V curve and the right shows the temperature dependence of leakage current [17].	37
3.4	The effects of exposing the semiconductor to radiation. The left figure shows the linear increase in semiconductor's leakage current as a function of 1 MeV neutron irradiation fluence and the right figure shows the change in effective doping concentration as a function of 1 MeV neutron irradiation fluence [18]. Furthermore the p type semiconductor bulk does not reach the type inversion.	38
3.5	The left shows a typical microstrip detector fabrication process from top to bottom and the right shows a typical p in n particle detector [19].	40
3.6	Cross-sectional view of the ATLAS ITk strip sensor. The left shows the structure [20] and the right shows the resulting electric field generated by Technology CAD (TCAD) [21].	41
3.7	The general surface and internal features of the ATLAS ITk strip sensors	42
3.8	General features of ATLAS ITk strip sensor strip segment and its equivalent circuit.	43
3.9	Two types of Punch Through Protection displaying their onset voltage [10]. Working together with the Poly-Si Resistor, PTP shorts the strip to bias.	45
3.10	The Stereo Annulus shape of the ATLAS12 End Cap sensor [22] . . .	47
3.11	The Stereo Annulus design of the ATLAS12 End Cap sensors [22] . .	47
3.12	Incorporation of the stereo annulus design of the ATLAS12 End Cap sensors during production [3,6,7].	49

4.1	Surface of a rejected ATLAS17LS ITk strip sensor	52
4.2	Topological maps of two ATLAS17LS strip sensors with two different thicknesses	54
4.3	The circuit setup for the strip sensor I-V curve test	56
4.4	I-V curve from ATLAS17LS W035 upon reception. An odd effect is highlighted in red near -800V.	57
4.5	I-V curve from ATLAS17LS W035 after a long term exposure in hu- midity. the strip sensor breakdown at -650V	58
4.6	The circuit setup for the strip sensor C-V curve test	59
4.7	C-V curve of ATLAS17LS W035 upon reception. This strip sensor is fully depleted at 326.09 V, the capacitance at full depletion is 32 080 pF and the derived depletion depth w is 314 μm	60
4.8	An equivalent circuit of the interstrip structure of ATLAS ITk strip sensors [1, 10].	61
4.9	The circuit setup for the strip sensor C_{IS} curve test	64
4.10	The circuit setup for the strip sensor R_{IS} curve test	65
4.11	The supersensor	69
4.12	The first prototype of UQCJ	70
4.13	I-V curve test of one ATLAS12EC R0 W007 strip sensor loaded on a probe station chuck and then on the UQCJI at DESY Zeuthen	71
4.14	The general outline of the	73
4.15	The final design of UQCJ: TK Jig	74
5.1	An exploded view of an ATLAS ITk strip sensor detector module [3]	77
5.2	The design of the hybrid boards for the ABC130 and HCC130 ASICs [3].	80
5.3	A standard output from ITSDAQ showing the V_{t50} , gain, and noise of a 1.01 fC charge injection and comparing to no charge injection at 0 fC [23]	82
5.4	The results of a 3 point gain [23]	83
5.5	The hybrid boards (left) and the ASICs (right) upon reception	85
5.6	The design of the hybrid boards for the ABC130 and HCC130 ASICs [3].	86

5.7	Unsuccessful hybrid module assembly. The ASICs were misaligned to the hybrid board during the glue curing process leaving space between the chip and the pads on the hybrid board. The R0H0 hybrid board used for this hybrid module was not flat. It is likely that the ASICs were misaligned due to the fact that the hybrid board was bowing during the assembly.	86
5.8	Wire bonding scheme for the ATLAS12EC hybrid boards to test frame and to the strip sensor [24]	87
5.9	Wire bonding scheme for an individual ABC130 to the hybrid board [24]. The left shows the data in put pads for AC pads of the strip sensor and the ASIC ID is set by the wirebond [25].	88
5.10	Troubleshooting the Hybrid module by visual inspection and thermal imaging.	90
5.11	A dedicated ATLAS12EC R0 sensor vacuum jig for detector module assembly	91
5.12	The hybrid module is picked up by the vacuum ASICs pick up tool and glue is applied to the backside of the hybrid board through a glue stencil	92
5.13	The hybrid modules are joined to the strip sensor using the ASICs pick up tool which is mechanically aligned to the vacuum sensor jig. . . .	92
5.14	The highlights show the R0 sensor module with excess seeping glue from R0H1 hybrid module and R0H0 hybrid module is misaligned. . .	93
5.15	A fully assembled ATLAS12EC R0 detector module mounted on a test frame [23]	94
5.16	Performance of the ATLAS12EC R0 module [23]	95
6.1	The leakage current and full depletion voltages of all of the ATLAS12 strip sensors. The VPX22729 and VPX22728 endcap strip sensors have lower full depletion voltages as seen in the right.	99
6.2	The leakage current and full depletion voltage of the ATLAS12 main barrel strip sensors.	100
6.3	The leakage current and full depletion voltage of the ATLAS12EC R0 strip sensors.	101
6.4	Sample coupling capacitance of the strip segments of the ATLAS12 strip sensor	103

6.5	Sample bias resistance of the strip segments of the ATLAS12 strip sensor	104
6.6	The leakage current and full depletion voltages of the new ATLAS17LS sensors.	105
6.7	Sample coupling capacitance of the strip segments of the ATLAS17LS strip sensor	106
6.8	Sample bias resistance of the strip segments of the ATLAS17LS strip sensor	107
6.9	Setup inside the coldbox.	109
6.10	Setup diagram of the Irradiation Campaign	110
6.11	Setup diagram of the Irradiation Campaign	111
6.12	The leakage current of the ATLAS12ECR0 VPX22728-W031 strip sensor before and after irradiation [26].	112

List of Abbreviations

ABC	ATLAS Binary Chip
ALICE	A Large Ion Collider Experiment
ASIC	Application Specific Integrated Circuits
ATLAS	A Toroidal LHC ApparatuS
CERN	Counseil Européen pour la Reserche Nucléaire
CMS	Compact Muon Solenoid
HCC	Hybrid Control Chip
HPK	Hamamatsu Photonics K. K.
ID	Inner Detector
IFX	Infineon Technologies A.G.
ITk	Inner Tracker
LHC	Large Hadron Collider
LHCb	LHCbeauty
SCT	Semi Conductor Tracker
SM	Standard Model
TRT	Transitional Radiation Tracker

Chapter 1

Introduction

The Conseil Européen pour la Recherche Nucléaire (CERN) is the single largest Accelerator Laboratory in the world. It was founded in 1954 [11] in the effort to probe beyond the understanding of the universe at the time. Since the foundation, CERN has discovered numerous fundamental physics concepts and particles. With the advancement of the human knowledge in particle physics, new discovery became more and more complex and required implementation of more advanced technology.

The recent focus of CERN has been in high energy physics (HEP) which requires a powerful particle collider such as the Large Hadron Collider (LHC) and advanced particle detecting apparatus such as the A Toroidal LHC ApparatuS (ATLAS) detector. The landmark discovery of the Higgs boson in 2012 [11, 27–30] has given the LHC the highest priority by the international HEP community [3]. The LHC and the associated particle detectors are scheduled to be upgraded with modern technology to expand the current understanding of particle physics.

The main topic of this M.Sc. thesis is on the properties of the new n^+ -in- p^- microstrip sensors presented in Chapter 3, the characterization procedure of these sensors presented in Chapter 4 and their integration as particle tracking detectors module for the ATLAS Inner Tracker (ITk) as presented in Chapter 5. The detector modules are to be attached to structural supports and then finally assembled into a complete particle tracker. There will be a total of 20225 [3] detector modules which need to be assembled, for which each of the components need to be carefully characterized and assembled. The ATLAS ITk strip detector collaboration aims to provide a large redundancy where only three of these detector modules are required for reproducing a single particle track, but each particle track by design will have at least thirteen detector modules in its trajectory. The large redundancy will provide

a failsafe system where the ITk can operate even with several detector modules out of commission.

This first chapter will briefly introduce the fundamental experimental high energy physics in Section 1.1, the LHC in Section 1.2 and the ATLAS detector in Section 1.3. The overview of the ATLAS ITk is given in Chapter 2. The basics of semiconductor strip sensors and the prototype silicon strip sensors of the ATLAS ITk strip detectors are introduced in Chapter 3. The sensors are characterized with the methods seen in Chapter 4. After the characterization process, the sensors are assembled into particle tracking detector modules as seen in Chapter 5. The actual overall characteristics of the prototype silicon strip sensors are shown in Chapter 6. Finally the overview and summary of this M.Sc. thesis can be found in Chapter 7.

With exceptions to the last two chapters, the general structure of this M.Sc. thesis will include a brief introduction of each topic in the first section of each chapter leading up to the last section of each chapter which will then describe the details of each topic.

1.1 A brief introduction to the fundamental experimental high energy physics

The modern understanding of nature is governed by the following fundamental forces and interactions [3].

- Weak Interaction
Mediated by charged W bosons and neutral Z bosons.
- Strong Interaction
Mediated by gluons.
- Electromagnetism
Mediated by photons.
- Gravity
Mediated by yet undiscovered gravitons.

In order to better understand the nature of these fundamental forces, the matter bound by these forces must be separated. The main aim of high energy physics is

to collide partons at a high center of mass energy in order to separate and then observe the interaction of the sub-nuclear particles within the partons. The center of mass energy of two partons colliding is defined by the Lorentz-invariant Mandelstam variable $\sqrt{s}$ as seen in Eq. 1.1 and in Fig. 1.1 [1].

Figure 1.1: Diagram of two particles colliding and two particles outgoing [1].

The square of total energy available in the collision ($s = (\sqrt{s})^2$) is defined as follows [1].

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2 = m_1^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2 + m_2^2 \quad (1.1)$$

From each collision, the outcome depends entirely on the probability of each potential interaction. These probabilities are represented by the cross-sections of the interactions (σ). The cross-sections are measured quantities from the particle collision experiments [31, 32]:

$$\sigma_{pp \rightarrow X} = \frac{N_{pp \rightarrow X}}{\epsilon \int \mathcal{L} dt} \quad (1.2)$$

here the cross-section of a $pp \rightarrow X$ interaction is derived from the number of recorded events ($N_{pp \rightarrow X}$) from the integrated luminosity $\int \mathcal{L} dt$ and a generalized efficiency for this process (ϵ). More details on the cross-sections can be found in Section A.1. The remainder of this section aims to expand on Eq. 1.2.

In the LHC, the two colliding particles are two protons. In the case of two protons colliding with the center of mass energy $\sqrt{s} = 13 \text{ TeV}$, the resulting inelastic probability cross-section of the proton-proton collision is 80 mb. The cross-section combined with the instantaneous luminosity of a bunch of protons colliding ($\mathcal{L}_{bunch}$) in units of $\text{cm}^{-2} \text{s}^{-1}$ and the collision frequency (f_r) can be used to calculate the expected number of proton-proton collisions (μ) as follows [12, 27].

$$\mu = \mathcal{L}_{bunch} \times \frac{\sigma_{inelastic}}{f_r} \quad (1.3)$$

The outgoing particles from the proton-proton collisions are the main focus of interest

in high energy physics.

1.1.1 The Standard Model (SM)

The effects of the four fundamental forces mentioned in the previous section except for the gravitational force are currently best represented by the Standard Model (SM) [15]. Using the SM, one can calculate the cross-sections of the outcome of proton-proton collisions at the Large Hadron Collider (LHC). A vast majority of the outgoing particles have very short life time and only the resulting final decay products of the collisions can be observed with particle detectors. Using this method, the Higgs boson with mass $m_H = 125.7 \pm 0.8 \text{ GeV}$ was discovered at the LHC in 2012 [29, 30]. The discovery of the Higgs boson added the last missing particle in the SM and provided the ultimate verification of the SM [15]. Since the discovery of the Higgs boson, the aim of the LHC has shifted towards the study of the properties of the Higgs bosons; the Higgs mechanism. Some of the current predictions of the Higgs decay branching ratios can be seen in Tab. 1.1.

Decay channel	Branching ratio	Rel. uncertainty
$H \rightarrow \gamma\gamma$	2.27×10^{-3}	$+5.0\%$ -4.9%
$H \rightarrow ZZ$	2.62×10^{-2}	$+4.3\%$ -4.1%
$H \rightarrow W^+W^-$	2.14×10^{-1}	$+4.3\%$ -4.2%
$H \rightarrow \tau^+\tau^-$	6.27×10^{-2}	$+5.7\%$ -5.7%
$H \rightarrow b\bar{b}$	5.84×10^{-1}	$+3.2\%$ -3.3%
$H \rightarrow Z\gamma$	1.53×10^{-3}	$+9.0\%$ -8.9%
$H \rightarrow \mu^+\mu^-$	2.18×10^{-4}	$+6.0\%$ -5.9%

Table 1.1: Some of the predicted final states of the Higgs boson and their respective branching ratio with the relative uncertainty. [1]

The branching ratios from Fig. 1.1 can then be used in Eq. A.4 to calculate the cross-sections. In the LHC, the actual count of these decay products (N) can be computed

by using the cross-sections (σ) and the integrated luminosity ($\int \mathcal{L} dt$) [1].

$$N = \sigma \int \mathcal{L} dt \quad (1.4)$$

For the discovery of the Higgs boson, the center of mass energy for the proton-proton collisions at the LHC was $\sqrt{s} = 8\text{TeV}$ and the total integrated luminosity was $\int \mathcal{L} dt = 5.8\text{fb}^{-1}$ [29,30]. The predicted Higgs processes have been reconstructed using the existing data with large uncertainties. One of the most challenging aspects of high energy experimental particle physics is the fact that these processes are obscured by very large background signals. One way to statistically reduce the uncertainty of the experimental measurements is by increasing the data. CERN intends to achieve this by increasing the luminosity of the LHC. In addition to the reduction in statistical uncertainty, the higher luminosity may lead to the observation and verification of some the exotic Higgs processes seen below [9]:

- Double Higgs Production

Figure 1.2: A feynman diagram for the Double Higgs Production. The cross-section of this interaction is $\sigma_{HH}=33.4\text{fb}$ at $\sqrt{s} = 13\text{ TeV}$ proton-proton collision [1,3,9].

The SM prediction of the cross-section for the above is $\sigma_{HH} = 33.4\text{fb}$ at center of mass energy $\sqrt{s} = 13\text{ TeV}$. The two Higgs bosons then decay into:

- $HH \rightarrow bbbb$
- $HH \rightarrow bbl\nu l\nu$
- $HH \rightarrow bb\tau\tau$
- $HH \rightarrow bbWW$
- $HH \rightarrow bb\gamma\gamma$

$$- HH \rightarrow WW\gamma\gamma$$

These are some of the potential decay products of the double Higgs production. One should note that the purity of the detection of these decay products depends not only on the analysis methods but also on the performance of the particle detector.

- $H \rightarrow ?$

Less than 0.1% of the produced Higgs bosons cannot be observed due to the fact that the decay products are beyond observation. Some of the possibility include decay processes such as $H \rightarrow ZZ^* \rightarrow 4\nu$. It is also possible that the Higgs boson decays into new particles not predicted by the SM. Some of the theories Beyond the SM (BSM) predict that these missing decay channels could lead to the discovery of dark matter [33].

Figure 1.3: The invisible decay channel of Higgs boson production [1,3,9].

The next sections of this chapter is dedicated to the brief introduction of the LHC and the ATLAS detector.

1.2 The Large Hadron Collider (LHC)

The LHC crosses the border of France and Switzerland and it is the most advanced facility in the world for investigating the nuclear structure [12, 27] of matter. It is also currently the most powerful particle accelerator in the world. Illustrated in Fig. 1.4 the LHC is a ring 27km in circumference and the proton beams cross at four main experimental sites. These four proton beam crossings are occupied by four particle detectors A Toroidal LHC ApparatuS (ATLAS), Compact Muon Solenoid (CMS), LHC-beauty (LHCb) and A Large Ion Collider Experiment (ALICE). The

LHC accelerates and collides protons with a very well defined proton momentum at the center of these beam crossings occupied by the four particle detectors. The LHC is responsible for providing the proton-proton collisions as seen in the left of Fig. 1.1 and the four particle detectors are responsible for observing the outgoing particles seen in the right of Fig. 1.1.

Figure 1.4: Schematic drawing of the LHC Complex. The four particle detectors ATLAS, CMS, LHCb and ALICE are highlighted in red [10–12].

At the time of the discovery of the Higgs boson, the center of mass collision energy of the LHC was $\sqrt{s} \leq 8 \text{ TeV}$ [29, 30]. The LHC is currently producing proton-proton collisions with the center of mass energy $\sqrt{s} = 13 \text{ TeV}$ and it has collected approximately the total integrated luminosity $\int \mathcal{L} dt = 50 \text{ fb}^{-1}$ [12, 27]. The design of the LHC is to eventually reach the collision energy $\sqrt{s} = 14 \text{ TeV}$ and to achieve the instantaneous luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [13]. This corresponds approximately to 23 proton-proton collisions per 25 ns. At this rate of data collection, it can take centuries before the next great discovery in HEP. In order to extend the current physics reach, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC) starting in 2023 with

an aim to reach $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$ in a span of 10 years.

Figure 1.5: The HL-LHC upgrade and the long shut down schedule for the LHC [3].

The HL-LHC will provide proton-proton collisions with center of mass energy $\sqrt{s} = 14 \text{ TeV}$ per 25 ns and it will reach instantaneous peak luminosity $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This corresponds to approximately 200 proton-proton collision events per 25 ns for each of the four particle detectors. In this M.Sc. thesis only the ATLAS detector will be discussed.

The ATLAS collaboration anticipates that the data collected during the HL-LHC operation will statistically reduce the uncertainty of the predicted Higgs decays seen in Tab. 1.1 as indicated in Fig. 1.6 [3].

With the HL-LHC upgrade in schedule, the ATLAS detector must also be upgraded. Many components of the ATLAS detector have been in operation for almost 10 years requiring maintenance [3]. Furthermore these detector components were never designed for the HL-LHC. The current components within the ATLAS detector first need to be replaced. It is worth noting that in the past 10 years, there have been great advancements in technology which can be used to replace and upgrade the components within the ATLAS detector. The next section will present the ATLAS detector and some of its components which will be upgraded.

Figure 1.6: The reduction of relative uncertainty of the verified decay channels of Higgs boson seen in Tab. 1.1. The HL-LHC data has been simulated by the ATLAS collaboration [3]. At the current state, the processes where the Higgs boson decay into bottom quarks are most dominant.

1.3 A Toroidal LHC ApparatuS (ATLAS)

The ATLAS detector is comprised of many components. Some of its defining features are the toroidal magnets placed throughout its main body as seen in Fig. 1.7. The proper classification of the ATLAS detector is as a general particle detecting apparatus as it does not specialize in just the heavy ionizing particles such as the ALICE detector. All of the components within the ATLAS detector work together to track

and reconstruct the outgoing particles from the proton-proton collisions produced by the LHC.

Figure 1.7: Schematic drawing of the ATLAS detector [3, 13, 14]

Within the ATLAS detector, its components are dedicated to extracting specific particle information. For example, the calorimeters are used for measuring the energy of the outgoing particles. The muon detectors are placed in the outer regions of the ATLAS detector to detect the high momentum outgoing muons from the proton-proton collisions. These specialized components still have to work together in order to properly detect and track the outgoing particles by employing a common triggering system throughout the ATLAS detector [28]. Located at the very center of the ATLAS detector is the Inner Detector (ID). The ID is responsible for detecting and tracking the charged particles produced by proton-proton collisions. The tracks of the charged particles reconstructed using the ATLAS ID is then used to locate and identify the primary vertices of particle interactions. The ID is the single most important tracking detector of the ATLAS detector. During the installation of the HL-LHC upgrade seen in Fig. 1.5, the ATLAS Collaboration aims to replace the ATLAS ID

with the new Inner Tracker (ITk).

The main topic of this M.Sc.thesis is on the development and evaluation of the silicon strip sensors and the strip detector modules for the new ATLAS ITk. The next chapter will present the fundamentals of the particle tracking detector, the current ATLAS ID and the new ATLAS ITk upgrade for the ATLAS detector. The description of the silicon strip sensors start in Chapter 3 and the description of the silicon strip detectors start in Chapter 5.

Chapter 2

The ATLAS Inner Tracker (ITk) upgrade

The ATLAS Inner Detector has been in operation for the past 10 years [3] [13]. It was originally designed for the current LHC with peak instantaneous luminosity $\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$ which corresponds to approximately 23 proton-proton collision events per 25 ns [13]. The sensors within the ATLAS ID are currently heavily damaged by the radiation resulting from 10 years of operation. Furthermore, one should note that the design specification of the HL-LHC requires the inner tracking detector of ATLAS to be able to resolve and track charged particles while the HL-LHC is operating at the peak instantaneous luminosity $\mathcal{L} = 7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ which corresponds to approximately 200 pileup events per 25ns. Furthermore the inner tracking detector of ATLAS must be able to withstand the radiation damage deposited in its components due to the integrated luminosity $\int \mathcal{L} dt = 3000 \text{fb}^{-1}$ from 10 years of operation of the HL-LHC. The ATLAS collaboration intends to maintain the inner tracking detector of ATLAS by replacing the aged and radiation damaged ATLAS ID with the new ATLAS ITk during the long shutdown prior to the start of the new HL-LHC phase.

The focus of this chapter is on the ATLAS ITk upgrade. The new ATLAS ITk will be using new technologies developed since the installation of the ATLAS ID which have better radiation tolerance and particle tracking performance. In addition the performance and the radiation tolerance of the new ITk will be further optimized by reducing the thicknesses of the materials used. This chapter will first briefly introduce the defining features of the ATLAS inner tracking detector in Section 2.1. The chapter will then introduce the ATLAS ID and focus on its limitations in Section 2.2. The new ATLAS ITk will then be introduced in Section 2.3. This chapter will then finally shift its focus to the main topic of this M.Sc. thesis; the ATLAS ITk strip detector (Section 2.4).

2.1 A brief introduction to the inner tracking detector within ATLAS

The very first defining feature of the ATLAS detector is the coordinate system. As seen in Fig. 1.7, the ATLAS detector is approximately cylindrical in shape and the coordinate system used in the ATLAS detector is the cylindrical coordinate system with the proton beam line as the z-axis as seen in Fig. 2.1.

Figure 2.1: Cylindrical coordinate system used for the ATLAS. The proton beamline of the LHC is defined as the z axis of the coordinate system [15].

Using the LHC pipe as the proton beam path, the pseudorapidity (η) of an emitted particle from the proton-proton collision can be defined by Eq. 2.1.

$$\eta \equiv -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad (2.1)$$

Here, θ is the azimuthal angle from the LHC tube and ϕ is the polar angle. The inner tracking detectors of the ATLAS detector are split in two geometries. The barrel section covers the sides of the cylinder and the endcap sections cover the circular ends of the cylinder.

2.1.1 Particle tracking performance

A particle tracking apparatus utilizes several layers of particle detectors which can identify passage of charged particles [17]. Each layer of the detector must provide a “hit” signal with a good position resolution as to where on the layer of the detector the charged particle has passed. Using this information a particle track can be reconstructed. A reconstructed particle track is best defined by the polar angle (ϕ), the azimuthal angle (θ), the curvature of the track, and the two perigee parameters d_0 and z_0 which are the distances of minimum approach of the charged particle track to the primary vertex of the interaction. The curvature of a track is typically calculated using the charge and momentum of the charged particle, and a schematic that describes the perigee parameters can be seen in Fig. 2.2.

Figure 2.2: A schematic of a single particle track in the ATLAS detector. The detectors are drawn in green, the particle track in purple, the primary vertex in red and the distance of minimum approach between the particle track to the primary vertex are highlighted in orange.

Some important parameters for the performance of a particle tracker are the following quantities:

- The resolution of the transverse momentum (p_T) of the charged particle track.
- The resolution of the distances of minimum approach from the primary interaction vertex σ_{d_0} and σ_{z_0} .

In case of the inner tracking detectors for the ATLAS detector, multiple layers of silicon pixel detectors and silicon strip detectors are used for tracking the charged particles [16]. By tracking the traversing particles and by using the reconstructed tracks within the ATLAS detector, the transverse momentum (p_T) of the charged particle [16] can be resolved as seen below [16].

$$p_T = qRB \quad (2.2)$$

where q is the charge of the particle, R is the curvature of the particle track in the radial component and B is the orthogonal magnetic field strength provided by the solenoid magnet surrounding the inner detector in the ATLAS detector. The uncertainty of the transverse momentum depends on the quality of the reconstructed track.

In addition, from a single reconstructed track one can also extract the perigee parameters d_0 and z_0 ; the distances of minimum approach from the primary interaction vertex. The resolution of these parameters are represented by σ_{d_0} and σ_{z_0} and they are defined as follows [3, 16]:

$$\sigma_{z_0} = \frac{r_1\sigma_{2z} + r_2\sigma_{1z}}{r_2 - r_1} + \frac{k_{1z}r_1}{p_T} \quad (2.3)$$

where σ_{z_0} is the z_0 resolution, r_n is the radius of the n -th hit on the n -th layer of the particle detector, σ_{n_z} is the intrinsic resolution in z of the n -th layer and k_{1z} is the scattering component in z . Similarly by replacing z by d , one can also calculate σ_{d_0}

$$\sigma_{d_0} = \frac{r_1\sigma_{2d} + r_2\sigma_{1d}}{r_2 - r_1} + \frac{k_{1d}r_1}{p_T} \quad (2.4)$$

The reconstruction precision of the above perigee parameters and the transverse momentum depends heavily on the position resolution of the individual particle detector layers. One can observe that the first hit signal from a particle track is best resolved when the first hit is closest to the primary vertex. For this reason the very inner region of the particle tracker must have the highest position resolution for the best particle tracking resolution. The ATLAS ID and ITk utilize $50\mu\text{m} \times 50\mu\text{m}$ pixels in pixel detectors to detect these first hit signals with maximum position resolution [3, 13]. The outer layers of the ATLAS ID and ITk are occupied by lower resolution silicon strip detectors.

One should recall that within the LHC and the ATLAS detector, two protons collide with very high center of mass energy. A single pile up event from a pair of protons colliding at the center of the ATLAS detector could result in multiple particle tracks. The current LHC produces approximately 23 proton-proton collisions or pileup events per 25 ns. The HL-LHC is expected to produce approximately 200 pileup events per 25 ns [3]. Fig. 2.3 shows an example of a simulated drawing of 200 pileup events in the ATLAS ITk. These 200 pileup events leave a large number of tracks that need to be resolved by the ATLAS ITk.

Figure 2.3: Simulated 200 pile up events inside the ATLAS ITk [16]

The ATLAS ITk must be capable of resolving and distinguishing thousands of charged particle tracks every 25 ns. This not only requires a very good position resolution of the tracking apparatus, it must also have a good hardware trigger to ensure that new tracks can be reconstructed every 25 ns.

2.1.2 Radiation damage

In this dense particle tracking environment one should also consider the large flux of particles through each detector layer which can result in lasting radiation damage [3,17]. The accumulation of integrated luminosity ($\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$) from 10 years of operation of HL-LHC will increase the level of radiation damage inflicted on all of the

components within the ATLAS detector. In particle physics, the radiation damage is often characterized by the 1 MeV neutron equivalent (n_{eq}) radiation fluence $\Phi_n^{1\text{MeV}}$ in a unit area [17, 34].

The radiation fluence Φ is defined as the number of particles (dN) passing through a cross-sectional area (dA) [17, 34].

$$\Phi = \frac{dN}{dA} \quad (2.5)$$

The energy fluence Ψ is defined as the energy (dE) deposition in a cross-sectional area (dA) [34].

$$\Psi = \frac{dE}{dA} \quad (2.6)$$

The actual absorbed dose from ionising radiation in a medium is defined by the absorbed dose (D) [34].

$$D = \frac{d\bar{\epsilon}}{dM} \quad (2.7)$$

where $\bar{\epsilon}$ is the mean energy imparted on the medium of mass M. The absorbed dose is not practical to measure in highly radiative environments such as inside a nuclear fission reactor, or at the collision points at the LHC. In these environments, the neutron equivalent ($\Phi_n^{1\text{MeV}}$) fluence is used instead [17].

$$\Phi_n^{1\text{MeV}} = \kappa \int_{E_{min}} \Psi(E) dE \left[\frac{n}{\text{cm}^2} \right] \quad (2.8)$$

$\Phi_n^{1\text{MeV}}$ is the fluence of one 1 MeV neutron needed for generating the same amount of damage compared to the fission fluence Φ_n

$$\Phi_n = \int_{E_{min}} \Psi(E) dE \left[\frac{n}{\text{cm}^2} \right] \quad (2.9)$$

and κ is the radiation hardness factor. The radiation hardness factor is experimentally measured for each source of the radiation damage. The three main sources of the radiation damage at the LHC are the protons, neutrons and pions [2]. The radiation hardness factors for these particles have been studied carefully during ten years of operation at the LHC and a summary can be found in Tab. 2.1.

Table 2.1: The radiation hardness factors of the pions, protons and neutrons at the LHC. These values come from the metology of radiation damage during 10 years of operation at the LHC [2].

	hardness factor κ
pions	8
protons	8
neutrons	0.5

The purpose of the ATLAS ITk upgrade is to construct and install a particle tracker that has better particle tracking performance which is also capable of withstanding a higher level of radiation damage than the ATLAS ID. The next section will briefly introduce the ATLAS ID primarily focusing on its limitations. The limitations will be compared to the upgrade requirements of the ATLAS detector for the HL-LHC upgrade.

2.2 The ATLAS Inner Detector (ATLAS ID)

The ATLAS Inner Detector is the current inner tracking detector for the ATLAS detector. Starting from the outer region of the ATLAS ID, the whole inner detector is enclosed by the Transition Radiation Tracker (TRT) then the Semi Conductor Tracker (SCT) and then the silicon pixel detectors. The arrangements of these detectors can be seen in Fig. 2.4. The TRT is comprised of 300,000 thin-walled proportional-mode drift tube gaseous detectors [13], the SCT is comprised of four layers of silicon strip detectors in the barrel section and eighteen disks of endcap silicon strip detectors where nine disks surround the barrel section. In addition there are three layers of silicon pixel detectors in the barrel section, and eight disks of endcap silicon pixel detectors where four disks surround the barrel section. The ATLAS ID collaboration has also installed an inner pixel layer called the Insertable B Layer (IBL) which is closest to the beam pipe as an upgrade to the ATLAS ID.

Figure 2.4: Cross-sectional view of one of 4 quadrants of the ATLAS Inner Detector [13]

The current ATLAS ID has pseudorapidity coverage of $\eta = \pm 2.5$ and total silicon area of 61.1 m^2 [13]. The SCT of the ATLAS ID offers spatial resolution of $16 \mu\text{m}$ in the radial component and $580 \mu\text{m}$ in the azimuthal component [13]. The pixel detectors of the ATLAS ID offer spatial resolution of $12 \mu\text{m}$ in the radial component, and $66 \mu\text{m}$ in the azimuthal component. Furthermore the SCT and the pixel detectors of the ATLAS ID were designed for a hardware trigger at 0.1 MHz and to withstand 1 MeV neutron equivalent radiation fluence $\Phi_n^{1\text{MeV}} = 0.2 \times 10^{15} \text{ cm}^{-2}$ and $\Phi_n^{1\text{MeV}} = 5.0 \times 10^{15} \text{ cm}^{-2}$ [3, 13]. Tab. 2.2 summarizes the ATLAS ID design limits and the upgrade requirements of the ATLAS detector for the HL-LHC upgrade. In order to meet the upgrade requirements, the ATLAS ITk will be replacing this ATLAS ID with these parameters in consideration.

Table 2.2: Summarized expected HL-LHC performance and the operational parameter of the current ATLAS ID [3]

Operational Parameter	ID, LHC, and ATLAS Design Limits	HL-LHC Capabilities and Upgraded ATLAS Requirements
Experiment Lifetime	10 years	Current age: ~ 7 years Age at upgrade: 14 years Full duration: 27 years
Peak Instantaneous Luminosity ($\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	1.0	Nominal: 5.0 Ultimate: 7.5 *with leveling
Pileup (proton collisions per 25 ns bunch crossing)	Design: 23 Operational Max: ~40 (peak), ~24 (avg.)	Nominal: 140 Ultimate: 200 *with leveling
ATLAS Trigger Rate (kHz)	Level-1: 100	Single Mode; Level-0: 1000 Dual Mode; Level-0: 4000 Level-1 (new): 400-600
Integrated Luminosity (fb^{-1})	Pixels: 400 SCT: 700 Inserted Beam Layer: 850	Nominal: 3000 Ultimate: 4000
Maximum High Energy Particle Fluence ($\times 10^{15} \text{ } 1 \text{ MeV } n_{eq} \text{ cm}^{-2}$)	Pixels: 5.0 SCT: 0.2	ITk Pixel: 18.7 ITk Strip: 1.2
Maximum Total Ionizing Dose (MGy)	Pixels: 3.0	ITk Pixel: 12.7 ITk Strip: 0.5

2.3 The ATLAS Inner Tracker (ITk)

The main goals for the ATLAS ITk upgrade are to improve the particle tracking performance, to increase the radiation tolerance and to improve the hardware triggering speed. The ATLAS ITk collaboration aims to achieve these goals by constructing a new all silicon ATLAS ITk which replaces the design of the ATLAS ID. The ATLAS ITk will utilize new technology developed since the installation of the ATLAS ID and it will have less volume of materials. In addition the quality of the new ATLAS ITk will be improved by more careful characterization processes for each of its components.

2.3.1 ITk layout

Similar to its predecessor, the inner regions of the ATLAS ITk will be occupied by the pixel detectors and the new strip detectors replacing the SCT in the outer region. The most notable change is the absence of the TRT. Furthermore the ITk has more pixel detector layers and disks and more strip detector layers and disks. The outer shell of the ATLAS ITk will be enclosed with a polyethylene moderator to moderate the accumulation of radiation fluence in the calorimeters surrounding the ITk [3]. The layout of the ATLAS ITk can be seen in Fig. 2.5.

Figure 2.5: A 3D CAD drawing of the new ATLAS Inner Tracker [3].

2.3.2 ITk performance requirements

The main performance requirements of the ITk are the pseudorapidity coverage $|\eta| \leq 4.0$ and at least 14 hits per particle track. Furthermore, there are preliminary requirements for the track parameter resolution seen in Tab. 2.3 and the radiation tolerance seen in Tab. 2.4.

Table 2.3: The required tracking performance of the new ATLAS ITk [3]. From Left to right are the parameter resolution, unit, upper limit of this resolution, and the range. For example σ_{z_0} at $p_T=1$ GeV must be less than 100 μm within the range of $|\eta|$ less than 0.5. The (∞) symbol next to the σ represents very high transverse momentum (higher than 100 GeV).

Track Parameter	Units	$ \eta $ Range if reduced
Inverse transverse momentum		
$\sigma(q/p_T)(\infty)$	TeV^{-1}	$< 0.3 (\eta < 2)$
$\sigma(q/p_T) (p_T = 10 \text{ GeV})$	TeV^{-1}	$< 0.15 (\eta < 2)$
$\sigma(q/p_T) (p_T = 1 \text{ GeV})$	TeV^{-1}	$< 0.15 (\eta < 2)$
Transverse impact parameter		
$\sigma_{d_0}(\infty)$	μm	$< 8 (\eta < 0.5)$
$\sigma_{d_0} (p_T = 1 \text{ GeV})$	μm	$< 100 (\eta < 0.5)$
Longitudinal impact parameter		
$\sigma_{z_0}(\infty)$	μm	$< 50 (\eta < 0.5)$
$\sigma_{z_0} (p_T = 1 \text{ GeV})$	μm	$< 100 (\eta < 0.5)$

Table 2.4: The expected resulting maximal 1MeV neutron radiation fluence and dose at different sections of the ATLAS ITk [3].

Layer	Radius [mm]	Maximal Fluence [$\text{n}_{\text{eq}}/\text{cm}^2$]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4
Pixels			
Layer 0	39	1.87×10^{16}	1268
Layer 1	75	0.59×10^{16}	549
Layer 2	155	0.22×10^{16}	129
Layer 3	213	0.15×10^{16}	87
Layer 4	271	0.11×10^{16}	53
End-cap	80	0.62×10^{16}	477

It is worth noting that the ID has suffered a heavy radiation damage. The radiation damage to the detector can be reduced by implementing new technology at the semiconductor level as seen in the next chapter. Furthermore the radiation damage will be reduced simply by reducing the radiation length of the detector material. The ATLAS ITk will be using significantly less material than the ATLAS ID to reduce the radiation lengths and also to increase the performance of the tracker [3] [35]. The

comparison of the material thicknesses of the current ATLAS ID and the material thickness requirement for the ATLAS ITk can be seen in Fig. 2.6.

Figure 2.6: The plots demonstrating the radiation lengths of components the current ATLAS ID and the material thickness requirement for the new ATLAS ITk [3].

The ATLAS ITk collaboration aims to meet the performance requirements of the new inner tracker for the ATLAS detector by implementing new technology and by following an optimized detector layout. At the current stage, both the pixel detector and the strip detector collaborations are producing prototype sensors. Some of the prototype sensors have been assembled into detector modules to test and finalize a standard technique to be used for assembling the detector modules. The performance of each individual component will contribute to the overall performance of the new ATLAS ITk. Of the two types of detectors, the silicon strip detector within the ATLAS ITk is the main focus of this M.Sc. thesis. The next section will briefly

introduce the ATLAS ITk strip detector.

2.4 The ATLAS ITk strip detector

The ATLAS ITk strip detector surrounds the ATLAS ITk pixel detector and occupies the outer region of the ITk. The strip detectors will have the pseudorapidity coverage of $|\eta| \leq 2.7$ and a net silicon area of $\approx 165 \text{ m}^2$ [3]. Furthermore, the strip detectors are designed to withstand 1 MeV neutron equivalent radiation fluence of up to $\Phi_n^{1\text{MeV}} = 1.2 \times 10^{15} n_{eq} \text{ cm}^{-2}$. This section will introduce the layout of the strip detector within the ATLAS ITk. It will then briefly introduce the individual components that make up the strip detector of the ITk.

2.4.1 Layout of the ITk strip detector

The ITk strip detector is comprised of four layers of barrel section silicon strip detectors. In addition twelve disks of endcap section silicon strip detectors. The twelve disks of the endcap are arranged such that there are six endcap disks on either side of the barrel. Each layer of the barrel section is 2.8m long and forms a cylinder that surrounds the proton beamline. Each disk of the endcap section is 6m in diameter. The mechanical building blocks of the barrel and the endcap sections are the staves and the petals. They can be seen in Fig. 2.7.

Figure 2.7: Schematics of one barrel stave can be seen at the bottom and one endcap disk petal can be seen at the top of this figure. The schematics also show the basic outline of how a detector module is mounted onto the structural supports [3].

The four barrel layers require 392 staves in total and each stave requires 28 strip detector modules. The twelve endcap disks require 384 identical petals in total and each petal holds nine detector modules with six different sensor geometries. Each detector module is assembled with custom PCB boards called the hybrid boards. Each hybrid board is occupied by a number of Application Specific Integrated Circuits (ASICs) called ATLAS Binary Chip (ABC) and a number of Hybrid Controller Chip (HCC). These ASICs provide initial signal processing and are the sources of the hardware trigger in the ATLAS ITk strip detector. Each barrel layer, and each endcap disk are slightly misaligned from one another to provide a good position measurement along the ITk strip detector. The preliminary design parameters of the ATLAS ITk strip detector can be seen in Tab. 2.5. The summarized number of channels and the components seen in this table are subjected to change motivated by the performance of prototype components.

Table 2.5: The preliminary design parameters of the ATLAS ITk strip detectors [3]. The barrel layers are denoted with L and the identical endcap sections are divided in 6 different diameters denoted with D.

Barrel Layer:	Radius [mm]	# of staves	# of modules	# of hybrids	# of of ABCStar	# of channels	Area [m ²]
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	z-pos. [mm]	# of petals	# of modules	# of hybrids	# of of ABCStar	# of channels	Area [m ²]
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		776	17888	24768	233856	59.87M	165.25

2.4.2 Radiation tolerance of the ATLAS ITk strip detector

In order to achieve the required radiation tolerance for the HL-LHC upgrade, the ATLAS ITk strip detector collaboration has been testing all components of the ITk strip detector. They were irradiated and tested as individual components and also after they have been assembled into prototype detector modules. One should note that most of the detector components are held in place by the adhesives. These adhesives used for the detector assembly are compiled and listed in Tab. 2.6. The choice of glue had to be carefully made based on results from irradiation tests.

Table 2.6: The glue requirement for the ATLAS ITk Strip detector modules [3].

Glue step	Special Requirements	Chosen glue	Comment
ABCStar to hybrid	UV curable	Dymax 6-621 or Loctite 3525	fully qualified incl. radiation tolerance
HCCStar to hybrid	higher thermal conductivity	silver-loaded epoxy adhesive TRA-DUCT 2902, BIPAX	fully qualified incl. radiation tolerance and activation
Hybrid to sensor		electronics grade epoxy Epolite FH-5313	fully qualified; availability unclear – alternative being investigated
Power board to sensor		electronics grade epoxy Epolite FH-5313	fully qualified; availability unclear – alternative being investigated
Module to Local Support	higher thermal conductivity to ensure low temperature of sensor	SE4445	qualified up to $2\text{E}15 \text{ n}_{\text{eq}}/\text{cm}^2$

At the current stage, mainly the strip sensors and the strip detector modules are being tested for their radiation tolerance. Individual sensors and detector modules must be able to perform within their technical specification after being irradiated with the required 1 MeV neutron equivalent fluences ($\Phi_n^{1\text{MeV}}$) previously shown in Tab. 2.4. The performance of one ATLAS ITk strip sensor before and after irradiation will be later presented in Section 6.2. However this requires the details of radiation damage in silicon strip semiconductor detectors which will be presented in Section 3.1.1.

2.4.3 Performance of the ATLAS ITk strip detector

Until the whole ATLAS ITk strip detector has been constructed and characterized as a single detector unit, the eventual performance of it cannot be determined. However, the ATLAS ITk strip detector collaboration expects to exceed the performance requirement of the HL-LHC upgrade by using the components designed and to be superior to that of the SCT of the ATLAS ID.

The current prototype readout ASICs used for the ITk strip detectors are the ABC130 and HCC130. The data processing speed of these ASICs are 1 MHz and the ABC130 ASICs can store up to 86 events for more than 6 μs . This exceeds the hardware trigger performance requirement for the ITk. In addition, the production models of these ASICs, the ABCStar and HCCStar are designed to have even more efficient data processing rate by having a parallel data processing layout improving the overall hardware trigger performance of the ITk. The names and the functionalities of the ASICs to be used for ATLAS ITk strip detectors can be seen in Tab. 2.7.

Table 2.7: The names and functionalities of the ASICs to be used on the ATLAS ITk strip detector [3].

Acronym	Full Name	Basic functionality	Prototype	Production Chip
ABC	ATLAS Binary Chip	Converts incoming charge signal into hit information	ABC130	ABCStar
HCC	Hybrid Controller Chip	Interface between ABC130 and bus-tape	HCC130	HCCStar
AMAC	Autonomous Monitor and Control Chip	Provides monitoring and interrupt functionality	AMAC-I	AMAC-II
FEAST	FEAST	Synchronous Step-Down Buck DC/DC converter	FEAST	upFEAST

Until recently, the performance of these ASICs could only be characterized after being assembled into a strip detector module. Some of the performance results of these ASICs will later be presented in Chapter 5.

The ATLAS ITk strip detector collaboration has also been producing several generations of prototype silicon strip sensors and the technical specifications of these strip sensors greatly exceed the design specifications of the SCT strip sensors. The main topic of this M.Sc. thesis is on the performance of these prototype ATLAS ITk strip sensors. A diagram showing the components and the assembly steps of the ATLAS ITk strip detector can be seen in Fig. 2.8.

Figure 2.8: The assembly diagram of the ATLAS ITk Strip Detector [3]

The ATLAS ITk strip detector is comprised of many components and the performance of each component by themselves and as detector modules will correlate to the overall performance of the new ATLAS ITk. While it is possible to simulate an ideal particle tracking strip detector, the components of the ATLAS ITk strip detector must be carefully characterized and then carefully assembled. One must stress the importance in characterizing the performance of each component and development of a standard detector assembly technique. The next three chapters of this M.Sc. thesis are dedicated to the first three steps of the assembly procedure of the ATLAS ITk strip detector illustrated in Fig. 2.8. Chapter 3 will present the fundamentals of the semiconductor strip detectors and the prototype silicon strip sensor produced for the ATLAS ITk strip detector. This is the core and the foundation of the ATLAS ITk strip detector. The silicon strip sensors are carefully characterized in a manner similar to that presented in Chapter 4 then the strip sensors are assembled into strip detector modules in a manner similar to that presented in Chapter 5.

Chapter 3

ATLAS ITk strip sensors

The ATLAS ITk strip sensors are radiation-tolerant n^+ -in- p^- large area silicon microstrip sensors [35]. The main aim of the ATLAS ITk strip detector collaboration has been the production of cost efficient and highly-radiation tolerant silicon strip sensors by incorporating a new strip detector technology where the n^+ strips are implanted on the p^- -type silicon wafers [35].

There were originally two main suppliers of the sensors Hamamatsu Photonics K.K. (HPK) and Infineon Technologies AG (IFX) [3, 35]. HPK and IFX have been working closely with the ATLAS ITk strip detector collaboration in the development and production of the new silicon strip sensors. The prototype silicon strip sensors produced by both suppliers have a common general conceptual design seen in Section 3.2.1. This M.Sc. thesis will focus only on the sensors produced by HPK as IFX no longer supplies the silicon strip sensors as of 2018. Three generations of prototype sensors will be discussed. The ATLAS07 (Section 3.2.2), the ATLAS12 (Section 3.2.3) and the most recent ATLAS17 (Section 3.2.4) strip sensors that were produced and distributed among the ATLAS ITk strip detector collaboration. Each generation of prototype strip sensors underwent a subtle change in response to its performance as a strip sensor (Chapter 4) and as an assembled strip detector module (Chapter 5).

Before going further into technical details of the ATLAS ITk strip sensors (Section 3.2), the basics of semiconductor physics will be covered in Section 3.1.1. The focus will then be shifted to the fundamentals of semiconductor micro-strip detectors in Section 3.1.2. The aim of this chapter is to present the strip sensors which make up the ATLAS ITk strip detector.

3.1 A brief introduction to semiconductor silicon microstrip sensors

The key element of a semiconductor sensor is the p-n junction [3,35]. The p-n junction makes it possible to fully deplete the free charge carriers within the semiconductor sensor and allows traversing charged particles to produce new charge carriers which in turn produce a good hit signal in the overall detector [1,35]. This section will introduce the basic characteristics of a p-n junction.

3.1.1 Semiconductors and p-n junctions

The unique semiconducting property of semiconductors comes from the small energy gap (E_g) between the electronic conduction band and the valence band in a semiconductor [1,17,36]. In case of silicon, the required energy to excite an electron from the valence band into the conduction band is [1,17,36].

$$E_g = 1.12 \text{ eV}$$

When there is an exchange of an electron from the valence band to the conduction band, the electron leaves a hole behind in its original band. This pair of electron and hole are the charge carriers in a semiconductor. The drift velocities of an electron (ν_e) and a hole (ν_h) are influenced by the strength of electric field ($\vec{E}$) and the mobility in the semiconducting bulk (μ^{medium}) [1,17,36].

$$\nu_e = \mu_e |\vec{E}|; \mu_e^{silicon} = 1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

$$\nu_h = \mu_h |\vec{E}|; \mu_h^{silicon} = 350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

The current carried by electrons and holes in a semiconductor is represented by the current density J_c

$$J_c = q(n\mu_e + p\mu_h)|\vec{E}| \quad (3.1)$$

where n is the concentration of electron carriers, p is the concentration of hole carriers and q is the electronic charge [1,17,36].

In a silicon semiconducting bulk, the concentration of p or n type charge carriers can be changed by the introduction of electrically active donor and acceptor impurity

atoms in the crystal lattice structure of the silicon bulk. The impurity in the silicon bulk can be formed deliberately by different doping techniques or accidentally during the fabrication process or externally by radiation damage. The n-type semiconductors have higher concentration of excess electrons and the p-type semiconductors have higher excess concentration of holes. The combination of the p and n type semiconductors forms a p-n junction seen in Fig. 3.1a). Fig. 3.1 also shows the resulting charge distribution ($\rho(x)$) in b) and the resulting electric field strength ($-E(x)$) in c) and the electrostatic potential ($-\psi(x)$) in d) [17]. The mathematical approximation of the charge distribution, electric field strength and electrostatic potential are used to derive the depth or width of the depletion zone.

The electric field and depletion depth of a p-n junction can be obtained by solving the Poisson equation [17]

$$\frac{d^2\Psi}{dx^2} = -\frac{\rho(x)}{\epsilon} \quad (3.2)$$

with the boundary condition that the charge density in the depletion zone $\rho(x)$ is approximately [17]

$$\rho(x) = \begin{cases} qN_d & , \quad 0 \leq x \leq x_n \\ -qN_a & , \quad -x_p \leq x \leq 0 \end{cases}$$

where x_n and x_p are the depletion lengths of n and p sides respectively. N_d and N_a are the n-type donor and p-type acceptor impurity concentrations. Outside of the depletion zone, the total charge is 0 resulting in the following boundary condition [17].

$$N_d x_n = N_a x_p$$

The solution to Eq. 3.2 yields

$$E(x_n) = E(-x_p) = 0 ; \quad E(x) = -\frac{d\Psi}{dx} ; \quad \Psi_n(0) = \Psi_p(0)$$

which is used for approximating the depletion depth of p and n junctions. The details of the derivation can be seen in Section A.2.

Figure 3.1: A schematic representation of p-n junction with thickness w . X is the charge carrier depletion depth produced by an external bias voltage (V_b) [17]

The depletion zone

The depletion zone in a p-n junction is formed due to the electric field in the junction [1, 17, 36]. The electric field strength can be increased by an external bias voltage supplied to the junction until the depletion zone is fully depleted. The total depth of the depletion zone in a p-n junction (X) is given by Eq. 3.3 [17]

$$X = x_n + x_p = \sqrt{\frac{2\epsilon(V_0 + V_b)}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad (3.3)$$

The x_p and x_n are the depletion depth of p and n junctions respectively, ϵ is the permittivity of the silicon, V_0 is the potential difference imposed by the doping concentration of the p-n junction, V_b is an externally applied bias voltage, q is the electronic

charge, and N_a and N_d are acceptor (p-type) and donor (n-type) impurity concentration [17]. In the case of $n^+ - in - p^-$ junction the depletion zone can be represented by Eq. 3.4.

$$X \approx x_p \approx \sqrt{\frac{2\epsilon}{qN_a}(V_0 + V_b)} \quad (3.4)$$

The depletion zone of a p-n junction is only fully depleted when the applied bias voltage (V_b) reaches the full depletion voltage (V_{FD}) where $X = w$.

$$w = \sqrt{\frac{2\epsilon}{qN_a}(V_0 + V_{FD})}$$

In most cases the V_{FD} dominates V_0 , hence one can write

$$w \approx \sqrt{\frac{2\epsilon}{qN_a}V_{FD}} \quad (3.5)$$

This depletion zone can serve as a particle sensor. Charged particles traversing this depletion zone with an energy higher than

$$E_{ion} = 3.62\text{eV}$$

produce an electron-hole pair in the depletion zone which creates current [17, 37]. In case of microstrip sensors the depth of the depletion zone must be characterized as it is the defining characteristic of a particle sensing medium.

Many of the variables in Eq. 3.5 cannot be experimentally measured without destroying the p-n junction. Instead, the depletion depth can be calculated using the capacitance of the junction when the junction is fully depleted [17].

Figure 3.2: A C-V curve of two detectors of 1cm^2 area. The detector in figure a) has resistivity of $8\text{ k}\Omega\text{ cm}$ and thickness $w=247\text{ }\mu\text{m}$ and the detector in figure b) has resistivity of $6\text{ k}\Omega\text{ cm}$ and thickness $w=300\text{ }\mu\text{m}$ [17].

Fig. 3.2 shows the relationship between the bias voltage and the capacitance (C-V curve) of two sensors with a known 1 cm^2 area. It is clear that when the bias voltage has reached the full depletion voltage (V_{FD}) or higher, the capacitance becomes constant. Rearranging Eq. 3.5 shows that (w) and V_{FD} have the following relationship.

$$V_{FD} \approx Kw^2 ; K = \frac{qN_a}{2\epsilon} \quad (3.6)$$

Using the parallel plate capacitor approximation for silicon sensors [1, 4, 5, 17, 36].

$$C = \epsilon \frac{A}{w} \quad (3.7)$$

one can then use the capacitance (C) at V_{FD} , and the area (A) of the silicon sensor to calculate the depletion depth (w) by putting together Eq. 3.6 and Eq. 3.7.

$$V_{FD} = K' \frac{1}{C_{FD}^2} ; K' = \frac{qN_a}{2} \epsilon A^2 \quad (3.8)$$

The C-V curve allows the measurement of the full depletion voltage and therefore approximately allows the measurement of the depletion depth. Furthermore the C-V curve can be used to identify the effective concentration of dopant (N_{eff}) [17]

$$N_{eff}(X) = \frac{2}{q\epsilon A^2} \frac{dV}{d\left(\frac{1}{C^2}\right)} \quad (3.9)$$

which can be used for measuring the concentration of the n^+ implant in the ATLAS

ITk strip sensors. In addition a fluctuation in this measurement can be used to determine potential contamination in the implant or the bulk of a p-n junction.

Leakage current in a p-n junction

For an ideal unpolarized p-n junction there is no net current through the junction. In a non-ideal polarized p-n junction silicon sensors, some of the charge carriers drift and produce a leakage current (I_r) [1, 4, 5, 17, 36].

There are two main categories of leakage currents. The surface leakage current and the bulk leakage current. The surface leakage current is produced by impurities, or damage to the surface structure of the p-n junction. In the case of ATLAS ITk strip sensors, this is an indication of damage of the insulating surface passivation layer, or of accumulation of foreign charge carriers at the surface of the sensor (i.e. dust). The bulk leakage current is produced by impurities and damage in the depletion zone. Furthermore the bulk leakage current is also temperature dependent. The leakage current of a p-n junction is typically characterized by a leakage current to bias voltage plot (I-V curve) shown in the left of Fig. 3.3

The temperature dependency in the bulk of a p-n junction is due to the temperature dependence of the intrinsic charge carrier concentration (n_{int}). Eq. 3.10 shows the intrinsic charge carrier concentration (n_{int}) as a function of temperature (T) and (k_B is the Boltzmann constant [1, 17, 36]).

$$n_{int} \approx 3.873 \times 10^{16} \times T^{\frac{3}{2}} e^{-\frac{E_g}{2k_B T}} \text{cm}^{-3} \quad (3.10)$$

One should also note that this charge carrier concentration is further modified by radiation damage. The temperature dependence of the charge carrier concentration leads to the temperature dependence in the bulk leakage current seen in Eq. 3.12 and in the right of Fig. 3.3.

$$I_r(T) = T^2 e^{-\frac{E_g}{2k_B T}} \quad (3.11)$$

Figure 3.3: The left shows a typical I-V curve and the right shows the temperature dependence of leakage current [17].

The temperature dependence of the leakage current in the semiconducting bulk can be suppressed by normalizing the I-V curve using Eq. 3.12 [17].

$$I_r(T_r) = I(T_m) \left(\frac{T_r}{T_m} \right)^2 e^{-\frac{E_g}{2k_B \left(\frac{1}{T_r} - \frac{1}{T_m} \right)^{-1}}} \quad (3.12)$$

where T_r is a reference temperature in Kelvin, and T_m is the temperature during the leakage current (I_r) measurement [17].

The leakage current in a microstrip sensor is typically very small until reaching a critical voltage called the breakdown voltage (V_{BD}). An I-V curve allows measurement of the leakage current which correlates general electronic noise in the bulk.

Radiation damage in the p-n junction

The radiation damage typically affects the bulk material of a p-n junction. The damaged nuclei in the bulk lattice structure can act as an electrically active region resulting in three effects [1, 4, 5, 17, 36, 38].

- The leakage current increases.
- Full depletion voltage increases.
- Charge Collection Efficiency (CCE) decreases.

As previously discussed in Section 3.1.1 the increase in leakage current is correlated to the 1 MeV neutron equivalent irradiation fluence $\Phi_n^{1\text{ MeV}}$. This can be seen in the left of Fig. 3.4.

Figure 3.4: The effects of exposing the semiconductor to radiation. The left figure shows the linear increase in semiconductor's leakage current as a function of 1 MeV neutron irradiation fluence and the right figure shows the change in effective doping concentration as a function of 1 MeV neutron irradiation fluence [18]. Furthermore the p type semiconductor bulk does not reach the type inversion.

The experimental results yield the relationship between the increase in leakage current to $\Phi_n^{1\text{ MeV}}$ is [1, 38]

$$I_r = \alpha \Phi_n^{1\text{ MeV}} V \quad (3.13)$$

where α is the current damage factor and V is the volume of the sensor seen in [38]. The full depletion voltage is proportional to the effective doping concentration (N_{eff}) as seen in Eq. 3.9 and the N_{eff} is also proportional to $\Phi_n^{1\text{ MeV}}$ as seen in Eq. 3.14 [1, 38] and to the right of Fig. 3.4.

$$N_{\text{eff}} = N_{\text{eff}}(0)e^{c\Phi_n^{1\text{ MeV}}} + \beta\Phi_n^{1\text{ MeV}} \quad (3.14)$$

where $N_{\text{eff}}(0)$ is the effective doping concentration before irradiation seen in Eq. 3.9, c is the constant of acceptor removal and β is the introduction rate of acceptor-like defects for a p-type silicon bulk [38]. This relationship comes from the experimental measurements [3, 38]. As a result of the radiation damage the full depletion voltage

is increased as seen in Eq. 3.15 [38].

$$V_{FD} = (N_{eff}(0)e^{c\phi} + \beta\phi)\frac{qw^2}{2\epsilon} \quad (3.15)$$

The radiation damage in the p-n junction also causes a ballistic deficit slowing the charge collection due to the radiation induced trapping centres within the bulk which then increases the time necessary to collect all the charge generated by traversing charged particles [38].

The ATLAS ITk Strip detector collaboration has chosen the p^- bulk silicon wafer because of its radiation tolerance and cost efficiency in comparison to oxygenated n-type silicon bulk wafers [35, 39] which involve more steps and hence increasing the manufacturing time and cost. The p^- bulk wafer is later implanted with n^+ strip structure forming the p-n junctions in between the backplane and the strips of the silicon strip sensor. The next section will introduce the semiconductor microstrip detector.

3.1.2 Semiconductor microstrip detector

A typical fabrication process of a silicon microstrip detector is demonstrated at the left of Fig. 3.5. From top to bottom, a layer of silicon oxide passivation is applied around a silicon wafer, then the top and bottom of the wafer is doped by ion implantation forming a p-n junction between the top and bottom surfaces of the silicon wafer. For a microstrip detector, a higher concentration of dopant (denoted by + sign next to type) is implanted in the strip pattern on the wafer to form the p-n junction between the backplane and the strips.

Figure 3.5: The left shows a typical microstrip detector fabrication process from top to bottom and the right shows a typical p in n particle detector [19].

The right of Fig. 3.5 shows a typical p^+ -in-n type silicon microstrip detector with a strip pitch $25\mu\text{m}$ with interstrip capacitance 1 pF cm^{-1} and the bulk capacitance 0.1 pF cm^{-1} . The figure also shows that the charge in the depletion zone produced by a traversing charged particle in between the strip and the backplane is collected by the read-out chips located on top of the strip sensor. This basic structure remains the same for the $n^+ - in - p^-$ strip detector, but the polarity of p-n junction and the sign of the bias voltage are reversed.

Electric field in the semiconductor bulk

It is important to note that the interstrip capacitance and interstrip resistance of a microstrip detector represent the electric field formed in between each strip and the electronic noise in an individual strip. In the case of a microstrip detector, the precision of the electric field in the depletion zone determines the position resolution of the microstrip detector. In order to achieve an accurate electric field, the ATLAS ITk strip sensors utilize a p-stop in between each n^+ implant; this can be seen in the left of Fig. 3.6 and the resulting electric field can be seen to the right of Fig. 3.6.

Figure 3.6: Cross-sectional view of the ATLAS ITk strip sensor. The left shows the structure [20] and the right shows the resulting electric field generated by Technology CAD (TCAD) [21].

The ATLAS ITk strip sensors are microstrip particle sensors with a unique design which incorporates n^+ implant in p^- bulk with p^+ field shaping implants.

3.2 ATLAS ITk strip sensor prototypes

The initial design of the ATLAS ITk strip sensors come from the ATLAS07 sensors produced for the ATLAS Semi Conductor Tracker (SCT). The SCT sensor design has been modified by the ITk strip detector collaboration but the general features displayed in Fig. 3.7 for the ITk strip sensor prototypes remain the same. This section will cover these general features and the notable changes made to each generation of prototype silicon strip sensor.

(a) Design of the surface features of the latest ATLAS17LS Strip Sensor [40].

(b) A conceptual internal structure of the ITk Strip Sensor.

Figure 3.7: The general surface and internal features of the ATLAS ITk strip sensors

3.2.1 General features of the ATLAS ITk strip sensors

All of the ATLAS ITk strip sensor prototypes have the surface features shown at the top of Fig. 3.7 and internal features shown at the bottom of Fig. 3.7. For each of the prototype sensor, the dimension and the design of the surface and internal features

have been modified with the goal of maximizing the performance of the sensor.

Strips

Each strip segment of the ATLAS ITk strip sensors is AC-coupled and biased with polysilicon resistors [22]. The polysilicon resistor at each end of a strip segment is accompanied by a dedicated Punch Through Protection (PTP) feature to short circuit the strip segments to the bias rail protecting the strip coupling capacitors [39]. Each strip segment also have two DC pads and two AC pads. The DC pads along the strip are directly connected to the n^+ implant of the strip segment and the AC pads are connected through the AC coupling capacitor of the strip segment. The number of strip segment in the ATLAS ITk strip sensors vary from 1026 to 1282. The first and last strip segments serve as the “field shaping strips” to allow the desired electric field shape as previously seen in the right of Fig. 3.6. All of these strip features can be seen in Fig. 3.8.

(a) Two segments of the ATLAS ITk strip sensor strips [40].

(b) Equivalent circuit diagram of a single strip segment [10].

Figure 3.8: General features of ATLAS ITk strip sensor strip segment and its equivalent circuit.

- AC Pad

The coupling capacitance between the n^+ implant and the metal strip is determined by the width of the strip implant [41]. This coupling capacitance is needed to prevent high leakage current from affecting the readout circuit. As the leakage current is expected to increase with the radiation fluence as seen in Section 3.1.1, it is important to check that the coupling capacitor is not damaged. The AC pads also serve as the contact points for measuring the coupling capacitance and the interstrip capacitance which can then also be used to derive the implant width [4, 5]. Furthermore the AC pad provides an electrical contact point for the readout chip (See bottom of Fig. 3.8).

- DC Pad

The DC pads serve as the contact points for measuring the coupling resistance, the bias resistance and the interstrip resistance. The DC pads are directly connected to the n^+ implant of the strip segment, bypassing the AC coupled capacitor.

- Poly-Silicon Resistor (Poly-Si Resistor)

The Poly-Si resistor couples the n^+ strip segment to the bias rail. This needs to be measured during the sensor characterization (see Chapter 4) to ensure that the strip is properly biased and that the Punch Trough Protection is operational.

- Punch Through Protection (PTP)

The PTP is a geometry dependent feature that prevents the AC coupling capacitor from breaking down by creating a short circuit in the current path parallel to the bias resistor. The distance between the bias rail and the n^+ implant of the strip segment is adjusted such that the implant directly shorts to the bias rail if the strip has accumulated charge beyond the onset voltage of the PTP structure. This prevents damage to the readout chip and the AC coupled capacitor of the strip segment.

Figure 3.9: Two types of Punch Through Protection displaying their onset voltage [10]. Working together with the Poly-Si Resistor, PTP shorts the strip to bias.

The PTP onset voltage and geometry has changed throughout each prototype for best performance [10, 39]. Fig. 3.9 and bottom of Fig. 3.8 demonstrates two types of the PTP structure working together with the Poly-Si Resistor to short the strip to the bias rail when the accumulated charge has voltage that is higher than the onset voltage of the PTP structure.

Bias rail

All of the strip segments are connected to the bias rail in parallel. The bias rail supplies a common ground for the whole sensor and for the readout electronics. The bias rail has multiple holes in the passivation layer for sensor probing and connection to the readout electronics.

Guard ring

The guard ring prevents electrical conduction between the edge metal of the sensor and the bias rail of the sensor.

Edge metal

The edge metal is electrically connected to the backplane of the sensor. The edge metal also has multiple holes in the passivation layer for sensor probing.

All of the above features have undergone subtle change in between generations of the ATLAS ITk strip sensors. The original design comes from the ATLAS07 SCT strip sensor. The subtle changes in the above features in each generation of silicon strip sensor have been guided by the feedback provided from the ATLAS ITk strip detector collaboration from various test results. During the sensor production, along with the main large strip sensor, several miniature (mini) sensors were also produced with test structure for the purpose of research and development (Seen as smaller sensors labeled P00-P24 in Fig. 3.12). The following section will only cover the major changes in the design and performance between each main sensor prototype starting with the ATLAS07.

3.2.2 ATLAS07

The ATLAS07 strip sensors are the initial research and development 10 cm x 10 cm large area sensors fabricated in 2007 [4, 6]. The technical specifications for these sensors can be found in Fig. B.1. The current main strip-sensor supplier HPK fabricated 30 ATLAS07 sensors, and 19 of these prototype sensors have been measured by ATLAS institutes [4]. Tab. 3.1 shows that the ATLAS07 strip sensors produced by HPK fall within the technical specification [4].

Table 3.1: The summarized table from [4] showing the comparison of measured parameter values with the technical specification

	ATLAS07 specification	Measurement
Leakage current	$< 20 \mu\text{A}$ at 600 V	200 nA–370 nA
Full depletion voltage	$< 500 \text{ V}$	190 V–245 V
Coupling capacitance at 1 kHz	$> 20 \text{ pF/cm}$	$> 28 \text{ pF/cm}$
Silicon bias resistance	$1.5 \pm 0.5 \text{ M}\Omega$	1.3–1.6 M Ω
Current through dielectric	$I_{diel} < 10 \text{ nA}$ Pinhole: $I_{diel} \gg 10 \text{ nA}$	$< 10 \text{ nA}$
Strip current	No explicit limit	$< 2 \text{ nA}$
Inter-strip capacitance	$< 1.1 \text{ pF/cm}$	
3 probe method 100 kHz		0.7 pF/cm–0.8 pF/cm
5 probe method		0.66 pF/cm–0.75 pF/cm ^a
Inter-strip resistance per cm	$> 10 \times R_{bias} \sim 15 \text{ M}\Omega$	$> 150 \text{ G}\Omega$

Starting with the ATLAS07 design, the ATLAS ITk strip detector collaboration was officially formed in 2009. The aim of the new prototype sensor at the time was on reducing the thickness, the leakage current, the full depletion bias voltage and

improving the radiation hardness.

3.2.3 ATLAS12

The ATLAS12 strip sensors are the first sensors designed by the ATLAS ITk strip detector collaboration to be used by the ATLAS ITk [35]. The first major change from ATLAS07 is the dimensions of the sensors. There are two main geometries for the ATLAS ITk strip sensors, the barrel and the endcap (EC) sensors. The barrel sensors are rectangular in shape and the EC sensors use a unique stereo annulus design [3, 7, 22] seen in Fig. 3.10.

Figure 3.10: The Stereo Annulus shape of the ATLAS12 End Cap sensor [22]

The unique EC design is further split in 6 sections. Starting from the innermost R0 (seen in the right of Fig. 3.12) to the outermost R5. All of the endcap sensors share the same number of strip segments. The innermost segments have 1024 strips and the outermost segments have 1152 strips.

Figure 3.11: The Stereo Annulus design of the ATLAS12 End Cap sensors [22]

The very first successfully produced endcap sensors using the annulus stereo design are the innermost ATLAS12EC R0 sensors. Due to the unique geometry of the EC sensors, they also require a unique design for the testing apparatus. In an effort to standardize sensor testing for all sensor geometries, a universal quality control jig was designed and developed at Carleton University (TK Jig). In addition, due to the fact that the final designs of the R1-to-R5 sensors have not yet been completed presented more challenges to the design of the TK Jig seen in Section 4.3.

Another notable change in the technical specification of the ATLAS12 sensors is that the leakage current has been reduced by a factor of ten. The specifications have been verified from testing 120 main sensors manufactured by HPK [5]. The technical specification of the ATLAS12 sensors can be seen in Tab. B.2 and the performance of the 120 main sensors in comparison to the technical specification can be seen in Tab. 3.2.

Table 3.2: The summarized table from [5] showing the comparison of measured parameter values with the technical specification.

Sensor property	Specification	Measured values
Maximum bow	$< 200 \mu\text{m}$	$51.7 \pm 12.4 \mu\text{m}$
Leakage current at $V_{\text{bias}} = 600 \text{ V}$	$< 2 \mu\text{A}/\text{cm}^2$	$< 1 \mu\text{A}/\text{cm}^2$ for 118 of 120 sensors
Depletion voltage	$< 300 \text{ V}$, wafer resistivity allowing	$365 \pm 8.6 \text{ V}$
Bias resistor value	$1.5 \pm 0.5 \text{ M}\Omega$	$1.49 \pm 0.111 \text{ M}\Omega$
Coupling capacitance	$> 20 \text{ pF}/\text{cm}$ at $V_{\text{bias}} = 300 \text{ V}$	$27.2 \pm 0.62 \text{ pF}/\text{cm}$
Inter-strip capacitance	$< 0.8 \text{ pF}/\text{cm}$	$0.77 \text{ pF}/\text{cm}$
Inter-strip resistance	$> 15 \pm 5 \text{ M}\Omega$	$> 30 \text{ G}\Omega$
Percentage good strips	$> 98\%$ per segment	> 99.97

Some of these ATLAS12 sensors have been assembled into working detector modules (see Chapter 5). Furthermore a detailed study of the effects of irradiation on ATLAS12EC sensor can be found in Section 6.2.

Figure 3.12: Incorporation of the stereo annulus design of the ATLAS12 End Cap sensors during production [3, 6, 7].

With successful production and evaluation of ATLAS12 sensors, the ATLAS ITk collaboration has designed and requested production of the ATLAS17 Long Strip (LS) sensors.

3.2.4 ATLAS17LS

The ATLAS17LS sensors have a different strip pitch, width, length from ATLAS12. HPK has informed the ATLAS ITk strip detector collaboration of the change in the specification seen in Tab. B.3 which specifies that the ATLAS17LS sensors has ten times lower leakage current than the ATLAS12 sensors [8]. In combination 14 ATLAS17LS sensors have been distributed to Carleton University and the University of Cambridge in 2018.

The technical specifications of these sensors have to be carefully verified. The following chapter is dedicated to the experimental setup and the experimental techniques for evaluating the performance of the ATLAS ITk strip sensors. The performance result of the first batch of the ATLAS17LS sensors tested can be seen in Tab. 6.6.

Chapter 4

ATLAS ITk strip sensor characterization

Since the ATLAS ITk strip sensors are externally produced by HPK, it is imperative for the ATLAS ITk strip detector collaboration to internally verify the integrity of individual strip sensors prior to distributing the strip sensors to a detector module assembly site. Carleton University is the main quality control site in Canada and it is responsible for distribution of these strip sensors throughout Canada [3]. The latest batch of strip sensors distributed to CERN from HPK is the ATLAS17LS sensors and the accompanying technical specification for these sensors can be found in Tab. B.3. Each strip sensor is also accompanied by a final inspection measurements prior to reception at CERN. It is important to note that even with careful inspection, the strip sensors can suffer various forms of damage and survive less than ideal environmental conditions during the transportation which can have a large impact on the strip sensors' performance. The final inspection measurements provided by HPK must first be verified. Upon reception, each strip sensor undergoes two types of mechanical inspection(Section 4.1) and two types of electrical inspection are performed for the bulk material of the strip sensor(Section 4.2.1). In addition to these tests, about 15% of each batch of the strip sensors must go through a full electrical characterization on the strips of the strip sensors (Section 4.2.2). While it is ideal to run every possible test on each strip sensor, only this small fraction of the strip sensors are fully characterized in order to meet the processing rate specified by the ATLAS ITk strip detector collaboration.

The expected total number of strip sensors that need to be processed before the end of 2023 is approximately 20,665 [3]. In order to meet this demand the quality control sites must achieve the maximum strip sensor characterization rate. The current expected rate is approximately 8 strip sensors per day [3]. The ATLAS ITk

strip detector collaboration aims to achieve this goal by the use of Universal Quality Control Jig (UQCJ:TK Jig) which can accommodate all strip sensor geometries and all possible characterization tests that need to be performed on each strip sensor. Section 4.3 contains the details of the requirements, the design process of the TK Jig and some of the tests performed with the TK Jig.

This chapter is dedicated to the setup and techniques for characterizing the strip sensors. In addition, the design and construction of the TK Jig will also be presented.

4.1 Mechanical characterization

The most obvious cause of physical damage to a strip sensor is due to mechanical stress. The physical damage caused from the mechanical stress can easily be detected with visual inspection.

In addition the precisely measured shape of the strip sensor is vital to the alignment of the strip sensor at the strip detector assembly site. Even a small deficiency in the flatness can lead to misalignment during the strip detector module assembly and eventually lead to misalignment of the whole ATLAS Inner Tracker. At the quality control site, the flatness is also measured to ensure that the strip sensors are within specification.

4.1.1 Visual inspection

There are two types of visual inspections, human visual inspection and assisted visual inspection using a microscope. The human visual inspection is done by looking at the top surface of the strip sensor from different angles to detect the difference in how the light refracts on the polished top surface of the strip sensor. This technique is used to detect cracks at the surface of the strip sensor. Due to the lattice structure of the silicon sensors, the cracks detected on the surface are good indicators for more serious fractures within the strip sensors. The left of Fig. 4.1 shows a highlighted crack on the polished top surface of a strip sensor. The depth of the crack cannot be determined but this small crack is an indicator for a damaged strip sensor beyond repair.

For a rejected strip sensor, HPK requests a digital photograph of the whole strip sensor. The total of 20Giga-Pixel photograph is requested for a rejected strip sensor for warranty purposes. This procedure is often disregarded as most of the obvious

physical defects can be isolated during the visual inspection and photographed. The right of Fig. 4.1 shows an inaccurate cut at the reference Fiducial mark “F” at the edge of the latest ATLAS17LS strip sensor. The photograph also reveals the accumulation of foreign materials on the surface of the strip sensor. The accumulation of foreign materials on the surface of the strip sensor is potentially introduced by cardboard paper enclosure for transportation of the strip sensors. In response to this photograph HPK has proposed a ESD safe plastic enclosure to replace the cardboard paper enclosure.

(a) Highlighted surface crack on a new ATLAS17LS strip sensor

(b) Highlighted inaccurate cut at the edge metal of strip sensor surface

Figure 4.1: Surface of a rejected ATLAS17LS ITk strip sensor

Even with no sign of physical damage to the surface, the strip sensors must retain the specified shape.

4.1.2 Flatness test

Carleton University uses a Confocal Laser Microscope (CLM) with a precision better than $1\mu\text{m}$ and measures the height on a 100-point grid on the top surface of the strip sensor. The University of Cambridge uses Coordinate Measurement Machine (CMM) with precision better than $2\mu\text{m}$ [5] and measures the height on a 121-point grid on the top surface of the strip sensor. The CLM and CMM measures the height (Z)

at the surface of the strip sensor (X and Y). It is possible for the strip sensor to be placed on a non-flat stage which can introduce a tilt effect in the strip sensor flatness measurement. Using the dimensions of the strip sensor surface area and the height measurements. The potential tilt effect is corrected as follows.

$$d_{zx} = \frac{\Delta Z_{\text{Total Range}}}{\Delta X_{\text{Total Range}}}, d_{zy} = \frac{\Delta Z_{\text{Total Range}}}{\Delta Y_{\text{Total Range}}}, Z_i^{\text{offset}} = d_{zx}X_i + d_{zy}Y_i$$

$$Z_i^{\text{corrected}} = Z_i - Z_i^{\text{offset}} \quad (4.1)$$

The corrected height ($Z_i^{\text{corrected}}$) is used to estimate the flatness of a strip sensor.

The flatness test can provide other indications of mechanical stress to the strip sensor during its production or transportation. Furthermore, the precision of the dimension of each strip sensor is important since the strip sensors are the foundation of the detector modules. The strip sensor needs to be flat in order to be reliably accepted and assembled into a working detector module. Bowing strip sensors can cause misalignment during assembly [3]. Fig. 4.2 shows two different thicknesses of sensors. The left figure shows a relatively flat standard thickness ATLAS17LS strip sensor with flatness measurement of $\pm 4.72 \mu\text{m}$ and the right figure shows a bowing thin variation of ATLAS17LS strip sensor with flatness measurement of $\pm 41.8 \mu\text{m}$. The thin strip sensor seen here cannot be assembled into a full detector module as it will be misaligned during the assembly procedure.

(a) Topological map of an ATLAS17LS strip sensor with standard thickness (b) Topological map of a thin ATLAS17LS strip sensor

Figure 4.2: Topological maps of two ATLAS17LS strip sensors with two different thicknesses

The strip sensors produced for the ATLAS ITk strip detector are yet to reach its production stage. In preparation for the production stage, it is important for the quality control sites to be able to correlate the physical damage and the strip sensor performance. The establishment of an standard identifier for reject strip sensors can further increase the strip sensor processing rate during the production stage. The current standard quality control procedure requires the continuation of electrical testing on the strip sensors even with signs of physical damage as the prototype strip sensor can still serve as a training aid.

4.2 Electrical characterization

All of the ATLAS ITk strip sensors produced by HPK must be processed through a quality control site in batches and each individual strip sensor in a batch must be electrically characterized. At the current stage only the bulk of each strip sensor is characterized (Section 4.2.1). While it is ideal to perform all possible electrical characterization for each and every sensor, only a fraction of the strip sensors are randomly selected and tested at the strip level (Section 4.2.2) in order to meet the

required strip sensor processing rate [3].

4.2.1 Electrical characterization for the bulk material of the strip sensor

The strip sensor electrical characterization can be simplified by treating the strip sensor as a large area diode and by reverse biasing this “diode”. With increasing reverse bias voltage, the leakage current is measured (I-V curve) to determine the electrical noise generated in different environmental conditions. Furthermore potential early junction break down can be observed during the I-V curve tests. The capacitance is also measured with increasing reverse bias voltage in order to determine the full depletion voltage of the strip sensor (C-V curve), and therefore calculate the depletion depth of an individual strip sensor.

A typical apparatus requirement is an LCR meter, a HV power supply which can supply up to 1000V. The exact configuration of the apparatus is different at each individual QC site. The following configurations are specific to the quality control site at Carleton University.

Leakage current-bias voltage curve (I-V curve)

At Carleton University, the Keithley 2410 HV power supply is used as a HV supply as well as an ammeter. The maximum hardware compliance current is 105 μA but during an I-V curve test, the compliance current is typically set to 10 μA using a dedicated LabVIEW software. Fig. 4.3 demonstrates the setup of the IV test. The actual HV and ground contact on the strip sensor is made through a micromanipulator (with 1 μm , 15 μm or 30 μm thick probe tips) or through wire bonds (25 μm diameter gold and aluminum using a wedge or a ball bonder). For a long term stability study, one ATLAS12EC strip sensor is permanently wire bonded to a testing jig designed by the University of Cambridge. Normally the strip sensors are tested using micromanipulators inside a probe station surrounded by a light-tight enclosure.

With the experimental setup in place, the Keithley 2410 HV power supply provides a reverse bias voltage ranging from 0V to 1000V in steps of 5 volts and with 10 second delay in each measurement. Due to the internal structure of the ATLAS ITk strip sensors, rapid increase in reverse bias voltage causes fluctuations in the leakage current potentially causing an early junction breakdown. The I-V curve test is expected to

be performed upon reception of the strip sensor in all sites not limited to only the quality control sites as it be used to quickly identify a major internal damage to the bulk material in the strip sensor.

Figure 4.3: The circuit setup for the strip sensor I-V curve test

For an I-V curve test, the operators at a quality control site must pay most attention to the following.

1. Are there any irregular effects in the I-V curve?

There are several odd phenomena which can be observed during the I-V curve test. A “burn-off” effect can be seen in Fig. 4.4. This is where the leakage current of this new ATLAS17LS strip sensor has dramatically increased close to -800V until re-stabilizing at -805V. This phenomenon is called the burn-off effect as the cause of the potential early junction breakdown has been burned off by the increasing leakage current and the phenomenon is no longer present after this initial I-V curve test. The cause of this effect is most likely due to the accumulation of dust on the surface of the strip sensor.

Figure 4.4: I-V curve from ATLAS17LS W035 upon reception. An odd effect is highlighted in red near -800V.

2. Does the strip sensor break down before reaching -1000V? If so, what is the break-down Voltage(V_{BD})?

The strip sensor should not break down before reaching at least -700V as specified in Tab. B.3. An example of an early junction breakdown of an ATLAS17LS strip sensor can be seen in Fig. 4.5. If the strip sensor breaks down before reaching the full depletion bias voltage, the strip sensor cannot be used as a particle tracking detector. One should also check if the strip sensor break down is caused by physical damage or any form of physical debris accumulated at the surface of the strip sensor. A thermal imaging device may assist in the identification and localization of this junction break down. It is also important to identify and resolve any deficiencies which could be introduced by the strip sensor testing apparatus such as holes in the light enclosure, defective wire bonds, or defective cables in the strip sensor testing circuit.

Figure 4.5: I-V curve from ATLAS17LS W035 after a long term exposure in humidity. the strip sensor breakdown at -650V

3. What is the leakage current at -700V? Also at the approximate full depletion Voltage (-300V)?

the strip sensor leakage current at operating voltage and (V_{FD}) should be within the technical specification which can be found in Tab. B.3.

4. How does the leakage current correlate to environmental conditions (Temperature and Humidity)?

A fraction of each batch of strip sensors are to be tested over a long period of time (for over 48 hours) at different temperature and humidity conditions. The ATLAS12 strip sensors have been reported to be not environmentally stable, it is important that this is not the case with the ATLAS17 strip sensors and the future production model strip sensors.

The standard I-V curve test per strip sensor takes up to 30 minutes and fully occupies the probe station. During the production stage, Carleton University is expected to perform 8 I-V curve tests per day [3]. This is 4 hours without including the time required for preparation and setup. The current setup time at Carleton University ranges from 5 to 30 minutes.

Capacitance-bias voltage curve (C-V curve)

At Carleton University, the Wayne Kerr (WK) 6420B model is used as an LCR meter and the Keithley 2410 as the HV source for the C-V curve test. The C-V curve test setup seen in Fig. 4.6 is very similar to the I-V curve test with the introduction of the LCR meter in parallel to the setup for I-V curve test. The setup also introduces a $1\text{ M}\Omega$ resistor in the HV setup with the LCR meter connected through a $2.2\text{ }\mu\text{F}$ capacitor at the HV and common ground.

Figure 4.6: The circuit setup for the strip sensor C-V curve test

The C-V test is performed to measure the full depletion voltage for the bulk material of the strip sensor (V_{bulk}^{FD}). The bulk capacitance of the strip sensor is measured by the LCR meter as the reverse bias voltage is increased [4, 5]. A typical C-V curve is a plot of $\frac{1}{C_{bulk}^2}$ as a function of V_{Bias} . The resulting curve is fitted with one linear function and a constant as seen in Fig. 4.7. The resulting point of intersection of the linear function and the constant indicates the C_{bulk}^{FD} and the V_{bulk}^{FD} . Using a simple parallel plate capacitor model the capacitance (C_{bulk}^{FD}) at full depletion voltage is used to derive the depletion depth (w) of the bulk (4.2).

$$w = \frac{\epsilon_{bulk} A_{bulk}}{C_{bulk}^{FD}} \quad (4.2)$$

Using the intrinsic silicon ϵ_{bulk} ($11.9\epsilon_0 \approx 1.054 \text{ pF cm}^{-1}$ [1,17]) the depletion depth can then be derived [5].

Figure 4.7: C-V curve of ATLAS17LS W035 upon reception. This strip sensor is fully depleted at 326.09 V, the capacitance at full depletion is 32 080 pF and the derived depletion depth w is 314 μm

If the profile of the C-V curve, the full depletion voltage (V_{FD}) and the depletion depth w are within specification of the strip sensor, the strip sensor is stored in a dry storage (under 10% relative humidity) until distribution to a strip detector module assembly site.

4.2.2 Full electrical characterization at the strip level

A fraction of these strip sensors undergo a full electrical characterization at the strip level [3]. Even if the characterization process of the bulk material of the strip sensor has not indicated any defects, individual strips on the strip sensor are responsible for detecting traversing charged particles whence the strip sensor becomes a detector module. These strips and their properties must be characterized. The main aim of the strip testing is to verify the uniformity of all strips and to identify the defective strip segments. At the strip level, several interstrip and individual strip properties

are compared with the technical specification which can be found in Tab. B.3. The electrical properties of strips can be simplified with an equivalent circuit as seen in Fig. 4.8.

Figure 4.8: An equivalent circuit of the interstrip structure of ATLAS ITk strip sensors [1, 10].

The individual strips and its neighbouring strips must be tested in order to fully characterize the strip properties of a strip sensor.

Full strip test

For the ATLAS ITk strip sensors, less than 2% of the strips per segment should be considered defective [8]. A full strip test is performed on all of the strips of a strip sensor to determine any defective strips. A defective strip is identified by the following [4, 5, 8]:

- Defective coupling dielectric
Any shorting at the AC pad while 100V is applied indicating defective coupling (Interstrip Capacitance).
- Defective metal strips
Any shorting within an individual strip metal (Full Strip Test) or to neighbouring strips (Interstrip Capacitance).
- Defective implant strips
Any shorting within an individual strip implant (Full Strip Test) or to neighbouring strips (Interstrip Resistance).

- Defective bias resistors

As seen in Chapter 3 the bias resistor and PTP structure protects the readout chip and must be tested.

- Microdischarge strips

During any of the strip test no shorting or microdischarge must be observed (The method of identifying the Microdischarge strips is to be negotiated in collaboration with HPK [8]).

The full strip test characterizes all of the properties above by fully depleting the bulk of the strip sensor and then applying 100V through the individual strips through the AC pads located along the strips. At this time the current, resistance and capacitance of individual strips are measured. As a typical strip sensor has more than 1000 strips with 2 or 4 segments, this test is typically performed with an automatic probe station. Due to the unique geometries of the ATLAS ITk strip sensors, the locations of the AC pads of the strips vary for each individual design of sensors. In a simple rectangular barrel strip sensor, a simple mathematical calculation can define all of the locations of all of the AC Pads. As for the endcap strip sensors, the stereo annulus shape of the strip sensors require calculations of the following [7]:

- The total number of the strips in the row N.
- The radius r of the endpoint.
- The angular pitch ϕ_p .
- The stereo angle ϕ_s .
- The distance of the original wafer centre from the wheel centre R.

Using the variables above, one can calculate [7]:

- The i-th strip angle ϕ_i :

$$\phi_i = (i - N/2 + 0.5)\phi_p \quad (4.3)$$

- The Radial position r'

$$r' = 0.5(-b + \sqrt{b^2 - 4c}) \quad (4.4)$$

Where b is

$$b = -2(2R\sin(\phi_s/2))\sin(\phi_s/2 + \phi_i) \quad (4.5)$$

and c is

$$c = (2R\sin(\phi_s/2))^2 - r^2 \quad (4.6)$$

- Using the radial position and the strip angle, one can calculate the position of the strip ends in cartesian coordinates:

$$x_i(r') = r'\cos(\phi_i + \phi_s) - R\cos(\phi_s) \quad (4.7)$$

and

$$y_i(r') = r'\sin(\phi_i + \phi_s) - R\sin(\phi_s) \quad (4.8)$$

The resulting cartesian coordinates are often used for the automatic probe station to probe the individual strips. The same calculation must be done also for the automatic wire bonders during the detector module assembly. For a bowing strip sensor, these calculations cannot be used for probing. Furthermore, the strip probing process can introduce vibrations which can lead to misalignment of the strip sensor during the strip tests. The electrical circuit setup is identical to the typical I-V curve test for the strip sensor bulk. The strip probing apparatus utilizes the Keithley 2410 as the power supply for the 100V supply and also as an ammeter. The LCR meter is connected in parallel to this apparatus to measure the capacitance and the resistance of the circuit.

The University of Cambridge utilizes a probe card with 32 probing needles designed for a strip sensor with strip pitch of $74.5\mu\text{m}$ for the rectangular barrel strip sensors. This probe card was also used for probing the ATLAS17LS barrel strip sensors which has the strip pitch of $75.5\mu\text{m}$. This could only be achieved with a careful alignment of the probe card and a careful identification of the strip pad locations. Each of the 32 probe needles of the probe card are connected to a switch matrix which allows near-parallel testing of 32 strips at each time. Furthermore, this probe card and probing method cannot be used for the endcap strip sensors due to the unique stereo annulus design of the endcap strip sensors.

Interstrip capacitance

The interstrip capacitance test involves depleting the strip sensor bulk using the Keithley 2410 at 300V and measuring the capacitance of three adjacent strips using AC pads of a strip sensor with the LCR meter as seen in Fig. 4.9.

Figure 4.9: The circuit setup for the strip sensor C_{IS} curve test

It is important to note that this test requires a minimum of five electrical contacts on the strip sensor. This introduces a risk of contacts shorting with one another. Furthermore, the limited range of the microscope allows this test to be performed only on the strips close to the edge metal if all electrical contacts are made with micromanipulators. The interstrip capacitance is expected to be less than 1 pF cm^{-1} [8]. Furthermore the interstrip capacitance for endcap sensors such as ATLAS12EC R0 must be scaled by [7, 8]

$$C_2 = f \frac{\ln(\frac{d_1}{a})}{\ln(\frac{d_2}{a})} C_1 \quad (4.9)$$

where d_1 is the average pitch of the strip sensor, C_1 is the measured capacitance, $d_2 = 75.5 \mu\text{m}$ the pitch of the barrel strip sensor, and $f=1.12$ and $a=20 \mu\text{m}$.

Interstrip resistance

The setup for testing the interstrip resistance is similar to the I-V curve test. The ground line for Keithley 2410 this time however goes through a $100 \text{ k}\Omega$ resistor and supplies ground for one DC pad. The interstrip resistance test also requires electrical

contact to the DC pads of the adjacent strips. The test also requires an additional power supply, Keithley 6517 and also an ammeter, Keithley 2000. The setup can be seen in Fig. 4.10.

Figure 4.10: The circuit setup for the strip sensor R_{IS} curve test

While the strip sensor is fully depleted, the Keithley 6517 supplies 5 Volts between the 3 strips, and the Keithley 2000 measures the current. Using Ohm's law [3] we can determine the interstrip resistance.

$$R_{IS} = \frac{V_{K6517}}{I_{K2000}} \quad (4.10)$$

The acceptable interstrip resistance is

$$R_{IS} > 10 \times R_{BIAS} \quad (4.11)$$

Any shorting observed during this measurement shows potential damage to the PTP-Poly-Si resistor structure or the strip implant [7, 8]. The R_{IS} test is currently not part of the standard QC procedure.

The standard procedure for strip sensor quality control has not yet been fully established as each QC site within the ATLAS ITk strip detector collaboration has limited resources and time. At the present stage, the priority for all QC sites is to verify the technical specification of the prototype sensors. The prototype sensors are now only being produced by HPK. This will allow a more focused research and development of the ITk strip sensors only with one supplier. While the initial evaluation of the ATLAS12 sensors has been within specification, the long term tests show that the performance of these sensors degrades rapidly over time and exposure to humid air. Furthermore, the irradiation tests performed on the ATLAS12EC sensors have not yet been fully analyzed. The ATLAS17LS sensors show signs of sensitivity to the relative humidity and the results of strip sensor testing can be seen in Chapter 6. At the present stage, all functioning strip sensors are assembled into a detector module as seen in Chapter 5 in an effort to develop a standard strip detector module assembly technique.

One should also consider the vast number of strip sensors that must be processed through individual QC sites. The number of components required for the construction of the ATLAS ITk strip detector can be found in Tab. 4.1. The ATLAS ITk strip detector collaboration must also consider the cost and time efficiency in each step.

Table 4.1: The ATLAS ITk strip sensor QC requirements as of 2017 [3].

Item		Number	Equivalent Sites	Ramp up	Assumed Days	Rate / Eq. Site/ Day
Sensors IV/CV		20665	4	no	650	7.9
Sensors Full Probing		2067	4	no	650	0.8
ABCStar (wafers)		670	1	In pre production	450	1.5
Barrel (panel)	Hybrids	2284	2	year @50%	1 550	2.1
End-cap (panel)	Hybrids	1542	1	year @50%	1 550	2.8
Barrel Modules		12688	8	year @50%	1 550	2.9
End-cap Modules		7976	7	year @50%	1 550	2.1
Barrel Cores		412	2	year @50%	1 550	0.4
End-cap Cores		403	2	year @50%	1 550	0.4

4.3 Apparatus for strip sensor testing: TK Jig

There are four main quality control sites for the ATLAS ITk strip sensors. In an effort to achieve the specified strip sensor processing rate a Universal Quality Control Jig (UQCJ) was proposed. The aim of the UQCJ was to accommodate all strip sensor geometries for all mechanical and electrical tests to be performed on the strip sensors. In addition the UQCJ must accommodate the apparatus and procedure for all QC sites. Under the supervision of Dr. Thomas Koffas and Dr. Bart Hommels, a set of requirements for UQCJ was prepared (Tab. 4.2).

Table 4.2: Requirements for the Universal Quality Control Jig

Testing	Flatness	Static Contact	Clamp	Vacuum	UnRestricted
Human Visual	No	No	Yes	Optional	Optional
Automatic Visual	Yes	No	Optional	Optional	No
Iv & CV	No	Yes	Optional	Optional	No
Flatness	No	No	No	No	Yes
Full Strip Probing	Yes	Yes	Optional	Optional	No
C_{IS} & R_{IS} & PnP	Yes	Yes	Optional	Optional	No

With the requirements set, the UQCJ (later named TK Jig) was designed and produced at Carleton University.

4.3.1 Design and prototypes

During the conceptual design phase, it was found that the requirements set in Tab. 4.2 were easily met. Using the Autodesk Inventor 2018 Computer Assisted Design (CAD) software, the initial conceptual design could be tested and improved upon with the use of the CAD software. In addition three more guidelines laid out by the supervisors for the fabrication process.

1. Make it work.

The priority is to design and build a jig that first achieves its goal.

2. Make it cheap.

The jig must be sufficiently inexpensive in order to be mass-produced for the

entire collaboration to benefit.

3. Make it fast.

The jig must also be easy and fast to handle as one of the main aim of UQCJ is to improve the strip sensor processing rate.

The exact quantity or the budget requirements of the UQCJ were never set. However, distribution of approximately 5 to 10 UQCJs per each QC site was the initial goal. Furthermore the design of the UQCJ absolutely required to surpass the performance of two existing strip sensor testing jigs.

- Cambridge Sensor Testing Jig

The Cambridge Jig was made of Delrin and cost over \$2000 each. With minor modifications, it could accommodate the ATLAS12EC and the barrel strip sensors for electrical tests. Also, due to the nature of Delrin, it was very sensitive to ambient humidity as it could absorb moisture.

- Carleton Flatness Jig

The Carleton Flatness jig was made of Aluminum and cost over \$1000 each. It could accommodate all strip sensor geometries but it could not be used for any of the electrical tests.

The UQCJ was required to combine the best traits of both jigs presented above and it was also required to cost less.

Supersensor

The first priority set for UQCJ was to accommodate for all shapes and sizes of the ATLAS ITk strip sensors. First the strip sensor geometries were drawn in CAD. These geometries were then superimposed. The supersensor is the superposition of all strip sensor geometries merged together in CAD (Fig. 4.11).

(a) Superposition of the ATLAS ITk strip sensor geometries.

(b) The supersensor template with overlay

Figure 4.11: The supersensor

The supersensor was used as a template of the UQCJ in order to satisfy the mechanical requirement of the UQCJ.

UQCJ: Conceptual Model and the first prototype (UQCJ-CM and UQCJI)

Prior to production of the first prototype jig, a conceptual model was built only with mechanical requirements in mind. The UQCJ-CM was built entirely with phenolic resin material costing less than \$20. The UQCJ-CM was initially tested with the Thermo-Mechanical model of ATLAS07 Barrel strip sensor and one rejected ATLAS12EC strip sensor at Carleton University. The conceptual model was not only compatible with both strip sensors, it was also compatible with smaller circular wafers and one smaller rectangular strip sensor (IFX Baby-Long). With the positive mechanical results from the conceptual model, the actual prototype UQCJI was made with Delrin and Aluminum. The baseplate of the UQCJI was made of the same aluminum baseplate of the Carleton Flatness Jig to maintain the flatness whereas the side components were made of Delrin to maintain the high-voltage electrical properties. The UQCJI cost less than \$100 and used the exact same design of the UQCJ-CM.

(a) Design of the first UQCJ prototype holding an ATLAS ITk strip sensor end cap R0 (b) UQCJ1 holding an ATLAS ITk strip sensor end cap R0

Figure 4.12: The first prototype of UQCJ

More mechanical tests were performed with UQCJ1 to confirm that the prototype jig made with Delrin and Aluminum had the same mechanical integrity as the conceptual model. The two main tests were:

- **Tipping test**
With a sample strip sensor loaded on the jig, the jig was tipped upside-down to test its grip on the strip sensor.
- **Microscopic vibration test**
With a sample strip sensor loaded on the jig, the jig was placed inside the probe station with improper vibration isolation and a probe needle was set down on the strip sensor's fiducial mark. Mechanical stress was then introduced to the probe station in different lengths and intensity. The probe needle was then lifted and the strip sensor fiducial mark was visually inspected for scratch marks produced by the probe needle. The scratches were less than $3\mu\text{m}$ in length.
- **Long term hold (Transport)**
With a sample strip sensor loaded on the jig, the jig was packaged in an Electrostatic Discharge (ESD) safe bag and the bag was transported in between Carleton University and Deutsches Elektronen-Synchrotron (DESY) Zeuthen. The sample strip sensor survived the transportation.

With successful mechanical tests, the UQCJI was then electrically tested (I-V and C-V curve tests) at Carleton University and Deutsches Elektronen-Synchrotron (DESY) Zeuthen. A new challenge for the UQCJ project was that during electrical tests the ATLAS12EC strip sensors were not environmentally stable and were not reliable reference strip sensors for the electrical tests. Fig. 4.13 shows I-V test result of a temperature and ambient relative humidity dependent ATLAS12EC R0 strip sensor on and off of the UQCJI. the strip sensor broke down during an I-V curve test while on UQCJI.

Figure 4.13: I-V curve test of one ATLAS12EC R0 W007 strip sensor loaded on a probe station chuck and then on the UQCJI at DESY Zeuthen

The ATLAS12EC R0 strip sensors regularly broke down early during the I-V curve test. However Fig. 4.13 still shows an encouraging result that the profile of the I-V curve of the strip sensor on and off the UQCJI are identical.

UQCJII

The design parameters of the UQCJI changed to further optimize the strip sensor testing time efficiency. Due to the fact that each individual QC site had different wire bonders, modifications were made to the design of the wire bonding pads of the UQCJI. As the UQCJ project was designed having jig modularity in mind, minor modifications were made to the existing jig. Grooves were made to the two side strip sensor holding pieces to minimize the travel distance between the strip sensor and the wire bonding pad.

UQCJIII

The UQCJII design used the imperial system of units. The UQCJIII was designed and built using the metric system. The Carleton Design office also recommended modifications to further reduce the production cost of the jig. The UQCJIII failed the mechanical tests. The sample strip sensor could slip under the strip sensor holding parts obstructing the field of view of the strip sensor surface features. Furthermore the uncontrolled force applied to the strip sensor presented a potential danger to the strip sensors.

UQCJIV

The UQCJIV uses multiple triangular pieces to hold the strip sensors. The triangular “cookies” use the simple geometry of a triangle to ensure that the strip sensor cannot slip under the cookie. The cookies also provide a visual indication for a firm contact with the edge of the strip sensor. The comparison of a linear strip sensor holding piece and the cookie can be seen in Fig. 4.14.

The cookies show a visual indication by lifting its thin “wings” when a firm contact when more than 5cN is applied. This result have been verified by the Vernier Dual-Range Force Sensor (DFS-BTA). While this is well under the force applied to the strip sensor by a vacuum pen used in strip sensor handling, it is sufficient to firmly hold the strip sensor during the strip sensor tests.

It is also important to note that the UQCJ project maintained its cost efficiency by avoiding custom made parts and reducing the number of steps required to take for the manufacturing process. The cookies present the most complicated manufacturing process and the University of Cambridge suggests injection mold for mass production.

(a) Left shows a sample strip sensor “pinched” by a linear strip sensor holding piece and the right shows the view under the microscope.

(b) Left shows the UQCJIV-cookie “lifting” at full contact, and the view under the microscope.

Figure 4.14: The general outline of the

Furthermore, the cookies reduced the number of contact points on the sample strip sensor allowing a much better field of view of the edge of the strip sensors as seen in Fig. 4.14.

UQCJIV:TK Jig

The UQCJIV design was further modified to ensure a secure wire-bonding pad for the strip sensor tests and the jig’s compatibility with the probecard used at the University of Cambridge. After encouraging results from both universities, the UQCJ was given a name; the TK Jig.

4.3.2 TK Jig

Figure 4.15: The final design of UQCJ: TK Jig

A single batch of TK Jig consists of:

1. One 1/4 inch thick 6 inch x 6 inch Tight-Tolerance High-Strength 2024 Aluminum plate (McMaster-Carr 8509K91)

The high strength aluminum plate is used as a flat base plate of the jig. This is a flat platform for flatness testing and on demand an electrically conducting medium for biasing the strip sensor through its backplane. This flatness is also important for the alignment of the strip sensor for tests involving an automatic probe station. In addition the flat base plate of the jig provides a good vacuum pull from the chuck of a probe station.

2. One 1/4 inch thick 12 inch x 12 inch Delrin sheet (McMaster Carr 8573K15) for the following:

- Two Delrin side frame of the jig.

The two side frames were built symmetrically to reduce manufacturing cost.

- Eight Delrin Cookies.

Three or more cookies are used to hold a strip sensor in place. The cookies are currently made in squares and then cut. Although only three cookies are required for full operation 6 is recommended.

- One Delrin Half-Moon.

This is a larger alternative to cookies to provide a rounder larger point of contact for the strip sensors.

- Seven Delrin screw heads

These screw heads are the ball joints for the screws and the cookies.

- One Delrin top side of the jig frame.

This frame is designed to provide a perpendicular force to the strip sensor from the side frame.

- One Delrin bottom side of the jig frame.

At the time of strip sensor handling, this part exists to prevent the strip sensor from sliding out of the jig.

3. M3 x 0.5mm x 50mm (McMaster Carr 92095A475)

These screws are used for handling the sensor with the cookies.

4. M3 x 0.5mm x 10mm (McMaster Carr 92855A310)

These screws are used for assembling the TK Jig.

The total production cost of a TK Jig at Carleton University is less than \$200 in parts and the estimated production time is 6 hours per jig. The ATLAS ITk strip detector collaboration intends to use the TK Jig for space, cost and time efficient alternative to a probe station. The TK jig is currently also in demand at the strip detector module assembly sites. The distribution of the TK jig to all of the sites responsible for handling the strip sensors will encourage a quick strip sensor test prior to each step in the assembly procedure of the ATLAS ITk strip detector ensuring a better quality control.

The next chapter focuses on the integration of the ATLAS ITk strip sensors in a detector module. Prior to distributing the strip sensors to an assembly site, the strip sensors are tested for the last time with an I-V curve test.

Chapter 5

ATLAS ITk strip detector module assembly

After the strip sensors are carefully characterized at the quality control site in the manner similar to that seen in Chapter 4, they are distributed to a detector module assembly site. Two examples of detector assembly sites are the University of Toronto and DESY Zeuthen. Upon reception and to ensure that nothing has occurred during transportation, all of the detector module components including the strip sensor undergo a brief quality control procedure before being assembled into a detector module. However as seen in Tab. 4.1 in the previous chapter, the assembly site also must meet the specified production rate which is to assemble 2 to 3 modules per day. Due to this time constraint, a time and cost efficient method and apparatus must be developed.

The exact details of the assembly has not yet been fully established within the ATLAS ITk strip detector collaboration. However at the current stage, the module assembly sites are experimenting with different assembly techniques before finalizing a standard assembly procedure. This chapter is dedicated to the development of the techniques for assembling an ATLAS ITk strip detector module. First the principle of operations of the ATLAS ITk strip detector module will be presented in Section 5.1. Later, one of the detector module assembly techniques will be presented in Section 5.2.

5.1 A brief introduction to the principle of operations of the ATLAS ITk strip detector module

As previously discussed, an ATLAS ITk strip detector module is built on top of a strip sensor. An exploded view of a typical detector module can be seen in Fig. 5.1.

Figure 5.1: An exploded view of an ATLAS ITk strip sensor detector module [3]

The three main components of a typical ATLAS ITk strip detector module are the following:

- The strip sensor
The details of the ATLAS ITk strip sensors have been discussed in Chapter 3 and characterization process have been presented in Chapter 4.
- The hybrid board
The hybrid boards are the PCB boards that are glued at the top surface of the strip sensor as seen in Fig. 5.1. The hybrid boards provide an interconnected platform for the ASICs and they are electrically grounded to the strip sensor bias rail. The shape and size of the hybrid boards vary to match the geometry of the strip sensor.
- The ASICs (ABC and HCC)
The ABCs are the read-out chips of the ATLAS ITk strip detector. The ABC ASICs are wirebonded to the AC pads of the strip sensor strip segments. They also wirebonded to the hybrid board to communicate with the HCC. The HCC

is wirebonded to the hybrid board and it is responsible for communicating with the backend electronics.

At the research and development phase, the module assembly sites utilize test frames with their own power circuit to test and power the detector modules. As a convention the power board as seen in Fig. 5.1 is not installed on the prototype strip detector modules.

The principle of operation of a fully assembled ATLAS ITk strip detector module has the following signal flow [3]:

1. the strip sensor is fully depleted and the front-end electronics are actively collecting charges accumulated by the strip implants.
2. A charged particle traverses through the depletion zone of a strip segment in the strip sensor. As a result new charge carriers are produced at the depletion zone.
3. The charge carried by the new charge carriers are then collected by the AC coupling capacitor in the strip segment of the strip sensor.
4. Given that the charge collected is not exceeding the onset value of the PTP structure along the strip segment, the charge is then passed into the ABC ASIC producing a signal. Since the excess charge is now collected from the strip segment, the strip segment is depleted again and ready for detecting more charged particles.
5. The ABC amplifies, shapes and stores the signal produced by the traversing charged particle and sends the signal to the HCC or a neighbouring ABC ASIC.
6. The HCC collects the data from all of the ABC ASICs and processes it out to the back end electronics classified as the End of Substructure card (EOS).
7. The EOS communicates with the whole triggering system of ATLAS to ensure that the registered signal forms a real charged particle track and outputs data. If the signal does not coincide with any other detectors within the ATLAS detector, the signal is considered to be electronic noise, and is discarded to a common ground.

The above general data flow is subjected to change due to the fact that the readout ASICs for the ATLAS ITk strip detector have not been finalized.

5.1.1 ABC and HCC

As mentioned in Chapter 1 and Chapter 2 the amount of data produced by the decay of a Higgs boson is tremendously large. Furthermore the amount of data produced by the expected 200 pile-up events per 25 ns at the center of ATLAS presents a great challenge in data processing [3]. In addition, the individual hit signals of a particle track must be processed in a time efficient manner. Any improvement in the processing rate of the hit signal must be considered. The current ITk strip detector prototype design uses the ABC130 and HCC130. In an effort to improve the data processing speed, these ASICs are to be replaced by the ABCStar and HCCStar. A main difference in the “130” and the “Star” designated ASICs is in the data handling as seen in Fig. 5.1.

Table 5.1: Comparison of data flow of the ABC130 and HCC130 seen in the left and the ABCStar and HCCStar seen in the right [3].

The data flow of the “130” ASICs is in series and “daisy-chained”. The ABC130 can detect 0.75 fC pulse each 75 ns from 256 input channels, taking 20 ns for shaping the signal and can store up to 86 events for 6.4 μ s in its buffer memory bank [3]. The design data processing speed is 160 MB s⁻¹ in between each ABC130 and in between the ABC130 and HCC130 [42, 43].

The data flow of the “Star” ASICs is in parallel from an individual ABC to the HCC. The ABCStar has the same pulse detection resolution and it is expected to take 25 ns for shaping the signal and can store up to 86 events for 128 μ s. The design data processing speed is 160 MBs⁻¹ in between the ABCStar and HCCStar.

The “Star” ASICs are currently under development and first, the prototype “130” ASICs must be utilized and carefully characterized as part of a detector module. The characterization process of the ASICs do fall within the scope of Carleton University, however it is beyond the scope of this M.Sc. thesis and the focus of this chapter is on the development of the techniques of assembly procedure of the ATLAS ITk strip detector modules.

5.1.2 The hybrid boards

Since the hybrid boards must be attached to the different geometries of the strip sensors, several different hybrid board designs exist to accommodate to all of the strip sensors.

Figure 5.2: The design of the hybrid boards for the ABC130 and HCC130 ASICs [3].

As seen in Fig. 5.2, the configuration of the hybrid board depends on the number of ABC ASICs to be used, and the location of the AC pads for the strip segments of the strip sensors. In the case of an ATLAS12 endcap R0 strip sensor, there are two hybrid boards with eight and nine pads for the ABC130 ASICs. The smaller hybrid board to be attached to the lower part of the R0 strip sensor is called R0H0. The

larger hybrid board to be attached to the upper part of the R0 strip sensor is called R0H1 [25].

The design of the hybrid board has been established for the ATLAS12 Barrel and endcap R0 sensors to use the ABC130 and HCC130 ASICs. The production method and the technical specification for these hybrid boards are currently under development. Furthermore the hybrid boards must be re-designed for the upcoming ABCStar and HCCStar ASICs to take advantage of the parallel processing capability of the HCCStar [3].

5.1.3 ABC130-HCC130 detector modules

The ATLAS ITk strip detector collaboration has successfully assembled hybrid modules by attaching the ABC130 and HCC130 ASICs on the hybrid boards. These hybrid modules have been attached to several different strip sensors to characterize the performance of the modules. In an effort to characterize some of the sample modules, the collaboration has been distributing Data Acquisition modules (DAQ load) made by assembling these hybrid modules with the miniature sensors. In addition the collaboration has been distributing a custom software based on ROOT 5 and ROOT 6 called the ITk Data Acquisition (ITSDAQ) software. The ITSDAQ software allows DAQ loads to directly communicate with a computer with a linux operating system through a Field Programmable Gate Arrays (FPGA) board. Two FPGA boards which are currently used for testing the DAQ loads are the ATLYS or NEXUS boards.

Using the ITSDAQ software a typical detector module must be characterized by performing a three point charge gain test. The three point charge gain test injects three different quantities of charge to a DAQload using the internal calibration capacitor built into the ABC130 ASICs, and the resulting gain, the value with 50 % hit rate (V_{t50}), and electronic noise with and without the charge injection are logged. Using the noise (σ) and gain, the ITSDAQ software also plots the ENC [3] of the detector module.

$$\text{ENC} = \frac{\sigma[\text{mV}]}{\text{gain}[\text{mV fC}^{-1}]} \quad (5.1)$$

A typical ENC of an ABC130 ASIC is in between 0.064 fC and 0.144 fC. A standard output from performing a point charge gain test on a module can be seen in Fig. 5.3.

Figure 5.3: A standard output from ITSDAQ showing the Vt50, gain, and noise of a 1.01 fC charge injection and comparing to no charge injection at 0 fC [23]

For a three point charge gain test, this is done for three different quantities of charge injections. The resulting Vt50, Gain, input and output noises are then used to plot the response curve of the module. Fig. 5.4 shows a sample output from the ITSDAQ software after performing a three point charge gain test.

Figure 5.4: The results of a 3 point gain [23]

The combination of the results of all the ABC130 ASICs in a detector module are then compiled and plotted with respect to individual input channels. This result will be presented the end of the next section in Fig. 5.16. The next section will walk through techniques used to assemble an ATLAS12EC R0 strip detector module. As the detector module starts forming its shape, the section will also present basic troubleshooting techniques. Finally, the section will discuss the performance of the detector module assembled using this technique.

5.2 ATLAS ITk strip detector assembly

The main steps of a strip detector assembly procedure are listed below:

1. All components are cleaned and tested.
2. ASICs are glued onto the hybrid boards.
3. ASICs are wire bonded to the hybrid boards and the assembly is then called the hybrid modules.
4. The hybrid modules are tested.

5. The hybrid modules are glued onto the strip sensor and the assembly is then called the strip sensor module.
6. The strip sensor module is wirebonded to a testframe.
7. The Hybrid module is again tested.
8. The ABC readout ASICs on the hybrid modules are then wire bonded to the AC pads of the strip sensor strip segments and the assembly becomes finally a fully operational strip detector module.

This section will walk through the individual steps seen above. The following module is built with the following components:

- ATLAS ITk endcap R0 strip sensor
Serial: VPX22720-W076
Type: S10938-5965
- ATLAS ITk endcap R0 hybrid boards
R0H0 hybrid board hosting 8 ABC130 ASICs and 1 HCC130 ASIC
R0H1 hybrid board hosting 9 ABC130 ASICs and 1 HCC130 ASIC
- ATLAS ITk strip sensor ASICs
ABC130_A1 Lot: A7Q8IKH
HCC130 Lot: A7Q8IKH
- ATLAS ITk strip detector module test frame
R0 testframe v3.0 July 2017 University of Freiburg

5.2.1 The hybrid module

The hybrid boards arrive to the assembly site taped to a cleanroom paper as seen in the left of Fig. 5.5. Upon reception the hybrid boards are removed from the cleanroom paper and thoroughly cleaned by removal of the adhesives on the surface and then ultrasonically cleaned. They are first submerged in SWAJ cleaning solution for 15 minutes in ultrasonic bath and then they are rinsed by being submerged in DI water for 15 minutes in the ultrasonic bath. The hybrid boards are then dried with compressed air for 10 minutes and inspected for holes, defects on the surface. Furthermore the flatness of the hybrid board is also tested using the CMM. During

the assembly procedure of this strip detector module, the R0H0 hybrid boards were not flat.

One should also note that the current cleaning procedure introduces potential risk of water damage. Furthermore it can also introduce abrasion to the hybrid board. This is an acceptable risk as the wire bonds require clean surfaces. A defective wirebond is much more difficult to troubleshoot than a small surface damage on the hybrid board. To reduce the risk of damage to the hybrid boards, there are low cost 3D printed transport frames under development in York University. These transport frames can potentially eliminate the need for cleaning procedure. In addition these transport frames for the hybrid boards could reduce risk of damage to the hybrid boards during transportation.

Figure 5.5: The hybrid boards (left) and the ASICs (right) upon reception

The ASICs arrive in gelpacks as seen to the right of Fig. 5.5. At the module assembly site only a brief visual inspection is done for the ASICs. The ABC130 ASICs are first mounted in correct orientation on the custom designed stencils for the R0H0 and R0H1 hybrid boards and lifted with vacuum pick-up tools dedicated for the R0H0 and R0H1 hybrid boards. This process can be seen in the bottom and top left of Fig. 5.6. Simultaneously the hybrid boards are mounted on a custom vacuum jig for the R0H0 and R0H1 boards and a 5 dot pattern of UV curable glue is applied to the hybrid board for each ABC130 ASIC. This procedure can be seen in the right of Fig. 5.6. The 5 dot pattern was selected for an even spread of the glue, and in total 2.1 mg of glue is applied per ABC130 ASIC.

(a) The ABC130 chips are placed in its hybrid (b) The hybrid boards are mounted on its spe-
board specific stencil (below) then picked up by cific vacuum jig and a 5 glue dots are applied per
the stencil specific vacuum pick-up tool(above). ABC130

Figure 5.6: The design of the hybrid boards for the ABC130 and HCC130 ASICs [3].

The vacuum ASICs pick-up tool is then mechanically joined with the vacuum hybrid board jig, and the glue is cured by UV LED for 2 minutes. During this step, any form of misalignment, or failure in the vacuum can cause misalignment of the whole detector module. Since the R0H0 hybrid board was not flat, the vacuum leaked from the jig holding this hybrid board. Fig. 5.7 shows the result of misalignment during the hybrid module assembly as a result of leak in the vacuum.

Figure 5.7: Unsuccessful hybrid module assembly. The ASICs were misaligned to the hybrid board during the glue curing process leaving space between the chip and the pads on the hybrid board. The R0H0 hybrid board used for this hybrid module was not flat. It is likely that the ASICs were misaligned due to the fact that the hybrid board was bowing during the assembly.

A misaligned hybrid module must be disassembled and cleaned before another attempt can be made to reuse the components that were used. The cleaning process

differs depending on which adhesive has been used for the hybrid module assembly. The quality control of the alignment of the hybrid board determines the how well the overall detector module is aligned.

After successfully gluing the ASICs to the hybrid board, the hybrid boards are mounted on the test frame using Kapton tape and the hybrid boards are wire bonded to the test frame. Fig. 5.8 shows a current wire bonding scheme for the hybrid module to be assembled with ATLAS12 EC R0 strip sensor.

Figure 5.8: Wire bonding scheme for the ATLAS12EC hybrid boards to test frame and to the strip sensor [24]

The wire bonds are made with a semi-automatic ultrasonic wedge wire bonder using 25 μm aluminum wires. While the misalignment of an individual ASIC is not crucial to the principle of operation for the hybrid modules, the alignment is absolutely crucial to take advantage of the automatic wirebonder. Several hundreds of wirebonds are made between the hybrid boards and the ASICs, and a small misalignment requires manual wire bonding and troubleshooting. The wirebonding scheme of an ABC130 ASIC to the hybrid board can be seen in Fig. 5.9.

Figure 5.9: Wire bonding scheme for an individual ABC130 to the hybrid board [24]. The left shows the data in put pads for AC pads of the strip sensor and the ASIC ID is set by the wirebond [25].

All of the ABC130 ASICs have the exact same wire bonding scheme except for the chip identification as seen in the blue highlight of the above figure. The input wirebonding pads at this time are not used since the hybrid board is not yet glued onto the strip sensor.

After the hybrid module has been properly wirebonded to itself, and to the test-frame, the hybrid modules are then tested using an ATLYS FPGA evaluation board and the ITSDAQ software. Since the ABC130 ASICs do not have input signals from the strip sensors yet, there is no “load” to be tested. Therefore, this test involves establishing communications to all of the ASICs on the hybrid module by performing a three point charge gain to the hybrid boards by using the internal calibration capacitors within the ABC130 ASICs.

Since the HCC130 and ABC130 use a daisy-chain data flow, the communication issues cannot be easily traced to an individual component on the hybrid module [25]. With the “Star” setup, parallel data flow should allow easier troubleshooting as it

would be easier to identify a single misbehaving ABCStar compared to troubleshooting an entire series of ABC130.

The most common cause for communication issues found in a hybrid module is due to a defective wirebond. While ultrasonic wire bonding is a relatively reliable technology, it requires a clean surface, stable hold of the bonding destinations and good bonding configurations [44]. The detector module assembly sites utilize an automatic wedge wire bonder at the room temperature. Even for wire bonding in the room temperature, the wedge tool of the wire bonders still need to reach above 120 °C [44]. For room temperature wire bonding, the wedge tool cools down from each wire bond and requires time to reheat in between each wire bond. This reduces reliability of the wire bonds and each defective wirebond needs to be manually inspected, removed and redone. Furthermore one should appreciate the density and the spacing in between each wire bond. The ABC130 ASICs are approximately 9.8 mm by 9.8 mm squares. Over 50 wire bonds are made to two sides of the ABC130 ASIC. This gives less than 0.171 mm in between each wire bond. For the input channels of ABC130 ASIC, 256 wire bonds which are 25 μ m thick made to one side of the ABC130 ASIC. This gives less than 68 μ m in between each wire bond. A small misalignment during this wire bonding procedure must be corrected as there is very little working space to troubleshoot a single wire bond.

Troubleshooting a defective hybrid module involves a thorough visual inspection and thermal imaging. The thermal imaging can identify a microdischarge or shorting along the hybrid module. The left of Fig. 5.10 shows a defective wire bond detected from the visual inspection. This type of defect in a wire bond is called the heel break where the wedge tool has not successfully bonded a wire to the HCC130 [44]. A major cause of the heel break is due to the misalignment of the wire bonding pads [44] or underheated wedge tool. The visual inspection is extremely time consuming due to the fact that it involves visually inspecting hundreds of wire bonds which are hard to observe. However the thermal imaging can help localizing the defect and guide a careful visual inspection for a small portion of the hybrid module. The right of Fig. 5.10 shows the thermal effect of one defective wire bond in the whole hybrid module. The thermal image helps localizing the defective wire bond as a defective wire bond normally results to microdischarges, and eventually overheating its surroundings.

(a) The highlighted section shows a defective wirebond on the HCC130. This is a heel break [44]. (b) A defective wirebond can short circuit anywhere along the hybrid module causing it to overheat. This is a thermal image of the R0H0 on a testframe with a defective wirebond.

Figure 5.10: Troubleshooting the Hybrid module by visual inspection and thermal imaging.

After a hybrid module has been successfully assembled, the hybrid modules are detached from the test frame in preparation for a full strip detector module assembly with the strip sensor. Even for an ideal hybrid module, it must be handled with extreme care. The wire bonds on the hybrid module can fail due to the following reasons:

- Physical damage

The hybrid modules must be transported without physical contact to any of the wirebonds. The hybrid modules are thin, light, small, and have many wirebonds at its top surface which makes careful handling difficult. Furthermore any less than ideal wirebonds can come loose due to vibrations.

- Temperature

A sudden change in temperature can cause rapid thermal expansion or contraction for the wires which can lead to break in the wirebonds.

- Corrosion

Even in a dry storage, the shelf life of 25 μm spool of Aluminum wire ranges

between 4 to 10 years [44]. In a less than an ideal condition for the bonded wires such as during the transportation or during the strip detector assembly, the wires can corrode and break.

Major semiconductor industries often preserve the wires with electrically insulating epoxy [44]. The wirebonds on the hybrid modules are exposed to all elements and require extremely careful handling.

5.2.2 The strip detector module

A full strip detector module is the assembled product of the hybrid module and a full size strip sensor. First the strip sensor is mounted on a dedicated vacuum jig as seen in Fig. 5.11.

Figure 5.11: A dedicated ATLAS12EC R0 sensor vacuum jig for detector module assembly

The flatness and the alignment of the strip sensor is very important as the hybrid module is assembled on top of the strip sensor and the assembly process relies on the mechanical alignment of the vacuum sensor jig and the vacuum ASICs pick-up tools. After the strip sensor has been prepared, the hybrid modules are mounted back to their respective vacuum jigs and picked up by the ASICs pick-up tools. EPOLITE FH-5313A-A-PAK epoxy is then applied to the back of the hybrid boards through a gluing stencil. This process can be seen in Fig. 5.12.

Figure 5.12: The hybrid module is picked up by the vacuum ASICs pick up tool and glue is applied to the backside of the hybrid board through a glue stencil

It is important to note that the epoxy starts hardening as soon as the glue and hardener mixes and the epoxy must be applied promptly to avoid premature hardening. Since the hybrid modules are held by the weak vacuum suction for the vacuum ASICs pick-up tool, the epoxy can bond the back of a hybrid module to the gluing stencil. During the assembly of this particular strip detector module, the R0H0 hybrid module was bonded to the gluing stencil temporally. Due to a good mechanical alignment of the gluing stencil to the ASICs pick-up tool, the R0H0 hybrid board was set back onto the ASICs pick-up tool with no loss in alignment. The gluing stencil is used to evenly spread the epoxy and to prevent the use of excessive glue.

After gluing, the hybrid modules are mechanically joined to the strip sensor. This process can be seen in Fig. 5.13. The ASICs vacuum pick-up tools have been mechanically joined to the vacuum strip sensor jig.

Figure 5.13: The hybrid modules are joined to the strip sensor using the ASICs pick up tool which is mechanically aligned to the vacuum sensor jig.

The next step involves dedicated weights for the individual hybrid modules. The dedicated weights are placed on top of the ASICs vacuum pick-up tool as seen at the right of Fig. 5.13 and the epoxy is left to cure for 24 hours. During this time, failure in vacuum can misalign the strip sensor module. Fig. 5.14 shows an assembled sensor module with signs of excess glue for the R0H1 hybrid module and misalignment of the R0H0 hybrid module. One should stress the R0H0 hybrid board was not flat at reception. This may be the cause of the misalignment of the R0H0 hybrid module on the strip sensor.

Figure 5.14: The highlights show the R0 sensor module with excess seeping glue from R0H1 hybrid module and R0H0 hybrid module is misaligned.

For this particular sensor module, one should recall that the ATLAS12EC R0 strip sensor has 4 segments of strips. The AC pads on the strip sensor are not covered by the excess glue from R0H1 hybrid module and the misaligned R0H0 hybrid module does not affect the assembly since the ABC130 ASICs are still aligned to the strips. From this point on in the strip detector assembly procedure, the strip detector module cannot be disassembled without destroying the sensor.

This sensor module is then mounted on the test frame again with Kapton tape. The Kapton tape can only be applied on surface of the PCB board of the hybrid modules. One should mind the wirebonds on the hybrid module and attempt to minimize contact to this wirebond. After the sensor module has been loaded on the test frame, the hybrid modules are then wire bonded to the test frames. This is the last opportunity to troubleshoot the hybrid modules.

After checking for potential communication issues on the hybrid module, the hybrid modules are directly wire bonded to the strip sensor bias rail (or bias ring) to supply a common ground throughout the strip detector module and the input pads of the ABC130 ASICs on the hybrid modules are wirebonded to the AC pads of the strip segments on the strip sensor. After this step the R0H0 hybrid module will have over 2048 wirebonds and R0H1 hybrid module will have over 2304 wirebonds. Troubleshooting the wirebonds after this step becomes exponentially more difficult.

One should note that as seen in Fig. 5.9 each ABC130 has 256 input channels for the AC pads of the strip sensor strip segments [25, 42]. The ATLAS12EC sensors have 1024 strips for the narrower 2 segments and 1152 strips for the wider 2 segments. For the best particle tracking resolution, all segments of the strips should be wirebonded to each input channel. The current standard strip detector module assembly procedure specifies 128 strip segments to be wirebonded to each ABC130.

The wire-bonding scheme of a strip detector module is currently under development. This section followed an established technique for the assembly of an ATLAS12EC R0 strip detector module. A completed detector module can be seen in Fig. 5.15. This detector module does not have all of its 4352 strip segments wirebonded to the readout ABC130 ASICs. The challenge of making 256 wirebonds in less than 9.8mm requires a careful approach.

Figure 5.15: A fully assembled ATLAS12EC R0 detector module mounted on a test frame [23]

After a full strip detector module is assembled, it is tested with ITSDAQ through an

ATLYS FPGA evaluation board. The performance of this particular strip detector module can be seen in Fig. 5.16.

Figure 5.16: Performance of the ATLAS12EC R0 module [23]

This module notably has non-uniform ENC throughout the channels, but the V_{t50} seems relatively uniform. This strip detector module needs to be carefully characterized over time. As previously mentioned in Chapter 4 the ATLAS12EC R0 strip sensors degrade due to exposure to relative humidity higher than 10%. Over time, if the strip sensor starts breaking early (at bias voltage around -80V as observed at Carleton University), the strip detector module becomes useless for detecting particles and the strip detector module cannot be used for the ATLAS ITk.

At the research and development phase of the ATLAS ITk strip detector modules, the technique for the detector assembly must be carefully correlated to the assembly rate. In addition the technique must also be correlated to the performance of the detector modules. The production models of the strip detector modules also needs to have a power board as previously discussed and found in Fig. 5.1. In the production stage, the strip detector modules with powerboards should then be mounted to the ATLAS ITk support structures (stave/petals).

In the timeframe of this M.Sc. thesis, the strip detector modules have stayed

mounted on the testframes. These were then transported to radiation test sites. One of the greatest challenges for the ITk strip detector collaboration is the transportation methods. Since most of the components used for the ATLAS ITk strip detector are sensitive to temperature, relative humidity and mechanical stress, a careful and reliable transportation method must be established. The very first ATLAS12EC R0 strip detector module was assembled in 2017. This first strip detector module suffered damage during transportation to CERN for the irradiation campaign later discussed in Section 6.2.

The next chapter will present the results yielded from characterizing the ATLAS ITk strip sensors and the effects of radiation damage on the ATLAS12EC R0 strip sensor.

Chapter 6

The performance of the ATLAS ITk strip sensors

This chapter does not follow the structure of rest of this document as it is dedicated to presenting the results yielded following the previous chapters. The performance characterization results of the ATLAS ITk strip sensors can be seen in Section 6.1, and the performance of one ATLAS12EC R0 strip sensor before and after irradiation can be seen in Section 6.2. The strip sensor testing was done at Carleton University and the University of Cambridge. the strip sensor characterization was done in a manner similar to that seen in Chapter 4. One ATLAS12EC R0 strip sensor was characterized at the Academy of Sciences of Czech Republic, Institute of Physics both before and after irradiation. the strip sensor was irradiated at CERN irradiation (IRRAD) facility in June and July 2017.

6.1 The performance of the ATLAS12, ATLAS12EC and ATLAS17LS strip sensors at the QC sites

There were several batches of the ATLAS ITk strip sensors which were characterized. Tables 6.1 and 6.3 list the strip sensor batches tested at Carleton University and the University of Cambridge. Carleton University is mainly responsible for performing quality control for the endcap strip sensors for the ATLAS ITk and the University of Cambridge is responsible for performing quality control for the barrel strip sensors.

Table 6.1: The batches of the ATLAS ITk strip sensors tested at Carleton University

Sensor Type	shape	Sensor Batch
ATLAS12	EC-R0	VPX22728
ATLAS12	EC-R0	VPX22729
ATLAS17	LS.Barrel	VPX26244

Table 6.2: The batches of the ATLAS ITk strip sensors tested at the University of Cambridge

Sensor Type	shape	Sensor Batch
ATLAS12	Barrel	VPX12518
ATLAS12	Barrel	VPX12519
ATLAS12	Barrel	VPX12318
ATLAS12	EC-R0	VPX22729
ATLAS17	LS.Barrel	VPX26244

For the prototype stage of the ATLAS ITk strip detector, both universities exchanged their strip sensors to verify their results. Several main strip sensor characteristics were studied. The leakage currents of the bulk material in the strip sensors were extrapolated at three different voltages, at the approximate full depletion voltage -300 V, the specified maximum operational voltage for the ATLAS12 strip sensors

−600 V and the specified maximum operational voltage of the ATLAS17LS strip sensors −700 V. The actual full depletion voltages were extrapolated from individual C-V curve tests. In addition, full strip tests were performed at the University of Cambridge. The following section will present the performance result of the ATLAS12 strip sensors and the ATLAS17LS strip sensors.

6.1.1 The performance of the ATLAS12 strip sensors

Figure 6.1: The leakage current and full depletion voltages of all of the ATLAS12 strip sensors. The VPX22729 and VPX22728 endcap strip sensors have lower full depletion voltages as seen in the right.

The combined results of the leakage currents and the full depletion voltage from all of the ATLAS12 strip sensors can be seen in Fig. 6.1. One can observe that the leakage current of the strip sensors of both barrel and endcap geometries follow a similar distribution pattern. One can also observe that the mean and the standard deviation of the leakage current increase with the bias voltage. As for the full depletion voltage, the strip sensors show a significant difference between the batches at Carleton University and the University of Cambridge. The distinction comes from the

fact that only the barrel strip sensors were tested at the University of Cambridge and also that only the endcap strip sensors were tested at Carleton University. The endcap strip sensors characterized at Carleton University have lower full depletion voltage, possibly due to the fact that the ATLAS12EC strip sensors were manufactured and distributed later than the ATLAS12 barrel strip sensors. The feedback provided to HPK from the ATLAS ITk strip detector collaboration in between the production of the two generation of strip sensors likely have motivated improvements in the newer batch of strip sensors. Since it is optimal to have lower full depletion voltage for the strip sensors in anticipation for the radiation damage from the HL-LHC operation, one can conclude that the ATLAS12EC strip sensors seen here are better performing. Furthermore, since the two strip sensor geometries seen in Fig. 6.1 are not identical, they were analyzed separately in Fig. 6.2 and Fig. 6.3.

Figure 6.2: The leakage current and full depletion voltage of the ATLAS12 main barrel strip sensors.

Fig. 6.2 shows the barrel strip sensors characterized at the University of Cambridge. One can note that the standard deviations of the leakage currents are more than twice the measured mean leakage current values at different bias voltages. The main issues seen with the ATLAS12 strip sensors were that the performance of the strip sensors

deteriorated outside a dry storage with less than 10% relative humidity. The higher leakage current represents lower strip sensor performance. Due to this environment and time dependent performance deterioration of these strip sensors, one can state that the ATLAS 12 barrel strip sensors cannot serve as the strip sensors to be used for the ATLAS ITk strip detector. Furthermore, one can also observe that the mean full depletion voltage of the ATLAS12 barrel strip sensors is (349.8 ± 3.2) V which is more than 2σ higher than the accepted <310 V in the technical specification [7]. It is clear that this batch of strip sensors failed the performance quality control. By comparison the performance of the strip sensors, the ATLAS12EC R0 strip sensors presented in Fig. 6.3 show an improvement.

Figure 6.3: The leakage current and full depletion voltage of the ATLAS12EC R0 strip sensors.

One can first notice that the ATLAS12EC R0 strip sensors have a narrower standard deviation of the full depletion voltage, and the mean full depletion voltage is significantly lower than the barrel strip sensors previously tested. One may also notice that the leakage current of the ATLAS12EC R0 strip sensors tested at Carleton University is in general higher than the barrel strip sensors tested at the University of Cambridge. This is a reflection of the time and environment dependence of strip

sensor performance deterioration. The HPK strip sensors are distributed from Japan to CERN in Switzerland and then distributed to the quality control sites. The strip sensors travel shorter distances and time to the U.K. than Canada. In order to eliminate any potential inconsistencies in the results, due to different characterization procedure or apparatus one ATLAS12EC R0 strip sensor was exchanged between the two universities. The chosen strip sensor was ATLAS12ECR0-VPX22729-W057. Both universities yielded consistent performance result of this strip sensor.

The distributed batches of the ATLAS12 main strip sensors were initially operating within the technical specification [5, 7]. However the performance of all of these strip sensors deteriorated over time. The most affected strip sensors had break down voltages that are lower than the full depletion voltages which means that the strip sensors simply cannot be used as components of a particle tracking detector. It has been observed that the strip sensors have lower break-down voltage when they are not kept in a dry storage with less than 10% relative humidity. One can suggest a long term observation of the capacitance of the strip sensor biased at full depletion voltage to detect potential deficiencies introduced to the bulk material of the strip sensor by moisture. Water vapour absorption in a silicon bulk material can result in changes in the dielectric coefficient introduced by impurity. The resulting changes in the dielectric coefficient of the bulk material can potentially be observed by monitoring the capacitance of the strip sensor biased at full depletion.

Full strip test

The ATLAS ITk strip detector collaboration has been troubleshooting this issue for an extended period of time. To eliminate the possibility of the performance deterioration of the strip sensors caused by the defects in the strips, full strip tests were performed on several strip sensors of this batch. One sample of a full strip test performed on an ATLAS12 strip sensor can be seen in Fig. 6.4 and in Fig. 6.5. These diagnostics tests can identify potential defects on the surface features of the strip sensors. Furthermore, the tests can identify damaged strips which may be responsible for the observed strip sensor defects. This section will show the results of a full strip test performed on one ATLAS12 barrel strip sensor VPX14757-W757. While the ATLAS12 strip sensors have 4 strip segments, only two inner segments of this strip sensor were tested.

Figure 6.4: Sample coupling capacitance of the strip segments of the ATLAS12 strip sensor

One can observe that the coupling capacitances of the strip segments of this strip sensor are relatively uniform. Seen in the bottom right of Fig. 6.4, this strip sensor has one defective strip segment (one in 2560 strips, less than 2%). Furthermore the average strip coupling capacitance is (65.34 ± 1.15) pF, and each strip segment is approximately 2.386 cm long. The resulting average strip coupling capacitance per unit of strip length is (27.38 ± 0.48) pF cm⁻¹ which is greater than 20 pF cm⁻¹. The strip segments of this strip sensor is well within the technical specification for the ATLAS12 strip sensor [5, 7].

Figure 6.5: Sample bias resistance of the strip segments of the ATLAS12 strip sensor

The measurement of the bias resistance of the same strip segments confirms that there is one defective strip segment as seen in the bottom right of Fig. 6.5. This is the same defective strip segment seen before. Furthermore, the average bias resistance of each strip is (1.37 ± 0.02) MΩ which again falls within the technical specification as seen in Tab. B.2. The full strip tests were performed for 20 strip sensors at the University of Cambridge yielding similar results.

One can conclude that the strips of the ATLAS12 main sensors are within the technical specification. However the bulk materials of the ATLAS12 strip sensors are not. This is in contradiction to the initial characterization results published in 2012 [5]. The ATLAS12 strip sensors deteriorate over time and present an issue to the ATLAS ITk strip detector collaboration. Many of these strip sensors were also distributed to strip detector module assembly sites. Due to the fact that these strip sensors are not reliable, one can also conclude that some of the potential issues seen in the strip detector modules may be due to the defective strip sensors.

6.1.2 The performance of the ATLAS17LS sensors

In 2018, the first batch of the ATLAS17LS barrel strip sensors were distributed to Carleton University and to the University of Cambridge. This section will present the performance characterization results of the ATLAS17LS batch VPX26244 produced

by HPK.

The leakage current and depletion voltages

Figure 6.6: The leakage current and full depletion voltages of the new ATLAS17LS sensors.

Similar to the ATLAS12 strip sensors, the bulk measurements of this batch of the ATLAS17LS strip sensors do not fall within the technical specifications. Furthermore, there is a much larger spread in the full depletion voltage of these strip sensors. As previously discussed, the full depletion voltages reflect the depletion depths of the strip sensors. The varying full depletion voltage of the bulk material of these strip sensors suggests that this batch of strip sensors were fabricated inconsistently. This could suggest possible inconsistencies in the depletion depth, inconsistent dopant concentration of the implants, inconsistent choice of the wafer used for the bulk material and also damage during fabrication or transportation. In an attempt to diagnose the deficiencies in these strip sensors, the full strip tests were performed.

Full strip test

The ATLAS17 Long Strip sensors have two segments of strips. Each segment is approximately twice as long as the strips of the ATLAS12 strip sensors. As a result the coupling capacitance of these strip segments is approximately twice the value of the ATLAS12 strip sensors. Fig. 6.7 shows the coupling capacitance of the strips of the ATLAS17LS VPX26244-W035 strip sensor.

Figure 6.7: Sample coupling capacitance of the strip segments of the ATLAS17LS strip sensor

This strip sensor has one defective strip segment and the average strip segment coupling capacitance is (118.3 ± 1.4) pF. Each strip segment is now 4.8306 cm and the resulting coupling capacitance per unit strip length of this strip sensor is (24.49 ± 0.29) pF cm⁻¹ which is within the technical specification. The bias resistance values of the strips of this strip sensor can be seen in Fig. 6.8.

Figure 6.8: Sample bias resistance of the strip segments of the ATLAS17LS strip sensor

The bias resistance values of the strips of this strip sensor confirm the defective strip segments seen before. The average bias resistance of this strip sensor is $(1.45 \pm 0.03) \text{ M}\Omega$, which is within the technical specification of the ATLAS17LS strip sensors.

Despite the discouraging bulk performance, the strip performance results do fall within the technical specification for these strip sensors. These performance measurements are summarized and compared to the technical specifications in Tab. 6.3.

Table 6.3: Comparison of the HPK made ATLAS17LS sensors batch VPX26244 to the technical specification.

Sensor Property	Specification	Measured Value of VPX26244
Maximum bow	$< 200 \text{ }\mu\text{m}$	$(23.1 \pm 4.8) \text{ }\mu\text{m}$
Leakage Current at $V_{bias} = 700\text{V}$	$0.1 \mu\text{A cm}^{-2}$	$(0.51 \pm 0.68) \mu\text{A cm}^{-2}$
Full Depletion Voltage	$< 300\text{V}$	$(318.1 \pm 13.2)\text{V}$
Bias Resistor Value	$(1.5 \pm 0.5) \text{ M}\Omega$	$(1.45 \pm 0.03) \text{ M}\Omega$
Coupling Capacitance	$> 20 \text{ pF cm}^{-1}$	$(24.49 \pm 0.29) \text{ pF cm}^{-1}$

In addition, this batch of the ATLAS17LS sensors had additional physical defects

observed at the surface. The initial visual inspection of these strip sensors showed accumulation of specs of dust on the surface structures and the dimensions of the full strip sensor were inconsistent with the design specification. One can take away from the results of this batch of the ATLAS17LS sensors that the issue in the bulk material of the ATLAS ITk strip sensors has not been resolved. These results were reported to HPK [40] promptly within the first week since reception of the strip sensors. The ATLAS ITk strip detector collaboration now awaits the next generation of prototype strip sensors. The next section will present the effects on one ATLAS12EC strip sensor before and after irradiation.

6.2 Irradiation damage to the ATLAS12EC strip sensor (Irradiation Campaign)

Along the SPS ring, CERN has an experimental site called Irradiation (IRRAD) Facility. The IRRAD facility provides up to 200 MeV proton beams from the SPS. In the summer of 2017, an ATLAS12EC R0 strip detector module was scheduled for an irradiation campaign at this site. This module was damaged before arrival at CERN. It was reported that some of the readout ASICs could not communicate to the backend FPGA. It was also reported that the communication issue may have been a result of a defective wirebond.

The aim of this campaign then changed to observing the effects of irradiation on a strip sensor at the 1 MeV neutron equivalent fluence $\Phi_n^{1\text{MeV}}$ which is equivalent to 10 years of HL-LHC run. the strip sensor was irradiated in a controlled environment with constant measurements of temperature, relative humidity and radiation fluence. Due to irradiation damage to the relative humidity sensor, the relative humidity of the controlled environment could not be continuously monitored. However the environment was constantly flushed with nitrogen ensuring low relative humidity throughout the irradiation campaign. Over the course of the irradiation campaign the ATLAS12EC R0 strip sensor accumulated approximately $1.5 \times 10^{15} n_{eq} \text{ cm}^{-2}$ fluence, exceeding the design requirement of the ATLAS ITk. This section covers the setup of the irradiation campaign, and the strip sensor performance before and after the irradiation.

The irradiation campaign in 2017 irradiated the following strip sensors:

- VOX22728-W037 P1

Slim Dicing miniature strip sensor

- VOX22728-W006 P2

Normal Dicing miniature strip sensor

- VOX22728-W036 P4

Slim Dicing miniature strip sensor, and also irradiated in June 2017.

- VOX22728-W003 O1

Normal Dicing miniature strip sensor

- VPX22728-W031

ATLAS12EC R0 strip sensor type S10938-5965

The above strip sensors were loaded onto a perspex frame as seen in Fig. 6.9.

Figure 6.9: Setup inside the coldbox.

Throughout the campaign, the highlighted Aluminum foil targets were used to actively monitor the 1 MeV neutron equivalent irradiation fluence ($\Phi_n^{1\text{MeV}}$), two analog temperature sensors NTC and TMP36 were taped to the perspex frame and they were used to actively monitor the temperature approximately at the surface of the strip sensor and one analog humidity sensor HIH5031 was also taped to the perspex frame. The whole assembly was mounted on the top lid of a cold box. The cold box had two

windows for the proton beam and it was held at -20°C and approximately under 10% relative humidity. The orientation of the proton beam path through these sensors can be seen in the left of Fig. 6.10.

Figure 6.10: Setup diagram of the Irradiation Campaign

It is important to note that inside the cold box, the whole perspex frame was held upside down by the lid of the cold box as seen in the right of the Fig. 6.10. Within the first hour of the installation, the HIH and TMP were damaged by the proton beam but the cold box was flushed with nitrogen throughout the experiment ensuring low relative humidity inside the cold box. For safety concerns none of the materials inside the cold box could be exchanged. The proton beam is a source of activating type of radiation. Any material affected by the proton beam will be radioactive and cannot be approached until a proper spectroscopy has been performed to measure its radiation emission levels. During the irradiation campaign, all of the readout electronics were located in the control room of the IRRAD facility through a 30m long patch panel. The readout electronics were connected to an Arduino Uno board which requires a 5 V DC signal to operate its sensors. The overall length of 40 m for the signal cables posed an issue to the signal attenuation degradation. This set up can be seen in Fig. 6.11.

Figure 6.11: Setup diagram of the Irradiation Campaign

the strip sensors were retrieved after 30 days of irradiation. Because of safety concerns, the strip sensors were placed within the IRRAD facility for over 200 days. During the strip sensor retrieval, it was discovered that the Aluminum foil targets were a poor choice of target for monitoring the irradiation fluence. The gamma spectroscopy of the strip sensors suggested the 1 MeV neutron equivalent fluence of $1.45 \times 10^{15} n_{eq} \text{ cm}^{-2}$ while the Aluminum foil targets suggested total fluence of $8.75 \times 10^{14} n_{eq} \text{ cm}^{-2}$. Furthermore the perspex frame was broken. Over the course of thirty days, the strip sensors accumulated $\Phi_n^{1\text{MeV}} = 1.45 \times 10^{15} n_{eq} \text{ cm}^{-2}$.

These strip sensors are characterized while held at sub freezing temperature since the activated atoms within the strip sensors generate heat. The ATLAS12ECR0 VPX22728-W031 strip sensor was tested and compared to its performance prior to the irradiation campaign. As anticipated the leakage current has significantly increased from the irradiation. In fact for this sensor, the leakage current has increased by a factor of 1000. The I-V curve of this strip sensor before and after its irradiation can

be seen in Fig. 6.12.

Figure 6.12: The leakage current of the ATLAS12ECR0 VPX22728-W031 strip sensor before and after irradiation [26].

One can note that the strip sensor leakage current immediately rises above $100 \mu\text{A}$ and approaches 1 mA which is far beyond the specified operating performance of this sensor. It has been also reported that this sensor does not fully deplete even at -500 V . The results of the interstrip capacitance and interstrip resistance suggest that the strip sensor was irradiated homogeneously [26]. Further studies are being done on this sensor within the ATLAS ITk strip detector collaboration. It is important to note that all of the strip sensors presented in this M.Sc. thesis are strip sensors whose design is still under development. Although the collaboration faces many new and recurring challenges, these challenges are expected for the strip sensors. The next chapter is dedicated to the summary and the conclusion of the development and evaluation of the ATLAS ITk strip sensors and strip detector modules

Chapter 7

Summary and conclusion

This M.Sc. thesis focused on three main topics: the properties and development of the prototype n^+ -in- p^- strip sensors of the ATLAS ITk strip detectors, the evaluation procedure of these prototype sensors, and the production of ITk strip detector modules using these prototype sensors. The performance of the new prototype ITK strip sensors have so far been exemplary upon the reception from the manufacturer. However there are currently unresolved issues such as rapid performance deterioration in an environment at higher than 10% relative humidity. As the very foundation of the ATLAS ITk strip detectors, these issues must be resolved promptly.

It is important to note that the purpose of the quality control sites such as Carleton University and the University of Cambridge is to identify and to perform diagnostics on the misbehaving sensors and to provide feedback to the rest of the collaboration. The performance characterization results provided by the two universities have already motivated a modification to the design of the newest batch of the ATLAS17LS sensors. During the development phase of the ATLAS ITk strip sensors, the QC sites play the largest role in the overall performance of the tracker.

Despite some of the set-backs presented during the development of the ATLAS ITk strip sensors, it is also important to note that these new sensors are still under research and development. Within the following year, the ATLAS ITk collaboration aims to fully develop reliable strip sensors. In addition the collaboration will fully develop and incorporate the Star-ASICs, and simultaneously develop and complete the strip detector module assembly procedure. Within the timeframe of this M.Sc. thesis, one must note that the majority of the investments throughout the ATLAS ITk strip detector collaboration have been in the procurement and establishment of the infrastructure necessary for the sensor characterization as well as the detector module

assembly. As a result the collaboration will gain more contributing members and therefore a greater community that can provide crucial feedback to the development of a better performing inner tracking detector for ATLAS.

The ATLAS ITk strip detector collaboration aims to install the ITk within the ATLAS detector starting in 2023. The new particle tracker will extend the current physics reach of the LHC and the ATLAS detector. In order to achieve its performance goals, all components of the ATLAS ITk are being carefully characterized.

List of References

- [1] K.A. Olive and et al., (*Particle Data Group*). Chin. Phys. C, 38, 090001, 2014.
- [2] M. Rogalla et al., “Radiation studies for gaas in the atlas inner detector
arxiv:hep-ex/9701011v1 22 jan 1997
freiburg-ehep-97-01,” 1997.
- [3] The ATLAS Collaboration., *Technical Design Report for the ATLAS Inner Tracker Strip Detector*
Reference: CERN-LHCC-2017-005
ATLAS-TDR-025. CERN, September 16, 2016.
- [4] J. Bohm et al., “Evaluation of the bulk and strip characteristics of large area n-in-p silicon sensors intended for a very high radiation environment,” *Nuclear Instruments and Methods in Physics Research*, vol. A636, pp. S104–S110, 2011.
- [5] L.B.A. Hommels et al., “Detailed studies of full-size atlas12 sensors,” *Nuclear Instruments and Methods in Physics Research*, vol. A831, pp. 167–173, 2016.
- [6] The ATLAS SCT Collaboration, Oct. 2007, *Technical Specification Supply of Silicon Microstrip Sensors of ATLAS07 specification Version 4.6*. CERN, 7th Oct. 2007.
- [7] ATLAS Upgrade Strip Sensor Collaboration , May 2012, *Technical Specification Supply of Silicon Microstrip Sensors of ATLAS12 specification Version 1.5.2*. CERN, 24 Aug. 2014.
- [8] The ATLAS ITk strip sensor collaboration, *Price Enquiry Technical Specification for the Supply of ATLAS17LS Strip Sensors*
Reference: DO-30717EPATLAS. CERN, June, 2017.
- [9] Anthony Morley
on be half of CMS and ATLAS Collaborations, “Higgs: Rare production and decay channels.” Accessed on 6 June 2018 at https://indico.cern.ch/event/517784/contributions/2464450/attachments/1459307/2253572/LHCP2017_Smaller.pdf.
- [10] Zhijun Liang, “Recent progress in silicon sensor development for atlas tracking detector upgrade.” Accessed on 6 June 2018 at https://www.phy.bnl.gov/~partsem/fy15/Zhijun_jan23v6.pdf.

- [11] CERN, “Cern public webpages.” Accessed on 22 March 2018 at <https://home.cern/>.
- [12] R. F., ““lhc upgrade (accelerator)” . cern 8th icfa seminar, daegu, korea 29/09/2005.” Accessed on 15 May 2018 at https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.luminosity.
- [13] ATLAS Inner Detector Community, *Inner Detector Technical Design Report Volume I*
Reference: CERN-LHCC-97-16
ATLAS-TDR-4. CERN, April 30, 1997.
- [14] The ATLAS Collaboration., *Technical Design Report for New Small Wheel*
Reference: CERN-LHCC-2013-006
ATLAS-TDR-020. CERN, July, 2013.
- [15] David Di Valentino, *Search for the Standard Model Higgs boson in the vector boson fusion-mediated diphoton decay channel using multivariate analysis techniques*. David Di Valentino at Carleton University, 2013.
- [16] Ben Smart
on be half of ITk simulation community, “How to design a silicon tracking detector
insights from the itk upgrade for the atlas detector at cern.” Accessed on 6 June 2018 at <https://agenda.infn.it/getFile.py/access?resId=0&materialId=slides&confId=15482>.
- [17] Leroy, C. and Rancoita, P-G., “*Principles of Radiation Interaction in Matter and Detection 2nd Edition*”. World Scientific Publishing Co. Pte. Ltd., 2009.
- [18] G. Lindstrom et al., “Radiation hardness of silicon detectors - a challenge from high-energy physics,” *Nuclear Instruments and Methods in Physics Research*, 1999.
- [19] G. Hall, “Semiconductor particle tracking detectors,” *Reports on Progress in Physics*, vol. 57, pp. 481–531, 1994.
- [20] Laura Rehnisch. et al., *Testbeam Studies on Pick-Up in Sensors with Embedded Pitch Adapters*
Reference: ATL-ITK-PROC-2018-005. The ATLAS collaboration, 29 May, 2017.
- [21] L. Poley et al., “Investigations into the impact of locally modified sensor architectures on the detection efficiency of silicon micro-strip sensors,” *Journal of Instrumentation*
IOP Publishing for SISSA Medialab, vol. P07006, 5 July 2017.
- [22] C. Lacasta et al., *Design of the first full size ATLAS ITk Strip sensor for the endcap region*
Reference: ATL-ITK-PROC-2018-010. The ATLAS collaboration, 20 February, 2018.
- [23] L. Rehnisch. private communication, June 2018.

- [24] C. S. Contell, ““bonding schemes for r0 hybrids”,” in *ITk Week*, 2017.
- [25] K. Mahboubi et al., “The front-end hybrid for the atlas hl-lhc silicon strip tracker doi: 10.1088/1748-0221/9/02/c02027,” *IOP Publishing for SISSA Deditlab*, 2014.
- [26] P. Marcela Mikestikova, Institute of Physics. private communication, May 2018.
- [27] L. at CERN, “Lhc machine outreach.” Accessed on 15 May 2018 at https://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/lhc_in_pictures.htm.
- [28] A. at CERN, “Atlas experiment - public results.” Accessed on 15 May 2018 at <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>.
- [29] The ATLAS Collaboration., *Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC*
Reference: CERN-PH-EP-2012-218
arXiv:1207.7214v2. CERN, August 31, 2012.
- [30] The CMS Collaboration., *Observation of a new boson at a mass of 125GeV with the CMS experiment at the LHC*
Reference: CERN-PH-EP/2012-20
2013/01/29
CMS-HIG-12-028
arXiv:1207.7235v2. CERN, January 28, 2013.
- [31] David Di Valentino, *Constraining Standard Model and Beyond Standard Model Higgs boson coupling in the four lepton decay channel with the ATLAS detector*. David Di Valentino at Carleton University, 2018.
- [32] The ATLAS Collaboration, *Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s}=13$ TeV with the ATLAS Detector at the LHC*
DOI:10.1103/PhysRevLett.117.182002. Physics Review Letter. 117 182002, 2016.
- [33] The ATLAS Collaboration, “Search for the dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13\text{TeV}$ pp collisions with the atlas detector arxiv:1710.11412v2 [hep-exp] 19 jan 2018
doi:10.1140/epjc/s10054-017-5486-1,” *European Physics Journals*, vol. C78 (2018) 18, 22 january 2018.
- [34] Mark Bailey
Additional Information from Clare Lee, “Ionising radiation metrology forum quantities, units and ionising radiation fundamentals november 2010.” Accessed on 6 June 2018 at http://www.npl.co.uk/upload/pdf/20101117_irmf_bailey.pdf.
- [35] Y. Unno et al., “Development of n+-in-p large-area silicon microstrip sensors for very high radiation environments- atlas12 design and initial results,” *Nuclear Instruments and Methods in Physics Research*, vol. A765, pp. 80–90, 2014.

- [36] Charles Kittel, *“Introduction to Solid State Physics Eighth Edition”*. John Wiley and Sons, Inc., 2005.
- [37] Fernow, Richard C., *“Introduction to experimental particle physics”*. Cambridge University Press, 1986.
- [38] G. Casse, P.P. Allport and M. Hanlon et al., “Improving the radiation hardness properties of silicon detectors using oxygenated n-type and p-type silicon,” *IEEE Transactions On Nuclear Science*, vol. 47.No3, pp. 527–532, 2000.
- [39] M. Mikestikova et al., “Study of surface properties of atlas12 strip sensors and their radiation resistance,” *Nuclear Instruments and Methods in Physics Research*, vol. A831, pp. 197–206, 2016.
- [40] Y. Unno. private communication, April 2018.
- [41] E. Barberis et al., *Measurement of Interstrip and Coupling Capacitances of Silicon Microstrip Detectors*
Reference: 0-7803-0883-2/93. IEEE, 1993.
- [42] The ATLAS ITk Collaboration, “Abc 130 specifications
project specification v4.3
project name: Abc130 asic.” Accessed on 6 June 2018 at https://indico.cern.ch/event/227566/attachments/374699/521269/ABC130_DRAFT_Specification04_3.pdf.
- [43] F. S. upgrade electronics ASIC design group, “Hcc draft specification v1.4
april, 2014 specification in progress..” Accessed on 6 June 2018 at https://indico.cern.ch/event/314811/attachments/603748/830854/HCC_Specification_V1.41FMN.pdf.
- [44] G. Harman, *Wire Bonding in Microelectronics: Materials, Processes, Reliability, and Yield (Second Edition)*. McGraw-Hill Professional, 1997.
- [45] David Griffiths, *Introduction to Elementary Particles*
Second, Revised Edition. WILEY-VCH, 2008.
- [46] Michael E. Peskin and Daniel V. Schroeder, *An Introduction to Quantum Field Theory*. Addison-Wesley Publishing Company, 1995.

Appendix A

Mathematical derivations

A.1 The cross-sections of the proton-proton interactions

The differential cross-section of two protons interacting is defined as follows [45, 46]:

$$\frac{d\sigma}{dt} = \frac{S}{16\pi s(s - 4m_p^2)} \frac{1}{4} |\mathcal{M}|^2 \quad (\text{A.1})$$

where S is the statistical factor which is $1/2$ for protons, m_p is restmass of the proton, and $|\mathcal{M}|^2$ is the invariant amplitude defined as follows [45, 46]:

$$|\mathcal{M}|^2 = \frac{g^4}{(t - m_p^2)^2} + \frac{g^4}{(u - m_p^2)^2} + \frac{2g^4}{(t - m_p^2)(u - m_p^2)} \quad (\text{A.2})$$

where t and u are the two other two Lorentz-invariant Mandelstam variables and the g is the coupling constant. The total cross-section is often calculated by the following integral [31, 45, 46]:

$$\sigma = \int \frac{d\sigma}{dt} dt \quad (\text{A.3})$$

The total cross-sections often do not have analytic solutions [32, 45, 46] and numerical solutions can be derived using measurements made with particle detectors. In a more general form the total cross-section is described by the Breit-Wigner formula [3, 15, 31, 45, 46].

$$\sigma(\sqrt{s}) = \frac{2J + 1}{(2S_1 + 1)(2S_2 + 1)} \frac{4\pi}{k^2} \left[\frac{\frac{\Gamma^2}{4}}{(\sqrt{s} - E_0)^2 + \frac{\Gamma^2}{4}} \right] B_{in} B_{out} \quad (\text{A.4})$$

Where $\sqrt{s}$ is the collision center of mass energy, J is the spin of the resonance, the two S are the polarization states of the two incident particles, E_0 is the center of mass energy at the resonance, Γ is the full width at half maximum height of the resonance and the two B are the branching ratios of the initial and final states of the interaction. One should mind that the measurement of the cross-section can be done in the following manner. For a $pp \rightarrow X$ process the cross-section is estimated as follows [31]:

$$\sigma_{pp \rightarrow X} = \frac{N_{pp \rightarrow X}}{\epsilon \int \mathcal{L} dt} \quad (\text{A.5})$$

here the $N_{pp \rightarrow X}$ is the number of recorded events, $\int \mathcal{L} dt$ is the integrated luminosity and ϵ is a generalized efficiency for this process.

The integrated luminosity ($\int \mathcal{L} dt$) is a time integral of the instantaneous luminosity ($\mathcal{L}$) [31].

$$\mathcal{L} = \frac{n_b n_1 n_2 f_r}{2\pi \sum_x \sum_y} \quad (\text{A.6})$$

Here, n_b is the number of bunches per beam, n_i is the number of protons within a bunch i , f_r is the revolution frequency of the beams, $\sum_x$ and $\sum_y$ are the proton beam widths.

A.2 Depletion Depth in a p-n junction

The electric field and depletion depth of a p-n junction can be obtained by solving the Poisson equation [17].

$$\frac{d^2 \Psi}{dx^2} = -\frac{\rho(x)}{\epsilon} \quad (\text{A.7})$$

The charge density in the depletion zone $\rho(x)$ is approximately [17]

$$\rho(x) = \begin{cases} qN_d & , \quad 0 \leq x \leq x_n \\ -qN_a & , \quad -x_p \leq x \leq 0 \end{cases} \quad (\text{A.8})$$

where x_n and x_p are the depletion lengths of n and p side respectively. N_d and N_a are the n-type donor and p-type acceptor impurity concentrations. Outside of the depletion zone, the total charge is 0 resulting in a boundary condition

$$N_d x_n = N_a x_p \quad (\text{A.9})$$

The resulting electric field strengths are

$$E(x_n) = E(-x_p) = 0 \quad (\text{A.10})$$

resulting boundary equation is

$$E(x) = -\frac{d\Psi}{dx} \begin{cases} E_n(x) = q \left(\frac{N_d}{\epsilon} (x - x_n) \right) & , \quad 0 \leq x \leq x_n \\ E_p(x) = -q \left(\frac{N_a}{\epsilon} (x + x_p) \right) & , \quad -x_p \leq x \leq 0 \end{cases} \quad (\text{A.11})$$

By constraining that the electrostatic potential is constant at the junctions

$$\Psi(x) = \begin{cases} \Psi_p & , \quad x = x_p \\ \Psi_n & , \quad x = x_n \end{cases} \quad (\text{A.12})$$

One can integrate

$$E(x) = -\frac{d\Psi}{dx} \quad (\text{A.13})$$

over dx and find

$$\Psi = \begin{cases} \Psi_n(x) = \Psi_n - q \left(\frac{N_d}{2\epsilon} \right) (x - x_n)^2 & , \quad 0 \leq x \leq x_n \\ \Psi_p(x) = \Psi_p + q \left(\frac{N_a}{2\epsilon} \right) (x + x_p)^2 & , \quad -x_p \leq x \leq 0 \end{cases} \quad (\text{A.14})$$

By imposing the continuity of potential at x=0 yields

$$\Psi_n(0) = \Psi_n - q \left(\frac{N_d}{2\epsilon} \right) (-x_n)^2 = \Psi_p(0) = \Psi_p + q \left(\frac{N_a}{2\epsilon} \right) (x_p)^2 \quad (\text{A.15})$$

$$\Psi_n - q \left(\frac{N_d}{2\epsilon} \right) x_n^2 = \Psi_p + q \left(\frac{N_a}{2\epsilon} \right) x_p^2 \quad (\text{A.16})$$

$$\Psi_n - \Psi_p = q \left(\frac{N_a}{2\epsilon} \right) x_p^2 + q \left(\frac{N_d}{2\epsilon} \right) x_n^2 \quad (\text{A.17})$$

The built-in voltage $V_0 \approx 0.3 - 0.6V$ for silicon at T=300 Kelvin is defined by

$$V_0 = - \int E(x) dx = \Psi_n - \Psi_p = \frac{k_B T}{q} \ln \left(\frac{N_a N_d}{n_{int}^2} \right) \quad (\text{A.18})$$

$$\frac{k_B T}{q} \ln \left(\frac{N_a N_d}{n_{int}^2} \right) = q \left(\frac{N_a}{2\epsilon} \right) x_p^2 + q \left(\frac{N_d}{2\epsilon} \right) x_n^2 \quad (\text{A.19})$$

and recalling

$$x_n = \frac{N_a x_p}{N_d} \text{ and } x_p = \frac{N_d x_n}{N_a} \quad (\text{A.20})$$

then

$$x_n = \frac{1}{N_d} \sqrt{\frac{2\epsilon V_0}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)^{-1}} \quad (\text{A.21})$$

and

$$x_p = \frac{1}{N_a} \sqrt{\frac{2\epsilon V_0}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)^{-1}} \quad (\text{A.22})$$

and finally

$$X = x_n + x_p = \sqrt{\frac{2\epsilon V_0}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad (\text{A.23})$$

In a polarized p-n junction, the electrostatic potential is biased, only changes the boundary condition to

$$\Psi(x) = \begin{cases} \Psi_p \pm V_b & , \quad x = x_p \\ \Psi_n \mp V_b & , \quad x = x_n \end{cases} \quad (\text{A.24})$$

depending on the polarity of the bias voltage V_b . Finally, the resulting depletion depth with the introduction to an external V_b is then

$$X = x_n + x_p = \sqrt{\frac{2\epsilon V_0 + V_b}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)} \quad (\text{A.25})$$

A.3 Resistors in a semiconductor detector

One should also note that the effective dopant concentration N_{eff} is defined as

$$|N_{eff}| = |N_a - N_d| \quad (\text{A.26})$$

and the Full depletion voltage V_{FD} is defined by

$$V_{FD} = \frac{w^2 q |N_{eff}|}{2\epsilon} - V_0 = \frac{w^2}{2\epsilon \mu \rho} - V_0 \quad (\text{A.27})$$

At large full depletion voltage in relation to the built in voltage

$$V_{FD} \approx \frac{w^2}{2\epsilon \mu \rho} \quad (\text{A.28})$$

From this relation we can see that a high resistivity semiconductor detector can have a low full depletion bias voltage.

Integrating over dx yields the inte

Equating the E_n and E_p

This depletion zone can serve as a particle detector. Ionizing particles transversing the depletion zone with an energy higher than

$$E_{ion} = 3.62 \text{ eV} \quad (\text{A.29})$$

produce an electron-hole pair in silicon [17] [37]. The excess energy

$$E_{ion} - E_g = 3.62 \text{ eV} - 1.12 \text{ eV} = 1.50 \text{ eV} \quad (\text{A.30})$$

is spent other excitations in the silicon lattice.

This corresponds to the 3D potential well Fermi energy of the silicon.

$$V_F = \frac{\hbar^2 \pi^2}{2mL^2} \left(\frac{3N}{\pi} \right)^{-\frac{2}{3}} \quad (\text{A.31})$$

N is the number of fermions in the system, and L is the Well dimension. The Fermi energy is in the middle of the conduction and valence bands of the material. The probability of placement of the electron and hole(charge carriers) are given by the Boltzman suppression. The intrinsic semiconductors are pure bulk of material

Appendix B

ATLAS ITk Strip sensor Technical Specifications

Table B.1: ATLAS07 Technical Specification provided to HPK by ATLAS SCT collaboration [6].

	ATLAS07
Wafer size	150 mm
Thickness	320 μm
Orientation	$\langle 100 \rangle$
Type	P
Ingot	FZ
Resistivity	$>2 \text{ k}\Omega\text{cm}$
Outer dimension	97.54x97.54 mm^2
Sensitive implant edge dimension	95.58x95.58 mm^2
Strip segments	4
Strip segment length (approximate)	23.82 mm
Strip implant	N
Strip pitch (round of 0.5 μm)	74.5 μm
Strip implant Width	16 μm
Strip bias resistor	Polysilicon
Strip bias resistance (R_{ib})	1.5+/-0.5 $\text{M}\Omega$
Strip readout coupling	AC
Strip readout metal	Pure Aluminium
Strip readout metal width	20 μm
Strip AC coupling capacitance	$>20 \text{ pF/cm}$
Strip isolation	$>10 \times R_{\text{b}}$ at 200 V
Strip isolation method	Narrow-common p-stop
Gap between strip segments	$<160 \mu\text{m}$ (rail) $<70 \mu\text{m}$ (no rail)
Microdischarge onset voltage	$>200 \text{ V}$ and $<2\%$ bad strips $<600 \text{ V}$
Maximum operation voltage (*)	600 V
Leakage current	$<200 \mu\text{A}$ at 600 V
Radiation tolerance	$9 \times 10^{14} \text{ 1-MeV n}_{\text{eq}}/\text{cm}^2$

(*) The voltage rating of the external high voltage cable is 500V and tested 1 KV

Table B.2: ATLAS12 Technical Specification provided to HPK by ATLAS ITk collaboration [7].

	ATLAS12
Wafer size	150 mm
Thickness	310 +/- 25 μm
Orientation	<100>
Type	P
Ingot	FZ
Resistivity	>4 k Ωcm (*1)
Outer dimension (after dicing)	97.54 x 97.54 mm ²
Inner edge dimension of bias ring	95.70 x 95.64 mm ²
Strip segments	4
Strip segment length (approximate)	23.86 mm
Strip implant	N
Strip pitch (round of 0.5 μm)	74.5 μm
Strip implant Width	16 μm
Strip bias resistor	Polysilicon
Strip bias resistance (R_b)	1.5+/-0.5 M Ω
Strip readout coupling	AC
Strip readout metal	Pure Aluminium
Strip readout metal width	20 μm
Strip AC coupling capacitance	>20 pF/cm
Strip isolation	>10 $\times R_b$ at 300 V
Strip isolation method	Narrow-common p-stop
Gap between strip segments	56 μm (rail region) 70 μm (no rail region)
Microdischarge onset voltage	>600 V
Maximum operation voltage (*2)	600 V
Leakage current	<2 $\mu\text{A}/\text{cm}^2$ at 600 V
Radiation tolerance	1.2 $\times 10^{15}$ 1-MeV n _{eq} /cm ²

(*1) The wafers with >3 k Ω cm may be accepted if >4 k Ω cm is difficult to acquire.

(*2) The voltage rating of the external high voltage cable is 500V and tested 1 KV.

Table B.3: ATLAS17LS Technical Specification provided to HPK by ATLAS ITk collaboration [8].

Wafer size	6-in. (150 mm)
Wafer type	p-type FZ
Wafer orientation	<100>
Wafer thickness (physical)	300 to 320 ± 15 μm
Wafer thickness tolerance	$\pm 5\%$
Wafer active thickness	>270 μm
Wafer resistivity	>3 k Ωcm (*)
Wafer oxygen concentration	0.8×10^{16} (Preference for 1×10^{16}) to 7×10^{17} cm^{-3}
Full depletion voltage	<300 V (preference for <150 V)
Maximum operation voltage	700 V
Outer dimension, length (after dicing)	97.621 ± 40 μm (Preference for ± 20 μm)
Outer dimension, width (after dicing)	97.950 ± 40 μm (Preference for ± 20 μm)
Sensor bow after process and dicing:	< 200 μm
Strip segments	2
Strip segment length (approximate)	48.306 mm
Strip implant	N
Strip pitch (round of 0.5 μm)	75.5 μm
Strip implant width	16 μm
Strip readout coupling	AC
Strip readout metal	Aluminium (*)
Strip readout metal width	22 μm
Strip AC coupling capacitance	>20 pF/cm
Resistance of readout Al strips	<30 Ω/cm (*)
Resistance of N-implant strips	<50 k Ω/cm (*)
Strip bias resistor	Polysilicon
Strip bias resistance (R_b)	1.5 ± 0.5 M Ω
Strip isolation method	p-stop
Interstrip resistance (R_{int})	>10 $\times R_b$ at 300 V at RT (temperature should be documented)
Interstrip capacitance (C_{int})	< 1 pF/cm at 300 V, measured at 100 kHz
Number of strip defects	< 1% per strip/segment, < 1% per sensor, <8 consecutive bad strips
Strip defects	due to dielectric breakdown (=punch-through), metal and implant strip defects (opens and shorts), bias resistor failures, or micro-discharging strip (if applicable)
Microdischarge onset voltage	>700 V
Leakage current	<0.1 $\mu\text{A}/\text{cm}^2$ at 700 V at RT (temperature should be documented)
Leakage current stability in dry (RH<5%) and elevated humidity (RH $\geq$ 60%)	(<15% for 24 hrs and between two conditions after temperature correction) TBD
Radiation tolerance	Verified by ATLAS (at -20 $^{\circ}\text{C}$)
Fluence (Ionizing dose)	Up to 2×10^{15} neq/ cm^2 (60 Mrad.)
Microdischarge onset voltage after irradiation	>700 V or $V_{fd} + 50$ V after irradiation (if V_{fd} lower)
Interstrip resistance after irradiation	> 10 $\times R_b$ at 400 V, at -20 $^{\circ}\text{C}$
Collected charge after neutron irradiation	> 7500 electrons per MIP at 500V