

Development of a Control Interface for Monitored and Automized Characterization of the Silicon Sensors for 2S Modules for the CMS Phase-2 Tracker Upgrade

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Contents

1. Introduction	1
2. The LHC and the CMS experiment	3
2.1. The Large Hadron Collider	3
2.1.1. The High Luminosity LHC	4
2.2. The Compact Muon Solenoid experiment	5
2.2.1. The CMS Phase-2 Tracker Upgrade	7
2.2.2. The p_T Module Concept	9
3. 2S Modules	11
3.1. The Silicon Sensors	11
3.1.1. Basic Principle of a Silicon Detector	11
3.1.2. The 2S Microstrip Sensors	12
3.2. 2S Modules	14
3.2.1. 2S Module Assembly	15
3.2.2. Sensor Quality Standards and Quality Assurance	16
4. The Probe Station Test Stand	19
4.1. Experimental Setup	19
4.2. LabVIEW Setup	21
4.3. Electrical Measurements	21
4.4. Optical Inspection	23
5. The Development of a Control Interface	25
5.1. The Graphical User Interface	25
5.1.1. The Front Panel	25
5.1.2. The GUI Tabs	27
5.1.3. Data Folder Structure	30
5.2. Inner Structure and Implementation	31
5.2.1. The Power Supply Loop	32
5.2.2. The Optical Inspection Loop	35
5.2.3. The Multimeter Loop	36
5.2.4. Other internal Aspects of the Program	37
6. Measurement of Setup Parameter	39
6.1. Preparation Studies with a Mini-Sensor	39
6.1.1. Optimisation of the Waiting Time	39
6.1.2. Error Reduction by Measurement Statistics	45
6.1.3. Accuracy versus Measurement Duration	46
6.1.4. Measurement Direction	49
6.2. Parameter Validation with a 2S Sensor	52
7. Evidence studies with the Control Interface and 2S Sensors	57
7.1. I-V Measurement	57
7.2. I/V-t Measurement	57
7.3. Isolation Test	59

7.4. Surface Inspection	62
7.5. Edge Inspection	63
8. Conclusion and Outlook	65
References	67
A. Appendix	71
A.1. User Input Request	71
A.2. Demonstration of the Training Effect	72
A.3. Temporal Behaviour of the Leakage Current	73
A.4. "Load" Function for the Isolation Test	74

1. Introduction

Particle physics deals with the discovery of elementary particles and the investigation of their properties. The observation of particles and nuclei, which are collectively referred to as “particles”, produced in high energetic collisions is only possible thanks to sophisticated detectors. Within particle physics, the term “detector” often refers to an entire experiment consisting of several individual sub-detectors. An evidence of a particle is obtained by the interaction of the particles with the material in the active detection area of a detector.

In the past years, many particles have been discovered and their properties have been described more and more precisely. Many observed experimental results of the last decades can be described by the Standard Model (SM) of particle physics. However, there are still open questions within the SM and originating from models beyond it. To get closer to answers to these questions, various generations of particle physics experiments were built and performed all over the world. Especially particle colliders are suitable to reach the limits of known physics due to the high centre-of-mass energies they can reach.

Nowadays the largest and most powerful particle collider is the Large Hadron Collider (LHC) based at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland [1]. It collides proton beams at four collision points with a centre-of-mass energy, $\sqrt{s}$, of 13 TeV. At one of the collision points the multi-purpose CMS (Compact Muon Solenoid) detector is located [2]. To be able to study physics at even higher energies the LHC is upgraded to the so-called High Luminosity LHC (HL-LHC) [3]. The HL-LHC also requires an upgrade of the sub-detectors of the CMS experiment, the so-called Phase-2 upgrade. Within this programme, this thesis focuses on the corresponding upgrade of the CMS tracker system [4]. The core of the new tracker system will consist of two types of newly developed silicon detection modules based on two microstrip sensors or on one microstrip and one macro-pixel sensor. The so-called 2S and PS modules are able to measure the path of a particle passing the sensors of a detector module precisely. A detailed description of the LHC and the CMS experiment, as well as of the HL-LHC and the CMS Phase-2 tracker upgrade is given in Chapter 2 of this thesis.

In total 7680 2S and 5616 PS modules have to be produced for this tracker upgrade. The Aachen assembly centre will contribute 1000 2S modules during the serial production. An overview about the 2S module assembly and an explanation of the working principle of the used microstrip sensors can be found in Chapter 3. The assurance of the sensor quality is monitored by various tests. These tests can be performed at a Probe Station (PSt) test stand, which is presented in Chapter 4.

The quality control during the serial production has to be optimised with regard to a balance between the accuracy and the duration of the tests. This thesis presents the development of a control interface, which unifies in total five tests, three electrical measurements and two optical inspections, at the PSt test stand. A description of the graphical user interface and the implementation is provided in Chapter 5. For the electrical measurements a configuration of the setup is required. To determine optimal parameters a preparation study with a prototype sensor (mini-sensor) followed by a validation study with a 2S sensor is performed. The studies including

the final trade-off between time efficiency and accuracy are presented in Chapter 6. Finally the usability of various implemented functionalities of the control interface for several 2S sensors is presented in Chapter 7.

The thesis closes with a summary of the obtained results in Chapter 8. Moreover, a short outlook of possible improvements and further applications of the control interface is given.

2. The LHC and the CMS experiment

This thesis focusses on a contribution to the Phase-2 Tracker upgrade for the CMS experiment at the HL-LHC. Therefore, both, the LHC and the CMS experiment, are presented in the following. When considering particle colliders, besides the centre-of-mass energy of a particle beam, the number of particle collisions is of high interest. The decisive measured variable is the so-called luminosity. The maximal luminosity, also named instantaneous luminosity, indicates the number of collisions per second, while the integrated luminosity directly relates to the number of observed events [5]. In the case of the LHC the particles are bundled into so-called bunches when they are brought to collisions. Thereby many simultaneous particle collisions arise during the collision of two bunches. These multiple collisions are called pileup.

2.1. The Large Hadron Collider

The Large Hadron Collider (LHC) is a synchrotron-based particle collider located at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland [1]. It was built in the tunnel of the Large Electron-Positron Collider (LEP) and has a circumference of 26.6 km. Proton beams and heavy ions are brought to collisions with centre-of-mass energies, $\sqrt{s}$, of 13 TeV and 2.76 TeV, respectively, to study various particle physics models in depth [1]. Nowadays the LHC has an integrated luminosity of about 190 fb^{-1} and reaches a maximal instantaneous luminosity of 21 Hz/nb [6]. It is the largest and most powerful particle collider in the world.

The particles, counter-rotating in two separated rings, are forced to collide at four so-called interaction points. At each interaction point an experiment is placed to detect the particle collisions and their final states (Fig. 2.1). Namely these are the **A** Large Ion Collider Experiment (ALICE), the **L**arge **H**adron Collider **b**eauty (LHCb), the **A** Toroidal LHC Apparatu**S** (ATLAS) and the **C**ompact **M**uon Solenoid (CMS) experiments. ALICE is focused on the detection of heavy ion collisions and the investigation of the strong-interaction sector of the SM [7]. The LHCb experiment is a forward detector specialized on the detection of rare decays of B hadrons [8]. The last two experiments, ATLAS and CMS, are general-purpose detectors designed to detect various particles with high precision in spatial and momentum resolution especially of proton-proton collisions [9, 10]. This thesis focuses on the CMS experiment, which is further introduced in Section 2.2.

To generate hadron beams with the required centre-of-mass energy a sophisticated system of pre-accelerators is used. In each step the beam energy is successively increased. In the Long Shutdown 2 (LS2), which is currently ongoing, the pre-acceleration system is updated. In Fig. 2.1 a simplified scheme of this system is shown. For simplification purposes only the proton pre-acceleration is explained in the following. The procedure is analogue for heavy ions. The first step is the acceleration of negative hydrogen ions (H^-) in the LINAC 4¹ (LINear ACcelerator) to a centre-of-mass energy of 160 MeV [11]. Afterwards, the electrons are removed from the ion gas and the proton beam is injected into the Proton Synchrotron (PS).

¹New commissioned linear accelerator instead of LINAC 2 after LS2.

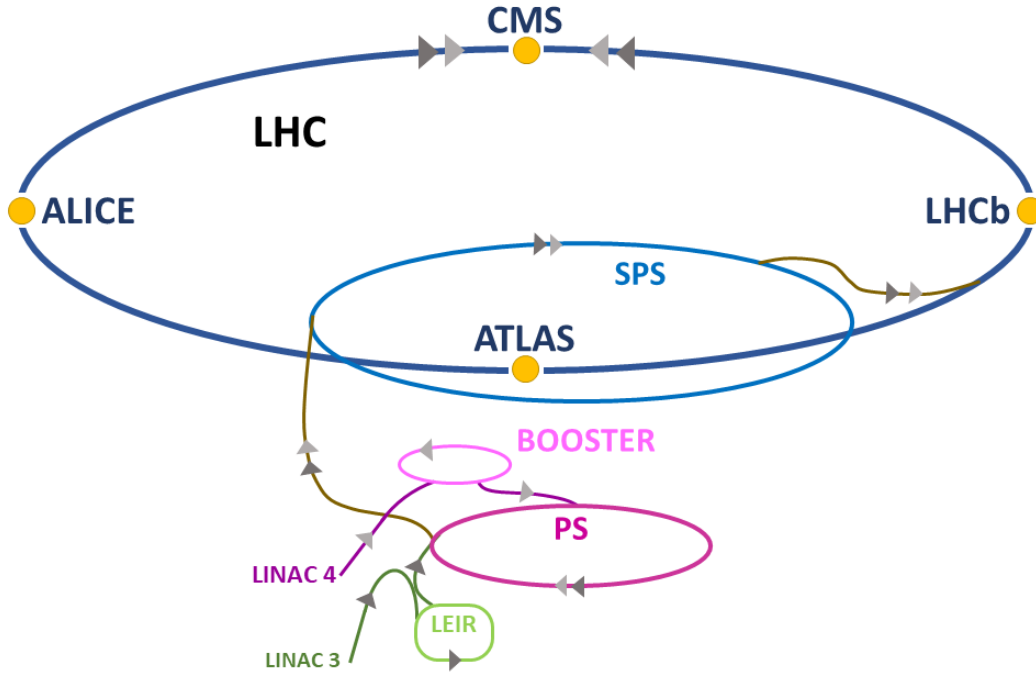


Figure 2.1: Schematic view of the LHC, its pre-accelerators and the location of the experiments ALICE, LHCb, ATLAS and CMS. LINAC 4 is the pre-accelerator for protons, LINAC 3 and LEIR are for the heavy ion acceleration. Simplified illustration according to Ref. [12].

The PS accelerates the proton beam to an energy of 2 GeV before its injection into the Proton Synchrotron Booster (PS Booster) and into the Super Proton Synchrotron (SPS) afterwards. Within the SPS, the beams are passing Radio Frequency cavities (RF cavities) to get bundled to so-called bunches. In total there are 2808 bunches per beam. It is the last step before the proton beam is injected to the LHC ring with an energy of 450 GeV and accelerated to the final energy of 6,5 TeV [13, 14].

The high energetic hadron beams are forced into the designated trajectory by superconducting magnets. The magnet strength is one main limitation factor of the reachable beam energy. In total 1232 dipoles and 4800 focussing and corrector magnets of higher order are installed in the LHC tunnel. They are made of NbTi Rutherford cables to reach a field strength above 8 T. Cryostats around the magnets working with superfluid helium ensure an operation temperature of 1.9 K [1].

2.1.1. The High Luminosity LHC

The LHC has been upgraded stepwise during the last years and will further be in the future. Higher energies and collision rates will provide significantly more accurate measurements due to higher statistics and will moreover facilitate the investigation of new physics. Especially the observation of rare processes at or below the recent sensitivity level will benefit from an upgrade. In total three Long Shutdowns (LS) are planned within the lifetime of the LHC. In the beginning in 2011-2012 in Run 1 the LHC reached a centre-of-mass energy of 8 TeV, an integrated luminosity of 30 fb^{-1} and a maximal instantaneous luminosity of 7.7 Hz/nb [6]. In Run 2 after the LS1 in 2013-2014 the LHC reaches a centre of mass energy of 13 TeV and thus comes

close to its design parameter of 14 TeV. Moreover, in Run 2 an integrated luminosity of 193 fb^{-1} and a maximal instantaneous luminosity of 21 Hz/nb is reached by reducing the bunch distance from 50 ns to 25 ns. The LS2 upgrade phase is currently ongoing. For Run 3 in 2022-2024 it is planned to achieve a centre of mass energy of 13.6 TeV to 14 TeV and to almost double the integrated luminosity to 350 fb^{-1} by a higher number of particles per bunch. An instantaneous peak luminosity of 20 Hz/nb will be obtained. From 2025 to 2027 the LS3 will take place, where the biggest upgrade of the LHC is planned. Various parts of LHC systems have to be upgraded to achieve the ambitious future performance goals. After Run 2 e.g. the inner triplet quadrupoles and their corrector magnets, radiation sensitive electronics and the quench protections system (QPS) will exceed their radiation tolerance. Moreover, the cryogenics, the collimation system and the QPS will need a modernisation to the latest technology [3, 15]. Afterwards, the integrated luminosity will reach 3000-4000 fb^{-1} and the instantaneous peak luminosity will reach 50-75 Hz/nb , which is 5 to 7.5 times of the nominal luminosity [13]. Therefore the new phase is called High Luminosity LHC (HL-LHC) [15, 16].

2.2. The Compact Muon Solenoid experiment

The CMS detector consists of a cylindrical multi-purpose detector installed around the beam axis of the LHC. It is 21 m long, 15 m wide and 15 m high. Its name originates from the huge solenoid magnet it is built around. The CMS experiment is designed to study the SM, e.g. it contributed to the successful search for the Higgs boson, as well as to investigate new physics like extra dimensions or dark matter [2, 17].

The CMS detector is composed of different sub-detectors (Fig. 2.2). To be able to give a precise description of the detector's structure the CMS coordinate system with Cartesian as well as cylindrical coordinates is used. The centre of the coordinate system is the interaction point. The z direction is defined along the beam axis, x is the horizontal direction perpendicular to z and y the vertical direction perpendicular to z . The radius r of the cylindrical coordinates is perpendicular to the z -axis. ϕ describes the angle of r to the x -axis within the x - y plane. The angle between the y -axis and the z -axis is η . From the inside to the outside, it is structured as follows.

The beam pipe is directly surrounded by the **silicon pixel detector**. It has to be mentioned, that the original CMS pixel detector was replaced in 2016/17 with an upgraded pixel system, referred to as CMS Phase-1 pixel detector [18]. The Phase-1 pixel detector is optimised to cope with the high instantaneous luminosity in Run 2 and Run 3. The 1,856 installed pixel sensor modules provide in total 124 million readout channel resulting in a very high granularity. The silicon pixel detector consists of four cylindrically arranged module layers in the barrel and three disks at the end caps. This geometry facilitates the reconstruction of very short living particles and their secondary vertices with high precision. Moreover, it is important for the formation of seed tracks for the outer track reconstruction and the high level triggering [2, 19].

The **silicon strip detector** is located around the silicon pixel detector. It is divided into four regions: the Tracker Inner Barrel (TIB) and Disk (TID), the Tracker Outer

Barrel (TOB) and the Tracker End Caps (TEC) (Fig. 2.3). The detector consists of 15,148 sensor modules, which are covering a sensitive area of about 198 m^2 . The detector modules consist of a silicon strip sensor, its mechanical support structure and readout electronics. In total 15 different sensor geometries are used to fit all requirements in the different places of the tracker [2, 20].

The next layer of the CMS detector is responsible for measuring particle energies. First the barrel part of the **Electromagnetic Calorimeter** (ECAL) is installed at a distance of 1.5 m to the beam pipe. The ECAL is a hermetic homogeneous calorimeter made of lead tungstate crystals with a high density. Electromagnetic interacting particles like electrons and photons are stopped completely. Their energy is determined by avalanche photodiodes which are measuring the scintillation light emitted by the ECAL crystals. Therefore, the ECAL has a fine granularity, is radiation tolerant and fast in measuring [2].

At a distance of 1.77 m to the beam axis the barrel part **Hadronic Calorimeter** (HCAL) is placed. The HCAL measures the energy of hadrons, particles composed of quarks and gluons, such as protons, pions or kaons, by inelastic interaction with an absorber material. Moreover, it is very important for the measurement of missing transverse energy, which indicates neutrinos or the existence of exotic unknown particles. The HCAL consists of four calorimeters: the hadron barrel, the endcap, the outer and the forward calorimeter. The HCAL is a so-called sampling calorimeter. It is structured in alternating layers of brass and/or steel plates, the absorber, and plastic scintillators, which detect the resulting hadronic showers. By this setup a particle's position, energy and arrival time are measured [2, 21].

The **magnet** used in the CMS experiment is a solenoid electromagnet made of superconducting niobium-titanium wires which reaches field strengths up to 3.8 T. It is 13 m long and has a diameter of 6 m. The magnet encloses the pixel detector, the HCAL and the ECAL. Due to the high magnetic field, the paths of charged particles, flying through the detector, are bent. The resulting curvature of a track is an accurate measure for the momentum of a particle [2].

The outer layer of the CMS experiment consists of the **muon chambers** giving the detector its name. Because muons interact only very rarely with the calorimeters, they are identified in the outermost region of the detector. In total 1400 muon chambers are installed: 250 Drift Tubes (DTs), 540 Cathode Strip Chambers (CSCs) and 610 Resistive Plate Chambers (RPCs). The chambers are enclosed in an iron flux-return yoke, which is magnetized by the solenoid. The muon system is robust and able to filter out background noise. It also gives an important contribution to the trigger system described in the next paragraph [2].

Another fundamental element of the CMS experiment is the **Trigger System**. Due to the high bunch crossing rate of 40 MHz, which corresponds to roughly one billion proton-proton interactions per second, it is an important part of the CMS experiment. Far more events are produced than can be read out, stored and analysed. To select only potentially interesting events and reduce the rate to a few thousand events per second, an elaborated two-stage trigger system is implemented. The first stage is the hardware-based Level-1 trigger. With a maximum output rate of 100 kHz data is filtered and temporarily stored in a wholly automatic process. The

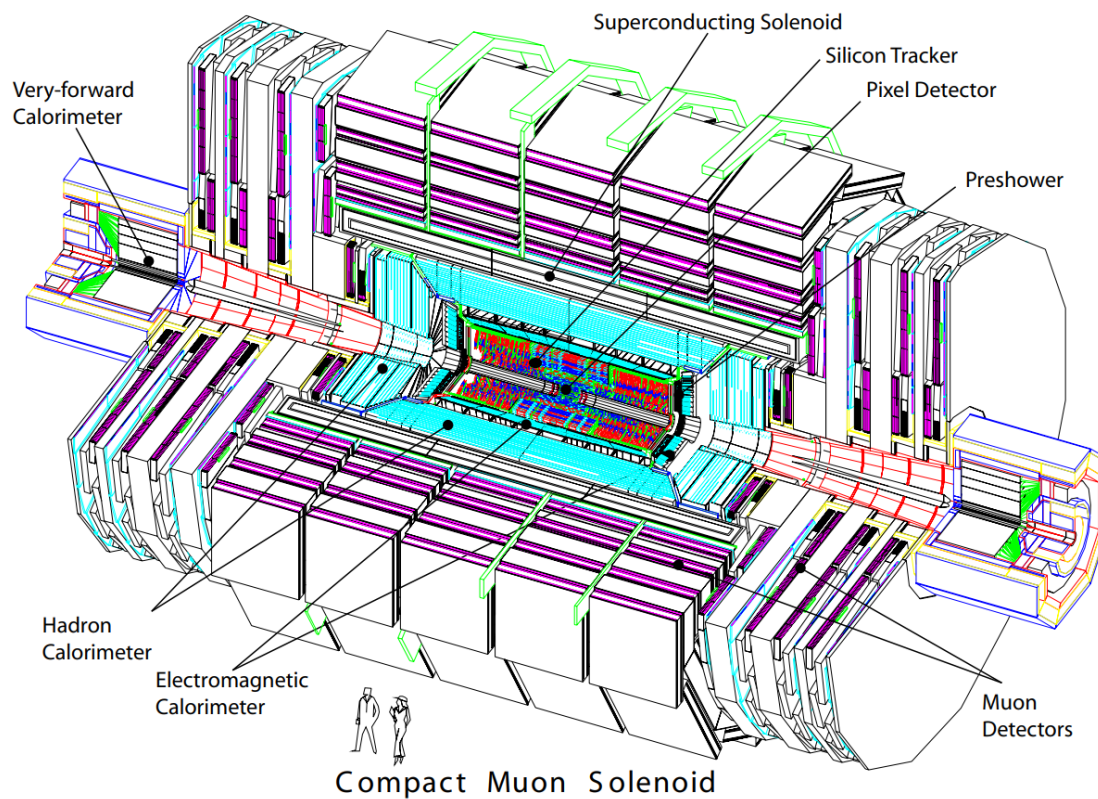


Figure 2.2: A perspective illustration of the sub-detector structure of the CMS experiment [2].

second stage is the software-based high-level trigger (HLT). Its algorithm assimilates and analyses information from various parts of the detector to recreate the entire event and decide if the data is stored permanently. It features an output rate of 1 kHz [2, 22].

2.2.1. The CMS Phase-2 Tracker Upgrade

In the course of the HL-LHC upgrade the CMS detector will be subject to a comprehensive revision, too, to meet the new requirements coming with the higher instantaneous luminosity in Run 3: a higher collision rate, a higher number of pileup and much higher radiation. From the outside to the inside of the CMS detector the following upgrades are performed in the LS3 [4]. Within the muon system some parts of the front-end electronics will be replaced by a more radiation tolerant version. Moreover, the system will be enhanced by improved resistive plate chambers and gas electron multiplier chambers. Within the barrel region of the HCAL the brass absorber plates and plastic scintillator layers will be replaced by silicon photomultipliers. The ECAL front-end electronics will be upgraded by new front-end boards which allows a finer granularity in the crystal readout. The endcaps of the HCAL and ECAL will be replaced both by a new electro-magnetic and hadronic sampling calorimeter, which is based on silicon pad sensors.

Furthermore, the tracker, including the pixel detector, will be replaced by a new system, the so-called Phase-2 tracker upgrade [4]. The new tracker systems will consist

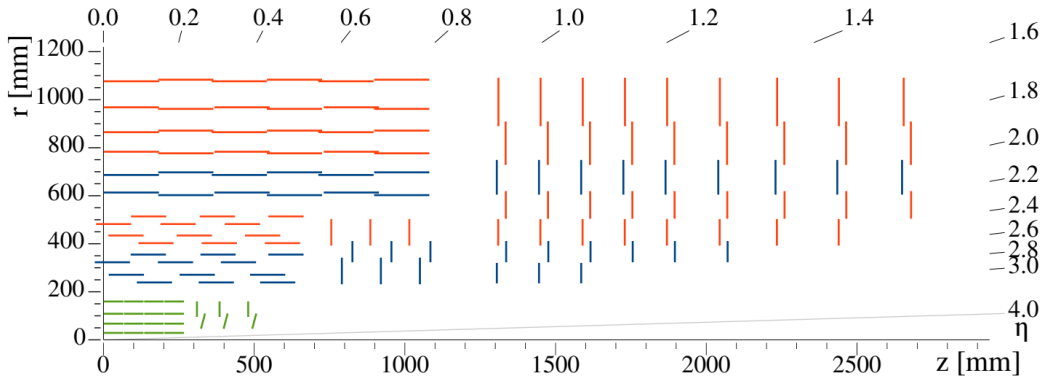


Figure 2.3: Schematic illustration of one quarter of the Phase-1 CMS tracking system in r - z view. Each line represents a detector module. The pixel detector is shown in green. The strip detector modules are shown in red and blue [4].

of two parts: The Inner Tracker, which corresponds to the old pixel detector, and the Outer Tracker. Target values of 140 to 200 collisions per bunch crossing require a high channel density to keep the channel occupancy below the per cent level (per mill level) in the Outer Tracker (Inner Tracker). This high level of pileup necessitates a robust pattern recognition and an improved two track separation compared to the present tracking system. The radiation tolerance is another important requirement: the expected fluences will reach up to $2.3 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ ($9.6 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$) in the Inner Tracker (Outer Tracker), with n_{eq} referring to the 1 MeV neutron equivalent fluence. In addition, the tracking system will contribute to the CMS Level-1 trigger for the first time. Trigger data at a rate of 40 MHz will be provided due to on-detector data reduction [23]. This is facilitated by the so-called Pixel Strip (PS) and Strip Strip (2S) modules (Ch. 3). Within the Inner Tracker silicon pixel modules are used and within the Outer Tracker silicon modules with microstrip and macro-pixel sensors, thus 2S and PS modules, are used [4]. As this thesis is concerned with the 2S modules in the Outer Tracking system, both will be described in more detail in the following.

The structure of the new Phase-2 tracker (Fig. 2.4) is based on the old design but with some significant changes. Only two types of modules are used in the Outer Tracker: PS and 2S. The idea is an on-detector data reduction to identify and reject uninteresting events with low transverse momentum [23]. This is called the p_T module concept. Both module types work based on this p_T concept (Sec. 2.2.2). The Outer Tracker is divided into three main regions: The Tracker Barrel with PS modules (TBPS) is the innermost layer around the Inner Tracker. As the name indicates it is composed of PS modules. The TBPS consists of a barrel part and rings at the endcaps. The modules within the rings are inclined and thus enable that particles straight from the collision point impact perpendicular the module's surface centre. After the TBPS three layer of 2S modules follow, the so-called Tracker Barrel with 2S modules (TB2S). The Tracker Endcap Double-Discs (TEDD) each consist of five double discs made of four module layers of the same type, 2S or PS, mounted with an overlap to cover the whole endcap area. By this improved geometric structure the new tracker will have a better granularity, an increased acceptance from $|\eta| = 2.5$ to $|\eta| = 4.0$ and thus provide a better resolution.

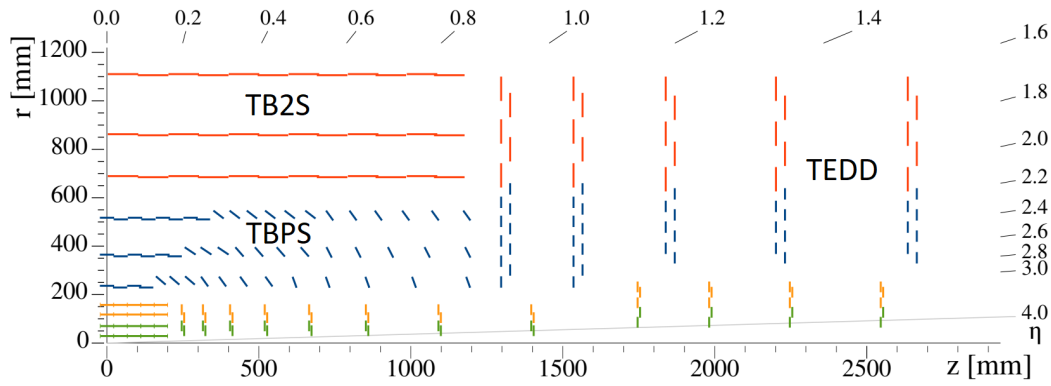


Figure 2.4: Schematic illustration of one quarter of the Phase-2 CMS tracking system in r - z view. Each line represents a detector module. The Inner Tracker is shown in yellow and green. The Outer Tracker PS modules are indicated in blue and the Outer Tracker 2S modules in red [4].

2.2.2. The p_T Module Concept

The p_T module concept enables a contribution of the Outer Tracker data to the Level-1 trigger (Fig. 2.5). If a charged particle passes the CMS detector, its path is bent in the magnetic field of the CMS solenoid. The strength of the curvature of the track is a measure for the particle momentum. Interesting events for physics analyses usually contain high transverse momentum tracks. To get fast information about the particle's transverse momentum each detector module consists of two silicon sensors placed parallel above each other with a distance of a few millimetres. The strips of both sensors are oriented parallel to each other. Each PS module consists of one strip and one macro-pixel sensor to obtain a fine segmentation close the interaction point in the z coordinate (r coordinate) in the barrel (endcaps) [4]. The macro-pixels are $1467 \mu\text{m}$ long with a pitch of $100 \mu\text{m}$ while the strips are 5.3 cm long with a pitch of $90 \mu\text{m}$. If a module is hit by a particle, the front-end chip on the module calculates a window in which the particle passage is expected in the second sensor. The width of the window depends on a predefined threshold on the transverse momentum. To reduce the incoming data stream of 40 MHz by roughly one order of magnitude, a p_T threshold of $2\text{-}3 \text{ GeV}$ is chosen. Particles with a lower momentum are ignored. If the readout logic registers the hit in the second sensor within the window, it generates a so-called "stub". The stubs are formed to tracks by the back-end electronics and then combined with the information of the calorimeters and the muon chambers. By this the signal for the Level-1 trigger to initiate a readout of the full event information is generated. The rate of the full readout is about 750 kHz [4].

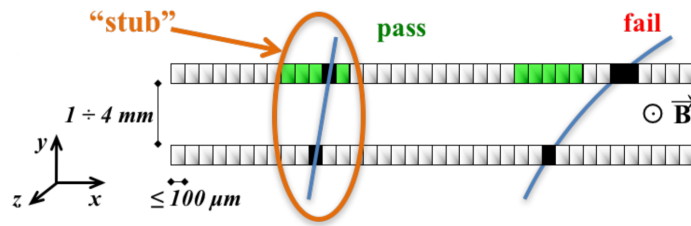


Figure 2.5: Schematic illustration of the p_T module concept demonstrated by two particles (blue tracks) with different p_T passing through the sensors of a detector module. A cut through both sensors in the plane perpendicular to the module's surface is shown. The black boxes indicate a strip, which is hit by a particle. The green boxes represent the stub window, where the hit in the top sensor is expected for a high transverse momentum particle [4].

3. 2S Modules

The main components of the 2S modules are two silicon microstrip sensors. Silicon sensors in general, and microstrip sensors in particular, are widely used in various particle physics experiments.

3.1. The Silicon Sensors

A big advantage of silicon sensors is that they are made of a stable, compact material comparing to gas or liquid based detectors, which enables the development of detectors with a high spatial resolution in the order of ten micrometers. Moreover, the high mobility of the charge carriers in the semiconducting silicon results in an electron-hole collection time below 10 ns [24]. Thus silicon based detectors have an excellent time resolution, which is optimal for the usage in the LHC with a bunch crossing rate of $1/25 \text{ ns}^{-1}$. In addition silicon is a widely used basic material for microelectronics circuits. Hence the sensor production benefits from the silicon wafer industry with regard to access to very pure silicon material, precise alignment machines, clean room technologies and more [25].

3.1.1. Basic Principle of a Silicon Detector

A silicon detector is a solid-state detector based on semiconducting silicon. The detection mechanism is based on the working principle of a semiconductor diode with the p-n junction operated in reverse bias mode. A voltage is applied in such a way, that the resistance of the diode is maximal (ideally infinite). A so-called space charge region (SCR) or depletion zone is formed at the border of the n- and p-doped silicon. Mobile charge carriers are recombined or drifted to the electrodes due to the electric field, thus an isolating region is created. The applied bias voltage enlarges the width of the depletion zone by forcing more free charge carriers apart. The relation between the bias voltage V_{bias} and the width w of the SCR can be described by [25, 26]:

$$w = \sqrt{\frac{2\epsilon_0\epsilon_{\text{Si}}V_{\text{bias}}}{qN_A}}. \quad (3.1)$$

Here, the free space permittivity is ϵ_0 , the dielectric constant of silicon is ϵ_{Si} , the electric charge is q and N_A is the doping concentration of the junction².

If a charged particle passes the sensor, electron-hole pairs are produced in the SCR. Due to the applied electric field the electrons drift to the anode and the holes to the cathode. This way a measurable signal is induced [24]. The SCR corresponds to the sensitive detector volume. Therefore it is aimed to maximise it to the whole sensor volume. The necessary voltage is called “full depletion voltage”. If Eq. 3.1 is solved for V_{bias} , and the width is substituted by the sensor’s thickness d , one can get an expression for the full depletion voltage V_{fd} :

²This relation holds for a n-in-p doped sensor. It is assumed, that the acceptor concentration of the bulk, N_A , is much bigger than the donator concentration N_D : $N_A \gg N_D$. Therefore the doping concentration of the junction can be approximated by N_A [26].

$$V_{\text{fD}} = \frac{d^2 q N_A}{2 \epsilon_0 \epsilon_{\text{Si}}}. \quad (3.2)$$

If the voltage is increased further, a so-called breakdown can be observed where the leakage current of the sensor increases dramatically³. The corresponding voltage is called breakdown voltage V_{break} .

Another important aspect is the sensitivity of the silicon sensors to outer conditions like humidity and temperature. A high humidity during the leakage current measurement can result in a higher leakage current and a lower breakdown voltage as silicon is hygroscopic [24]. Moreover, the dependence of the leakage current I on the temperature T can be described by [24, 27]:

$$I(T) \propto T^2 \exp\left(-\frac{E_g}{2k_B T}\right). \quad (3.3)$$

Here, k_B is the Boltzmann constant and E_g is the energy gap between the conduction and the valence band of the semiconductor.

3.1.2. The 2S Microstrip Sensors

A silicon microstrip sensor is a subtype of a semiconductor sensor. A microstrip sensor consists of N identical, one-dimensional structured strips made of high doped silicon (Si). This arrangement corresponds to a row of diodes positioned next to each other, which generates a fine segmentation and therefore a spatial resolution. The strips can be connected to the readout electronics. This layout (exemplarily shown in Fig. 3.1) allows a very accurate track reconstruction in the one dimension perpendicular to the strips. Another advantage is the simple readout, because only N readout channels are needed⁴ and the electronic contacts can be placed at the edge of the sensor.

The 2S sensors are made of n-in-p doped silicon (n-doped strips in p-doped bulk material), due to its radiation tolerance. Figure 3.2 shows a picture of a 2S sensor with a zoom to its upper left corner. The sensor's active area of $9.1440 \times 10.0548 \text{ cm}^2$ is divided into two halves with 1016 strips each. The strips are 5.274 cm long and have a width of $22.5 \mu\text{m}$ and a pitch of $90 \mu\text{m}$. The sensors have an active thickness of $290 \mu\text{m}$ which results in a depletion voltage of about 300 V according to Eq. 3.2. The strips are capacitively coupled (AC coupling) by a silicon oxide (SiO_2) isolation layer with metal strips on the top [24]. Each strip is equipped with a wire bond pad for the electrical contact.

The sensor's active area is surrounded by three rings. First a bias ring to accommodate the contact of each strip (DC pad) to the ground potential via polysilicon bias resistors. The second one is a guard ring to ensure the high voltage stability. At last

³This breakdown of the current can be explained by two models for breakdown types: first the "avalanche breakdown", due to charge multiplication in collisions with the lattice. Second the "Zener breakdown", where electrons pass from the valence to the conduction band due to the tunnel effect [24]. However, the observed breakdowns under real production conditions as considered in this thesis, probably origins of damages and pollution on the sensors' surface.

⁴For a pixel sensor N^2 readout channels are needed.

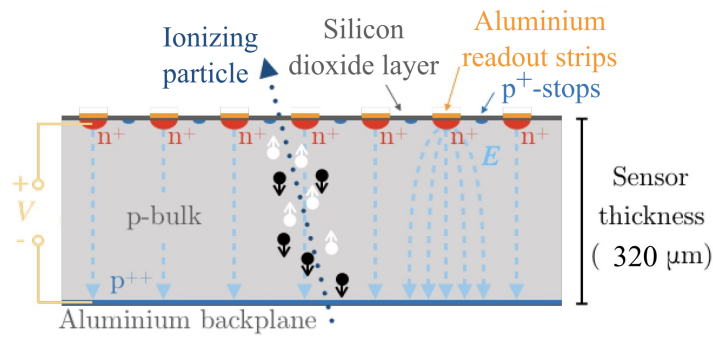


Figure 3.1: Illustration of a vertical cut through a n-in-p doped silicon sensor. n-doped strips are shown in red, p-doped silicon bulk material in grey and the backplane in blue. The readout strips are shown in orange. The electrons and holes produced by a passing particle are indicated by white and black circles [28]).



Figure 3.2: Picture of a 2S sensor with a zoom to the upper left corner (according to [27]).

a highly p^+ doped edge ring is used to protect the sensor from damage originating from wafer dicing [4]. Moreover the outermost ring holds various information, e.g. about the sensor ID and the strip numbers.

During the usage of the sensors in the HL-LHC they will be exposed to high radiation. Thus a good quality of the sensors with regard to charge collection (CC), noise behaviour and strip isolation before and after irradiation must be ensured. A very good parameter to monitor the sensor's quality is its leakage current. Especially the generated noise and the module heating are connected with the leakage current. Moreover, it is very sensitive to contamination and mechanical damages like scratches. Due to these two factors it is also important to monitor the cleanliness of the sensor surface directly during the module assembly process.

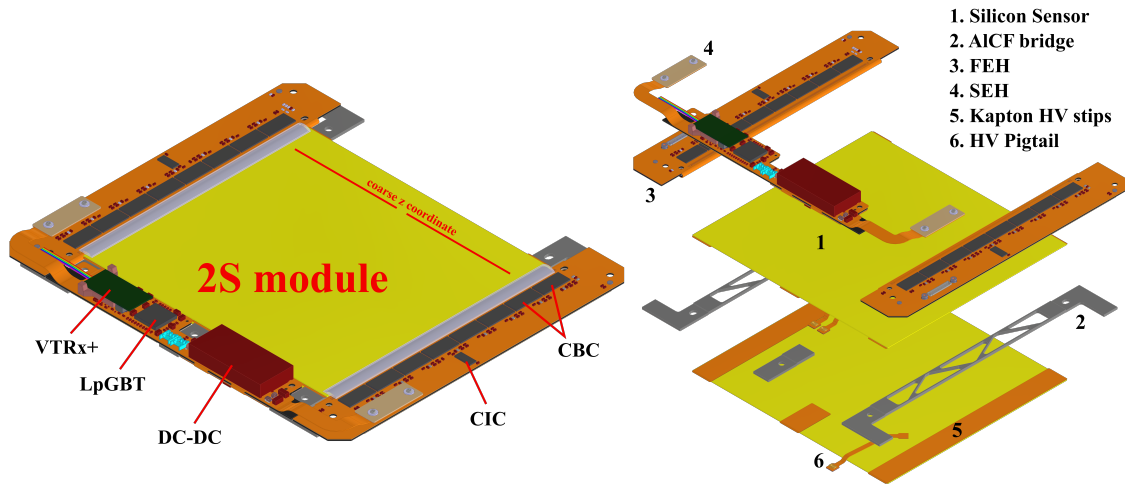


Figure 3.3: Three dimensional illustration of an assembled (left) and exploded (right) view of a 2S module [29].

3.2. 2S Modules

The 2S modules together with the PS modules are important components of the new Outer Tracker for the CMS Phase-2 upgrade. A schematic illustration of a fully assembled module and an exploded view of it can be seen in Fig. 3.3. A module consists of a pair of microstrip **silicon sensors** (Fig. 3.3, (1.)). In the following, the most important components, beyond the sensors, are introduced.

To keep the sensors apart three **AlCF Spacers**, called “bridges”, are glued between them (Fig. 3.3, (2.)). The bridges are the main support structure for the whole module. Moreover, the bridges provide holes for the integration of the modules into the whole tracker system. In addition they are used for the positioning during the module assembly. The bridges are made of Aluminium Carbon Fibre (AlCF) composite material, which provides mechanical strength as well as a good thermal conductivity [4].

There are two **Front-End Hybrids** (FEH) wire-bonded to the sensors at opposite sides (Fig. 3.3, (3.)). The sensor’s strips are only half as long as the full length of the sensor, therefore one FEH reads out half of the data from both sensors. This simultaneous readout is important to identify stubs within the p_T module concept (Sec. 2.2.2). Moreover, the FEHs manage the whole signal processing. The signal induced by an ionising particle passing the active sensor area is measured in total by eight Front-End ASIC⁵ CMS Binary Chips (CBC) per FEH. Therefore each CBC reads out 127 channels from each top and bottom sensor. The data from the eight CBCs is processed by one Concentrator Integrated Circuit (CIC), where it is buffered, aggregated and formatted. [4].

At a side of the module between the FEHs one **Service Hybrid** (SEH) is mounted (Fig. 3.3, (4.)). It manages the back-end connections and the serialization of both FEHs’ data streams. The data from the CICs on the two FEHs is serialized via a

⁵Application-Specific Integrated Circuit (ASIC)

Low power GigaBit Transceiver (LpGBT) ASIC. The LpGBT sends and receives data to/from an optoelectrical transceiver, the Versatile TRansceiver plus (VTRx+). From there the data is processed by the back-end readout. Moreover, the LpGBT is responsible for controlling the FE ASICs. The SEH is also responsible for the power supply to all readout and data transmission components and for the distribution of the applied high voltage. A 2-step DC-DC conversion scheme provides the supply voltage for the VTRx+, the LpGBT, the CIC and the CBCs of 1.25 V. The VTRx+ needs an additional voltage of 2.55 V. Two DC-DC converter ASICs, the buck Point Of Load 12V and 2.5 V input voltage converter (bPOL12B and bPOL2V5), convert the input voltage of 11 V to the desired low voltages [4].

Three HV isolating **Kapton strips** are placed between the sensor's backplanes and the bridges (Fig. 3.3, (5.)). The strips are made from 25 μm thin Kapton MT foil with a dielectric strength of around 0.2 kV/ μm to protect the sensitive electronics of the module against the sensor bias voltage. Moreover, the MT foil provides better thermal conductivity for dissipating the heat from the sensors than general Kapton foils [4].

On the backside of the sensors so-called **HV pigtails** are glued (Fig. 3.3, (6.)). These small Kapton flex tails apply the bias high voltage coming from the SEH to the sensors. One of the two sensors of a 2S module additionally has a temperature sensor integrated into the Kapton tail [4].

3.2.1. 2S Module Assembly

In total 7680 2S and 5616 PS modules will be produced for the Phase-2 tracker upgrade. The production will take place in various institutes located in Germany, Belgium, USA, Pakistan and India. The Aachen assembly centre will contribute 1000 2S modules. Before the series production can start, the recent prototyping phase has to be completed. During the prototyping the first fully assembled modules with all final components are built. This way the assembly centres can optimise their production conditions. The construction is mostly a manual jig-based assembly with robotic assistance in certain steps.

Several complex steps are required for the assembly of a 2S module. In the following a short recap of the planned assembly process during the serial production at the Aachen assembly centre is provided. A detailed description of the prototype assembly can be found in Ref. [27].

During the series production it is important to focus on a time-efficient assembly process. After the delivery of the 2S sensors to the institute the first step is the **gluing of the Kapton strips** to the backside of the sensors using a "*Kapton gluing jig*" and a robot combined with a volumetric dispenser. The second step is the **glueing of the pigtails**. Afterwards, the **pigtails** have to be **bonded and encapsulated** in order to achieve a reliable electric connection between the sensor backside and the pigtails. The next step is the **bare module assembly**. With the help of the "*Sensor gluing jig*" the AICF bridges are glued onto the Kapton strips between the backsides of the two sensors. For the success of the p_T module concept this step has to be precise to 400 μrad [4]. After the bare module assembly the hybrids have to be mounted with the "*hybrid gluing jig*". The SEH is plugged into the FEHs and then both are

glued to the bare module. For the subsequent wire **bonding of the hybrids** a precise alignment of the SEH and FEHs is important. At last the wire bonds have to be encapsulated.

To ensure the sensor quality during the assembly process test measurements are performed after several assembly steps. The five possible tests are presented as a short summary in the following, a more detailed description of the setups can be found in the next chapter 4. For the **I-V measurement** the leakage current of a sensor is measured while the supplied voltage is ramped from -1000 V to 0 V . It is the basic measurement for the quality assurance of the 2S sensors. The second one is the **I/V-t measurement**, where a desired voltage is applied to the sensor and the temporal behaviour of the leakage current is measured for a longer period of time. This is an optional measurement, which is not performed regularly within the test procedure, but can be used to further investigate irregularities of the sensors behaviour. The third one is the **Isolation Test**, also called HV test. It is only performed after the assembly of the Kapton strips and pigtails. For the Isolation test a high voltage is applied to the pigtails and it is stepwise increased up to 1000 V to control the quality of the Kapton isolation. The last two tests are the **Surface Inspection** and the **Edge Inspection**. Both are optical inspections to observe damages or pollution of the sensors.

During the prototyping, and probably also during the following preproduction, always a **reception** is done. Therefore a leakage current measurement and a surface inspection is done after the delivery of the 2S sensors. Within the serial production the quality of the sensors is tested first after the gluing of the Kapton strips and the gluing, bonding and encapsulation of the pigtails. Therefore an isolation test, is done as well as an I-V measurement, a surface inspection and an edge inspection for each sensor. It is still under investigation which tests are performed within the serial production after the following bare module assembly and the glueing and bonding of the hybrids. Spot check measurements of the I-V curves are probably performed. During the prototyping phase several tests are done after each assembly step. Furthermore, the I-V measurement and Isolation Test data can be compared to the leakage current measurement directly after the production at the manufacturer via a database. Thus the quality of the 2S sensors is ensured and it is guaranteed that only intact sensors are used for the further module assembly.

3.2.2. Sensor Quality Standards and Quality Assurance

The fully assembled modules have to fulfil several specifications regarding to dimensional specifications, other mechanical specifications (e.g. strength, reliability), electrical (HV/ground) and electronic readout requirements. For this thesis, the electrical requirements for the sensors and the measurement conditions are particularly relevant.

The 2S sensors are manufactured by Hamamatsu Photonics K. K. (HPK). Before the delivery to CERN, the sensors are characterised by HPK. From CERN the sensors are distributed batchwise to the Sensor Quality Control (SQC) centres. The SQC centres characterise the sensors by a per-batch-qualification to ensure that delivered sensors

are within the specification. That means about 5-10 % of the sensors of each delivered batch are controlled. Afterwards, the sensors are sent to the module assembly centres where they are characterised again before the module assembly.

All sensor quality information from HPK, the SQC centres and the module assembly centres as well as the tracking information about the sensors' locations are collected in a central CMS Construction Database (ConstrDB). Therefore it is possible to check all quality measurement results for consistency during the whole history of the sensors.

The sensors must fulfil in general the following **electrical requirements** at a room temperature of 22 – 23°C and a relative humidity (rH) lower than 30% [30]:

- $V_{fD} < 350 \text{ V}$,
- $V_{break} > 800 \text{ V}$,
- $I_{600} < 7.25 \mu\text{A}$, where I_{600} is the leakage current at $V_{bias} = 600 \text{ V}$,
- $I_{800} < 2.5 I_{600}$,
- $|\langle \Delta I_{600} \rangle / \langle I_{600} \rangle| < 20\%$, long term stability over 48 h, with the mean leakage current fluctuation $\langle \Delta I_{600} \rangle$ and the mean leakage current $\langle I_{600} \rangle$.

The I-V curves of the are measured to ensure these quality standards. It had to be mentioned, that the last point, the long term stability, is not controlled by default at the assembly centres. Moreover, the sensors must withstand standard handling procedures such as placement on probe stations and assembly jigs. The surface of the sensors must stay clean, free of dust and other contaminations. Scratches on the surface or damages at the edges of the sensors must be avoided. All of this can deteriorate the sensors' quality. It is important that during the handling for shipping and assembly the sensors' leakage current stays stable, the breakdown voltage is not reduced and no additional bad strips⁶ of an assembled module are developed.

⁶Strips that cannot be read out due to high noise or missing connection to the readout.

4. The Probe Station Test Stand

Every transport and handling of the 2S sensors is a potential risk to their performance. At the Aachen assembly centre the module assembly takes place in two different clean rooms. Moreover various jigs are used into which the sensors or bare modules are inserted. Therefore it is reasonable to verify the sensors' quality after several assembly steps. The core of the sensor quality measurement test stand is a probe station. There, both the leakage current measurement and the visual inspection take place.

4.1. Experimental Setup

The main component of the test stand is the Probe Station (PSt) PA 200 manufactured by FORMFACTOR [31]. In Fig. 4.1 a picture of the test stand can be seen, in which the different components are labelled by numbers (1-15). In the centre of the PSt is the sample holder (2), the so-called chuck, which is mounted on a x - y - z stage, to enable a three dimensional movement of the chuck. Its navigation can be controlled via an external control panel (3) or via a PC using the PSt software Velox 2.4 by FORMFACTOR. The samples (4), thus the 2S sensors, can be fixed via vacuum applied by a vacuum pump (5). Above the sample holder a microscope (6) is mounted. It is also movable via the controller or the PSt software independently from the chuck. A live recording of the microscope can be observed on a screen (7). The sensors placed on the chuck are contacted via a tungsten needle (8) with a tip radius of $7\text{ }\mu\text{m}$. The needle is held by the arm of a three dimensional positioner. It enables a precise contact due to a micrometer screw for each spacial direction used for the manual positioning. The positioner itself is fixed with vacuum to a table. The whole PSt setup is placed in a light-tight box (9), to protect the sensors from light during the electrical measurements.

To supply the (negative) bias voltage a Keithley 2410 high voltage power supply (10) by Tektronix [32] is connected to the PSt. The connections of the 'high' and 'low' output depend on the required test according to the assembly step. The management of the measurements is done via a LabVIEW software ((11), Ch. 5). Therefore the power supply is connected via a National Instruments (NI) GPIB cable to an Intel NUC⁷ (Next Unit of Computing) computer (12) [33].

Next to the microscope a Sony alpha 6400 camera [34] with a Sony FE 90mm/F2.8 Macro G OSS lens [35] (13) for the visual inspection is mounted. As it is attached to the microscope support structure; its position can also be adjusted via the control panel. The captured images are sent via USB to the Intel NUC. There they are shown in the LabVIEW software.

In the PSt box five photo diodes, two temperature sensors (Pt1000) and one humidity sensor (hih4000) by Honeywell [36] are placed (Fig. 4.2, labelled by letters (a-g)) to monitor the light incidence, the temperature (a) and the relative humidity (rH) (a) especially during the electrical measurements. The light sensors are located close to different possible light sources, namely the lid of the PSt box (b), the internal lights (c), the fibre optics of the microscope (d) and the camera display (e). Addi-

⁷It will be replaced by a more powerful computer in the future.



Figure 4.1: a) The Probe station test stand with associated components and b) a closer look to the centre of the test stand.

tionally one light sensor is placed in the middle of the PSt box side (f) to measure general light sources. Moreover, a temperature sensor (g) is stuck directly on the chuck to measure its temperature. This is a temporary solution, a better solution for the temperature measurement of the chuck still has to be found. The light, temperature and humidity sensors are connected to a Keithley 2700 multimeter/data acquisition system (14) by Tektronix [37], which are read out by LabVIEW. The humidity sensor is additionally connected to an NI multifunction I/O device [38] to supply an operation voltage of 5 V. The multimeter is connected via a GPIB cable to the Intel NUC computer. The measured data of all the sensors are displayed in the LabVIEW interface. All connections are presented in Fig. 4.3 within the next section.

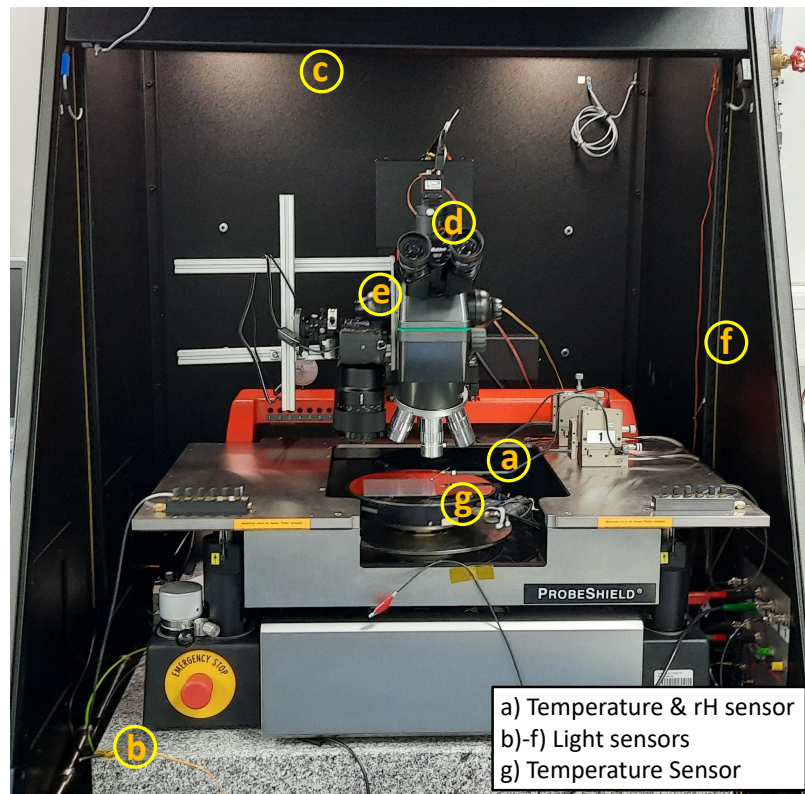


Figure 4.2: The positioning of the sensors for the monitoring of the environmental conditions in the PSt.

4.2. LabVIEW Setup

This thesis is mainly about the mentioned LabVIEW (LV) control interface installed on the Intel NUC computer. To simplify and automate all measurements at the probe station test stand, a central LabVIEW program including a graphical user interface was developed. The LV control program is connected to multiple components of the test stand. In Fig. 4.3 a map of the connections between the LV program and the test stand components can be seen. The LV program controls the HV power supply, reads data from the multimeter and starts various python programs running on the NUC for several control measurements, e.g. the picture taking with the camera for the surface inspection (Ch. 5). The movement of the microscope and chuck is controlled with the Velox PSt software via the control panel. It has to be mentioned that the PSt software is not connected to the NUC computer due to network security reasons related to the operating system of the PSt computer.

4.3. Electrical Measurements

Three different electrical tests can be performed at the probe station test stand. For all electrical tests the PSt lid must be closed to avoid external light influencing the measurements. Moreover the probing space is flushed with dry air to reach the required limit on the relative humidity $rH < 30\%$.

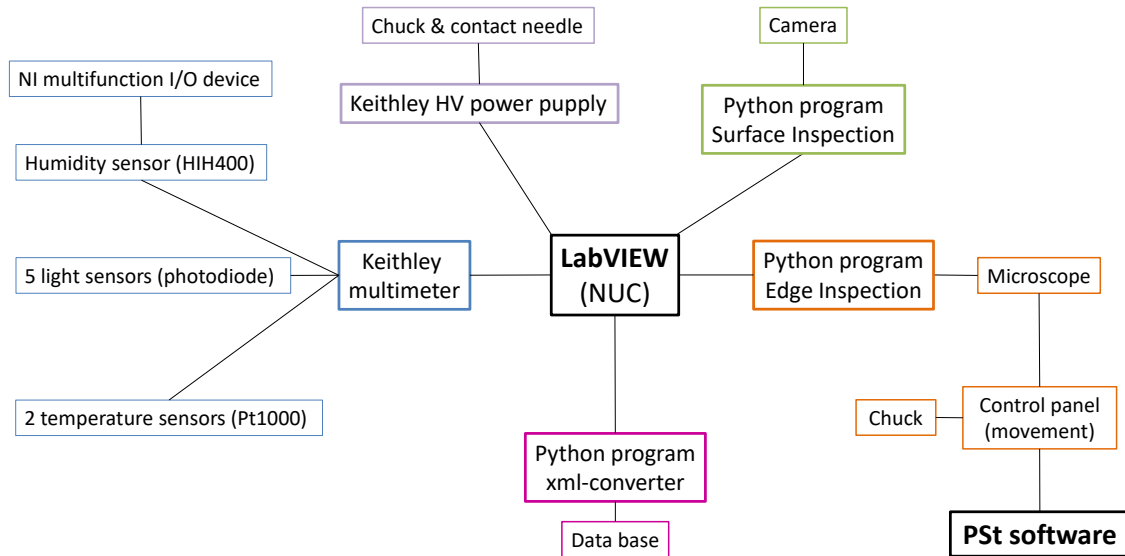


Figure 4.3: Map showing the connections between the LabVIEW program and the test stand components.

The first is the “basic” leakage current measurement, the so-called **I-V measurement**. For this test the bare sensor is placed on the chuck and its bias ring is contacted to the HV supply. A photo is shown in Fig. 4.4. For this measurement the ‘ground’ output of the power supply is attached to the chuck and the ‘high’ output to the needle positioner. After each assembly step a different configuration for the HV supply has to be chosen. For example, after the assembly of the FEHs the sensors are grounded by contacting the HV ground pads of a FEH. When the SEH is assembled, the HV is applied via a cable attached to the SEH [27]. The leakage current I is measured for voltage values V in steps of 10 V from -1000 V down to 0 V. The second test is the so-called **I/V-t measurement**. The setup is equal to the I-V measurement. The leakage current is measured for a fixed plateau voltage within a selectable time t . Thus the temporal behaviour of the sensors leakage current can be observed.

The third measurement is the **Isolation Test**. It is associated to the assembly of Kapton strips and the pigtailed. For this test the sensor is placed in the Kapton gluing jig⁸ and both together are placed on the chuck (Fig. 4.5). Vacuum is used to attach the sensor to the jig. The stops of the jig are isolated with insulating Kapton tape. The ‘ground’ of the power supply is attached to the jig and the ‘high’ output to the pigtailed. Then voltages from 0 V to 1000 V or -1000 V in steps of 10 V are applied. The measured leakage current is an indicator for the quality of the Kapton insulation. Spark, which are indicators for bad alignment or holes in the Kapton strips, between the sensor and the jig can be observed by a sudden rise of the leakage current.

⁸A new jig for this measurement is still under construction.

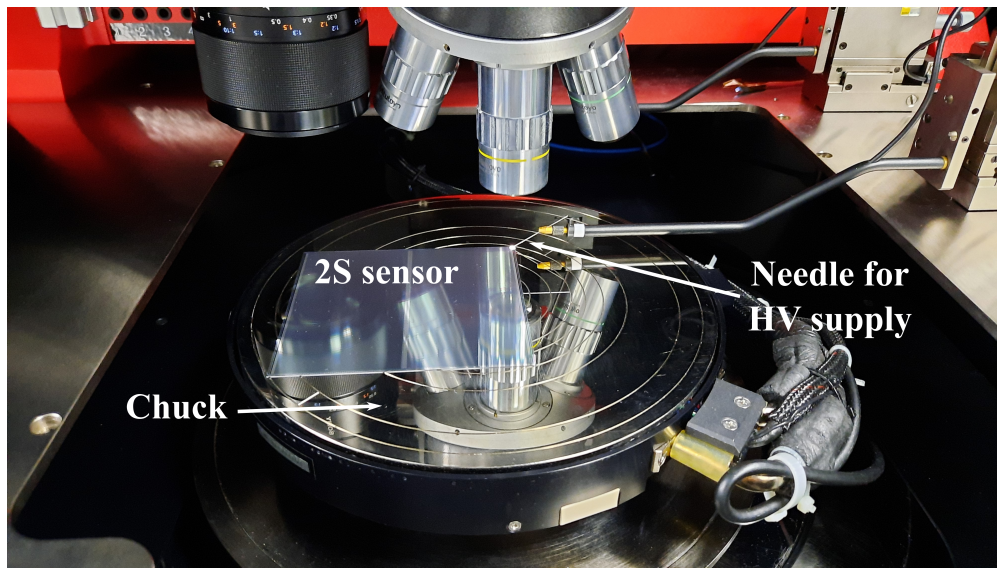


Figure 4.4: A 2S sensor placed on the chuck for the I-V measurement. The bias ring is contacted with a needle for the HV supply.

4.4. Optical Inspection

The quality of the sensor is strongly connected to the intactness of its surface and backplane. Every contamination and each scratch on the sensor can increase the leakage current or could lead to a lower breakdown voltage. For a 2S sensor to be used for a module, it must be ensured that it complies with the quality standards. To monitor the optical intactness of the sensor a so-called **Surface Inspection** is performed. The sensors are placed on the chuck to take high resolution pictures with the camera. The chuck moves on a pre-defined path to take pictures of several parts of the sensor's surface (40 photos in total).

The second optical inspection is the so-called **Edge Inspection**. For a precise positioning of the sensors in the sensor gluing jig and thus for a precise module assembly it is important that the edges of the sensors are free from chips that may appear due to the cutting of the sensors from the silicon wafer. For this inspection the Kapton gluing jig⁹ with the sensor is placed on the chuck. The chuck moves on a pre-defined path, so that all three relevant edges are scanned with the microscope. The four points where the stops of the jigs for the further assembly will touch the sensors are scanned additionally along the vertical direction. In total about 60 pictures are recorded and saved for a later review.

⁹The usage of this jig is a preliminary solution. A specialized jig is still under construction.

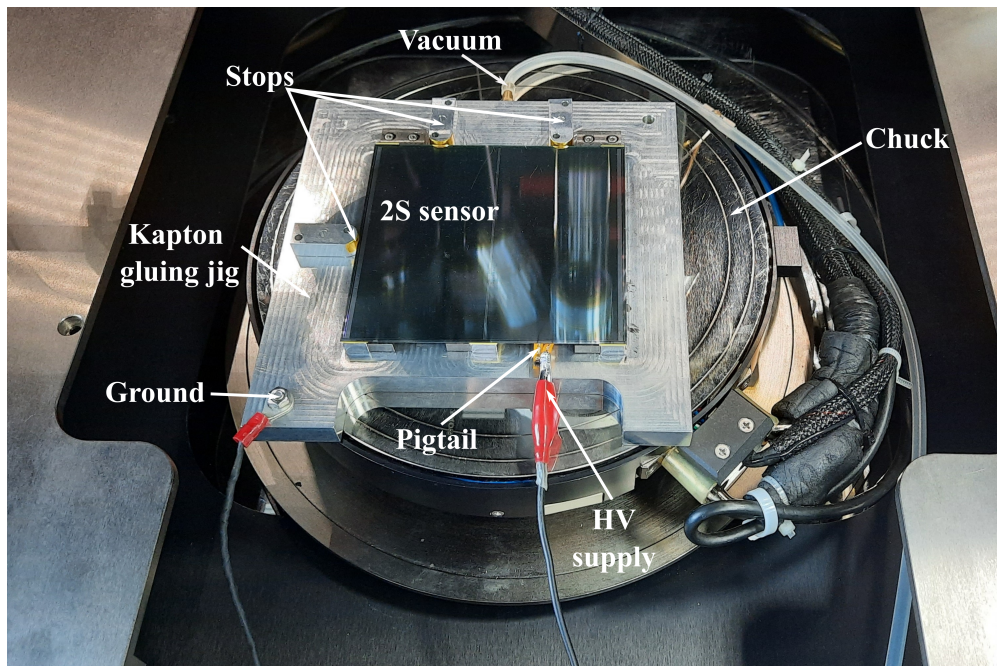


Figure 4.5: A 2S sensor in the Kapton gluing jig placed on the chuck connected for the Isolation Test.

5. The Development of a Control Interface

5.1. The Graphical User Interface

From a users point of view the LV program works basically as depicted in Fig. 5.1. More detailed descriptions of the program's substructure can be found in the following sections of this chapter. After starting the program the user is required to give key information about the current usage of the program. In the following this request is called "User Input". It comprises data about the operators name, the sensor or module ID of the device to be inspected, the current assembly step and a text field for comments. After providing general information the user can choose from the different tests that can be performed at the PSt. External information (e.g. environmental conditions) and the recently requested User Input are integrated in the recent measurement and in the resulting data output in form of measurement results. These results are saved in a folder structure based on the User Input. Between the different tests one can switch as often as desired. If the user chooses another measurement a pop-up window always asks to update the User Input. In this way, forgetting to update the information can be avoided. To end the program an exit button has to be used.

5.1.1. The Front Panel

The Graphical User Interface (GUI) consists of three main parts, which can be seen on the front panel. A screenshot of the front panel is shown in Fig. 5.2. At the top a tab structure (highlighted in red) can be seen. It consists of six tabs, which can be selected by mouse click. Five of the tabs refer to the possible measurements at the PSt test stand: "I-V Measurement", "I/V-t Measurement", "Isolation Test", "Surface Inspection" and "Edge Inspection". The sixth tab allows to monitor the

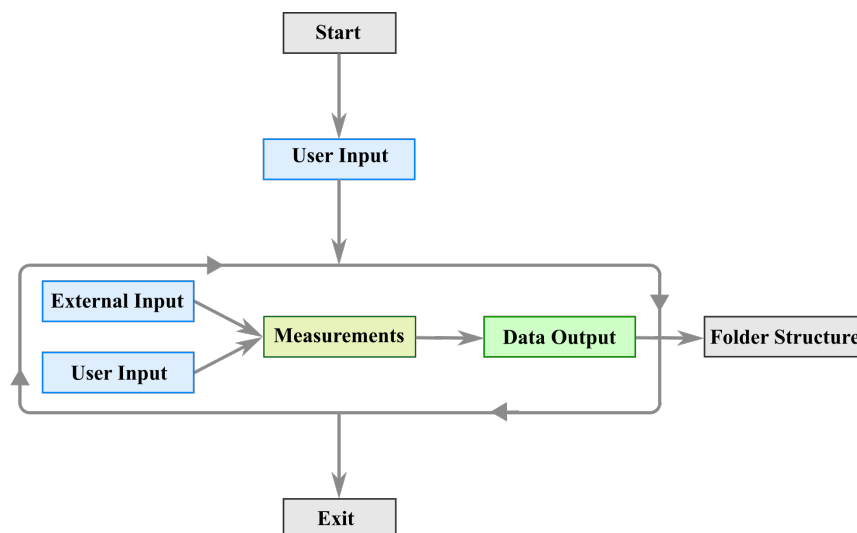


Figure 5.1: Schematic of the structure of the user interface from a users point of view. The chronological execution can be read from top to bottom. The grey box with the arrows indicates a repetitively executed structure. The User Input shown twice represents the same substructure, which is executed in different situations.

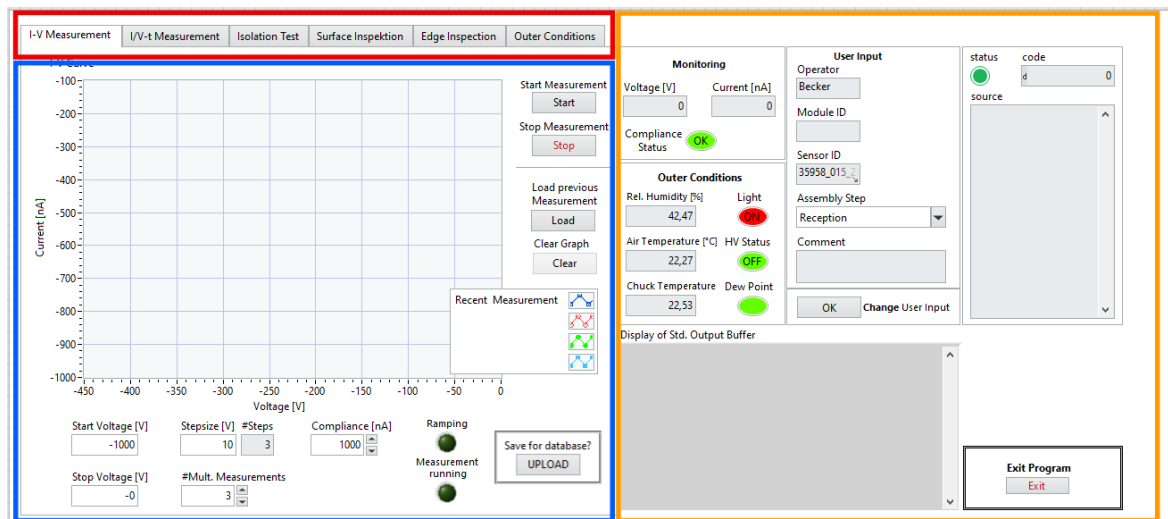


Figure 5.2: A screenshot of the front panel is shown. The tab structure is highlighted in red, a permanent overview in orange and the recent measurement in blue with the I-V measurement as example.

environmental conditions and the test stand status, in the following called “Outer Conditions”.

On the right a permanent overview (highlighted in orange) is shown, which is independent from the chosen tab. On the one hand it contains a Monitoring part, where the momentary applied voltage and current are displayed for all electrical measurements. Moreover, the compliance status is indicated by a boolean indicator. Below this, the recent Outer Conditions are shortly summarised. That is, the relative humidity, the air temperature and the chuck temperature, which are displayed as numerical values. Moreover, the light status, the HV status and the dew point are shown by a boolean signal. Red means light and HV is on, green means off, respectively. For the dew point a red indicator means that the dew point is reached within 5°C. The determination of the light status and the dew point calculation are described in Sec. 5.2.3. On the other hand this overview contains the User Input. It can be changed by a click on the “OK” button next to “Change User Input” and then changing the data in the pop-up window that opens. A screenshot of it can be found in the App. A.1. Far right an error display is shown, where the error reports are shown if the program ends irregularly. On the lower left there is a text field where the standard output of various sub-python programs is displayed (e.g. for the Surface Inspection). On the lower right an “Exit” button is placed, which ends the whole program.

The majority of the GUI is dedicated to viewing the recent measurement (blue). This part is different for each tab. A detailed description of each tab is given in the following.

5.1.2. The GUI Tabs

The User Interface includes six tabs, which are shown in Fig. 5.3. Three tabs are dedicated to the electrical measurements, two tabs to the optical inspection and one tab to a detailed monitoring of the Outer Conditions.

The interfaces of the three electrical measurements are very similarly structured (Fig. 5.3, A, B and C). A graph, in which the measurements are plotted, is placed in the middle. For the I-V Measurement (A) and the Isolation Test (C) the leakage current (in nA) is plotted against the applied bias voltage (in V). The graph¹⁰ of the I/V-t Measurement (C) displays the time (in s) on the x -axis. There are two y -axes, of which the left one shows the measured leakage current (in nA) while the right one shows the applied voltage (in V). Buttons for the measurement control are placed to the right of the graph. The “Start” and “Stop” buttons start and stop the particular measurement, respectively. The “Clear” button clears the graph from all displayed measurements. For the I-V Measurement and the Isolation Test there is the option to load and display up to four measurements recorded with the program in the past simultaneously by using the “Load” button. A demonstration of the Load function is shown in chapter 7. Below the graph the user can adjust several parameters. The corresponding settings have the same structure for the I-V Measurement and the Isolation Test. Here, the user can set a Start and a Stop Voltage as well as the desired Stepsize (in V). Moreover, the user can choose how many measurement points for each voltage value are taken. The corresponding option is called “#Mult. Measurements”. The mean of these multiple measurements is always shown in the graph. For the I/V-t Measurement the user can choose a Plateau Voltage (in V), which is the target value for this long term measurement. Furthermore, the duration of the measurement can be set (in s) with the “Total Time” option. If the user chooses the “inf” check mark, where “inf” is an abbreviation for infinity, the Total Time value is set to approx. 50,000 days¹¹. The measurements can be interrupted any time by a “Stop” button action. In addition the user can choose the “Time Interval” (in s) in which the measured values are averaged and always the last e.g. 10 s are displayed. In addition all three electrical tabs have the option to set a compliance for the power supply (in nA) to protect the sensor from too high currents. All options that can be changed by the user have a default value (Tab. 5.1), which is pre-set when the program is started. Moreover, the three tabs contain two boolean indicators. The one above is for the bare “Ramping” procedure and the other one is for ramping plus data taking, abbreviated to “Measurement running”. To provide the user a better overview about the status of the measurements the “Ramping” indicator is displayed in green, if the ramping is ongoing, and if the data taking is running the “Measurement running” indicator is set to green, respectively. For the I-V Measurement and the Isolation Test there is the additional option to upload the recent or a past measurement to the CMS database.

The Surface Inspection (SI) tab (Fig. 5.3, D) consists mainly of two displays. On the left the pictures taken by the camera are shown. On the lower right display the user can observe the track (blue points) of the measurement. The picture seen on

¹⁰Internal in LV it is not a “Graph” but a “Chart”.

¹¹The Total Time in seconds is represented by an unsigned integer 32 (U32). Setting it to its maximum value corresponds converted to days to a maximum of approximately 50,000.

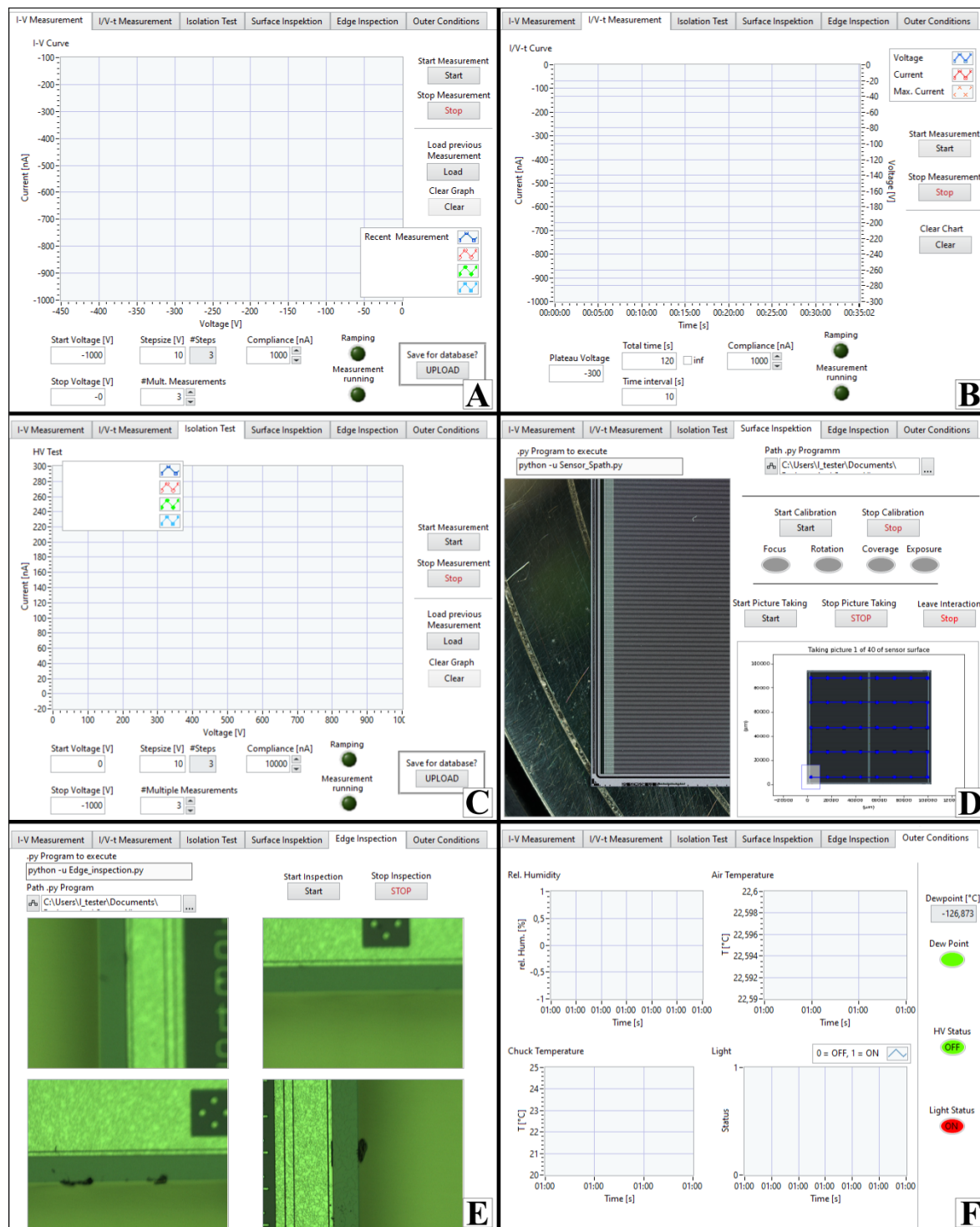


Figure 5.3: Screenshots of measurement displays of the front panel. The I-V Measurement (A), the I/V-t Measurement (B), the Isolation Test (C), the Surface Inspection (D), the Edge Inspection (E) and the Outer Conditions (F) are shown.

the left corresponds to the position on the sensor marked by a grey rectangle. Both displays are updated after each recording of a picture. At the upper left a text box is shown, where the command line input for the execution of the SI python program is written. Thus the user can change it easily. At the upper right the system path to the

	I-V Measurement	Isolation Test	I/V-t Measurement
Start Voltage [V]	-1000	0	-
Stop Voltage [V]	0	1000	-
Stepsize [V]	10	10	-
#Mult. Measurements	3	3	-
Compliance [nA]	1000	1000	1000
Plateau Voltage [V]	-	-	300
Total time [s]	-	-	1800
Time interval [s]	-	-	10

Table 5.1: Default parameter of the electrical measurements.

SI python program can be changed. Above the lower right display the measurement control buttons “Start” and “Stop” are placed, to start and stop the taking of pictures, respectively. In addition the front panel design is prepared for some future options. In Fig. 5.3, D, they are greyed out, to clarify, that these options cannot be used yet. It is planned that the SI python script not only takes pictures from the sensor surface, but also analyses them for potential points of damages or pollution. A map with the corresponding coordinates will be shown after the pictures were taken in the display at the lower right. If the user clicks on a marked position, a picture of the corresponding part of the surface will be opened in the windows photo viewer. With the “Stop” button on the right this so-called “Interaction” option must be exited. Furthermore, a calibration for the camera is planned, which will be started with the “Start” and stopped with the “Stop” button. The calibration will be done by the execution of a python program. It will optimise the camera focus, the chuck rotation, the coverage of the sensor surface and the exposure of the camera to ensure a good quality and high resolution of the taken photos. The indicators below will show by a light green colour if the calibration was successful.

The Edge Inspection (EI) tab (Fig. 5.3, E) consists mainly of four displays, which are showing the pictures taken at the points where the jig’s stops will be placed. After one stop position is scanned, the last taken picture is displayed permanently, while the other stop positions are scanned. That enables the user to get a brief overview of the quality of the most important positions of the edges. At the upper left controls are placed, where the command line input for the execution of the EI python program is written and the folder path of the corresponding program is chosen. At the upper right a “Start” and a “Stop” button is placed to control the measurement execution.

The Outer Conditions (OC) tab (Fig. 5.3, F) consists mainly of four graphs¹², which are showing the temporal development of the measured relative humidity (in %) (upper left), air temperature (in °C) (upper right), chuck temperature (in °C) (lower left) and light status (lower right) during the runtime of the LV program. Moreover, on the upper right a numerical and a boolean indicator for the dew point is placed.

¹²Internal in LV they are not “Graphs” but “Charts”.

The indicator changes to a red colour if the dew point and the recent chuck temperature match within 5°C. At the right centre a boolean indicator for the HV status and below one for the light status is placed. If the HV or the light is on, the indicators have a red colour, otherwise they are green.

5.1.3. Data Folder Structure

The measured data are stored in a tree folder structure (Fig. 5.4) on the NUC computer. The first folder branch is the differentiation between sensors and modules, secondly for each sensor or module a folder is created with its ID. Then it is split up in a folder for each assembly step. The following assembly steps can be chosen: Reception, Kapton Strips glued, Pigtails glued, Pigtails bonded & encapsulated, Bare Module, FEHs glued, SEH glued, FEHs HV bonded, FEHs strips bonded, Strips encapsulated. Furthermore, a folder named after the time stamp is created for each measurement, where all data are stored. By using the information of the User Input the measurement data are stored in the related branch of the folder tree. If the corresponding folder does not yet exist, it will be newly created. To save all information of the User Input, a text file with all associated information is created.

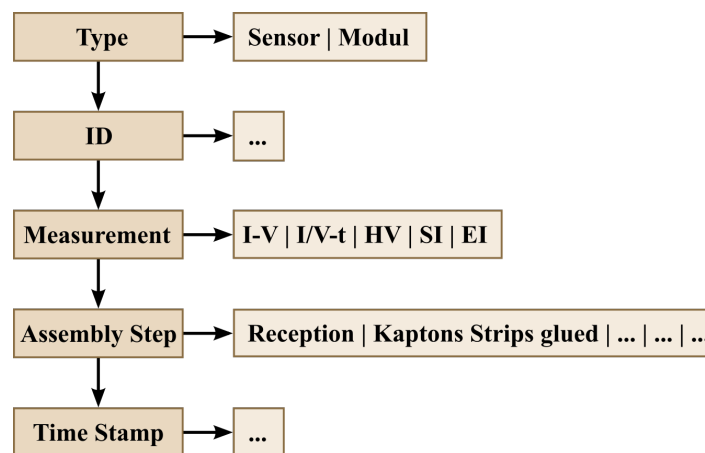


Figure 5.4: Schematic overview of the tree folder structure used for the data storage. The left column shows the main folder structure. The extensions on the right marked with arrows indicate the subfolders.

5.2. Inner Structure and Implementation

Internally the basis architecture of the program is structured as shown in Fig. 5.5. After starting the main LV program, a sub-program, a so-called sub-virtual instrument (subVI), for the User Input request is called. Then six `While` Loops start to run until the program is ended by the “Exit” button. There are three main loops. The first one is for managing all power supply related processes. This includes the execution of the I-V measurement, the I/V-t measurement and the Isolation Test. The second loop is responsible for all multimeter related processes, especially for reading and processing the data from the humidity, temperature and light sensors. The third loop is responsible for calling python programs¹³ for the Surface Inspection as well as for the Edge Inspection measurements. Moreover, there is a “Compliance” loop, which checks the compliance status of the current during electrical measurements. Furthermore, a loop to change the User Input is running permanently. The last loop manages several side utilities. On the one hand this “Utilities” loop is responsible for the “Stop” button reaction for various measurements, on the other hand it executes the “Save for DB” option as well as other small side functionalities.

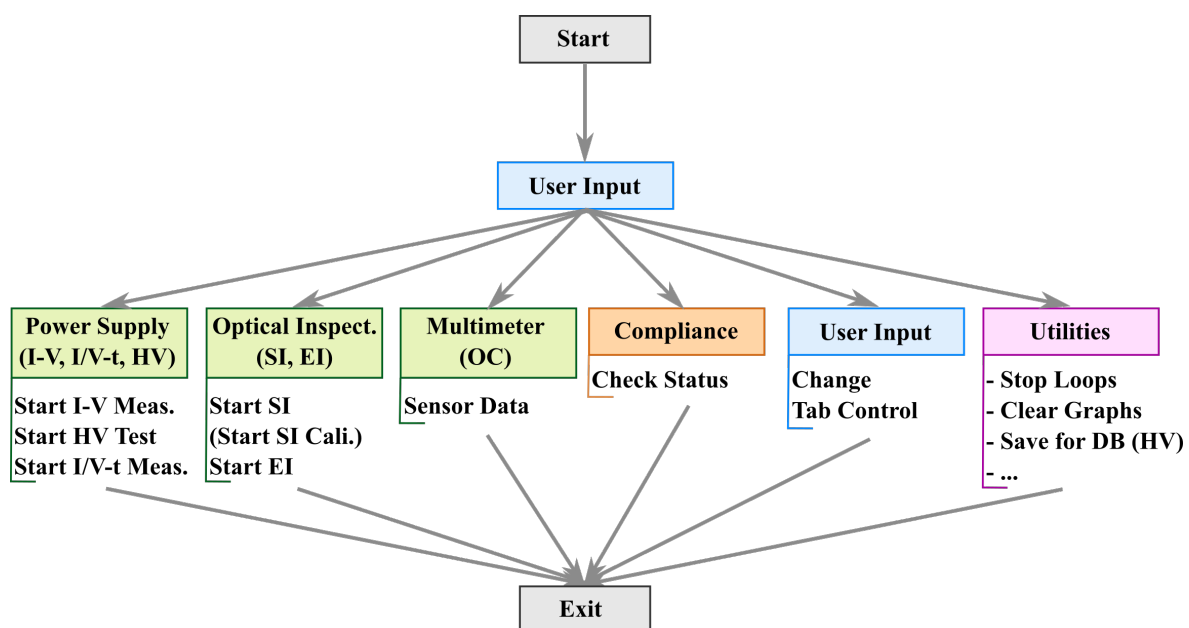


Figure 5.5: A schematic overview of the inner structure of the main LV program with a focus on the loops running internally during the execution. The timeline has to be read from top to bottom.

¹³These python scripts are provided and continuously improved by Nicolas Röwert, RWTH.

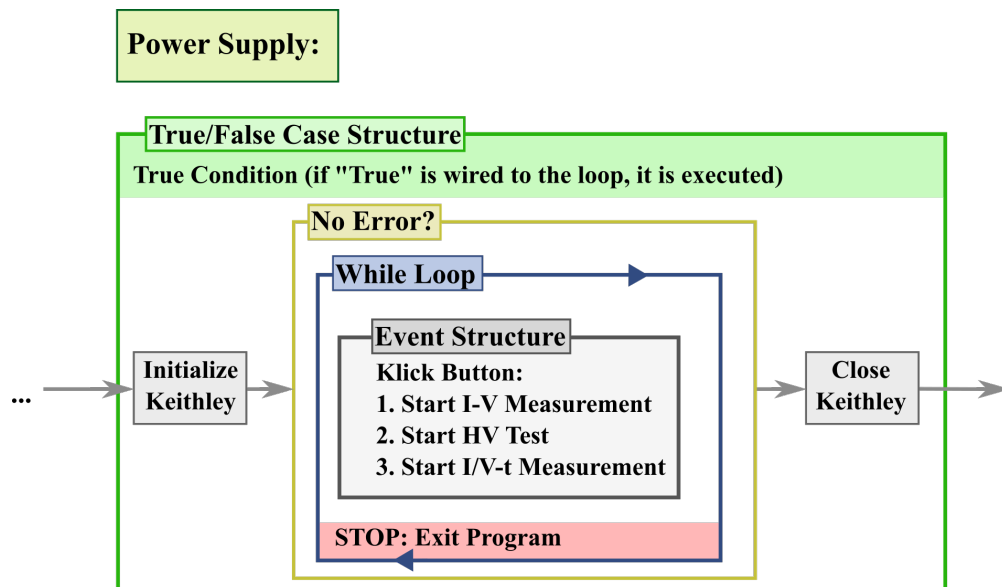
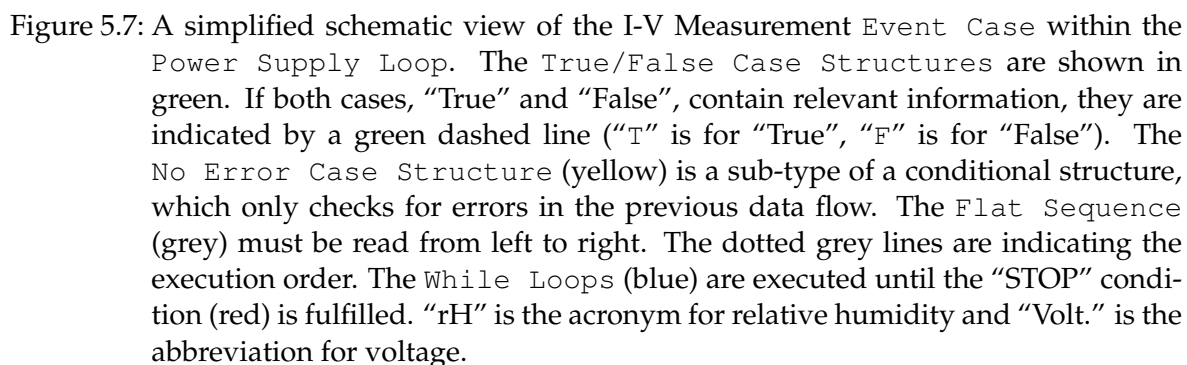


Figure 5.6: A schematic view of the inner structure of the Power Supply Loop of the main LV program is shown. A True/False Case Structure is shown in green. The No Error Case Structure (yellow) is a sub-type of a conditional structure, which only checks for errors in the previous data flow. The While Loop (blue) is executed until the “STOP” condition (red) is fulfilled. The Event Structure (grey) waits for a “Start Measurement” button action for one of the three electrical measurements.

5.2.1. The Power Supply Loop

A schematic view of the implementation of the Power Supply Loop can be seen in Fig. 5.6. It is reduced to the essential parts of the code. The outer structure is a Case Structure to simplify the debugging of the program. With wiring a “F”, so a “False”, to the structure the whole Power Supply Loop can be commented out. The first subVI within the loop initializes the Keithley power supply and sets various configurations for the measurements. If no error occurs during the initialization, a While Loop starts running until the main program is exited. Within this loop an Event Structure is placed, which waits for a mouse click event on the “Start measurement” buttons of the I-V, I/V-t measurements or the Isolation Test. The program for the execution of each measurement is located in this Event Structure. A closer description can be found in the next paragraph. The While Loop ensures that the expected events are queried until the program is terminated. After the user decided to end the main program, the While Loop is exited and a subVI ends all power supply configurations.

The Event Case within the Power Supply Loop handles the execution of the three electrical measurements. In the following, only the structure of the code for the I-V Measurement is described. The Event Cases for the I/V-t Measurement and the Isolation Test are structured in a similar fashion. In Fig. 5.7 a schematic depiction of the most relevant part of the LV code for the I-V Measurement is shown. Within the Event Case it is checked first by a Case Structure if all conditions to run the measurement are fulfilled. If all conditions are “True”, the “T” case is



In the next step it is checked whether the desired start voltage for the I-V curve has an absolute value greater than 10 V to decide if a ramping process has to be initiated. To protect the sensor from damages due to fast changes in the applied voltage, a maximal ramp speed of $\pm 10 \text{ V/s}$ is used. During the ramping it is frequently monitored if all conditions for a safe execution of the measurements still hold. If not, the ramping will be stopped and the measurement is aborted. It has to be mentioned

that the programme is designed to apply negative as well as positive bias voltages. When the start voltage is reached the `Flat Sequence` executes the code for the main measurement. Before the first data are measured, a `Case Structure` asks again if the absolute value of the start voltage is greater than 10 V. If this is “True” the applied voltage is read and the start point for the measurement (here called output voltage) is set to the read voltage. By taking the momentary voltage value as start point for the measurement an accidental sharp increase of the applied voltage is avoided. If the start voltage is not greater than $|10|$ V, the output voltage is set to the start voltage. Moreover, a voltage of ± 1 V is applied, to prevent high fluctuations in the first measuring points if the measurement is performed from low to high voltages. Then the program waits for 1 s to be sure that the charges on the sensor have settled. If still all conditions for a save measurement are fulfilled, a `While Loop` starts ramping to the stop voltage in the desired step size. If the step size is larger than 20 V the user is advised to check this parameter. The ramping speed is limited to a maximum of 1 step/s. Within this loop a second `While Loop` executes the number of requested multiple measurements. Then the mean of the multiple measurements is calculated and shown in the graph on the front panel. Both `While Loops` continue until one of the following conditions is fulfilled: the user stops the measurement, the measurement is finished, the compliance value for the current is reached, the limits for the relative humidity are exceeded or the photodiodes measure any light. Finally a `subVI` ramps the voltage down to 0 V with a maximal ramp speed of 10 V/s. This `subVI` is always executed to make sure the voltage is ramped to 0 V also if an error occurs in the previous execution of the program.

It has to be mentioned that not only a text file with the User Input and measurement data are created and stored for the I-V Measurement and the Isolation Test, but also a JSON¹⁴ file with all relevant information for a later upload to the data base.

¹⁴The JavaScript Object Notation (JSON) is a language independent open standard file format [39]. It is often used for data storage and transmission. The data are stored in key-value pairs.

5.2.2. The Optical Inspection Loop

The Optical Inspection Loop consists of substructures for the Surface Inspection and the Edge Inspection, which are chosen by an Event Case within a While Loop. In the following first the SI is described and depicted (Fig. 5.8). Afterwards the EI is shortly described.

At first, the User Input is checked for completeness and correctness. Within the following Flat Sequence, if no error occurred in the data flow, first the measurement folder is created and a text file with the User Input information is saved. If there is still no error, the python script for the execution of the SI measurement is started. It steers the chuck along the travel path and triggers the camera so that 40 images of the sensor surface are taken. All images are saved in the corresponding current folder branch, which is transmitted to the program as storage location. Moreover, it is planned that the python program analyses the pictures for damages and pollutions automatised within a sub-program. The sub-program will provide the information about the points of potential damages or pollution to the LV program in the form of a picture with markers indicting the positions of potential damages, their coordinates and a folder with separate image sections of the relevant photos. Right after the python program is started, two While Loops start running. The first loop reads the buffer output of all python programs and displays it on the front panel. Thereby the user can see the recent status of the measurement as written output. The second loop is responsible for showing the last photo taken by the camera. Hence a direct monitoring of the cleanliness of the sensor's surface by the user is possible. Moreover, a picture of the travel path is displayed, where the current position of the chuck corresponding to the shown photo is marked. Both While Loops are stopped if the python program is finished or the user stops the measurement manually via the "Stop" button. The next two steps in the Flat Sequence are, if again no error has occurred, to process the information about potential damages on the sensor surface. At first the picture with markers on the points of potential damages and pollution is shown. Moreover, the LV program reads in the coordinates of the mentioned points, which are provided by a text file. Then a user interaction via mouse clicks on the picture is enabled by a Event Structure embedded in a While Loop. The mouse click position is compared to the given coordinates. If the user clicks on a marked position the corresponding photo section is opened in the windows photo viewer. This enables a fast manual investigation and evaluation of the automated damage and pollution analysis by the user. The While Loop for the user interaction has to be ended by the related "Stop" button.

The Edge Inspection is implemented mostly analogous to the first parts of the Flat Sequence of the SI. Therefore no separate sketch of the code is shown and only the differences are shortly summarised in the following. After the EI python program is started to execute, five While Loops start to run. One loop is still for the reading and displaying of the buffer output. The other four While Loops check if pictures at one of the stops are taken and display them. The execution of the program as well as the execution of all While Loops can be stopped by the "Stop" button.

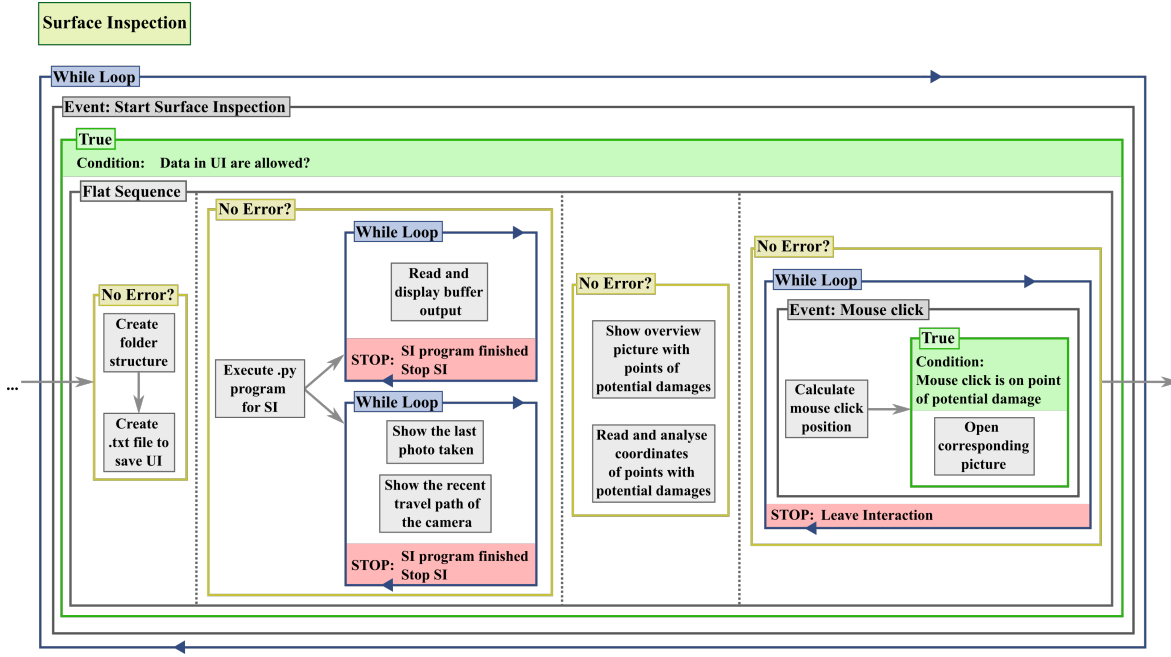


Figure 5.8: An simplified schematic of the Surface Inspection is shown. While Loops (blue) are executed until the condition in the red boxes are fulfilled. The Event Structure (grey) waits for a “Start Surface Inspection” or “Start Edge Inspection” action. Here only the SI case is shown. A True/False Case Structure is shown in green. The Flat Sequence (grey) must be read from left to right. The dotted grey lines are indicating the execution order. The No Error Case Structure (yellow) is a sub-type of a conditional structure, which only checks for errors in the previous data flow.

5.2.3. The Multimeter Loop

In Fig. 5.9, a simplified schematic depiction of the Multimeter Loop is shown. Similar to the Power Supply Loop the outer structure is a Case Structure (green) to be able to comment out this part of the program for potential debugging issues. Then the Keithley Multimeter is initialised by a subVI. Afterwards an Error Case Structure makes sure that the following While Loop is executed only if there are no errors in the data flow. Until the user stops the LV program, the data of the multimeter are read every 1.5s. The data of the photodiodes are analysed and it is checked whether one or more of the measured resistances exceed a certain threshold. The thresholds are manually calibrated for each diode after the placement in the PSt. The threshold for the photodiode close to the camera display, for example, is determined by comparing the diode’s resistance for a switched on to a switched off display. Only if all resistances of the photodiodes are below their individual threshold the light status is set to “OK”. Moreover, the relative humidity rH and the temperatures T_{air} and T_{chuck} are determined and based on this the dew point τ is calculated [40]:

$$\tau = \frac{c \cdot \ln\left(\frac{P}{a}\right)}{b - \ln\left(\frac{P}{a}\right)} \quad (5.1)$$

with the constants $a = 6.112 \text{ hPa}$, $b = 17.67$ and $c = 243.5 \text{ }^\circ\text{C}$. P , which is derived from the Magnus formula for the saturated vapour pressure, is given by

$$P = a \cdot \exp\left(\frac{b \cdot T_{\text{chuck}}}{c + T_{\text{chuck}}}\right) \cdot \frac{\text{rH}}{100}.$$

This formula holds for temperatures T in the range $-40 \text{ }^\circ\text{C} \leq T \leq 50 \text{ }^\circ\text{C}$. Finally the evaluated data are plotted for the Outer Conditions tab and displayed as numbers in the permanent overview at the side of the front panel. After the user exits the program a subVI ends all multimeter configurations properly.

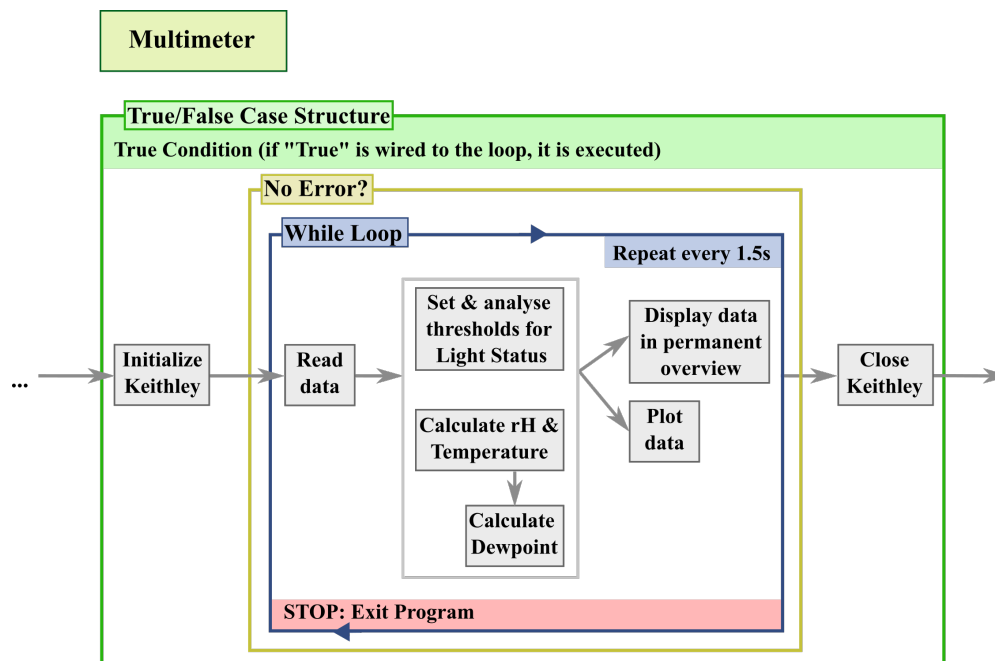


Figure 5.9: A simplified schematic of the inner structure of the Multimeter Loop of the main LV program. A True/False Case Structure is shown in green. The No Error Case Structure (yellow) is a sub-type of a conditional structure, which only checks for errors in the previous data flow. The While Loop (blue) is executed every 1.5s until the “STOP” condition (red) is fulfilled.

5.2.4. Other internal Aspects of the Program

An important part of the program is the compliance check for the electrical measurements. In addition to the compliance check performed by the power supply internally, a While Loop for testing the compliance status begins to run continuously directly after the start of the program. By this it is ensured that various processes described before are aborted, if the leakage current reaches the compliance value. The compliance value can be set by the user for the I-V, I/V-t measurement and the Isolation Test individually. If the absolute value of the recently measured current value is equal or higher than the predefined compliance within 5 nA, the corresponding indicator is set to “True”. Thus all loops with a termination condition linked to the compliance are aborted. Moreover, the visual indicator on the front panel shows by a red colour that the leakage current reached the compliance value.

Another structure to be described is the User Input (a front panel screenshot is shown in App. A.1). The corresponding subVI is called not only right after starting the program, but also in two other cases. The first is, if the user clicks the “Change User Input” button at the permanent overview of the front panel. A While Loop together with an Event Structure frequently check if this user action is done. The second is if the user changes a tab. This is implemented in order to prevent the user from forgetting to change the given information about e.g. the sensor ID or the assembly step. Only if the OC tab is called, the User Input pop-up window is not launched.

The last internal structure to be mentioned is summarising called Utilities. It consists of a While Loop with an Event Structure inside. It handles various different actions, such as e.g. the execution of the “Stop” button command for all measurement tabs as well as the “Clear Graph” and “Load” buttons in the electrical measurements. Moreover, the data base upload is programmed within this structure. Due to the relevance of the data base upload option the simplified internal structure is shortly described in the following. After the button action “Upload” in the Isolation Test tab, the user is requested to choose which measurement should be uploaded. The recently taken measurement or a measurement taken in the past can be selected. Then a python script¹⁵, which first requests the data base to get a run number allocated, converts the JSON file to an XML¹⁶ file, and then uploads the corresponding file. The standard output of the python script is shown in the permanent overview in the corresponding text box indicator. There the user can check if the upload process was successful.

¹⁵The python script for the file conversion and the data base upload is provided by Stefan Maier (KIT) and just slightly changed.

¹⁶The XML (Extensible Markup Language) file format is an open standard format commonly used for the representation of data structures [41].

6. Measurement of Setup Parameter

The free parameters for the electrical measurements have to be chosen with respect to the optimisation between time efficiency for series production and measurement precision. In the following the I-V measurement is used for this optimisation. The determined parameters are transferred to the Isolation Test and I/V-t measurement. Internally the I-V measurement and the Isolation Test have basically the same code structure and the I/V-t measurement is very similar to them. Thus no separate parameter studies for the Isolation test and the I/V-t measurement are done. The parameters, that have to be investigated are the waiting time after each ramp step, the number of multiple current measurements for each voltage point, the integration time, the duration of a full measurement process and if the data acquisition is done when ramping up or down. A definition and description of these parameters is provided in the following sections. All measurements shown are temperature corrected to 22°C with regard to the quality standards in Sec. 3.2.2 using Eq. 3.3.

6.1. Preparation Studies with a Mini-Sensor

The first parameter studies are performed with a silicon sensor from a prototype series (FZ320N-W10). The name describes some characteristics of the sensor. A Float Zone Silicon (FZ) waver with a thickness of 320 μm is used. The N refers to the doping of the material. These prototype sensors are also called mini-sensors. 2S sensors are used only for the final validation of the results with the mini-sensor (Sec. 6.2). The 2S sensors are foreseen for the recent prototype module assembly at the Aachen assembly centre. Due to the vulnerability of the 2S sensors, they should not be used for the repetitive measurements for the parameter optimisation. In part, the mini and the 2S sensor are well comparable. Both are silicon strip sensors with the same microscopic structure as described in Ch. 3.1. Moreover, they both have a physical thickness of 320 μm . Apart from these similarities they have a different polarity. While the 2S sensors are n-in-p doped, the mini-sensor consists of p-in-n doped silicon. Furthermore, the mini-sensors are, as the name suggests, much smaller than the 2S sensors. With an edge length of about 5 cm, they have an area that is about one-fourth compared to that of the 2S sensors. Accordingly one can assume, based on their similarity, that the mini-sensors are usable to optimize the measurement parameters, which have to be confirmed with the 2S sensor measurement, and for testing the workflow of the LV program.

6.1.1. Optimisation of the Waiting Time

A full measurement process consists of two parts: bare ramping and ramping including the leakage current measurement after each ramp step. Bare ramping means the ramping to the Start Voltage, if its absolute value is greater than 10 V, and/or the ramping from the Stop Voltage back to 0 V, if its absolute value is greater than 10 V. To distinguish between pure data acquisition after each ramping step, which is ramping plus measurement, pure ramping and a full measurement process, the former is called just “measurement”, pure ramping is called “ramping” and the latter is called “run” in this chapter. The focus of the presented analysis is on the

measurement procedure. The question to be examined is how much time should be waited after a ramp action before the first measurement is taken, which is called waiting time t_{wait} in the following. This parameter is an internal variable of the LV program and cannot be changed via the front panel. Each time a voltage is applied to the sensor the charge carriers are rearranging until they are in equilibrium. This rearranging has a fast decaying temporal evolution, but one wants to avoid measurements during the main rearrangement process. The leakage current of the I-V curves of the mini-sensors decreases a little after each measurement, probably due to charge displacements. A difficulty is the reproducibility of different measurements with the same sensor. This behaviour called "training effect" is shown in the App. A.2.

To investigate the effect of ramping on the sensor's leakage current behaviour, a run with a high number of measurement repetitions right after a ramp step is performed. In Fig. 6.1 I-V curves of the mini-sensor FZ320N-W10 with different waiting times are shown. During the measurement the voltage is ramped from -10 V to -1000 V (in Fig. 6.1 the absolute value is plotted). After each ramping step 15 measurement points are recorded before the next step is performed. The measurements are done without a waiting time after the ramp action in addition to the time the LV program needs internally to execute the code. The first twelve points after a ramping step, which are shown in Fig. 6.1, correspond to a total approximate waiting time of 10 s after the first measurement is taken. Longer waiting times are excluded due to the necessity of temporal efficiency in the serial production. Each curve corresponds to one measurement point after a mean waiting time displayed in the legend. The uncertainties on the leakage current measurement due to the measurement accuracy of the Keithley 2410 can be determined by [42]

$$\sigma = \pm(0.029\% \cdot I_{\text{leak}} + 0.3\text{ nA}). \quad (6.1)$$

In Fig. 6.1 the uncertainties are not shown, as they are too small with a size of $\mathcal{O}(10^{-1})\text{ nA}$ to be seen in this depiction. Hence also in all following shown I-V curves no uncertainties are plotted. The measurement points are connected by lines, to get a better view of their colour ordering. It should not indicate a linear behaviour of the leakage current between two points.

In Fig. 6.1 one can observe that the curves are diverging for higher voltages. This observation is reproducible for other sensor runs. Probably this could be explained by higher current fluctuations on the sensor. In Fig. 6.2 a zoom to the voltage range of $|860|\text{ V}$ to $|1000|\text{ V}$ is shown. An ordering of the different curves within the whole voltage range cannot be seen, however at single points, e.g. $|1000|\text{ V}$, an ordering from red ($\bar{t}_{\text{wait}} = 10$) s to purple ($\bar{t}_{\text{wait}} = 0$) s is clearly visible. Therefore a more detailed analysis of the data is done and presented in the following paragraphs. In order to obtain a more comprehensive result, two additional runs were performed. Both of them lead to the same observations and thus support the results presented in the following.

In Fig. 6.3 the leakage current for a specified voltage shifted by its mean to the zero line ($I_{\text{leak}} - I_{\text{mean}}$) and normalised by dividing through its mean is plotted against the time. The mean I_{mean} is calculated based on the first 10 s of each voltage step. Here a

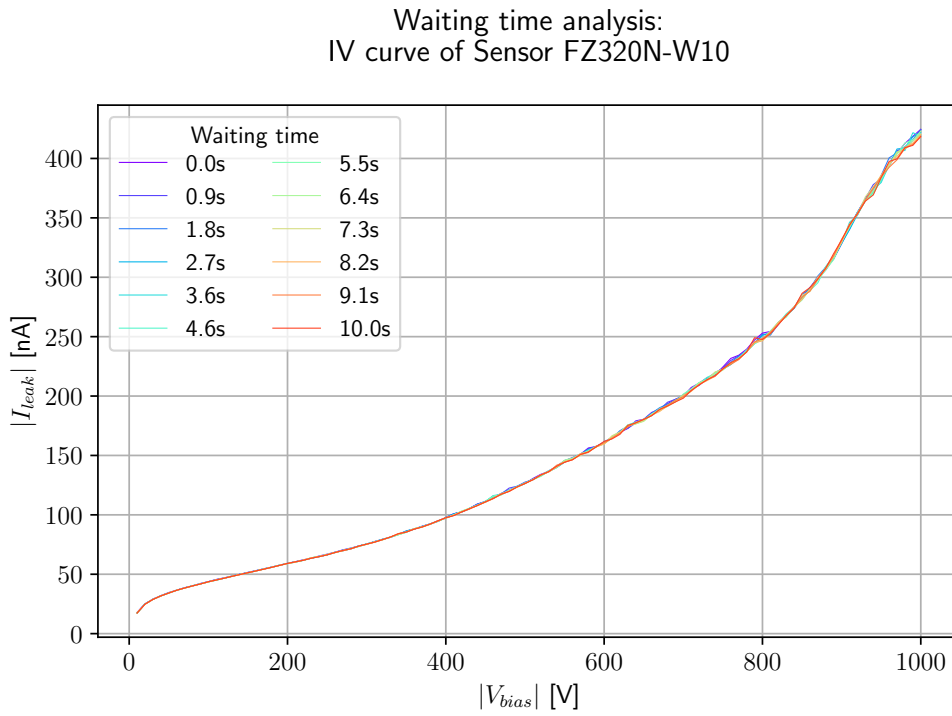


Figure 6.1: I-V curves of the sensor FZ320N-W10. For each measurement point taken within the first 10 s after ramping an individual curve is plotted. The mean passed time since the first measurement is taken is shown in the legend. Lines are drawn to guide the eye.

time of 0 s corresponds to the first measurement taken after a ramp step, including the LV internal processing time for the execution of the measurement. For the sake of overview, the temporal behaviour is only plotted for voltage values in steps of 100 V, as intermediate values show the same behaviour. The uncertainties are calculated by Gaussian error propagation of the Keithley 2410 measurement accuracy (Eq. 6.1). A temporal development of the leakage current can be observed for each ramp step. It is assumed that there is no correlation between the current settling of two consecutive ramping steps within the measurement accuracy, if the temporal distance between the ramping steps is long enough. On average a temporal development can be observed especially during the first three seconds. Especially for the highest voltages there is a drop of the leakage current. For low and medium voltages the current is relatively constant. Slightly higher variations at opposite sides of the range of the power supply are expected, due to a lower voltage accuracy by the Keithley power supply. For an applied voltage of 100 V an accuracy of ± 0.12 V is given, for an applied voltage of 1000 V an accuracy of ± 0.3 V is given. A measurement range of 1000 V is used for the calculation [42]. The power supply accuracy cannot be the only source of the fluctuations. More probable is, that e.g. higher surface currents on the sensor could be a reason for the higher leakage current fluctuations at high voltages.

To investigate the fluctuation of the leakage current a histogram of the relative fluctuation is plotted (Fig. 6.4). The fluctuation is calculated as the difference of the

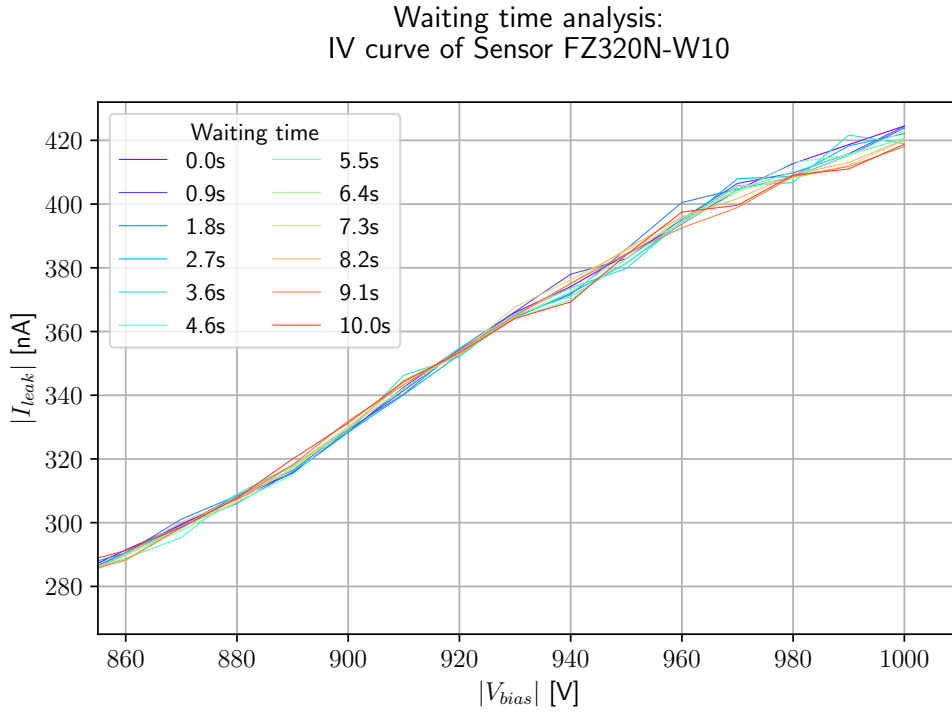


Figure 6.2: Zoom into the voltage range of 860 V to 1000 V of the I-V curve of the sensor FZ320N-W10. For each measurement point taken within the first 10 s after ramping a single line is plotted. The mean passed time since the first measurement is taken is shown in the legend. Lines are drawn to guide the eye.

maximal leakage current, $I_{\max}$, and the minimal leakage current, $I_{\min}$, normalised by the mean, I_{mean} . The difference between the maximal and minimal current is calculated for each voltage step. Again measurement points which are taken within the first 10 s after a ramp step are taken into account. The mean I_{mean} is calculated in the same way as described in the previous paragraph.

The fluctuations are typically within 1-2 % with a tail up to 3 %. In the manual of the Keithley 2410 power supply a value for the current measurement accuracy $(I_{\max} - I_{\min})/I_{\text{mean}}$ of 0.118 % is given [43]. Thus the measured fluctuations are small, but larger than the measuring device accuracy.

The relative standard deviation of the leakage current is shown in Fig. 6.5. The standard deviation of the leakage current $\text{std}(I_{\text{leak}})$ divided by its mean I_{mean} is plotted against the applied bias voltage. The standard deviation and the mean are calculated for the first 10 s of each measurement step as before. Moreover, the uncertainty resulting from a Gaussian error propagation of the Keithley accuracy (Eq. 6.1) divided by the mean I_{mean} is shown.

The relative uncertainties have a large spread. For low ($\lesssim 120$ V) voltages and higher voltages ($\gtrsim 460$ V) there are slightly higher uncertainties. But all measured relative uncertainties are still below 1 %. Furthermore, one can observe that the uncertainty for low voltages up to approximately 200 V is dominated by the Keithley measurement inaccuracy, while for higher voltages the current fluctuations within the sensor are dominant.

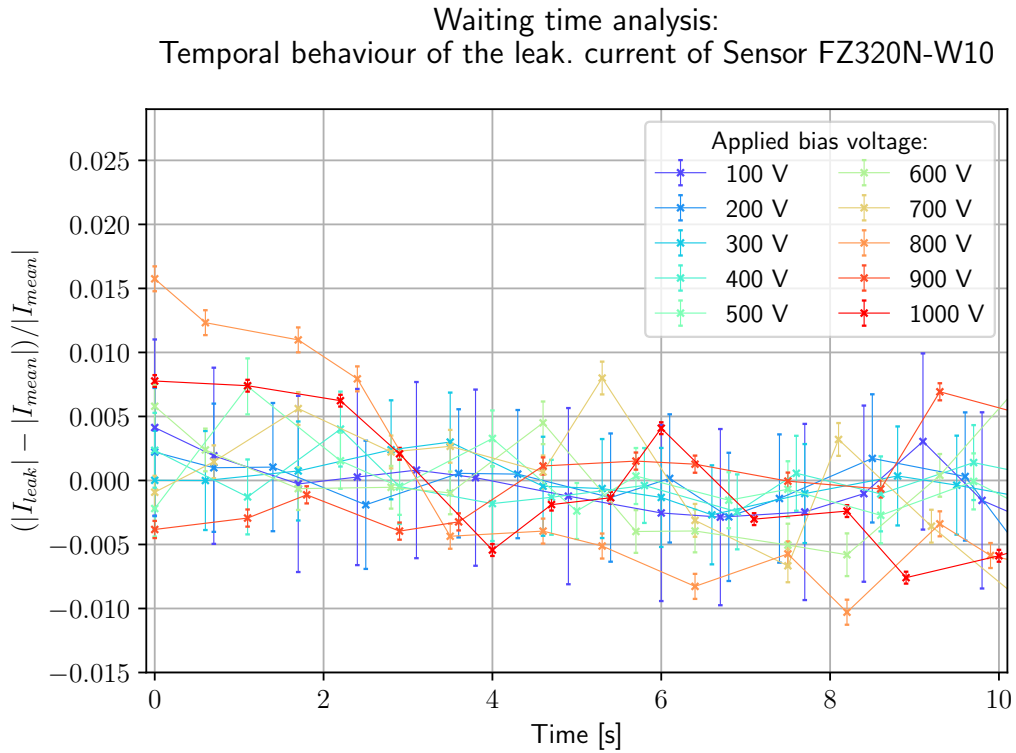


Figure 6.3: The temporal behaviour of the normalised leakage current shifted to the zero line is shown for voltages in steps of 100 V. The uncertainties of the y -axis are calculated by Gaussian error propagation of the power supply measurement accuracy of the leakage current. Lines are drawn to guide the eye.

Finally the impact of the waiting time on the run duration has to be considered. To perform an I-V measurement or a Isolation test a preparation time of about five minutes is needed. This includes, depending on the assembly step, the placement of the sensor on the chuck, the placement of the needle on the sensor or the wiring of the jig and e.g. the pigtails. The duration of a full measurement run depends on several parameter, which are discussed in the following paragraphs. To have a rough estimate of the full duration, a run takes between 5 minutes and 15 minutes. In Tab. 6.1 the additionally required run times for waiting times from 1 s to 4 s are shown. An additional measurement time of more than five minutes, which corresponds in the best case to a doubling of the total run time in comparison to the pure run duration, is not justifiable, as long as the measurement uncertainties are in the range of a few percent. With regard to the temporal behaviour shown in Fig. 6.3 and the additional run time shown in Tab. 6.1 a waiting time of 1-2 s is recommended. However, a final decision is made within the analysis in Sec. 6.1.3.

t_{wait}	1 s	2 s	3 s	4 s
additional run time	+1.40 min	+3.20 min	+5.00 min	+6.40 min

Table 6.1: Additionally required run times for different waiting times.

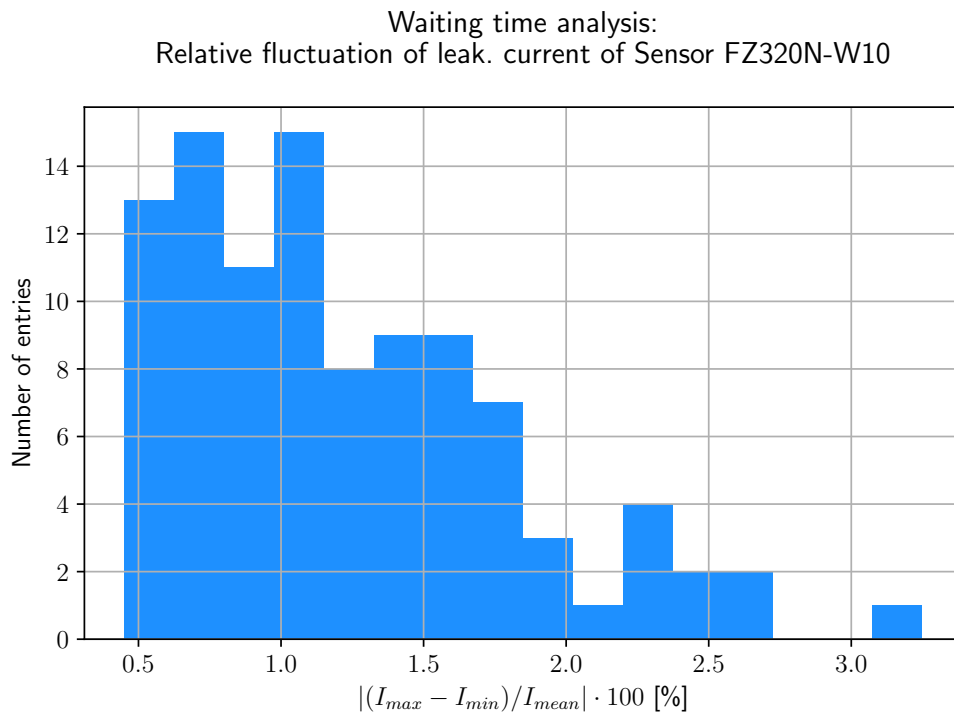


Figure 6.4: Histogram of the relative fluctuation within the first 10 data points of the sensors leakage current.

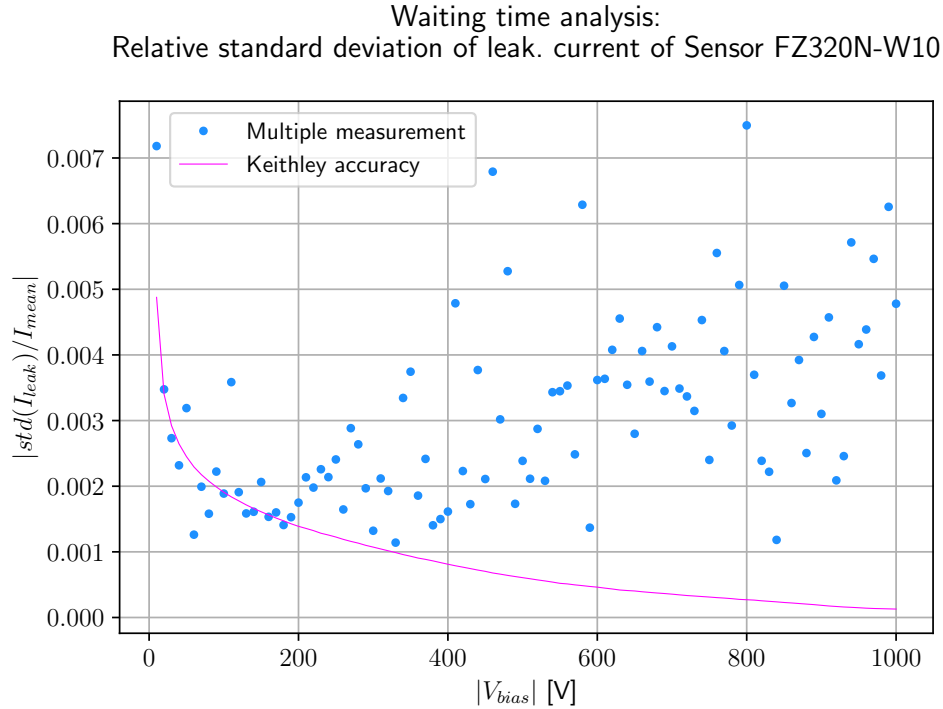


Figure 6.5: The relative standard deviation of the leakage current is plotted against the voltage (blue). The Keithley 2410 accuracy is indicated by the pink line.

6.1.2. Error Reduction by Measurement Statistics

The focus in this paragraph is on the parameter “number of multiple measurements”, N . This refers to the number of measurement points which are taken after each ramping step and after waiting the previously determined time. These multiple measurements are necessary, as their mean is calculated in order to reduce the uncertainty on the measurement for each voltage step. However, a number of multiple measurements greater than five is excluded due to time constraints. The following discussion aims at defining a default value for this parameter. The user can still change the number of multiple measurements on the front panel. The data of one run is analysed with regard to several aspects for different choices of multiple measurements. The results for different parameters are compared with each other, thus the results within one run, due of the impact of the training effect. For this analysis, the same data as for the previous analysis is used, supplemented by two additional measurement runs, which lead to similar results. To ensure that the waiting time does not dominate the analysis, the first five measured data points are neglected. Here it is exploited that in total 15 data points are recorded for each voltage step in this run (in the previous section only the first ten points were used for the analysis). This corresponds to a mean time passed of 4.6 s (legend Fig. 6.1). Therefore the information about the number of multiple measurements always refers to the first data points after this 4.6 s.

In Fig. 6.6 the I-V curve of the mini-sensor FZ320N-W10 is shown. It is based on the same data set as Fig. 6.1 but evaluated for the number of measurements N . In Fig. 6.7 a zoom to the voltage range of $|860|$ V to $|1000|$ V is shown. Again all curves are close together.

To take a closer look at the uncertainties of the runs with a different number of multiple measurements, the relative current deviation from a run with a high number of multiple measurements is shown. In Fig. 6.8 the curve with the highest number of multiple measurements, i. e. $N = 10$, is taken as reference for the analysis. The relative current deviation $r = (|I_{\text{leak}}^N| - |I_{\text{leak}}^{10}|) / |I_{\text{leak}}^{10}|$, thus the difference of the leakage current of runs with one, three and five multiple measurements I_{leak} and the reference current I_{leak}^{10} divided by I_{leak}^{10} , is plotted against the bias voltage. In order to obtain an estimation of the uncertainties, the error on r is calculated with Gaussian error propagation. The uncertainty on the leakage current mean is the standard deviation. The uncertainties on the leakage current of the curve with $N = 10$, I_{leak}^{10} , are neglected. Uncertainties on the applied voltage are neglected. For a better readability of the plot, the uncertainties are shown as error bands. For $N = 1$ there is no error band, as the calculation of a spread for a single measured value is meaningless. In order to give a more quantitative characterisation the maximum absolute value $\max|r|$ of r is determined for each run. These values are displayed in Tab. 6.2.

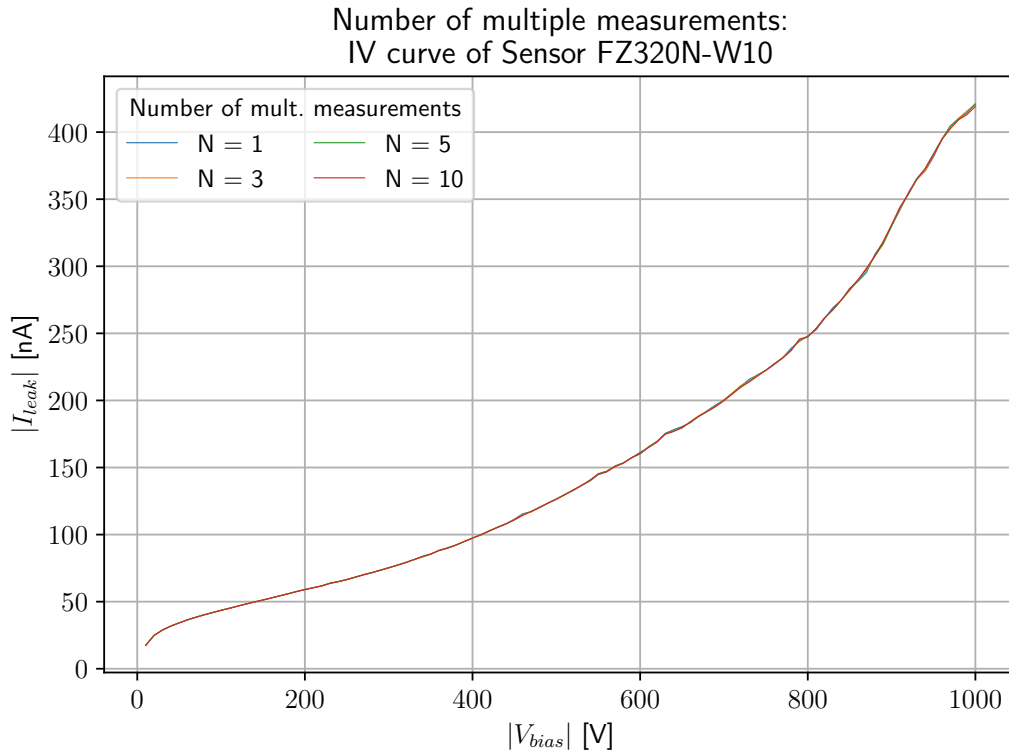


Figure 6.6: The I-V curve of the Sensor FZ320N-W10 evaluated for the number of measurements N (see legend). Lines are drawn to guide the eye.

	$\max r $ [%]
$N = 1$	1.092
$N = 3$	0.737
$N = 5$	0.505

Table 6.2: The maximum absolute value $\max|r|$ of r is presented.

In Fig. 6.8 one can observe high deviations of the $N = 1$ run compared with the runs with $N = 3$ and $N = 5$. This is quantified by the calculated maximal relative deviation $\max|r|$ in Tab. 6.2. As expected the deviation for five measurements is the lowest. With $\max|r^{N=5}| = 0.505\%$ the maximal relative deviation for five measurements is only the half of $\max|r^{N=1}| = 1.092\%$ and a still less than $\max|r^{N=3}| = 0.737\%$. Furthermore, one can observe the error bands overlapping to a large extent in Fig. 6.8. Therefore it is reasonable to take both, three and five measurements into account as possible options. The option of $N = 1$ is excluded due to its large error and $N = 10$ due to its long duration, as mentioned before. A final decision is made within the following section 6.1.3.

6.1.3. Accuracy versus Measurement Duration

The still outstanding discussion is the final “cost-benefit” consideration of the measurement duration and the measurement accuracy. The choice has to be made be-

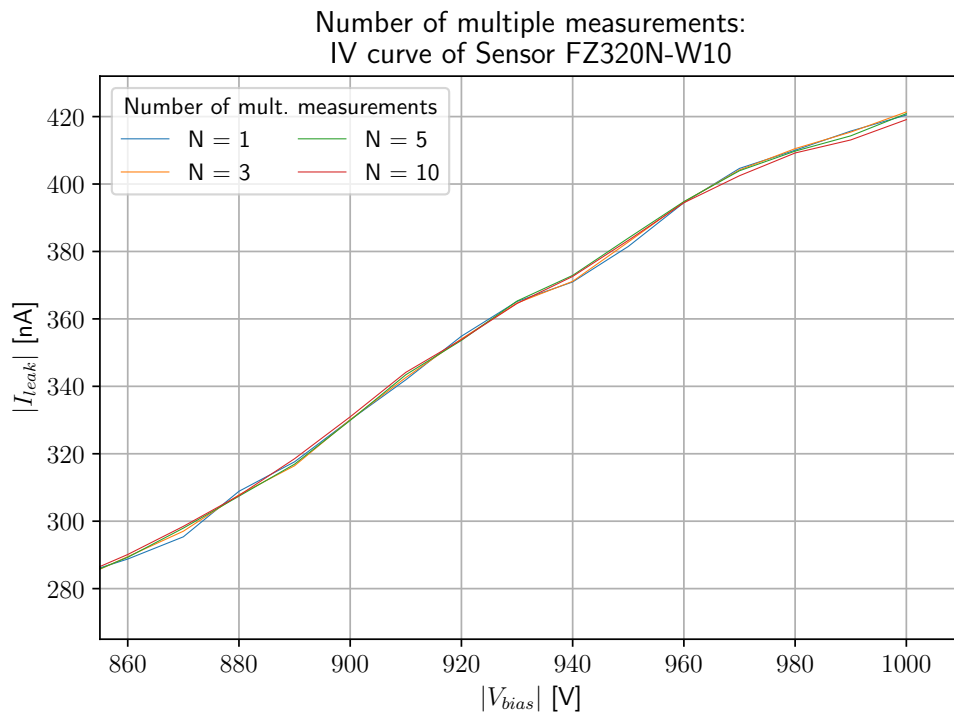


Figure 6.7: Zoom to the voltage range of 860 V to 1000 V of the I-V curve of the sensor FZ320N-W10 evaluated for the number of measurements N (see legend). Lines are drawn to guide the eye.

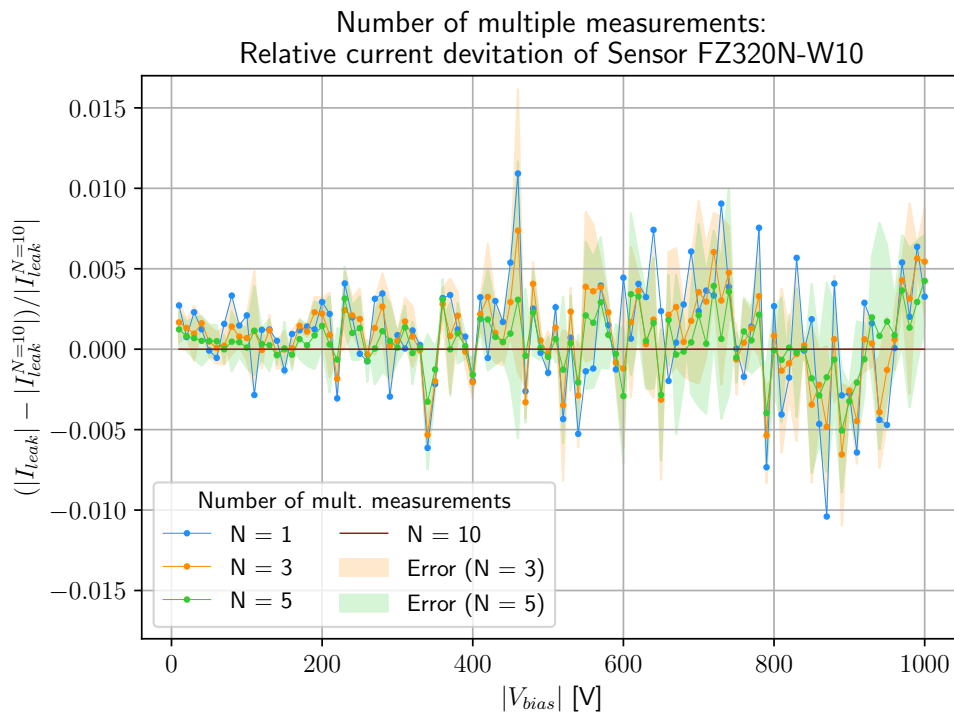


Figure 6.8: The relative current deviation is plotted against the bias voltage for different parameters (see legend). The uncertainties are indicated by error bands.

tween a waiting time of one or two seconds and three or five multiple measurements. Here it should be mentioned again that the waiting time is an internal parameter of the LV program, which cannot be changed by the user. In contrast the number of multiple measurements can be changed by the user on the front panel, thus the aim is to find a default value. Therefore the duration of measurements, ramping and full runs with different parameters is measured and presented in the following.

In order to address the question of duration the so called integration time t_{int} , which is an internal Keithley power supply configuration, has to be considered. This parameter configures how long an input signal is measured by the A/D converter. The unit of the integration time is the so-called number of power line cycles (NPLC) and can be chosen between 1 NPLC and 10 NPLC, whereby one PLC is 20 ms. It affects the speed as well as the accuracy of the measurement, where 1 NPLC is the fastest integration time with the highest amount of noise and 10 NPLC the slowest with the best noise rejection [43].

For the first estimation of the total duration time T^{total} , the integration time is set to its maximum value of 10 NPLC, because it is the setting with the highest measurement accuracy. The runs are done for combinations of a waiting time of 1 s and 2 s and for both with a number of measurements of 3 and 5. The results are shown in Tab. 6.3. The given values for the total duration time are subject to fluctuations of a few seconds. This can be caused by a varying execution speed of the LV program e.g. due to RAM capacity of the NUC. One can see that the total duration time is the highest for $N = 5$, but also for $N = 3$ and a waiting time of 2 s a full run still needs more than 10 min. In the context of building 1000 modules within two years which corresponds to four modules per day with two sensors each, this is a lot of time within the series production. Based on this consideration together with the results in Sec. 6.1.1 the parameter of the waiting time is set to 1 s. With regard to Sec. 6.1.2 the number of multiple measurements is set to a default value of 3. These choices are based on an analysis using the mini-sensor, and have to be confirmed by a measurement with a 2S sensor.

A total duration of about 10 min is too much for the series production. Therefore the influence of the integration time on the duration is investigated in the following. The runs discussed in the previous paragraphs were recorded with an integration time of 8 NPLC. It is investigated if a high measurement accuracy is still given for $t_{\text{int}} = 8 \text{ NPLC}$ (Tab. 6.3). For the duration a time of $T^{\text{total}} = 8.29 \text{ min}$ is measured.

A reduction of the total duration of 1 min corresponds to a time-saving in the order of several 24 h-days in the assembly process. Therefore, further studies with a series of parameter variations, especially of the integration time, are performed. A reduction of the integration time reduces not only the time for the measurement, which is also reduced by lower values for t_{wait} and N , but the time needed for the bare ramping is reduced, too. An integration time of 10 NPLC leads to a ramping duration of 3.10 min, while it needs only 2.30 min with an integration time of 5 NPLC. More results of runs with varied parameters can be found in Tab. 6.3 and the corresponding I-V curves are shown in Fig. 6.9.

One can see, that the integration time has a high influence on the duration of a run, but also on the smoothness of its I-V curve. Regarding Fig. 6.9 one can clearly ex-

t_w [s]	N	t_{int} [NPLC]	T^{total} [min]
1	3	10	09:30
1	5	10	12:46
2	3	10	10:50
2	5	10	14:32
1	3	8	08:29
1	1	1	05:04
1	10	1	07:56
1	1	10	06:55
1	3	5	07:20
1	5	5	09:19

Table 6.3: Run durations for several combinations of parameters. The final choice parameters are printed bold.

clude the parameter combination $N = 1$ and $t_{\text{int}} = 1$ NPLC (blue curve), due to its high fluctuations. Moreover, the parameter combination $N = 1$ and $t_{\text{int}} = 10$ NPLC (green curve) is excluded, because strong fluctuations can be observed over the entire course of the curve. The curve with the parameters $N = 5$ and $t_{\text{int}} = 5$ NPLC (violet curve) has a smooth profile, but the measurement duration of 9.19 min is too long in comparison to the other runs. Therefore this parameter combination is excluded, too. A choice of the lowest integration time together with a high number of multiple measurements, thus the parameter combination $N = 10$ and $t_{\text{int}} = 1$ NPLC (yellow curve), provides a good run duration of 7.56 min and the smoothness of the curve is mostly acceptable. But in comparison to a parameter choice of $N = 3$ and $t_{\text{int}} = 5$ NPLC (red curve), the yellow curve shows more fluctuations especially at high voltages and its measurement duration is also approximately 30 s longer. Moreover, an integration time of 1 NPLC corresponds to the lowest measurement accuracy. Therefore a parameter combination of $t_{\text{wait}} = 1$ s and $N = 3$ and $t_{\text{int}} = 5$ NPLC resulting in a total measurement time of approximately 7.20 min is chosen for the final measurements with the 2S sensors.

6.1.4. Measurement Direction

The last question to be answered is if there is a preference to start measurements at low voltages, measure to high ones and finally ramp down to 0 V or vice versa. This discussion concerns default values, thus which values are set to the “Start Voltage” and “Stop Voltage” indicators on the front panel. It is expected that the charge carriers on the sensors rearrange faster going from high to low electric field strengths, which would show up as a hysteresis of the I-V curve. The SQC specifications suggest to measure from high to low voltages, too. In order to confirm this expectation an analysis of the ramping and measurement behaviour is presented in the following. As parameters a waiting time of $t_{\text{wait}} = 1$ s and a number of multiple measurements $N = 3$ is chosen, as determined in Sec. 6.1.3. For the integration time a

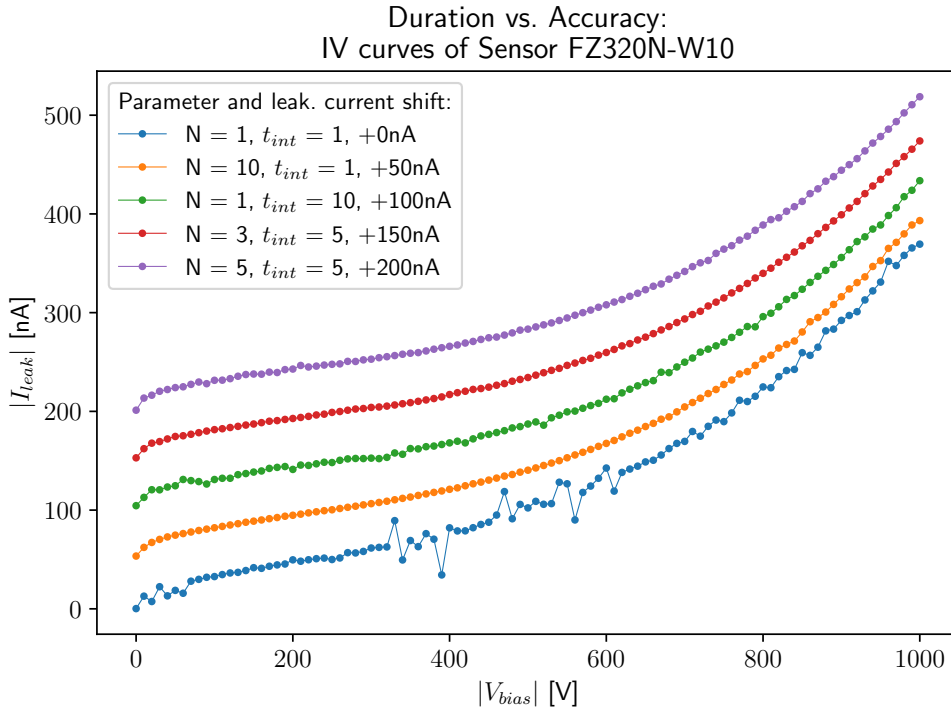


Figure 6.9: I-V curves of sensor FZ320N-W10 measured with different parameters. The waiting time is 1 s for all curves. The leakage current is shifted by a constant (see legend “+ y nA”). The integration time is given in NPLC. Lines are drawn to guide the eye.

higher value of $t_{int} = 10$ NPLC is deliberately chosen in order to have the highest possible accuracy during the ramping phase.

In Fig. 6.10 I-V curves of different runs with the same mini-sensor are presented. It is exploited that the LV program saves not only the data within the measurement action (i.e. ramping plus measurement), but also the bare ramping process from 0 V to the “Start Voltage” or from the “Stop Voltage” to 0 V. Thus the behaviour of the leakage current of a full run is shown. Four runs with the measurement from low to high voltages (Run 1 to Run 4) and two measurements from high to low voltages (Run 5 and Run 6) are presented. All measurements are performed with the same parameter set. A mean of the multiple measurements ($N = 3$) has already been calculated. To be able to observe differences between the six runs, the leakage current is shifted by a constant y . For the observation of a hysteresis the absolute value of the leakage current is less important, but the difference between the data of measurement and ramping is. One can clearly observe a higher difference of the leakage current between the ramping and the measurement data for the runs with measurement from low to high voltages. In contrast the run 5 (red) and Run 6 (orange) show hardly any hysteresis.

To have a quantified indicator of the hysteresis the mean difference of the ramping leakage current I_r and the measurement leakage current I_m , $\overline{\Delta I}$, and its uncertainty, $\sigma_{\overline{\Delta I}}$, is calculated for each run, whereby $\Delta I = |I_r - I_m|$. The difference, $\overline{\Delta I}$, is calculated point by point for each voltage step and then the mean is taken. The results can be found in Tab. 6.4. For the calculation of the uncertainty $\sigma_{\overline{\Delta I}}$ it is assumed

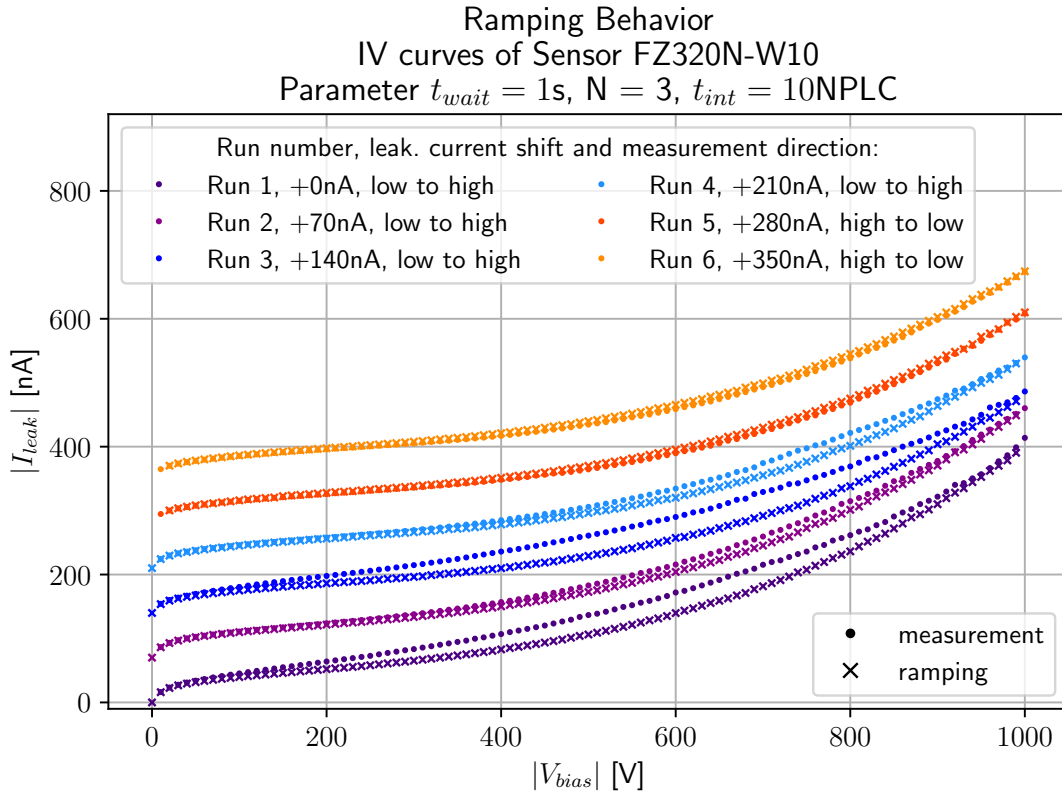


Figure 6.10: I-V curves and their ramping behaviour of different runs with the sensor FZ320N-W10 are presented. Run 1-4 and Run 5-6 have are measured with the same parameters, respectively. The leakage current is shifted by a constant (see legend “+ y nA”). The remarks in the legend “low to high” and “high to low” refers to the measurement direction, thus to the applied voltage. The dots indicating the data of the measurement process. The crosses indicate the data recorded during the bare ramping process.

that the biggest uncertainty originates from the sensors behaviour itself and that the measurement uncertainty from the Keithley power supply can be neglected. For the measurement leakage current I_m the standard deviation σ_{I_m} of the multiple measurements is taken as dominant uncertainty. For the ramping leakage current I_r a standard deviation cannot be calculated as it is a single measurement. However, it is clear that the ramping process underlies the same charge fluctuations as the measurement process. Therefore the same uncertainty $\sigma_{I_r} = \sigma_{I_m}$ is assumed for both processes. One can clearly see, that the mean difference in the leakage current is much higher for Run 1 to Run 4 than for Run 5 and Run 6.

Taking into account the observation in Fig. 6.10 and the mean differences of the leakage current in Tab. 6.4, one can clearly confirm that a measurement from high to low voltages is recommended. Thus the default values for the “Start Voltage” and the “Stop Voltage” are set to -1000 V and 0 V, respectively.

	$\overline{\Delta I}$ [nA]	$\sigma_{\overline{\Delta I}}$ [nA]
Run 1	23.33	0.27
Run 2	11.12	0.09
Run 3	25.12	0.09
Run 4	11.89	0.06
Run 5	3.83	0.07
Run 6	4.15	0.05

Table 6.4: The mean difference $\overline{\Delta I}$ of the ramping leakage current and the measurement leakage current and its uncertainty $\sigma_{\overline{\Delta I}}$ are shown for each run.

6.2. Parameter Validation with a 2S Sensor

The parameters resulting from studies with a mini-sensor have to be validated by a study with a 2S sensor, for which we use the one with the serial number 34358.027_2-S_MAIN0. This means the main part of the analysis done in the previous chapter is repeated for the I-V measurement of a 2S sensor. To preserve the sensor, it is contacted once and only three I-V curves with different parameters are recorded. The first run is done with the intention to have the highest possible accuracy, thus providing an I-V curve to compare to. This means a number of $N = 20$ multiple measurements and an integration time of $t_{\text{int}} = 10$ NPLC are chosen. The waiting time is set to $t_{\text{wait}} = 1$ s for all three runs, as it would be observable within the temporal behaviour of the data if this parameter is chosen too small. The second run is performed with the parameters of choice, i.e. $t_{\text{wait}} = 1$ s and $t_{\text{int}} = 5$ NPLC. The number of multiple measurements is set to $N = 10$, to be able to analyse the temporal behaviour of the leakage current. Hence a measurement with the chosen parameter $N = 3$ can be examined by taking only the first three measurements per voltage step. The last run is performed with an integration time of $t_{\text{int}} = 10$ NPLC and a number of multiple measurements of $N = 10$. It is recorded to be able to investigate the influence of the integration time on the leakage current fluctuation.

In Fig. 6.11 the I-V curves for both the “most accurate” and the parameters of choice are shown. One can observe that both curves overlap very well for most of the measurement range. The difference above 900 V probably originates from a training effect, as both runs are recorded right after each other. To ensure that the chosen parameters are a sufficient parameter choice, the analysis of Sec. 6.1.1 is transferred to the 2S data in the following.

The temporal behaviour of the leakage current for the parameter of choice is analysed (Fig. 6.12), to ensure that the chosen waiting time of 1 s is long enough to suppress a leakage current shift due to the rearranging of free charge carriers. Therefore the normalised leakage current for a specific voltage shifted by its mean to the zero line $(I_{\text{leak}} - I_{\text{mean}})/I_{\text{mean}}$ is plotted against the time passed after the first data was taken. The same analysis for leakage current measurement with the most accurate parameters can be found in the App. A.3.

In Fig. 6.12 there is no time-dependence shift of the curves observable. The measurement points are with except of the curve for 200 V evenly distributed within a

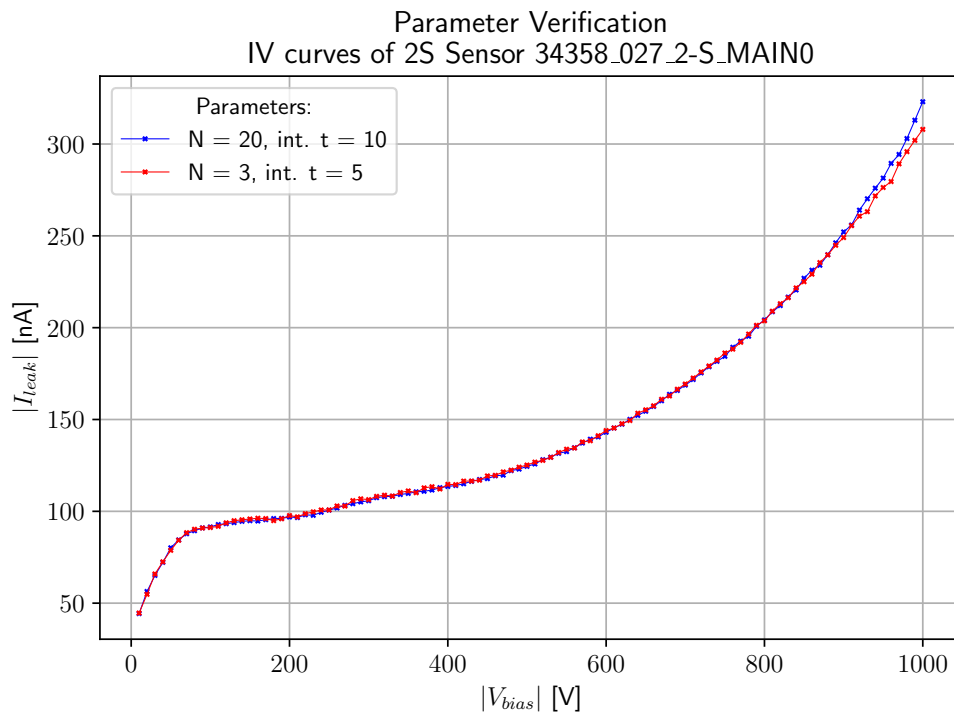


Figure 6.11: I-V curves for the “most accurate” (blue) and the parameters of choice (red) are shown. Lines are drawn to guide the eye.

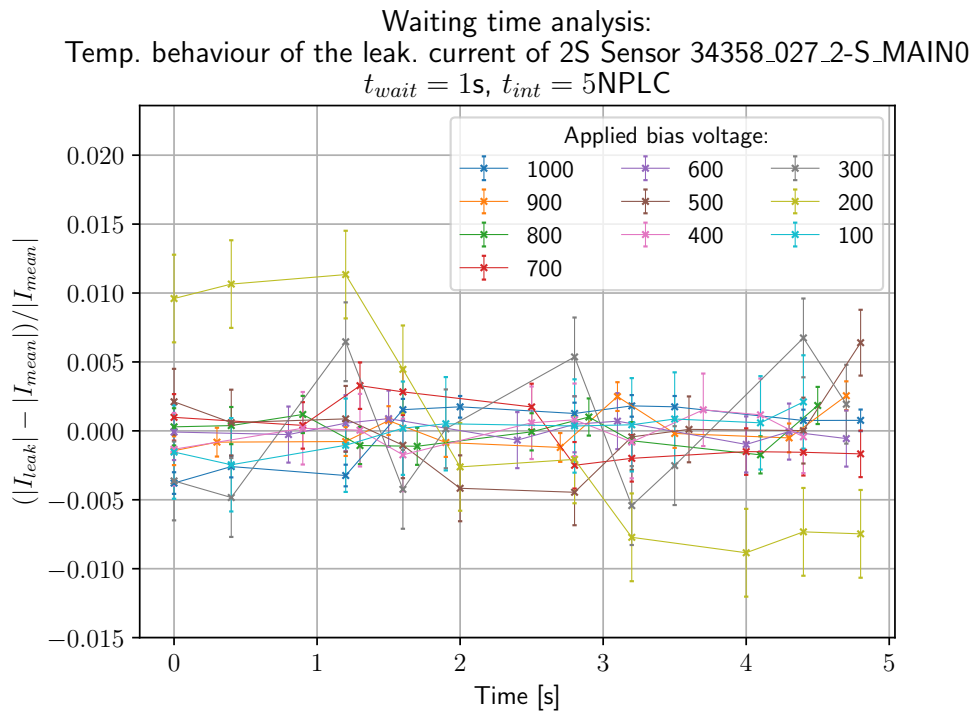


Figure 6.12: The temporal behaviour of the normalised leakage current shifted to the zero line of a 2S sensor is shown for voltages in steps of 100 V. Lines are drawn to guide the eye.

deviation of 1.5 % around the zero line. Therefore one can conclude that a waiting time of 1 s is sufficient to ensure that no temporal shift influences the measurement accuracy.

To take a closer look at the accuracy of the measurements and therefore to the number of multiple measurements, the relative standard deviation of the I-V curve with the parameters of choice is compared to the most accurate parameters. In addition a run with an integration time of 1 NPLC is shown, to be able to investigate the influence of this parameter, too. The analysis is performed analogue to Sec. 6.1.1. In Fig. 6.13 the relative standard deviation of the I-V curve with the most accurate parameters (blue), with the parameters of choice (red) and with the lowest integration time (green) is plotted against the bias voltage. The measurement at 10 V is not shown, because its relative standard deviation for the lowest integration time run is about one order of magnitude larger than all other values. Moreover, the Keithley 2410 accuracy for all three runs is determined with Eq. 6.1 and shown in the plot. One can observe that the relative standard deviation has a similar trend for all three cases. Furthermore, an ordering in the values for the relative standard deviation from green, over blue to red can be seen. The maximum of the green curve is at approximately 3.1 %, the one of the blue curve is at approximately 1.3 %, and that of the red curve at approximately 1.3 %, hence the maximal deviation of the lowest integration time run is more than twice compared to both of the other runs. That the relative standard deviation for $N = 3$ is lower than the relative standard deviation for $N = 5$ was not the expected result and cannot be reasoned. The measurement accuracy of the Keithley 2410 is for both measurements not the dominant contribution to the relative standard deviation. Overall one can conclude, that a number of multiple measurements of three, an integration time of 5 NPLC together with a waiting time of 1 s provides a good balance of the parameters for the leakage current measurement.

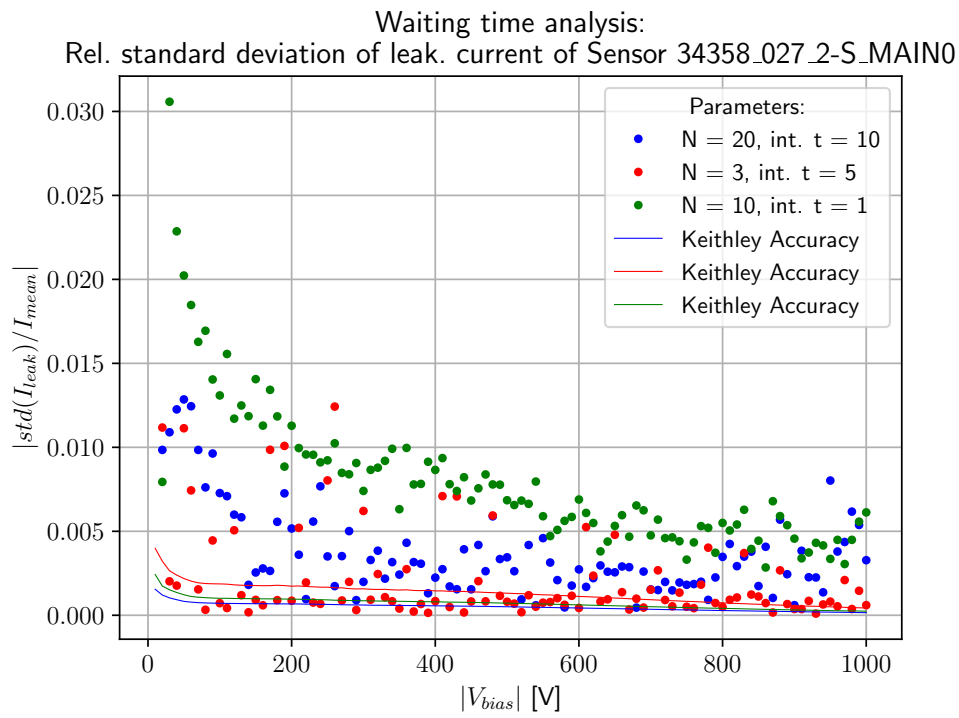


Figure 6.13: The relative standard deviation measurements of the leakage current with different parameters of a 2S sensor is plotted against the voltage. The Keithley 2410 accuracy is indicated for each set of parameters by a line.

7. Evidence studies with the Control Interface and 2S Sensors

Finally the application of the developed control interface for the usage of a 2S sensor characterisation is presented. In the following, a short presentation of the functionalities for each measurement tab is given by using the characterisation of different 2S sensors.

7.1. I-V Measurement

I-V curves of different 2S sensors recorded with the presented control interface are shown in Fig. 7.1. The leakage current of eight sensors of three different batches is characterised. The batch number is indicated by the first number shown in the legend, while the second number indicates the sensors number within a batch. As there is no doubling of the sensor numbers beyond the batches, the sensors will be shortly named by their numbers without mentioning the batch in the following. Furthermore, the data measured at the Karlsruhe Institute of Technology (KIT) SQC are shown. All measurements shown here (Aachen and KIT) are temperature corrected to 22°C. The addition “low to high” indicates, that the data are measured from low to high voltages contrary to the chosen default setting in Ch. 6.

In Fig. 7.1 one can clearly observe that there are deviations between the measurements performed at Aachen and at the KIT for many sensors. All I-V curves measured in Aachen have a higher leakage current than the I-V curves measured at the KIT, while a small decrease of the leakage current due to the training effect is expected. The sensors 027 (dark blue), 008 (purple) and 033 (pink) still have similar I-V curves for both measurements, while the others show a strongly increased leakage current already starting at low voltages. One can observe that only one sensor of the batch 35958 and all sensors of the batch 36245 show a strong deviation from the measurement at the KIT. The relative humidity during the measurements was between 16 % and 23 % for all measurements, thus the relative humidity is probably not the reason for the deviations. A possible reasons for this behaviour may be connected to a difference in the batch quality, but with the low statistics one cannot make a reliable conclusion.

Another functionality of the I-V measurement tab of the LV program is the option to load up to four previously recorded measurements simultaneously in the graph shown on the front panel. As demonstration Fig. 7.2 shows a screenshot of the tab structure of the front panel. Three different I-V curves of sensor 35958_027_2-S_MAIN0 are plotted. The user is now able to compare the different measurements. A comparison between the I-V curves of different sensors is possible, too. Therefore, the user is able to compare e.g. different I-V curves within a delivered batch with little effort.

7.2. I/V-t Measurement

The I/V-t measurement of the 2S sensor 35958_015_2-S_MAIN0 is presented in Fig. 7.3 and Fig. 7.4. It has to be mentioned that this sensor has a strongly increased leak-

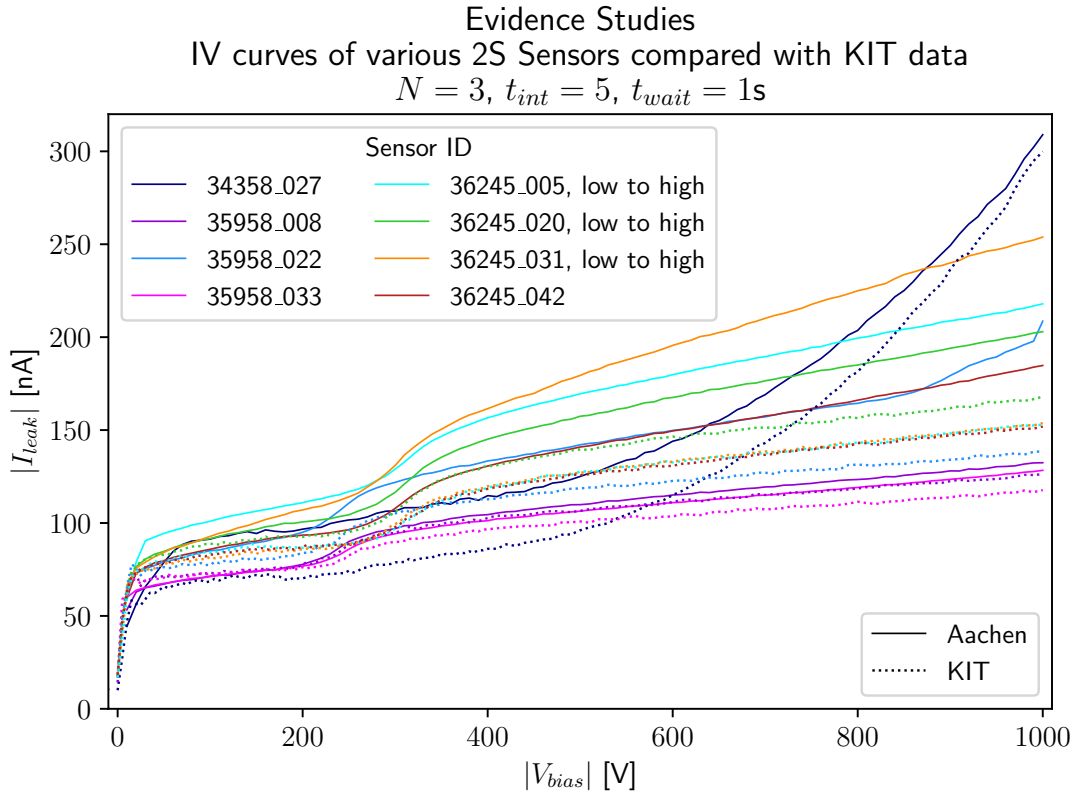


Figure 7.1: I-V curves measured in Aachen (solid lines) and at the KIT (dashed lines) of different 2S sensors. The remark in the legend “low to high” refers to the measurement direction. Lines are drawn to guide the eye.

age current in comparison to typical I-V curves. This behaviour has no influence on the quality of the I/V-t measurement, but explains the high measured values for the leakage current shown in the following plots. Figure 7.3 shows a plot displayed on the front panel saved within the data tree structure by the control interface. The leakage current (red) and the voltage (blue) are shown on the left and right axis, respectively. For both the mean of all data points within a time interval of 10 s is plotted against the time passed since the start of the measurement. Moreover, the maximal current within each time interval is indicated by red crosses, to be able to observe current peaks. In Fig. 7.4 the same data analysed after the recording are shown. Four y -axes are plotted: the leakage current I_{leak} (red), the bias voltage V_{bias} (blue), the relative Humidity rH (pink) and the temperature T (green). The axes are plotted against the time passed since the start of the measurement. The voltage and the temperature have a very constant course and are thus shown as lines for a better readability. For the leakage current and the relative humidity every measured data point is plotted.

One can see by comparing with Fig. 7.3, that the plotting of the maximal current indicates peaks very well. Furthermore, one can see a correlation between high fluctuations of the relative humidity and peaks in the current at approximately 22 min. However, with the present data a statement about a causal link between both cannot be made.

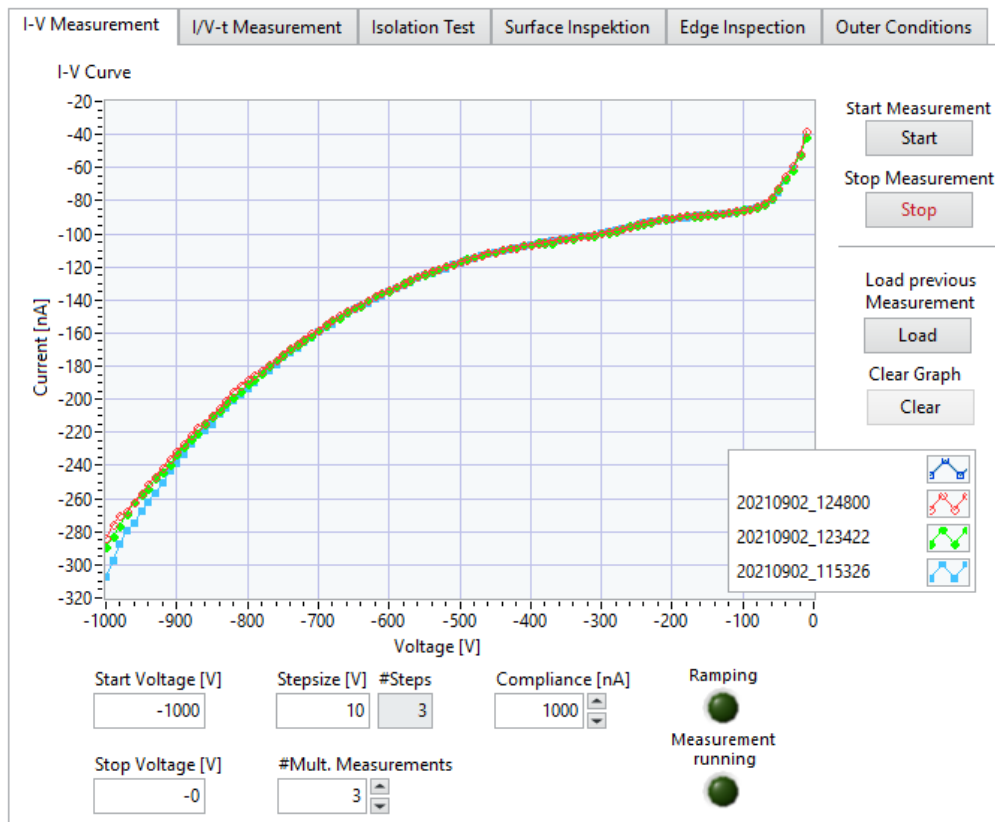


Figure 7.2: Screenshot of the I-V measurement tab of the front panel. Via the “Load” functions three previously recorded I-V curves of the 2S sensor 35958_027_2-S_MAIN0 are loaded in the graph on the front panel. The numbers in the legend represent the date and the time of the measurement.

In general the time dependant evolution of the leakage current can be monitored very well during the measurement by directly plotting the leakage current and the applied voltage. Moreover, a more detailed analysis of the recorded data in retrospect is possible to investigate potential correlations between the environmental conditions and the leakage current or to monitor the development of e.g. the relative humidity only.

7.3. Isolation Test

The first characterisation measurement during the serial production will be the Isolation Test. This is performed after the Kapton strips are applied and the pigtails are glued and bonded to the sensors’ backside. To test if the isolation of the Kapton strips is sufficient a voltage of ± 1000 V is applied by a stepwise increase analogue to the I-V measurement. In Fig. 7.5 the results of an Isolation Test with an old¹⁷ 2S sensor is shown. The test was stopped manually by the user at a voltage of 940 V, hence no larger values are plotted. At 810 V a peak of the leakage current can be observed, which is probably caused by a spark over to the jig or to a pollution on

¹⁷The sensor is still intact, but was used for several measurements and a bare module assembly in the past.

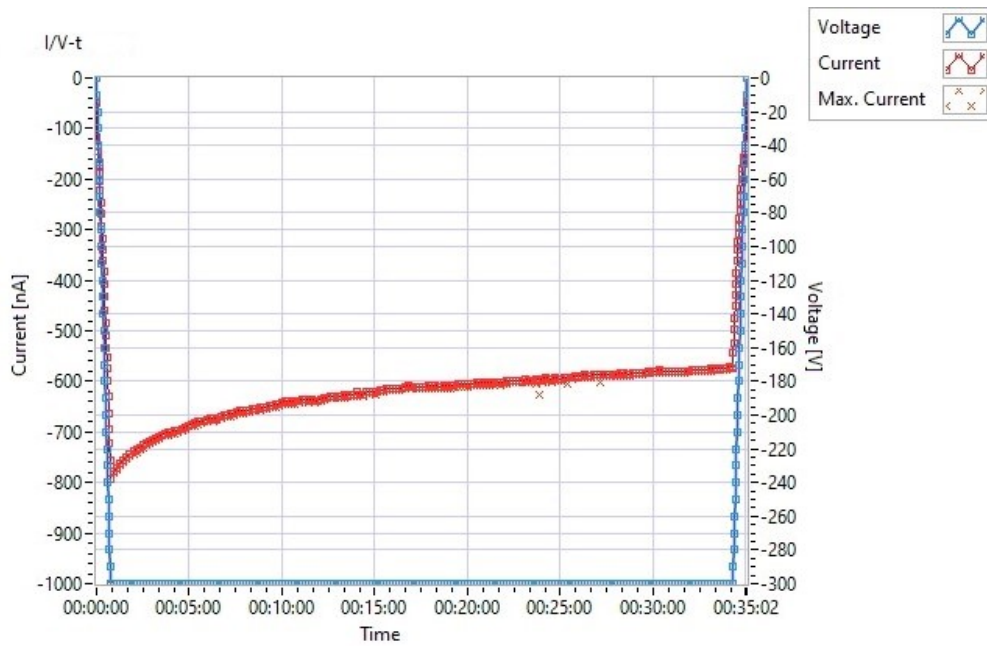


Figure 7.3: A picture of the I/V-t graph shown on the front panel recorded by the LV program is shown.

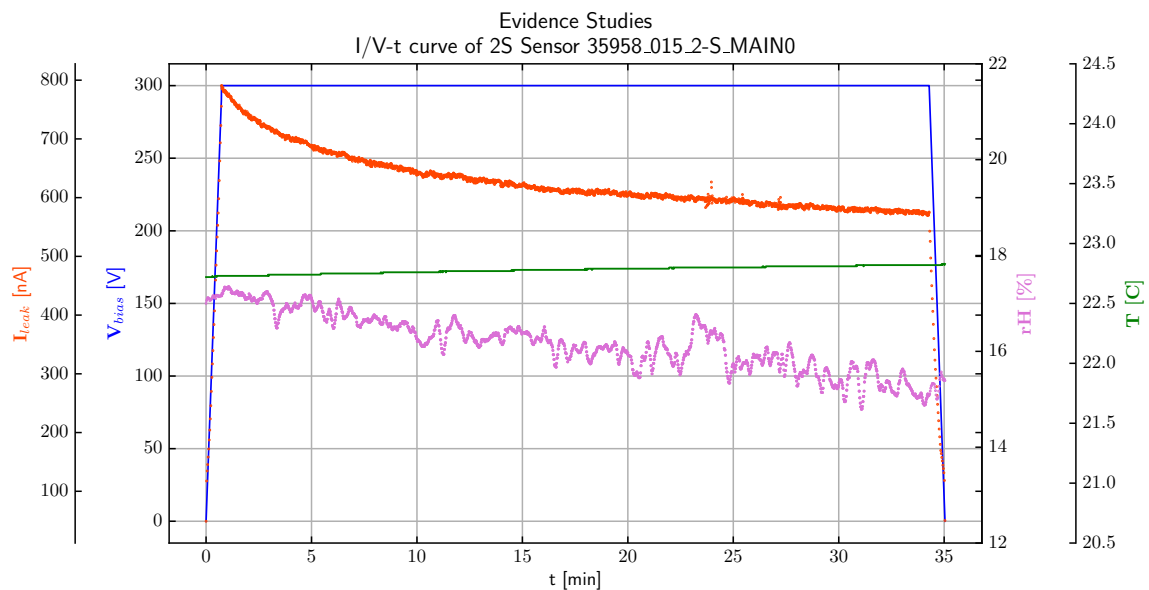


Figure 7.4: An analysis of the I/V-t measurement is presented. The leakage current I_{leak} is shown in red, the bias voltage V_{bias} in blue, the relative humidity rH in pink and the temperature T in green.

the sensor's backside. As the compliance was set to 1000 nA and the single point measurement has a value of 824 nA the program did not ramp down after the peak. A further inspection of the sensors Kapton insulation status should now be initiated by the user. Moreover, one can observe a slight increase of the leakage current up to approximately 21 nA, which is still a good performance of the Kapton insulation. For the Isolation Test the "Load" function is available, too, but due to its similarity

to the I-V measurement function it is not shown here. A screenshot of an example for the Isolation Test can be found in the App. A.4.

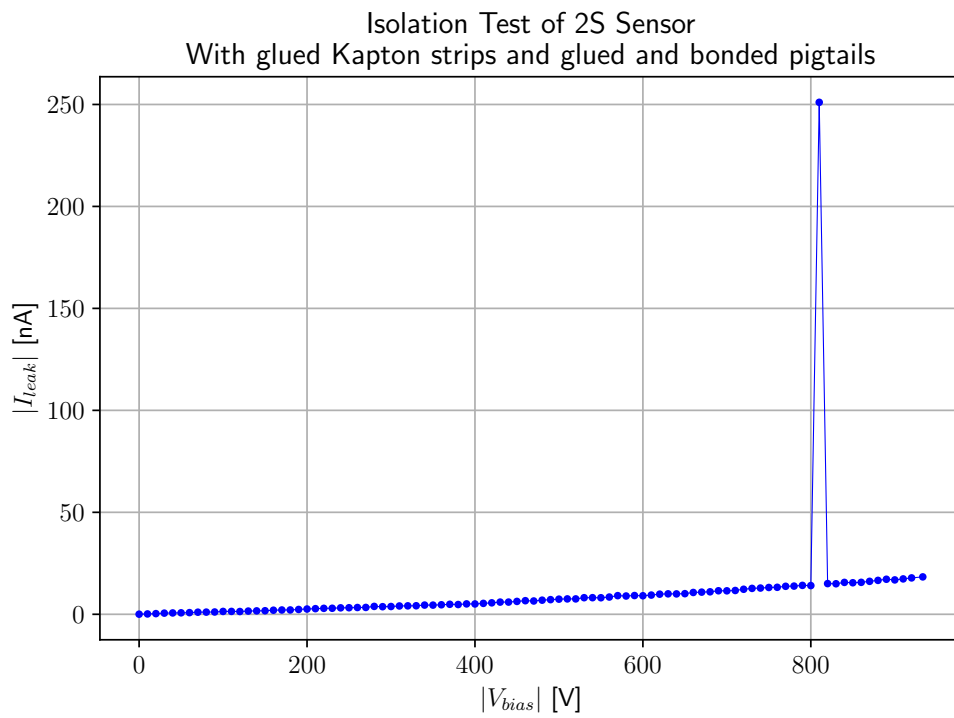


Figure 7.5: A plot of the Isolation Test of an old 2S sensor with assembled Kapton strips and glued and bonded pigtails is shown.



Figure 7.6: Screenshot of the front panel during the SI of sensor 35958.015.2-S.MAIN0.

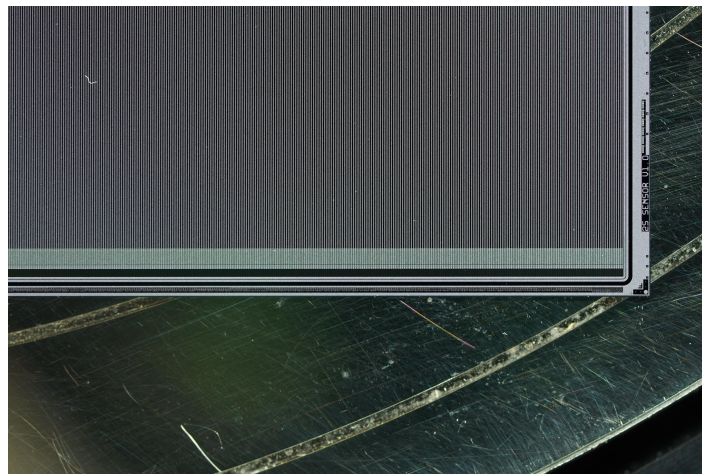


Figure 7.7: One recorded photo of the surface of sensor 35958.015.2-S.MAIN0 taken with help of the LV program. A lint on the surface can be observed.

7.4. Surface Inspection

The optical inspection is done via recording pictures of the sensor. A screenshot of the front panel during the measurement process (Fig. 7.6) and an exemplary picture of the sensor's surface (Fig. 7.7) are shown for sensor 35958.015.2-S.MAIN0 in the following. On the picture of the sensor in Fig. 7.6 one can clearly observe a lint but nevertheless a clean surface of the sensor. Right from the picture the user can see the position of the taken picture on the surface. Moreover, the output buffer provides an indication of the SI status for the user. In Fig. 7.7 a picture of the sensor's upper left edge is shown. One can see the good resolution of the recorded picture, which also shows a lint lying on the sensor's surface.

7.5. Edge Inspection

The edge inspection is also performed for the 2S sensor 35958_015_2-S_MAIN0. In Fig. 7.8 a screenshot of the front panel during the EI is shown. The user can easily observe abnormalities at the four locations of the stops of the jig, thus one is able to further study the recorded pictures and, if applicable, initiate a further inspection of the edges. Moreover, a recent status of the EI is continuously shown in the output indicator right beside the EI tab. A larger view of the lower right picture is also shown in Fig. 7.9. A chip on the sensor's edge can be seen.

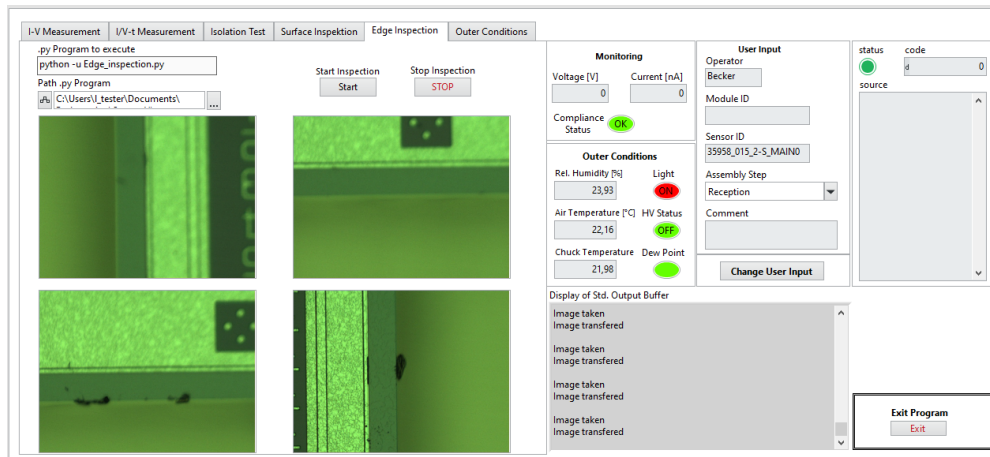


Figure 7.8: Screenshot of the front panel during the EI of sensor 35958_015_2-S_MAIN0.



Figure 7.9: Photo recorded during the EI of the edge of sensor 35958_015_2-S_MAIN0 taken with the help of the LV program. A chip at the edge can be observed.

8. Conclusion and Outlook

In this thesis the development of a control interface for a monitored and automated characterisation of silicon sensors for 2S modules for the CMS Phase-2 tracker upgrade is presented. To unify the execution of all possible quality control tests at the PSt test stand within one program the presented control user interface is programmed with LabVIEW. All tests are evaluated by evidence studies with 2S sensors. It is foreseen to use the here presented program especially during the serial production of the 2S modules at the Aachen assembly centre to speed up the control tests and ensure the sensors' quality.

The implementation of a graphical user interface, which unifies and simplifies the execution of three electrical tests and two optical inspections at the PSt test stand, was successful. The three electrical tests are the I-V Measurement, the I/V-t Measurement and the Isolation Test, while the optical inspections are the Surface Inspection and the Edge Inspection. Within the implementation of the electrical measurements the protection of the sensors from damage has the highest priority. Therefore, the code is programmed in such a way that neither voltage steps greater than 20 V can be performed by accident nor the leakage current can exceed a chosen compliance value, not even if a breakdown of the leakage current happens. Moreover, it is excluded that a high voltage is applied to the sensors as long as any sources emit light within the PSt box. All tests and inspections allow an easy and fast data acquisition. For the optical measurements it is foreseen to implement additional functions, e.g. the calibration of the camera position for the SI. The basic LV structure is already provided.

A study to choose the optimal parameters for the electrical measurements is performed. The investigated parameters are the waiting time after a voltage ramp step t_{wait} , the number of multiple measurements per ramp step N and the Keithley 2410 internal configuration of the integration time t_{int} . A "cost-benefit" consideration of the measurement accuracy and its duration lead to the following parameter choices: $t_{\text{wait}} = 1 \text{ s}$, $N = 3$ and $t_{\text{int}} = 5 \text{ NPLC}$. Hereby, N is only a default parameter, which can be changed by the user, while the other two are internal settings of the LV program. With these parameters a total duration of approximately 7.20 min for an I-V measurement or the Isolation Test is achieved. Furthermore, it was observed that measurements from high to low voltages provide better results for the I-V curves.

In the last chapter the application of the developed control interface is presented. All main functions of the program are shown for the usage with 2S sensors. The interface allows the user to monitor the progress of all tests performed at the PSt right during the measurements. Therefore one is able to directly initiate a more detailed examination of the recorded data if discrepancies to the expected results occur. Moreover, the program provides lots of additional data, e.g. of the outer conditions, to allow for further analyses after the data acquisition.

Summarising, the presented user interface provides an easy handling of all tests at the PSt test stand. All measurements presented in this thesis are performed with sensors, but, of course the tests can be performed with modules, too. For the serial production of 1000 2S modules at the Aachen assembly centre it is essential to ensure

a time efficient test procedure, which provides a secure testing environment for the sensors at the same time. The control interface contributes to this aim.

A further improvement could be the extension of the optical inspections by a calibration and an automatised detail evaluation. Therefore the enhancement of the python scripts, which are responsible for the SI and EI execution, is needed, while the basic LV structure is already provided. Furthermore, not only a measurement but also a control of the PSt chuck temperature would be desirable, to ensure more constant environmental conditions for the electrical measurements. Moreover, a study of the influence of the relative humidity to the leakage current of a 2S sensor based on this control interface (I/V-t Measurement) would be of interest. Therefore the interface is useful also for the preparation of the serial production.

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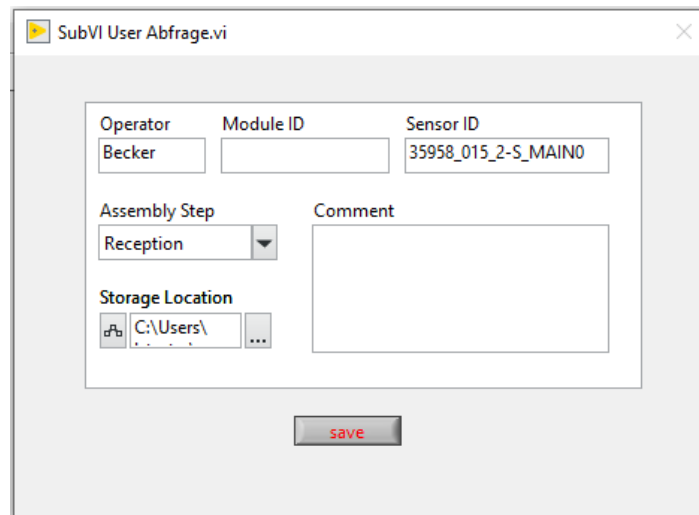
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A. Appendix

A.1. User Input Request

A screenshot of the pop-up window which requests for the User Input. The request is executed by a subVI.



The screenshot shows a pop-up window titled "SubVI User Abfrage.vi". It contains several input fields and a button. The "Operator" field is filled with "Becker". The "Module ID" field is empty. The "Sensor ID" field is filled with "35958_015_2-S_MAIN0". The "Assembly Step" dropdown menu is set to "Reception". The "Storage Location" field shows "C:\Users\" with a file explorer icon and a button to open the file explorer. The "Comment" field is a large empty text area. A "save" button is located at the bottom center of the window.

Figure A.1: User Input pop-up window.

A.2. Demonstration of the Training Effect

The training effect on the leakage current of a mini-sensor is demonstrated. Six measurement runs recorded on two different days are presented. One can observe a reduced leakage current even after days.

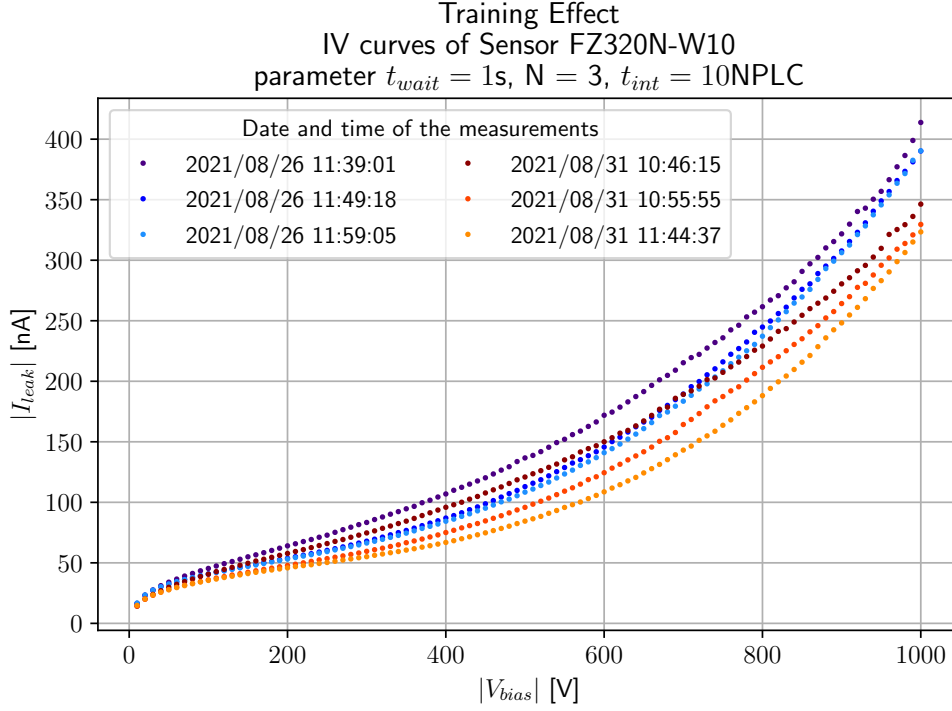


Figure A.2: I-V curves of a mini-sensor measured on two different days at different times within one hour. All runs are recorded with the same parameters.

A.3. Temporal Behaviour of the Leakage Current

The normalised and shifted leakage current is plotted against the time passed after the first measured data point for each voltage step. The run is performed with the most accurate parameters.

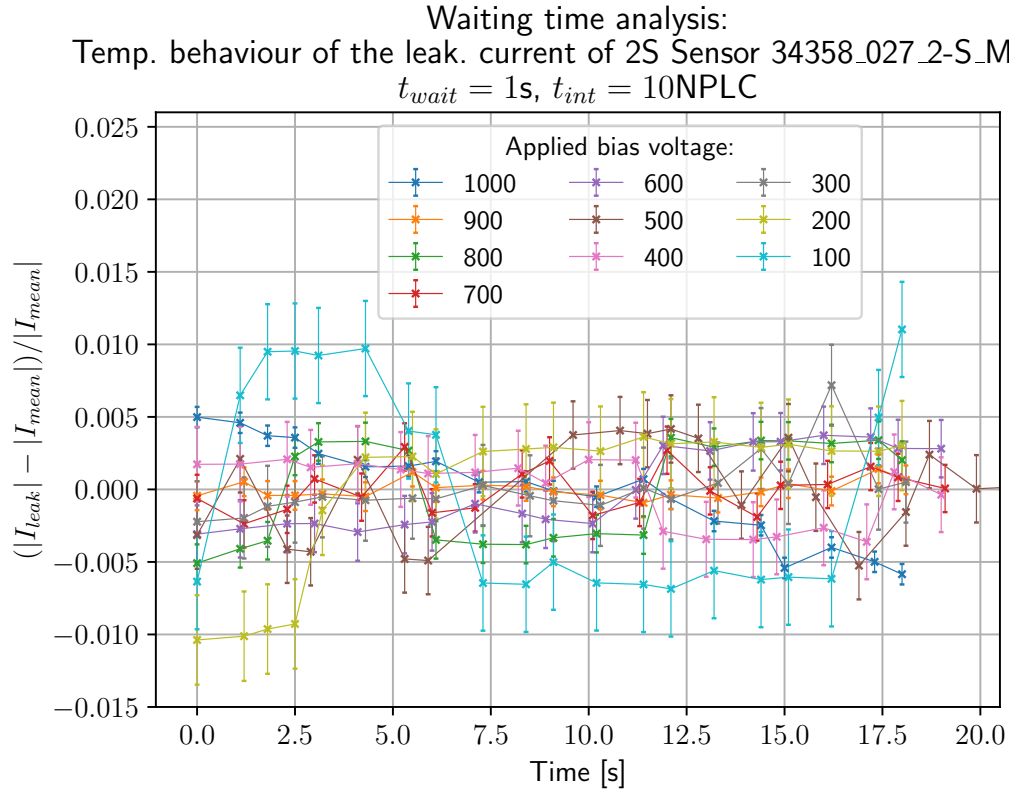


Figure A.3: Most accurate parameters: The temporal behaviour of the normalised leakage current shifted to the zero line for voltages in steps of 100 V.

A.4. “Load” Function for the Isolation Test

A demonstration of the “Load” function for the Isolation Test is given.

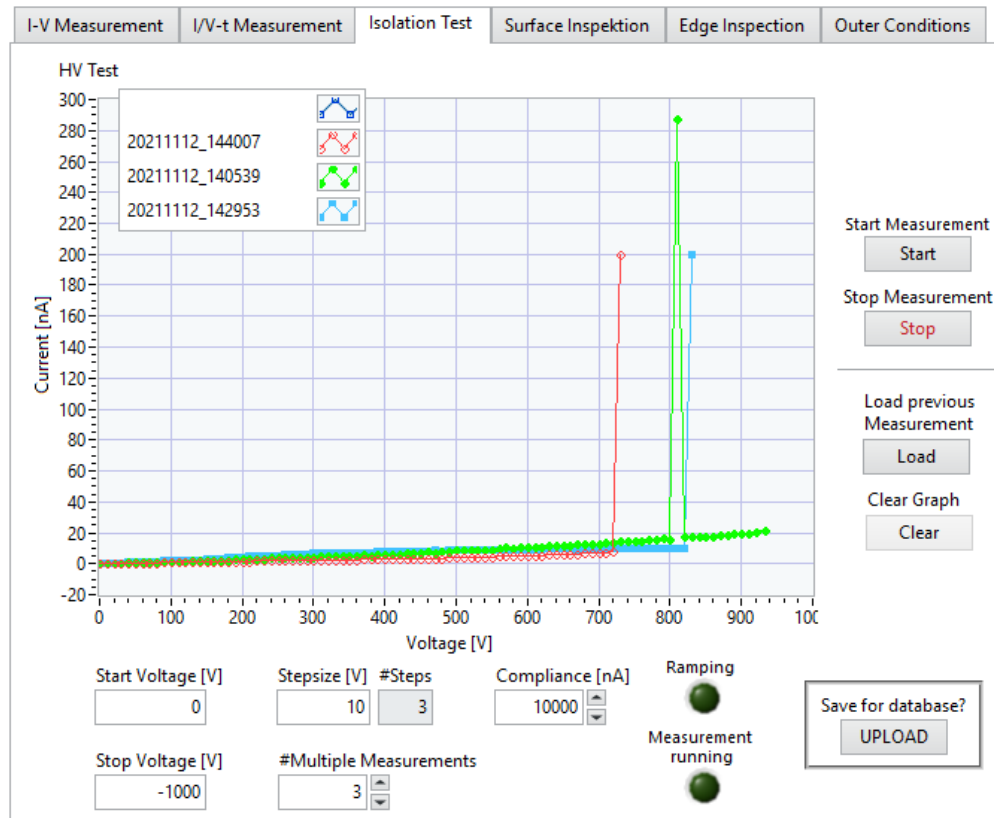


Figure A.4: Screenshot of the Isolation Test tab of the front panel. Via the “Load” functions three past HV tests of an old 2S sensor are loaded in the graph on the front panel.

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Becker, Anna

Name, Vorname/Last Name, First Name

335674

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Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.

Para. 156 StGB (German Criminal Code): False Statutory Declarations

Whoever before a public authority competent to administer statutory declarations falsely makes such a declaration or falsely testifies while referring to such a declaration shall be liable to imprisonment not exceeding three years or a fine.

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(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.

(2) Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Abs. 2 und 3 gelten entsprechend.

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(1) If a person commits one of the offences listed in sections 154 through 156 negligently the penalty shall be imprisonment not exceeding one year or a fine.

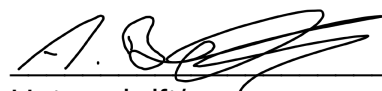
(2) The offender shall be exempt from liability if he or she corrects their false testimony in time. The provisions of section 158 (2) and (3) shall apply accordingly.

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