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Research and development on novel monolithic active pixel sensor prototypes manufactured in 65 nm CMOS imaging technology

Working title

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Zusammenfassung

Forschung und Entwicklung neuartiger monolithisch aktiver Pixelsensorprototypen in 65 nm CMOS Technology

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Abstract

Research and development on novel monolithic active pixel sensor prototypes manufactured in 65 nm CMOS imaging technology

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Contents

Chapter 1

Technology and principles of silicon-based charged particle detection

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. A Large Ion Collider Experiment (ALICE)Complementary Metal Oxide Semiconductor (CMOS)Monolithic Active Pixel Sensors (MAPS)Tower Partners Semiconductor Co., Ltd. (TPSCo)

Chapter 2

Application of monolithic active pixel sensors in high energy physics

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Inner Tracking System (ITS)second generation of the Inner Tracking System (ITS2)third generation of the Inner Tracking System (ITS3)

Chapter 3

Sensor prototypes manufactured in 65 nm CMOS imaging technology

With its upgrade plans for the third generation of the Inner Tracking System ITS3 as described in section ref, the ALICE experiment breaks new ground with the development of novel pixel sensors. The dedicated MAPS for the ITS3 are planned to be manufactured in the commercially available TPSCo $65\,\mathrm{nm}$ CMOS imaging process [1]. This represents the first large-scale application of the $65\,\mathrm{nm}$ CMOS imaging technology (cf. section ref) for sensors in High-Energy Physics (HEP) experiments such as ALICE, and thus paves the way for further future applications in this field.

Chapter 4

Experimental methods for sensor characterisation and calibration

In order to verify the required performance specifications of a newly developed sensor (prototype), specific measurement campaigns need to be carried out. Targeting different aspects of the sensor functionality, these measurements range from basic electrical characterisation of different circuit elements or electrical building blocks of the sensor, as described in chapter 3, to the full-scale evaluation of derived performance quantities. As such, two basic types of measurements requiring different tools and setups can be identified.

On the one hand, there are *laboratory measurements*, which typically involve relatively simple and flexible setups. Exploring the electrical operational behaviour of the sensor under well-defined environmental conditions and input parameters, these tests are essential in order to determine the so-called *dynamic range*.

The dynamic range of silicon pixel sensors and especially MAPS is commonly defined as the ratio between the largest and smallest reliably, detectable signal. Here, the lower limit of the signal amplitude is mainly given by the noise performance of the sensor, while the upper limit is related to limitations in the front-end circuitry. In order to be reliably registered, the signal amplitude must be sufficiently larger when compared to the typical signal amplitude caused by noise, i.e. the noise level. This implies a signal selection criterion based on the Signal-to-Noise Ratio (SNR). In the context of silicon pixel sensors, the signal is often discriminated against a chosen, adjustable threshold value, which effectively makes this the lower limit of the signal amplitude to be considered in the dynamic range. The upper limit of the reliably, detectable signal amplitude is typically given by the saturation of the front-end amplifier output. Apart from this, other limitations such as charge sharing and time-walk effects may also be considered when defining the upper bound of the dynamic range. Furthermore, distortions in the pulse shape of the signal potentially leading to non-linear timing output or hit occupancy effects such as *pile-up* of different signals can be taken into account reference. Such effects become particularly relevant in high-rate environments where overlapping events could cause a loss of information.

As outlined in chapter 3 the *working point* of a sensor is determined by a set of externally supplied bias currents and voltages. In the scope of this work and the considered MAPS prototypes, the dynamic range can also be understood as a range of working points corresponding to stable operating conditions. Laboratory measurements provide the means of determining this parameter space of stable operating conditions, which serve as the basis for more elaborate measurements aiming at the final sensor calibration and thus enabling physics measurements. Here, stable operating conditions refer to settings for which the sensor maintains a reliable and expected signal detection given a known stimulus, while exhibiting a reasonably low noise occupancy and consistent behaviour considering signal shape and pixel resetting.

On the other hand, there are *beam tests*, which utilise beams of charged particles[1] provided by an accelerator facility. As such, this kind of measurement aims at studying the full detection performance under conditions that closely resemble the intended use case of the sensor in the final detector system. By choosing external parameters like the particle type and momentum, different application scenarios can be emulated in a controlled, well-known experimental environment. Therefore, beam tests provide valuable data for sensor prototypes and electrical test structures, which is used to identify and improve deficiencies in the chip design leading to the next iteration of the sensor until all requirements are met in the final version. This often makes beam tests the last validation step before large-scale sensor production, assembly and integration into a larger detector system.

In the following sections, the main types of laboratory measurements are presented in the context of the two tested sensor prototypes, Digital Pixel Test Structure (DPTS) and small-scale version of the Monolithic Stitched Sensor (babyMOSS). This includes a description of the experimental setups and tools, the objectives and procedures of the measurements, as well as a summary and discussion of the main characterisation results. In addition, a calibration method for decoding the hit information from the DPTS is introduced. Finally, the general event reconstruction method is outlined in the context of the beam test results obtained for the DPTS.

4.1 Laboratory MAPS characterisation measurements

In the scope of pixel sensors and especially the prototypes considered in this work, these tests rely on table-top instrumentation. While oscilloscopes or dedicated electrical probes are used to monitor the response of the sensor itself or smaller functional building blocks such as the front-end amplifier output within a single pixel, chillers or climate chambers are used to provide stable and controlled environmental conditions such as temperature, pressure and air humidity.

For performing these kinds of measurements a signal that can be sensed and processed by the front-end circuitry is required. As described in chapter 3 both sensor prototypes under investigation, the DPTS and the babyMOSS provide the possibility to inject a signal charge into each pixel of the sensor. In this case the amount of injected charge can be adjusted via external biasing parameters of the corresponding pulsing circuit. As such this kind of signal generation is suitable for sensor calibration, i.e. determining the working point of a sensor. Another possibility is the use of radioactive sources in order to generate a signal charge within a hit pixel. Knowing the energy spectrum of radioactive isotopes like Iron-55 makes a calibration of the signal height with respect to the deposited charge possible and thus enabling energy

[1]There are also beam lines for electrically neutral particles (photons, neutrons, etc.), which are not relevant for this work.

measurements. Finally, it is also possible to not explicitly provide a controlled stimulus for the pixel. Instead, a signal can be registered from electronic noise arising in the front-end circuitry for several reasons as described in chapter reference. Given a fixed and well-defined measurement time interval, this approach provides the means to characterise the sensor in terms of noise performance.

Laboratory tests are essential in the early phases of sensor development as they provide fast feedback and enable a detailed understanding of individual functional blocks or sensor responses under specific input conditions and working point settings. In the following the most important laboratory measurements for this work are described, and typical characterisation results are presented.

4.2 DPTS testbeam campaigns

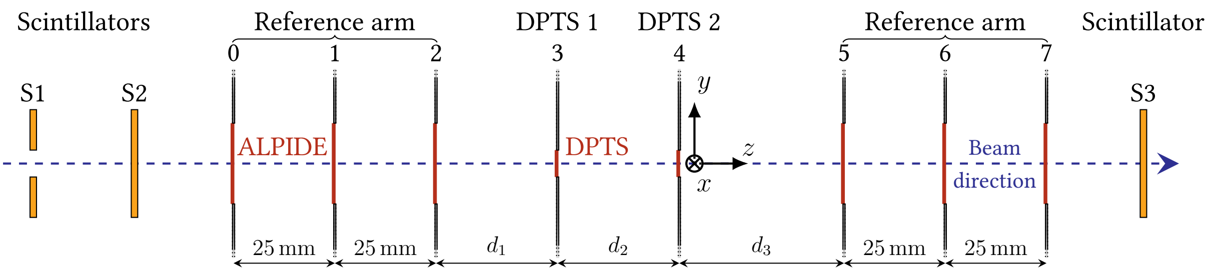

Figure 4.1 Exemplary sketch of a beam telescope (not to scale) as used for DPTS testbeam campaigns. The DPTS sensors act as Device Under Test (DUT). They are placed in between reference planes equipped with ALPIDE sensors. The scintillators (S2, S3) are usually operated in coincidence, and the one with a 1 mm hole (S1) may provide a veto (anti-coincidence). The trigger for the data acquisition can be either provided by a combination of scintillators or directly by one of the two DPTS.

Chapter 5

Performance results for the small-scale sensor DPTS

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Chapter 6

Calibration results for the stitched sensor BabyMOSS

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Chapter 7

Summary, conclusion and outlook

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Appendices

A.1 Nomenclature

The following abbreviations, acronyms, and naming conventions are used throughout this manuscript. For convenience, they are listed in alphabetical order alongside with the pages on which they are used.

ALICE A Large Ion Collider Experiment. 1, 3

babyMOSS small-scale version of the Monolithic Stitched Sensor. 5

CMOS Complementary Metal Oxide Semiconductor. 1, 3

DPTS Digital Pixel Test Structure. 5

HEP High-Energy Physics. 3

ITS Inner Tracking System. 2
ITS2 second generation of the Inner Tracking System. 2
ITS3 third generation of the Inner Tracking System. 2, 3

MAPS Monolithic Active Pixel Sensors. 1, 3, 4

SNR Signal-to-Noise Ratio. 4

TPSCo Tower Partners Semiconductor Co., Ltd.. 1, 3

A.2 List of figures

Publications

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[1] Tower Semiconductor. *https://towersemi.com/*. Accessed April 2025. Official website of Tower Semiconductor. URL: https://towersemi.com/technology/cmos_image_sensor/.

[2] R. Diener et al. "The DESY II test beam facility". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 922 (2019), pp. 265–286. ISSN: 0168-9002. DOI: 10.1016/j.nima.2018.11.133. URL: https://www.sciencedirect.com/science/article/pii/S0168900218317868.

Tools and templates

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Acknowledgements

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Declaration of originality

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Place, Date	Author