The Tangerine project: Development of high-resolution 65 nm silicon MAPS

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Outline

• Introduction
  - Monolithic active pixel sensors
  - The Tangerine project
• Sensor design
• Lab and testbeam investigations
• Simulation studies
• Conclusions and outlook
Monolithic active pixel sensors (MAPS)

- MAPS combine **sensitive volume and readout electronics in a single volume**
  - This enables lower material budget, reduced complexity, and reduced production cost compared to hybrid sensors
  - A low material budget is essential for particle tracking applications
- MAPS have made significant progress in recent years
  - First MAPS used in the STAR experiment
  - Currently used in ALICE; the **ALPIDE chip**
  - The MALTA and MonoPix developments: candidates for ATLAS
  - Current developments for the next ALICE tracker upgrade and the EIC
Monolithic active pixel sensors (MAPS)

- The ALPIDE chip is the current state-of-the-art MAPS sensor installed in a collider experiment
  - It utilises a relatively recent development allowing for a **small collection electrode**, which reduces both detector noise and power consumption
  - The ALPIDE chip is made using a 180 nm CMOS imaging process

- Recently, access has been granted to a **65 nm** CMOS imaging process, and this is envisioned to be used for the next ALICE inner tracker upgrade sensor

- The 65 nm process allows a **higher logic density** compared to previously used processes, leading to reduced pixel size or more in-pixel functionality
  - It also allows for decreased power consumption
  - The process is so far **unused in particle physics applications**, however. It is **crucial** to test it

Artistic view of the ALPIDE chip cross section. Figure from here
The Tangerine project (Towards next generation silicon detectors)

- Started in 2021 with the aim of developing and investigating particle detection sensors in new silicon technologies

- This presentation focuses on Work Package 1 of the project; monolithic active pixel sensors in a novel CMOS imaging technology (65 nm)
  - The project encompasses all aspects of sensor developments: electronics design, sensor design, prototype test chip characterisation

- The goal is development of a sensor with high precision and low material
  - Spatial resolution below 3 µm
  - Time resolution of less than 10 ns
  - Very low material budget, corresponding to at most 50 µm of silicon (0.05% X/X₀)
  - Per-pixel charge measurement

- Primary initial goal (2023): development of a sensor for telescope use, for testbeams
  - This will demonstrate the capabilities of the 65 nm technology in a particle physics context
Sensor design

- The sensor design comprises both sensitive volume and electronics design

- For the sensitive volume design, there are three available processes (all with a small collection electrode) originally designed for a 180 nm CMOS imaging process:
  - Standard process
    - ALPIDE-like
  - Modified process
    - Blanket layer of n-doped silicon, creating a **deep planar junction**
  - N-gap process
    - Blanket n-layer **with gaps at pixel edges**

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S. Senyukov et al. doi:10.1016/j.nima.2013.03.017  
M. Münker et al 2019 JINST 14 C05013
Current sensor architecture

The DESY “MLR1” chip

- The main purpose is to test a newly designed charge-sensitive amplifier circuit
  - Two amplifier variants are available, each with a Krummenacher type feedback network for continuous reset and leakage current compensation
- Also contains a 2x2 pixel matrix with analogue readout
  - Pixel size: 16.3x16.3 µm²
- Electronics and readout design for future submissions is ongoing
  - Final target matrix size: 256x256 pixels
  - Each pixel is intended to have a signal amplitude readout via a time-over-threshold measurement
    - One suggestion is to achieve this by sending analogue “ramps” from the periphery to each pixel, and through this store the threshold crossings of a pixel for later readout
Sensor prototype characterisation - How to test?

- Tests performed in **labs** and at **testbeams**
- Lab tests performed using radioactive sources and current injection pulses
  - Makes it possible to extract **signal waveforms** from the prototype chip
- Testbeams performed at accelerator facilities
  - A beam of particles is shot through the sensor
  - Using a “telescope” made up of reference planes, the particle track position at the sensor can be extracted
    - This can provide measurements of sensor detection efficiency and resolution, and figures of merit for different in-pixel hit positions
  - Initial goal of the Tangerine project: create reference planes for a new telescope for testbeam usage
Lab results - Waveforms

- The analogue pixel signals can be read out, and the output can be used to investigate the behaviour of the in-pixel charge-sensitive amplifiers.

- Tests performed using a $^{55}$Fe source in the lab, and electrons from a testbeam facility.

- Different bias voltages and control currents are used on the chip, to investigate their impact on waveform parameters.

- Example: the signal amplitude for different bias voltages (labelled VSUB)
  - All four pixels shown
  - Each data point has approximately 2500 events

- These are the first results of a 65 nm MAPS at DESY!
Testbeam setup

- The device under test is surrounded by reference planes (which form a telescope)

- A beam of particles is shot through the reference planes and the device under test

- A reference track is reconstructed by using particle hit data from the reference detector planes

- Device under test placed between reference planes
  - Can thus find particle position at device under test from using the reconstructed track
Testbeam - MAMI

- Testbeam in autumn 2021 at the Mainz Microtron (MAMI)
  - Provides a very small beamspot, approximately 1 mm\(^2\)
  - Electron beam energy relatively low; 0.855 GeV
  - High beam current (up to 100 µA), giving a high hit rate
- Tests performed mainly on the 4-pixel matrix of the DESY MLR1 chip
  - Design needs some correction to perform well, but issues are understood, and lessons can still be learned about sensor operation in a testbeam
- Image shows interpolated track positions at the sensor, for tracks associated to a hit in a certain pixel (colour coded)
- The four different pixels have distinct regions
  - The current sensor design thus works as a pixellated sensor, even if design updates are needed to reach high efficiency

Pixel matrix hit positions, associated with hits in different pixels (image by F. Feindt)
Sensor simulations

- The electric fields in the investigated sensor types are highly non-linear, so detailed electric field simulations are performed using technology computer-aided design (TCAD)
  - Numerically solves equations using sensor doping information
    - Note: the exact doping concentrations used at the silicon foundry are not available to this project, so generic doping profiles are used, and varied to gain insight into how sensor performance is affected by different parameters
  - Different pixel geometries and layouts can be simulated in great detail

- High-statistics Monte Carlo simulations are performed using Allpix²
  - The simulated electric field and doping concentration from TCAD can be imported, and used in simulations for each pixel in a pixel matrix
  - Simulations of the full pixel hit chain can be carried out relatively quickly
    - This involves charge deposition, individual charge carrier behaviour, and digitisation

- Together TCAD and Allpix² are a powerful combination! Detailed sensor behaviour and performance can be simulated accurately with high statistics
Detailed electric field simulations using TCAD

- Using *estimates* of doping concentrations of different parts of the sensor, in-pixel electric fields are simulated
  - The estimated concentrations are not related to any real process, but the studies give insight into the effect of varying different parameters of the pixel geometry

- Different doping concentrations are investigated and evaluated, and electric fields produced for different geometries, conceptually similar to the three processes developed for the 180 nm sensors (see slide 6)

- Some aspects in the sensor design can be controlled (such as the n-gap size), and some are fixed. The simulation studies endeavour to optimise the sensor performance by changing non-fixed aspects

- The figures below show example electric field magnitudes, streamlines, and depletion boundaries for the three main investigated geometries

Images by A. Velyka and A. Simancas
High-statistics Monte Carlo simulations using Allpix²

- Using Allpix² to generate incident particles and simulate their energy deposits in a pixellated sensor model (via an interface to GEANT4)
  - Each pixel in the sensor model contains the electric fields and doping concentrations from TCAD
- Deposited energy generates electron-hole pairs, and the individual charge carrier propagation is simulated
- This finally gives the charge per incident particle event that reaches the collection electrode in each pixel
- A threshold is then set in simulations, to exclude pixels that would not produce a hit with this threshold level
  - Noise is also added to the signal in this step
- The Monte Carlo truth information is stored along with the simulated per-pixel output, and analysis is performed
- Allpix² allows the simulation of a particle hit to be performed quickly, and thus makes it practical to generate many particles hitting many different sensor positions
  - High-statistics data are obtained
  - Makes it relatively easy to test and compare different configurations and setups
- The framework is well-tested and validated against known data and experiments, e.g. for small collection electrode MAPS sensors; https://www.sciencedirect.com/science/article/pii/S0168900220303181?via%3Dihub

![Particle beam passing through a single sensor, in Allpix²](https://example.com/particle-beam.png)
# Figures of merit for study

## Efficiency
- Denotes the fraction of particles incident on the sensor that produce a signal in the sensor
- Goes between 0 and 1
  - If all particles traversing the sensor produce a signal, the sensor is 100% efficient
  - Desirable to have as high as possible
- Strongly related to threshold value
- Can find mean efficiency across the sensor, and look at efficiency versus hit position

## Cluster size
- Number of pixels that register hits for a single incident particle (charge sharing)
- This will depend on the position of the incident particle, but with a large number of particles a mean value can be found, as well as the cluster size versus hit position

## Spatial resolution
- Comparing the incident particle position to the reconstructed particle position on the sensor
- In the simulations so far, this is done by comparing the Monte Carlo truth position to a charge-weighted mean position of a cluster of pixels
- Doing this for many events creates a distribution of values
  - Spatial resolution taken to be the RMS value of the central 99.73% of the distribution
Example study: process comparisons for a 20x20 µm$^2$ pixel size

- Comparing the performance of the three different sensor process variations (see slide 6)

- Simulating a 5 GeV electron beam, incident head-on on a single pixellated sensor
  - 500 000 single-electron events per data point
    - Error bars are thus very small
  - Varying pixel hit threshold, and plotting figures of merit versus threshold value

- Figure shows **mean efficiency** in the sensor for different threshold values
  - Colours indicate different processes
  - The modified process and the n-gap process have a larger operating margin than the standard process
In-pixel efficiency maps

- Map of the in-pixel efficiency of 4 pixels, at a threshold of 200 electrons
- Red means 100% efficient
  - The standard process thus loses more efficiency at pixel edges and corners compared to the other processes
In-pixel efficiency maps, gifs (see .pptx file in presentation mode for them in motion)

- From this, it is clear that the standard process loses efficiency at lower thresholds than the other two.
- It is also clear that the modified process loses the square shape of the efficient region (i.e. efficiency at pixel corners) at lower thresholds than the n-gap process.
Example study: process comparisons for a 20x20 µm² pixel size

- The figure shows the **mean cluster size** of the sensor, for different threshold values
  - I.e. the number of pixels that register a signal for an event
- This number tends to 1 as threshold increases, as the charge generated by a traversing particle will eventually not be enough to register as a hit in more than one pixel
  - A MIP is expected to generate a signal of approximately 700 electrons in a 10 µm thick sensitive volume
- The standard process has a larger cluster size than the others, due to the **larger undepleted volume at pixel edges**
  - This leads to charges moving by diffusion, and thus a larger charge cloud
Example study: process comparisons for a 20x20 µm² pixel size

- The figure shows the sensor **spatial resolution** in the x direction, for different threshold values
  - As the simulated pixel in this case is square and symmetric, it looks identical in the y direction

- The resolution relates to cluster size, as the reconstructed hit position is taken as a pixel **charge-weighted mean cluster position**
  - The standard process thus has the best spatial resolution of the three
    - However, the efficiency of the standard process is lowest

- Conclusion: A **balance** needs to be reached between efficiency and resolution
  - The threshold should be kept as low as possible, but what is possible depends heavily on the electronics design and noise

- Using the method of combining TCAD simulations and Monte Carlo simulations, we can **quickly produce high-statistics data of different situations**
Other simulation studies performed

- Comparisons of different **doping concentrations** in different parts of the sensor
- Comparisons of **different pixel sizes**
- Comparisons of different **bias voltage configurations**
- Studies of different **in-pixel geometries**; e.g. different extents of the gap in the n-layer
- Studies of **hexagonal pixels** are beginning
  - Work has been ongoing with generic doping profiles in TCAD for a while, and will soon be studied using Allpix\(^2\)

- There is **significant progress in understanding the impact of different parameters**, and the conceptual design of a new sensor is being converged on!
Current status and future work

• We have tested the first prototype chip (MLR1) thoroughly
  - Both lab tests and testbeam measurements have been performed
  - In-pixel inefficiencies have been found, but are well understood

• Starting tests on an analogue pixel test structure, to compare sensor flavours and see if simulation results match reality

• Testbeam in Mainz again in April, and testbeam at DESY in June
  - Will test the analogue pixel test structure further

• Simulations using generic doping profiles already give insights for use in sensor optimisation

• Currently preparing for our next sensor submission! “Engineering Run 1” is on the way, and will hold the next iteration of our chip
  - Testing new things in electronics; improved electronics design and sensor design

• Conclusion: there are exciting times ahead!
Backup slides
The Tangerine collaboration

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Example study: process comparisons for more pixel sizes

Efficiency

- Figure shows **mean efficiency** for different **pixel sizes** for the different processes

- The standard process efficiency drop severely at pixel sizes larger than 20x20 µm²

- The other two keep efficiency high (and even increasing) as pixel size increases, with the n-gap process being the most efficiency
  - The n-gap process is designed to eliminate inefficiencies at pixel edges and corners, which becomes more important the larger the pixel size is
Example study: process comparisons for more pixel sizes

Efficiency

- Figure shows **mean efficiency** in the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes
Example study: process comparisons for more pixel sizes

Cluster size

- Figure shows **mean cluster size** of the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes
Example study: process comparisons for more pixel sizes

Spatial resolution

- Figure shows **spatial resolution in x** of the sensor for different threshold values
  - Colours indicate different processes
  - Different line styles indicate different pixel sizes