Tests and Simulations of the MIMOSIS CMOS Monolithic Active Pixel Sensor

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Progress in the field of heavy-ion physics is being driven by continuous advancements in instrumentation and particle detectors. These technologies are essential for testing both novel and refined physics concepts. This thesis was conducted in the context of the MIMOSIS CMOS Monolithic Active Pixel Sensor project. MIMOSIS is designed as a charged particle detection sensor to equip the Micro Vertex Detector (MVD) of the Compressed Baryonic Matter (CBM) experiment, which is currently under construction at the FAIR accelerator facility in Darmstadt, Germany.

CBM is a future, fixed-target, heavy-ion experiment designed to explore the QCD phase diagram in the region of high net-baryon densities and moderate temperatures. It will complement the studies conducted by the STAR and ALICE collaborations by utilizing the high-rate proton and heavy-ion beams delivered by FAIR. A variety of ion species will be provided at energies ranging from 2 to 11 *A*GeV, with collision rates of up to 10^7 per second. These high-quality beams are paired with the construction of high-precision detectors.

CBM comprises several subsystems, among which the Micro Vertex Detector (MVD) is the first detector downstream of the target. The MVD is located in a vacuum inside the dipole magnet of CBM. It consists of four planar stations hosting approximately 300 MIMOSIS sensors. The detector is designed to handle heavy-ion and proton beams at rates of up to 100 kHz for Au+Au collisions and 10 MHz for p+A interactions. Its primary function is to separate primary collision vertices from the secondary vertices of short-lived decaying particles. Furthermore, it contributes to the tracking of low-momentum particles in conjunction with other tracking detectors.

The physics objectives of the MVD and its operational environment impose extremely demanding requirements on the MIMOSIS sensors. Each sensor must combine spatial and temporal resolutions of 5 µm and 5 µs, respectively, while being thinned down to approximately 50 µm of silicon. It must also handle a peak hit rate of up to 700 kHz/mm^2, with non-uniform occupancy leading to on-chip spatial gradients approaching 100%.

In addition, the sensors must withstand Total Ionizing Doses (TID) of up to 5 MRad and Non-Ionizing Energy Loss (NIEL) fluences up to 7×10^{13} n_{eq}/cm^2, while maintaining performance until scheduled replacement. Furthermore, the sensor must be able to tolerate heavy-ion impacts arising from possible beam steering mistakes, beam halo ions, and nuclear fragments from the target. The latter are estimated to produce Linear Energy Transfer (LET) values of up to 35 MeV cm^2/mg.

These conditions require the sensor to be hardened against Single Event Effects (SEE), such as latch-ups and bit flips. A low power consumption below 100 mW/cm^2 is required, and the sensor must operate reliably across a temperature range from -40 to 30°C, with a temperature gradient of up to 5K across its area. Heat dissipation will be managed by conduction to an external heat sink via support structures made out of TPG/CVD-diamond.

The MIMOSIS sensor R&D project is a joint collaboration between IPHC-Strasbourg, GSI-Darmstadt, and Goethe University Frankfurt. The project is structured into four prototyping stages: MIMOSIS-0, 1, 2, and 3. This thesis was carried out in the context of testing the two full-scale prototypes, MIMOSIS-1 and MIMOSIS-2. These two sensors feature 1024 x 504 pixels with a pitch of ~ 27 x 30 μm^2. Each chip provides an active area of about 3.1 x 1.3 cm^2, in addition to the digital front-end electronics integrated on the same substrate.

MIMOSIS-1 offers 12 different combinations of pixel types, realized using three different fabrication processes. For each process, the sensor hosts four distinct pixel matrices, each implementing a unique pixel flavour that differs in its sensing node circuitry. In the subsequent prototype, MIMOSIS-2, one fabrication process was excluded, and new sensors featuring a 50 µm thick epitaxial layer were introduced alongside the existing 25 µm thick ones. One of the pixel variants in each prototype is derived from the ALPIDE sensor, developed for the ALICE-ITS2, while the remaining designs were specifically modified to optimize sensor performance.

The tests for MIMOSIS-1 and MIMOSIS-2 were conducted using various particle beams at CERN, DESY, and COSY, covering both non-irradiated and irradiated chips. These beam campaigns first validated the complete sensor detection and signal processing chain. The tests confirmed that both sensors provided pixels that comply with the CBM-MVD requirements. Two pixel type variants were identified as the best candidates for the final sensor version, delivering the best overall performance. All this was determined noting the dependence of each pixel variant on steering settings and operational parameters, such as the applied bias voltages and signal discrimination thresholds. All evaluations were carried out under conditions in which each performance property was influenced by, and in competition with, others across numerous degrees of freedom. The selection process was inherently complex and required identifying the optimal compromise among these competing characteristics.

In addition, a first step was completed in updating the sensor simulation model, which is required for detector-level GEANT-based simulations used in CBM. This was done utilizing the Allpix^2 framework that provided input to the CBM dedicated simulation framework named CBMRoot. An important part of CBMRoot models the signal digitization in the CBM sub-detectors. For the case of the MVD, it relies on the detector response model developed in the past based on beam test data obtained with earlier, so-called MIMOSA sensors. This is considered obsolete for MIMOSIS as it is fabricated with a completely different process and features new device physics. The charge propagation inside the pixel is changed as a result of the different pixel depletion and electric field. Moreover the binary output of MIMOSIS hampers measuring and parametrizing the sensor response as it was the case for the MIMOSA analogue output.

Allpix^2 simulated the charge creation, propagation and collection inside the pixel volume from the first principles. The propagation and collection relied on the electric field and doping concentration maps that were imported from TCAD device simulations accounting on a detailed engineering model of the MIMOSIS sensor. The first step of the simulation aimed to compare the results of the full simulation chain to the results from the sensor beam test, in particular the cluster size distribution. After validating this, the digitization model was obtained in a next step and as the following.

A defined amount of charge carriers were artificially deposited in the active volume of the sensor. The pixel 3D volume was scanned and charge carriers were deposited in equidistant 30×30×30 points separated by ∼1 µm in each dimension. A 3 × 3 pixel matrix was studied with its seed-center pixel being the one where the deposition happened. The Charge Collection Efficiency (CCE) of each of the 9 pixels was calculated as a function of the deposition position. Visualizing the CCE maps and its dependence on the change in the deposition position yielded a performance as expected in our case sensor types. These CCE values as function of the deposition position were stored in a look-up table that was implemented in CBMRoot. Tests within CBMRoot including its full simulation chain are foreseen in order to validate our model. While the results of the allpix-squared simulation by itself reproduces well the experimental results, benchmarking the CBMRoot version of the model could not be completed within the time frame of this PhD and will remain subject to future studies.