Design and characterization of an innovative monolithic silicon sensor with additional gain for the ALICE 3 Time of Flight detector

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Abstract

Precise Time-of-Flight (TOF) measurements play a fundamental role in Particle IDentification (PID) and event time tagging in High-Energy Physics (HEP) experiments, in particular in low-momentum regions. Therefore, excellent time resolution is mandatory to extend PID capabilities in future detector upgrades. Several experiments will rely on TOF capabilites, including the next-generation heavy-ion experiment named ALICE 3, which will be installed at the Large Hadron Collider (LHC) at CERN. The installation is planned during the Long Shutdown 4 (LS4) of the LHC and it will be ready for the data taking in 2036. The ALICE 3 TOF detector will provide precise PID and, to this aim, the excellent time resolution of 20 ps is required. To meet this challenge, several silicon sensor technologies are currently under investigation, among these, the monolithic approach.
In recent years, Monolithic CMOS Active Pixel Sensors (MAPS) constitute a major step forward in particle detector technology, particularly in tracking systems used in HEP experiments. However, their high-resolution timing capabilities have not yet been completely exploited. A potential solution to this challenge was found by combining the Low Gain Avalanche Diode (LGAD) approach with the advantages of a monolithic sensor. Therefore, the first prototype of monolithic CMOS sensor with additional gain in 110 nm LFoundry technology (also called MADPix) was developed within the ALICE 3 TOF working group in collaboration with the ARCADIA project.

This thesis is focused on the R&D work concerning the design and development of an innovative monolithic silicon sensor, where both simulation and experimental data results are reported. A solid and fully functional simulation chain, combining Technology Computer-Aided Design (TCAD) and Monte Carlo simulations, is employed to investigate the electrical behavior, the gain and timing performance of the proposed devices. Thanks to a careful simulation work, excellent agreement with the experimental data was achieved. This resulted in a robust simulation workflow capable of accurately reproducing the intrinsic device physics and providing reliable predictive capabilities for future device generations. In addition, in this work the experimental results on the first 110 nm CMOS avalanche detector prototype are shown. A full characterization was performed on sensors from the two sensor productions realized to date, employing both laboratory measurements and tests with particle beams. The timing performance of the MADPix chip was studied during several beam test campaigns that took place at the T10 beamline of the CERN PS, where a beam of protons and pions with a momentum of 10 GeV/c is available. A time resolution of approximately 80 ps was achieved using the latest generation of sensors. In addition, an irradiation campaign was conducted to assess the effects of radiation-induced defects on both gain and timing performance. Although the loss of gain and degradation of time resolution are evident and inevitable when the irradiation levels increase, the operating temperature plays a key role in mitigating these effects. By cooling the detector, the radiation-induced loss of performance can be partially compensated, and the timing resolution can be recovered at the maximum fluence expected for ALICE 3, corresponding to $1 \cdot 10^{13}$ n_{eq}/cm^2.

Although still far from the 20 ps requirement of the ALICE 3 TOF system, the results presented in this thesis demonstrate that monolithic CMOS-LGAD detectors are a viable and competitive solution for future fast timing applications.

Further technological optimizations are now ongoing to improve the present time resolution. These efforts include the investigation of thinner sensors and optimized device geometries aimed at achieving a more uniform and stronger electric field across the active volume. A new short-loop production has already been submitted using thinner substrates, aiming at achieving an enhanced timing resolution.