Development of Monolithic Active Pixel Sensors for the next generation of vertex detectors

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MAPS built out of the CMOS technology provide attractive features for vertex detectors in subatomic physics. In less than ten years, the many prototypes of the MIMOSA series have demonstrated their potential. Today, the first applications in the STAR experiment and for the EUDET collaboration are only a short time ahead. Nevertheless, more demanding specifications, as for instance at the ILC, still necessitate substantial developments. We report on the test of recent sensors which aim at matching short term requirements and providing guidance for longer term applications.

Keywords: CMOS sensors; Pixel detectors; Silicon detectors; Vertex detector.

1. Introduction

Vertex detectors for particle physics require granular, thin and swift sensors. These specifications triggered in 1998 at the IPHC Strasbourg the development of MAPS[a] based on the industrial CMOS process for integrated circuits [1]. The architecture of such CMOS sensors relies on the thin (10 to 20 μm) epitaxial layer present in this technology as a sensitive volume for ionizing particles. The collected signal is directly coupled inside the device to the electronic layer allowing for a pre-amplification. An additional signal treatment is eventually done in the periphery of the pixel matrix.

[a]Monolithic Active Pixel Sensors

In this contribution we first summarize the established performances of CMOS sensors. Then, we review envisionned applications before describing the on-going developements. We conclude on the timeline of these efforts.

2. Basic performances

During the nine last years, more than 20 CMOS sensors from the MIMOSA[b] series have been fabricated in seven different technologies at the IPHC. One of the goals was to assess the principle of operation of such sensors and identify the best suited industrial processes for MIP detection. In 2003, the prototype Mimosa 9, was fabricated in the AMS 0.35 μm OPTO process which offers a 14 μm thick epitaxial layer. The sensor includes submatrices with different pixel pitches of 20, 30 and 40 μm and has been characterized in the CERN-SPS beam using a silicon strip telescope [2]. The prominent figure of merit obtained is the signal to noise ratio for the so-called seed pixel having collected the highest charge within the cluster of pixels fired by the impinging MIP. The maximum probability value for this ratio reaches 26.3$\pm$0.2 which leads in turn to a high detection efficiency with a low fake hit rate per pixel. For instance, an efficiency of 99.9 % is obtained with a fake hit rate of $6\,10^{-6}$ per pixel . These characteristics do not vary within a temperature range of -20 to +40 °C.

Radiation tolerance has also been investigated with two other prototypes Mimosa 11 and Mimosa 15 fabricated in 2005 [3]. They both inherit from the Mimosa 9 pixel architecture but include a modificated pixel design to alleviate the effects of ionizing and non-ionizing radiations. A Mimosa 11 sensor was exposed to 10 keV X-rays to reach a cumulated dose of 500 kRad. Its test at +40 °C demonstrated that the noise increase is reduced by a factor at least 2 compared to the increase observed in the standard diode of Mimosa 9. After having irradiated at different fluences Mimosa 15 sensors with 1 MeV neutrons, the particle detection efficiency has been estimated in an electron beam at DESY. At a fluence of 2.10^{12} n_{eq}/cm^2, the efficiency at -20 °C, for a 30 μm pixel pitch, remains above 99 % and drops at around 80% only at 6.10^{12} n_{eq}/cm^2.

[b] Minimum Ionizing MOS Acitve pixel sensor

3. Forthcoming applications

The STAR collaboration is collecting data at the Relativistic Heavy-Ion Collider located at BNL since 2000 to investigate the physics of the quark gluon plasma. The collider will upgrade its luminosity in 2012 by a factor of 10. STAR plans to increase its vertexing capabilities by complementing its apparatus at low radii with a pixel detector in order to reconstruct charm hadron decays. The short life time of such hadrons combined with the relatively low momentum of the numerous particles produced in the event mostly call for a low material budget and a high granularity vertex detector.

In this case, the use of MAPS is appealing. The current project [4], called Heavy Flavor Tracker, includes a 10^8 pixel detector with the following specifications for the CMOS sensors : a 30 μm pixel pitch, a binary digital output with 0-suppression and an integration time of 200 μs. The collision environment constraints the sensor thickness down to 50 μm, the power consumption per sensor down to 100 mW and the radiation tolerance to reach a few tens of kRad per year.

At a larger time scale, the ILC will provide e^+e^- collisions from 200 MeV to ∼1 TeV for investigating with extreme sensitivity the physics of the standard model and beyond in the next decade. Such an experimental program imposes to reconstruct all particles produced in most of the final states, including light and heavy flavor tagging of all jets. An emblematic consequence of this goal is the required impact parameter resolution: $\sigma_{ip} \leq 5\ \mu\mathrm{m} \oplus \frac{10\mu\mathrm{m.GeV}}{p \sin^{3/2}\theta}$. In addition, the beamstrahlung process will induce a high multiplicity of electrons reaching O(10) hits/cm^2 per bunch crossing at a radius of 15 mm from the interaction point. In this environment, The required radiation tolerance per year stands around O(100) kRad of ionizing radiation and 10^{10} $\mathrm{n}_{eq}/\mathrm{cm}^2$ of non-ionizing radiation.

To face these more severe constraints, with respect to the STAR-HFT project, the proposed solution based on MAPS for the ILC relies on 5 concentric layers equiped with sensors having a pixel pitch ranging from 20 to ∼33 μm and with a digitized zero-suppressed output [5]. Such a detector will include 300-400 million pixels, read out in 25 to 100 μs, depending on the layer.

The EUDET collaboration [6] uses CMOS sensors to equip a beam telescope for the precise characterization of detectors developped in the context of the ILC. The requirements are very similar to the STAR-HFT ones except for a shorter integration time of $\sim$100 μs and a better spatial resolution, based on a smaller pixel pitch of 18 μm.

4. Ongoing developments

Analog output pixel arrays are limited to frame read-out frequencies of O(10^3) s^{-1}. A major development goal is to increase the read-out speed by one or two orders of magnitude. This is achieved by organizing the matrix in columns read out in parallel while the fast treatment, discrimination or digitization followed by zero suppression, occurs in a short band at the columns end. Two recent circuits feature this architecture in the AMS 0.35 μm OPTO process. First, Mimosa 16, which was fabricated in 2006. It includes 128 pixels (25 μm pitch) deep columns, each ended with a discriminator. It was tested with a 120 GeV π beam at the CERN-SPS. The data [5] show that with a common threshold for all discriminators, an efficiency of $\sim$99,9 % with a fake hit rate per pixel below 10^{-4} is achievable as well as a spatial resolution better than 5 μm. A second and larger sensor, Mimosa 22, was submitted to fabrication in October 2007 in the same process. The column depth extends to 576 pixels of 18 μm pitch for a targeted integration time of $\sim$100 μs. Evaluation will begin soon.

The zero-suppression architecture was designed and implemented in a standalone (pixels free) integrated circuit, named Suze-01, fabricated in 2007. Its tests have started and indicate that the logic is operational with the highest frequency foresseen. The merge of the Mimosa 22 sensor with Suze-01 will happen in 2008, resulting in the final EUDET detector.
Meanwhile, several standalone circuits containing different ADC architectures, 4 to 5 bits and 1 to 16 channels, were produced and are currently under test [5]. The integration of the most suitable ADC and zero-suppresion into a Mimosa 16 like sensor will provide the first ILC-prototype.

Finally, the possibility to fabricate real size sensors (a few cm^2) is a main concern. An engineering run of several wafers in the AMS 0.35 μm OPTO process was performed in late 2006. It included in particular three chips, Mimosa 17, Mimosa 18 and Mimosa 20, which have respectively a matrix area of 59 mm^2, 26 mm^2 and 184 mm^2. The fabrication yield of these large area sensors is ongoing. Performance results are already available for Mimosa 18. Four of these sensors (10 μm pixel pitch, serial analog output) were assembled as a beam telescope [7]. The latter was installed on an e^-

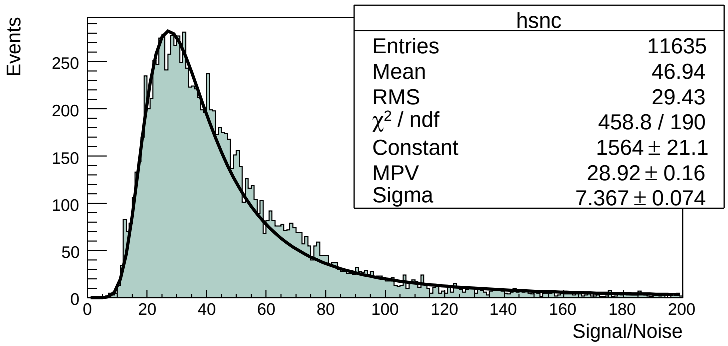

Fig. 1. Signal to noise ratio distribution for the seed pixel of hits produced by 120 GeV pions.

beam at DESY and π beams at the CERN-SPS in Summer 2007. The signal to noise ratio observed in the seed pixel with the highest charge in a cluster peaks at 28.9 ± 0.1, see figure 1.

5. Conclusion

CMOS sensors have by now demonstrated their potential for vertex detectors. A part of the developments focuses now on producing final sensors for short term applications: the STAR experiment will equip the two inner layers of its vertex detector in 2012 with MAPS, with a first intermediate version in 2009; while the EUDET collaboration will use CMOS sensors for its beam telescope as early as 2009.
The roadmap for more demanding applications in term of signal processing, read-out speed or radiation tolerance still requires some R&D. Nevertheless a first prototype for an experiment at the ILC is expected by 2010.

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