Achievements and perspectives of CMOS pixel sensors for charged particle tracking

Marc Winter[*,a], for the IPHC-IRFU collaboration[b]

[a]IPHC, 23 rue du loess, 67037 Strasbourg Cedex 02, France
[b]IRFU / SEDI, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

Abstract

Main achievements of more than one decade of CMOS pixel sensor R&D for charged particle tracking are reviewed in this paper, together with the goals driving present R&D activities, i.e. read-out speed and radiation tolerance. A fast read-out sensor developed for the EUDET beam telescope and the STAR vertex detector is described as well as its first test results. Preliminary results are also provided on non-ionising radiation tolerance improvements offered by CMOS processes featuring a depleted epitaxial layer. Finally, the recent access to 3D Integration Technologies, which alleviate most essential CMOS sensor's limitations, has translated into 2- and 3-tier sensor designs, to be fabricated in Spring 2009. Their main design features and expected performances are reviewed.

Key words:
CMOS pixel sensors, 3D sensors, vertex detectors, beam telescopes, vertexing, tracking

1. Introduction

More than a decade has passed since the first CMOS sensor (MIMOSA-1) was proposed for vertexing [1], motivated by the ILC project. Numerous other applications have emerged since then, and the success of this technology is reflected by the growing number of groups (> 10) involved in its development.

The scope of the paper is to overview the most prominent achievements of the CMOS pixel technology for charged particle tracking, to sketch its perspectives in terms of 2D sensors and to make a long-term projection based on the benefits expected from 3D Integrated Technologies (3DIT).

As compared to other pixel technologies, CMOS sensors are particularly attractive for high precision tracking devices such as vertex detectors or beam telescopes. Their main advantages follow from their high granularity and thin sensitive volume, combined with the possibility to integrate read-out micro-circuits on the same substrate as the sensing elements. Because of the thin, essentially undepleted, sensitive volume, these micro-circuits ought to introduce very low noise in the read-out chain, in order to accomodate the modest signal charge collected through thermal diffusion, which ranges typically from several tens to a few hundreds of e^- only.

2. Performances of analog output sensors

Close to twenty different MIMOSA[1] prototypes with analog output have been designed at IPHC and fabricated in industry. Most of them were manufactured in a 0.35 μm Opto process, featuring an epitaxial layer of $\sim$ 14 or 20 μm. More than 100 individual chips were mounted on a beam telescope and characterised on particle beams at CERN (Geneva) or DESY (Hamburg) [2].

2.1. Detection performances

The observed pixel noise is in the order of $\sim 10\ e^-$ENC, translating into a typical Signal-to-Noise Ratio (SNR) of $\sim$ 20-30, depending essentially on the pixel pitch and the sensing diode dimensions. These results, first observed with small prototypes, were reproduced with full scale sensors composed of several 10^5 pixels. A detection efficiency $\gtrsim$ 99.8 % was repeatedly achieved, even for operating temperatures as high as +40°C.

The single point resolution was measured for various pixel pitch values. It ranges from $\lesssim 1 \mu m$ for a 10 μm pitch to $\sim$ 3 μm for a 40 μm pitch. It is well below the binary resolution reflecting the pitch values due to the charge sharing between neighbouring pixels, a consequence of thermal diffusion of the signal charges in the epitaxial layer.

The radiation tolerance was essentially investigated with 10 keV X-Rays and $\sim$ 1 MeV neutron sources or beams. Ionising radiation mainly increases the shot noise due to a leakage current growth. This effect was alleviated by modifying the pixel design [4], translating into sensors tolerating integrated doses of $\lesssim$ 1 MRad without noticeable drop in detection efficiency. Non-ionising radiation mainly impacts the charge collection efficiency, which drops much faster than with (depleted) hybrid pixel sensors. The magnitude of the effect depends on the pixel pitch and sensing diode dimensions. Sensors with 10 μm pitch were observed

*Corresponding author. Tel.: +33-3-8810/6382; fax: /6234.
Email address: `marc.winter@ires.in2p3.fr` (Marc Winter)
[1]standing for Minimum Ionising particle MOS Active pixel sensor.

to still exhibit 99.5 ± 0.1 % detection efficiency after an exposure to a fluence of $\sim 10^{13}$ n_{eq}/cm^2, while the tolerance barely exceeds $2{\cdot}10^{12}$ n_{eq}/cm^2 for a 20 μm pitch.

2.2. System integration studies

Their thin sensitive volume allows thinning CMOS sensors to a few tens of microns without affecting the signal generation. Numerous MIMOSA sensors were indeed thinned by industry to ~ 50 μm, without noticeable damage or detection performance loss. Such sensors are currently equipping beam telescopes, like the one of the EUDET FP6 project [5], used intensively by the HEP community since 2007. 50 μm thin sensors are also used for prototyping futur vertex detector concepts, such as the PIXEL detector of the STAR experiment at RHIC [6], for which sets of 10 reticule size sensors were assembled on a flex cable. The latter was mounted on a carbon fiber composite mechanical support. The overall ladder material budget amounts to ~ 0.3 % X_0 only. For the ILC vertex detector, attempts are being made to reduce the latter to $\lesssim 0.2$ % X_0. An important input towards this goal may come for the possibility to stitch the sensors, which would substantially suppress the flex cable material.

3. Swift sensors with digital output

The read-out frequency of reticule size sensors made of several 10^5 pixels is limited to ~ 1 kHz in absence of any signal filtering. Aiming for higher read-out frequencies fosters grouping the pixels in columns read out in parallel and digitising the signals on the chip. *MIMOSA-22* is the final prototype of the R&D line exploring this approach. It is essentially made of 128 columns of 576 pixels with 18.4 μm pitch. Each column is ended with a discriminator. Each pixel hosts signal pre-amplification micro-circuits and Correlated Double Sampling (CDS). The sensor is read out in 92.5 μs. Its beam test results are summarised in Table 1 for 2 discriminator threshold values [3].

Table 1: Detection efficiency, average fake hit rate and single point resolution measured at the CERN-SPS with *MIMOSA-22* for 2 discriminator threshold values (3 and 4 mV).

Thresh.	Detection eff.	Fake rate	Resolution
3 mV	99.8±0.05 (stat) %	$\sim 4{\cdot}10^{-4}$	~ 3.7 μm
4 mV	99.7±0.05 (stat) %	$\sim 7{\cdot}10^{-5}$	~ 3.5 μm

The observed detection efficiency remains close to 100 % for threshold values high enough to keep the fake hit rate $< 10^{-4}$, a value ensuring that signal processing micro-circuits will not be saturated by pixel noise fluctuations. The single point resolution is < 4 μm, below the binary resolution (5.3 μm) reflecting the pixel pitch. These results fully validate the architecture. The latter was reproduced in the reticule size sensor *MIMOSA-23* foreseen to equip the STAR PIXEL detector. The sensor is composed of 640 columns of 640 pixels with a 30 μm pitch. Being read out in 640 μs, it is currently being tested at LBNL. It will serve as a forerunner of the final, faster, sensor (called *ULTIMATE*), which will incorporate zero-suppression micro-circuitry and be read out in only 200 μs.

Zero-suppression was investigated for the EUDET project with the *SUZE-01* micro-circuit, which also incorporates output memories and is adapted to 128 columns read out in parallel. Its tests proved its nominal functionning up to clock frequencies well above the design value of 100 MHz.

Based on these results, a complete, full scale sensor (called *MIMOSA-26* [7]) was designed and fabricated within the EUDET project. It combines the architectures of *MIMOSA-22* and *SUZE-01* in a comprehensive charge sensing and signal read-out chain, providing discriminated signals in a binary mode including the pixel address. It features 1152 columns of 576 pixels (18.4 μm pitch), read out in $\lesssim 110$ μs. Recently back from foundry, it is currently being characterised. Preliminary test results indicate pixel and fixed pattern noise values nearly identical to those of *MIMOSA-22*, and a nominal operation of the zero-suppression logic at the nominal clock frequency.

The chips are being integrated in the final set-up of the EUDET telescope and will next be characterised at the CERN-SPS. If their performances are satisfactory, the *MIMOSA-26* design will next be extended to the *ULTIMATE* sensor mentioned earlier, equipping the two layers of the STAR PIXEL detector. *ULTIMATE* will be made of 1152 columns of 1024 pixels featuring an 18.4 μm pitch. Its design should be completed by the end of 2009.

4. Fast sensor evolution and future applications

Several potential applications of the sensors motivate further development of the *MIMOSA-26* architecture in ordre to achieve read-out times well below 100 μs. This applies to the innermost layer of an ILC vertex detector [8], calling for $\lesssim 25$ μs read-out time, and to the vertex detector of the CBM experiment at FAIR [9], where a still twice shorter read-out time is desirable.

Such short integration times foster reducing the number of pixels per column. For this purpose, the sensors are foreseen to be read out from two sides, instead of one only, translating into a twice faster read-out.

5. Evolutions of the CMOS technology

5.1. Depleted epitaxial layer

Besides increasing the read-out speed, attempts are also made to improve the non-ionising radiation tolerance. With the recent advent of CMOS processes involving a depleted epitaxial layer, new perspectives occured: the mean free path of the charge carriers gets substantially reduced and the total charge released by traversing particles concentrates in fewer pixels which, therefore, exhibit a larger SNR. The depletion also speeds up the charge collection, which benefits to the read-out speed (see sub-section 5.2).

The exploratory sensor *MIMOSA-25* was fabricated in 2008 in a CMOS process featuring a $\sim$ 14 μm depleted epitaxial layer. The chip response was assessed with a ^{106}Ru (β) source. Striking differences with undepleted sensors were observed in the cluster characteristics (see Fig. 1). The average charge collected in the seed pixel is $\sim$ 3 times larger, amounting to $\sim$ 2/3 of the cluster charge. Moreover, the latter was nearly fully contained in 4 neighbouring pixels, instead of $\sim$ 9 for undepleted sensors. The chip was exposed to fluences of up to $3{\cdot}10^{13}$ n_{eq}/cm^2. The observed charge loss consecutive to the irradiation was moderate ($\lesssim$ 20 % for $3{\cdot}10^{13} n_{eq}/cm^2$), despite a 20 μm pixel pitch. The effect of a yet higher fluence, i.e. $10^{14} n_{eq}/cm^2$, is being investigated, but the results obtained so far already indicate that depleted epitaxial layer technologies improve the sensor radiation tolerance by at least one order of magnitude w.r.t. undepleted ones. The final word on this issue will come from beam tests foreseen at the CERN-SPS in May 2009.

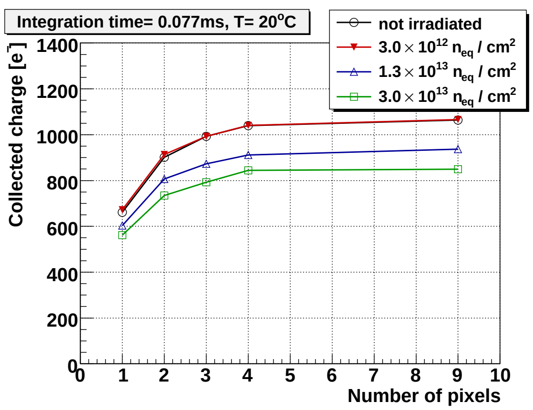

Figure 1: Charge collected with MIMOSA-25 (depleted epitaxial layer, 20 μm pixel pitch) exposed to a β source, before and after irradiation with $\sim$ 1 MeV neutrons. The charge is displayed as a function of the number of pixels gathered in a cluster. The fluences considered are 0.3, 1.3 and $3{\cdot}10^{13} n_{eq}/cm^2$.

5.2. 3D integrated technologies

The performances of CMOS pixel sensors may still improve with 3DIT. The latter allow combining in a single device several interconnected integrated circuits (tiers), manufactured in different CMOS processes. Each circuit may be fabricated in a process optimal for a dedicated functionnality (charge sensing, analog read-out, digital processing, etc.). Moreover, each pixel may be connected to a complex read-out chain distributed over several tiers.

The first MIMOSA-like 3D prototypes, called CAIRN[2], are being designed. 3 different sensors will be fabricated within an engineering run coordinated by FNAL [10] in a 130 nm fabrication process combining 2 tiers. They explore 3 alternative signal processing approaches for an ILC vertex detector.

[2]standing for CMOS Active pixel sensors with Integrated Read-out Networking.

One design features 12 μm pitch pixels, each connected to a discriminator followed by a 5-bit time stamping latch and an overflow bit. A hit will be flagged with 30 μs time resolution during the 950 μs long ILC train, the sensor being read out after the train. The rare cases with 2 hits during a single train will be flagged with the overflow bit. Another design concerns a fast read-out micro-circuit with high pixel output amplification. This 2-tier read-out chip will be connected using 3DIT to a depleted epitaxial layer chip similar to *MIMOSA-25* (see sub-section 5.1). Finally, the third design consists in splitting the pixel array into sub-matrices, each running independently and organised in pixel columns read out in parallel. Very short read-out times (few μs) and minimal power dissipation are expected from this architecture.

All chips will be fabricated in Spring 2009, the first test results being expected before the end of the year.

6. Summary

The developement of CMOS pixel sensors for charged particle tracking has ended up with reticule size, 50 μm thin, high resolution sensors with analog output equipping beam telescopes and very light prototype ladders ($\lesssim$ 0.3 % X_0) of future vertex detectors. The sensor read-out frequency, limited to $\sim 10^3$ frames/s, calls for an improvement by one ordre of magnitude or more. A column parallel architecture with integrated zero-suppression was developed for this purpose. It has been validated at real scale and is now being adapted to each specific application. The tolerance to non-ionising radiation, which is limited by thermal diffusion of the charge carriers in the sensitive volume, is likely to improve by at least one ordre of magnitude with recently accessible manufacturing processes using a depleted epitaxial layer.

Performances of CMOS sensors can presumably still be much improved with the help of vertical integration. This new R&D line is yet in its exploratory phase but several different prototypes are going to be fabricated and tested in 2009. A first idea of the outreach of 3DIT CMOS sensors should therefore come out before the end of the year.

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