HIGH PRECISION THIN CMOS SENSORS FOR FUTURE VERTEX DETECTORS

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CMOS pixel sensors are developed at IReS-LEPSI since 1999 for future vertex detectors needing very high granularity and minimal material budget. The first prototypes, made of small arrays of a few thousands of pixels, demonstrated the viability of the technology and its high tracking performances. In the last two years, new results on the radiation tolerance and tracking performances of the sensors were obtained, and the first real scale prototype was fabricated and tested. Moreover, a new manufacturing technology was investigated, without epitaxial layer but based on a lightly doped substrate. The contribution summarises the performances observed and provides an outlook on the sensor applications.

1. Introduction

The developement of CMOS sensors for charged particle tracking was triggered by the physics program anticipated at the e^+e^- Linear Collider (LC)[1], which requires b and c jets flavour identification of unprecedented efficiency and purity. This calls for a highly granular, light and multi-layer vertex detector, installed very close to the interaction region[2]. Existing devices do not reach the outstanding performances ambitionned: CCDs meet the granularity and thickness requirements but are too slow and radiation sen-

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sitive. Hybrid Pixel Sensors, on the contrary, provide the necessary speed and radiation tolerance but have penalising granularity and thickness.

CMOS sensors may provide the right balance of advantages of the two technologies. Manufactured in standard CMOS technology, they allow to integrate signal processing micro-circuits (amplification, noise subtraction, discrimination, digitisation, etc.) on the detector substrate, which may be thinned down to a few tens of microns. The key element of this new tracking technique is the use of an n-well/p-epi diode to collect, through thermal diffusion, the charge generated by the impinging particle in the thin epitaxial layer underneath the read-out electronics[3].

The ability of these sensors, called MIMOSA[a], to provide charge particle tracking was established a few years ago[4]: the first prototypes (MIMOSA-1 and -2), made of small arrays of a few thousands of pixels, showed a detection efficiency of about 99 % and a single point resolution of $\sim$ 1.4-2.3 μm. Overall, MIMOSA-1 exhibited better performances than MIMOSA-2, its thicker epitaxial layer ($\sim$ 14 μm against 4 μm) originating larger signal charges. More studies were performed since, which allowed to study how the single point resolution evolves after digitisation on a small number of bits and to estimate the double hit resolution. Moreover, a real scale (i.e. $\sim$ 3.5 cm^2) prototype, composed of $\sim$ 1 million pixel, was designed, fabricated and tested at the CERN-SPS. Finally, a new fabrication technology, relying on a lightly doped substrate, was investigated. The main results of these different studies are reviewed in this report.

2. Achievements on spatial resolution

Besides the single point resolution already reported earlier[4], the double hit resolution was also investigated, using the data collected with MIMOSA-1. It was obtained by artificially moving, step-by-step, a signal cluster of one frame towards the signal cluster of another frame. Two algorithms were applied to each cluster pair: one expressing the topology of single clusters and one corresponding to cluster pairs. Applying this procedure to a few thousands of cluster pairs, the probability to distinguish two neighbour clusters was computed as a function of the distance between the two cluster centers. Due to the sizeable cluster multiplicity and to the rather comfortable signal-to-noise ratio ($\sim$ 25-30), excellent cluster separation is observed down to distances below 30 μm.

[a]standing for Minimum Ionizing MOS Active pixel sensor.

A typical difficulty associated to the small pixel size is the data flow due to the large pixel density. Besides the necessity to adapt the read-out electronics to this constraint, the signal charge needs to be digitised on a restricted number of ADC-bits. MIMOSA-1 and -2 test data were used to estimate the consecutive loss in single point resolution. The measured charge, originally recorded on 12 bits, was converted off-line into a 3-, 2- or 1-bit information. The analysis shows that a 3-bit encoding would still allow a single point resolution close to 2 μm (in case of MIMOSA-1), a value satisfying the requirements of the most demanding applications envisaged.

3. First real scale prototype

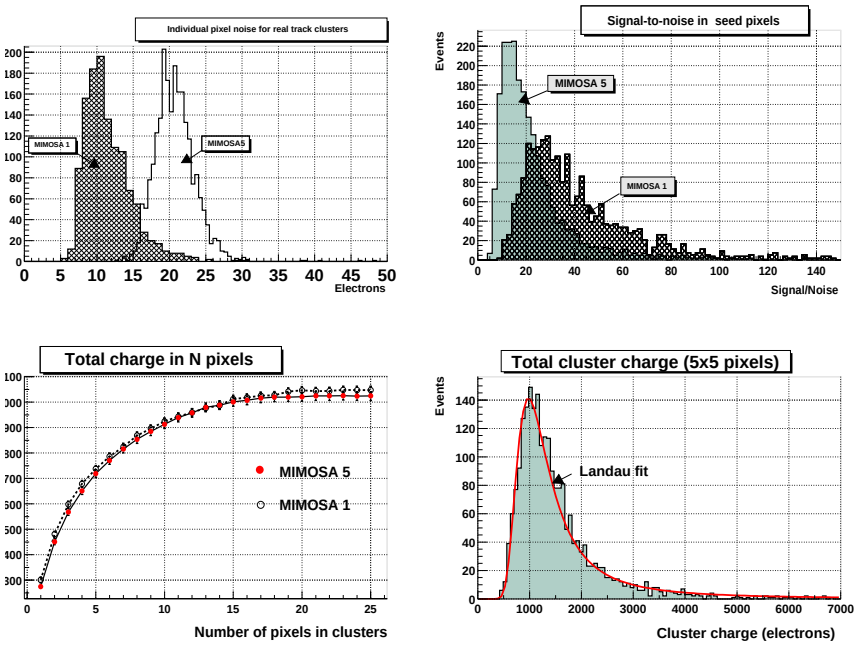

Figure 1. MIMOSA-5 test results, compared to those of MIMOSA-1. The top figures show the pixel noise (left) and the seed pixel signal-to-noise ratio (right). The bottom figures display the signal charge as a function of the cluster multiplicity (left) and the cluster total charge distribution (right).

The first real scale sensor (MIMOSA-5) was designed and fabricated in 2001, and tested in 2002 and 2003 on a 120 GeV/c π^- beam at the CERN-SPS. Made of 10^6 pixels (17x17 μm^2 wide), it was thinned down to 120 μm.

The tests showed that the sensor reproduces the tracking performances of the small prototypes rather well (e.g. $\sim$ 99 % detection efficiency, single point resolution of $\sim$ 2 μm). Moreover, the average gain dispersion over the sensor surface was of the order of a few per-mill only. The results are summarised on Figure 1, where they are compared to those obtained with MIMOSA-1, which was manufactured with the same fabrication process (AMS 0.6 μm). One observes that despite the twice larger noise of MIMOSA-5 (a direct consequence of the large number of pixels read out serially), the tracking performances of both sensors are similar. The tests were repeated with several MIMOSA-5 units, leading to very similar results.

This achievement provides strong support to the feasibility of light and very granular vertex detectors made of CMOS sensors. The performances of MIMOSA-5 are actually close to the requirements for the upgrade of the vertex detector of the STAR experiment foreseen in 2006. The design effort needed to fully adapt MIMOSA-5 to this application, which includes thinning the sensors down to $\sim$ 50 μm, has been set up.

4. Tolerance to neutrons

The radiation tolerance w.r.t. bulk damage[5] was investigated by exposing MIMOSA-1 and -2 sensors to fluences of up to $10^{13}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$. As the fluence approaches $10^{12}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$, charge losses occur. The noise was observed to increase only moderately and the gain remained unchanged. All together, these variations translate into a decrease of the detection efficiency starting to be significant near $10^{12}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$, a value several orders of magnitude above the rate expected at a LC, which lies in the range of 10^{9}-$10^{10}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$ per year[1].

5. Performances of a prototype without epitaxial layer

A prototype (MIMOSA-4) was fabricated in a 0.35 μm process without epitaxial layer, based on a low doping substrate ($\sim 10^{14}$ atoms/cm^3). Its tests at the CERN-SPS exhibited a detection efficiency close to 100% and a single point resolution of $\sim$ 2.5 μm. Moreover, chips exposed to 200 kRad ionising radiation or to a fluence of $1.4\cdot10^{11}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$ did not show a significant performance loss[6].

These results demonstrate that technologies without epitaxial layer can also provide very good tracking performances, a feature which allows to follow a trend in industry to rely on such fabrication processes.

6. Summary and Outlook

The small MIMOSA prototypes fabricated in the first years of the R&D on CMOS sensors have shown that this technology provides excellent charged particle tracking performances, viz: ~ 99 % detection efficiency, $\lesssim 1.5$ μm single point resolution (remaining ~ 2 μm when encoded on 3 bits), < 30 μm double hit resolution and $\lesssim 10^{12}\mathrm{n}_{eq}\cdot\mathrm{cm}^{-2}$ tolerance to neutrons. The viability of the detection technique is now also assessed with real scale, 120 μm thick, chips made of 10^6 pixels and providing ~ 2 μm spatial resolution. Their performances being close to those required for the coming STAR vertex detector upgrade, a dedicated sensor is being developed for this application, which includes thinning the sensors down to ~ 50 μm.

Most of the sensors fabricated exploit the epitaxial layer as a sensitive volume. A prototype manufactured in a process without epitaxial layer but relying on a lightly doped substrate, exhibited excellent tracking performances (e.g. detection efficiency $\gtrsim 99.5$ %, ~ 2.5 μm single point resolution). These results demonstrate that fabrication processes without epitaxial layer can also be considered for charged particle tracking.

The sensors MIMOSA-1, -2, -4 and -5 have minimal amount of functionnalities integrated on the chip and their pixels are essentially read out serially. Matrices of 1 million pixels of this type may provide frame readout times in the order of 1-10 ms. Several applications (e.g. LC) require read-out times well below 100 μs. The next steps of the development focus therefore on chip architectures allowing fast signal treatment integrated on the sensor substrate. This implies subdividing the sensors into short columns read out in parallel and implementing zero suppression microcircuits. Small prototypes exploiting different approaches of charge sensing and signal treatment were designed for this purpose. Their tests are expected to be completed in 2004.

References

1. *TESLA Technical Design Report*, DESY report (March 2001); **http://tesla.desy.de/new_pages/TDR_CD/start.html**
2. M. Winter, *Proc. of the International Conference of High Energy Physics*, Amsterdam (Netherlands), July 2002.
3. R. Turchetta et al., *Nucl. Inst. Meth.* **A458**, 677 (2001).
4. Y. Gornushkin et al., *Nucl.Instr. Meth.* **A478**, 311 (2002).
5. M. Deveaux et al., *Nucl. Inst. Meth.* **A512**, 71 (2003).
6. W.Dulinski et al., *Proc. of the IEEE Nuclear Science Symposium*, Portland (Oregon), September 2003; *to be printed in IEEE Trans. Nucl. Sci.* (2004).