Monolithic Active Pixel Sensors for a Linear Collider

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Abstract.
A new generation of semi-conducting pixel sensors for detecting minimum ionising particles (m.i.p.) was designed and first prototypes were fabricated in a standard CMOS technology, guided by the very high vertex detector performances demanded in future collider experiments. The device architecture resembles CMOS cameras, a recent alternative to CCD sensors for visible light imaging. The performances of the first prototype of Monolithic Active Pixel Sensors (MAPS), called MIMOSA[1], were evaluated with high energy π^- beams at CERN. Preliminary test results demonstrate that the sensors detect m.i.p.s with very high efficiency and signal-to-noise ratio and provide excellent spatial resolution.

INTRODUCTION

The development of CMOS sensors for the detection of m.i.p.s was initiated in 1999, motivated by the unprecedented vertexing and tracking performances required by the physics programme of the next e^+e^- Linear Collider, which is largely oriented towards top quark and Higgs boson studies [1]. Silicon pixel detectors appear as best suited to provide the high granularity needed to reconstruct accurately the impact parameters of charged particle tracks for these physics objectives.

In comparison to the existing semi-conductor techniques, i.e. Charged Coupled Devices (CCD) and Hybrid Active Pixel Sensors (HAPS), CMOS sensors can be as thin and granular as CCDs, but with intrinsic properties translating into higher radiation resistance and faster read-out potential. They may thus be considered as combining specific advantages of CCDs and HAPSs.

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1) standing for **M**inimum **I**onising **MOS** **A**ctive pixel sensor

PRINCIPLE OF OPERATION - DESIGN FEATURES

The basic idea of MAPSs optimised for m.i.p. detection consists in integrating a sensor in a twin-well process, where an n-well / p- epitaxial layer diode is used in order to achieve a sensitive area for m.i.p.s of 100 % (see Figure 1). The signal created by m.i.p.s in CMOS sensors originates in a low resistivity epitaxial silicon layer, where excess carriers are produced at a rate of about 80 electron-hole pairs per micron. The electrons liberated diffuse towards the n-well diode contact within a typical time of a few tens of nanoseconds. Because of the three orders of magnitude between the dopping levels of the p- epitaxial layer and of the p^{++} wells and substrate, potential barriers are created at the region boundaries, that act like mirrors for the excess electrons.

A first prototype was fabricated in a standard 0.6-μm commercial CMOS process. It is made of 4 independent matrices having slightly different designs[2]. Each matrix consists of 64x64, 20 μm wide, pixels. The epitaxial layer of a sensor was measured to be about 14 μm thick. A diode was implemented at the center of each pixel, except for one matrix where four diodes connected in parallel were implemented in each pixel, aiming to reduce the charge dispersion and collection time.

Basic prototype parameters, such as the total conversion gain and the pixel equivalent noise charge were determined with a 5.9 keV X-ray source of ^{55}Fe. The charge collection time was measured with laser shots to be less than 150 ns. More details on the chip architecture, principle of operation, results of the device simulation and of the tests with the X-ray source can be found in [2], [3].

BEAM TEST RESULTS

The response of the sensors to m.i.p.s was studied with a 120 GeV/c pion beam delivered by the CERN-SPS. The sensors were mounted inside a telescope made of 8

2) A second prototype was realised in 0.35-μm technology, which is still being tested.

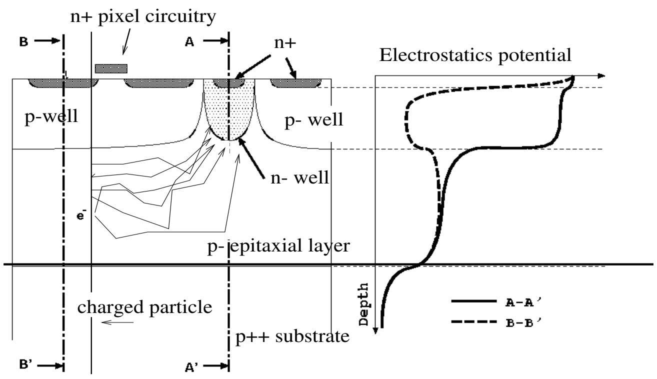
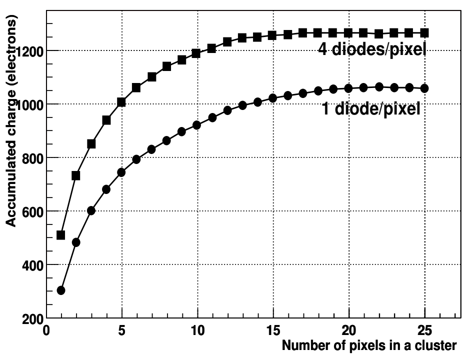


FIGURE 1. Internal structure of a pixel designed for charged particle tracking.

planes of silicon strip detectors, grouped in pairs of planes providing two orthogonal coordinates. Tracks were reconstructed in the telescope by requiring at least one hit per plane and by adjusting a straight line to the 8 telescope coordinates. After internal alignment, the intersection of the tracks with the sensor plane was known within $\sim 1\ \mu m$. The intersections were compared to the result of an independent cluster algorithm applied to the sensor data, merging pixels exibiting a signal-to-noise ratio (S/N) larger than 5 with their neighbours. The noise value entering the S/N calculus was estimated from two consecutive steps: a large fraction of the noise, e.g. the kTC component and most of the frequencies of the Fixed Pattern Noise, was eliminated through correlated double sampling signal processing; the remaining noise characteristics were estimated from the first 250 events of each run. A modest irreducible noise of ~ 20 electrons survived this treatment.

As anticipated from the simulations and from the calibrations with the X-ray source, the charge produced by m.i.p.s was spread over several pixels. The variation of the cluster charge with its size is shown in Fig.2 (left), where pixels were successively added to the cluster in decreasing order of their signal amplitudes. The absolute amount of the collected charge is about 20 % larger for the 4-diode design, but the cluster signal-to-noise ratio (see Fig.2 right) is more favorable for one diode per pixel due to smaller equivalent noise, the mean value of the signal-to-noise ratio exceeding 40 for this design. The cluster reconstruction algorithm was adapted to these features by accepting up to 9 pixels per cluster, which thus contained more than 90 % of the total charge collected.

The sensor spatial resolution was determined by comparing the track intersection from the telescope with the impact position calculated from the sensor response. The latter was used in two different ways: the m.i.p. impact was either taken as the position of the seed pixel center, or as the center of gravity of the charges collected within a 3x3 pixel cluster. The result of the comparison is illustrated in Fig.3, which displays the distance between the track intersection and the impact position derived from the sensor response. The distribution based on the seed



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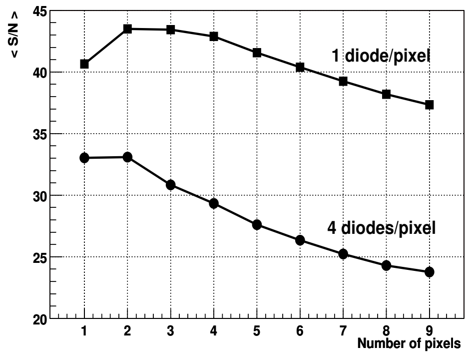

FIGURE 2. Most probable value of the collected charge (left) and mean value of the S/N (right) as a function of cluster size, for 1 and 4 diodes per pixel.

pixel position reproduces the binary resolution of the pixels (5.8 μm), whereas a fit to the (gaussian) distribution based on the charge center-of-gravity leads to a standard deviation of 1.8 μm, which translates into a resolution of 1.6 $\pm$ 0.1 μm after correction for the accuracy on the track intersection from the telescope.

CONCLUSIONS AND OUTLOOK

The first prototypes of CMOS sensors for m.i.p. detection were designed and fabricated. Their tests demonstrate that this detection technique works very efficiently and provides outstanding spatial resolution. Thanks to the technology used for their fabrication, monolithic pixel devices are likely to provide a cost-effective solution for high precision tracking systems, combining advantages of CCDs and HAPSs. This makes them an attractive candidate for vertex detectors at a future linear collider.

The next steps of the development aim for macroscopic detector modules (i.e. $\sim$ 10 cm^2) and for integrating various functionalities on the sensor substrate which should result in a faster read-out and a reduced data flow. Furthermore, thinning procedures will be investigated.

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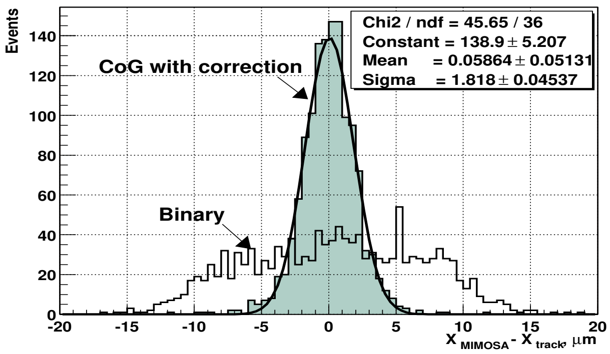

FIGURE 3. Residual distribution between the track intersection (X_{track}) from the telescope and the reconstructed impact position (X_{MIMOSA}) from the sensor response, using the seed pixel only (Binary) or the charge center-of-gravity of 3x3 pixel clusters (CoG).