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Monolithic active pixel sensors for fast and high resolution vertex detectors

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Abstract

Future high energy physics experiments require high luminosities and efficient and pure bottom and charm tagging. Monolithic Active Pixel Sensors (MAPS) promise to be particularly well suited for these tasks. In contrast to other technologies, MAPS are fabricated using standard CMOS processes, which allows to implement on-chip data processing (system-on-chip).

The paper concentrates on two aspects of the current R&D programme: the prototype for the upgrade of the vertex detector of the STAR experiment at the Brookhaven National Laboratory; architectures to handle the event rates expected at the International Linear Collider (ILC). The STAR experiment requires a sensor which operates at ambient temperatures. For this application, CMOS processes optimised for low leakage currents may be best suited. First results are presented which are obtained with a prototype (MIMOSA-9) build in such a process. Two concepts are presented for a vertex detector at the ILC: fast parallel readout and in situ storage.

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1. Introduction

CMOS imaging sensors became popular in the nineties for digital photography. An extensive research was triggered in industry leading to very high granularity, low noise and thin sensors. In 1999, this technology was pioneered by IReS and LEPSI for minimum ionising particle (MIP) detection [1]. Meanwhile R&D is performed at many institutes [2]. At IReS and LEPSI, several prototypes were manufactured to investigate different CMOS processes and pixel designs. In beam tests, the sensors have proven a single point resolution better than 2 μm (20 μm pixel pitch), a detection efficiency better than 99% and a radiation tolerance of up to $10^{12}\,n_{eq}/cm^2$ and several 100 kRad of ionising radiation [3]. The demonstrated performance is sufficient for the upgrade of the STAR vertex detector planned in 2007 [4]. A prototype, called MIMOSTAR, has been developed in order to fully adapt the sensor to the STAR requirements. It is discussed in Section 2. Further developments within the field of high energy physics concentrate on a vertex detector suitable for the International Linear Collider (ILC). The corresponding strategies are elaborated in Section 3.

2. The STAR vertex detector upgrade

This upgrade is associated to the planned luminosity increase and beam pipe radius reduction. The latter allows to extend the vertex detector by two layers at mean radii of ~1.5 and ~4.5 cm. To fulfil the physics goals, the following requirements have to be met: the sensors have to stand an integrated irradiation dose of $\mathcal{O}(10^{11})\,n_{eq}/cm^2$ and $\mathcal{O}(10)$ kRad of ionising radiation in one year [4]; the single

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point resolution must be better than ~4 μm; the readout time should not exceed 4 ms; the sensors must work at temperatures up to ~40 °C. The available space only allows for an air cooling system. This leads to the constraints on the operation temperature. The first two requirements are already met. The on going R&D concerning the latter two requirements are described below.

2.1. Processes with reduced leakage currents

Increasing demands for low noise and high resolution digital cameras pushed manufacturers to optimise CMOS processes for imaging sensors, translating into reduced leakage currents. A new prototype, MIMOSA-9, was manufactured in one of these processes, called AMS 0.35 μm OPTO. The chip is composed of eight matrices with different pixel designs and pitches and was produced in processes with 20 μm epitaxial layer (specification of the manufacturer) and without. The pixels contain n-well/p-epi (or n-well/p-substrate) diodes with surface areas ranging from 3.4×4.3 to $6 \times 6\,\mu m^2$. They are either standard "3-transistor" or self-bias pixels [5]. For standard 3-transistor pixels, a reset is applied after each readout cycle to clear the collected charge. In self-bias pixels, the transistor is replaced by a forward biased diode which constantly charges the pixel with a low current $\mathcal{O}$(fA). The sensors were tested at temperatures between −20 and 40 °C in the laboratory with X-rays emitted by a ^{55}Fe source and at the CERN-SPS with pions of ~120 GeV. Pedestals and noise are suppressed by correlated double sampling (CDS): for each event, two consecutive frames are read (10 MHz clock) and subtracted. Preliminary results were obtained with sensors featuring an epitaxial layer (see Figs. 1, 2 and Table 1).

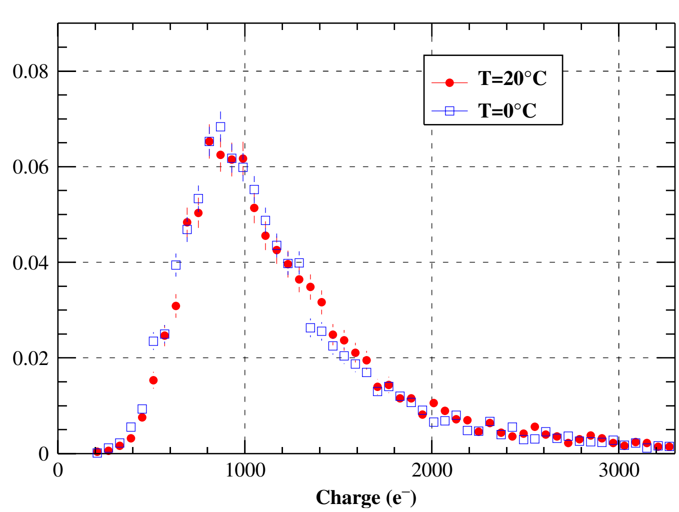

Fig. 1. Charge from MIPs collected within a cluster of 5×5 pixels at 0 and 20 °C. The pixels are self-bias pixels with 30 μm pitch and diodes of $5 \times 5\,\mu m^2$. The most probable value of the collected charge is ~800 electrons.

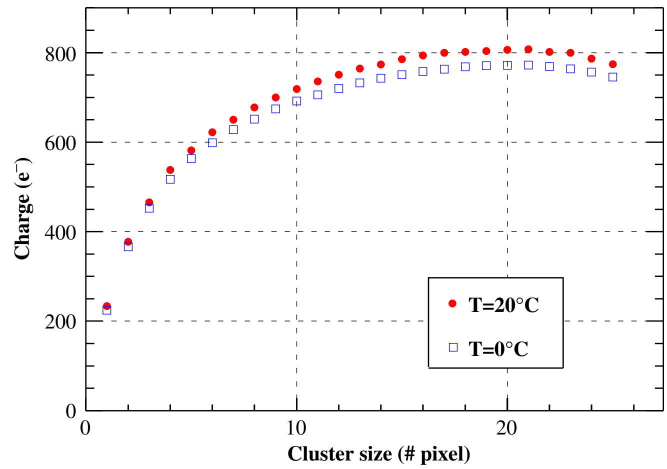

Fig. 2. Collected charge as a function of the number of pixels contributing to the cluster at 0 and 20 °C (self-bias pixels with 30 μm pitch). The pixels are ordered w.r.t. the collected charged. The last pixels contribute with noise only. Due to the ordering procedure, these noise contributions are positive at first and then negative.

Table 1
Performance of MIMOSA-9

Pitch (μm)	Diode (μm^2)	S/N	Efficiency (%)
40	4.3 × 3.4	26	99.6
	6 × 6	28	97.8
30	4.3 × 3.4	33	99.9
	5 × 5	35	99.8
20	4.3 × 3.4	38	99.9
	6 × 6	38	99.9

The table shows the average signal-to-noise ratio (S/N) of the seed pixel and the tracking efficiency at a temperature of 20 °C. The matrices are equipped with self-bias pixels, which have different pixel pitches and collection diodes. The uncertainties affecting the tracking efficiency are smaller than 0.1%.

Fig. 1 shows the charge collected from MIPs within a cluster at 0 and 20 °C. The clusters are composed of 5×5 pixels around a seed pixel. A cluster is accepted if the signal-to-noise ratio of its seed pixel exceeds 5 and the total signal-to-noise ratio of the 8 pixels around the seed pixel is larger than 3. Fig. 2 displays the most probable value of the collected charge as a function of the number of contributing pixels. At 20 °C, the total cluster charge is collected with ~12 pixels, and amounts to ~770 electrons. The charge collected by 3×3 pixels is 10% lower.

Assuming a 100% efficient charge collection and an average of 80 electrons produced per μm of trajectory, the epitaxial layer would have a thickness of ~10 μm. This conflicts with the manufacturer's claim but was finally confirmed [6].

The temperature may affect the collected charge in several ways: the mobility decreases with decreasing temperature; the lifetime increases with decreasing temperature; the characteristics of the self-bias diode change with the temperature. When reducing the temperature to