CMOS Sensors for the detection of Minimum Ionising Particles

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Introduction

In Particle Physics (or High Energy Physics, HEP) experiments, detectors are built around the point where beams of high-energy particles interact. The particles generated fly away from the interaction point over the full solid angle. Several types of detectors are required to fully reconstruct the trajectory, the energy, the momentum and the type of particle. The different detectors are installed around the interaction type in a layered structure. The innermost are the so-called *Vertex* and *Tracking* detectors, whose goal is to reconstruct the trajectory of the generated particles, and then the exact position of the point where they were generated (the *vertex*). In present experiments, two kinds of area devices are used: the Hybrid Active Pixel Sensors (HAPS) or the Charge Coupled Devices (CCD). Both devices are made of silicon. Minimum Ionising Particles (MIPs) traversing silicon generates a small amount of 80 e/h pairs per micron. In HAPS, the detecting element is a diode built over a high resistivity (kΩ cm) substrate, typically 300 micron thick. A voltage of a few tens of Volts applied to the substrate is able to fully deplete the detectors and a relatively large charge signal is generated. This signal is read by dedicated electronics, normally fabricated in CMOS technology, in a geometry that matches the detector one. The connection between the two substrates is made by bump bonding[2]. The main advantage of HAPS is speed (they are planned to be used at the CERN Large Hadron Collider, where collisions can occur every 25 ns) and the main disadvantage is cost (two substrates plus the connexion) and power consumption (in the order of tens of μW/pixel). In CCDs for Particle Physics, a p-type, thin (about 10 μm thick), epitaxial layer (in the order of 10 Ω cm resistivity) is built over a low-resistivity p substrate (~ 0.1 Ω cm). The surface of the CCDs is depleted and electrons generated in the epitaxial layer diffuse and drift towards the collecting anode. The potential barrier at the interface between the p++ and the p-epi substrate acts like a mirror surface for the generated electrons. Because of the serial readout, CCDs are slow and are only used in some low-rate experiments[3].

Recently, CMOS Monolithic Active Pixel Sensors (MAPS) have been proposed[4] as a novel device for Vertex/Tracking detectors in HEP. Differences exist in the specifications between a

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[1] was with LEPSI, Strasbourg, France

[2] see for example, K. H. Becks et al., *Progress in the construction of the DELPHI pixel detector*, Nucl. Instr. and Methods A395, (1997) 398-403

[3] see for example, C. Damerell, *Vertex Detectors: the state of the Art and Future Prospects*, RAL-P-95-008, December 1995

[4] R. Turchetta et al., *A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology*, Nuclear Instruments and Methods A 458 (2001) 677-689

CMOS sensor for visible light and for HEP. The requirements for a sensor in HEP are outlined in table 1. Because of the requirements of full solid angle coverage, the sensor has to be sensitive over its full area. This demands the use of a detecting element structure similar to the one already used in CCDs for HEP and proven to be valid also for enhancing the fill factor of visible light APS[1]. Because of the thickness of the epitaxial layer in modern CMOS technology, the signal is small, and in the order of a few hundreds of electrons. In order to be able to detect the particle with good efficiency and good false hit rejection, the signal over noise has to be higher than about 20, which sets a stringent limit over the noise, possibly smaller than 10 e- rms. In the normal use in an experiment, where only a few percents of the pixels are hit, only the signals of those pixels should be read out, i.e. on-line (and possibly on-chip) zero-suppression has to be done in order to limit the amount of data transmitted. This means that the limit of noise should eventually include non-uniformities. It must however pointed out, that higher column fixed pattern noise can be tolerated, provided there is some mean of on-chip, per-column adjustment. The power consumption should be as low as possible, possibly in the range of nW/pixel, i.e. closer to the one of CCDs in HEP experiments. The spatial resolution has to be in the order or better than 10 μm, which means that pixels can be relatively large, or in the order of 10 to 20 μm. Radiation resistance is also required.

Results

In order to achieve the constraint of 100% fill-factor a standard CMOS technology, the detecting element can be an n-well/p-epi diode (fig. 2). Only NMOS transistors are used in the present pixel design (fig. 1). A fast, Minimum Ionising Particle (MIP) traversing the sensor generates about 80 electron/hole pairs/μm. The electrons generated in the epitaxial layer are here confined by the potential barriers on the p-well/p-epi and p-substrate/p-epi frontiers. A small contribution comes also from the electrons generated in the heavily doped substrate and diffusing in the p-epi. Electrons in the epi-layer diffuse and drift to the collecting n-well anode. Because of the loose requirements on the spatial resolution, the pixel pitch is only 20 μm, leaving most of the pixel area unused (fig. 3).

The first prototype sensors, consisting of several independent arrays of 64*64 pixels, have been fabricated in standard 0.6 (MIMOSA I) and 0.35 μm (MIMOSA II) CMOS technologies[2][3][4]. Both technologies feature a twin-well on p-epi. The thickness of the epi layer is about 14 and 5 respectively for the 0.6 and 0.35 μm technologies. The main differences between the arrays are in the number of collected diodes (1, 2 or 4) and in the use of gate all-around transistor for reduced radiation effects. In the 1-diode configuration, the diode takes only 2.3% of the overall surface.

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[1] B. Dierickx, G. Meynants, D. Scheffer, Near 100% fill factor CMOS active pixels, Proceedings of the IEEE CCD & AIS workshop, Brugge, Belgium, 5-7 June (1997); Proceedings p. P1

[2] G. Deptuch et al., Simulation and Measurements of Charge Collection in Monolithic Active Pixel Sensors, presented at "Pixel2000, International Workshop on Semiconductor Pixel Detectors for Particles and X-Rays", Genova (Italy), 5-8 June 2000, to be published on NIM A

[3] G. Claus et al., *Particle Tracking Using CMOS Monolithic Active Pixel Sensor*, presented at *"Pixel2000, International Workshop on Semiconductor Pixel Detectors for Particles and X-Rays",* Genova (Italy), 5-8 June 2000, to be published on *NIM A*

[4] G. Deptuch et al., *Design and Testing of Monolithic Active Pixel Sensors for Charged Particle Tracking*, presented at *"IEEE Nucl. Science Symposium and Medical Imaging Conference",* Lyon (France), 15-20 October 2000, submitted to *IEEE Trans. on Nucl. Sc*

	HEP
Fill factor	100 %
Signal	Small: ~ 80 e- / µm, i.e. <~ 1 K e-
Dynamic range	S/N > 20 for single-pixel ~ 100
Noise	< 10 e- rms
Power consumption	As low as possible < µW / pixel ?
Spatial resolution	As good as possible <~ 10 µm
Pitch	~ 20 µm
Radiation resistance	Up to 20 MRad / 10^{14} n cm^{-2}

Table 1. Requirements for a MAPS for HEP.

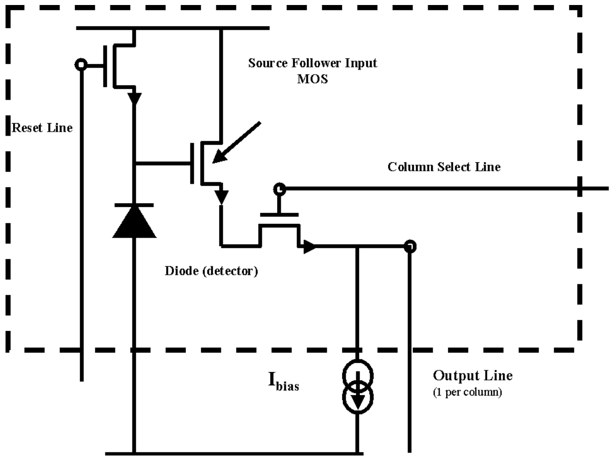

Figure 1. Schematic of the pixel. Because of the diode choice, only NMOS transistors are used.

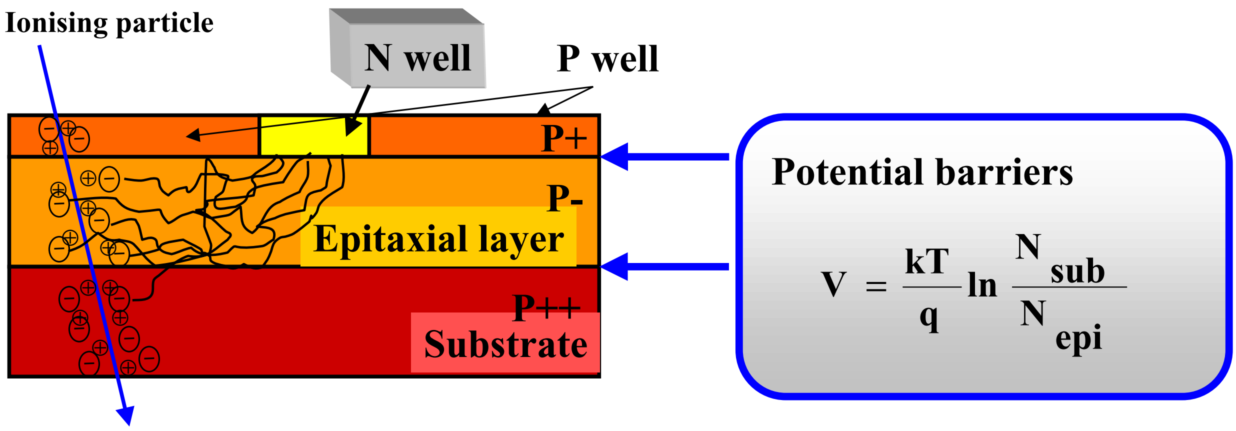

Figure 1. An ionising particle traversing the sensor generates about 80 pairs/µm. Electrons diffuse and drift towards the collecting anode.

In order to prove that CMOS sensors can be used as tracking devices, we performed tests with beams of high energy (15 GeV/c) particles in the SPS accelerator in CERN (Geneva, Switzerland). During these tests, the analogue information coming from the sensors was converted into a digital value. The data were stored on a mass storage unit and analysed off-line, i.e. once the tests finished. In this way, the kTC and the FPN noise could be eliminated. The charge generated by a particle spread over several pixels. A cluster of pixels has thus to be defined in order to compute the total collected charge (fig. 3). If a sufficiently large number of pixels is considered in the cluster, the total collected charge is larger than 1000 electrons, consistent with the thickness of the epitaxial layer. The exact amount depends on the detail of the charge collection process, hence on the pixel structure. The measured detection efficiency on the 0.6 µm sensor is 99.5 ± 0.2%, consistent with the hypothesis that the full sensor area is active. The spatial resolution measured by using charge interpolation among pixels is 1.6 μm (fig 4).

Conclusions

The results shown above represent a proof of principle for the feasibility of a Tracking/Vertex detectors with MAPS. At present CMOS sensors are candidates as tracking detectors for a future Linear Collider, an electron-positron collider which could be built around 2010. The design of the detectors is not yet fixed, although some guidelines appeared dictated by the physics requirements. The pixel pitch could be in the order of 25 μm, in order to achieve a spatial resolution of a few microns. The readout speed indicates a column-parallel readout at 50 MHz. Data should be digitised with a few bits (4 or 6) resolution, then grouped in clusters and zero-suppressed. Depending on the requirement of the experiments, a dedicated circuit containing the ADC and the subsequent digital processing stages is currently planned. For the MAPS itself, deep submicron technologies (0.25 μm and below) are considered. They offer inherent radiation hardness[1], which has to be traded-off with a reduced thickness of the epitaxial layer, yielding a reduced charge signal. Present developments are focused on the internal pixel structure in order to optimise it for very low signals in a "dark" environment, while keeping the required radiation hardness. A first prototype array (64*8) with different pixel architectures, including in-pixel kTC and FPN suppression, have been submitted in a 0.25 μm technology. Results will be available during the autumn of this year (2001).

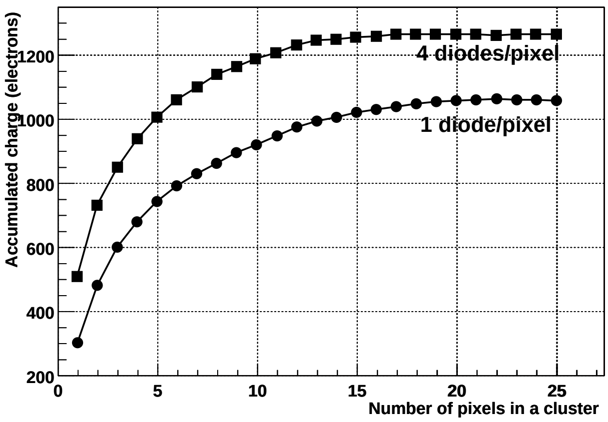

Figure 3. Measured collected charge vs. the number of pixels included in the cluster for two different pixel structures in MIMOSA I.

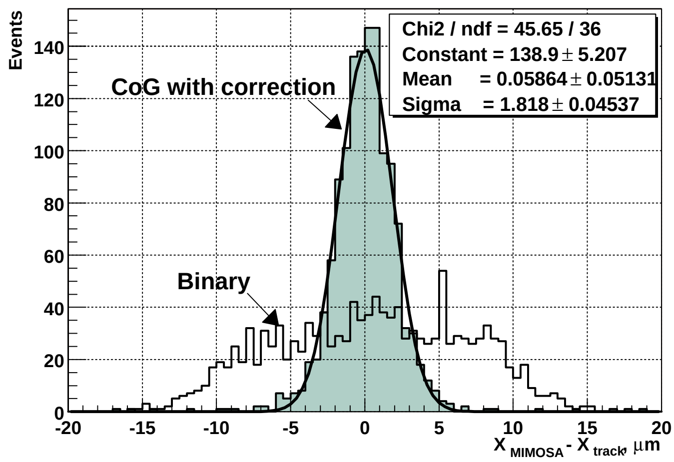

Fig. 4. Distribution of the differences between the impact point positions as measured by the MAPS and as measured by a reference telescope (intrinsic resolution of 1 μm). In the case of binary readout (position given only by the co-ordinate of the pixel with the higher signal), the distribution spans between ±10 μm, consistent with the 20 μm pitch. By using charge interpolation, the precision of the sensor is improved and is 1.6 μm as measured by the standard deviation of the distribution (corrected for the error in the reference telescope).

[1] M. J. French et al., *Design and results from the APV25, a deep submicron CMOS front-end chip for the CMS tracker*, to be published in *Nuclear Instruments and Methods A*