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CMOS Pixel Sensors for High Precision Beam Telescopes and Vertex Detectors

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CMOS sensors of the MIMOSA series are developed at IPHC since a decade and have ended up with full scale devices used in beam telescopes and in demonstrators of future vertex detectors. Since a few years, a fast architecture is being developed in collaboration with IRFU, which aims to speed up the read-out by 1-2 orders of magnitude. The first full scale sensor based on this architecture was fabricated recently and is being tested. Made of ∼660,000 pixels covering an active area of $\sim 2\ cm^2$, it delivers zero-suppressed binary signals, which allow running at ∼10 kframes/s. It equips the beam telescope of the E.U. project EUDET and serves as a forerunner of the sensor equipping the 2 layers of the Heavy Flavor Tracker detector of the STAR experiment at RHIC. This paper overviews the main features and test results of this pioneering sensor.

Finally, the issue of radiation tolerance will be addressed, in the context of a newly available CMOS process using a depleted substrate. A prototype sensor was fabricated in this process. First results indicate that fluences of $10^{14}\ \mathrm{n}_{eq}/\mathrm{cm}^2$ may be tolerable for CMOS sensors.

Overall, the paper provides an overview of the status and plans of CMOS pixel sensors at the frontier of their achievements and outreach.

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[*] Speaker.

1. Principle of operation

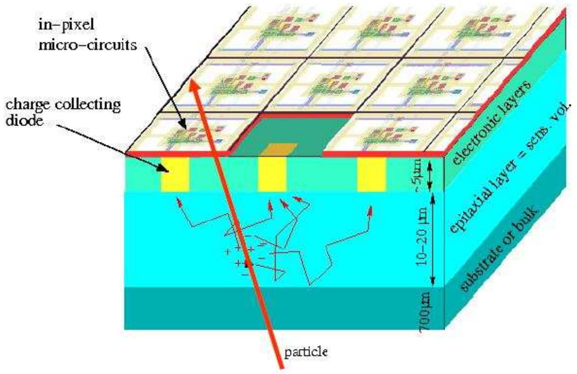

Figure 1: Principle of operation of a CMOS sensor.

As for any silicon based sensor, the signal generated by a charged particle traversing a CMOS[1] sensor is due to the electron-hole pairs created in the sensitive volume. The sensitive thickness of CMOS sensors is typically 10-20μm, which translates into $\sim$ 1000 e^- created by a minimum ionising particle, typically collected on a 9-pixels cluster. The charge carriers propagate thermally and are collected by diodes formed by n-wells in contact with the p-type substrate. This detection principle is illustrated in fig. 1. The intrinsic advantages of this technology come from the extremely high granularity (down to few microns), the small thickness (few tens of microns) and the signal processing micro-circuits integrated on the sensor substrate. But they are at the expense of moderate radiation tolerance and intrinsic speed. Additionally, the small signal per pixel calls for a low noise read-out electronics. Furthermore, since the n-wells are used to collect the charge, the in-pixel micro-circuitry relies mainly on NMOS transistors.

2. Achievements and applications

The IPHC was pioneering the development of CMOS sensors for high energy applications [2]. In the last ten years more than thirty sensors were developed, designed and tested, most of them in AMS 0.35 μm OPTO technology. Their main characteristics are: they can be operated at room temperature; the typical value for the noise is 10-15 e^-; the signal-to-noise ratio most probable value ranges from 15 to 30; the detection efficiency is nearly 100% for a fake hit rate below 10^{-4}. The sensors can tolerate a dose of up to 1 MRad; the tolerance to non-ionising radiation depends on the pitch: a sensor with a 10 μm pitch can stand a fluence of 10^{13} n_{eq}/cm^2. The resolution ranges from 1 to 5 μm, depending on the pitch and the granularity of the charge encoding. Such sensors deliver unfiltered analog outputs and have a typical read-out speed of 1 kFrame/s, which may be inadequate for certain applications. A binary output architecture was developed in the last years, that allows to read up to 10 kFrame/s. The first full-scale sensor with this architecture, MIMOSA 26, was produced. The chip is organised in 1152 columns of 576 pixels, each terminated with a discriminator and read out in parallel. The discriminated signals are processed through a zero-suppression circuitry integrated in the chip. The latter has an active area of 10.6×21.2 mm^2 for a pixel pitch of 18.4 μm. The average power dissipated is 280 mW/cm^2. The layout is shown in fig. 2. The chip was validated in the laboratory and is being fully characterised at CERN-SPS.

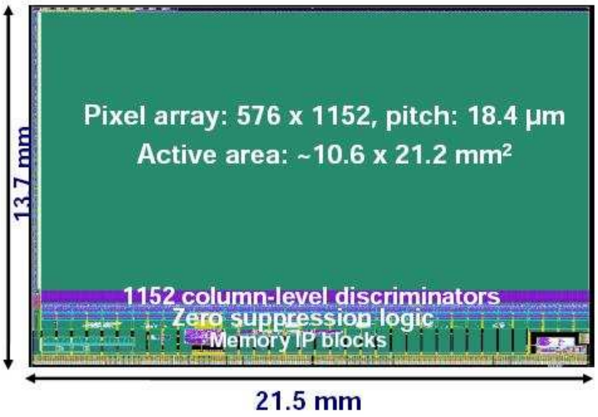

Figure 2: Layout of the MIMOSA 26 chip.

MIMOSA 26 was developed to equip the reference planes of the EUDET beam telescope [3]. A twice larger version of MIMOSA 26 will equip the Heavy Flavor Tracker of the STAR experiment [4]. MIMOSA 26 provides also the sensor architecture for the Micro-Vertex detector of the CBM experiment, but more R&D is required to reduce further its integration time [5]. The sensor is a forerunner for a sensor adapted to the vertex detector of ILD [6]. The requirements imposed on the latter by the physics are extremely severe, especially in terms of granularity (3 μm single point resolution), material budget (0.2% $X_0/layer$) and integration time (25 μs for the innermost layer). R&D is carried out on the readout speed and the system integration for this goal. More precisely, the IPHC is participating to the PLUME project [7], developing a light double-sided ladder (0.3% X_0) equipped with six MIMOSA 26 sensors. This project is pursued to explore the main system integration issues in view of the ILD Technical Design Report of 2012.

3. Developments

Besides developing fast readout architectures, the IPHC is involved in a R&D line exploiting a new process featuring a high resistivity epitaxial layer ($\sim 10^3\ \Omega \cdot cm$). In this case, with voltages of $4-5\ V$, the depleted depth reaches several microns, to be compared with a fraction of micron in low resistivity epitaxial layers. This improves substantially the tolerance to non ionising radiation. The technology was prototyped with the MIMOSA 25 chip. First results obtained with a $^{106}Ru\ \beta$ source are shown in fig.3. It displays the charge collected as function of the number of pixels in the cluster before and after irradiation (continuous curves). It is compared with a reference sensor (black crosses) featuring a low resistivity epitaxial layer. MIMOSA 25 exhibits a radiation tolerance higher by 1-2 orders of magnitude. A different technology with high resistivity epitaxial layer is also under study, in a collaboration led by CERN, in view of the upgrade of detectors for super-LHC.

The most promising CMOS sensor R&D line is offered by $3D$ integration techniques, where layers (tiers) with different functionalities, are stapled together and connected through vias. As compared

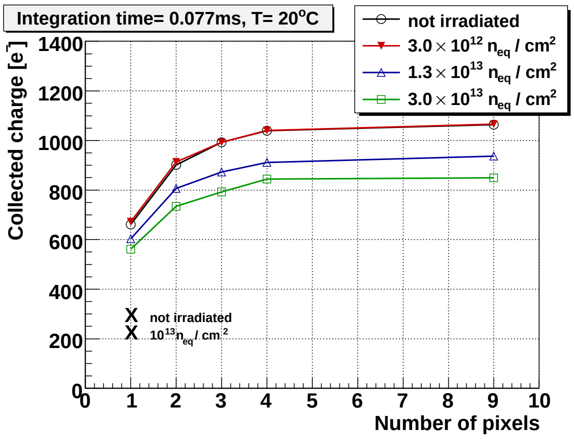

Figure 3: Collected charge vs. number of pixels in a cluster for MIMOSA 25 (20 μm pitch) and for a sensor (10 μm pitch) with low resistivity epitaxial layer before and after irradiation with 1 MeV neutrons. These data were obtained by illuminating the sensor with a ^{106}Ru β source.

to the standard planar technology, the 3*D* approach expands strongly the in-pixel functionalities. Moreover, different technologies can be combined, selecting the most adapted for the layer's purpose. The approach is still emerging and needs to be assessed, especially for its material budget and power dissipation. Within a consortium led by FERMILAB, different architectures were submitted for fabrication, which try to combine high level signal processing with low power dissipation [8].

4. Summary and conclusions

CMOS sensors have shown to be mature for real scale applications, especially where high resolution and very low material budget are needed. Their integration in real experiments is under way: a fast, binary output sensor, MIMOSA 26, equips the EUDET beam telescope and its extension will equip the STAR HFT. Its architecture is a promising candidate for the ILD vertex detector and the CBM micro-vertex detector. New perspectives are now opening up to improve dramatically the sensor performances: depleted sensitive volume and 3*D* integration technologies could lead the way to a much wider range of applications of CMOS sensors in tracking and vertexing devices.

References

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