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Developments on CMOS with LF, AMS and TJ technology

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Summary. — HV-CMOS sensors represent a solid candidate detector for the future of high-energy physics experiments. The LFoundry (LF) 150 nm, the Austria Micro System (AMS) aH18 180 nm and the TowerJazz (TJ) 180 nm HV-CMOS process has been under investigation for pixel detectors at the High Luminosity Large Hadron Collider (HL-LHC). The pixel response of an LF prototype in terms of gain and times of signal, an efficiency estimation of an AMS one along with measurements on fall and rise times, ToT and time walk and for TJ results from a test beam at CERN showed that this technology can qualify for the design of the outer pixel layers of the ATLAS Inner Tracker (ITk).

1. – Introduction

With the upgrade of the LHC experiments to the HL phase, instantaneous luminosity will be increased to $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Therefore, a new tracking system for the ATLAS Experiment [1] with high segmentation geometry and radiation-hardness is needed. The inner tracker will be enhanced and entirely made of semiconductor detectors (ITk). Its η coverage will pass from 2.5 to 4, granularity will be 5 times increased and it will be 20 times more radiation-hard in its most sensible regions. Pixel sensors are inserted in the innermost layers because of their high granularity and spatial resolution, better than $10\,\mu$m. Hybrid sensors collect charges by drifting electrons and holes in the depleted volume, they are radiation-hard but their readout electronics and sensor are placed in different wafers, needing additional material. Monolithic MAPS have all in the same wafer but charges are collected through diffusion of charge carriers, with a slow timing response and a limited radiation-hardness. HV-CMOS sensors have similar geometry but also a depleted region and charges can drift, their electrode can be as large as the whole pixel or smaller. These sensors are fast and radiation-hard so they represent solid candidates for the outermost central pixel layer of the upgraded ITk. Prototypes in

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different technologies have been tested in the INFN Milano laboratory and CERN test beams.

2. – Results

The LFCPix Demonstrator [2] built in the LFoundry 150 nm technology consists in a matrix of 36×158 PMOS and NMOS pixels with size of $50 \times 250\,\mu\text{m}^2$. The substrate is a high-resistivity ($\rho > 2000\,\Omega$ cm) p-type layer below a Deep-N-Well (DNW) which contains the full readout electronics and each pixel shows an injection capacitance of 2 fF.

Calibration has been taken comparing spectra from an X-rays tube with a molybdenum target and of an injected signal from an external pulser. In the first case, the expected spectrum is a Bremsstrahlung background with 2 peaks due to the K_α and K_β transitions of molybdenum. The response gain g is calculated from $V_{peak} = gQ_{X\text{-}rays}$ (see fig. 1). $Q_{X\text{-}rays}$ is the charge generated in the sensor and it is equal to $eE_{peak}/3.6\,\text{eV}$, where 3.6 eV is the average energy for creating an electron-hole pair and E_{peak} is the K_α energy line without the silicon ionizing potential. The gain k is obtained from $V_{peak} = kV_{pulser}$, where $V_{pulser} = 300\,\text{mV}$. With both X-rays and pulser the PMOS pixels show a better amplitude (0.062 and 0.068 V) and so a better gain with a smaller uncertainty (10% and 7%) than the NMOS (0.054 and 0.057 V and 12% and 13%). The correlation coefficient between k and g has been found to be always higher than 0.99 for each pixel. The injection capacitance has been calculated as k/g and it is equal to 2.41 fF with uncertainty of 0.13 fF, in agreement with the expected value.

The MuPix8 [3] is produced by AMS with an aH18 process at 180 nm, it is made of a matrix of 144×200 pixels with size of $80 \times 81\,\mu\text{m}^2$. The sensitive region is an epitaxial p-type layer, approximately $20\,\mu$m thick, with a resistivity of $80\,\Omega$cm, the electrode is a large DNW and pixels have a nominal injection capacitance of 0.76 fF.

Measurements of amplitude, rise and fall times and time over threshold (ToT) as a function of the injected charge in a range between 2000 and 7300 electrons demonstrate a linear behavior up to 6500 electrons, after which the signal saturates. Therefore, it is possible to measure the charge for highly ionizing particles. The threshold for detecting an event can be extracted from the efficiency and it has been found to be 1701 electrons. Noise can be calculated from the non-ideal behavior of the efficiency distribution (its shape is not a step function) and its value is 99 electrons. It is mainly due to the experimental setup and it is possible to operate at lower thresholds.

The configuration with small electrodes has been studied on a modified version of the ALICE Investigator chip [4] realized in TowerJazz 180 nm technology. In this modified

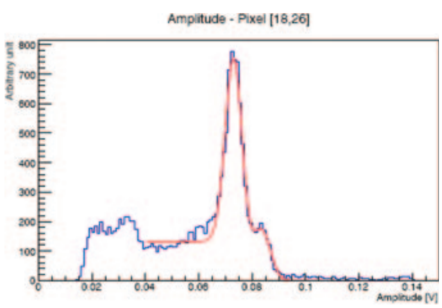

Fig. 1. – Spectrum obtained with X-rays on a molybdenum target for a single pixel.

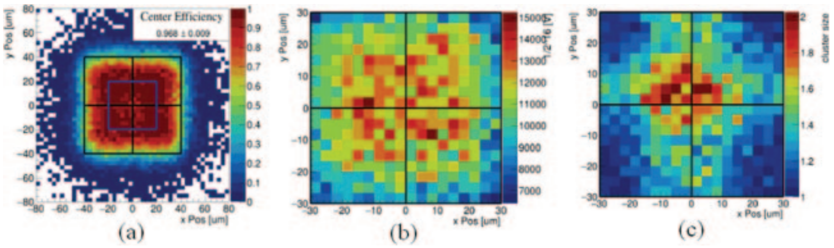

Fig. 2. – Efficiency (a), amplitude (b) and cluster size (c) as a function of transverse to beam coordinates.

process a planar junction is located below the small-size electrode, providing a detector capacitance of few fF. The sensor has been irradiated with $10^{15}\, n_{eq}/\text{cm}^2$.

Different test beams have been performed at CERN during 2017 with 180 GeV pions. Measurements of efficiency, amplitude and cluster size as a function of the transverse to beam coordinates are visible in fig. 2 for a small matrix of pixels $30 \times 30\,\mu\text{m}^2$. Efficiency is uniform and close to 1 for almost the whole chip, while the cluster size never exceeds 2 pixels, therefore limiting charge sharing. This technology can be proposed as a candidate for the outermost pixel layer of ITk. The promising results obtained from the Investigator have motivated the design of a large-size demonstrator [5] consisting of 512×512 pixels with $36.4 \times 36.4\,\mu\text{m}^2$ size, $3\,\mu$m electrode and $30\,\mu$m spacing. It implements an asynchronous readout scheme to further reduce power consumption within the pixel matrix.

3. – Conclusions

Different HV-CMOS technologies have been investigated for the HL-LHC. They all show acceptable signal and noise performance. These may qualify for the design of the outer pixel layers of ITk if radiation tolerance at the required levels can be achieved and a readout system compatible with the ITk trigger rate and latency is implemented.

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