From vertex detectors to inner trackers with CMOS pixel sensors

JC 66

Yang Tao

Motivation

The 350 nm CMOS technology used for the STAR-PXL sensors was considered as too poorly suited to upcoming applications like the upgraded ALICE Inner Tracking System (ITS), which requires sensors with one order of magnitude improvement on readout speed and improved radiation tolerance. This triggered the exploration of a deeper sub-micron CMOS technology, Tower-Jazz 180 nm, for the design of a CPS well adapted for the new ALICE-ITS running conditions.

All these developments allowed the conception of a CPS, called MIMOSA-28 (cf. Table 1), suited to the STAR-PXL detector operated at RHIC/BNL, the first vertex detector based on the CPS technology.

Table 1
Properties (design goals for MISTRAL-O) of sensors discussed in this paper.

	MIMOSA-28	FSBB-M0	Mi-22THRb	MISTRAL-O
CMOS process	350 nm	180 nm	180 nm	180 nm
Pixels (col. × row)	960 × 928	416 × 416	64 × 64	832 × 208
Pixel pitch [μm^2]	20.7 × 20.7	22 × 33	39 × 50.8 or 36 × 62.5	36 × 65
Sensitive area [mm^2]	19.2 × 19.9	13.7 × 9.2	8.1 or 9.2	13.5 × 30.0
σ_{sp} [μm]	$\gtrsim$3.6	$\gtrsim$4.5	~10	~10
$t_{r.o.}$ [μs]	185.5	41.6	~5	20.8
TID [MRad]	>0.15	>1	>0.15	>0.15
NIEL [$10^{12} n_{eq}/cm^2$]	>3	>10	>1	>1
Power [mW/cm^2]	160	<160	N/A	$\lesssim$80
Pads over pixels	No	No	Yes	Yes
On-chip sparsification	1D	2D	None	2D

The performance reached by the MIMOSA-28 sensor are not suited to match some of the more demanding requirements of the new ALICE-ITS (cf. Table 2), mainly in terms of $t_{r.o}$ and power consumption (outer layers), and to a lesser extent in terms of radiation tolerance (inner layers).

Table 2
Sensors design goals of STAR-PXL (operational) and new ALICE-ITS inner (ITS-in) and outer (ITS-out) layers. σ_{sp} refers to the spatial resolution, and TID and NIEL to the ionizing and non-ionizing doses, respectively.

	STAR-PXL	ITS (in)	ITS (out)
σ_{sp} [μm]	<4	<5	<10
$t_{r.o.}$ [μs]	185.5	30	30
TID [MRad]	0.15	2.70	0.10
NIEL [$10^{12} n_{eq}/cm^2$]	3	17	1
$T_{operation}$ [°C]	35	30	30
Power [mW/cm^2]	160	<300	<100
Surface to cover [m^2]	0.15	0.17	>10

ALICE-ITS upgrade : R& D of sensors for outer layers

Tower-Jazz 180 nm CMOS process:

- its aspects is the smaller feature size, improving the $t_{r.o}$ (higher integration density) and tolerance to ionizing radiation.
- the process grants thicker epitaxial layers with higher resistivity, improving the signal-to-noise ratio and tolerance to non-ionizing radiation.

Ryuta : what is the “laser soldering”?

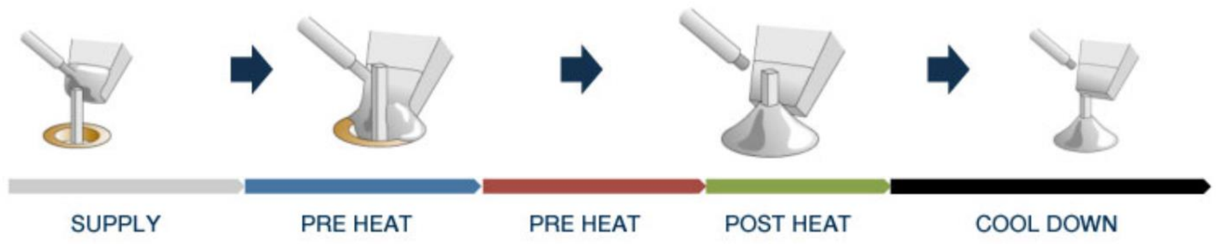
MISTRAL-O chip :

MISTRAL-O needs to be about 10 times faster than MIMOSA-28 together with twice less power consumption (cf. Table 2). It has as well to be pin-to-pin compatible with the ALPIDE design, which includes **pads over the pixel matrix suited to laser soldering**.

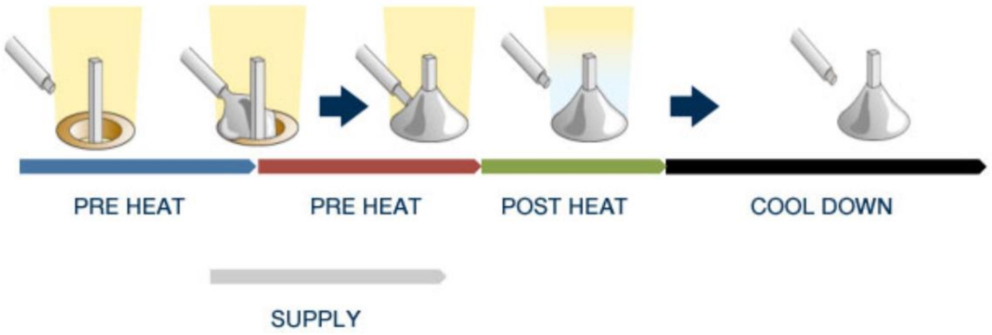
Two different heat application principles

Tip soldering process	**Laser soldering process**
1. The tip is heated to around 350C / 662F. 2. The tip is placed onto the soldering point and heat is applied up to the melting temperature (heat transfer) 3. Solder is supplied.	1. The laser illuminates the soldering point. 2. The illuminated area emits heat (surface heat emission). 3. The heat transfers into the surrounding area and is raised to the melting temperature. 4. Solder is supplied

[Tip soldering process]



[Laser soldering process]



The most important characteristic of laser soldering is its non-contact soldering ability, and there is no contact at all with either the PCB or the component. There is no physical load placed on the PCB, only laser light and the solder supply. Laser's great advantages are in its ability to efficiently apply pinpoint heat, to apply light to confined spaces where a tip cannot fit, and to handle tightly-spaced assemblies, by changing the light angle and taking other steps. Maintenance work can also be reduced.

Rolling shutter readout in the novel CMOS-process

FSBB-M0 : a full scale prototype by new 180 nm CMOS-process

- Reduce the number of pixels in a column to be readout (928 → 416)
- Increase the size of the pixel along the column (20.7µm → 33 µm).
- The rolling shutter readout mode addresses simultaneously all pixels belonging to **a pair of neighboring rows**. Therefore, each discriminator addresses 208 pixels instead of 928, with a proportionnally reduced $t_{r.o}$.

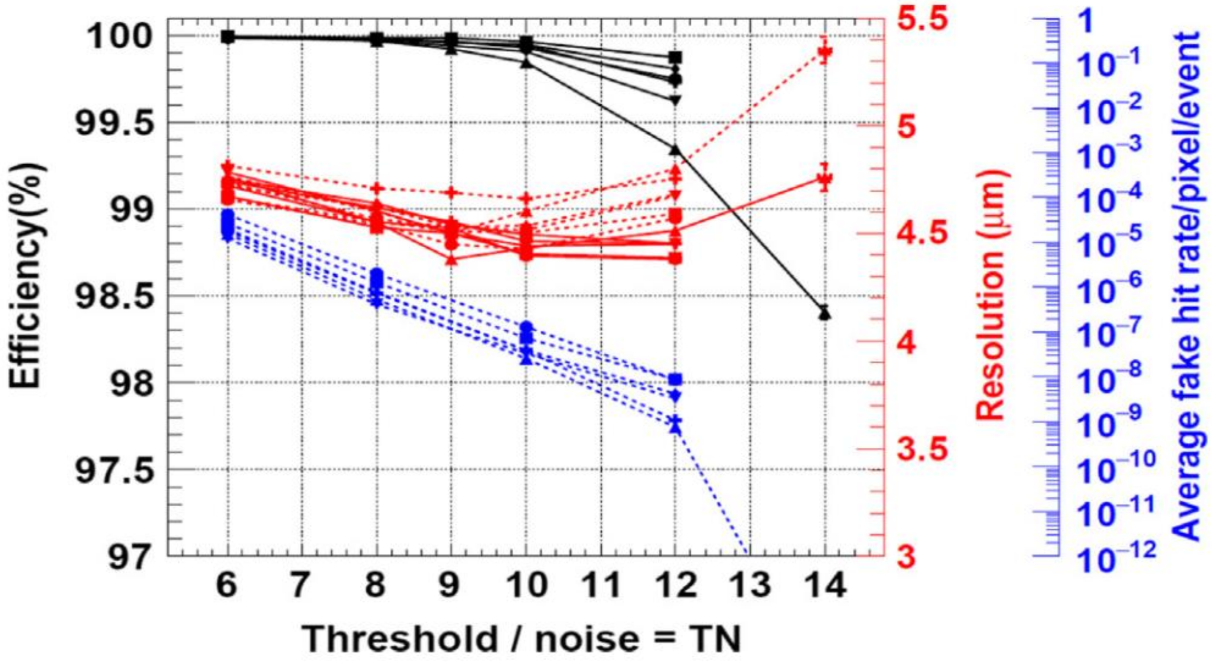


Fig. 2. Detection efficiency (top black curve), dark occupancy (middle dotted-blue curve) and spatial resolution (bottom curves) along short (solid) and long (dotted) pixel sides as a function of the discriminator threshold (in multiples of thermal noise) of the FSBB-M0 sensor. The performance of 6 sensors is superimposed. $T_{operation}$ = 30°C.

These measurements were performed before and after irradiation with an X-Ray source (up to 1.6 MRad) and with 1 MeV neutrons (up to $10^{23} n_{eq}/cm^2$) . The sensors were next tested with particle beams at the CERN-SPS with negatively charged pions of ~120GeV/c, and at DESY with electrons of 3 − 6 GeV/c.

A nearly 100% detection efficiency and a dark occupancy of < 10^{-5} was observed for all non-irradiated sensors tested. The dark occupancy could be reduced by an order of magnitude by masking a small fraction (<0.5%) of the noisiest pixels, with negligible impact on the detection efficiency.

CERN-SPS (DESY) beam test

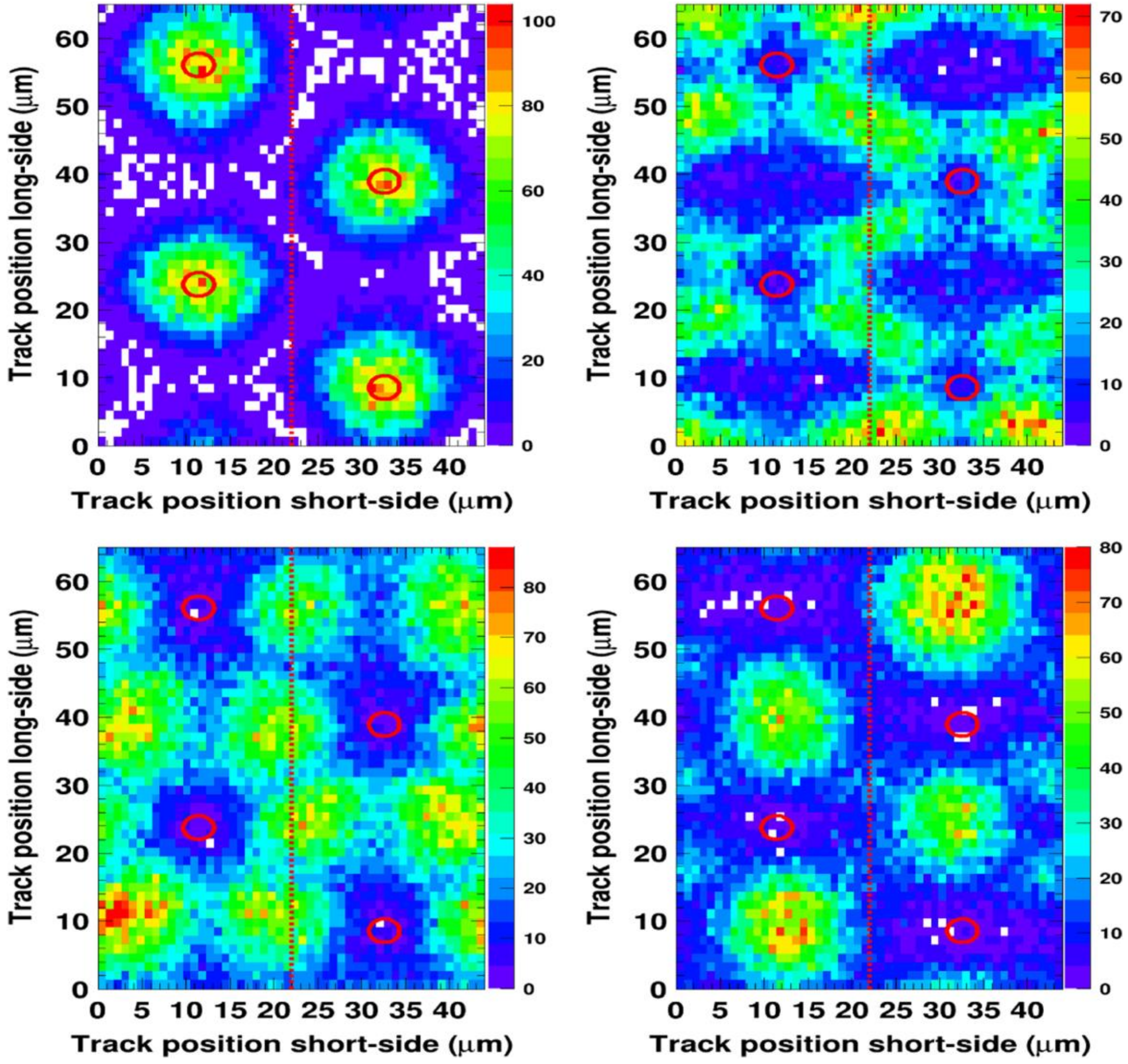


Fig. 3. Track impact position at DUT with respect to the closest collection diode (red circles). The four nearest collection diodes are shown. The vertical red-dotted line shows the boundary between two columns of pixels. The plots from left to right and top to bottom corresponds to hit pixel multiplicities from 1 to 4, respectively. The telescope pointing resolution is 2.2 μm.

Telescope pointing resolution(σ_{Tel})

? ? ?

Spatial resolution(σ_{sp}):

- subtracting the σ_{Tel} from the track-hit residue

Suyu : Why can we get the spatial resolution by substracting σ_{Tel} from the track-hit residue?

Digital resolution($\sigma_{\mathrm{digital}}$):

- $\sigma_{\mathrm{digital}} = pitch/\sqrt{12}$

Large pixel design and validation

Mi-22THRb

Table 1
Properties (design goals for MISTRAL-O) of sensors discussed in this paper.

	MIMOSA-28	FSBB-M0	Mi-22THRb	MISTRAL-O
CMOS process	350 nm	180 nm	180 nm	180 nm
Pixels (col. × row)	960 × 928	416 × 416	64 × 64	832 × 208
Pixel pitch [μm^2]	20.7 × 20.7	22 × 33	39 × 50.8 or 36 × 62.5	36 × 65
Sensitive area [mm^2]	19.2 × 19.9	13.7 × 9.2	8.1 or 9.2	13.5 × 30.0
σ_{sp} [μm]	$\gtrsim$3.6	$\gtrsim$4.5	~10	~10
$t_{r.o.}$ [μs]	185.5	41.6	~5	20.8
TID [MRad]	>0.15	>1	>0.15	>0.15
NIEL [$10^{12} n_{eq}/cm^2$]	>3	>10	>1	>1
Power [mW/cm^2]	160	<160	N/A	$\lesssim$80
Pads over pixels	No	No	Yes	Yes
On-chip sparsification	1D	2D	None	2D

The sensors were next tested with particle beams at the CERN-SPS with negatively charged pions of ∼120GeV/c, and at DESY with electrons of 3 − 6 GeV/c.

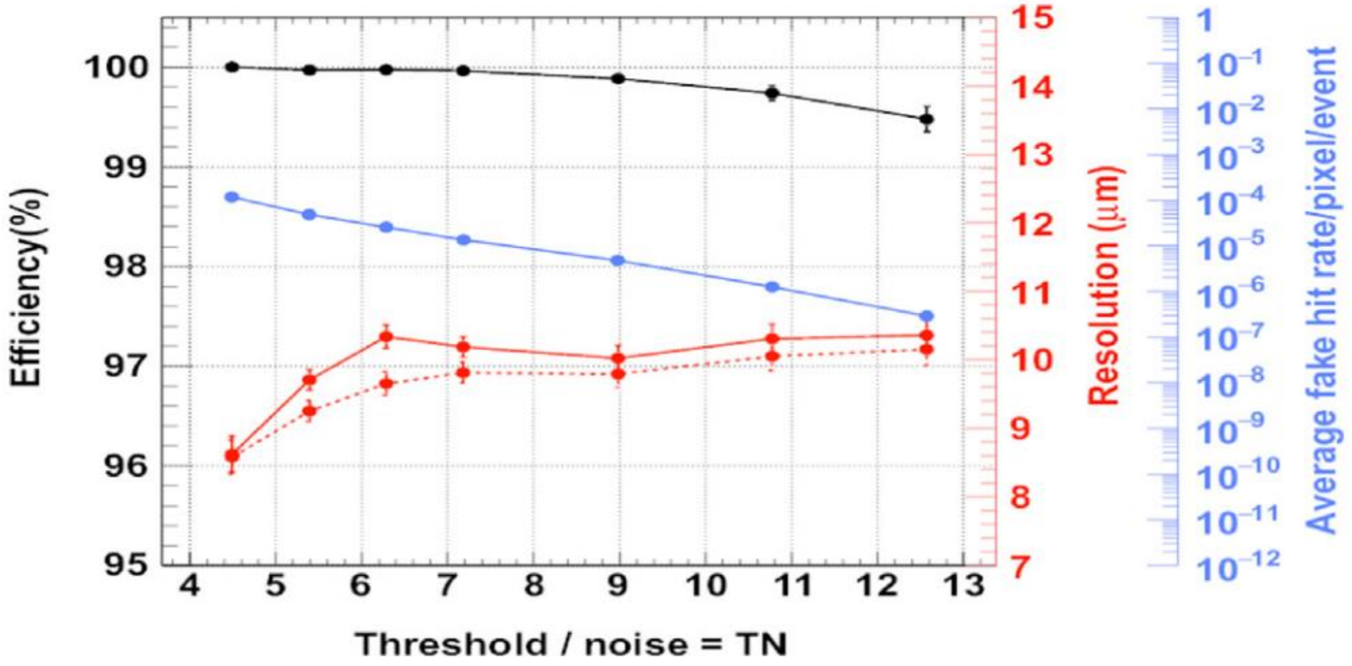


Fig. 4. Detection efficiency (top black curve), dark occupancy (middle blue curve) and spatial resolution (bottom curves) along short (solid-red) and long (dotted-red) pixel sides as a function of the discriminator threshold (in multiples of thermal noise) of the Mi-22THRb sensor with pixels dimensions of $39 \times 50.8\ \mu m^2$. $T_{operation} = 30°C$.

For both pixel dimensions, a nearly 100% detection efficiency was observed for non-irradiated sensors. Satisfactory detection efficiency (>99%) was also obtained for sensors irradiated at doses relevant of the ALICE-ITS outer layers.

Summary

This paper summarizes the R & D results for the design of a CPS well adapted to the ALICE-ITS outer layers. Two prototypes were fabricated and fully tested. The first one addressed the validation of the rolling shutter readout architecture implemented in the new Tower-Jazz 180 nm CMOS-process, with nearly four times shorter $t_{r.o}$. than the MIMOSA-28 sensor equipping the STAR-PXL. The second prototype addressed a large pixel design, including bonding pads over the pixel matrix, to further squeeze $t_{r.o}$. and the power consumption, while complying with σ_{sp} and radiation hardness requirements of the ALICE-ITS outer layers.