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Design concept for the CREMAPS CMOS Monolithic Active Pixel Sensor

1. Motivation for the sensor design

The CREMAPS sensor design reflects the needs of modern experiments on charged particle trackers, which are in particular a very light material budget and an extremely precise spatial resolution in combination with a high rate capability and advanced radiation tolerance. CMOS Monolithic Active Pixel Sensors may reach a spatial resolution of few µm while their total thickness remains at 50µm. R&D challenges consist in increasing the radiation tolerance and the rate capability of the device. A particular requirement deriving from a possible use of the sensor in fixed target heavy ion experiments consists in the capability to handle occupancy fluctuations in time in an efficient way. Moreover, the sensors maybe exposed to numerous heavy ions either from the beam or target fragments and must tolerate their impacts without being disabled by single event effects of integrated radiation damage.

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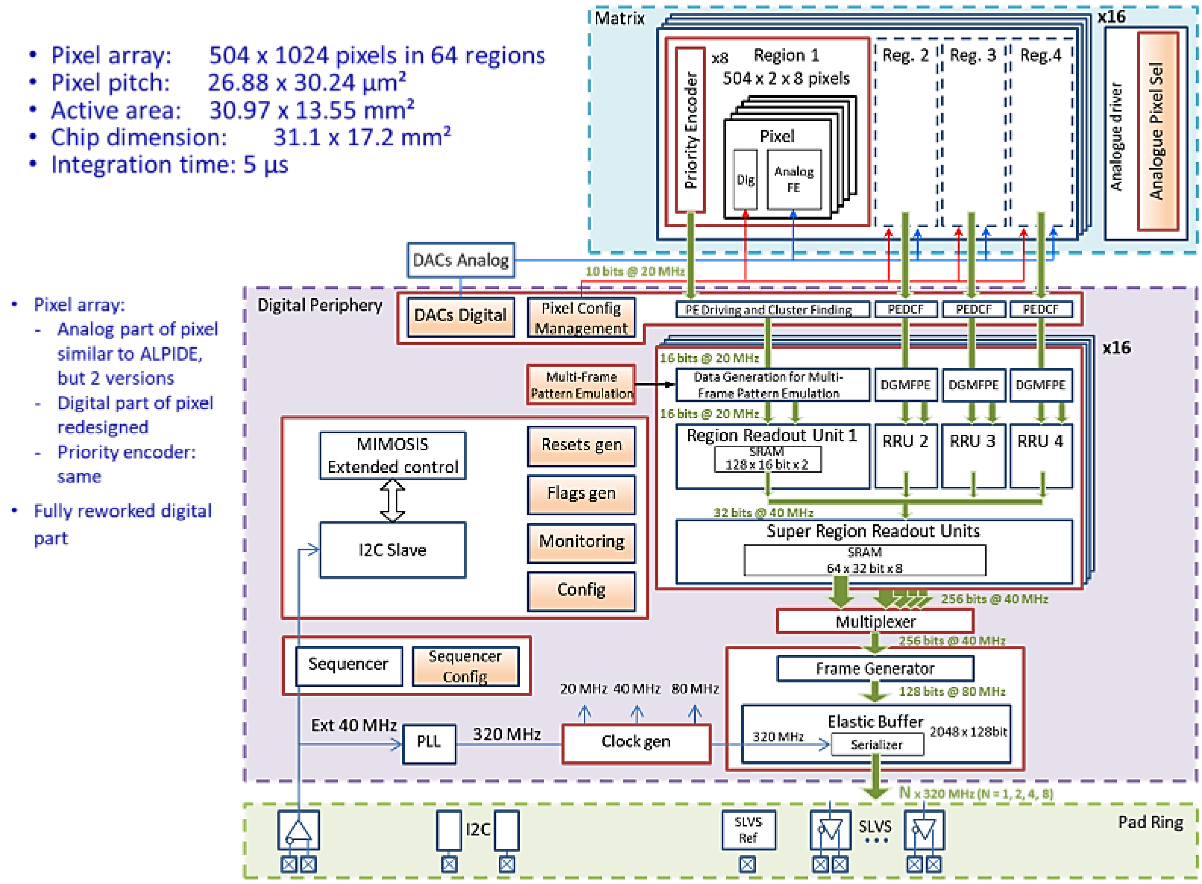

Figure 1: Global layout of MIMOSIS.

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2. Global sensor layout

The CREMAPS sensor prototype will be a reticle size CMOS Monolithic Active Pixel Sensor designed in Tower/Jazz 180nm technology. An overview of its design is depicted in Figure 1. It hosts a ~4 cm² sensitive pixel matrix consisting of 504 x 1024 pixels with a height of 26.88 µm and a width of 30.24 µm. Each pixel incorporates a full amplifier-shaper-discriminator chain. The on-pixel digital front-end is modified and relies on a non-triggered, frame based readout. The start and end time of a frame is set by an end-of frame signal, which is generated by an internal sequencer. The frame length may be set in multiples of the 20 MHz clock cycle of this sequencer by means of detector control and will amount to 5 µs by default. In case the on-pixel discriminator detects a hit, this information is stored in an on-pixel memory cell and forwarded to the pixel's output buffer at frame end. Hereafter, the pixel may resume with hit detection. Each pixel features a pulse injection system, and a disabling circuit. The latter is to switch off the typically few hot pixels of the sensor individually and such to reduce the dark rate.

The 1008 pixels of two neighboring columns are read out by a common priority encoder, which is operated at a nominal clock frequency of 20 MHz. The data obtained is first fed into a simple cluster finder, which is suited to identify sets of up to four consecutive active pixels in the sense of the serpentine shaped readout. This allows to recognize 2D-clusters of up to 2x2 pixels, provided they are located in a single double column. The 16-bit data words generated by the cluster finder are forwarded to a so-called region buffer, which is suited to hold a maximum of 100 data words as provided by a total of 16 columns. This turns into a theoretical maximum pixel occupancy of 2.5\% at this level. A 16-bit header holding the number of the region is added to the data of each frame and complements the otherwise insufficient position information stored in the individual data words.

The data from four region buffers are concentrated via a priority-encoded 40 MHz, 32-bit data bus to the so-called super region buffer. After this first step of data concentration, the data of the 16 super region buffers is sent to a common and priority-encoded 256-bit-wide, second data concentrator bus, which provides its output via a so-called frame generator to an elastic output buffer. The frame generator adds header and trailer information indicating, among others, the frame number and as such a time stamp. Moreover, idle words, which are required to fill up the transmission of the wide data busses, are removed. The elastic buffer holds a maximum of 16384 data words. It sends the data to the outside world via up to eight 320 Mbps differential data links.

3. Design studies performed with previous sensor prototypes.

The validity of the above mentioned design concept was studied with two previous prototype sensors named MIMOSIS-0 and MIMOSIS-1. The first of both sensors was to demonstrate the validity of the pixel concept and of the priority encoder used for reading out the pixel matrix. The full size prototype MIMOSIS-1 featured a full pixel matrix and moreover the full bus structure described above. It was already designed pin-to-pin compatible to the CREMAPS-prototype. However, for simplification, the circuits for the above mentioned pixel grouping were not yet realized. Moreover, the MIMOSIS-1 was not yet fully hardened against the consequences of single event effects as caused by heavy ion impacts. Both sensors featured different pixel options and were built on different wafers, which turns into a total of 12 different pixels and wafers to be tested in case of MIMOSIS-1.

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MIMOSIS-0 and MIMOSIS-1 were tested with an intense laboratory test program. Moreover, MIMOSIS-1 was operated in heavy ion and light particle beams during a total of four beam times in 2021 and its tolerance to heavy ion impacts as much as its tracking performance was measured. The analysis of the data collected is ongoing. In summary, it was shown that:

- The noise of the sensors is as low as 5-17 e ENC depending on the specific pixel and the related setting of the steering voltages.
- The time resolution of the analog readout chain of the pixel is in the order of 300-600 ns (depending on the pixel and the precise setting) despite no time walk correction can be applied.
- The spatial resolution of the pixels amounts to <5 µm as expected. It is improved by the fact that one particle may fire in average 1.1 – 3.0 pixels, which allows to exploit a resolution of the positioning derived from the correlation between the cluster multiplicity and the distance of the impact to the closest sensing node. This procedure is most efficient in case of high average cluster multiplicities. Therefore, the spatial resolution deteriorates mildly to ~7 µm if the cluster multiplicity is reduced by applying strong depletion fields or by massive radiation damage. In consequence, there is a trade-off between radiation tolerance and spatial resolution to be respected.
- The detection efficiency to minimal ionizing particle amounts >99% and better performances are expected as soon as the time walk is correctly considered during the data analysis.
- The sensor shows a reasonably good immunity to Single Event Effects and survived an exposure to multiple 10 s spills with each 3 x 10^9 ~1 AGeV Pb beams without destruction.

4. Design improvements and remaining options

While a significant part of the design could be validated with the above mentioned prototypes, the CREMAPS prototype will hold additional features, in particular the on-chip grouping of pixel clusters, which is intended to reduce the data stream created and the computational cost for analyzing the data. The tolerance to heavy ion impacts will be improved by further triplicating the most important logic blocks and compensating possible bit flips caused by the ions by means of triple voting. In response to the experiences made with the MIMOSIS-1 prototype, a number of smaller matters will be improved. Those improvements include for example the option to send slow-control and fast control signals through non-synchronized clocks of different frequencies, which is of substantial advantage as both signals are created by different external units. Moreover it will be possible to steer the sensor reliably with a 40 MHz clock, which is internally multiplied to 320 MHz by a PLL. For MIMOSIS-1, the fast clock had to be injected directly, which would impose integration challenges as soon as the sensor is integrated into sizeable detector systems. The studies of the MIMOSIS-1 prototype suggests that the best possible combination of pixels and wafers is not yet reached and thus an improved compromise of spatial resolution and radiation tolerance can still be found. Accounting for this, the CREMAPS prototype will be once more designed with different pixel and wafer options. Despite this solution turns into the sensor consisting of four sub-matrices of different pixels, it is ambitioned to design those sub-matrices such that the pixels of the full sensor surface may be operated simultaneously with suited settings of the steering voltages.

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