Recent results and perspectives of the Monopix Depleted Monolithic Active Pixel Sensors (DMAPS)

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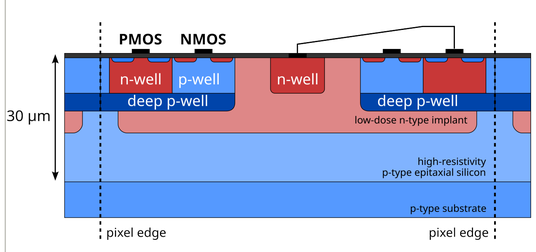
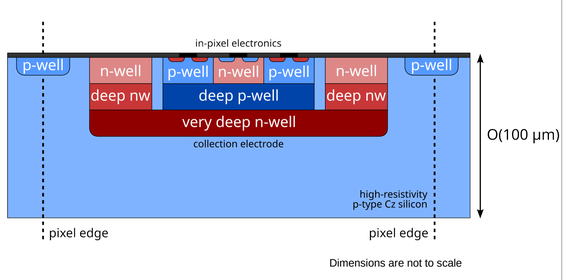
The Monopix design

The Monopix design implements monolithic active pixel detectors in commercial CMOS imaging technologies. High-resitivity substrates with high-voltage capabilities facilitate depletion of the charge-sensitive volume, maximizing the charge collection potential and enabling fast signal generation by drift.

The presented prototypes, TJ-Monopix2 and LF-Monopix2, differ in the size of the readout electrode relative the pixel area. The small collection electrode approach (TJ-Monopix2) offers low analog power consumption and minimal noise operation due its low detector capacitance. Its sensor geometry has to be tuned carefully to achieve a significant radiation tolerance (> 10^{14} 1 MeV neq cm^{-2}). A design with large collection electrode (LF-Monopix2) that houses all in-pixel readout electronics exhibits a larger radiation tolerance by default at the cost of a higher detector capacitance.



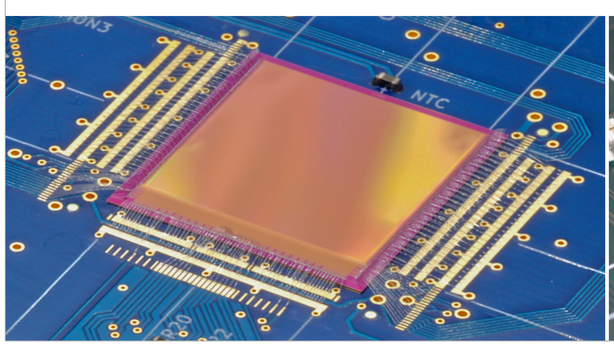


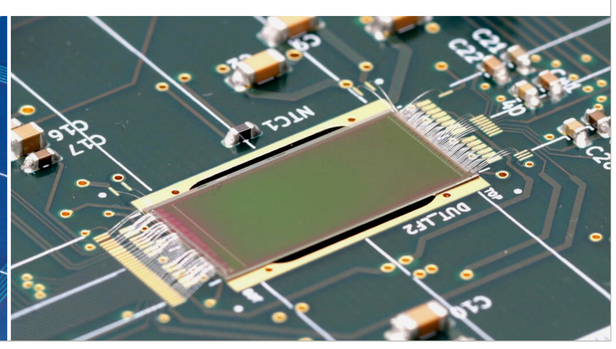
TJ-Monopix2:

- 180 nm TowerSemi technology
- 512 x 512 pixels of 33 x 33 µm² each
- 7-bit ToT energy measurement @ 40 MHz
- 3-bit in-pixel tuning DAC
- O(2 fF) detector capacitance
- 1 µW per pixel analog power

LF-Monopix2:

- 150 nm LFoundry technology
- 56 x 340 pixels of 150 x 50 µm² each
- 6-bit ToT energy measurement @ 40 MHz
- 4-bit in-pixel tuning DAC
- O(250 fF) detector capacitance
- 28 µW per pixel analog power

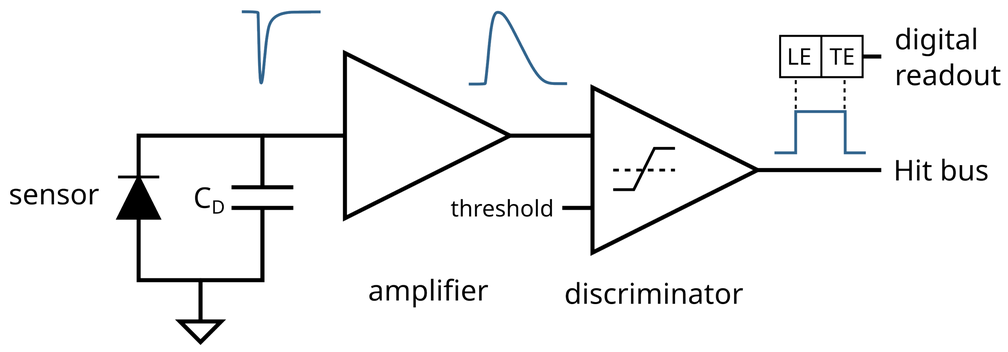




Front-end working principle

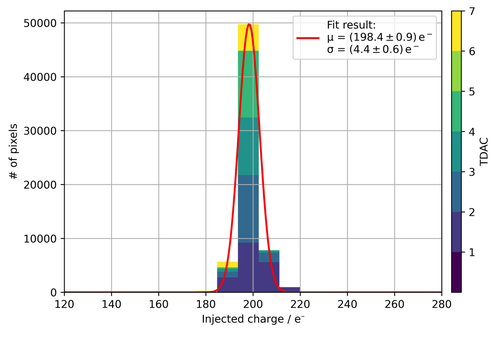
According to V = Q / C, the front-end input signal in TJ-Monopix2 is considerably larger than in LF-Monopix2 and can be amplified with a single-stage voltage amplifier while LF-Monopix2 makes use of a conventional charge-sensitive amplifier.

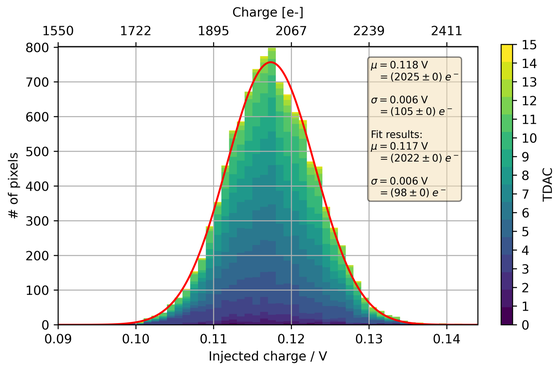
The matrix of both prototypes is read out using an established column-drain architecture derived from the FE-I3 readout chip.



Threshold response

Under typical operating conditions, the prototypes achieve a threshold response of 200 e⁻ and 2000 e⁻ for TJ-Monopix2 and LF-Monopix2, respectively, with most probable charge values of 2500 e⁻ and 6000 e⁻ for minimally ionizing particles.



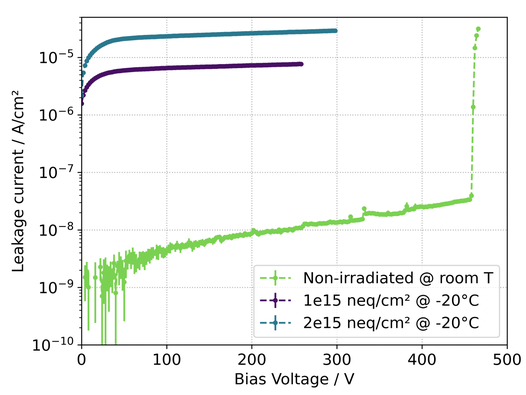


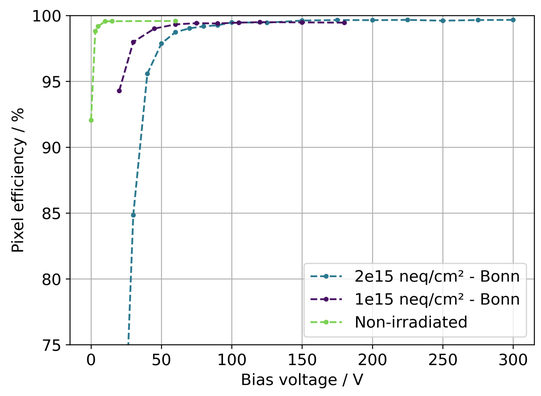
LF-Monopix2 exhibits an equivalent noise charge (ENC) of approx. 100 e⁻, while the small detector capacitance in TJ-Monopix2 is beneficial for noise levels as low as 5 e⁻.

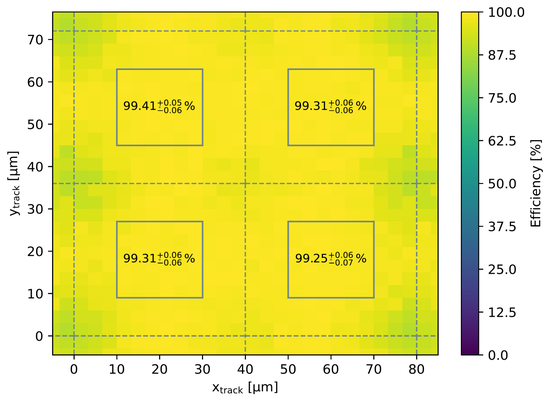
Radiation hardness

With dedicated design efforts, the breakdown voltage of LF-Monopix2 is increased to larger than 450 V before irradiation. The ENC increases from 90 e⁻ to 180 e⁻ after a NIEL fluence of 2 x 10^{15} neq cm^{-2}. Its large bias voltage capabilities allow for hit detection efficiencies above 99 % at these NIEL fluence levels.

NIEL fluence [neq]	0	1 x 10^{15}	2 x 10^{15}
Threshold [e⁻]	2040	2090	2070
ENC [e⁻]	87	120	178



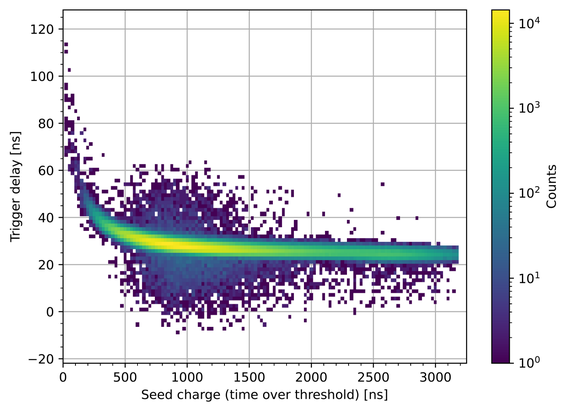


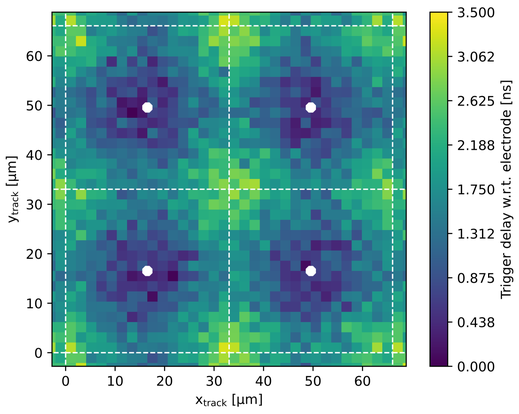


In the TJ-Monopix design series, a modification has been developed together with the foundry to increase the radiation hardness of the small collection electrode design. In this geometry, hit detection efficiencies above 98 % could be achieved at a NIEL fluence of 1 x 10^{15} neq cm^{-2}. A lower detection threshold in TJ-Monopix2 is expected to reduce the losses in the pixel corners for a more homogeneous detection efficiency above 99 %.

Timing performance

The amplifier implemented in TJ-Monopix2 facilitates fast detection of the deposited charge with a time resolution of less than 100 ps for charge values in the order of the most probable charge of minimally ionizing particles. Measurements in particle beams demonstrate a total time resolution of the pixel of about 1.3 ns (time walk corrected) which is dominated by physics processes and propagation delays within the pixel (up to 3 ns without time walk correction).

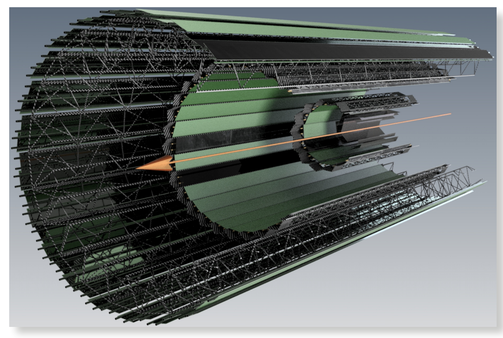




Conclusion & Outlook

Both presented depleted monolithic active pixel sensors demonstrate a good performance for high-radiation and high-rate environments in particle physics experiments. LF-Monopix2 exceeds its target radiation tolerance (1 x 10^{15} neq cm^{-2}) with no significant degradation at the available NIEL fluences.

TJ-Monopix2 offers a high granularity and fast readout combined with a low power consumption. First results hint to an improved radiation tolerance compared to its predecessor. With its performance, it serves as a baseline for a future Belle II vertex detector in the same CMOS technology.



F. Forti *Snowmass Whitepaper: The Belle II Detector Upgrade Program* arXiv:2203.11349

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Publications

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