# *Topmetal-II⁻*: a direct charge sensor for high energy physics and imaging applications

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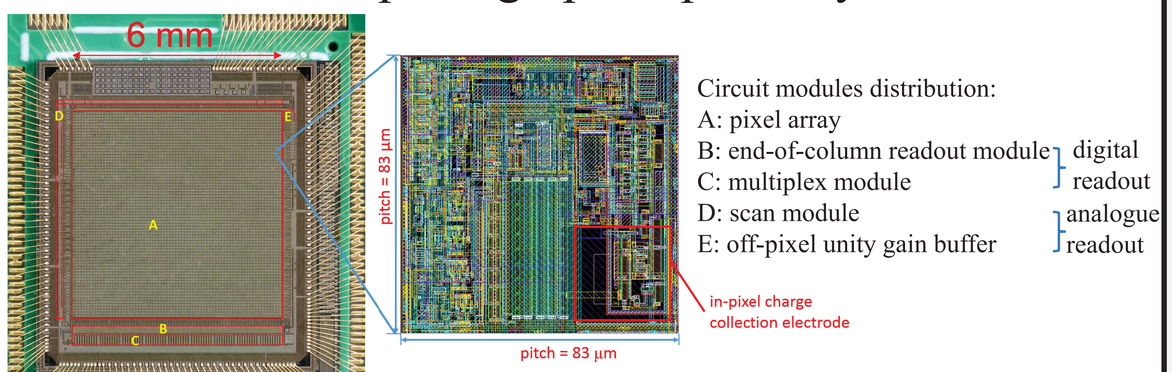
## Abstract

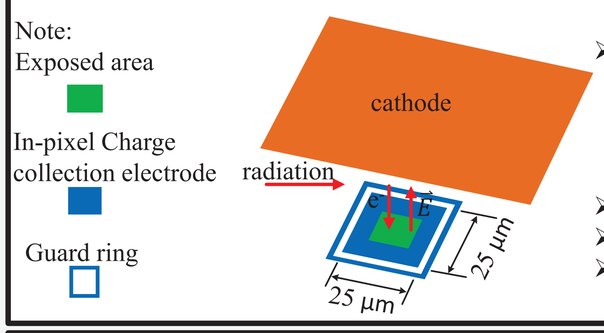
*Topmetal-II⁻*, a direct charge sensor, was manufactured in an XFAB 350 nm CMOS process. The *Topmetal-II⁻* sensor features a 72 x 72 pixel array of 83 μm pitch between pixels. It is suitable for Time Projection Chamber (TPC) [1] charge readout. This paper focuses on the implementation of circuitry in the sensor including the analogue readout channel and a column based digital readout structure. The analogue readout channel allows access to the full waveform from each pixel through time-shared multiplexing. The digital readout channel records hits identified by a variable threshold in each pixel. Preliminary tests show that an ENC of < 15 $e^-$ , a charge-voltage conversion gain of 190 mV/fC, and a threshold of 200 $e^-$ for the digital readout.

## Sensor photograph & pixel layout



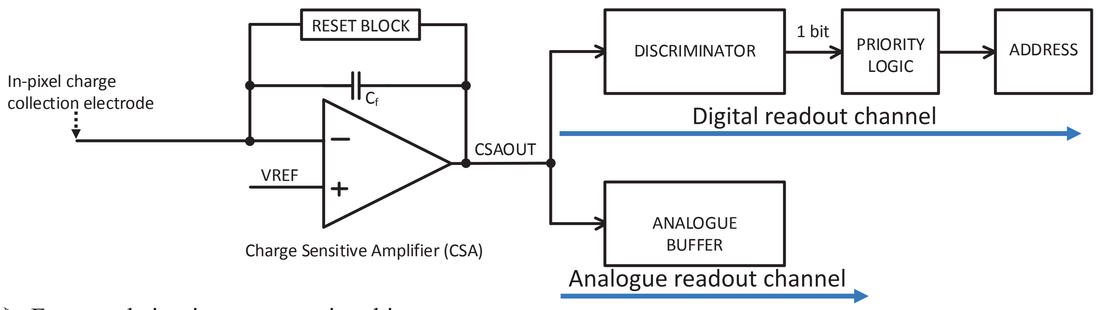

Circuit modules distribution:
A: pixel array
B: end-of-column readout module } digital readout
C: multiplex module
D: scan module } analogue readout
E: off-pixel unity gain buffer

## Charge Collection Electrode



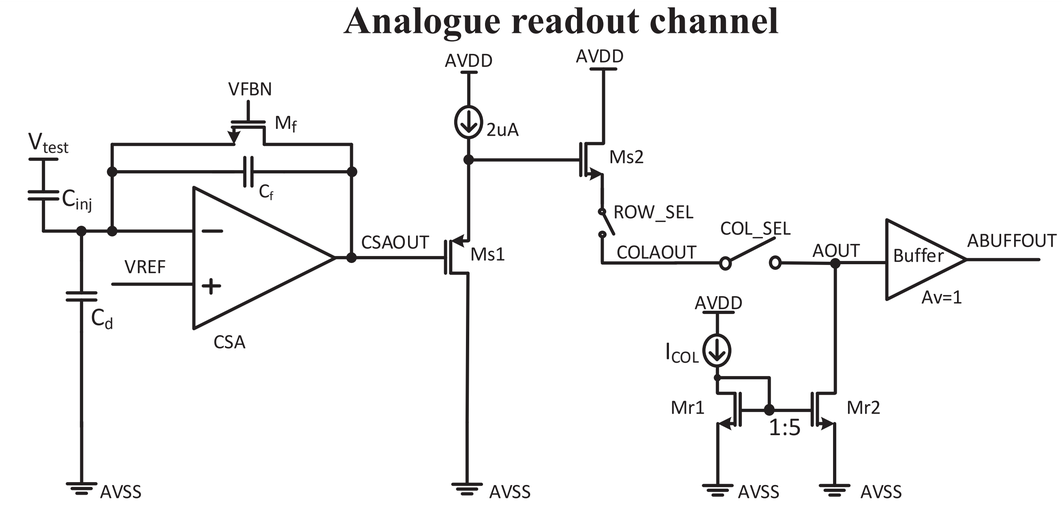

- Charge collection electrode: top metal [2]
  - Total area: 25 x 25 μm²
  - Exposed area: 15 x 15 μm²
  - Position: right bottom of each pixel, connect to the front-end circuitry directly in the pixel.
- Guard ring is connected to a test PAD.
- Electric field: ~ $10^2$ V/cm.
- Radiation ionizes the gas, charges drift to the in-pixel charge collection electrode.

## Pixel Structure

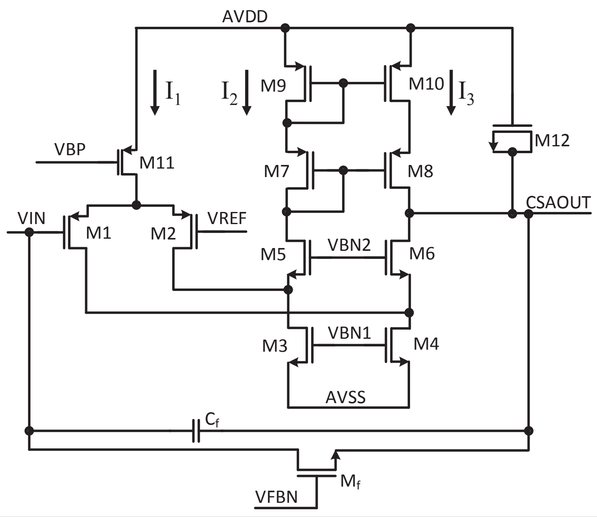



- Front-end circuit processes signal in two ways:
  - Analogue readout channel: allow access to the full waveform from each pixel through time-shared multiplexing.
  - Digital readout channel: record hits identified by a variable threshold in each pixel.
- CSA output feeds into both analogue and digital readout channels.
- Shaper-less architecture: lower power consumption and smaller pixel area.

## Analogue readout channel

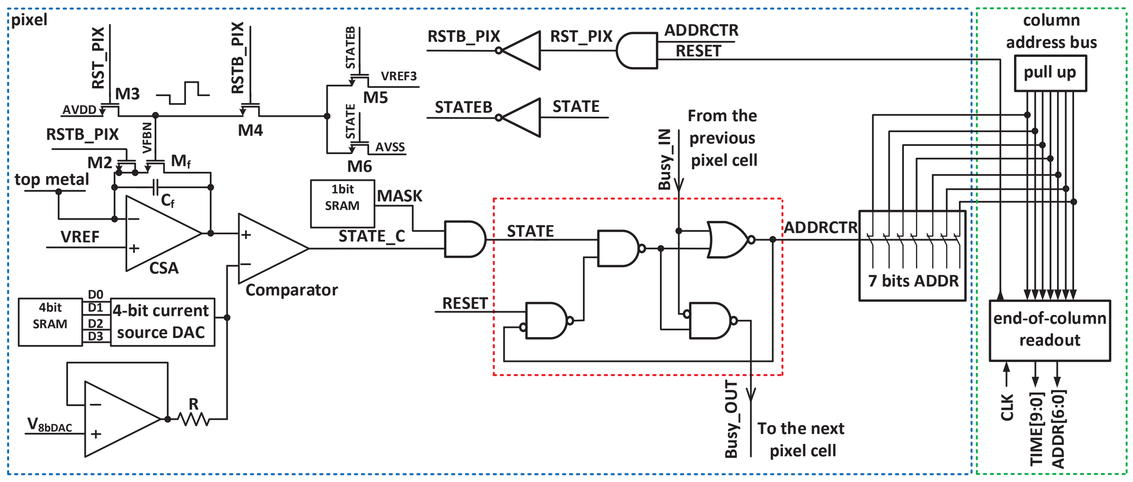



- CSA
  - Feedback capacitance: $C_f$ = 5.1 fF (design value).
  - Feedback resistor (continuous discharge): NMOS transistor with a tunable gate bias voltage VFBN to control the discharge time.
  - Tunable reference voltage VREF to adjust the CSA operating point.
  - Total power consumption: 1.2 uW.
  - $C_d$: detector capacitance, ~ 23.5 fF .
- In-pixel Buffer:
  - Fixed bias current (~ 2 uA) source follower: separate the CSA output node from the ROW_SEL switch, in order to reduce the charge injection by switching.
  - Tunable bias current ($I_{COL}$) source follower: the current source is shared with all pixels.
- Off-pixel Buffer:
  One unity gain buffer for multiplex analogue output.
- Test capacitor ($C_{inj}$)
  Testability feature, $C_{inj}$ (design value: 5.5 fF) is implemented in the pixel. $C_{inj}$ is the parasitic capacitor between guard ring and in-pixel charge collection electrode.




Amplifier in the CSA:
(1) Differential folded cascode amplifier. The transistor M12 as an additional capacitive load reduces the bandwidth hence as well as the noise.
(2) Current distribution:
$I_1 \approx 317$ nA
$I_2 \approx 16.8$ nA
$I_3 \approx 16.8$ nA

## Digital readout channel




- CSA
  - Resettable feedback:
    VFBN ($M_f$ gate voltage) is set by M3 ~ M6 to control $M_f$ conductance.
    - VREF3: provide the correct DC operation point.
    - AVSS: turn off $M_f$ and retain signal.
    - AVDD: turn on $M_f$ and discharge $C_f$.
  - Dummy transistor M2: reduce the charge injection effect after releasing the reset signal RST_PIX.
- Comparator
  Tunable threshold.
  - Coarse tune: a global 8-bit voltage output DAC common to all pixels.
  - Fine tune on a pixel by pixel basis: a local 4-bit current output DAC in each pixel allows to mitigate the threshold dispersion.
- 5-bit SRAM for the configuration.
  4-bit SRAM for the comparator threshold DAC and 1-bit SRAM to enable and disable digital readout.
- Priority logic (red dashed block in the above figure)
  - Priority encoder:
    - $f = \begin{cases} STATE, & if\ \overline{RESET}\ ||\ ADDRCTR = 1 \\ 0, & if\ \overline{RESET}\ ||\ ADDRCTR = 0 \end{cases}$
    - $Busy\_OUT = Busy\_IN\ ||\ f$
    - $ADDRCTR = \overline{Busy\_IN}\ \&\&\ f$

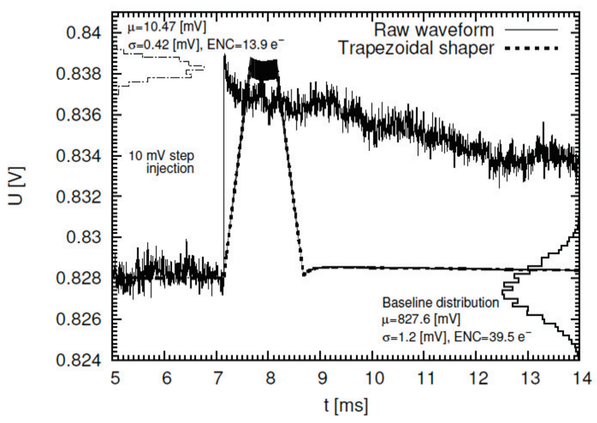
    where f is an intermediate variable
  - Reset decoder:
    $RST\_PIX = RESET\ \&\&\ ADDRCTR$
  - The column level RESET signal is generated by the end-of-column readout circuit and decoded in the local pixel.
  - Pixels in the same column are daisy chained by connecting Busy_OUT to Busy_IN between adjacent pixels. Priority is given to the pixel with a hit at the highest position in the chain.
  - Hit pixel with the highest priority: Busy_IN = 0 & Busy_OUT = 1.
- 7 bits addresses
  - Uniquely coded 7-bit address for each pixel.
  - Active pixel pulls the column address bus to its own address, signaling a hit to the column readout module.

## Preliminary tests & ENC calculation

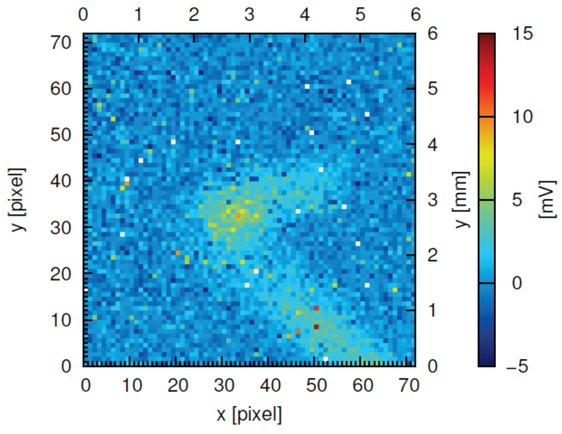
Analogue readout channel:

- External voltage pulse ($V_{test}$ = 10 mV) is injected through the test capacitor $C_{inj}$.
- Trapezoidal filter shapes the digitized waveform in software.
- Voltage signal peak height: $\mu = 10.47\ mV, \sigma = 0.42\ mV$.
- $ENC = \frac{\sigma}{\frac{\mu}{Q_i}} = \frac{\sigma}{\mu} * \frac{C_{inj} * V_{test}}{q}$ [$Q_i$: input charge, q: the elementary charge.]
  $C_{inj}$ (design value: 5.5 fF) → ENC of the CSA: $< 15\ e^-$.
- Charge-voltage conversion gain: 190 mV/fC.

Analogue readout channel output and shaping of one pixel




2D image of Alpha tracks




Baseline distribution: $ENC = \frac{\sigma(Baseline)}{\frac{\mu(voltage\ signal\ peak)}{Q_i}} = 39.5\ e^-$

We set the smallest step size of the internal 4-bit DAC to be 6 mV so that its total dynamic range can cover the mismatch in CSAs and comparators over the entire array. In this case, 6 mV becomes the worst case threshold uncertainty, which corresponds to 200 e-

## Conclusions

The *Topmetal-II⁻* sensor was successfully implemented and proven to function correctly. It achieved an ENC of < 15 $e^-$, a charge-voltage conversion gain of 190 mV/fC, and a threshold of 200 $e^-$ for the digital readout. It was observed the alpha tracks. Our team are striving a better performance sensor and developing the *Topmetal* sensor family.

## References

[1] M. Berger, et al. A Time Projection Chamber for Continuous Readout, Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2013 IEEE.
[2] Y. Fan, et al. Development of a highly pixelated direct charge sensor, Topmetal-I for ionizing radiation imaging, arXiv:1407.3712.