A low-noise CMOS pixel direct charge sensor, *Topmetal-IIa*, for low background and low rate-density experiments

Mangmang An[a,b]*, Chaosong Gao[a], Guangming Huang[a], Xing Huang[a], Yang Li[a], Yashu Li[a], Jianchao Liu[a], Jun Liu[a], Yuan Mei[c], Hua Pei[a], Weiping Ren[a], Hanhan Sun[a], Quan Sun[d], Xiangming Sun[a], Zhengxiang Wang[a], Le Xiao[a], Poyi Xiong[a], Ping Yang[a], Wei Zhang[a], Ping Zhou[a], Wei Zhou[a]

[a]PLAC, Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, Hubei 430079, China

[b]School of Physics and Electronic Engineering, Hubei University of Arts and Science, Xiangyang, Hubei 441053, China

[c]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

[d]Department of Physics, Southern Methodist University, Dallas, TX 75205, USA

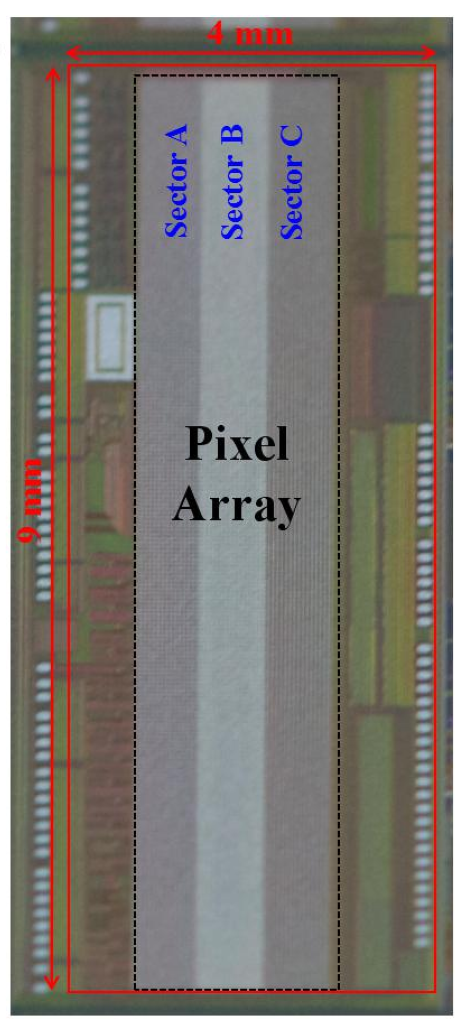
Introduction

Topmetal-IIa is a highly pixelated sensor with 40μm pitch between 45 × 216 pixels fabricated in a standard 0.35μm CMOS technology without post-processing for direct charge collection and imaging through exposed metal electrodes in the topmost metal layer. Each pixel contains a low-noise charge-sensitive preamplifier to establish the analog signal, which is read out through time-shared multiplexing over the entire array. Compared to the two previous *Topmetal* chip, *Topmetal-I* [1] and *Topmetal-II⁻* [2], this one realizes better noise performance as expected. Some simulation results confirm the low-noise design, and initial test results show that the sensor achieved a 12.4e⁻ analog noise per pixel. These characteristics enable its use as the charge readout device in future Time Projection Chambers without gaseous gain mechanism, which has unique advantages in low background and low rate-density experiments.

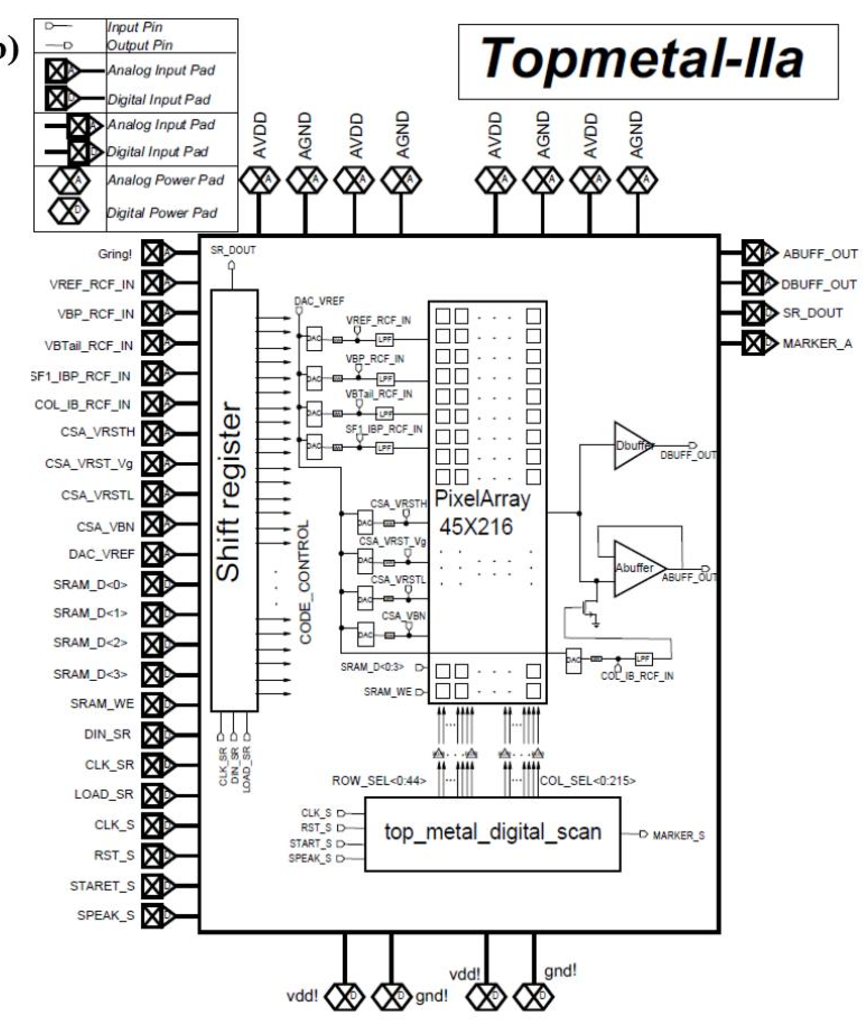
Sensor photograph and Top-level block diagram

A photograph of one fully fabricated *Topmetal-IIa* sensor is shown in Fig. (a) and its top-level block diagram is shown in Fig. (b). The sensor measures 4 × 9 mm² (red box in Fig. (a)), in which a 1.8 × 8.64 mm² charge sensitive area containing 45 × 216 pixels is located in the center of the chip.

(a)



(b)



Major funtional units of the sensor are depicted in the top-level block diagram. The analog output from each pixel is fed to two different output Buffers via an array-wide row/column multiplexing circuitry.

Single pixel structure, readout and Simulation

The inner structure of the signal pixel and the analogue readout pathway are shown as below:

- Exposed metal electrode &Gring: A ring electrode(Gring), which is in the same topmost metal layer as *Topmetal*, surrounds the exposed metal electrode while being isolated from it.
- Charge Sensitive Amplifier (CSA): The CSA with C_f = 1.3fF converts the injected charge to voltage signal (CSA_VOUT) and feeds it into the two stage source follower.
- Low-Pass Filter (LPF): CSA's sensitive voltage biases are individually provided by the peripheral LPF with tunable cut-off frequency, aiming to improve the noise performance.
- "Rolling shutter" readout: Analogue signal is fed to two array-shared analog buffers, of which one is capable of 50Ohm driving strength aiming to elimilate the external buffer hence reducing the entire readout system noise.

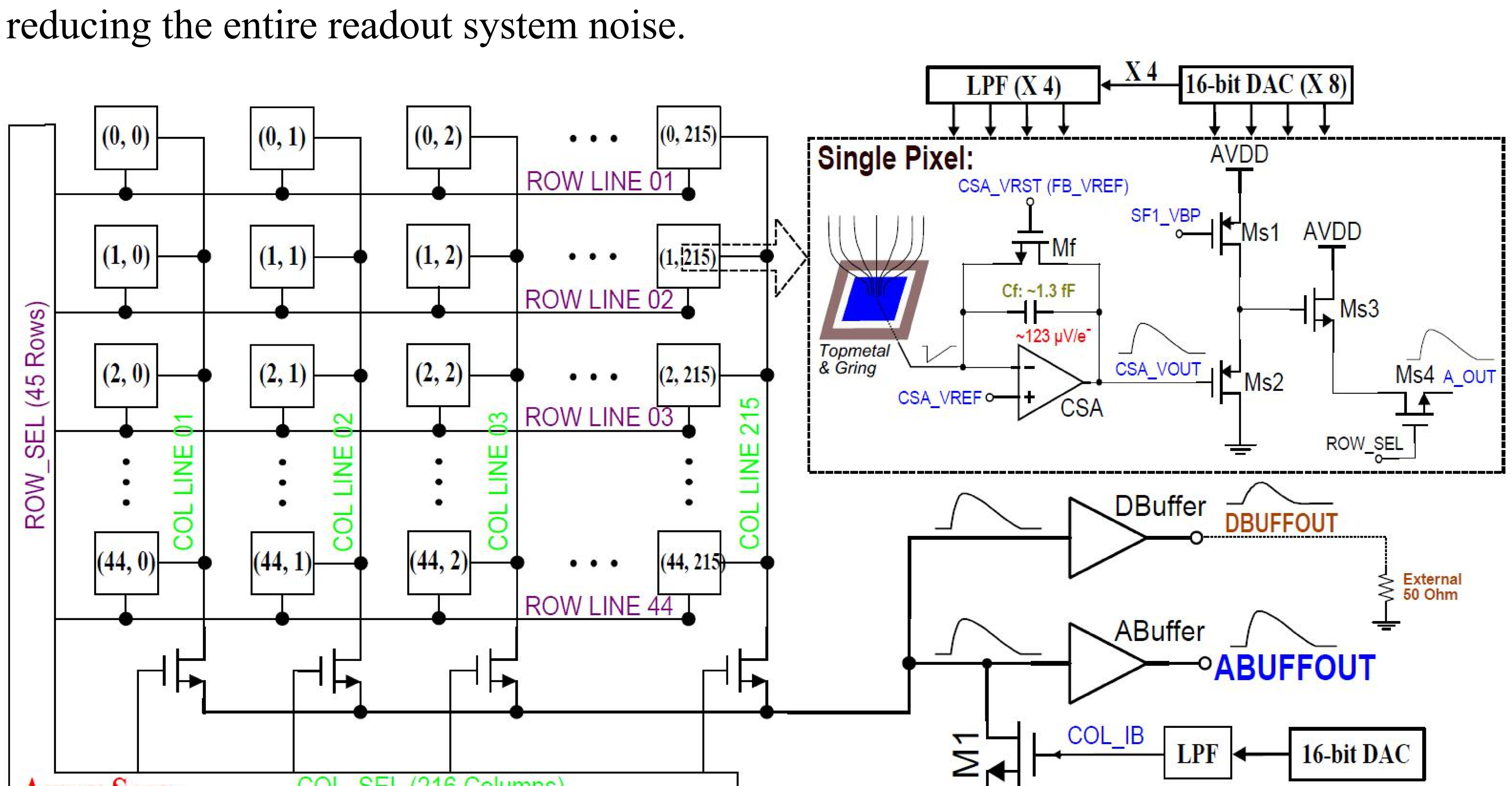


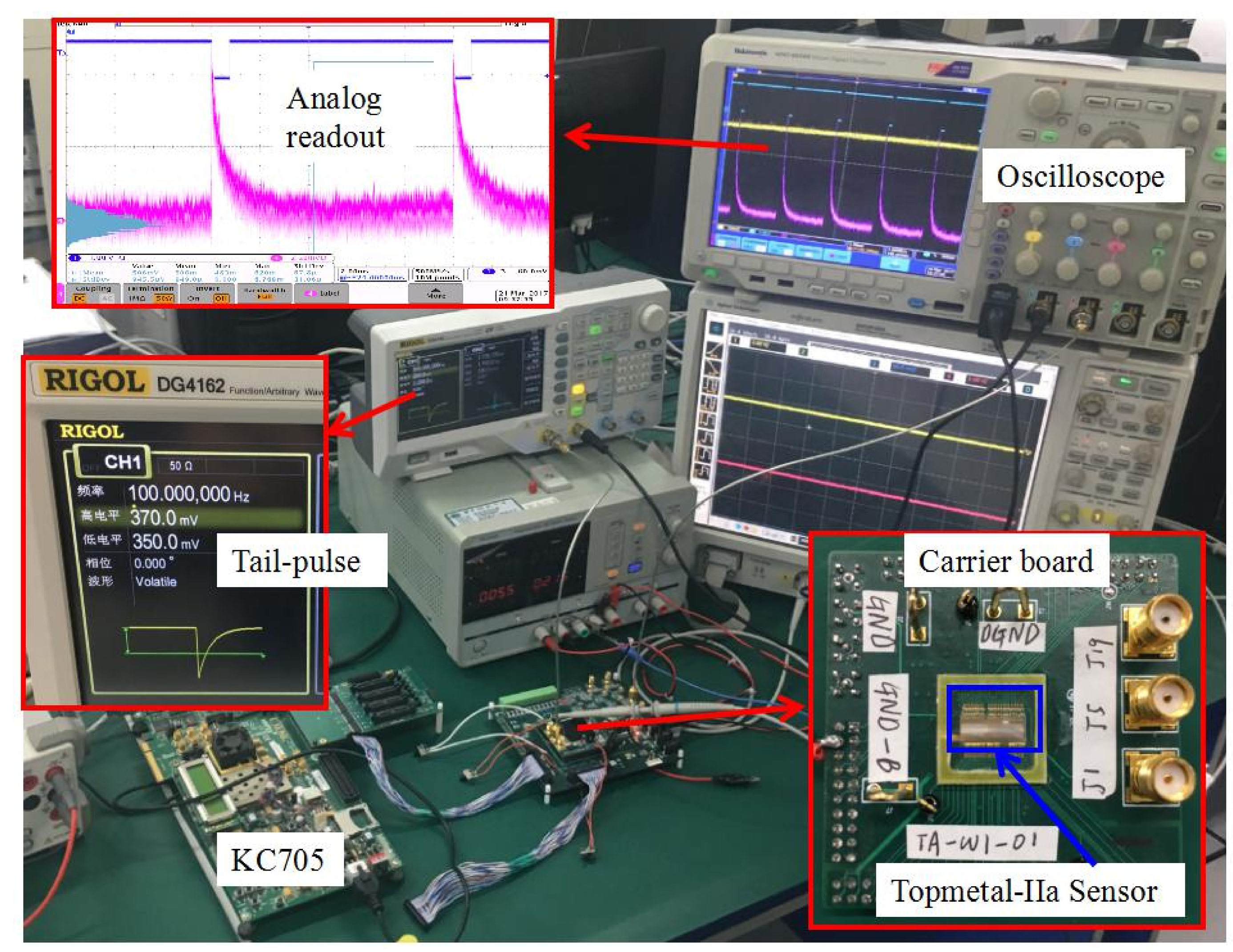
Table 1：3 × 3 Pixel array Analog readout Simulation results @Q_{in} = 1000 e⁻, Full Process corner

Process corner	Temperature [℃]	Signal response: Amplitude [mV]	Signal response: Rising time [μs]	Signal response: Decay time [ms]	Noise: rmsNoise [mV]	Noise: ENC [e⁻]
tm	0	99.7	4.1	110	0.963	9.66
	27	96.9	13.3	99	0.808	**8.18**
	85	96.1	**28.3**	8.8	**1.513**	**15.76**
wp	0	**100.7**	6.4	128	0.973	9.66
	27	97.9	4.8	106	0.973	9.93
	85	100	3.6	**4.5**	1.339	13.39
ws	0	86.4	6.2	**151**	0.989	11.44
	27	83	7.8	115	0.824	9.92
	85	**81.4**	**5**	7.9	**0.74**	9.08
MIN		**81.4**	**5**	**4.5**	**0.74**	**8.18**
MAX		**100.7**	**28.3**	**151**	**1.513**	**15.76**

Preliminary test results

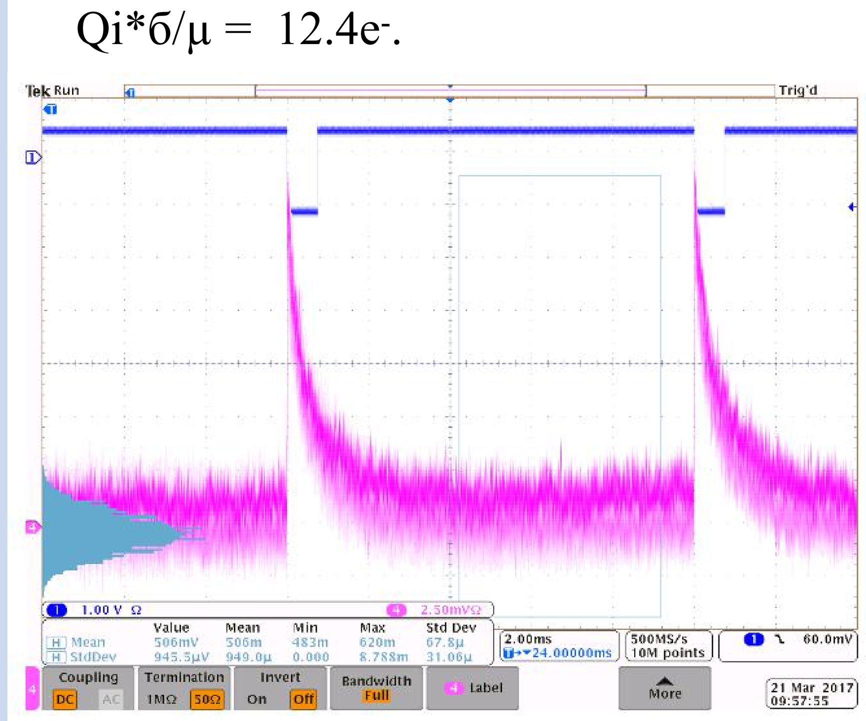
Initial test setup is shown as below:

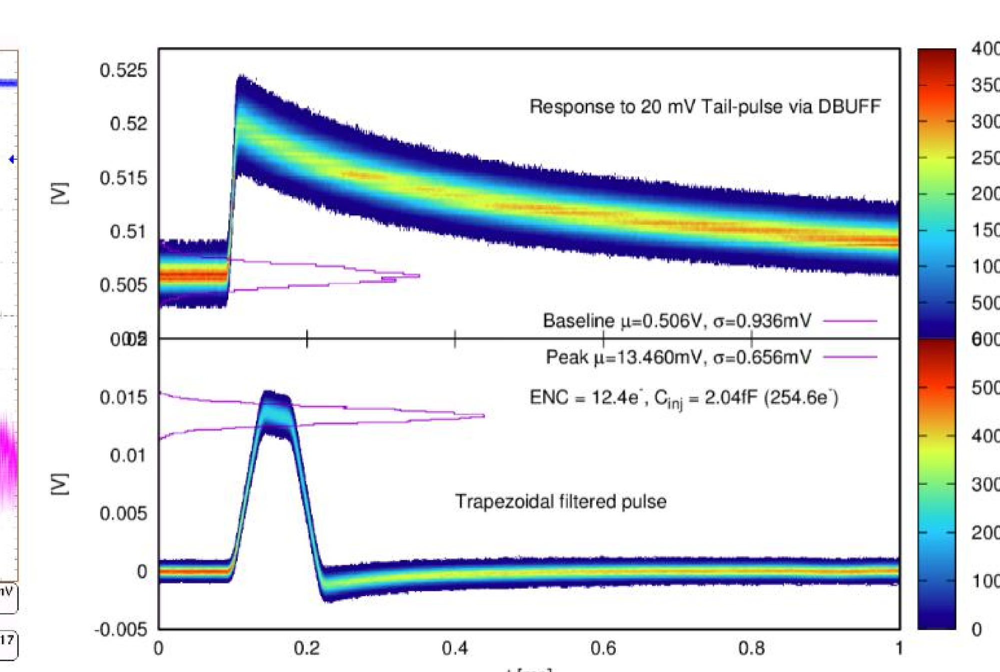
- We applied a repetitive Tail-pulse (see the left insert in the setup) with an amplitude of 20mV on Gring. Since there is a coupling capacitance, Cinj = 2.04fF, at each transition edge of the Tail-pulse, an equivalent charge Qin = 20mV*Cinj ≈ 254.6e⁻ is injected to the CSA.
- The frequency of the Tail-pulse is chosen to be low enough (100Hz) so that the CSA output has sufficient time to fall back to the baseline before the next pulse arrives.
- The repetition of the Tail-pulse is 10000, and data acquisition of the analog readout is directly sampled via the DBuffer by the 50Ohm-termination channel of the Oscilloscope.



Using the Scan module selection feature to stop at a pixel and digitize its analog output continuously:

- Historgram measurement of OSC shows the StdDev of the baseline of the DBuffer ouput is 945.5μV;
- Digital Trapezoidal Filter: By collecting many pulses, the pulse height has a mean value μ= 13.46mV, and a standard deviation б=0.656mV. The Equivalent Noise Charge (ENC) is Qi*б/μ = 12.4e⁻.





Conculsions and Outlook

We present the design and characterization of a CMOS pixel direct charge sensor, *Topmetal-IIa*, fabricated in a standard 0.35μm CMOS process. Both the simulation and preliminary electrical measuements confirmed the low-noise design and correct readout implementation. Initial test results show that the sensor achieved a 12.4e⁻ analog noise per pixel.

Based on the simulation results, the analog noise per pixel is expected below 10e⁻, thus futher more tests are ongoing. To improve beyond *Topmetal-IIa*, besides optimizing the LPF design, we can further increase the working margin of CSA's sensitive voltage biases. We will investigate these options in future *Topmetal* sensor development.

Acknowledgments and References

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References:

[1] Y. Fan et al. Developement of a highly pixelated direct charge sensor, *Topmetal-I*, for ionizing radiation imaging, arXiv: 1407.3712.

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*amm_email@163.com