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Test of *Topmetal-II*$^-$ in liquid nitrogen for cryogenic temperature TPCs

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ABSTRACT

Topmetal-II$^-$ is a highly pixelated direct charge sensor that contains a 72×72 pixel array of 83 μm pitch size. The key feature of *Topmetal-II*$^-$ is that it can directly collect charges via metal nodes of each pixel to form two-dimensional images of charge cloud distributions. *Topmetal-II*$^-$ was proved to measure charged particles without amplification at room temperature. To measure its performance at cryogenic temperature, a *Topmetal-II*$^-$ sensor is embedded into a liquid nitrogen dewar. The results presented in this paper show that *Topmetal-II*$^-$ can also operate well at this low temperature with a noise (ENC) of 12 e$^-$ lower than that at room temperature (13 e$^-$). From the noise perspective, *Topmetal-II*$^-$ is a promising candidate for the next generation readout of liquid argon and xenon time projection chamber (TPC) used in experiments searching for neutrinoless double beta decay and dark matter.

1. Introduction

Over the years people have been interested in rare event experiments like neutrinoless double beta decay [1] and dark matter [2] searches. Liquid argon and xenon are considered to be good media for low rate TPC detectors such as ICARUS [3] and LANNDD [4]. The traditional readouts of liquid argon or xenon TPCs are basically multi-wire electrodes. It is challenging to reduce the distance between two wires to a few hundreds microns or tens of microns for a large scale liquid argon or xenon detector [5].

On the other hand, a direct charge CMOS sensor with large pixel array is a good choice of readout for such low rate and large scale detectors, since CMOS sensors offer small resolution and high granularity. Timepix [6] chip is a good example of direct charge readout sensor that has a good performance at $-125°$ C (148 K) with a noise of 99 e$^-$ [7]. Coupled with an aluminum mesh [8] where gas amplification occurs, Timepix can be applied in a dual phase argon TPC with high detection efficiency [9].

We have designed a CMOS sensor named as *Topmetal-II*$^-$ with rather low noise and high spatial resolution. It can be applied into a TPC detector as a charge collector to measure single electrons generated by alpha particles [10] at room temperature without any charge multiplier being necessary. This result prompted us to test if *Topmetal-II*$^-$ can work at the temperature of liquid argon (83.8 K).

In this paper, we mainly study how *Topmetal-II*$^-$ works in liquid nitrogen (77 K) and compare the performance of the sensor at room temperature and in liquid nitrogen.

2. Topmetal-II$^-$

Topmetal-II$^-$ is a direct charge sensor with high spatial resolution. Charges can be collected via metal nodes on each pixel when an electric field is applied above the top of sensor. A wire-bonded *Topmetal-II*$^-$ sensor is shown in Fig. 1. It consists of a 72×72 square pixel array. Each pixel size is 83×83 μm^2.

The total structure of *Topmetal- II*$^-$ has been described in an earlier paper [10]. Here the internal structure of single-pixel analog readout is briefly presented in Fig. 2. Each pixel consists of a charge collection electrode, a charge sensitive amplifier (CSA), an analog readout channel and a digital readout channel (not shown in figure). Analog and digital readout channels operate independently. There is a guard ring at the periphery of the metal nodes of each pixel and the sensor's performance is measured by injecting pulse into the CSA through the guard ring. The capacitance between the guard ring and top metal of pixels (C_d) extracted by IC design software is about 5.5 fF.

3. Test results of *Topmetal-II*$^-$

In order to compare the performance of *Topmetal-II*$^-$ at room temperature and cryogenic temperature, the operating setup of

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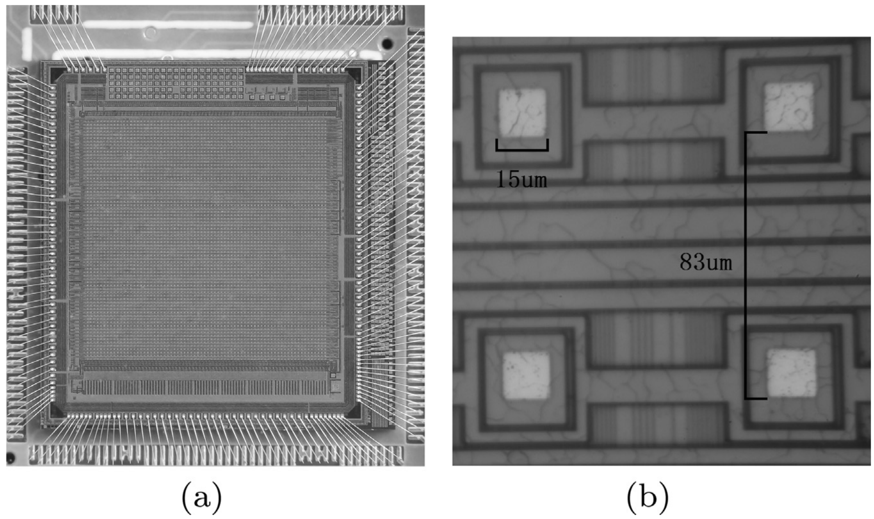

Fig. 1. (a) Photograph of a single *Topmetal-II*$^{-}$ sensor. It consists of 72 × 72 pixels. (b) Zoom-in picture shows that each pixel size is 83 × 83 μm^2. The size of each charge collection electrode (in light color) is 15 × 15 μm^2.

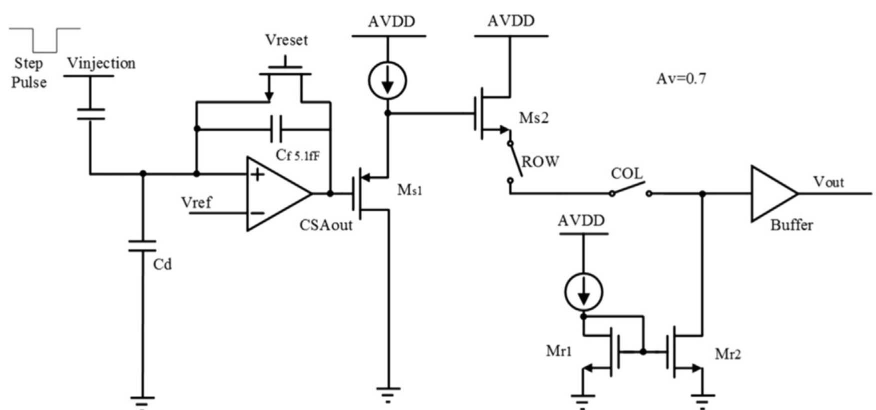

Fig. 2. Internal structure of analog readout of a single pixel.

this sensor embedded inside liquid nitrogen has to be well designed. *Topmetal-II*$^{-}$ sensor is connected to a PCB board, the PCB board is fixed on a lifting platform. We have no special protection on *Topmetal-II*$^{-}$ sensor. The sensor is slowly moved into a liquid nitrogen dewar under the surface level about 4 cm. After 15 min, the sensor is powered on and configured, then the signal is observed through an oscilloscope. This process is repeated many times. Three sensors are observed before and after the experiment using microscope, no significant difference is found.

We first tested the performance of *Topmetal-II*$^{-}$ at room temperature in ambient air and then put it into a liquid nitrogen dewar to measure its performance. The following results show that *Topmetal-II*$^{-}$ works properly in liquid nitrogen and performs better than at room temperature with lower electronic noise for a single pixel in the absence of drift field.

3.1. Decay time constant

For measuring decay time constant, a square wave of 200 mV (± 100 mV) peak-to-peak amplitude is applied to the guard ring (internal test circuits of the sensor) of *Topmetal-II*$^{-}$ in the absence of drift field. An equivalent charge of $C_d \times 200$ mV = 6.8×10^3 e$^-$ is injected to each pixel, where positive equivalent charges are injected at rising edges of the square wave and negative equivalent charges are injected at falling edges. The sensor chip can be tested at a single pixel level and the result is shown in Fig. 5.

The decay time constant of a single *Topmetal-II*$^{-}$ pixel varies with temperature, thus different reset voltages V_{reset} should be applied at room temperature and in liquid nitrogen to measure the variations of decay time constants with V_{reset} and be adjusted to achieve similar desired mean values. In liquid nitrogen, *Topmetal-II*$^{-}$ sensor can work with higher reset voltage (V_{reset}) than that at room temperature. As shown in Fig. 3, the decay time constant of a pixel changes much faster with V_{reset} in liquid nitrogen than at room temperature.

Since total pixel array in a sensor is connected to the same V_{reset}, uniformity of pixels at the same sensor is very important. The decay time constant distributions of total pixel array both at room temperature and in liquid nitrogen are shown in Fig. 4. The distribution tends to be broader in liquid nitrogen than at room temperature, while both cases show good uniformity among pixels. For our measurements, the pixels with a decay time constant less than 3.3 ms are dead pixels, the number of which is about 500. The presence of these dead pixels will have a bad effect on the accuracy of total charge. Therefore, in the design of next *Topmetal* sensors, we will improve the uniformity of decay time constants among pixels.

3.2. Noise test

A pulse of 200 mV (peak-to-peak) is injected to guard ring as shown in Fig. 5. The baseline voltage shifts about 123 mV from 733 mV to 856 mV, and the electronic noise is much lower (σ 1.3 mV) in liquid nitrogen than that (σ 2.2 mV) at room