Development of a highly pixelated direct charge sensor, *Topmetal-I*, for ionizing radiation imaging

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Abstract

Using industrial standard 0.35 μm CMOS Integrated Circuit process, we realized a highly pixelated sensor that directly collects charge via metal nodes placed on the top of each pixel and forms two dimensional images of charge cloud distribution. The first version, *Topmetal-I*, features a 64 × 64 pixel array of 80 μm pitch size. Direct charge calibration reveals an average capacitance of 210 fF per pixel. The charge collection noise is near the thermal noise limit. With the readout, individual pixel channels exhibit a most probable equivalent noise charge of 330 e⁻.

Keywords: Topmetal, pixel, charge sensor

1. Introduction

Charge sensors are at the heart of many ionizing radiation detectors. Modern imaging systems often require a simultaneous determination of the amount, position and time structure of charges from ionization. In these cases, a charge sensor of sub-millimeter spatial resolution is highly desirable.

Solid state detector systems, mainly segmented silicon and germanium crystals coupled to CMOS pixel sensors, are widely deployed. CMOS pixel sensors such as Medipix/Timepix¹[1, 2] and FE-I3/FE-I4 [3] are readily available. They have pixel sizes of tens to hundreds of microns. They are coupled to the crystals through processes such as the flip-chip bump bonding.

On the other hand, for gaseous and liquid detectors, wire and Printed Circuit Board (PCB) are still the most popular readout schemes. Those detectors are often configured as Time Projection Chambers (TPCs [4]). Noticeable imaging systems of such kind are LXeGRIT [5] and μ-PIC [6]. For practical reasons, it is difficult to realize a multi-wire readout with a wire pitch smaller than a millimeter. Novel designs using PCB have reached a pitch of hundreds of μm [6]. However, such designs still face challenges of signal readout multiplexing and speed.

Gaseous and liquid detectors have distinct advantages over solid state detectors: they are more easily scalable to large mass and are resilient to radiation damage. Only with an equally scalable yet high resolution charge readout scheme, their superior properties can be exploited in imaging applications. The CMOS pixel sensor is an excellent candidate for this task, because of the fine pixel size, as well as the possibility of embedding complex circuitry for signal paths.

There have been attempts towards the use of CMOS pixel sensors in a TPC to read the charge signal, with limited success. The D³ experiment [7] uses FE-I3/FE-I4 sensors developed for the ATLAS [8] experiment, behind a gaseous electron multiplication stage, to detect charge tracks resulting from potential dark matter interactions. A similar attempt was made to use the Timepix sensor as the readout for a TPC [9].

The development of CMOS sensors is usually dictated by the requirements of large experiments or the consensus of consortiums. Existing sensors either have some high level processing already built-in to handle the massive data rate common in collider experiments, or are lack of low noise analog channels. The readout for gaseous and liquid detectors are often slower, but have more stringent requirement on noise performance.

We set out to realize a CMOS sensor that is uniquely suitable for charge readout in gaseous and liquid detectors. We implemented a direct charge sensor with 80 μm pitch between pixels using the industrial standard 0.35 μm CMOS process. Its behavior in charging collection is well characterized.

2. Sensor Structure and Operation

A photograph of one fully fabricated and wire-bonded *Topmetal-I* sensor is shown in Fig. 1. The sensor is implemented in a 6 × 8 mm² silicon real-estate area. With 80 μm pitch distance between pixels, the 64 × 64 square
pixel array makes up a $5.12 \times 5.12 \text{mm}^2$ charge sensitive region. Readout interface logic and analog buffers are placed around the pixel array.

![Figure 1: Photograph of a Topmetal-I sensor (left). The sensor chip is placed on a PCB and gold wire-bonded. The $64 \times 64$ pixel array, with 80 µm pitch distance between pixels, constitutes an approximately $5 \times 5 \text{mm}^2$ charge sensitive area in the center of the sensor. The sensor is divided into four $64 \times 16$ sub-arrays with dedicated analog buffer inside each sub-array. Two test pixel columns are implemented in the leftmost sub-array (right).](image)

The pixel array is divided into 4 sub-arrays for efficient analog readout. As shown in Fig. 1, each sub-array is of 64 rows by 16 columns in size and has one dedicated analog output buffer per sub-array. A single external clock drives the analog row/column multiplexing readout circuitry in each of the 4 sub-arrays synchronously.

The internal structure of a single pixel is illustrated in Fig. 2. The Topmetal is implemented with the PROSEPAD component in the standard CMOS process, which is a patch of metal in the topmost layer and has a part of it not covered by the passivation layer. We designed the metal patch to be $25 \times 25 \text{µm}^2$ in size, with the central $15 \times 15 \text{µm}^2$ exposed hence sensitive to external charge. The metal patch is large enough to be mechanically and chemically stable, while small enough to suppress the cross-talk between neighboring pixels to a negligible level.

Charges arrived at the sensor and collected by the Topmetal result in an electric potential change at the “Node”, which is a detectable signal. The potential of the “Node”, $V_{\text{node}}$, is captured by means of a source follower that drives the signal through row/column multiplexer for analog readout. The equivalent capacitance of Topmetal to ground is measured to be approximately 210 fF. It means 1000 electrons collected by Topmetal would correspond to 0.8 mV voltage drop on the “Node”.

The resetting circuit for the “Node” allows controlled removal of charge collected by the Topmetal and the initial potential setting of the node. When a logic high is applied to the reset gate, the “Node” potential is set to $V_{\text{reset}}$ and any excess charge on the “Node” is neutralized by the power supply driving $V_{\text{reset}}$.

Two test columns are implemented in the leftmost sub-array (Fig. 1). Pixels in the first test column have identical structure as the rest of the pixels, except that the “Node” is internally connected to ground. They serve as markers in the multiplexed readout. Since their $V_{\text{node}}$ is fixed internally, they are immune to the noise generated by the Topmetal capacitance. Noise measurements on the first test column measures the noise due to the analog readout path only, decoupled from that from the Topmetal. Pixels in the second test column have the “Node” capacitively coupled to an external pin. They were designed to test the pixel response to pulses injected from the external pin. The pin is tied to ground during normal operations.

![Figure 2: Internal structure of a single pixel. The Topmetal is a metal patch exposed to the environment external to the sensor to collect charge directly. The components enclosed in the dotted box is unique to each individual pixel, the column selection transistor is shared by all the pixels in the same column, and the output buffer is shared by all the pixels in the same sub-array. The capacitor $C$ and the resistor $R$, connected by dashed lines, are not real components implemented in the sensor. They illustrate the equivalent circuitry of the Topmetal. Its behavior is discussed in the text. Only the analog channel is shown.](image)

Charge signal in each pixel is also converted into digital values by means of a threshold discriminator (comparator), a delayed resetter, and a 5-bit counter. Muxing readout for digital data at array level is also implemented. The digital data chain is suitable for charge event counting applications. However, in this letter, we focus on the physical behavior and analog characteristics of the device.

### 3. Signal Formation

The Topmetal can be modeled as a resistor with large resistance $R$ and a capacitor with small capacitance $C$ connected in parallel (Fig. 2). The time constant $\tau = RC$ is on the order of 10 seconds. During charge collection, the equivalent charge current $i$ will run through the resistor while charging up the capacitor at the same time. The following differential equation gives the general behavior of the circuitry:

$$i(t) = \frac{U}{R} + C \frac{dU}{dt}.$$  \hspace{1cm} (1)

$U$ is the voltage across the capacitor, which is then measured.
The solution to the differential equation is

\[
U(t) = \begin{cases} 
U_0 e^{-t/\tau} & i = 0 \\
(U_0 - iR)e^{-t/\tau} + iR & i = \text{constant} \\
e^{-t/\tau} \left( U_0 + \frac{1}{C} \int_0^t i(x)e^{x/\tau} \, dx \right) & i(t)
\end{cases}
\] (2)

The time-dependent \(i(t)\) solution is the most generic. The solutions for \(i = 0\) and \(i = \text{constant}\) are two special cases. The boundary conditions are set such that no matter whether there is a charge current \(i\) or not, at \(t = 0\), the output voltage \(U(t = 0)\) is set to a defined reset value \(U_0\). When collecting electrons (negative charge), \(i < 0\), otherwise \(i > 0\).

The sudden arrival of a charge pulse can be modeled as \(i(t) = Q\delta(t-t_q)\), where \(t_q\) is the arrival time of the charge pulse. At \(t = t_q\), the voltage decay curve \(U(t)\) drops by the amount of \(Q/C\), as shown in Fig. 3.

Ideally, we can build an algorithm to find the sudden drops and reconstruct their amplitudes to measure the charge collected. However, due to the noise, as seen in Fig. 3 such an approach is unlikely to be robust. Also, in the case of continuous charge current, there will be no sudden drop. Instead, to extract the charge information, we employ a “double subtraction” scheme.

Prior to the charge measurement, we remove the charge source, but operate the sensor in the same condition, to establish a baseline. The baseline, \(U(t)\) \(i = 0\), is a time-series measurement of node voltage without charge input. During the charge measurement, we record \(U(t)\) \(i\), in a similar fashion. The baseline and charge measurements are synchronized by a periodical reset signal. The time between two resets defines an event window, and \(t_2-t_1\) is the charge integration time. We subtract the voltage right after reset, \(U(t_1)\), from the voltage at the end of the window, \(U(t_2)\), in each case, then subtract the difference in baseline from that in charge measurement. The quantity \(\Delta U\) is shown in Eq. 3.

\[
\Delta U = [U(t_2) - U(t_1)] - [U(t_2) - U(t_1)]_{i=0} = -iR \left( e^{-t_2/\tau} - e^{-t_1/\tau} \right).
\] (3)

In the limit where \(t/\tau \to 0\),

\[
e^{-t_2/\tau} - e^{-t_1/\tau} \approx -(t_2 - t_1)/\tau,
\] (4)

hence

\[
\Delta U \approx \frac{i(t_2 - t_1)R}{RC} = \frac{Q}{C}.
\] (5)

Eqs. 3, 5 are derived assuming a constant current \(i\). It can be shown that the same relation Eq. 5 holds for sudden charge arrivals.

We operate at a charge integration time window of tens of milliseconds, so that Eq. 4 is satisfied. Therefore we can use the simple proportional relation Eq. 5 to compute the charge value. We also refer to one \(\Delta U\) measurement an “event”.

The node voltage behavior in a characteristic pixel is shown in Fig. 3. When the reset is activated \((t = 0)\), the node is set to the voltage of \(V_{\text{reset}}\). As soon as the reset is deactivated, due to charge injection on the MOS transistor \(\text{[10]}\), the node voltage drops to a deterministic value. In this example, the node voltage right after reset is about 1.295 V. Up to a small fluctuation, the baseline curve behaves identically after each reset for the same pixel. Then, when there is no charge being collected, the node voltage changes exponentially towards a stable value. When the charges arrive, the voltage curve shows a sudden drop.

Due to the inhomogeneity of the CMOS process, the baseline curves behave differently among pixels. The most significant variation is in the decay time constant. Nevertheless, it is only necessary to calibrate the baseline curves for every pixel once prior to the charge detection.

To image 2D distributions of the charge cloud, the above procedure is performed on each pixel in the array. The temporal behavior of each pixel is decoded from the multiplexed readout signal. The interval of sampling is the pixel clock period times the number of pixels in a subarray \((1024)\). The time between resets is set to be slightly larger than the desired charge integration time. \(\Delta U\) is then computed for each pixel and the 2D distribution is established.

4. Charge Calibration

To demonstrate that the Topmetal-I sensor is capable of directly detecting charge, and to calibrate for charge measurements, we constructed a rudimentary drift chamber, using an \(241\text{Am}\) alpha source to ionize air, then drift the negative charge towards the sensor in an electric field.
We wire-bonded a Topmetal-I sensor onto a PCB and placed supporting circuity on the PCB to drive the sensor and to transmit analog signals out via coax cables. On the other end of the coax cables, signals are digitized by a 14-bit high speed ADC. To create a uniform drift field with field lines perpendicular to the sensor, we placed a large aluminum plate 5 cm above, and parallel to the sensor, serving as the cathode. While the sensor substrate and the PCB are placed close to ground potential, the aluminum plate is held at $-1000 \text{V}$, creating an electric field of $200 \text{V/cm}$.

A collimated $^{241}\text{Am}$ source embedded in the cathode emits alpha particles perpendicular to the sensor. The alphas ionize air along their paths. Negative charge generated during the process is drifted towards the sensor and eventually collected by the sensor. Alphas from the $^{241}\text{Am}$ source have a range of about 4 cm in air at standard temperature and pressure \[11\]. The distance between the cathode and the sensor (5 cm) was chosen so that alphas would deposit their full energy in air before hitting the sensor. An averaged image of the charge cloud from alphas seen by the sensor is shown in Fig. 5.

The event time window is 33.5 ms and the integration time is 32 ms. Effectively we are collecting data at an event rate of 30 Hz. The collimator limits the alpha rate to be much lower than the data event rate. The conditions are chosen so that within a data event, there can be either zero or one alpha, and the probability of two or more alphas in the same event becomes negligible. Meanwhile, the integration time is long enough to fully collect the charge after an alpha interaction, since it takes only microseconds for electrons to drift for 5 cm \[12\].

On average, each alpha particle emitted from the $^{241}\text{Am}$ source deposits 5.45 MeV \[13\] energy in air resulting in ionization. The air has an ionization $W$-value of 35 eV \[14\]. Since alphas are fully stopped before hitting the sensor, and electrons are fully collected during the integration time, each alpha event results in a mean value of approximately $1.56 \times 10^8 \text{e}^-$. Since each event has either zero or one alpha, if we plot a histogram of the voltage signal due to charge, we should be able to identify a peak correspond-
ing to single alphas, and use the relation
\[ C = Q / \sum_{mn} \Delta U_{mn} \] (6)
to compute the capacitance \( C \) of a single pixel. \( Q \) is the
total charge and the summation is over pixels that see
charge.

\( \Delta U \)'s of pixels within a 17 pixel radius (Fig. 5) are
summed up to fill the histogram in Fig. 6. The region
is chosen such that 90\% of charge is contained in the region
given the signal is modeled by a two-dimensional Gaussian
distribution. We will not attempt to correct for the potential
loss of 10\% charge, instead, we treat it as a systematic
uncertainty of the measurement. The single-alpha peak is
clear in Fig. 6 and is well characterized by a Gaussian
function. From the mean voltage value of the single-alpha
peak, we measure the pixel capacitance \( C = 207 \text{fF} \). The
uncertainty, a combination of uncertainty from the fit and
the systematic uncertainty, is found to be 12\%.

To validate the result, we used a less stringent collimator
to increase the total ionization per unit time. Under
the same electric field, we measured the ionization current
with a picoammeter to be around 10 pA. The ionization
current is then collected by the Topmetal-I sensor operating
under exactly the same condition. The measurement
yields a similar capacitance value, with larger uncertainty.

To evaluate the noise performance of the sensor, we
use the baseline dataset alone, and compute the Root-
Mean-Square (RMS) of voltage drop \([U(t_2) - U(t_1)]_{i=0}\)
of each pixel across all events. The noise is then calculated
as \( C \times \text{RMS}([U(t_2) - U(t_1)]_{i=0}) \), where \( C \) is the above
measured pixel capacitance. The RMS voltage drop
distribution of the entire pixel array is shown in Fig. 7. The
distribution has three distinct clusters. The cluster with
the lowest RMS value contains the test pixels in the first
column. Those pixels have their voltages tied to a fixed
value at all times. The RMS value of them comes solely
from the analog readout noise. It provides a measurement
of the analog readout noise independent of the noise from
the Topmetal capacitance. The second test column is capa-
citively coupled to an external pin therefore has higher
noise. The RMS of the main array has its most probable
value at 0.253 mV, which corresponds to about 327 e\(^{-}\). The
uncertainty of this value is solely determined by the
uncertainty of capacitance measurement.

During normal air-cooled operations, the sensor tem-
perature stabilizes at about 57\°C. A 207 fF capacitor at
such temperature has an intrinsic thermal noise of 192 e\(^{-}\)
[15]. Using the first test pixel column, we determine that
the analog readout system has an ENC of 254 e\(^{-}\). The
quadratic summation of the two noise values yields 318 e\(^{-}\),
which is very close to the most probable ENC value of the
main pixel array. It indicates that the equivalent capacitor
of the Topmetal is operating near its thermal noise limit.

\[ \text{Counts/2\µV} \]
\[\text{RMS [mV]}\]
\[\text{ENC [e\(^{-}\]}\]}
| Column1 | Column2 | Main array |
|---------|---------|-----------|
| 259     | 284     | 310       |
| 336     | 362     | 388       |
| 414     |         |           |

Figure 7: RMS fluctuation distribution of pixels. The left most
two peaks correspond to test pixels in the first and second column
respectively. ENC is computed assuming \( C = 207 \text{fF} \).

5. Summary

We have demonstrated the possibility of implementing a
highly pixelated sensor for direct charge collection using
industrial standard 0.35 \µm CMOS technology. No post-
processing is necessary. Although in this first attempt,
Topmetal-I, the sensor noise is moderately high, its capa-
ibility in observing charge from single-alpha events in air
directly already shows its potential in applications.

The design and production of CMOS ICs are tradition-
ally perceived as inhibitory expensive. However, recent
advancement in the industry has made the mature tech-
nologies such as the 0.35 \µm process affordable. Also, the
direct charge collection capability, without the need of any
post-processing, makes the overall integration cost much
lower than for example technologies used in producing hy-
brid solid-state detectors.

To improve beyond Topmetal-I, besides reducing the
pixel size, we can further reduce the noise and record the
charge arrival time. By placing a charge sensitive amplifier
in each pixel, and reducing the Topmetal size hence its
capacitance, we foresee an ENC better than 10 e\(^{-}\) per pixel
should be achievable. Information on charge arrival time
can be obtained using an individually addressable pixel
structure. We will explore these options in future series of
Topmetal sensors.

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