New Counting ASIC for X-Ray Imaging Devices

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Outlook of the talk

- ASIC objectives
- Pixel and matrix global schematics
- preamplifier schematics
- electrical test results
- future work
- Conclusions
ASIC objectives

Main objective was to study a new preamplifier schematics for an X ray counting ASIC.

Thus, a very simple test matrix was designed, only including the very basic elements of a counting ASIC

Measurement objectives:

- electrical characterization (this talk)
- Coupling the ASIC to a pixelated photoconductor (namely CdTe or CdZnTe), (future work)
The pixel schematics only includes the basic functions
Pixel schematics: variation of the input pad

2 kinds of pixels differ from the input pad surface (i.e. capacitance): 30µm x 30µm and 15µm x 15µm.
Schematics of the 2 pixels equipped with analog outputs

The pixel schematics includes 2 sizes for the detector input pad.
Matrix schematics

32 x 32 pixel test matrix: 90µm x 90µm pixels

- Half of the matrix with small input pads
- Half of the matrix with large input pads

Row driver

Column multiplexor

Analog outputs on 2 specific pixels

Digital output
ASIC layout

- 4.6 mm
- 15µm pads
- 30µm pads
- Analog outputs
- Row driver
- Column driver
- Process CMOS 0.35µm from ST Microelectronics
Pixels layout

- test injector
- analog preamp
- Comparator
- Counter

<table>
<thead>
<tr>
<th>Pad Size</th>
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<tbody>
<tr>
<td>30µm pad pixel</td>
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<tr>
<td>15µm pad pixel</td>
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Dimensions:
- 90 µm (a)
- 90 µm
- 30 µm
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Objectives of the preamplifier

Objectives are the same as for almost all counting ASICs, i.e.:

- high counting rate,
- high sensitivity,
- low power consumption.
Initial analysis: standard preamplifier schematics

The basic objective was to overpass the power consumption limitation of standard preamplifier schematics.

Problem:

Gain is defined by $-\frac{C_1}{C_2}$

Thus high gain requires high $C_1$, thus low input impedance $(1/jC_1w)$.

Thus, if stages are to be cascaded, previous stage has to have a low output impedance, and then has a high power consumption.
Preamplifier basic ideas: DC state

Use 2 current sources, $I_{0A}$ and $I_{0B}$, with $I_{0A} = I_{0B}$.

But it is of course practically impossible to get 2 identical current sources on a circuit, so the final schematics will be…
Preamplifier basic ideas: DC state

The feedback loop:
- changes $I_{0B}$ to a slave source current which copies $I_{0A}$
- stabilizes the output voltage to $V_{Out\_ref}$
To explain the schematics behavior, let us come back to the basic idea with $I_{0A} = I_{0B}$ and $V_{output}$ stabilized to $V_{out-ref}$.
Preamplifier basic ideas: DC state

One way to explain the DC state is to recognize in the schematics, 2 following amplifiers:

- **a NMOS following amplifier**

  And then,
  
  \[ V_A = V_{\text{input}} - K_N \]

  with \( K_N \) a constant value depending on the NMOS threshold voltage \( V_{TN} \) and on \( I_{OA} \)

  and

- **a PMOS following amplifier**

  And then,
  
  \[ V_B = V_{\text{input}} + K_P \]

  with \( K_P \) a constant value depending on the PMOS threshold voltage \( V_{TP} \) and on \( I_{OB} \)
Preamplifier basic ideas: dynamic behavior

Let us now look to the dynamic behavior.

\[ V_{\text{input}} + K_p \]

\[ V_{\text{input}} - K_N \]
Preamplifier basic ideas: dynamic behavior

If $V_{\text{input}}$ is increased by $\Delta V_{\text{input}}$,

Then $V_A$ and $V_B$ also increase by $\Delta V_{\text{input}}$ (due to the 2 previously identified following amplifiers).
Preamplifier basic ideas: dynamic behavior

If \( V_{\text{input}} \) is increased by \( \Delta V_{\text{input}} \),

Then \( V_A \) and \( V_B \) also increase by \( \Delta V_{\text{input}} \).

**VA increases:**
This means that a negative charge \( Q_eA \) leaves from \( C_{1A} \) to \( C_2 \), through the NMOS.

\[ Q_eA = -C_{1A} \times \Delta V_{\text{input}} \]

**VB increases:**
This also means that a negative charge \( Q_eB \) leaves from \( C_{1B} \) to \( C_2 \), through the PMOS.

\[ Q_eB = -C_{1B} \times \Delta V_{\text{input}} \]

**In a more physical way, this means that DC currents flowing through the NMOS and the PMOS have been temporary modified.***
Preamplifier basic ideas: dynamic behavior

Thus

\[
\Delta V_{\text{output}} = \frac{(QeA + QeB)}{C_2} = -\frac{(C_1A+C_1B)}{C_2} \times \Delta V_{\text{input}}
\]

or

\[
\text{Gain} = -\frac{(C_{1A}+C_{1B})}{C_2}
\]
Preamplifier basic ideas

Conclusions:

\[ \text{Gain} = - \frac{(C_{1A} + C_{1B})}{C_2} \]

Static gain is defined by a ratio of capacitors,

It is independent upon the input preamplifier capacitance

Power consumption separately defines the preamplifier bandwidth

Current is reused, in the NMOS the PMOS, thus limiting the power consumption for a targeted gain.

DC input value has no influence on the charge transfer. So, this stage is very tolerant to input voltage offsets

\textit{NB: this stage cannot deliver permanent current. It has to be connected to a high impedance input stage, but this is no problem with CMOS technology.}
The final pixel schematics is composed of:
- a current-voltage converter (a MOSFET acting as a resistor)
- 2 voltage-voltage previous amplifiers
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Electrical test results

All following results correspond to a total pixel analog power consumption of

$$1400 \text{ nA} \times 3.3 \text{V} = 4.6 \text{ µW}$$
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  - analog sensitivity
  - counting performance versus stimuli intensity
  - noise
  - counting performance versus stimuli delta_t
  - electrical images

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**Sensitivity**

**500 electrons** test injection is visible on the scope, but signal / noise is not good enough for counting.
1200 electrons test injection is good enough for counting
Sensitivity

5000 electrons test injection is very easy to count

NB : Digital output is delayed on the scope display, to improve visibility
Sensitivity

10 000 electrons test injection creates an overshoot.
Not acceptable.
Sensitivity

Sensitivity is very high and tunable

Adjusting feed back loop biasing, improves and **tunes the sensitivity**.

![Selection of preamplifier sensitivity](image)

**Sensitivity**

- **675 mV/ke**
- **270 mV/ke**
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Counting a series of 1000 test pulses versus pulses intensity

Results for different feedback loop biasing

Circuit behavior is good over 1 decade variation of the input pulse
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Noise

Noise can be derived from the S curve. Charge difference between 2.5% and 97.5% counts is 4 sigmas.

Counts for a series of 1000 pulses; for 3 different feedback loop biasings.

Counts

4 sigmas

4 sigmas

electrons / pulse

Counts

rms noise = 150 electrons

Not dependent upon the feedback loop biasing.
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Counting versus stimuli $\delta_t$

1000 couples of 3000 electron pulses were injected through the 5 fF input capacitor.

$\delta_t$ was varied

100 mV = 3000 electrons
Counting versus stimuli delta_t

 Counts with a series of 1000 couples of 3000e- stimuli

Counts

Counts with a series of 1000 couples of 3000e- stimuli

Delta_t between pulses (ns)

3000 electron pulses distant by more than 150ns are correctly counted
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Electrical images were obtained injecting a series of 1000 pulses, simultaneously on all the pixels.

Pulses intensity was varied.
Electrical images

Series of 1000 pulses on all the pixels

15µm pads  30µm pads

15µm pads  30µm pads

15µm pads  30µm pads

800e- pulses  900e- pulses  1000e- pulses

1000 electron pulses are almost perfectly counted with 15µm input pads

30µm input pads degrade the performance. About 100 electrons more are required to get the same performance.

Performance is expected to degrade by a few hundred electrons when the ASIC is coupled to a detector
Electrical images

Series of 1000 pulses on all the pixels

<table>
<thead>
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<th>15µm pads</th>
<th>30µm pads</th>
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<td>800e- pulses</td>
<td>900e- pulses</td>
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Analog sensitivity is high enough to overpass comparators threshold variations.

An homogeneous image is obtained, without requiring pixel threshold adjustment.
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Future work

1- The ASIC will be more deeply studied: in particular behavior at other power consumptions will be looked at

2- The ASIC will be coupled to photodetectors (namely CdTe or CdZnTe)

3- A redesign will be done.
   In particular the overshoot for large input pulses will be cancelled
Present ASIC overshoot simulation

Simulated analog output for input pulses of
500 ; 1000 ; 2000 ; 4000 ; 8000 ; 16000 ; 32000 electrons
Next ASIC overshoot simulation

Simulated analog output for input pulses of 500; 1000; 2000; 4000; 8000; 16000; 32000 electrons

Sensitivity is lower, but still high (300mV / ke-)
Overshoot and speed are greatly enhanced
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Conclusions

A new preamplifier for X ray counting ASICs has been tested. It gives:

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Pixel power consumption</td>
<td>4.6 µW</td>
</tr>
<tr>
<td>Tunable sensitivity</td>
<td>270 to 675 mV / ke-</td>
</tr>
<tr>
<td>Rms noise</td>
<td>150 e-</td>
</tr>
<tr>
<td>Input pulse dynamic range</td>
<td>1 000 to 10 000 e-</td>
</tr>
<tr>
<td>Minimum delta_t @ 3000e- pulses</td>
<td>150 ns</td>
</tr>
<tr>
<td>Minimum image threshold</td>
<td>≈ 1 000 e-</td>
</tr>
</tbody>
</table>

In the next future, the ASIC will be coupled to a detector. Next ASIC will increase the input pulses dynamic range.
Thank you for attention