LOW NOISE LOW POWER READOUT CIRCUIT FOR SOFT X RAY DETECTION

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ABSTRACT

A new low power CMOS ASIC for the detection of X-rays was optimized for low power and low noise. Theoretical calculations and optimizations are presented and compared with experimental results. Noise as low as 120+25 C_pF ENC rms was obtained including a silicon detector of 1.3 pF and 0.3nA of leakage. The power consumption is less than 100 W. Other circuit parameters are also shown.

KEYWORDS: Charge sensitive amplifiers, Equivalent noise charge, Sharper.

1. INTRODUCTION

During the last years, an important effort has been dedicated to the development of electronics circuits for nuclear radiation measurements using crystalline and amorphous silicon diodes detectors. Recently we reported [1] a full custom integrated circuit designed for X-ray photon detection in a new system approach to digital radiography. For pixel array architectures, a big amount of pixels is needed to obtain high resolution and thus low power consumption and small area per channel are required in the readout circuits. Detection of soft X-ray used in medical applications also requires high gain preamplifiers and very low overall noise in the circuit. In this paper we present calculations and experimental results obtained for low noise optimization, while maintaining low power consumption and other required parameters.

2. READOUT CIRCUIT CHARACTERISTICS

The front end of the readout circuit consists of a Charge Sensitive Amplifier (CSA), designed to integrate the charge collected at the detector during a period of time much bigger than its collection time in order to create a voltage pulse at the output of the circuit. CSA are low pass filters with an integration time mainly dependent on the output impedance, peak voltage and feedback capacitor. Their noise is mainly due to the high transconductance input MOS transistor. To cut this unnecessary noise a narrow band filter called Shaper must be included and its parameters optimized to achieve required signal to noise ratio. JFET transistors have less noise than MOS, but are difficult to implement using standard CMOS technology employed in our circuit.

Fig. 1 shows the first two blocks of the ASIC corresponding to the CSA and SHP, designed to obtain a maximum output voltage swing of 3V, a shaping time less than 5 µs for a capacitive load of 20 pF, a power consumption less than 100 µW and a single voltage supply of 5V, so it can be used in portable systems, space and large matrix detectors. The calculated gain was 3446 mV/fC, to allow detection of charges above 400 electrons, if noise is

maintained below 200 electrons. The detector used in [1] had a capacitance of \( C = 1.3 \text{ pF} \) and diode leakage of \( I_s = 0.35 \text{ nA} \). Fig. 2 shows the schematics of the detector diode with an AC coupling to the readout circuit.

3. NOISE OPTIMIZATION

Noise was theoretically minimized optimizing the detector bias resistor \( R_{bias} \), the input transistor transconductance \( g_m \), and the shaping time of the filter \( \tau \). The noise in the circuit, expressed by the Equivalent Noise Charge (ENC) at the input, was calculated through equations [2,3]:

\[
ENC_d = \sqrt{\frac{2qI_s}{R_{bias}} + \frac{4kT}{R_{bias}} \cdot \tau \cdot \frac{(1.57 \cdot 7.39)}{q^2 4\pi}}
\]

\[
ENC_{th} = \sqrt{\frac{8kT}{3g_m} \frac{1}{q^2 4\pi \tau} \frac{C_f^2}{(1.57 \cdot 7.39)}}
\]

\[
ENC_f = \sqrt{K_f \frac{C_f^2}{C_{\text{int}}^2 W L q^2}} (1.57)
\]

where detailed description of the parameters and their values are shown in Table I.

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![Figure 1. Electronic readout circuit of the channel including the integrator CSA and Shaper.](image-url)
Total noise is calculated by:

\[ ENC_{tot}^2 = ENC_d^2 + ENC_j^2 + ENC_{th}^2 \]  

(4)

Optimized shaping time was calculated using the condition:

\[ \frac{dENC_{tot}}{d\tau} = 0, \]  

(5)

obtaining the value:

\[ \tau \cong C_r \sqrt{\frac{8kT/3g_m}{2qI_L}} \]  

(6)

The dependence of \( ENC_{tot} \) on each of the parameters is calculated using a program written in "Mathematica" and is shown in Fig. 3. Table I indicates the optimized and used parameters in the circuit design and optimization.

Figure 2. Model of a detector diode connected in AC.

Figure 3. Dependence of \( ENC_{data} \) vs. all other parameters, using values reported in Table 1, for \( T=300^\circ C \).
Table I. Optimized and other circuit parameters for ORBIT 2 μm, N well process.

<table>
<thead>
<tr>
<th>Parameter (description)</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel width of the input transistor of the CSA</td>
<td>W</td>
<td>788</td>
<td>μm</td>
</tr>
<tr>
<td>Length width of the input transistor of the CSA</td>
<td>L</td>
<td>2</td>
<td>μm</td>
</tr>
<tr>
<td>Lateral diffusion of the input transistor of the CSA</td>
<td>L_D</td>
<td>0.112</td>
<td>μm</td>
</tr>
<tr>
<td>Current in the input transistor of the CSA</td>
<td>I_ds</td>
<td>3</td>
<td>μA</td>
</tr>
<tr>
<td>Transconductance of the input transistor of the CSA</td>
<td>g_m</td>
<td>352.5</td>
<td>μA/V</td>
</tr>
<tr>
<td>Detector diode capacitance</td>
<td>C_d</td>
<td>1.3</td>
<td>pF</td>
</tr>
<tr>
<td>Total capacitance at the CSA input</td>
<td>C_t</td>
<td>4.16</td>
<td>pF</td>
</tr>
<tr>
<td>Leakage current in the detector diode</td>
<td>I_L</td>
<td>0.3864</td>
<td>pA</td>
</tr>
<tr>
<td>Bias resistor for the AC connection in the detector diode</td>
<td>R_bias</td>
<td>50</td>
<td>MΩ</td>
</tr>
<tr>
<td>Feedback capacitance of the CSA</td>
<td>C_f</td>
<td>30</td>
<td>fF</td>
</tr>
<tr>
<td>Feedback resistance of the CSA</td>
<td>R_f</td>
<td>&gt; 100</td>
<td>Ω</td>
</tr>
<tr>
<td>1/f technology process coefficient</td>
<td>K_f</td>
<td>1 x 10^{-27}</td>
<td>C^2/m^2</td>
</tr>
<tr>
<td>Time constant of the Shaper</td>
<td>τ</td>
<td>2.1</td>
<td>μs</td>
</tr>
<tr>
<td>Technology transconductance parameter</td>
<td>K'</td>
<td>52.5</td>
<td>μA/V^2</td>
</tr>
<tr>
<td>Integrator order</td>
<td>n</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

ENC rms noise for each of the contribution was:

\[
\begin{align*}
    \text{ENC}_c &= 96.2311 \text{ electrons} \\
    \text{ENC}_f &= 21.1393 \text{ electrons} \\
    \text{ENC}_d &= 184.15 \text{ electrons} \\
    \text{ENC}_c &= 208.85 \text{ electrons (with detector)} \\
    \text{ENC}_c &= 98.5256 \text{ electrons (without detector)}
\end{align*}
\]

**4. NOISE MEASUREMENTS**

We used two different methods to measure the noise. In the first method the output waveform of the Shaper is stored and analyzed using a digital oscilloscope. Fig 4a shows the pulse characteristics, while Fig. 4b shows noise at the output of the circuit without detector for an input capacitance of \(C_i = 3\text{pF}\).

![Figure 4a](image1.png) ![Figure 4b](image2.png)

*Figure 4. a) Curve (1)- CSA input signal equivalent to 3000 electrons; curve (2) - CSA output signal and curve (3)- Shaper output signal. All points in the memory are included for mathematical processing. b) Curve (1) - CSA input signal equivalent to 3000 electrons; curve (2) - CSA output signal and curve (3)- Shaper output signal. Only the points inside the window were included for mathematical processing.*
ENC was calculated from $ampl(3)$ in Fig.4a and $rms(3)$ in Fig.4b using the following relations:

$$ENC = \frac{ampl(1)[electrons](rms(3))}{ampl(3)} = \frac{3000electrons \cdot 74.3mV}{1.654V} = 134electrons$$  \hspace{1cm} (7)$$

Repeating the same for different values of input capacitance, points were traced and fitted to the equation:

$$ENC_{\text{experim}} [electrons] = 120 + 2.5 \times Cin [pF]$$ \hspace{1cm} \text{(8)}$$

The second method used was to vary the amount of injected charge by changing the peak input voltage pulse applied through a capacitance equal to the CSA feedback capacitance. The output of the Shaper was connected to a counter with a fixed threshold voltage of 4 V. The pulse generator was set in burst mode with 2000 pulses. The amount of pulses was counted for each voltage step and different input capacitance values indicated in Table 2.

The pulse amplitude vs Cin was plotted for each column in Table 2; differentiated and fitted to a gaussian function. The width of each adjusted function is a double sigma ($2\mu$) shown in Table 3. The linear equation that better fits to all points can be expressed as:

$$ENC_{\text{theor}} [electrons] = 90 + 2.5 \times Cin [pF]$$ \hspace{1cm} \text{(9)}$$

Table II. Input voltage pulses in [mV] vs. the amount of pulses counted, by the counter at the shaper output, for different input capacitance values in [pF].

<table>
<thead>
<tr>
<th>Pulse [mV]</th>
<th>Cin [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1990</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table III. Width of the gaussian curve (ENC rms) for each value of input capacitance [pF].

<table>
<thead>
<tr>
<th>Cin [pF]</th>
<th>ENC [mV]</th>
<th>(2\sigma)</th>
<th>(2\sigma)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.81776</td>
<td>163.552</td>
<td>81.776</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>1.1946</td>
<td>238.92</td>
<td>119.46</td>
<td></td>
</tr>
<tr>
<td>6.02</td>
<td>1.0514</td>
<td>210.28</td>
<td>105.14</td>
<td></td>
</tr>
<tr>
<td>9.86</td>
<td>1.0222</td>
<td>204.44</td>
<td>102.22</td>
<td></td>
</tr>
<tr>
<td>17.3</td>
<td>1.2045</td>
<td>240.9</td>
<td>120.45</td>
<td></td>
</tr>
<tr>
<td>26.7</td>
<td>1.4591</td>
<td>291.82</td>
<td>145.91</td>
<td></td>
</tr>
<tr>
<td>39.6</td>
<td>1.8779</td>
<td>375.58</td>
<td>187.79</td>
<td></td>
</tr>
<tr>
<td>47.4</td>
<td>1.9731</td>
<td>394.62</td>
<td>197.31</td>
<td></td>
</tr>
<tr>
<td>55.6</td>
<td>2.1545</td>
<td>430.9</td>
<td>215.45</td>
<td></td>
</tr>
</tbody>
</table>
From both experimental methods used above to calculate the noise of the circuit we see that values are similar, that confirm the accuracy of measurements, and indicates correctness of theoretical optimizations, \( ENC=98 \text{ electrons} \) against the experimental one \( ENC=123 \text{ electrons} \). The small difference can be attributed to circuit parasitic capacitances that change the filtering properties.

5. CONCLUSIONS

Theoretical calculations for noise optimization and experimental measurements of the noise in a low power, high output swing readout circuit for signal particle detection is presented, which ensure detection of as low as 400 electrons. Validity of the theoretical prediction is demonstrated using 2 methods to determine the experimental noise. The circuit presents noise as low as \( ENC=123 \text{ electrons} \) rms for \( C=1.3 \text{ pF} \) input capacitance while keeping a power consumption lower than 100 W, and providing an output swing of 3 V which can be analyzed by laboratory equipment without other amplification stages.

6. REFERENCES


Authors Byography

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Born in Habana, Cuba in the 1967, electro-physical engineer and master graduate from Moscow Energy Institute, Russia, in 1992. Doctorate in Sciences in the year 2000 in the IPN-CINVESTAV Mexico. He worked during 5 years in development of devices and integrated circuits for the nuclear physics, particularly the nuclear medicine and the astrophysics in the Habana Nuclear Center of Development, Cuba, and in the International Center of Physical Theoretician of Trieste, Italy. Among the works carried out there are a digital system of mammogram and a gamma rays telescope. Currently works for the DAI Telecom, Italy, in the design of new circuits integrated and teams for telecommunications, particularly, in cell phones GSM and UMTS.
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Born in La Plata, Argentina December 2, 1961. He studied Physics at Exact Faculty Sciences of the University of La Plata where obtained the Bachelors degree in Physics in 1992. Since 1993 he works in the Microprocessor Laboratory which belongs to the International Center for Theoretical Physics, IAEA-UNESCO in Trieste, Italy. He collaborates regularly with the Italian National Institute of Nuclear Physics as associated investigator in the environment of the experimental physics of high energies. Currently works in the Experiment Compass of the CERN in the acquisition systems development and prosecution of data for gaseous detectors of elementary particles. Part of his activity is dedicated to physics and engineers training the third world in the field of the design of VLSI and logical devices programmable. He has published diverse scientific works related to the experimental physics and the instrumentation scientific development.

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