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Time-Domain Noise Analysis of 8-Channel CMOS Readout Circuits for CZT X-Ray Detector Array

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An 8-channel CMOS low-noise readout IC is designed for CdZnTe (CZT) X-ray detector arrays. Each channel of the IC is composed of a continuously discharged preamplifier and a comparator. The preamplifier is operated in pulse-mode and this is realized with a feedback capacitor and a pair of MOSFETs. The noise of this readout IC is calculated by the time-domain Hspice noise simulation. The calculated RMS total noise voltage at the output node of the preamplifier is 0.246 mV. The prototype chip is fabricated by 1.5 μm CMOS technology through MOSIS and the measured noise voltage of the preamplifier output is 0.435 mV.

KEY WORDS: Time-domain noise simulation, Hspice noise simulation, Low-noise readout circuits

I. Introduction

CZT detector arrays for imaging and spectroscopy become increasingly important because of their low dark current, which makes it powerful to operate in room temperature, and excellent photoabsorption efficiency for X-rays or gamma-rays [1]. For the imaging applications such as non-destructive inspection (NDI), a multi-channel low-noise fast readout IC is required [2].

In this study, a fast readout IC is designed for a 16-pixel CZT array with 1 mm^2 pixel area and 3 mm thickness. For the fast readout to count the number of incident photons, the preamplifier is operated in pulse-mode and this is realized by a feedback capacitor and a pair of MOSFETs. So the feedback capacitor of the preamplifier is continuously discharged by the MOSFETs [3]. The next stage of the preamplifier is a comparator.

To calculate the noise voltage of the preamplifier output, the noise sources are modeled in the time-domain and simulated by using the Hspice circuit simulator in the time-domain. The noise analysis in the time-domain is not a general approach but several studies have shown that the time-domain noise analysis can be a solution in the problems that the frequency-domain noise analysis cannot deal adequately [4-8]. The frequency-domain noise analyses of the preamplifier-shaping amplifier circuits have been presented in many studies focused on a charge sensitive preamplifier [9-10]. This paper presents CMOS analog readout circuits composed of a continuously discharged preamplifier and a comparator. Since the existing frequency noise analysis is not appropriate to calculate the output noise voltage of this preamplifier, the time-domain noise analysis is used.

The noise sources of the detector and readout system are the shot noise of detector and the thermal and *1/f* noise of the preamplifier's input transistor. The noise voltage at the preamplifier output for each noise source is simulated in the time-domain. Based on the results of these transient noise simulations, the RMS noise voltage of the preamplifier output is obtained. The design of the readout IC and transient noise simulation results are presented in Section II.

A prototype chip has been fabricated by using the 1.5 μm low-noise analog CMOS technology through MOSIS. The measured characteristics of the chip including the noise and the performance test are presented in Section III.

Results of this study show that the time-domain Hspice noise simulation could be useful to evaluate the noise performance of the readout IC.

II. Chip Design and Transient Noise Simulation

1.Chip Design

The readout IC is comprised of 8 readout channels. Each channel consists of a preamplifier and a comparator as shown in **Fig. 1**. The preamplifier is operated in pulse-mode with the feedback capacitor C_F and a pair of feedback NMOS and PMOS resistors. This enables the readout IC to operate in the frequency region over 10 MHz and count the number of incident photons with the minimum loss of counts.

When a detector current signal reaches a readout channel, it charges the feedback capacitor with a time constant that is determined by the feedback capacitance and the input amplifier's forward impedance. This time constant should be fast compared to the typical charge collection time of CZT detectors. The preamplifier's output signal discharges with a time constant that is determined by the feedback capacitance and the feedback CMOS resistors. The impedance of CMOS feedback resistors is controlled by the gate voltage. The simulated open-loop gain of the preamplifier is 66 dB. The cutoff frequency f_{-3dB} is 180 kHz and the gain bandwidth (GBW) is over 150 MHz. The power dissipation for the preamplifier is about 4 mW.The signal from the preamplifier is discriminated by the following comparator.

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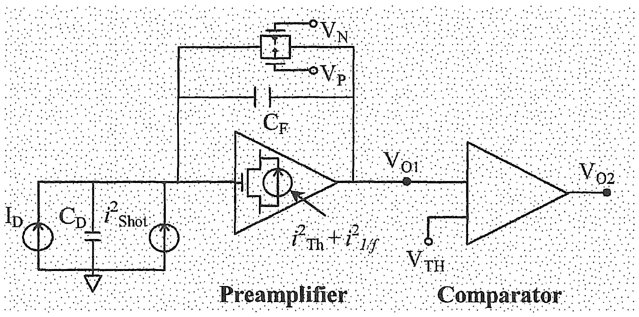

Fig. 1 Block diagram of one channel showing the preamplifier, the comparator and the noise sources.

2.Transient Noise Simulation

The main noise sources of this readout IC are shot noise from the detector and thermal and *1/f* noises from the input transistor of the preamplifier as shown in **Fig. 1**. These three noise sources are modeled in the time-domain with the random number [6-8]. Shot and thermal noise sources are a white noise in the frequency-domain, so they can be modeled as a Gaussian distribution of amplitude in the time-domain [6-8]. Random number sets for these white noise sources are generated and made as time-domain noise sources in the Hspice simulator by constructing a series combination of piecewise linear sources. The time interval between the random numbers is set by the noise bandwidth and the number of random number is determined by the transient simulation time.

The generated noise sources in the time-domain are shown in **Fig. 2**. The Hspice transient simulation of the readout IC is performed with all noise sources and this is shown in **Fig. 3**. The total RMS noise voltage of the preamplifier output is calculated from the simulation result and this is 0.246 mV. This value is much lower than that of the trip voltage of the comparator's hysteresis. The original Hspice circuit simulator can perform the noise simulation only in the frequency-domain and obtain its noise power spectrum. However, with the time-domain noise sources of this study, the RMS output noise voltage can be obtained through Hspice transient noise simulation

III. Experimental Results

The prototype readout IC has been fabricated by AMI 1.5 μm low noise analog CMOS process. The chip contains the 8-channel readout and several test blocks. The actual active area is 4 mm × 4 mm. The measured open-loop gain characteristic of the preamplifier is shown in **Fig. 4**. The DC gain is about 70 dB and the gain bandwidth is over 150 MHz. The measured *1/f* noise spectrum of the PMOS input transistor is shown in **Fig. 5**. From this measurement, the value of K_F is 3.36×10^{-26} V^2F.

The performance of the readout IC was tested by the test pulse through the calibration capacitor C_{cal}. The test pulse is divided by the voltage divider and the actual magnitude of the test pulse is 18 mV. The injected charge Q_{in} by this test pulse with the calibration capacitor of 10 pF is 180 fC. If this preamplifier is a kind of charge sensitive preamplifiers, the theoretical peak value of this preamplifier output with the feedback capacitor C_F of 0.05 pF would be 3.6 V. However the peak value of the preamplifier output is 220 mV. This lower peak value of the preamplifier output is due to the short discharge time constant by the feedback MOSFETs and capacitor.

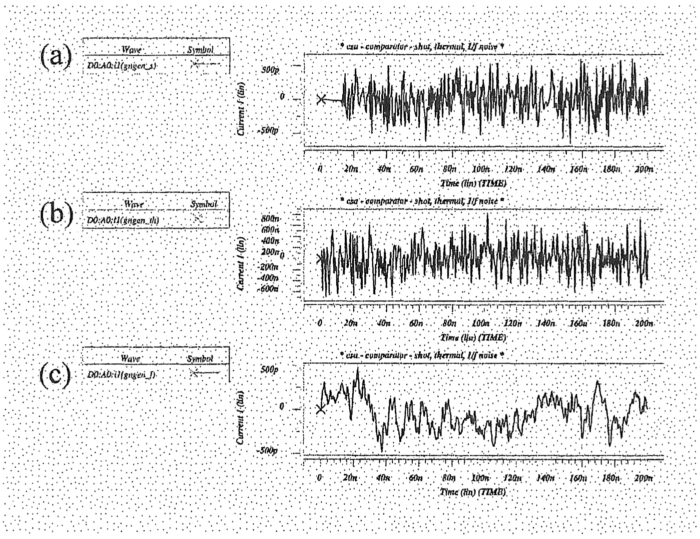

Fig. 2 Generated time-domain noise sources in Hspice code: **(a)** Shot noise current of the detector leakage current; **(b)** Thermal noise current of the input transistor; **(c)** *1/f* noise current of the input transistor.

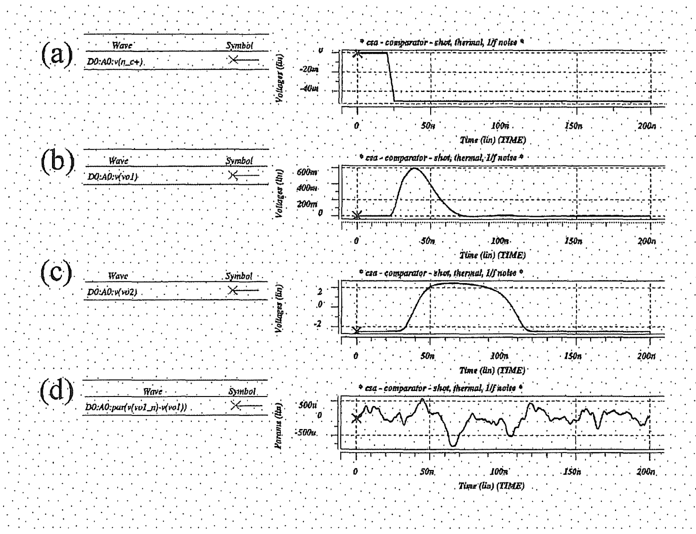

Fig. 3 Hspice transient noise simulation of the readout IC with time-domain noise sources in **Fig. 2: (a)** Test pulse; **(b)** Preamplifier output; **(c)** Comparator output; **(d)** Noise of preamplifier output.

In spite of this low peak value of the preamplifier output, it is confirmed that the comparator works well. The fluctuation of the preamplifier output was measured by the TDS 714L digital oscilloscope and the measured RMS noise voltage of the preamplifier output is 0.435 mV. This measured value is a little larger than the simulation results. The origin of this difference can be the random sampling error of the noise sources and the limitation of the noise bandwidth f_B.

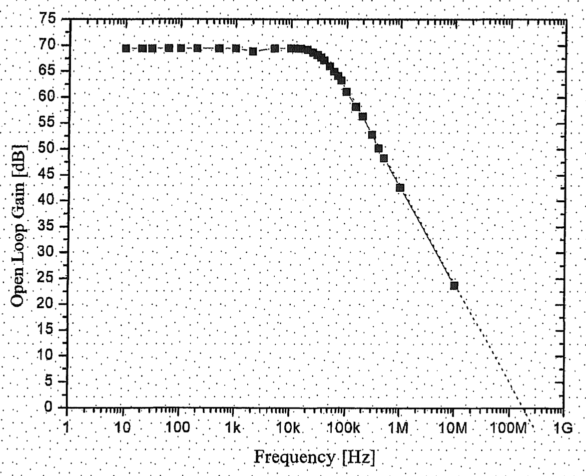

Fig. 4 Measured open-loop gain of the preamplifier.

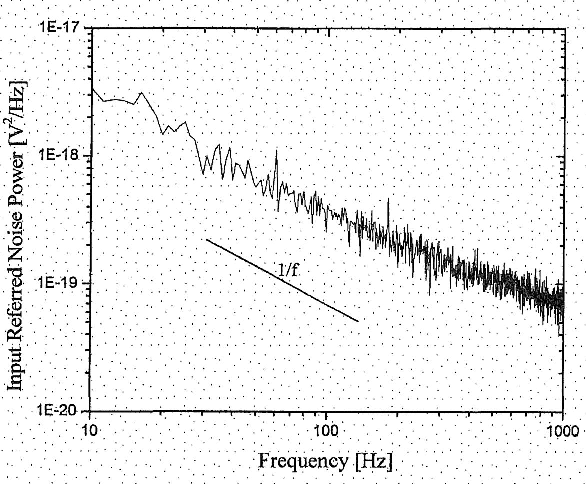

Fig. 5 Measured 1/f noise power spectral density of the input PMOS transistor (KF = 3.36 × 10-26 V2F).

When generating the random numbers for the noise sources, the calculated power of random number set was a little smaller than the expected noise power. In section II, the noise bandwidth f_B was limited to 1 GHz to generate the time-domain noise sources but actually the bandwidth of the noise sources spreads much more over 1 GHz. Therefore the powers of the time-domain noise source and the noise output can be underestimated.

IV. Conclusion

In this paper the time-domain noise analysis of a fast readout IC for CZT detector arrays is presented to determine the system performance in terms of the output noise voltage of the preamplifier circuit. The noise sources of this readout system are the shot noise of the detector, the thermal and *1/f* noise of the preamplifier's input transistor. These noise sources are modeled in the time-domain. To minimize the dead time of the readout IC, the preamplifier and comparator should ensure the high-speed operation and the noise voltage of the preamplifier output should be smaller than the trip voltage of comparator's hysteresis. The GBWs of the preamplifier and comparator are over 100 MHz. To see the effect of each noise source on the system performance, Hspice transient noise simulation was performed and it was confirmed that the thermal noise source dominates over the other noise sources in this system. The simulated total RMS noise voltage of the preamplifier output is 0.246 mV. A prototype chip was fabricated by AMI 1.5μm low noise analog CMOS process. The measured noise voltage of the preamplifier output is 0.435 mV. This value is much smaller than the comparator's hysteresis trip voltage of 40 mV. The error between the time-domain noise simulation and the measurement results is due to the random sampling error and the limitation of the noise bandwidth f_B. From the results of this study, it is confirmed that the time-domain Hspice noise simulation can be an alternative tool to design a low-noise circuit, even in the condition that the transfer function of the readout circuit is not known.

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