Development of Time-over-Threshold ASICs for radiation sensors

Tadashi Orita[1], Mizuki Uenomachi[2], Kenji Shimazoe[2]

[1]Kavli IPMU, The University of Tokyo

[2]Department of Nuclear Engineering and Management, School of Engineering, The University of Tokyo

Abstract

Time-over-Threshold (ToT) method is a time width signal processing applied to various areas of research such as high energy physics and medical application. It can not only obtain a trigger timing information as an output signal rise edge, but also an incident radiation energy as an output signal time width. We have been developing ToT processing based ASICs for gamma-ray imaging devices. The current mode ToT ASIC for MPPC realizes high timing performance. For improving ToT's non-linearity between time width and incident radiation energy, we also developed dynamic ToT ASIC and slew-rate limited type ToT ASIC.

Introduction

The Time-over-Threshold (ToT) method is a time width signal processing method. Unlike the conventional signal processing that converts detector signals caused by the incident radiation into voltage pulses and obtains the radiation energy by measuring their pulse heights, the ToT obtains the energy by measuring the pulse width of the digital output. The comparator in ToT compares the voltage pulses with a threshold voltage and outputs digital pulses (Fig.1). And the digital circuit such FPGA is directly connected to ToT's output and counts output pulse widths (Fig.2). The ToT circuit doesn't need ADC circuit and is simple to compose. However, ToT has the nonlinearity between the incident radiation energy and the output pulse width. Therefore, the result spectra contains distortions which need to be reduced. All ASICs were produced with TSMC 0.25um process .

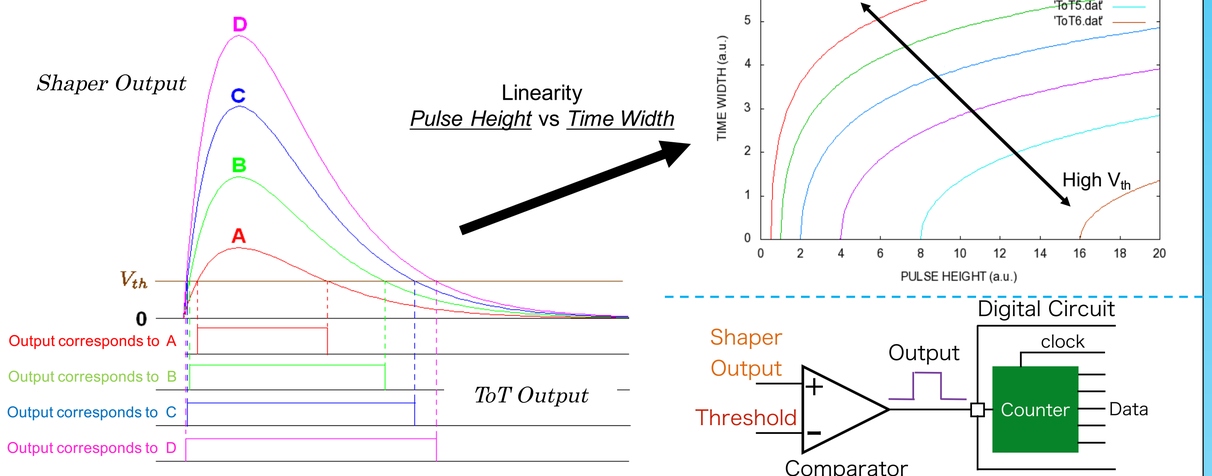


Fig.1 ToT Diagram

Fig.2 Scheme of ToT

Time-over-Threshold ASIC

➢ Current mode ToT ASIC[1]

We designed the 48 channels front-end ASIC for MPPCs of the TOF-PET application (Fig.3). One channel circuit of this ASIC is shown in Fig.4. It is composed of a current buffer, a current comparator, a 4-bit current DAC and a control register. The detector signal to the current buffer is copied with the current mirror and output to the comparator. The 4-bit current DAC works as a threshold current generator for the current mode ToT circuit. Fig.5 and Fig.6 shows the ^{22}Na energy spectra and the coincidence time distribution of ^{22}Na source with two MPPC + ASIC. The scintillators coupled to the MPPCs are Ce:GFAG and each scintillator size is 2.0mm by 2.0mm by 2.0mm. The energy resolution at 511keV peak was 13.5%. The coincidence timing resolution was 200ps (FWHM).

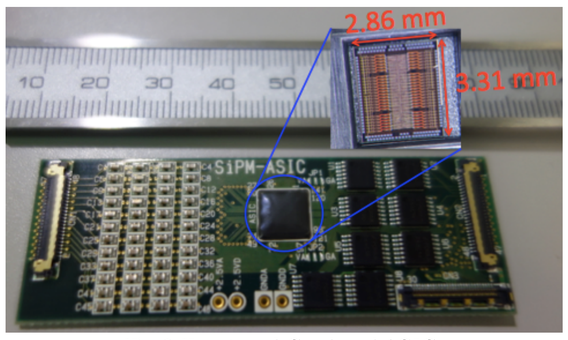


Fig.3 Front-end Card and ASIC

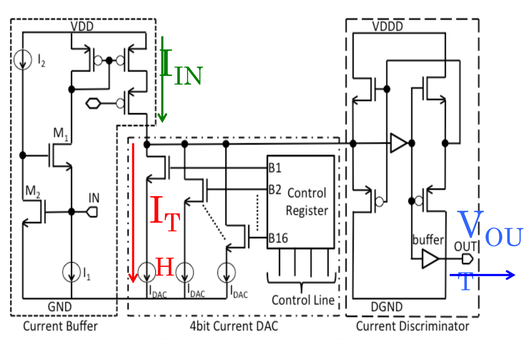
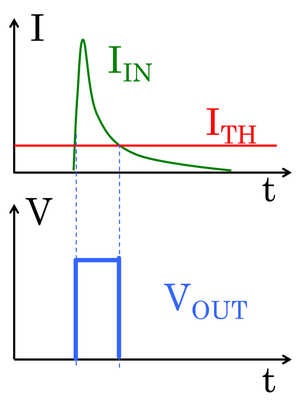


Fig.4 1ch Circuit Schematic



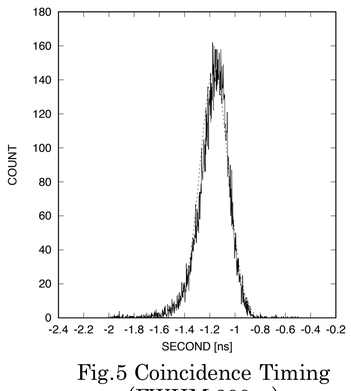


Fig.5 Coincidence Timing (FWHM 200ps)

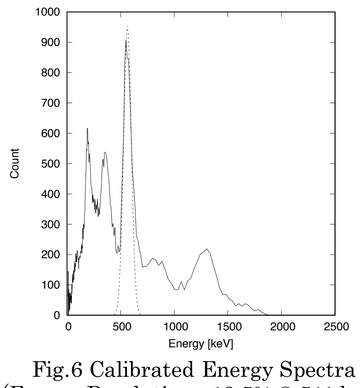


Fig.6 Calibrated Energy Spectra (Energy Resolution : 13.5% @ 511 keV)

Linearity Improved type Time-over-Threshold ASIC

In order to accurately acquire wide energy band spectra by improving ToT's non-linearity, we proposed two new ToT ASICs.

➢ Dynamic ToT (dToT) ASIC [2]

The dToT method is a new ToT technique in which the threshold voltage is not kept constant but is dynamically altered to catch up to the input signal after a signal pulse detection (Fig.8). For the proof of concept of dToT , we designed a 8 channel dToT ASIC to readout from a GAGG scintillator coupled to an APD detector (S8664-1010). Each channel had a CR-RC shaping and a dToT signal processing (Fig.10). As shown in Fig.9, The dToT improved the linearity between the incident energy and the output pulse width (average INL : 4.7%). We measured ^{22}Na spectra with APD detectors and this ASIC. Because of its high ENC (~8000e-), the energy resolutions at the 511keV were deteriorated to about 20%.

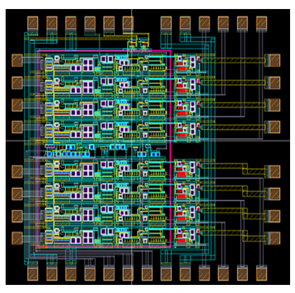


Fig. 7 dToT ASIC Layout

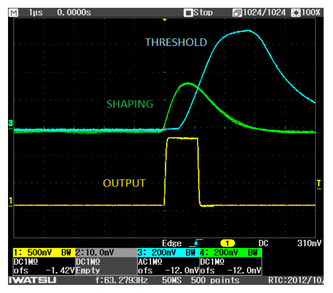


Fig. 8 Waveforms

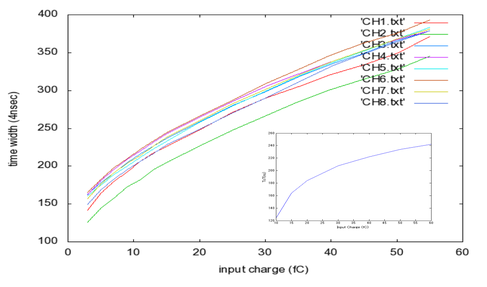


Fig. 9 Linearity

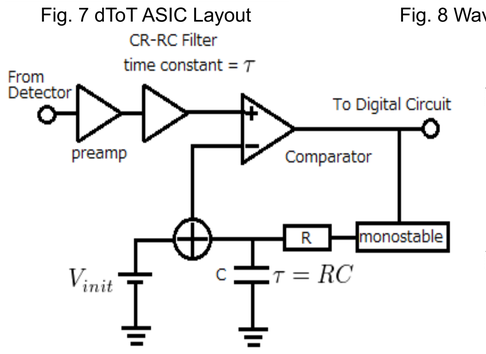


Fig. 10 Diagram of 1ch dToT ASIC

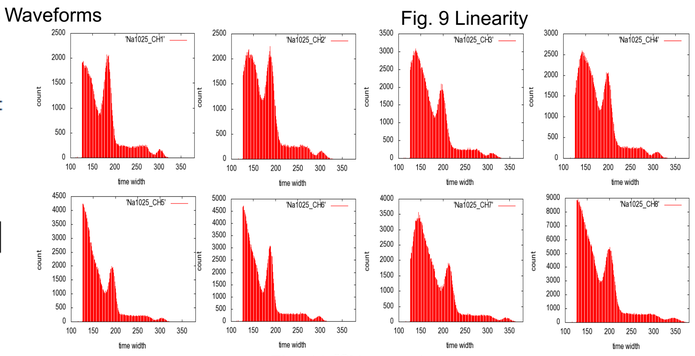
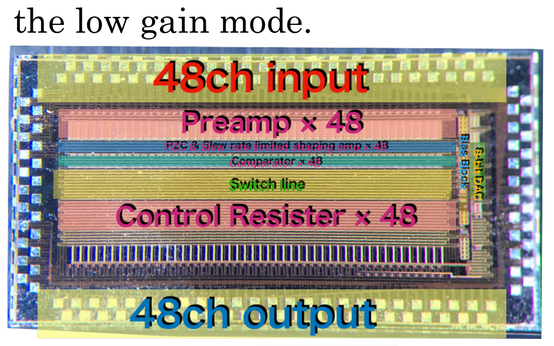


Fig. 11 ^{22}Na spectra

➢ Slew Rate Limited ToT ASIC [3]

This ASIC was composed of 48 channels for silion-based ion detectors (Fig.12). In this processing method, we applied a slew rate limited CR-RC shaping in the signal processing chain. Its threshold voltage was constant. In the pixel circuits designed by CERN[4], the charge sensitive amplifier with the constant current feedback was used to improve the ToT's non-linearity. In this work, by limiting a slew rate in the shaping amplifier, the slopes of the rise and fall of the waveform were made to be constant (Fig13). As the signal charge from the detector became large, the signal waveform became broad. This waveform effectively improved the ToT's linearity (Fig.14). Its ENC was 560±56 electrons. Its gains were 8.68 mV/fC in the high gain mode and 2.98 mV/fC in the low gain mode. Its dynamic ranges were 60fC in the high gain mode and 300fC in the low gain mode.



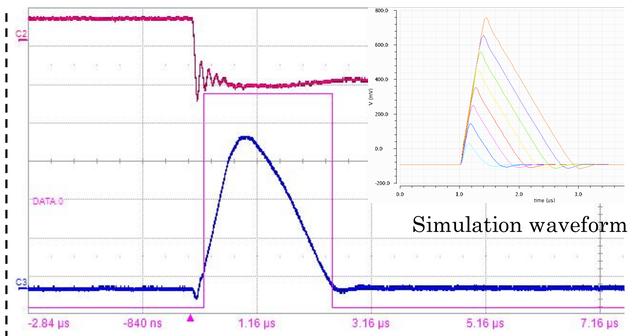


Fig.13 Waveforms

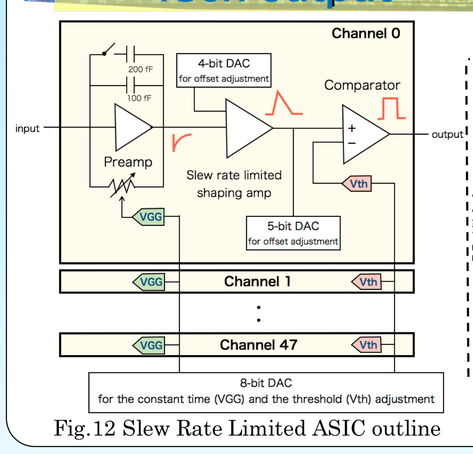


Fig.12 Slew Rate Limited ASIC outline

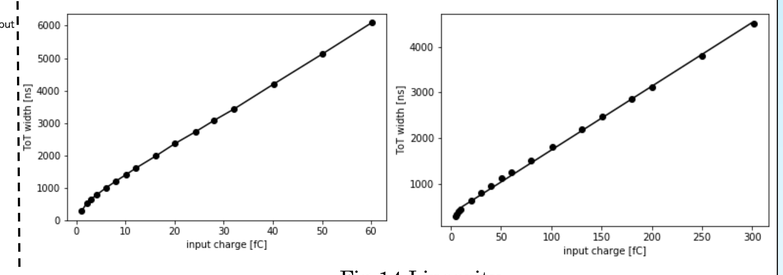


Fig.14 Linearity
Left: High Gain mode, Right : Low Gain mode

Conclusion

We developed ToT ASICs such as the current mode ToT ASIC, the dynamic ToT ASIC and the Slew Rate Limited ToT ASIC. All ASICs can be composed simply and obtain the incident energy without ADCs. The ToT ASIC has a non-linearity but can be applied to some applications that we only need one energy peak or we do not need a high energy resolution. By applying the dynamic threshold or slew rate limited shaping in the circuit, we can improve ToT's non-linearity and implement their signal processing circuits in the CMOS ASIC.

Reference

[1]. Orita, T., et al. "The current mode Time-over-Threshold ASIC for a MPPC module in a TOF-PET system." NIMA (2017) https://doi.org/10.1016/j.nima.2017.11.097

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[4]. Pacher, L., Monteil, E., Rivetti, A., Demaria, N., & Rolo, M. D. R. (2015, October). A low-power low-noise synchronous pixel front-end chain in 65 nm CMOS technology with local fast ToT encoding and autozeroing for extreme rate and radiation at HL-LHC. In Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2015 IEEE (pp. 1-4). IEEE.