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Development of the Pulse-Shape Discrimination LSI for *Astro-E* Hard X-ray Detector

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Abstract

We have developed a pulse-shape discrimination LSI for *Astro-E* Hard X-ray Detector (HXD). In the detector, the X-ray and non X-ray background will be reduced drastically by use of well-type phoswich counters in the compound-eye configuration. The well-type phoswich counter will use GSO(Ce) or YAP(Ce) scintillator for its detection part, and well-shaped BGO for the shielding part. The pulse-shape discriminator (PSD) described here will be used to select clean hits on the detection part, rejecting those deposited some energy in BGO. The PSD is designed as a bipolar semi-custom LSI to reduce its power consumption and size, and to enhance its reliability. The first delivery of the PSD-LSI has been tested to be acceptable for *Astro-E* HXD.

I. INTRODUCTION

Astro-E is the fifth Japanese satellite for X-ray astronomy scheduled for launch in year 2000. The satellite will carry on board three experiments, one of which is the Hard X-ray Detector (HXD)[1, 2]. The cross-sectional views of the detector are shown in Figure 1. The HXD consists of a matrix of 16 well-type phoswich counters[3], with total photon collecting area of 350 cm². The well-type phoswich counter has cross section shown in Figure 2.

The well-type phoswich counter uses scintillators with a short decay time, such as GSO(Ce)[4] or YAP(Ce)[5] (60 ns and 30 ns respectively), for its detection part. It is glued onto the bottom of the deep (350 mm) well made of a scintillator with high stopping power and long scintillation decay time, eg. BGO[6] (300 ns). The light output from both the detection part and the deep well, are read out by one photomultiplier from the bottom of the well. Hard X-ray signals that deposited their full-energy in the detection scintillator are selected by a pulse-shape discriminator (PSD). Because the well or the shielding part has approximately 50 times more volume in the present de-

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Figure 1: Cross sectional views of *Astro-E* HXD. The detector consists of 16 well-type phoswich counters shown in Figure 2. Neighboring units act also as active shield for other units. The matrix of phoswich counters are surrounded by additional BGO units which also serve as active shield.

sign, the purity of the selection by this PSD is the key for rejecting events which deposit some energy in BGO.

Detectors similar to *Astro-E* HXD has been used in balloon experiments[7]. Through these balloon flights, off-aperture X-rays and internal background of the scintillator are known to be reduced to several times 10^{-6} c/s/cm²/keV.

Figure 2: Cross section of one well-type phoswich counter for the HXD. Either GSO(Ce) or YAP(Ce) scintillator will be used for its detection part.

II. PULSE-SHAPE DISCRIMINATION

Pulse-shape discriminators have been used for many years in phoswich detectors in X-ray and γ -ray astronomy (ex. [8, 9]). They have also been used for particle identification using scintillators such as CsI(Tl) in nuclear physics experiments.

Among several methods of pulse-shape discrimination, we have selected the double-integration method[10] for *Astro-E* HXD. This method measures the charge contained in the early part of the pulse and compares it with the total charge in the pulse. In the present implementation, the signal is integrated by two shaping amplifiers with different shaping times and their outputs are compared. The method is schematically shown in Figure 3.

Figure 3: The principle of the double integration method: the signal is integrated by two amplifiers with different shaping times, and the output pulse heights are compared.

The shaping time of the slow shaper is set to be longer ($\tau = 500$ ns) than the scintillation decay time of either the detection part or the shielding part, while the shaping time of the fast shaper is set to be shorter ($\tau = 100$ ns) than the decay time of the shielding part, but longer than that

of the detection part. Then, the fast shaper integrates almost fully the charge from the detection part, GSO (or YAP), but only partially the charge from the shielding part, BGO. The slow shaper integrates almost fully both GSO (or YAP) and BGO signals. The GSO (or YAP) and BGO signals are then distinguished by comparing the two output pulse heights. This method is known to be stable against external electronic noise and reliable. One demerit is that the circuit required is somewhat complicated. This demerit will however be solved by implementing the circuit as an LSI.

III. DEVELOPMENT OF AN LSI FOR PULSE-SHAPE DISCRIMINATION

A. Specifications for the PSD-LSI

In *Astro-E* HXD, 16 units of well-type phoswich counters need to be operated within a tight limitation in power consumption. The LSI technology allows us to clear this limitation. The specifications of the PSD-LSI are as follows:

- Packed in a 24-pin DIP ceramic package.
- Hard against radiation damage anticipated in the space environment.
- Power consumption lower than 250 mW/chip.
- Input: Signal from the charge sensitive preamplifier, threshold voltage for the slow trigger, offset adjustments, peak-hold gate signal, and two reset signals.
- Output: Two peak-held pulse heights, slow trigger for hit-pattern latching, and PSD-signal for event selection.
- Logic levels: Positive ECL logic for triggers and gate inputs, negative TTL(CMOS) logic for outputs.
- Dynamic range of the peak-held pulse height to cover the X-ray energy range from 40 keV to 700 keV.
- The peak-held pulse height to be linear to 1% in most of the dynamic range.
- The peak-held output to be reset within 1 μ s.

The detail description of the circuit and its functions will appear later in this paper.

B. Semi-Custom LSI A600

To meet the specification set by the satellite environment, (power, size, and radiation hardness), the semi-custom bipolar LSI A600 by Fujitsu Ltd. was selected for fabrication. Bipolar transistors are generally considered to be hard against radiation damage. To our advantage, there have been already many circuits designed by A600/A400 in the field of radiation detection and astronomical instrumentation[12, 13, 14, 15]. One application

closest to the present one is the semi-custom LSI built for the bubble data recorder of *Yokoh*, the Japanese satellite to observe solar X-rays.

C. Circuit Design

The present LSI circuit has been designed on Analog Workbench II (AWB) on SparcStation-2, and has approximately 200 transistors. The block diagram of the LSI circuit is shown in Figure 4.

Figure 4: The block diagram of the PSD, together with some external components. The region enclosed by the dashed line is in the chip, and the small circles on its border stands for the pins.

The peak-hold circuits are controlled by two inputs, PH.GATE (peak-hold gate) and PH.RESET (peak-hold reset). The peak-hold circuits are kept in the peak-holding mode while PH.GATE is at the high level. The peak-held pulse height is restored quickly by feeding a pulse to PH.RESET.

One of the two comparators detects signal in the slow shaper output, which gives out relatively large amplitude for hits in BGO, and generates a slow trigger for hit-pattern latching of neighboring counters. The other comparator compares the peak-held pulse heights of the fast and slow shapers and generates the PSD-signal (PSD.OUT). The PSD-signal is held at the high level if the difference is within a preset limit, but at the low level if the difference is greater than the limit. When the PSD-signal is at the high level, the events are passed to the ADC and the readout circuits. The PSD reduces unwanted hits to minimize the dead time caused in the subsequent signal processing.

Two additional functions, hysteresis and offset adjustment, are installed in the comparator to generate the PSD-signal. Hysteresis prevents oscillation while comparing two peak-held pulse heights and can be controlled through the PSD.RESET terminal. Offset adjustments, VOFF.+ and

VOFF.-, compensate the offsets in the two peak-held pulse heights before being compared.

IV. RESULTS OF THE FIRST TEST

A. Test with a Waveform Generator

We have evaluated the performance of the first delivery of the PSD-LSI by using a waveform generator. The setup is shown in Figure 5. The preamplifier output signal was

Figure 5: Setup for the performance evaluation. The preamplifier output signal was simulated by a waveform generator. The rise time is set to 60 ns or 300 ns (which corresponds to GSO or BGO signal, respectively) and the fall time is set to 30 μ s.

simulated by a waveform generator. The rise time of the signal was set at 60 ns (GSO) or 300 ns (BGO), and the fall time at 30 μ s. The three control signals, PH.GATE, PH.RESET, PSD.RESET were generated by gate and delay generators. The timing chart of signals is shown in Figure 6.

Figure 6: Timing chart of the input signals to the PSD-LSI. The upper panel shows the preamplifier output signal simulated by a waveform generator. Three digital signals shown in the lower panel are all in ECL level.

We observed the transient response to GSO and BGO signals by a digital oscilloscope as shown in Figure 7. The peak-held pulse heights of the two shaping amplifiers differ for GSO and BGO signals as intended. The PSD-signal

(PSD.OUT), which senses the difference between the two peak-held pulse heights, is held at the high level for GSO signals, and at the low level for BGO signals, as intended.

The peak-held pulse heights are reset quickly at a rate approximately $14 \text{ V}/\mu\text{s}$ when the circuit receives PH.RESET. When the level is at the highest ($\sim 8 \text{ V}$, see below) the initial level is restored within $\sim 0.6 \mu\text{s}$ which meets the specification.

Figure 7: Temporal response of the circuit. Inputs are pseudo GSO signal for the upper figure, and pseudo BGO signal for the lower figure. The input pulse height is set at -600 mV . The upper panels in each figure show the output of the peak-hold circuit (solid line) and the shaper (dashed line). Two digital outputs TRGOUT.S and PSD.OUT are shown in the lower panels.

The slow trigger (TRGOUT.S) switches to the low level as the slow shaper output rises beyond the threshold.

Power consumption of the circuit has been measured to be 243 mW per chip, which also meets the specification.

Linearity of the peak-held pulse height to the input pulse

height is an important characteristic in the specifications. The peak-held pulse height was sampled $4 \mu\text{s}$ after the leading edge of the peak-hold gate. The measured linearity is shown in Figure 8. The temperature of the circuit was regulated at 10°C throughout the measurement.

Figure 8: Linearity of peak-hold output as a function of the pulse height of the input signal to the shaper (GSO signal). The top figure is that of the fast shaper, and the lower figure is that of the slow shaper. The peak-held pulse height was sampled $4 \mu\text{s}$ after the the opening edge of the peak-hold gate.

The peak-held pulse height is linear to the input signals in the range from -120 mV to -1.2 V for the fast shaper, and in the range from -100 mV to -1.35 V for the slow shaper, both within 1% . For input signals smaller than $\sim -100 \text{ mV}$, corresponding to relatively low energy X-rays, the linearity deteriorates to several % level. This, however, will not affect the detector performance seriously. In our application, the usable range will extend down to inputs of $\sim -60 \text{ mV}$.

In summary, the circuit has shown acceptable linearity

to the input pulse height from -60 mV to -1.2 V, corresponding to the energy of hard X-rays from 40 keV to 700 keV.

B. Test with a Simple Phoswich Counter

We have tested the LSI with a simple phoswich counter made of GSO and BGO as the second step. The experiment setup is shown schematically in Figure 9. The an-

Figure 9: Test for the first LSI with a simple phoswich counter made of GSO(Ce) and BGO.

ode signal of the photomultiplier was directly fed to the discriminator to generate the fast trigger, while the last dynode output was fed to the shaping amplifiers through a charge sensitive preamplifier (Clear Pulse 506E). Peak-held pulse heights were digitized by a CAMAC ADC. The PSD-signal (PSD.OUT) was also read out. The result obtained with 662 keV γ -rays from ^{137}Cs is shown in Figure 10.

One can see in Figure 10 that pure GSO events show up as a narrow band. We note that the Compton-scattered events form a bridge between the two blobs corresponding to 662 keV in GSO and 662 keV in BGO. Low energy BGO events are rejected efficiently by the threshold in the fast trigger, reducing unwanted triggers. The pure GSO events are selected by requiring PSD.OUT as shown in Figure 11.

Figure 12 shows the energy spectra obtained with the simple phoswich counter with and without PSD.OUT. The corresponding energy spectrum obtained by the GSO scintillator alone is also shown in the figure for reference. The large peak around 300 keV in the spectrum before the selection (dashed line) corresponds to 662 keV in BGO. Comparing the two spectra, before and after selection, one can see that events which deposited some energy in BGO (i.e. pure BGO events and forward Compton-scattered events) are reduced (solid line) by the use of PSD.

The Compton scattered events are suppressed by requiring PSD.OUT (Figure 12). Suppression is however not perfect because large angle Compton-scattered γ -rays will not hit the BGO crystal and because some γ -rays hit GSO after being scattered by the wall and floor in the test setup shown in Figure 9. In previous experiments where GSO is placed in the well-shaped BGO, Compton scattered events were suppressed to a much lower level[3].

Figure 10: Response of a simple phoswich counter with the PSD-LSI to exposure of 662 keV γ -rays plus room background. The horizontal and vertical axes show the peak-held pulse heights of fast and slow shapers, respectively. Dark stripes of dots correspond to GSO events, BGO events, and Compton scattered events as marked in the figure.

Figure 11: Event selection by PSD.OUT of the PSD-LSI. One can see by comparing with Figure 10, that GSO events are selected out cleanly.

Figure 12: Energy spectrum obtained by projecting Figure 10 and Figure 11 to the vertical axis. The energy axis is calibrated for pure GSO events. The solid line and the dashed line shows the spectrum with and without PSD.OUT, respectively. The energy spectrum obtained by the GSO scintillator alone is also shown as a dotted line for reference.

V. CONCLUSION

A new pulse-shape discrimination LSI for *Astro-E* HXD has been developed and fabricated. The delivered LSI performed as expected in the initial tests reported here. The major specifications, such as the dynamic range and linearity have been tested with a simplified version of the real detector successfully, demonstrating that clean-hits on the detection part can be selected. After some more tests, the LSI will be integrated into the readout circuit for the flight model of *Astro-E* HXD.

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