The Study of Calibration for the Hybrid Pixel Detector With Single Photon Counting in HEPS-BPIX

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Abstract—The calibration process for a hybrid pixel detector designed for the High Energy Photon Source in China, called HEPS-BPIX, is presented in this article. The relationship between the energy and threshold is quantified for the threshold calibration based on a threshold scanning. For threshold trimming, a precise algorithm based on local digital to analog converter (LDAC) characteristics and a fast algorithm based on LDAC scanning are proposed in this article to study the performance of threshold digital to analog converters (DACs) that will be applied to pixels. The threshold dispersion was reduced from 46.28 mV without the algorithm to 6.78 mV with the precise algorithm, whereas it was 7.61 mV with the fast algorithm. For temperatures from 5 °C to 60 °C, the threshold dispersion of the precise algorithm varies in the range of 5.69 mV. In contrast, it is 33.21 mV with the fast algorithm, which can be recorrected to 1.49 mV. The measurement results show that the fast algorithm could obtain the applicable threshold dispersion for a silicon pixel module and took less time. In comparison, the precise algorithm could obtain better threshold dispersion but was time-consuming. The temperature dependence of the silicon pixel module noise was also studied to assess the detector working status. The minimum detectable energy threshold could be reduced to 0.83–4.36 keV at a temperature of 5 °C.

Index Terms—Hybrid pixel detector, single photon counting, temperature dependence, threshold calibration, threshold trimming.

I. INTRODUCTION

A HYBRID pixel detector for the High Energy Photon Source (HEPS), called HEPS-BPIX (HEPS-Beijing pixel) has been developed at the Institute of High Energy Physics of the Chinese Academy of Sciences (IHEP, CAS). It is based on BPIX readout chips and operates in single photon counting mode. The detectable energy is from 8 to 20 keV. The total area of the prototype detector is 16 cm × 12 cm, which consists of 16 modules [1].

II. DETECTOR DESCRIPTION

A silicon pixel module in the HEPS-BPIX consists of a silicon sensor, eight readout chips, and a printed circuit board (PCB). As shown in Fig. 1, the silicon sensor is connected to the 2 × 4 readout chips by bump bonding with indium and then connected to the PCB by wire bonding [10].

A. Sensor

The silicon pixel module sensor is fabricated on 4-in-diameter n-type silicon wafers with 300 μm thickness. A silicon pixel module has a total of 208 × 288 pixels with 150 μm × 150 μm a pixel size. It consists of eight readout chips that are designed with 104 × 72 pixels [1]. Two rows or columns of larger pixels with 150 μm × 250 μm size

In the single photon counting detectors, the incident X-ray photon is converted to a charge cloud by hitting the sensor. The charge cloud moves in the electric field and creates a current pulse proportional to the photon energy. The charge pulses are amplified and reshaped in the readout chip, and then, they are digitized and counted one by one through comparison to a threshold. The effects of dark currents and readout noise can be diminished by setting a suitable threshold. The counting result is stored digitally in the pixel and can be read out quickly [2]–[5].

All pixels are parallel and have independent signal process cells in the readout chip. Due to the individual variation in the processes, a threshold dispersion causes different responses between pixels and affects the imaging results. This threshold dispersion could be minimized by trimming the threshold of the readout chips [6]–[9].

This article presents the calibration process for the silicon pixel module in the HEPS-BPIX detector. The relationship between energy and threshold is quantified to determine appropriate thresholds according to specific experimental requirements. Two algorithms of threshold trimming are implemented and discussed. This article has the following structure: Section II presents the description of the detector. Section III shows the process of threshold calibration and threshold trimming. The temperature dependencies of noise and threshold trimming are also presented in Section III. Finally, some discussions and conclusions are presented.
B. Readout Chip

The principal properties of the readout chip in HEPS-BPIX are listed in Table I.

Each pixel is followed by an independent cell for processing the signal. As shown in Fig. 2, a pixel cell of the readout chip is composed of an analog part and a digital part. The analog part consists of a charge-sensitive amplifier (CSA), an ac coupled amplifier, and a discriminator. The charges generated in the sensor are collected and preamplified by the CSA. The pulse signals can be injected into the CSA with a 1.6 fF capacitor to emulate the charge pulses generated in the sensor. It can be described by the following formula:

\[ Q_{\text{test}} = \Delta V_{\text{test}} \times C_t. \]  

(1)

The amplitude of the pulse signals is proportional to the input energy of the sensor. Every 100-mV pulse signal is equivalent to 1000 e\(^{-}\) input charges [11]. For the silicon pixel detector, each 1 keV X-ray can generate 278 e\(^{-}\) charges, which respond to approximately 30 mV of input signals. The ac coupled amplifier is used to reduce the electronic noise. Then, the pulse signal is compared to the threshold of the following discriminator. The threshold of each pixel can be set by an 8-bit global digital to analog converter (GDAC) of all pixels and its own 5-bit local digital to analog converter (LDAC). The parameter file, including the values of the GDAC and LDAC, could be configured during the test. The LDAC trimming circuit, limited by the area in each pixel, is nonlinear and even nonmonotonic. As a result of the dc differential voltage for the discriminator input, the global threshold set by GDAC should be more linear. In the digital part, the outputs of the discriminator are counted by a 20-bit counter. The configuration parameters are latched by the 20-bit shift registers [1], [11].

The silicon pixel module is followed by a module control board and a data acquisition (DAQ) system running on the host computer to form a module detector system. The module detector system supports parallel readout of eight chips [12]. Several silicon pixel modules can realize a larger pixel detector system. A control board is used to control and summarize the data of several modules [13]. The HEPS-BPIX 1 M is composed of an array of 4 \(\times\) 4 modules with one million pixels. The calibration process of a module detector system with 208 \(\times\) 288 pixels is presented in this article.

III. Calibration Process

The calibration of a silicon pixel module includes threshold calibration and trimming for threshold dispersion. For the threshold calibration, the quantified relationship between the threshold and energy is measured to set the GDAC value responding to the input X-ray energy. For threshold trimming, a precise algorithm based on LDAC characteristics and a fast algorithm based on LDAC scanning are implemented. Both of them can find the proper values of LDAC, which results in minimum threshold dispersion from pixel to pixel. Finally, the temperature dependencies of noise and threshold trimming are tested to evaluate the noise.

A. Test Method

In the pixel signal process cell of the readout chips, we can see that the cell parameters are measured by the counting results related to the discriminator’s threshold. Thus, the cell parameters (i.e., offset, noise, and the threshold for the input) can be tested by threshold scanning, which counts for inputs by changing the threshold step by step [14]. The results of threshold scanning are shown in Fig. 3. The threshold calibration and trimming for a silicon pixel module in this article are based on the threshold scanning of noise and input signals.
1) With Noise: the pixel noise above the threshold is counted. In the pixel cell discriminator, the white noise without input should be a Gaussian distribution [15]. Considering the offset voltage at the discriminator, the noise count rate \( f_{\text{noise}} \) of a system can be described by the following formula:

\[
f_{\text{noise}}(V_{\text{TH}}) = f_0 \exp\left(\frac{-(V_{\text{TH}} - V_{\text{offset}})^2}{2\sigma_n^2}\right)
\]

where \( f_0 \) is the noise count rate at \( V_{\text{TH}} = V_{\text{offset}} \), \( V_{\text{TH}} \) is the threshold voltage of the discriminator, and \( \sigma_n \) is the root mean square of the noise at the input of the discriminator.

A threshold is used to quantify the maximum noise of a pixel and is called the equivalent noise threshold. As shown in Fig. 3, it corresponds to the threshold of \( f_{\text{noise}} = 0 \). For a single photon counting detector, no noise count without input is required. Setting the LDAC value above the equivalent noise threshold can reduce the noise count. Meanwhile, it determines the minimum detectable energy threshold.

2) With Input Signals: the curve consists of two parts: one is the counting result for the noise, which is similar to the curve without input, and the other is the counting result for the input signal. The S-curve method is used to analyze the threshold scanning for the input signal. The pulse height from the shaper output signal is compared with the pixel threshold of the discriminator. When the threshold is lower than the height of the input signals, the counting result is a full count of the discriminator. When the threshold is higher than the inflection point of the S-curve, the counting result is a noise count. A threshold is used to quantify the relationship between the GDAC and energy by scanning differ-ent GDAC values with noise. For a single photon counting detector, it is necessary to quantify the relationship between the GDAC values and the energies.

B. Threshold Calibration

The threshold voltage of each pixel’s discriminator can be set by 8-bit GDAC shared by the same readout chip and its own 5-bit LDAC. Usually, the GDAC is set to respond to the energy for all pixels in a readout chip, and the LDAC is used to minimize the threshold dispersion [14]–[18]. Therefore, it is necessary to quantify the relationship between the GDAC values and the energies.

The quantified relationship between the GDAC and energy can be acquired by scanning the GDAC values with different energies at the same LDAC value. This experiment is performed at the 1W2B beam station of the Beijing Synchrotron Radiation Facility (BSRF) with an energy range from 6 to 20 keV. It provides monochromatic and uniform X-rays by scattering. However, the flux of the X-ray source varies with energy. The curves are obtained by setting the local threshold of all pixels to the middle LDAC value of 15 and repeatedly scanning the GDAC values with energies from 6 to 14 keV. Fig. 4 shows the threshold scans of a pixel for the noise and different X-ray energies. The full counts influenced by the fluctuation of X-ray flux vary with different energies. For the same X-ray energy, the counts keep decreasing due to the charge sharing between neighboring pixels in the sensor.

The equivalent noise threshold acquired by scanning different GDAC values with noise can be used to separate the part of noise counts and the part of counts for input energy. Fitting the S-curve for the input count part. The \( V_{\text{TH}} \) corresponding to the inflection point of the S-curve can be calculated by derivation. It is the GDAC that responds to the input energy.

The average GDAC of all pixels with the same energy is the GDAC of chips responding to this energy. The quantified relationship between the GDAC and energy is shown in Fig. 5 and
can be described by the following formula:

\[
GDAC = 8.43 \times E - 26.54.
\]  \hspace{1cm} (4)

It is linear, and \(8.43 \pm 0.33\) GDAC LSB responds to 1 keV. The average of the equivalent noise threshold is 17.19 GDAC LSB. Therefore, the minimum energy threshold is approximately 5.19 keV. For the detectable energy, the GDAC can be set to the corresponding energy.

C. Threshold Trimming

The threshold calibration is used to convert the pixel threshold value into energy. The GDAC value is global for a whole chip. There is an energy threshold dispersion from pixel to pixel with the same GDAC value for all pixels. The purpose of threshold trimming is to find the proper LDAC values to minimize the energy threshold dispersion of the threshold calibration. There is a 5-bit LDAC for each pixel in the readout chip, which means that only 32 values can be set. According to \(\sigma\) at the middle LDAC of value 15 for each energy, \(3\sigma\) is approximately 60 GDAC LSB. Setting the LSB value of LDAC twice that of GDAC LSB can cover the dispersion. Theoretically, the threshold dispersion can be reduced by transferring the GDAC to the LDAC for each pixel without additional tests. However, limited by the pixel area of the readout chip, the LDAC values are not linear and even not monotonic. This algorithm is not adapted to the nonlinear situation of LDAC, which can cause another threshold dispersion. Therefore, two algorithms with necessary tests are implemented and discussed to find proper LDAC values. All threshold trimming experiments are tested with electronic input signals. The electronic tests are affected by the test capacitance’s fluctuation of pixels, while X-ray tests are not. The results of three pixels tested with X-ray and electronic input signals are shown in Fig. 6. The energy of the X-ray is 9 keV, while the amplitude of the corresponding electronic input signal is 270 mV according to (1) in Section II. For pixel 1 and pixel 2, the difference of inflection points tested by X-rays and electronic input signals is about 1 LDAC LSB, the inflection points for pixel 3 are the same.

1) Precise Algorithm: The LDAC characterizations of each pixel, which can describe the behavior features of the trimming circuit, are used to find proper LDAC values to minimize the threshold dispersion.

As shown in Fig. 7, setting the same GDAC for all pixels, different amplitudes of the input signal are scanned repeatedly with different LDAC values. The completed \(S\)-curve for each LDAC is obtained by repeated scanning for the input signal in a specific range from 60 to 600 mV.

The 32 \(S\)-curves of a pixel are shown in Fig. 8(a). The blue and green curves in Fig. 8(a) respond to the LDAC values...
which the threshold voltage is around pixel’s offset. Based on the $S$-curve method, the characteristic curves are acquired. As shown in Fig. 8(b), $32 V_{THa}$ respond to 32 LDAC values for each pixel. Averaging thresholds for all pixels, setting the LDAC value at which the threshold is the closest to the average threshold for the pixel can minimize the dispersion of pixel thresholds. The result is shown in Fig. 9. The threshold dispersion was reduced from 46.28 mV without the algorithm to 6.78 mV with the precise algorithm. Scanning different amplitudes with the GDAC and the trimmed LDAC values, the equivalent noise charge (ENC) and threshold are shown in Table II.

This threshold trimming is a time-consuming process. For each LDAC value, scanning the 55 amplitudes of input signals requires 1760 steps. The test time was 147 min with 5 s per step. Adding the calculation time, which varies due to the algorithm processor speed, the total time for LDAC characteristic tests of a silicon pixel module is approximately three hours, which would consume more time with a smaller step.

2) Fast Algorithm: To find the proper LDAC values, time-consuming LDAC characteristic tests can be omitted by LDAC scanning with a fixed input signal.

As shown in Fig. 10, setting the same GDAC for all pixels, the equivalent noise threshold can be obtained by scanning for noise with different LDAC values. Then, the input amplitude corresponding to energy is fixed, scanning the LDAC from 1 to 32, and each pixel can obtain an $S$-curve. The scanning curves of 59904 pixels for the noise and a fixed input are shown in Fig. 11.

The tested curve and fitting $S$-curve for a pixel are shown in Fig. 12. According to (3), removing the counts for noise and fitting the counts for input to an $S$-curve, the $V_{THa}$ corresponding to the $S$-curve’s inflection point is the LDAC

![Fig. 8. Precise algorithm for LDAC characteristic measurement. (a) 32 $S$-curves of a pixel. (b) Threshold-LDAC characterization curves of five pixels.](image)

![Fig. 9. Threshold trimming results with the precise algorithm. For the untrimmed sample, the LDAC values of all pixels are 15.](image)

![Fig. 10. Procedure of the fast algorithm.](image)

![TABLE II

| ENC | Threshold |
|-----|-----------|
| Mean/σ | δ/σ | Mean/mV | δ/mV |
| Untrimmed | 171.3 | 22.3 | 255.47 | 46.33 |
| Precise algorithm | 162.2 | 18.0 | 263.56 | 6.78 |
Fig. 11. Fast algorithm. (a) Scanning curves of 59,904 pixels with noise. (b) Scanning curves of 59,904 pixels with a fixed input.

Fig. 12. Tested curve and fitting $S$-curve for a pixel.

threshold of this pixel. The inflection point of the fitting $S$-curve can be calculated by derivation.

Scanning different amplitudes with the GDAC values and the trimmed LDAC, the result of threshold trimming is shown in Table III and Fig. 13. The threshold dispersion was reduced from 46.28 mV without the algorithm to 7.61 mV with the fast algorithm.

This algorithm is similar to a flat field for all pixels, and the noise can be reduced by setting the LDAC above the equivalent noise threshold. It can shorten the test time by scanning only 32 LDAC values for noise and an input pulse signal. The test time was 6 min with 64 steps and 5 s per step. Adding the time of simple calculation, the total time of a silicon pixel module is approximately 8 min.

### D. Temperature Dependence

All the threshold calibration and threshold trimming tests were performed at room temperature. The pixel process cell in readout chips consists of many transistors whose many parameters, such as threshold voltage, mobility, and intrinsic carrier concentration of silicon, vary with temperature [19], [20]. Therefore, we tested the stability of the equivalent noise threshold and threshold trimming versus temperature changing from 5 °C to 60 °C with a step of 5 °C.

As shown in Fig. 14, the equivalent noise thresholds at each temperature are obtained by setting the middle LDAC value to 15 and scanning different GDAC values for noise. The equivalent noise threshold rises with increasing temperature. Compared with the room temperature of 25 °C, the equivalent noise thresholds at 5 °C decrease 7 GDAC LSB, which means that the minimum detectable energy threshold can be reduced to 0.83–4.36 keV. As shown in Fig. 15, the ENC and the threshold dispersion rise with the increasing temperature. With the trimmed LDAC values at room temperature (25 °C), the change in the threshold dispersion of the precise algorithm is in the range of 5.69 mV, while it is 33.21 mV for the

|               | ENC   | Threshold |
|---------------|-------|-----------|
|               | Mean/e-| δ/e- | Mean/mV | δ/mV |
| Untrimmed     | 171.3 | 22.3   | 255.47  | 46.28 |
| Fast algorithm| 162.2 | 49.2   | 266.12  | 7.61  |

Table III

Fig. 13. Threshold trimming result with the fast algorithm. For the untrimmed sample, the LDAC values of all pixels are 15.
fast algorithm. After recorrection with the fast algorithm at each temperature, the change in threshold dispersion of the fast algorithm is 1.49 mV.

E. X-Ray Imaging

After the calibration, the silicon pixel modules were imaged at the 1W2B beamline of the BSRF. Set GDAC 74 for 12 keV, and the LDAC values are obtained by the fast algorithm. The imaging results for the powder diffraction ring of the LaB₆ sample at 12 keV X-rays are shown in Fig. 16. Analyzing the imaging data of the silicon pixel module, Fig. 17 shows the diffraction angles and the relative intensity of each diffraction ring. The four Bragg diffraction angles of the LaB₆ sample are 0.26, 0.36, 0.44, and 0.51 rad.

IV. DISCUSSION AND CONCLUSION

This article presents the calibration process for the silicon pixel module in the HEPS-BPIX detector system, including threshold calibration and threshold trimming for threshold dispersion. For the threshold calibration, the energy and threshold relationship is quantified, which is $8.43 \pm 0.33$ GDAC LSB for 1 keV energy. The minimum detectable energy threshold is approximately 5.19 keV with an equivalent noise threshold of 17.19 GDAC LSB. In the range of detectable energy, the GDAC can be set to the corresponding energy. For threshold trimming, the threshold dispersion was reduced from 46.28 mV without the algorithm to 6.78 mV with the precise algorithm, whereas it was 7.61 mV with the fast algorithm. With the trimmed LDAC values at room temperature (25 °C), the threshold dispersion of the precise algorithm changes in the range of 5.69 mV, while it is 33.21 mV for the fast algorithm. After recorrection with the fast algorithm at each temperature, the change in threshold dispersion of the fast
algorithm is 1.49 mV. The measurement results show that the precise algorithm can obtain better threshold dispersion with LDAC characterizations for a silicon pixel module, but it is time-consuming, whereas the fast algorithm can obtain acceptable results faster by LDAC scanning. The fast algorithm is effective and well adapted for recalibrating the temperature and calibrating the X-ray.

The temperature dependence of the silicon pixel module noise is also studied. The equivalent noise threshold rises with the increasing temperature, and the minimum detectable energy threshold can be reduced to 0.83–4.36 keV at 5 °C. Working at a low temperature is important for a good detector status. In addition, after the calibration, the silicon pixel module is applied to the measurement of X-ray diffraction ring. In the future, more studies about the calibration of threshold trimming with X-rays will be performed and compared with electronic input signals.

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