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Characterisation of silicon strip detectors with a binary readout chip for X-ray imaging

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Abstract

In this paper we describe the development of a multichannel readout system for X-ray measurements using silicon strip detectors. The developed system is based on a binary readout architecture and optimised for detection of X-rays of energies in the range 6–30 keV. The critical component of the system is the 32-channel front-end chip, RX32N, which has been optimised for low noise performance, small channel to channel variation and high counting rate operation. The performance of the chip is demonstrated by measurements of complex X-ray spectra using silicon strip and pad detectors. The obtained results allow to use the system at room temperature with the detection threshold in the range from 500 to 10 000 electrons, which is enough in many crystallographic and medical imaging applications. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The silicon strip and pixel detectors are used mainly as position sensitive sensors for track reconstruction in particle physics experiments. In the last decade several papers have been published on the possibilities of using these kinds of detectors for low-energy X-ray detection in material science and medical applications [1–4]. Pixel detectors offer the possibility of two-dimensional imaging [1,2], but the active area of such devices is still limited by the cost. An alternative solution is a system with silicon strip detectors [3] offering one-dimensional spatial resolution which is sufficient in many applications. An effective use of standard silicon strip detectors at room temperature for low-energy X-ray measurements is limited to the energy range between 5 and 20 keV. For the energies below 5 keV one usually faces a limitation due to the noise of the readout electronics and the channel-to-channel

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variation of gain and offset. Concerning the upper energy limit, there are two effects which should be taken into account: (i) the reduction of the detection efficiency due to the finite thickness of the detector, typically below 500 μm, (ii) the degradation of the intrinsic spatial resolution due to Compton scattering and the effect of parallax for incident angles different from 0° [5]. For energies higher than 20 keV the scattering effects become comparable or larger than the effect of charge diffusion during its transport to the readout electrodes. In such a situation, there is no particular advantage of using the pulse height information for estimating the position and so improving the spatial resolution. Therefore, we have chosen the binary architecture for our front-end electronics, in which only 1-bit information (yes/no) is provided in response to the photon absorbed in the silicon strip detector. The readout system consists of two ASICs: RX32N front-end chip and COUNT32 counter chip comprising 32 20-bit asynchronous counters and the readout logic.

In this paper we present a short description of the design and performance of the front-end chip. The chip set was used for the readout of silicon pad and silicon strip detectors. Complex X-ray spectra measured with both types of detectors are presented and discussed. Intrinsic limitations of silicon strip detectors with respect to energy and spatial resolution are discussed.

2. The architecture of front-end chip

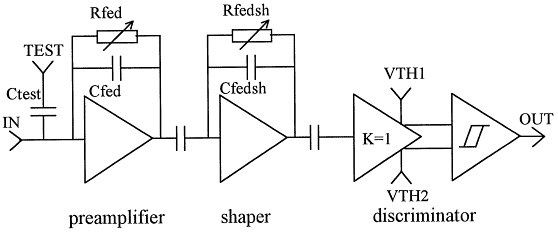

Fig. 1. Block diagram of the single channel of RX32N chip.

The RX32N chip contains 32 channels of front-end electronics to extract, shape and discriminate the signals from silicon strip detectors. The chip was designed and manufactured in the AMS 0.8 m CMOS process [6]. Each channel of the front-end chip comprises three basic blocks: preamplifier, shaper and discriminator as shown in Fig. 1. The first two stages were designed taking into account the noise and speed performance. Since the optimisation of the noise and speed performance lead to contradictory requirements concerning the shaping time of the circuit, we chose the shaping time constant of about 500 ns as a reasonable compromise. The chip can work with DC coupled detectors which requires that the preamplifier can sink detector current in the range from a few pA up to several nA through the MOS transistor in the feedback loop. The resistance R_{fed}, of this transistor is controlled by an external reference current. A relatively short shaping time allows to use the chip for the readout of detectors with the leakage currents up to few nA without significant degradation of the signal-to-noise ratio. The size of the input transistor was optimised for a detector capacitance of about 2–5 pF per strip, assuming applications with rather short strips in the range 1–2 cm. The preamplifier is followed by a shaper circuit providing noise filtering and semigaussian pulse shaping with a rise time tuneable via R_{fedsh}.

The front-end channel is ended with a continuous time discriminator. A differential scheme for setting the discriminator threshold allows the circuit to be used either for positive or negative input signals. Since the only practical solution is a common threshold applied to all channels in the chip, special attention was paid to matching problems in the discriminator design in order to minimise the channel-to-channel offset spread. More details on the chip design can be found in [6].

3. Silicon detectors

One of the issues to be considered when using silicon strip detectors for detection of low-energy X-rays is the effect of charge division between neighbouring strips. This effect results in the distribution of the charge collected on individual strips to be different from the distribution of the charge generated in the detector volume. In order to evaluate the effect of charge division we used our binary system for the readout of a silicon pad detector and a silicon strip detector. The pad detector was an array of five diodes with area $1 \times 1\,\mathrm{mm}^2$ and thickness of 300 μm. The leakage current per one diode was 40 pA, and the total capacitance of a fully depleted diode was about 0.6 pF. For low-energy X-ray photons, incomplete charge collection due to scattering and diffusion takes place only in about 10 μm wide region around the edge of the pad. Given the pad area of $1\,\mathrm{mm}^2$, we can assume that these edge effects are negligible for the measured signal distributions. The tested silicon strip detector had 384 2-cm long DC coupled strips with 50 μm pitch. The width of the strips was 25 μm and the thickness of the detector was 300 μm. The leakage current per strip was 100 pA, and the total capacitance above the depletion voltage was 4 pF per strip, including the capacitance to the backplane and the interstrip capacitances to the neighbouring strips. Therefore, we can expect charge sharing to affect a large fraction of the events, namely about 20%.

4. Test results

4.1. Chip performance

Given the binary architecture implemented in the RX32N chip, the analogue parameters, like gain and noise are obtained by scanning the threshold of the discriminator for a given charge injected to the input of the preamplifier. For each value of the threshold a series of voltage step pulses of a given amplitude is sent to the input via the test capacitor of nominal value $C_{\mathrm{test}} = 75\,\mathrm{fF}$. This value depends, however, on the processing parameters and therefore is not known accurately enough to be used for absolute calibration. In order to eliminate the uncertainty on the actually injected charge, we calibrated the system using several low-energy X-ray sources from the range (8–20 keV) while assuming that 3.67 eV on average is needed for generation of one electron–hole pair in silicon.

In the RX32N chip, we can tune the shaping time constant, which offers a possibility to optimise the signal-to-noise ratio for a given detector capacitance and a given detector leakage current, or to tune the circuit for maximum counting rate at the expense of some degradation of the signal-to-noise ratio. While changing the shaping time the overall gain of the circuit changes. The result for three different values of the rise time at the shaper output is shown in Fig. 2.

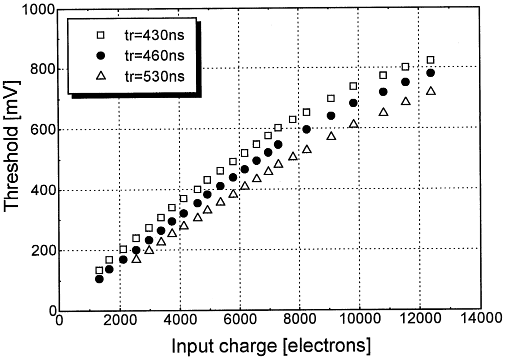

Fig. 2. Linearity of the front-end part of RX32N chip for three different rise time.

One can see that the circuit is linear up to 8000 electrons of input signal, which corresponds to an energy range of X-rays up to 30 keV. The equivalent noise charge (ENC) of the circuit has been evaluated, as described in [6], by measuring the counting rate as a function of the input charge at a fixed threshold of the discriminator for a given rate of test pulses. In this way, we measure directly the error function of the noise at the shaper output. For the system tested with the detectors mentioned above, the measured parameters of the chip are summarised in Table 1.

Since for all 32 channels a common threshold (VTH1-VTH2) is applied, one of the most critical issues for the RX32N chip is the spread of gain and comparator offsets. Our goal was to keep this spread negligible compared to the noise level. The gain and offset spreads were measured with the strip detector using Cu-8, Rb-13.4 and Mo-17.4 keV X-ray sources. The distribution of the peak position for 32 channels is in the same range for all measured X-ray lines as one can expect if the factor limiting the threshold spread is the spread of the discriminator offsets and not the spread of the amplifier gains. Fig. 3 shows the distributions of the peak position for 32 readout channels. Taking into

Table 1
Gain and noise for various rise time at the shaper output

Rise time (ns)	Gain (μV/electron)	ENC – pad detector (el rms)	ENC – strip detector (el rms)
430	70	97	176
460	77	93	166
530	87	85	161

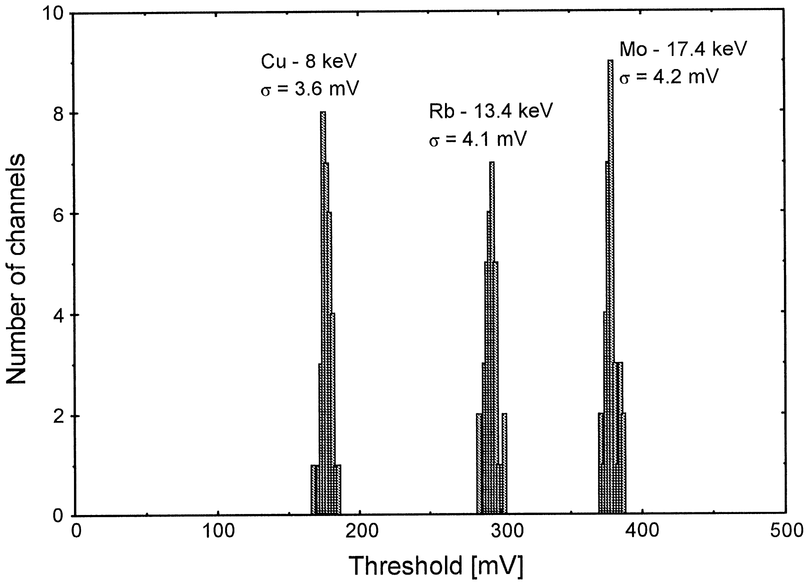

Fig. 3. Distribution of the gain and discriminator offset in 32-channel RX32N chip measured with X-ray sources: Cu-8, Rb-13.4 and Mo-17.4 keV.

account the gain of the circuit, one obtains an equivalent input spread of $\sigma_{\mathrm{ch/ch}} = 56$ el rms which is almost by a factor 2 smaller compared to the noise.

Another parameter which is important for many practical applications is the maximum counting rate. Given the fully parallel architecture of our readout system, including the counters which serve as the buffer memory, the counting rate considered for the total area of a detector depends on the detector segmentation. Concerning the counting rate limit for the single readout channel there are two points to be considered. First, in order to keep the noise contribution from the feedback resistor in the preamplifier within an acceptable range, this resistor has to be sufficiently large. This leads to a long discharge time of the feedback capacitance, which produces a shift of the operating point of the preamplifier for high rate of the pulses. A second limitation appears in the shaper where, although the tails of the pulses are much shorter than in the preamplifier, because their amplitudes are higher and above a certain rate of pulses, pile-up starts to degrade the resolution and eventually leads to the loss of some fraction of the pulses. The counting rate limit is not sharp and depends on the signal amplitudes. The RX32N chip operates satisfactory up to 200 kHz for periodic signals of amplitude corresponding to 8 keV photons absorbed in silicon, as shown in Fig. 4. The test signals in the

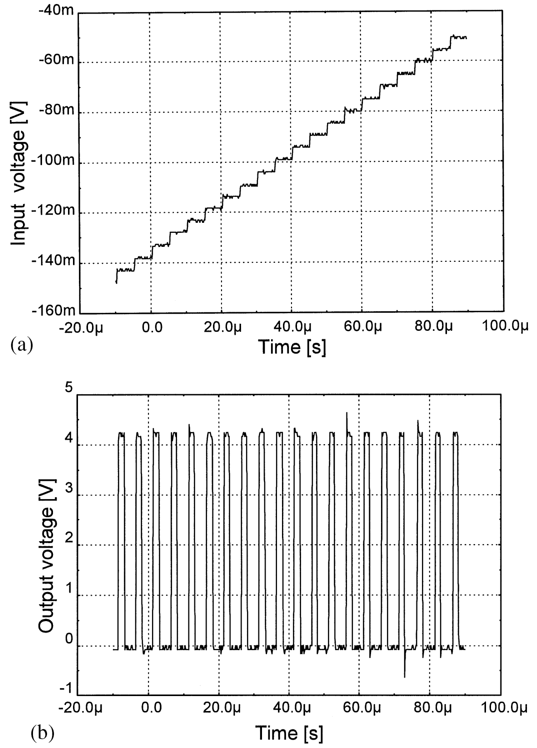

Fig. 4. Speed test for the RX32N chip: (a) input test signal, (b) discriminator output.

staircase form (Fig. 4a) were applied to the input in order to avoid discharging the feedback capacitor by the negative charges which are injected by the falling edges when using rectangular test pulses. The response of the discriminator is shown in Fig. 4b where one can see that the chip is working stable and does not lose pulses up to 200 kHz.

4.2. X-ray measurements with pad and strip detectors

In order to demonstrate the performance of the RX32N chip working with silicon strip detectors we measured various X-ray spectra. As X-ray source we used a ^{238}Pu radioactive source, which generates three distinct X-ray lines at 13.6, 17.2 and 20.1 keV of comparable intensity. In addition, we could obtain a fluorescent X-ray line of lower energy by inserting a copper or iron foil between the source and the detector. Choosing properly the thickness of the foil according to the absorption coefficient and the fluorescence yield we could obtain an intensity of the characteristic fluorescent radiation from the foil comparable to the intensity of the primary radiation from the source. The full spectrum of such source was also measured using a standard high-resolution spectrometer with 3 mm thick Si(Li) detector cooled to liquid nitrogen temperature. This spectrum is shown in Fig. 5. The full-width at half-maximum (FWHM) for $U_L\beta_1$ line is 150 eV, which corresponds to $\sigma = 18$ el rms when expressed in electrons.

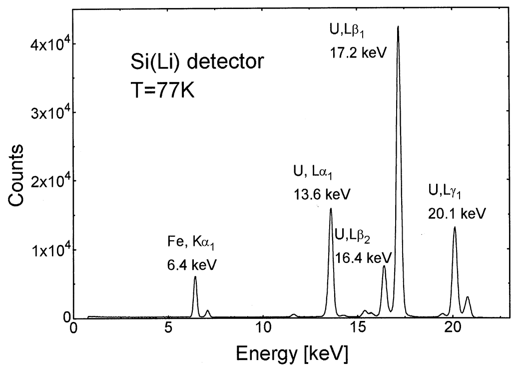

Fig. 5. Combined spectrum of ^{238}Pu radioactive source and Fe characteristic radiation measured with Si(Li) high-resolution spectrometer.

With the RX32N chip we can measure only the integral spectrum by scanning the discriminator threshold. The result of the differentiation of such a spectrum is the amplitude distribution. The results obtained with our chip connected to a pad detector working at room temperature is shown in Fig. 6. Comparing the spectra shown in Figs. 5 and 6 one can see that the noise performance of our system is significantly worse which is, however, not surprising given the fact that the spectrum in Fig. 5 was measured with a detector and electronics of a completely different class. In addition, the detector and front-end transistor for the case shown in Fig. 5 were cooled to liquid-nitrogen temperature and the spectrum was measured using a very long shaping time constant of 10 μs.

The sigma of noise obtained from the $U_L\beta_1$ line from Fig. 6 is 130 el rms, which is somewhat higher compared to the value obtained with the generator as shown in Table 1. The difference indicates that

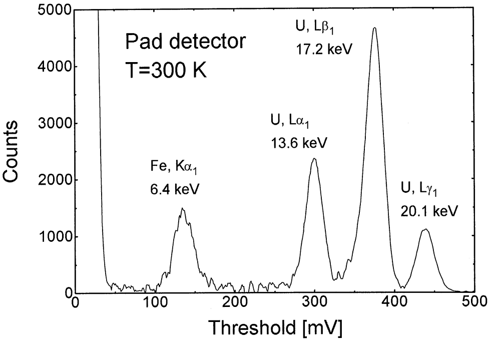

Fig. 6. Combined spectrum of ^{238}Pu radioactive source and Fe characteristic radiation measured with silicon diode array and RX32N chip.

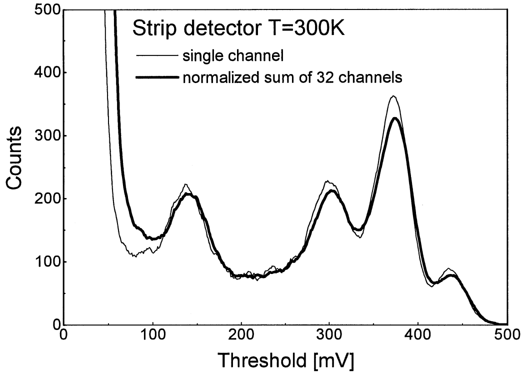

Fig. 7. Combined spectrum of ^{238}Pu radioactive source and Fe characteristic radiation measured with silicon strip and RX32N chip, measured on a single strip and summed from 32 strips measured simultaneously.

the scattering and edge effects are still not completely negligible in the case of 1 × 1 mm^2 area. Due to the different thickness of the Si(Li) and our detector, the detection efficiencies are also different. The effect is more relevant for higher energies and the relative intensities of the peaks of various energies are different for the two detectors, even if we keep the measurement geometry identical in both cases. The reduction of the height of the ^{238}Pu relative to the iron peaks is due to the reduction of the detection efficiency in the 300 μm thick detector.

Fig. 7. shows the spectrum for a single channel measured with the strip detector at room temperature and the summed spectra from 32 strips measured simultaneously with the RX32N chip using a common threshold for all channels. The higher FWHM of the peaks in Fig. 7 as compared to the ones from Fig. 6 can be explained by taking into account the parameters of the strip detectors and the results in Table 1. However, one can notice a general trend, that even for well-separated peaks like Fe and U, the peak-to-valley ratio is now smaller than in the case of the pad detector. This is due to the effect of charge division between neighbouring strips, which takes place for a fraction of the events. For a given X-ray energy, the spectrum of the charge collected on a single strip has a continuous tail extended towards low energies down to zero due to the events for which only a fraction of the charge generated in the silicon bulk is collected on the given strip. The effect does not degrade significantly the widths of the peaks since they contain mainly the events for which the total charge is collected on a single strip but we do observe a significant background which reduces the peak-to-valley ratios. The effect, although significant, is not harmful and for a spectrum like the one shown in Fig. 7, one can easily discriminate the Fe energy line of 6.4 keV. Another important observation is that the summed spectrum is not degraded compared to the single-strip spectrum, which confirms that the spread of the discriminator offsets is negligible compared to the noise.

5. Conclusions

We demonstrated the performance of the system for one-dimensional imaging for low-energy X-ray applications at room temperature. The uniformity of the presented multichannel system and its noise performance are satisfactory. The limitation due to charge division in silicon strip detectors is not negligible when the amount of generated charge in the detector is small, yet it allows effective operation of the system.

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