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Silicon Detector System for High Rate EXAFS Applications

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Abstract

A multichannel silicon pad detector for EXAFS (Extended X-ray Absorption Fine Structure) applications has been designed and built. The X-ray spectroscopic measurements demonstrate that an adequate energy resolution of 230 eV FWHM (corresponding to 27 rms electrons in silicon) can be achieved reliably at -35°C . A resolution of 190 eV FWHM (corresponding to 22 rms electrons) has been obtained from individual pads at -35°C . At room temperature (25°C) an average energy resolution of 380 eV FWHM is achieved and a resolution of 350 eV FWHM (41 rms electrons) is the best performance.

A simple cooling system constituted of Peltier cells is sufficient to reduce the reverse currents of the pads and their related shot noise contribution, in order to achieve resolutions better than 300 eV FWHM which is adequate for the EXAFS applications.

I. Introduction

A multi-detector system consisting of 100 silicon X-ray detectors together with low noise amplification has been proposed for EXAFS research [1]. In order to achieve high rate performance, $>10^6$ events/s, while retaining the moderate energy resolution required (300 eV FWHM dictating μs shaping times for input element capacities of a few pF) a system of 100 detectors operating in parallel must be considered. Silicon technology offers the capability of compact, easily fabricated arrays of detectors having sensitivity into the 15–20 keV energy range. To achieve low noise the first stage FET is often cooled to 120 K and is charge restored with optical feedback, however such systems are complicated, cumbersome, and give higher resolution than is necessary in this application which only requires the separation of a fluorescent X-ray peak from its elastically scattered partner, typically 600 eV higher in energy; thus 300 eV FWHM will be adequate.

The goal of this development is to achieve a simple, compact high rate system taking advantage of planar silicon technology to produce a high quality low leakage current array and the ‘resistorless’ Forward Bias FET charge amplifier [2] that yields the required resolution at or slightly below room temperature thus avoiding a system encumbered by liquid nitrogen cooling.

II. Description of the system

In Fig. 1 the detector lay-out is shown. It consists of 6 matrixes of 20 p-i-n diode detectors built on an ultra high purity, high resistivity $5 \text{ K}\Omega\cdot\text{cm}$, (1,1,1) n-type silicon wafer. The wafer thickness is $400 \mu\text{m}$. This silicon thickness provides detection efficiency $> 70\%$ over the important X-ray energy region 2–11 keV. Full depletion is obtained with a reverse bias voltage of 80 V. The p^+ collecting cathodes are surrounded by a p^+ guard structure used to reduce the fringing of the electric field lines nearby the detector edges and to sink out the surface currents [3]. Reverse currents ranging from 20 to 60 pA per pad, depending on the wafer quality, equivalent to $0.9\div 2.5 \text{ nA/cm}^2$, have been measured at room temperature (25°C). At -35°C the reverse currents drop to less than 2 pA per pad. The measured capacitance of each pad is about 1.2 pF at full depletion including the 0.5 pF pad-to-guard contribution. As the input capacitance of the adopted charge preamplifier (see later discussion) is 2.5 pF a good mismatch factor [4] of 1.46 is obtained, just 3.3% higher than the 2 value corresponding to the perfect matching case.

Fig. 2 shows a simplified schematic of the adopted low noise hybrid charge preamplifier. It is the recently proposed Forward Bias FET Amplifier (FBFA) [2] that does not need any feedback resistor or optoelectronic feedback to restore the charge accumulated on the feedback capacitor. The charge is restored through the gate to source junction of the input FET T1, which is slightly forward biased by means of the detector leakage current that feeds T1's gate. An additional low frequency feedback loop closed on T2's base is set by T3, R2, R3. It stabilizes the output dc level for a wide range of detector leakage currents. An extensive description of the preamplifier working principles can be found in ref. [2] and is not given here.

The feedback capacitor of 50 fF (C_F) provides a gain of 20mV/fC or $3.2 \mu\text{V}/\text{electron}$, giving an output signal amplitude of 8.8 mV for 10 keV X-rays. The input FET T1 is the commercially available *Interfet* NJ14. This device is available as a die which we have glued directly on the p^+ pad contact with conductive epoxy, realizing a direct electrical contact between the bottom gate of the FET and the detector cathode. This avoids an external connection between detector and preamplifier and minimizes the stray capacitance and the dielectric noise due to the connection itself [5,6]. Furthermore an eventual slight cooling of the detector, useful for reverse current reduction, involves a cooling of the FET itself as well, which increases the FET transconductance and improves its noise performance somewhat.

Hybrid custom designed unipolar gaussian amplifiers with a shaping time of $3 \mu\text{s}$ are used in operative conditions at -35°C . Tests at different shaping times have been performed with an Ortec 572 spectroscopy amplifier.

In Fig. 3 a block scheme of the multi-detector system is depicted. The gaussian shapers provide a slow output pulse set at the optimum shaping time ($3 \mu\text{s}$) for high resolution processing, and a fast output pulse with a peaking time of 150 ns for deadtime corrections. Single Channel Analyzers recognize the signals with amplitude in between a given voltage window. This permits selection of the fluorescence signals and rejection of the elastic

scattering signals. The scalars serve to count the number of events per unit time providing the fluorescence signals rate estimation. A switch matrix permits individual control and analysis of any single system channel, and a standard acquisition and histogramming procedure is used for gain calibration. The system control and calibration, and data computation are realized by means of a CPU unit. The most recently developed part of the system is the detector-preamplifier-shaper chain. The software tool, ADCs, DACs, and computer connections are extensively described in ref. [1].

A 20 channel X-ray spectrometer has been assembled and tested at room temperature and at $-35\text{ }^{\circ}\text{C}$. In Fig. 4 the front-end system assembly is sketched. The detector is mounted on a teflon board where thin copper leads are layed out to fan out the signals from the detector to the charge preamplifiers. Also the charge preamplifiers are layed out on teflon boards in order to reduce the dielectric losses and the related dielectric noise.

Peltier cells are present for optional cooling of detector and FETs down to $-10\text{ }^{\circ}\text{C} \div 35\text{ }^{\circ}\text{C}$. A single FET power consumption is 6 mW, resulting in a total power dissipation for the 20 pad array of about 120 mW. A water cooler is mounted on the upper copper base in order to improve the thermal dissipation efficiency from the Peltier cells to the environment external temperature. The system is operated in a vacuum chamber and a beryllium window is provided for radiation entrance.

III. Test of the system

The system has been tested with ^{55}Fe and ^{241}Am X-ray sources. In Fig. 5a and 5b the corresponding spectra obtained at $-35\text{ }^{\circ}\text{C}$ are plotted. A peak to low energy background ratio of ~ 300 is measured for the ^{55}Fe K_{α} peak. Table 1 summarizes the best energy resolutions evaluated on pulser peak. The performance achieved with a single larger pad is also reported.

The 20 pad array resolution is $380\text{ eV} \pm 30\text{ eV}$ FWHM at full room temperature ($25\text{ }^{\circ}\text{C}$) and $220\text{ eV} \pm 30\text{ eV}$ FWHM at $-35\text{ }^{\circ}\text{C}$. All of the pads in the array were satisfactory for low noise operation.

Equivalent Noise Charge (ENC) experimental values have been taken as a function of shaping time or total input capacitance. A set of different shaping times ranging from $0.5\text{ }\mu\text{s}$ to $10\text{ }\mu\text{s}$ was available in the Ortec 572 shaping amplifier, and total input capacities from 3.6 pF to 7.5 pF were set by varying the detector bias voltage and consequently the space charge depletion depth.

ENC vs shaping time T is fitted by the relationship [6]:

$$\text{ENC}^2 = k_1 \frac{1}{T} + k_2 + k_3 T \quad (1)$$

where k_1 , k_2 , and k_3 do not depend on T . The term k_1/T arises from the series white noise contribution, the term k_2 arises from the series '1/f noise' (f is the frequency) and the parallel 'f noise' (dielectric noise), and the term $k_3 T$ arises from the parallel white noise. The fitting to the ENC values is shown in Fig. 6 along with the 3 contribution described in (1).

As can be seen the parallel white noise is very low (less than 10 rms electrons for shaping times $< 3 \mu\text{s}$) because the detector leakage current is as low as 1.5 pA, and no feedback resistor is used. The dominant noise is given by k_2 , which accounts for the f -dependent noise contributions.

ENC vs total input capacitance C_t is fitted by the relationship [6]:

$$\text{ENC}^2 = h_1 C_t^2 + h_2 \quad (2)$$

where h_1 and h_2 do not depend on C_t . The term $h_1 C_t^2$ arises from the series noises (white and $1/f$), and the term h_2 arises from the parallel noises (white and f). The fitting to the ENC values vs C_t is shown in Fig. 7 for 3 different shaping times. As can be seen, h_2 can be estimated on the basis of (2) from the fitting curve value taken at $C_t = 0$. As the parallel white noise is expected to contribute less than 4 rms electrons for the considered shaping times, the overall parallel noise (20rms electrons) is dominated by the dielectric noise (parallel ‘ f noise’). This is the largest noise contribution affecting the system.

We can now reconsider the fitting of Fig. 6. The noise contribution given by k_2 (arising from the ‘ $1/f$ noise’ and the ‘ f noise’) is 22 rms electrons, just 10% more than the 20 rms electrons given by the dielectric noise alone. The series ‘ $1/f$ noise’ gives a contribution of a few rms electrons, consistent with the expected value¹. Thus a reduction of the dielectric noise would significantly improve the system performance. As the dielectric noise is originated by the dielectric losses in the feedback capacitor and in the cathode to guard capacitance ($\sim 0.5\text{pF}$ in this case), improvements will be possible in future, with better feedback capacitors and high quality oxides grown between cathodes and guard structure. Test arrays of 20 detectors with different pad to guard spacings are included on the periphery of this wafer for further optimization.

An important aspect of segmented detectors operation is the cross-talk phenomenon [4]. Two different types of cross-talk can affect the system. The first one, illustrated in Fig. 8, is due to the capacitive coupling (C_s) between the feedback connection and the the closest pad cathodes. This cross-talk effect involves a sign inversion at the preamplifier outputs. As the cross-talk intensity depends on the ratio C_s/C_f , C_s must be minimized by shielding the feedback connection.

The second one, illustrated in Fig. 9, is due to the direct capacitive coupling (C_p) between pads. As opposed to the former one, this cross-talk effect involves no sign inversion at the preamplifier outputs.

The measured cross-talk between adjacent channels observed at the shapers outputs is reported in Fig. 10. As it is a non inverting cross-talk, the dominant effect arises from the pad to pad coupling. For the 20 pad array it is equal to $2.6\% \pm 0.5$, which is adequate for the EXAFS applications.

¹The contribution to ENC of the series ‘ $1/f$ noise’ can be easily calculated for a given $1/f$ noise coefficient a_f [6]. For the NJ14 a_f is lower than $1 \times 10^{-14} \text{V}^2$.

IV. Conclusions

A 20 channel silicon detector system for EXAFS applications has been built and tested. When operated at -35°C by means of a simple Peltier cooler, the system energy resolution is adequate for the EXAFS applications. Further improvements in the wafer quality will permit very adequate operation at room temperature. The cross-talk effects are below 3%. Presently the maximum rate is limited to 2×10^5 events/s per detector. A significant increase of the maximum rate will thus be achieved with a 120 channel detector.

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Fig. 1.
Top view of the detector. The individual pad size is $1.5 \times 1.5 \text{ mm}^2$.

Fig. 2.
Forward Bias FET Charge Preamplifier

Fig. 3.
Block scheme of the system.

Fig. 4.
Front-end system assembly.

Fig. 5a.

Fig. 5b.

Fig. 5.

Fig. 5a ^{55}Fe spectrum at -35°C 3 μs shaping time.

Fig. 5b. ^{241}Am spectrum at -35°C . 3 μs shaping time.

Fig. 6.
Fitting to the ENC values vs T

Fig. 7.
Fitting to the ENC values vs C_t .

Fig. 8.
Feedback to pad cross-talk.

Fig. 9.

Pad to pad cross-talk. G is the direct transmission gain of the preamplifier

Fig. 10.
Measured cross-talk.

Table 1

Pad $15 \times 1.5\text{mm}^2$		Pad $2 \times 2\text{mm}^2$	
T= 25 °C	T= -35 °C	T= 25 °C	T= -35 °C
350 eV FWHM (41 rms el) 2 μs sh time	190 eV FWHM (22 rms el) 3 μs sh time	520 eV FWHM (61 rms el) 1 μs sh time	293 eV FWHM (34 rms el) 10 μs sh time