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Preamplifier-Shaper IC
for X-Ray Spectroscopy**

B. Krieger, I. Kipnis, and B.A. Ludewigt
Engineering Division

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B. Krieger, I. Kipnis, and B.A. Ludewigt

Engineering Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

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B. Krieger¹, I. Kipnis² and B. A. Ludewigt¹

¹Ernest Orlando Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

²Hewlett-Packard Company, 39201 Cherry Street, Newark, CA 94560

Abstract

An integrated circuit featuring 48 channels of charge-sensitive preamplifiers followed by variable-gain pulse shaping amplifiers is being developed as part of an x-ray spectrometer with a highly segmented detector to handle high fluxes in synchrotron experiments. Such detector systems can provide excellent energy resolution combined with one-dimensional spatial information.

The IC combines many basic spectroscopy amplifier functions with a low-noise preamplifier section to produce a unique circuit capable of driving conventional ADC modules directly. An important feature of the design is the novel CR-RC² pulse shaper. In this section, high-linearity transconductor circuits are required in order to provide a broad range of continuously variable peaking times while still maintaining the linearity and noise performance necessary for x-ray spectroscopy. Reported here are first measurements made on the performance of a 16-channel prototype integrated circuit.

At present, the preamplifier-shaper circuit achieves an equivalent input noise of 26 electrons rms at 2 μ s peaking time with a 0.2 pF external capacitor, which is similar to the capacitance of a single detector element. The design was fabricated in standard 1.2 μ m CMOS technology.¹

I. INTRODUCTION

An integrated circuit has been designed for the charge integration, pulse shaping and amplification of signals from a highly segmented silicon detector. This preamplifier-shaper IC for x-ray applications (XPS) uses an improved charge integration of the type used in [1] and is intended to drive CAMAC-based multi-channel A/D boards directly, which have been developed at the Lawrence Berkeley National Laboratory (LBNL) [2]. A spectrometer based on a multi-element silicon detector, the XPS IC, and multi-channel A/D boards will be used in very high count rate synchrotron x-ray fluorescence applications which require excellent energy resolution.

The integrated circuit with 100 μ m channel pitch is wire-bonded directly to the detector in order to minimize the noise. In addition to the low-noise preamplifier, the IC includes a high-linearity CR-RC² pulse shaper, programmable gain stages and a large signal output stage. This circuit eliminates the need for the discrete shaping amplifier modules required in earlier work [1, 3].

II. INTEGRATED CIRCUIT DESIGN

A. Performance Goals

The basic performance requirements of the XPS IC are as follows:

- (1) <20 electrons rms noise at 3 μ s peaking time with 0.2 pF external capacitance.
- (2) <1% non-linearity for an input charge range of 10:1, up to an absolute charge of 10,000 electrons rms, at 3 μ s and shorter peaking times.
- (3) Continuously variable peaking time range of 0.5 μ s to 8 μ s with CR-RC² shaping.
- (4) Charge gain of 100 mV/fC with variable gain stages ranging 20x – 800x to cover maximum input charges of up to 10,000 electrons.
- (5) Output stage capable of driving 100 pF of cable capacitance in parallel with 3 k Ω AC-coupled load at 2.5 V maximum output signal.

A block diagram of a single channel of the IC is shown in Figure 1. It includes a charge integrator with a pulsed feedback/continuous feedback switch and saturation indication output, 1x – 4x variable “front-end” gain switches at the CR stage input, RC sections with 2.25x overall gain, 1x:4x selectable “back-end” gain stage, and an AC-coupled 10x:20x gain output amplifier. The total power dissipation is ~10 mW/channel quiescent.

B. Design Considerations

To optimize the noise performance of the charge integrator, the input device capacitance was designed to match the sum of the detector, bonding pads, stray, and feedback capacitances estimated to be 0.6 pF total. The topology of the integrator circuit is essentially the same as that in [1], with an added pulsed reset option for better noise performance.

Beyond the stringent noise requirements placed on integrated circuits for spectroscopy applications, the high linearity (>99%) needed poses a particularly difficult and conflicting design goal for the integrated continuous-time filters that implement the pseudo-Gaussian pulse shaping function. In this application, the desire for a broad peaking time range of 0.5 μ s – 8 μ s makes meeting the linearity and noise requirements an even greater challenge. For instance, the standard differential pair transconductor that is often used in G_m-C filters achieves a non-linearity of <1% for only 28% of the gate overdrive voltage (i.e. 0.28 [V_{gs}-V_t]), resulting in a severely restricted dynamic range at the input [4]. Due to the quadratic dependence of the gate-overdrive voltage on the bias current, this limitation is exacerbated by the fact that the bias current in the transconductor must be decreased to produce longer peaking times. Finally, the noise performance of the filters also suffers at low G_m (long peaking times).

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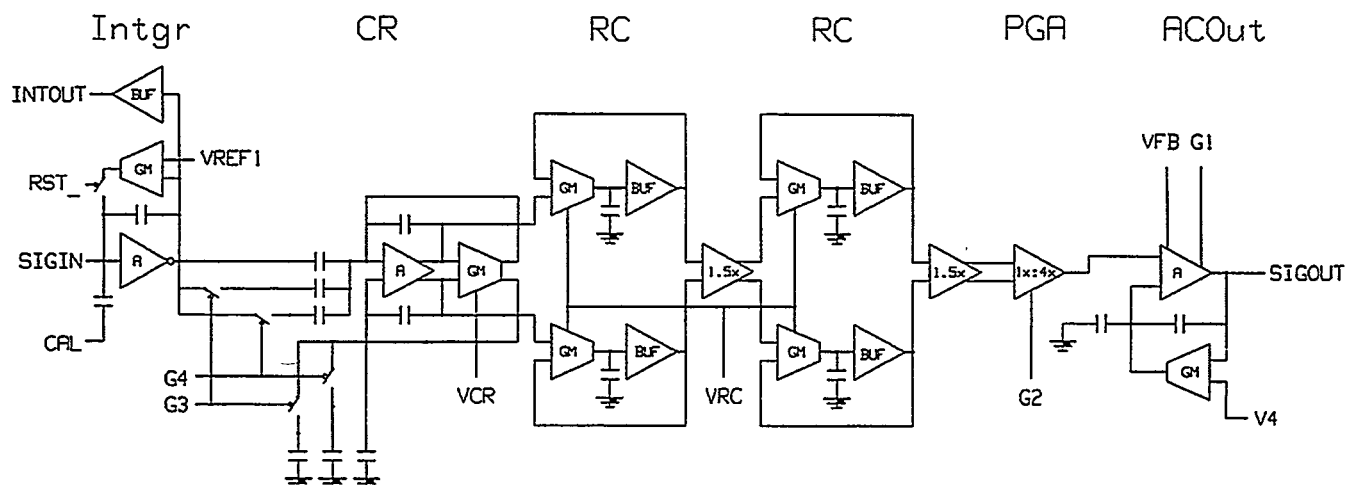


Figure 1: Block diagram of a single XPS channel.

Several design techniques have been developed to mitigate the linearity limitation discussed above [5, 6], making it possible to produce a tunable pulse shaper with sufficient linearity in integrated form. Two linear transconductor designs of particular interest for CMOS applications [4, 7] have been implemented in the CR and RC-RC sections of the XPS shaper, respectively. It is important to note that even with the use of an ideal transconductor, a 20-fold peaking time range requires a 400-fold bias current range for topologies based on the FET differential pair--this still poses a serious constraint on the input dynamic range at long peaking times (low bias current), and requires careful sizing and biasing of the input transistors for operation over a given transconductance and input voltage range.

To mitigate the effects of noise in the filter at long peaking times, additional gain beyond that of the charge integrator is necessary before the shaping section. A switchable gain has therefore been implemented to allow optimum noise performance for signals below 2500 electrons, while still maintaining the ability to handle full energy signals of 10,000 electrons with similar signal-to-noise ratio.

III. MEASUREMENTS

Noise, linearity, channel-to-channel variation, and spectrum measurements have been performed. Some performance characteristics for the sixteen channel prototype IC are summarized in Table 1. The measurements were performed at 2 μ s peaking time under the following nominal conditions: 4x front-end gain setting, 1x back-end gain setting, 10x final gain setting, dc-feedback integrator mode.

Table 1
Measured Characteristics of Prototype XPS IC

Input Coupling	< 0.6%
Ch-Ch gain variation	~2% s.d.
Ch-Ch variation in T _p	~3% s.d.
Power/Ch	~10 mW quiescent

For noise measurements, a charge pulse of 3000 el. was injected. A digital sampling oscilloscope was used with 256

waveform averages performed for each signal amplitude measurement at the output with a 30 pF cable load. The output noise was measured with an RMS voltmeter for the computation of equivalent input noise.

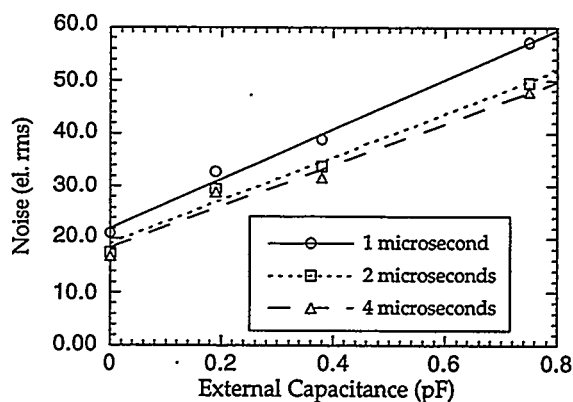


Figure 2: Noise vs. capacitance at 4x front-end and 1x back-end gain settings for various peaking times.

Figure 2 shows the noise performance of the XPS front-end for various peaking times as a function of external capacitance. At the nominal operating condition, 2 μ s peaking time with 0.2 pF external capacitance, the noise is approximately 26 electrons rms. This measurement is consistent with the 250 eV FWHM of the 5.9 keV peak in the ^{55}Fe spectrum shown in Figure 3. This spectrum was obtained with the XPS IC input wire-bonded to a silicon strip detector with a ~0.2 pF capacitance. The assembly was cooled to -5C and the spectrum was taken with 2 μ s peaking time.

For linearity measurements, input charges between 500 el. and 5000 el. were injected into a calibration capacitor at the channel input. The maximum non-linearity seen in Figure 4 is less than 0.2% over the entire input charge range at 2 μ s peaking time. However, the uncertainty in the measurements is approximately $\pm 0.5\%$. The data indicate that the measurement precision is likely much better, and clearly demonstrate that the linearity requirement is exceeded. Increased non-linearity is expected for longer peaking times at larger input charges due to the lower operating I_d of the

transconductor circuits in the shaping section. This condition leads to a restricted dynamic range in these circuits as discussed previously.

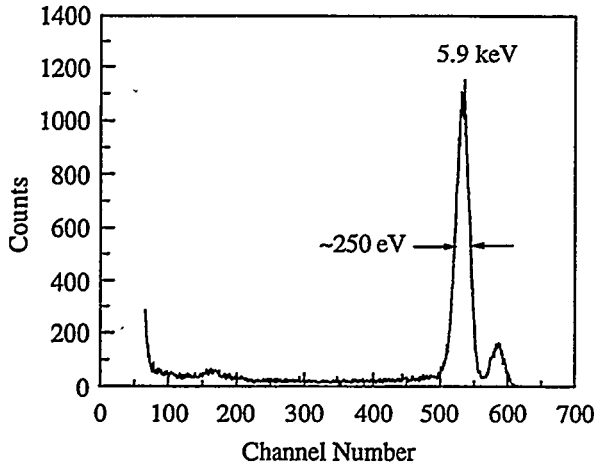


Figure 3: ^{55}Fe spectrum measured with the XPS IC.

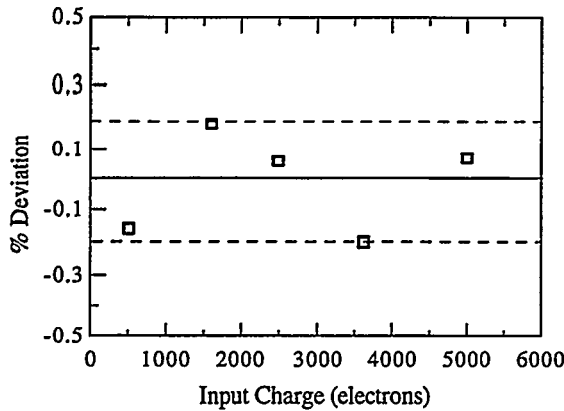


Figure 4: Non-linearity in % measured for input charges between 500 el. and 5000 el. for 2 μs peaking time.

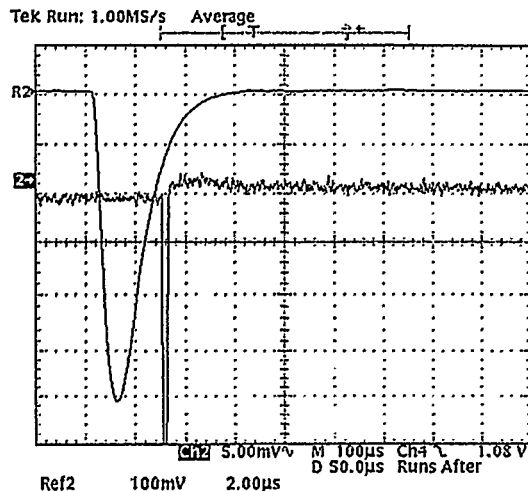


Figure 5: Output pulse shape as full waveform ("R2") and expanded in amplitude and compressed in time ("2").

Finally, Figure 5 shows a 1 μs shaped output pulse (trace "R2") along with a version greatly expanded in amplitude and compressed in time (trace "2"). This plot demonstrates the

capability of the AC-coupled output stage to operate with no significant post-shaping differentiation of the pulse. Note: the measurement was taken in the dc-feedback integrator mode which has no pole-zero-compensation.

IV. CONCLUSIONS

An IC has been developed and tested which combines a low-noise charge-sensitive preamplifier with a CR-RC² pulse shaper, providing variable peaking times and high-linearity over a wide range of input charges, variable gain stages and a large signal output stage. While the noise performance and linearity goals of the shaping section have largely been realized for mid-range peaking times, improvements will be implemented in some areas. First, for peaking times at and above 4 μs there is excessive channel-to-channel variation in both gain and peaking time. Design modifications to the shaper section, possibly to include a binary capacitor array, should greatly enhance the useable peaking time range towards the 0.5 μs - 8 μs goal or beyond. Second, improvement of the noise performance to attain 20 electrons rms with 0.2 pF detector capacitance is anticipated with some modification of the front-end circuits. Finally, although the input coupling is quite low, significant load-dependent input-output coupling was observed. It is expected that a more careful review of the PCB and/or IC layout will eliminate this effect.

The XPS prototype IC described in this paper is capable of driving a CAMAC based multi-channel ADC board directly, and replaces costly discrete shaping amplifiers in the intended x-ray fluorescence application. The XPS IC also represents a significant step towards a general-purpose integrated spectroscopy amplifier.

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