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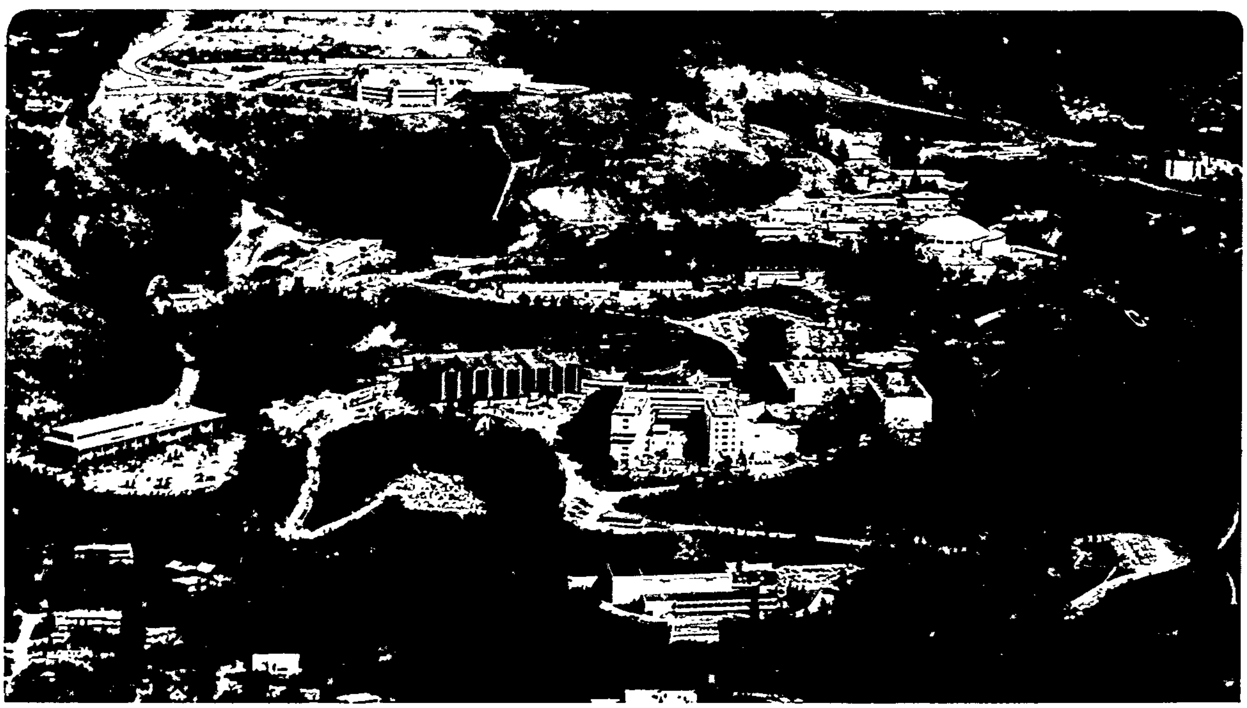

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Progress in Multi-Element Silicon Detectors for Synchrotron XRF Applications

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Abstract

Multi-element silicon strip detectors, in conjunction with integrated circuit pulse-processing electronics, offer an attractive alternative to conventional lithium-drifted silicon and high purity germanium detectors for high count rate, low noise synchrotron x-ray fluorescence applications. We have been developing these types of detectors specifically for low noise synchrotron applications, such as extended x-ray absorption fine structure spectroscopy, microprobe x-ray fluorescence and total reflection x-ray fluorescence. The current version of the 192-element detector and integrated circuit preamplifier, cooled to -25°C with a single-stage thermoelectric cooler, achieves an energy resolution of <200 eV full width of half maximum (FWHM) per channel (at 5.9 keV, 2 μs peaking time), and each detector element is designed to handle ~20 kHz count rate. The detector system will soon be completed to 64 channels using new application specific integrated circuit (ASIC) amplifier chips, new CAMAC (Computer Automated Measurement and Control standard) analog-to-digital converters recently developed at Lawrence Berkeley National Laboratory (LBNL), CAMAC histogramming modules, and Macintosh-based data acquisition software. We report on the characteristics of this detector system, and the work in progress towards the next generation system.

I. INTRODUCTION

Many synchrotron x-ray fluorescence (XRF) experiments have exceeded the performance limits of commercially available detectors and could greatly benefit from improved detector instrumentation [1,2]. These detectors must offer both excellent energy resolution and high count rate capability, in order to exploit the recent advances in synchrotron radiation produced by the new synchrotrons, such as the Advanced Light Source at LBNL and the Advanced Photon Source at Argonne National Laboratory. High purity germanium and lithium-drifted silicon detectors, cooled to liquid nitrogen temperatures and coupled with conventional low noise pulse-processing electronics, provide excellent energy resolution, but limited count rate capability. These types of detectors can be multiplied into arrays to increase the overall count rate performance, but detector arrays with more than approximately 20 elements, constructed using conventional technology, become very expensive and often impractical. High resistivity silicon detector arrays, fabricated with hundreds of elements on a single substrate, coupled with low noise integrated circuit pulse-processing electronics, offer an attractive alternative to conventional detector technologies for synchrotron XRF applications.

In pursuit of the goal of low noise, high count rate XRF detectors, we have been developing multi-element silicon detectors using photolithographic processing techniques, and the associated low noise pulse-processing electronics using ASIC chips. The first results were achieved using a silicon strip detector and an integrated circuit (IC) preamplifier and have been reported previously [3]. The detector and preamplifier have since been redesigned and optimized to achieve lower noise performance, and the results are reported in the following section: "Detector Tests".

The pulse-processing electronics have been further optimized by extending the preamplifier chip into a complete amplifier. A new analog to digital converter (ADC) has been designed and built in the CAMAC format. The detector system includes full data acquisition in a Macintosh-based environment, and is described in the section: "XRF Spectrometer". Sixty-four channels of this system will be fully functioning and will be tested in the Spring of 1996. Additional changes and plans to complete the spectrometer to its full 192 channels with all pulse-processing electronics based on ASICs are also discussed.

II. DETECTOR TESTS

In order to improve the energy resolution from the initial 350 eV FWHM [3] to the goal of <200 eV FWHM, several modifications were made to the detector geometry and to the IC preamplifier. The detector capacitance and leakage current were reduced by decreasing the detector strip length to 2 mm. A high pitch (100 μm) to width (10 μm) ratio was chosen to minimize the interstrip capacitance. The detector cross-section is shown in Figure 1. The detector strips were arranged in two rows of 100 strips each. Each strip had a leakage current of ~5 pA at room temperature (~3 nA/cm^2), and a capacitance of 0.2 pF. Figure 2 is a photograph of several detector strips wire-bonded to the preamplifier chip.

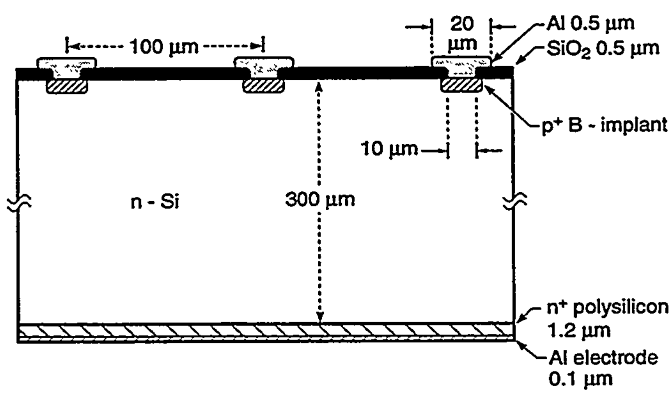

Figure 1. Cross-section of silicon array detector.

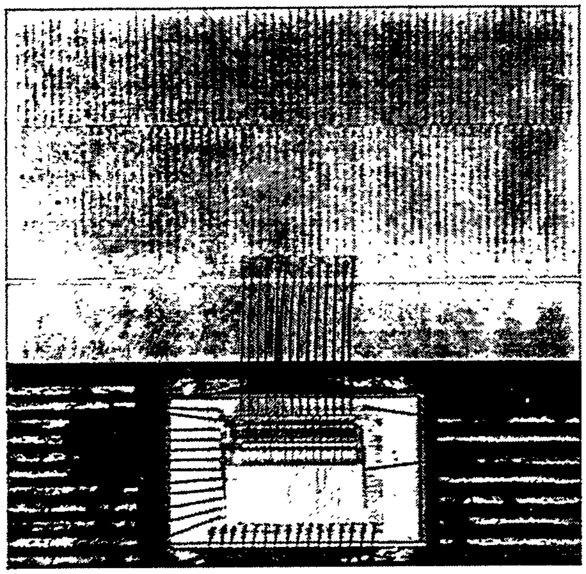

Figure 2. Photograph of several detector strips wire-bonded to the 16-channel preamplifier chip.

The 16-channel preamplifier, a modified version of the one described in [3], was fabricated using a standard 1.2 micron CMOS (Complimentary Metal Oxide Silicon) technology. Each channel contains a low noise, high gain charge-sensitive preamplifier followed by a simple active filter that provides a variable CR-RC shaping function. The integrator is configured as a single stage common-source cascode amplifier with a cascode active load. The size of the input transistor was optimized to match the sum of the detector, bonding pads, stray and feedback capacitances. The gate length of 1.2 μm and gate width of 150 μm results in a capacitance of 0.2 pF. The feedback network introduces a differentiation with a variable time constant and is externally controlled via a current mirror common to all channels. The shaper amplifier circuit is similar to the integrator with rise and fall times externally controlled via current mirrors common to all channels, resulting in a variable shaping time from 500 ns to 50 μs. The two amplification stages on the chip provide a gain of 200 mV/1000 electron step response.

The detector and preamplifier chip were tested using conventional NIM-based (Nuclear Instruments and Methods standard) low noise amplifiers, an 8-channel CAMAC ADC and data acquisition software using a Macintosh computer. In this manner, several channels could be tested at one time and coincidence measurements could be performed on neighboring strips to determine the charge sharing characteristics. Figure 3 shows the system noise as a function of amplifier peaking time, at -25°C. At <1 μs peaking time, the noise is dominated by the preamplifier's equivalent noise voltage. At longer peaking times, the shot noise contribution of the detector leakage current begins to dominate, resulting in the minimum noise occurring between 2 μs and 4 μs.

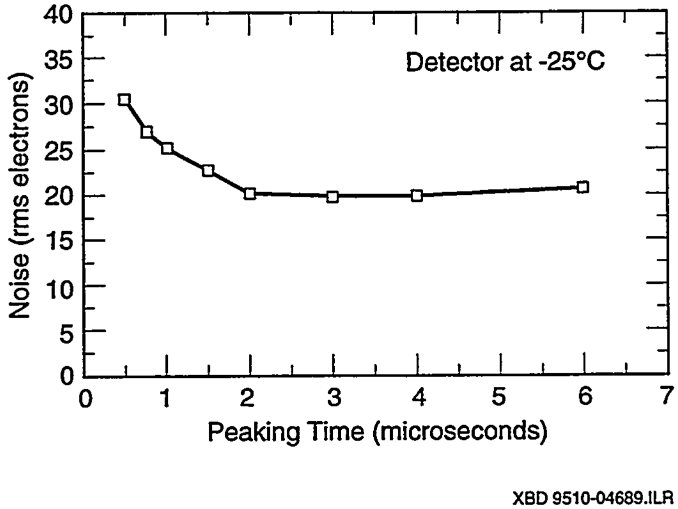

Figure 3. System noise as a function of amplifier peaking time, detector and preamplifier at -25°C.

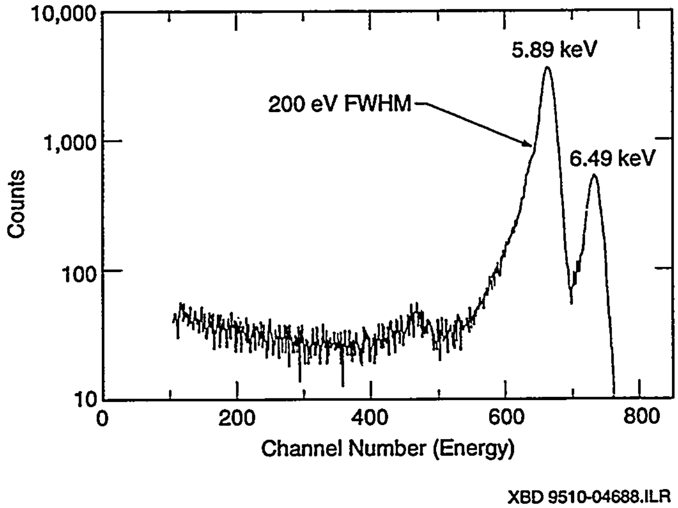

Figure 4. Spectral response of detector to ^{55}Fe (-25 °C, 2 μs peaking time).

Figure 4 shows the spectral response of a single detector strip to an ^{55}Fe source (all strips showed virtually the same response). The Mn K_α and K_β peaks at 5.9 and 6.5 keV are clearly resolved, with an energy resolution of ~200 eV FWHM (-25°C, 2 μs peaking time). Figure 5 shows the spectral response to a ^{109}Cd source. The spectra from this detector compare well with standard, low noise Si(Li) detectors, with the following exceptions: There is a slight broadening of the photopeak on the low energy side of the 5.9 keV photopeak, and the background below the photopeak is approximately 15 times higher than in a typical Si(Li) detector. The background intensity decreases with increasing bias voltage, and varies significantly with position on the detector. The counts in the background below the photopeak originate, in this case, from predominantly two sources: charge *loss* and charge *sharing*. Charge loss occurs when a portion of the electron-hole pairs created from an absorbed photon is not collected at all, and the signal measured is a reduced value from the full photon value. Charge loss can occur from charge trapping at surfaces, recombination of charge before it reaches the signal electrodes, slow drift times compared to the signal processing times, and a variety of other insignificant energy loss mechanisms [4]. Charge sharing, on the otherhand, can occur when there is no charge loss, but the total number of electron-hole pairs from an absorbed photon are shared among neighboring strips, resulting in a reduced signal on each of the strips.

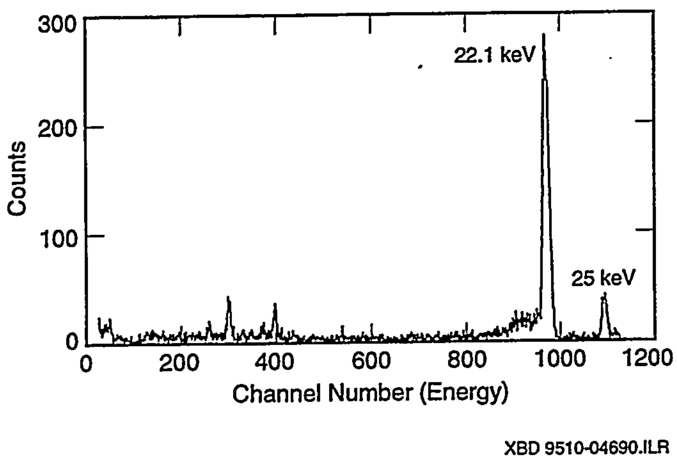

Figure 5. Spectral response of detector to ^{109}Cd (-25 °C, 2 μs peaking time). Lower energy peaks are from fluorescence of the steel collimator in front of the detector.

The extent of charge sharing was measured by collecting only those signals on adjacent strips which occurred in coincidence. These measurements showed that less than 3% of all events from the 5.9 keV photons from an ^{55}Fe source in one strip also produced a signal in an adjacent strip. As the photon energy increased, the number of shared events also increased, and was measured to be ~10 % for the 22 keV x-rays from a ^{109}Cd source. Thus, the charge *sharing* measured by the coincidence measurements was only a small fraction of the total number of counts occurring in the spectral background, while the majority of counts in the spectral background could be attributed to charge *loss*.

We assumed that the most likely candidates for charge loss were recombination of charge at the oxide/substrate interface between the electrode strips and/or weak field regions between the strips. A systematic exploration of detector spectral response, versus x-ray position on the detector surface, was performed using a 5 μm diameter x-ray probe beam generated from the Microprobe Beamline at the Advance Light Source synchrotron. These measurements showed that the charge collection and spectral response from photons absorbed directly on the detector strips were excellent, while the charge collection of photons absorbed in between detector strips was significantly degraded. Subsequent computer simulations of the detector show that the regions in between the strips contain undepleted regions, high electron concentrations and flat equipotential dstribution, all of which could lead to the poor charge collection observed. These issues, and the results from computer simulations of other possible detector geometries, will be discussed in a subsequent publication, as they are beyond the scope of this paper. Future design iterations of the detector will attempt to address the charge loss problem.

III. XRF SPECTROMETER

A fully parallel, 64-channel detector system is being constructed for use in synchrotron XRF experiments. The detector will be a modified version of the previous one discussed above, but will have essentially the same topological layout and overall dimensions. Modifications to the detector will include processing changes and additional structural elements on the detector designed to reduce the extent of the charge collection problems, and hence improve the peak/background performance of the detector. The energy resolution will remain at <200 eV FWHM per channel.

The preamplifier chip discussed in the previous section has been redesigned to include a shaping amplifier with variable gain settings and the capability to drive CAMAC based ADCs. The design of the amplifier chip is similar to the previous one with the following significant modifications and additions: It features 48-channels on a 100 μm pitch. The dc-feedback has been replaced with a pulsed feedback for better noise performance. An output line for saturation indication has been added and the reset pulse is initiated by an outside circuit. Three bits are provided for variable gain settings (2V output for 10^4 electrons at minimum gain). The shaper features CR - $(RC)^2$ pulse shaping for continuously varying peaking times from 0.5 μs to 10 μs and a rise-time to fall-time ratio of about 2/5. The power consumption is less than 20 mW/channel. Figure 6 is a block diagram of one channel.

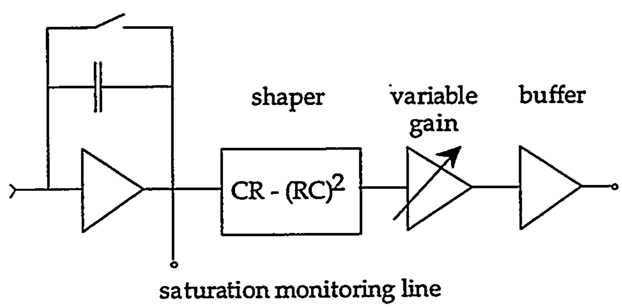

Figure 6. Block diagram of one channel of the 48-channel amplifier circuit.

A new CAMAC-based ADC has been designed and built at LBNL specifically for parallel data processing of high count rate signals, such as are encountered in the synchrotron. applications targeted here. There are 16 ADC channels (not multiplexed) per single width CAMAC module. The peak-sensing, self-gating ADC's have an adjustable peak acquisition time between 0.5 and 8 μs and digitizing time of 8 μs [5]. The digital signals are transferred through a FERA bus (Fast Encoding and Readout ADC) to the CAMAC histogramming memories, and the histograms are collected using KMAX software (trade name of computer software by Sparrow, Corp.) in a Macintosh environment.

The 64-channel spectrometer will consist of a strip detector, amplifier IC chips, four 16-channel CAMAC ADC's, two 32-channel CAMAC histogramming modules, KMAX software and a Macintosh personal computer.

IV. CONCLUSIONS

We have developed and tested a multi-element silicon x-ray detector, with a low noise integrated circuit preamplifier chip, which achieves <200 eV FWHM per channel (at 5.9 keV, -25 °C, 2 μs peaking time). The detector and electronics are designed to handle ~ 20 kHz per channel, such that the total count rate will be dependent only on the number of channels. A 64-channel spectrometer will be built using the strip detector, new amplifier IC chip, new CAMAC ADC's, and Macintosh-based data acquisition software and will be demonstrated in a synchrotron EXAFS experiment in the Spring of 1996. Further design iterations of the spectrometer will include complete integrated circuit pulse-processing electronics and an expansion to 192-channels.

V. REFERENCES

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VI. ACKNOWLEDGMENT/DISCLAIMER

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