Preprint
UCRL-JC-151987

Digital Signal Processors for Cryogenic High-Resolution X-Ray Detector Readout

S. Friedrich, O. Drury, S. Bechstein, W. Henning, M. Momayezi

This article was submitted to
Extreme Optics and Sensors (EDS 2003) Workshop, Tokyo, Japan,
January 14-17, 2003

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

January 1, 2003

Digital Signal Processors for Cryogenic High-Resolution X-Ray Detector Readout

Stephan FRIEDRICH, Owen B. DRURY
Advanced Detector Group, Lawrence Livermore National Laboratory, 7000 East Ave., L-270, Livermore, CA 94550, U.S.A.
friedrich1@llnl.gov
Sylke BECHSTEIN
Physikalisch-Technische Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin, Germany
Wolfgang HENNIG, Michael MOMAYEZI
X-ray Instrumentation Associates, 8450 Central Ave, Newark, CA 94560, U.S.A.

Abstract

We are developing fast digital signal processors (DSPs) to read out superconducting high-resolution X-ray detectors with on-line pulse processing. For superconducting tunnel junction (STJ) detector read-out, the DSPs offer on-line filtering, rise time discrimination and pile-up rejection. Compared to analog pulse processing, DSP readout somewhat degrades the detector resolution, but improves the spectral purity of the detector response. We discuss DSP performance with our 9-channel STJ array for synchrotron-based high-resolution X-ray spectroscopy.

1. Introduction

Superconducting tunnel junctions (STJ) are fast high-resolution X-ray detectors with broadband efficiency for X-rays up to 10 keV [12]. Over the last two decades, they have received wide attention for high-resolution spectrometry in astrophysics [11, 13, 14], biophysics [3] and material science [1, 8, 9]. STJs consist of two superconducting electrodes separated by a thin insulating tunnel barrier. Their operation as X-ray detectors is based on measuring the excess tunneling current produced when X-rays absorbed in one of the electrodes create excess charges in proportion to the X-ray energy [9].

The Advanced Detector Group at Lawrence Livermore National Laboratory is developing STJ detectors for high-resolution X-ray spectroscopy in biophysics, material science, astrophysics and national security applications. We currently use 3×3 arrays of vertically stacked Nb-Al-AlOx-Al-Nb STJs with 165 nm Nb absorbers, 50 to 200 nm Al traps and 265 nm bottom Nb electrodes. These STJs have achieved an energy resolution below 10 eV for X-ray energies up to 1 keV [10], and can be operated at count rates above 10,000 counts/s per pixel [2]. However, vertically stacked junctions, while allowing fast detector operation, are affected by artifacts that arise whenever X-rays are transmitted through the top absorber film and are absorbed in the bottom electrode or in the substrate. Since events from the bottom electrode or the substrate have a slightly different response function, they produce signals of different magnitude, thereby degrading the resolution or leading to a line-splitting artifact [2, 5] (figure 1).

One solution to avoid line splitting and substrate artifacts is to use higher-Z absorber materials like Pb for more efficient absorption in the top film [1]. Another solution, which is the one we are pursuing here, is to separate top and bottom layer events based on the rise time differences of their waveforms (figure 1). For this we have designed a fast digital signal processor (DSP) that provides online event discrimination to improve the spectral response of STJ detectors. Here, we present a data acquired with this DSP system and discuss its performance for high-resolution X-ray spectrometry.

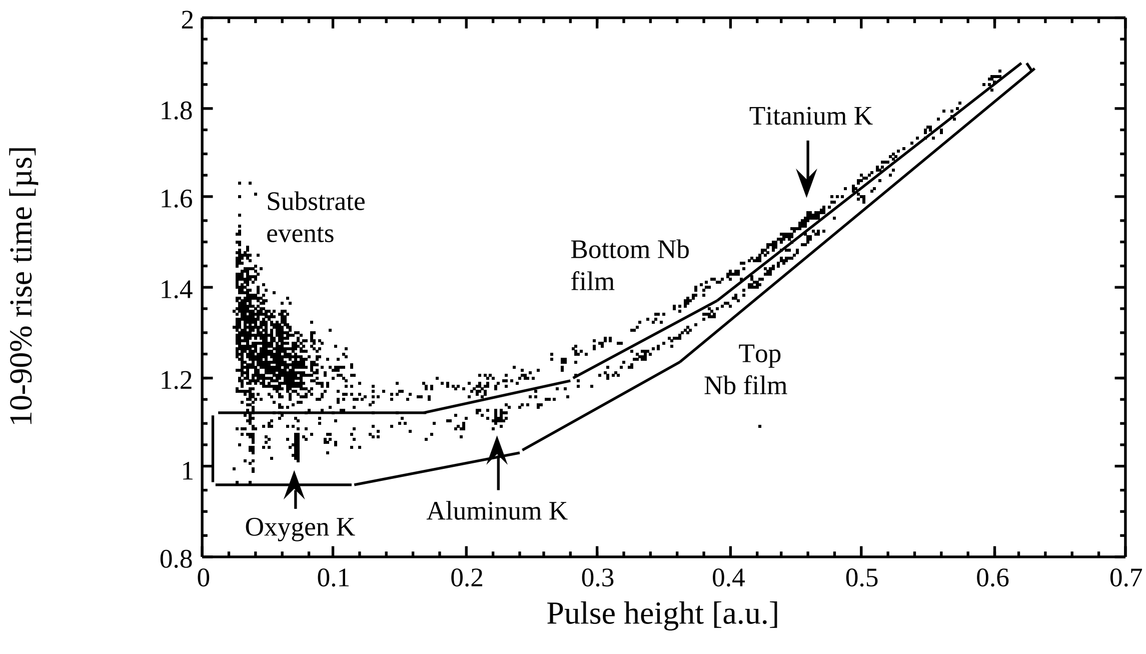

Figure 1: Scatter plot of pulse height vs. rise time for 2000 X-rays from a TiO_2 fluorescence target on an Al target holder. The two bands correspond to absorption in the top and the bottom Nb electrode. The wide distribution of events at low energy and long rise time are due to substrate events. The polygon encloses the region of events from the top Nb electrode only.

2. Digital Signal Processor Design

The DSPs used in the experiments here are based on the Digital Gamma Finder (DGF) DSP series by X-ray Instrumentation Associates originally developed to read out conventional germanium detectors [7]. The DGF is a 4-channel all-digital waveform acquisition and spectrometer card based on the CAMAC standard, which accepts signals directly from the detector's preamplifier. After an analog signal conditioning stage, incoming waveforms are digitized by a 14-bit 40 MSamples/second analog-to-digital converter. Triggering, pile-up inspection and digital "box-car average" filtering of the data stream is performed in real time in a field-programmable gate array (FPGA). Digitized waveforms of up to 100 µs in length for each event can be stored in a first-in-first-out (FIFO) register. When a trigger occurs, an on-board DSP microcomputer reads out the data, reconstructs the pulse height from the difference in signal levels before and after the trigger event, and increments a 32k multi-channel analyzer (MCA) spectrum. Waveforms, pulse heights, and timestamps can be stored in memory and read out by a host PC for off-line analysis.

For STJ read-out, the preamplifier output signals are used by the DSP microcomputer to perform pulse shape analysis on-line. For each pulse waveform, the pulse height and the 10-90 % signal rise time are calculated. The host software then produces a scatter plot of pulse height vs. rise time, in which the user can define an acceptance window as an arbitrary polygon with up to 50 corner points as shown in figure 1. During acquisition, each pulse is subsequently checked if it falls into this user-defined acceptance window of pulse height and rise time. If not, the event is discarded. This removes not only events that originate from X-ray absorption in the bottom Nb electrode and the Si substrate, but also greatly reduces pile-up in high count-rate applications.

The data discussed here were acquired using waveforms 5 µs long with a pre-trigger delay of 2 µs. The peaking time was 3 µs and a gap time, i.e. the time before and after the trigger event used for pulse height evaluation, was 2 µs. The decay time parameter (equivalent to a pole-zero cancellation in analog systems) was 2.86 µs.

3. Results and Discussion

X-ray fluorescence experiments are performed at beam line 4.0.2 at the Advanced Light Source synchrotron at Lawrence Berkeley National Laboratory [6]. X-ray current signals (~1 nA/10 eV) are captured with a custom-designed lownoise preamplifier with an FET input stage at room temperature [4]. The preamplifier output is fed directly into the DSP for digitization, pulse shaping, event discrimination and spectral analysis. For comparison with our previous setup, we repeat the experiment with the DSP replaced by a Canberra 2026 analog shaping amplifier with 3 µs shaping time and a Canberra 8715 analog-to-digital converter read out from a DEC Alpha workstation. Details of the experimental setup have been published [2, 6].

The STJ response function from an Al_2O_3 sample for excitation at 800 eV is shown in figure 2. Almost all fluorescence is due to the oxygen K line at 525 eV. The acquisition time was only ~4 seconds at a rate of ~5000 counts/s, and the resolution at 525 eV is ~20 eV with the DSP read-out (figure 2, dotted line). At a comparable count rate, the resolution of this 200 µm × 200 µm detector at 525 eV is ~17 eV FWHM with the analog data acquisition system. The difference is due to the fact that trapezoidal shaping developed for step-like Ge-detector pulse shapes is not ideal for processing STJ pulses, whose fall time of around 3 µs is much shorter. However, it is not straightforward to implement a Gaussian or an optimal filter for on-line pulse processing with the present FPGA processors with-

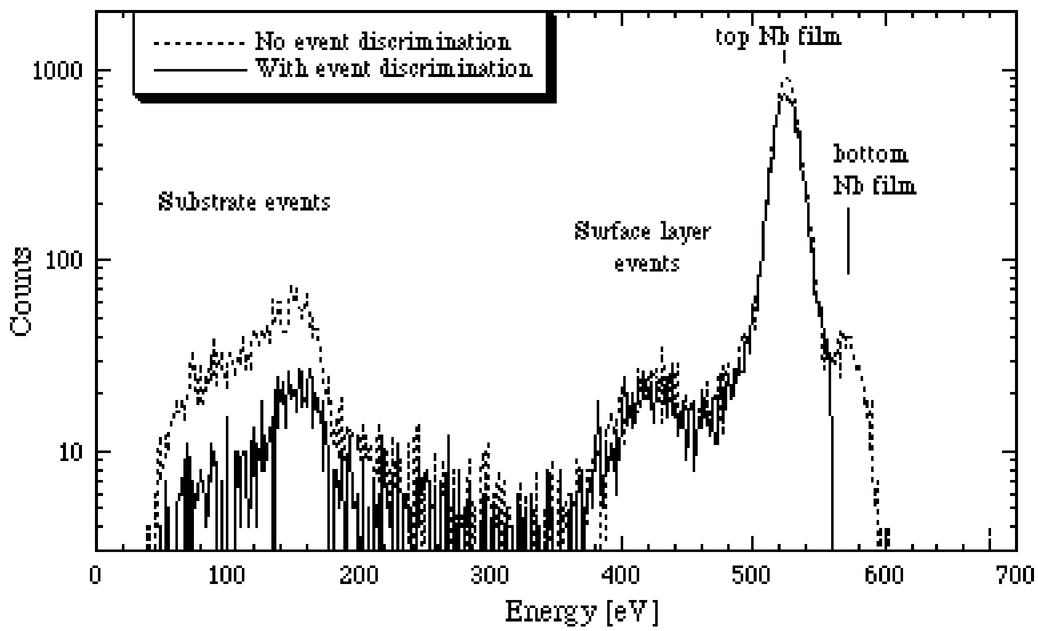

Figure 2: Fluorescence spectrum of Al_2O_3 at an excitation energy of 800 eV taken with the DSP at a rate of ~5000 counts/s. The response function of the 200 µm × 200 m µm STJ (dotted line) can be improved by on-line event discrimination against bottom layer and substrate events based on rise time differences (solid line). The total acquisition time was only 3.9 s.

out slowing down the acquisition rate. We therefore trade off some resolution for high count rate capability and improved spectral response. While future digital filters in the DSP read-out might improve the detector resolution to match or even exceed the performance with analog read-out, a resolution of ~20 eV FWHM is entirely sufficient for many synchrotron applications, as long as the count rate capabilities are not compromised.

There are two types of artifacts in the STJ response. First, while most of the 525 eV X-rays are absorbed in the top Nb film, about 5% are absorbed in the bottom Nb film. These events produce a different response and cause an additional peak in the spectrum at ~570 eV. Second, X-rays absorbed to the side or under the STJ in the Si substrate create phonon-mediated signals in the spectrum below ~200 eV. The signals are smaller because of the finite phonon transmission from the Si substrate into the Nb base film, and they have long rise times since phonon velocities are low. While it is always possible to use masks and block X-ray absorption next to the STJ, substrate events below the STJ cannot be eliminated this way and cause increased artifacts at higher energies.

Figure 2 also shows how on-line pulse processing with DSPs can improve the spectral purity of the response function if only absorption events from the top Nb film are captured (solid line). This discrimination relies on the longer rise time of pulses absorbed in the substrate and the bottom Nb film. Rise-time discrimination greatly suppresses the number of substrate events, and eliminates absorption events from the bottom Nb film. The spectra illustrate how improved spectral response allows the analysis of elements whose fluorescence would otherwise be obscured by artifacts. For instance, L-edge spectroscopy of dilute chromium-containing specimens, most of which contain oxygen, would not be possible with our current spectrometers without DSPs, since the weak Cr L fluorescence at 573 and 583 eV falls into the energy range of the artifact from oxygen X-rays absorbed in the bottom Nb film. Obviously, in cases where the line splitting artifact does not do any harm, one would not want limit the efficiency by only considering X-rays from the top Nb film. In such cases it is possible to calibrate events from the top and bottom Nb film separately and subsequently add the partial spectra off-line.

Data acquisition rates up to ~5,000 counts/s per STJ channel are typical for experiments with our spectrometer at third-generation synchrotron beam lines. We have shown that the DSPs used here can operate at these rates. We have not yet systematically tested DSP performance at higher rates. However, these DSPs were developed to read out conventional germanium detectors at >500,000 counts/s, so we have no reason to believe that DSP readout speed would limit the STJ performance at any point [7]. In fact, DSPs might turn out to extend the range of STJ operation to count rates or order 100,000 counts/s per channel. This is because DSPs measure pulse heights as the difference between signal levels before and after a trigger event, and therefore –in contrast to analog shaping amplifiers- do not require pulse waveforms to decay to zero before accepting the next signal pulse. Future experiments will quantify these gains, and the trade-offs involved in optimizing DSP performance.

4. Summary

We have implemented digital signal processor (DSP) read-out for superconducting high-resolution X-ray detectors. We have demonstrated that DSPs can perform on-line event discrimination at ~5000 counts/s to reduce artifacts in the detector response due to pile-up and due to photon absorption in the bottom electrode and the substrate. We expect DSPs to also perform well at higher rates. While the detector resolution is reduced slightly (~20 eV FWHM at 525 eV) compared to the conventional analog pulse shaping (~17 eV) because the DSP's fast digital filter is not ideal for fast-decaying waveforms, this is not a limitation for many synchrotron-based applications. Scaling to large numbers of detectors for increased spectrometer sensitivity is straightforward.

5. Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

6. References

1. Angloher G. et al. 2001, J. Appl. Phys. 89, 1425
2. Frank M. et al. 1998, Rev. Sci. Inst. 69, 25
3. Frank M. et al. 1999, Mass Spec. Rev. 18, 1555
4. Friedrich S. et al. 1997, IEEE Trans. Appl. Superconductivity 7, 3383
5. Friedrich S. et al 2001 (a), IEEE Trans. Appl. Superconductivity 11, 836
6. Friedrich S. et al. 2001 (b), Nucl. Inst. Meth. A 447-448, 1117
7. Hubbard-Nelson B., Momayezi M., Warburton W.K. 1999, Nucl. Inst. Meth. A422, 411; see also http://www.xia.com.
8. Katagiri M. et al. 2002, AIP Proceedings 605, 177

9. Kurakado M. 1982, Nucl. Inst. Meth. 196, 275
10. le Grand J.B. et al. 1998, Appl. Phys. Lett. 73, 1295
11. Li L. et al 2001, J. Appl. Phys. 90, 3645
12. LTD-9: For a recent overview of the field of cryogenic X-ray detectors, see "Proceedings of the 9th International Workshop on Low Temperature Detectors", AIP Conference Proceedings 605, eds. Porter F.S., McCammon D., Galeazzi M., Stahle C.K., Eds. (2002)
13. Mears C.A., Labov S.E., Barfknecht A.T. 1993, Appl. Phys. Lett. 63, 2961
14. Verhoeve P. et al. 1998, Appl. Phys. Lett. 72, 3359