Maia X-ray Microprobe Detector Array System

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Abstract. Maia is an advanced system designed specifically for scanning x-ray fluorescence microprobe applications. It consists of a large array of photodiode detectors and associated signal processing, closely coupled to an FPGA-based control and analysis system. In this paper we will describe the architecture and construction of the system.

1. Introduction

As x-ray sources become more powerful, the fluorescence detector is increasingly the system bottleneck in x-ray microprobe systems. Maia addresses this by providing a very large array of small detectors and adopting a novel data acquisition and analysis strategy. Most present microprobe systems either do 'step-and-acquire' measurements, acquiring an energy spectrum from a commercial detector at each image pixel. This is very slow, taking many hours of scanning to acquire even small images. Another common technique is to set spectral energy windows (regions of interest, ROI) and make continuous raster scans. This is fast, but prone to misidentification of elements due to emission line overlaps. Maia provides the best of both methods, i.e. full spectra and fast acquisition, by acquiring data photon-by-photon in streaming mode, and developing elemental maps in real time using a novel analysis method, Dynamic Analysis [1, 2], and using on-the-fly scanning. This requires custom detectors and a novel readout / processing scheme.
2. Architecture
Maia has five major components:

1. A sensor array of 384 diodes, each 1 mm x 1 mm, built on high-resistivity silicon, 400μm thick, arranged symmetrically around a central 2.4 mm diameter hole.

2. An array of low-noise charge amplifiers and pulse shapers, one for each sensor diode [3].

3. A peak detector and de-randomizer circuit which multiplexes the amplifier outputs to a fast Analog-Digital Converter (ADC) for digitization [4].

4. A real-time processor, Hymod\(^1\), which contains a large Field Programmable Gate Array (FPGA), together with a powerful microprocessor system and its associated memories and data interfaces [5].

5. A comprehensive control and analysis software package which implements Dynamic Analysis either off-line in a computer or in real-time in the Hymod parallel processor.

Figure 1 illustrates the general architecture of the system.

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2.1 Diode array
The diode array is fabricated in-house at BNL, using the facilities of the Instrumentation Division Semiconductor Laboratory. It consists of a 20 x 20 array of diodes, each 1 mm x 1 mm, constructed

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\(^1\)Hymod: “Hybrid Modular” FPGA-centric processor module.
on a 0.4 mm thick high-resistivity (4-6 kΩ-cm) n-type silicon wafer. The entrance surface was uniformly implanted with phosphorous, and the pixellated side was patterned with boron implants. The implant depth of the phosphorous is roughly 1 μm, and the boron is slightly shallower. Contacts on both sides were formed by depositing aluminum containing 4% silicon to a thickness of 300 nm. The silicon content prevents problems with reactions at the interface leading to destruction of the junction. A cross-sectional schematic of this structure is illustrated in figure 2(a). The central 4 x 4 group of pixels is missing in order to make space for a 2.4 mm diameter hole (and associated guard-ring structures) through which the focused x-ray beam passes. Thus, the total number of detectors is 384. This “backscattering” geometry allows very close approach of the sample to the detector for optimal solid angle, while not restricting the size of the object to be scanned.

Figure 2(a). Cross-section of high-resistivity silicon photodiode structure (not to scale).

Figure 2(b). TCAD simulation of the potentials around the boundary between two diodes in a monolithic structure. Red= +120 V, violet= 0 V

Assuming that the implanted regions of the diodes are low-field regions and hence constitute dead layers, together with the aluminum contact layer, we would expect good performance of these devices starting at around 1 keV. There are local dips in efficiency due to the absorption edges of silicon and aluminum at 1.84 and 1.56 keV respectively, where it can fall to 30% or so. The vacuum enclosure has a 50 μm thick beryllium window which reaches 50% transmission around 2 keV. At the other end of the energy scale it is useful up to an energy at which the silicon bulk becomes transparent and so inefficient as a detector. Depending on one's criteria, this might be around 16 keV (50% absorption), although the detector is still functional up to 60 keV, at which point the amplifier saturates.

One difficulty with such monolithic devices is the fact that photo-generated charge produced in the bulk, near the boundary between adjacent diodes (up to four), can be split among them, producing what appear to be photons of lower energy simultaneously in each of the pixels. This is referred to as charge sharing, and needs to be considered if the best performance of the detectors is to be obtained. Figure 2(b) shows the potentials inside the bulk under full depletion conditions. It can be seen that the potentials produced provide a barrier for positive charge motion between pixels, but if the charge is produced close to the boundary, lateral thermal diffusion will cause some charge to be directed to a neighbouring diode. This charge division process can occur in any ratio, depending on the details of the sensor structure and the position of the absorption event. For a uniform flood illumination this results in an approximately uniform detected pulse height distribution between the photopeak and zero in each diode. The ratio between the photopeak intensity and the lowest point in this plateau is called the peak-valley ratio. The strength of this low-energy plateau, and hence the peak-valley ratio,
depends on the area fraction of the detector which is affected by charge sharing. Thus, larger diodes will have a smaller shared fraction and hence a better peak-valley ratio in general. Our diodes are quite small, and so to maintain a good peak-valley ratio we need to take some additional action.

To solve this problem we chose to add an absorber in front of the entrance surface of the sensor shaped to place all such regions in shadow so that only fully-collected charges will be analyzed. Since we deliberately place the detector very close to the point source, i.e. the focused x-ray spot producing fluorescence from the sample, the shape of this shield is not trivial. It must take account of parallax as all the detectors are off-axis. The solution adopted was to make a layered shield of molybdenum, with three layers, each 0.1 mm thick, having systematically different shapes to shadow the boundary regions even at the edges of the sensor array[6]. Figure 3(a) shows this idea, and figure 3(b) is a photograph of the sensor array fitted with such a shield.

The four silicon tabs seen on the corners of the array serve to provide a good thermal contact with the cold plate on which the sensor is mounted. The cold plate is an aluminum nitride block which is cooled by Peltier devices attached to all four sides. The block is machined to clear the active region of the detector and to provide attachment points for the sensor tabs on each corner.

![Figure 3(a). The geometry of the layered absorber designed to prevent photon absorption in the regions of the sensor affected by charge-sharing. Reference [6] contains a full description of the design.](image1)

![Figure 3(b). A photograph of the sensor with its absorber attached. The silicon extensions at each corner serve to provide thermal contact with the Peltier coolers.](image2)

2.2 Low-noise amplifiers

Amplification of the small signals produced in the sensor is performed by an Application-Specific Integrated Circuit (ASIC). The chip, HERMES$^2$, provides 32 channels of very low-noise charge amplification and filtering to produce Gaussian-like pulses. It provides two gain ranges, 0.75 and 1.5 V/fC, and four shaping times in binary steps from 0.5 $\mu$s to 4 $\mu$s. Channels can be individually disabled in the event of a bad sensor diode, and an external test pulse can be connected to the input of each channel, to allow testing in the absence of a sensor. Since the operation of the input charge amplifier relies on the sensor leakage current to provide its input bias current, the circuit provides for the injection of a 1 pA current on a per-channel basis. This is most often used for system testing

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$^2$High Energy Resolution Multi-Element Spectrometer
before sensors are bonded, when no leakage current is present. The ASIC also includes pulse-height
discriminators and counters for each channel [3], but these are not used in the Maia application.

Figure 4. Block diagram of the HERMES ASIC. It contains 32 copies of the circuits shown in the
figure [3].

2.3 Peak detector / derandomizer
The Gaussian pulses, which arrive randomly in time, are passed to another ASIC, SCEPTER [4],
whose function is to capture the peak height of each pulse and pass it to a fast Analog-Digital
converter (ADC). SCEPTER also provides a de-randomization function, allowing efficient use of
high-speed ADCs which can only perform conversions synchronously. The chip (see figure 5)
contains eight peak-detector modules which are multiplexed among the 32 input channels, providing a
regular stream of analog values to the ADCs. The module also provides an analog measure of the time
the pulse spends above a defined threshold value, and this is also digitized by a separate ADC and
combined with the peak height data for further processing. The time-over-threshold value can be used
together with the pulse height information to detect pulse pile-up and reject those events. Reference
[4] describes the operation of this ASIC in detail.

Figure 5. Block diagram of the SCEPTER ASIC. 32 inputs are
multiplexed among 8 peak
detectors. Routing of inputs to one
of the peak detectors is automatic,
and simultaneous inputs are
correctly handled [4].

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3Simultaneous Capture of Events with Programmable Timing and Energy Readout
Twelve of each of these ASICs are required to instrument the 384 detectors in the sensor array. The ASICs and sensor are interconnected by 25 μm diameter aluminum wire bonds, as illustrated in figure 6. As can be seen, some of these bonds are extremely long, far outside of the length considered normal for such bonds. It takes some care and skill to form them. Nevertheless, we considered various alternative configurations involving some kind of interposer and we have found that this is the technique which provides the lowest capacitance interconnection, resulting in the lowest noise.

Figure 6. The wire bonds connecting the ASICs to the sensor and to each other. This is the lowest capacitance solution to this interconnection problem, but requires significant skill on the part of the bonder.

The printed circuit board which supports the ASICs is a complex multilayer board with roughly 400 components. A picture of the entire board is shown in figure 7. Some of the components dissipate significant power and, since the board is mounted in an evacuated chamber, there is no convection cooling to remove it. As a result it is necessary to bond the PCB to a water-cooled copper plate. The Peltier elements which cool the sensor to -20 °C also dissipate several Watts of power. The hot side of these elements is also thermally coupled to this plate.

Figure 7. The circuit board mounted on its water-cooled copper heat-sink. This is necessary to maintain a low temperature in a vacuum environment, since there is significant power dissipation from the electronics and also the Peltier coolers. The copper plate is 111 mm x 130 mm, and the active area of the sensor is 20 mm x 20 mm, with the central 4 mm x 4 mm left inactive to accommodate the central hole.
A mechanical model of the detector construction is shown in figure 8(b) [5]. It shows the internal construction. A significant effort was put into minimizing the assembly thickness in order to accommodate the short focal lengths of zone-plate microscopes. As seen in the figure, the beam entrance window is recessed into the vacuum chamber and in operation the zone plate and order-sorting aperture are inserted into this recess to allow its focus to exit onto the sample. The working distance of the sample from the front of the vacuum chamber is around 2 mm. Since the sample translation is parallel to this front face this requirement is not a problem and extended samples can be imaged.

Figure 8(a). A photograph of the complete detector head. The lower module contains the detector module shown in figure 7, while the upper module contains the digital interface to the Hymod. As a scale reference, the holes in the optical table are 25 mm apart.

Figure 8(b). Computer model cross-section of the detector mechanics. It shows the re-entrant entrance cavity to take a zone plate assembly, and the molybdenum tube which shields the sensor from radiation scattered by either entrance or exit beryllium windows [5].

2.4 Real-time processor
The digitized values of peak-height and time-over-threshold are combined with several other values and passed to the Hymod module. This device consists of a large Field-Programmable Gate Array (FPGA) which performs high-speed computation on the data, closely coupled to a fast microprocessor and its associated memories and interfaces. Since each detector and its analog processing chain is slightly different, the system must keep track of which photon event came from which detector so that appropriate energy calibration can be performed. It must also associate each photon with a particular sample position in order to reconstruct the scanned image. Thus, each photon generates a “photon event”, which contains the following information:

- Peak height
- Time-over-threshold
- Detector number

This information is encoded into a 32-bit packet and sent for processing. Other events are generated by the system and merged into the data stream. A change in the sample stage coordinates, for example, is such an additional event type. All packets are 32 bits, and contain a tag identifying what type of event it is. Processing can consist of simply logging the data to high-speed disks, or immediate
processing in the FPGA, or both. The FPGA processing generates elemental maps photon-by-photon, in real time, such that elemental maps are produced on-screen as the scan progresses. This is a major advance, since it allows the user to see very quickly if she is getting the data she wants, and if not, to stop the scan and make adjustments. The system does much more than this, and the reader is referred to reference [5] for further details. A flow-chart of the processing is shown in figure 9.

![Flow-chart of processing pipeline within Hymod](image)

Figure 9. A flow-chart of the processing pipeline performed within Hymod. In the diagram, E refers to photon energy, T refers to the time-over-threshold value (used to detect pile-up) and N refers to the index of the detector which collected the photon. Hymod is capable of handling up to 50 million events per second [8].

A comprehensive software package has been written to provide the User Interface for the detector.

3. Future directions

Our primary development goals aim to improve both energy resolution and throughput. Both will require significant effort, both in ASIC design and novel sensor structures. A new ASIC is currently under test, and promises to markedly reduce the contribution of electronic noise to the overall system noise level. It does this by improvements to the preamplifier design, removing all of the counting logic, which is not used by Maia, and by making all digital signals differential so that noise from fast digital signal edges is greatly reduced. Many of the circuits used are based on those used in earlier ASICs developed at BNL [7]. We are also studying alternative sensor structures with a view to reducing their capacitance, which is a significant component of the noise budget for the current Maia design. In general, signals from lower-capacitance sensors can be processed faster, leading to higher throughput. Silicon Drift Detectors (SDDs) are an obvious, though complex choice. However, other, simpler solutions may exist and we are investigating them. In order to accommodate any eventuality, the new ASIC can accept either electron or hole signals. In the more distant future, we are looking at moving from the wire-bonding interconnect scheme to a solder bump bonding process. This would serve two functions; it would reduce the risk of failure of the bonding process and it would reduce the footprint of the sensor-ASIC block. Against those advantages, there is the disadvantage that the power
dissipated in the ASICs is in close thermal contact with the sensor, and so more cooling power would be needed.

4. Conclusions
We have developed a detector system specifically designed for x-ray fluorescence microprobes. We took the non-traditional step of working in a backscattering geometry, rather than at 90 degrees to the incident beam. This makes possible a reduction in the sample-to-detector distance to a few millimeters without restricting the scan range of the sample. Samples of order 1 m x 1 m have been scanned. Contrary to popular belief, Compton scattering is not overwhelming. It can in fact provide a useful estimate of sample density and can be used for imaging, for example to provide registration between metal images and surrounding organic material such as is found in a biological organism. The data acquisition system is also non-traditional, borrowing as it does from high-energy physics practice. It streams data continuously, event-by-event, rather than as complete spectra. Ryan's Dynamic Analysis method [2] takes advantage of this architecture to allow real-time analysis of elemental contributions as data collection proceeds.

The Maia system has been used for a wide range of applications. The papers by Ryan et al [8] in these proceedings and by Lombi et al [9, 10, 11] describe some of them in detail. It has enabled a new mindset for fluorescence elemental mapping, where large images with high resolution (high-definition imaging) are acquired, rather than making a low-resolution image first in order to decide which regions of the sample merit finer scans. This earlier method can easily result in missed features due to its inevitable under-sampling. If the coarse scans are made using a larger probe beam to avoid undersampling, small particles are effectively diluted and may also be missed. The speed of acquisition also enables other modalities involving scans in additional dimensions, e.g. fluorescence tomography (e.g. [12]) or XANES imaging (e.g. [13])

5. Acknowledgments
This work was supported at BNL by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886. The CSIRO work took place within the CSIRO Sensors and Sensor Networks Transformational Capability Platform. NJIT authors were supported by the National Science Foundation, Major Research Instrumentation Grant DMR 0722730. SLAC is supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

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