NOISELESS, HIGH FRAME RATE (> KHZ), PHOTON COUNTING ARRAYS FOR USE IN THE OPTICAL TO THE EXTREME UV

John Vallerga*, Jason McPhate, Anton Tremsin and Oswald Siegmund
Sciences Laboratory, 7 Gauss Way, University of California, Berkeley 94720-7450

Bettina Mikulec and Allan Clark
University of Geneva, 24, quai Ernest-Ansermet, 1211 Geneva 4, Switzerland

ABSTRACT

We describe the development of an imaging photon counting detector based on microchannel plates (MCPs) with specialized readout integrated circuits (ROICs). The detector consists of a photocathode, MCPs that amplify the photoelectron, and a ROIC that has event counters on every pixel. In this detector, it is the event counts that are integrated, not the charge, and there is no associated readout noise. Also, the integrated signal per pixel is already digital and the frame can therefore be readout very fast without noise penalty. The quantum efficiency is dependent on the photocathode chosen and can be tailored to the application (e.g. FUV solar blind to the near infrared). Both the electronic counters and the MCPs can be gated to nanosecond accuracy for ranging applications.

The first application for this detector concept is a 256x256 optical wavefront sensor using the Medipix2 ROIC funded by the NSF Adaptive Optics Development Program. This detector can achieve a frame rate of 1 kHz with zero readout noise and 37% QE at 600 nm. We have demonstrated the spatial resolution and event rate (~1 GHz) of this detector with a laboratory vacuum test detector in the UV and are in the process of integrating this detector into a vacuum tube with a GaAs photocathode. We will also present possible future ROICs to be used with MCP technology to achieve faster frame rates or more pixels or both and discuss the possibility of using avalanche photodiodes (APDs) as the input photoconverter/amplifier rather than MCPs to increase the optical QE.

1. INTRODUCTION

Advances in adaptive optic (AO) systems for ground based telescopes are placing ever more stringent requirements on the wavefront sensor (WFS) components of these systems. In particular, the push toward larger telescopes requires AO systems with many more actuators, each requiring a wavefront phase measurement. To accommodate the growing number of phase elements, WFS for the next generation of giant telescopes will have to grow accordingly. The ideal WFS[1] would have many image elements (512 x 512 pixels), very low read noise (≤3 electron), operate at kilohertz frame rates, and have high optical and near infrared (NIR) quantum efficiencies (≥80%).

Typically WFS have employed charge coupled devices (CCDs) because of their excellent optical/NIR quantum efficiency (QE). However, as WFS get larger, with more pixels per phase element to accommodate larger telescopes, the “read noise” associated with the analog to digital conversion of the charge collected in each pixel of a CCD becomes a significant penalty. Newer advances in CCD technology (such as massively parallel readouts[2] or on-chip structures that amplify the collected charge before the readout amplifier [3]) mitigate this penalty, but cannot entirely eliminate it.

Unlike charge integrating arrays (e.g., CCDs) photon counting detectors register each photon as a single count and so have no “read noise”. Examples of such devices include avalanche photodiodes (APDs) and imaging microchannel plate (MCP) detectors. While silicon based APDs are fast and can have high QE in the optical and near infrared (IR) they have not been incorporated into large arrays. Imaging MCP detectors[4] can have large areas (100 x 100 mm), high spatial resolutions (25 µm FWHM), low background rates, and event timing resolution less than 1 ns. Their QE is determined by the photocathode that absorbs the incident photon and releases the photoelectron. Recent advances in gallium arsenide (GaAs) and gallium arsenide phosphide (GaAsP) photocathodes for image intensifier devices have resulted in optical/NIR QEs exceeding 50%[5]. Bolstered by this advance in optical/NIR photocathode technology we are actively developing an MCP-based, photon counting WFS detector with a GaAs photocathode and the Medipix2 ROIC [6].
Why would one sacrifice QE for noiseless operation? Because even with an optical QE only 40% of that of the best CCDs, noiseless detectors can still be the better choice in low fluence per frame applications. For a Shack-Hartmann wavefront sensor, where the goal is to accurately determine the centroids produced by a lenslet array imaging a pupil plane, zero readout noise allows the use of more pixels to better sample the spot distribution. Fig. 1 is a comparison of the ability of two hypothetical detectors to measure a phase difference in a Shack-Hartmann configuration: a CCD with 90% QE and a noiseless imager (“Medipix”) with 37% QE [7]. The three different CCD curves correspond to different number of pixels used to sample the centroid spot (2x2, 6x6 and 8x8) while the noiseless detector used 8x8. Notice in Fig. 1 that the noiseless detector is better than the CCDs at low fluence levels in determining a centroid and therefore a phase slope. Even with a QE ratio of 2.5, not until the fluence reaches 60 input photons does the CCD (6x6 weighted) match the Medipix/MCP/GaAs tube. The phase difference error (rms) across the subaperture for a noiseless Medipix tube is 1.0 radian at 20 input photons and 0.58 radians at 60 input photons. This corresponds to a phase error of $\lambda/6$ and $\lambda/11$ respectively for this sampling and seeing conditions. If this can be achieved with less photons, it means that dimmer natural guide stars can be used or laser guide stars with less power. Alternatively, faster frame rates for the same intensity guide star.

Most photon counting, imaging MCP-based detectors use readout schemes that are inherently serial in nature. For instance, a delay line anode which uses the difference in arrival times of an event signal at each end of the anode to calculate the event position, can only have one signal on the anode at a time without confusion of the events. With typical delay times of 50 ns for larger detectors, dead time associated with “pulse pileup” starts to become significant at global rates as low as 2 MHz. The obvious way to avoid this problem is to use a more parallel readout structure (a pixelated counting device) behind the MCPs. The AO WFS detector we are developing uses just such a device, allowing us to maintain the “noiseless” readout of photon counting, while operating at global counting rates approaching 1 GHz and frame rates of a kilohertz. For a detailed comparison of the performance characteristics as a WFS of the photon counting MCP/Medipix detector discussed here versus state-of-the-art CCDs see [7].

Fig. 1 Plot of resultant rms phase difference (in radians) due to centroid error using different detectors and centroiding algorithms. Plotted is a noiseless detector using an 8x8 pixel array (“Medipix 8x8”) to sample a 3 pixel FWHM Gaussian distributed spot. The other three lines are for a 90% QE CCD with 2.5e- rms readout noise sampling the same star spot using an 8x8, 6x6 and quad cell format. In all cases besides the quad cell, the weighted center of gravity centroid algorithm [7] was used to determine the centroid error.
2. A NOVEL DETECTOR DESIGN

Our novel detector scheme employs a CMOS ROIC pixelated counting device to readout the MCPs. Specifically, we are using the “Medipix2” [8] device, an ROIC designed and constructed by the Microelectronics Group at CERN for the multi-national MEDIPIX collaboration [http://www.cern.ch/medipix], which we have joined. The members of the consortium have input into the features that will be present in future versions of the Medipix ROIC and share the large costs associated with developing and fabricating a new ROIC.

The detector (Fig. 2) is a vacuum sealed MCP imaging tube with a GaAs photocathode on the entrance window and a Medipix2 readout chip. A photon interacting with the photocathode produces a photoelectron which is proximity focused onto the input surface of the MCP. The MCP amplifies this single photoelectron with a gain on the order of $10^4$. The resultant charge cloud exits the MCP and lands on an input pad of the Medipix2 pixel where it is counted as one event. The Medipix2 pixel counters integrate until they are readout in a digital, noiseless process. Also because the data is digital, it can be read out at a fast clocking speed, allowing the entire frame to be read out in 286 µs. This detector should achieve optical/NIR QE’s of approximately 35% (the photocathode QE mitigated by the open area ratio of the MCP).

To verify that the Medipix2 device was a viable readout device for an MCP detector we developed an open-face, MCP detector with a Medipix2 readout and no photocathode. Stimulation was performed primarily with UV light from a Hg penray lamp. This detector works very well and has allowed us to experiment and optimize detector parameters such as the MCP to Medipix gap and the accelerating voltage across this gap, important parameters for the final sealed tube design. We were able to use this detector to perform rudimentary verification that the MCP/Medipix combination will work as a Shack-Hartmann type WFS. We have also used the detector to detect low energy beta particles. Results obtained from this developmental detector have been previously published [6,9]. The knowledge acquired from this developmental detector has been used to determine the parameters of the optical tube design presented in Section 3.

2.1 The Medipix2 ROIC

The Medipix2 is a pixel detector readout chip consisting of 256 x 256 identical 55 x 55 µm pixel elements, each working in single photon counting mode. Each pixel consists of a preamplifier, a windowed discriminator, and a 14-bit pseudo-random counter (Fig. 3). The counter logic, based on a shift register, also behaves as the input/output register for the pixel. Each cell has an 8 bit configuration register which allows masking, testing, and 3-bit individual threshold adjust for the discriminator. Fig. 4 shows the electrical schematic of the Medipix2 layout and how the shift registers relate to the parallel readout. The total active area of the chip is 2.0 cm² and is 3-side buttable (Fig. 5, supporting larger, 512 x [n*256], arrays) with 127 wirebond output/input pads along the inactive edge. The application of the Medipix2 to this detector has been discussed in greater detail previously[6]. Here we concentrate on the implementation using the Medipix2 as a readout in an MCP imaging tube.

Readout of the Medipix2 chip can be performed via either a serial or a parallel interface. Upload to the chip is performed with a serial interface. Both serial and parallel interfaces are clocked by a fast external clock (on the order of 100 MHz). The serial input and output employ low voltage differential signal (LVDS) line pairs. The fast clock, for example, is brought into the chip via an LVDS line pair. In serial mode a full 256 x 256 x 14-bit frame can be read in ~9.2 ms using a 100 MHz clock. The parallel readout is a 32-bit CMOS bus that outputs each 256 x 1-bit row of a frame in eight reads. A 100 MHz clock speed results in a parallel full frame read time of 286 µs.
Fig. 3: Schematic of the major functional blocks contained within a Medipix2 pixel. A fast charge event on the input is amplified and shaped by the preamp, discriminated, and counted at the shift register (if Shutter is disabled). The digital number count is clocked out at high rate through the shift registers of the pixel column when Shutter is enabled. Digital configuration bits are input through this same shift register to control thresholds, masking, and electrical testing.

2.2 Microchannel plates
Microchannel plates consist of an array of holes in a specialized glass substrate whose surface has a high secondary electron coefficient. When biased with a high voltage across the plate, electron(s) entering a pore are accelerated and eventually impact the channel wall, releasing more electrons which continue the process resulting in an avalanche of electrons exiting the rear surface. Typical gains (electrons out/ electrons in) for a single MCP range up to $5 \times 10^6$, depending on the voltage applied and the length to diameter ($L/d$) ratio. For the relatively low gain $10^4$ we use for the MCP/Medipix detector either a single MCP with high $L/d$ ratio or a “chevron” pair can be used (two MCPs stacked with their pore bias angles reversed at the interface). The advantage of the chevron is that any ions generated in the residual gas of the tube at the MCP output cannot be accelerated back to the photocathode, possibly damaging it. They would be absorbed in the first MCP because of the “bend” at the interface. We have chosen to use a chevron stack of 10 μm pore diameter MCPs for the Medipix imaging tube.

2.3 High QE photocathodes in the optical
GaAs photocathodes have been used extensively for a number of years, mainly in night vision applications as the photocathode for Generation III image intensifiers. During that time many advances in performance have been achieved. As demonstrated in Fig. 6, quantum efficiencies in excess of 50% can now be achieved from 550 nm to 850 nm making them very attractive for optical/NIR astronomical applications. However, these photocathodes are extremely environmentally sensitive and must be kept at ultrahigh vacuum to prevent QE degradation. They are deposited on windows and built into vacuum tubes constructed to seal and maintain vacuum levels of $10^{-9}$ Torr or better. Furthermore, production of reliable GaAs

Fig. 4: Schematic of the readout architecture of the Medipix2 chip organized into 3328 bit columns read out via a 256 bit fast shift register with a 32 bit parallel readout.

Fig. 5: Image of the input face of a Medipix2 chip. The dimensions are 1.6 cm high and 1.4 cm wide. The active area has 256 x 256 pixels and is buttable on 3 sides. Inactive bottom edge has input/output wirebond pads.
photocathodes is expensive to implement, so working with an established volume production facility is important.

3. OPTICAL MCP/MEDIPIX IMAGING DETECTOR DESIGN

Although the approach of using a volume supplier of GaAs devices to process the photocathode greatly reduces the cost of achieving high QE imaging device it places significant constraints on the detector design. In particular our vacuum tube and entrance window must be compatible with the fixtures of the production facility, effectively dictating the use of a standard size tube and window. The interior of a standard night vision type vacuum tube is only marginally larger than the Medipix2 device, making space constraints inside the vacuum tube very restrictive. Also the sensitivity of the photocathode to contamination means that everything that goes into the tube must be extremely low outgassing.

The Medipix2 device also places significant constraints on the design. The input/output contact pads of the Medipix are primarily along one edge and are spaced on a 120 µm pitch. About half of the 127 contacts on the Medipix need to be brought out of the vacuum, requiring a relatively fine spacing of contacts and dense population of hermetic vias on the header to which the Medipix is bonded. Also the readout rates we wish to achieve require attention be given to impedance matching and power and ground filtering on the Medipix header. Add to all this the requirement that the header and die bond material must be able to withstand the temperatures (~300 °C) reached during the vacuum tube processing while still being extremely low outgassing to avoid photocathode degradation.

Achieving good spatial resolution requires a relatively small gap between the photocathode surface of the window and the input face of the MCPs. To keep the MCP output charge cloud spread to a minimum the gap between the MCPs and the Medipix must also be minimized. Both of these affect the allowable stack up tolerance of the piece parts of the tube body as well as the tolerance on the braze line thicknesses between parts. The MCP to Medipix gap also constrains the maximum permissible wirebond loop height. Externally controlled high voltage potentials need to be applied across the photocathode to MCP gap (improves spatial resolution), the MCP input to output surfaces (controls MCP gain), and the MCP to Medipix gap (minimizes charge cloud spreading). All these requirements lead to a fairly standard metal ceramic brazed body tube assembly with tight stack up tolerances, employing a drop faced entrance window and having a rather complex ceramic thick-film hybrid header for mounting the Medipix readout device (Fig. 7 and Fig. 8).

3.1 Medipix header

At the heart of the MCP/Medipix imaging tube is the mounting header for the Medipix2 chip. Internally this header provides the mounting surface and electrical interface for the Medipix2 chip and externally functions as the signal interface to the readout electronics. It must provide a hermetic seal on the vacuum tube while getting approximately 60 individual signals from the Medipix to the outside of the tube. It must be very low outgassing and compatible with not just tube processing temperatures, but also active vacuum brazing temperatures (~850 °C). The interior contact pads need to be compatible with Al wedge wireboning with spacing close to that of the Medipix 120 µm pad pitch. For these reasons we chose to have a hybrid header made using thick-film screening technology on a ceramic substrate. We have used this technology with great success in many of our UV photon counting detector devices [10]. The thick-film technology provides an extremely robust final product that is compatible with active brazing.
3.2 Vacuum tube design and assembly

To facilitate the production and processing of the GaAs photocathode our tube design needed to comply with the standard sizing of the image intensifier industry. We are using a tube designed around 25 mm diameter MCPs with approximately 18 mm diameter active area. We have selected to use a fairly standard combination of drop face window and upper tube stack height that will yield a nominal 300 µm photocathode to MCP gap. The smaller this gap and the higher the voltage applied across the gap the smaller the spatial blur will be incurred from the initial lateral velocity of the photoelectron. This gap is smaller than we need for the resolution requirements of the Medipix tube, but allows us to use the tube for more demanding projects (and operate at a lower gap voltage for the Medipix project). The back flange of the tube and the adapter flange of the brazed header assembly are designed to provide a nominal 500 µm gap between the MCPs and the Medipix. This gap can be adjusted by post braze.
machining of the tube body rear flange. Making this gap smaller (or increasing the voltage across the gap) reduces the footprint at the Medipix of the charge cloud exiting the MCPs. A more compact charge footprint means more charge falling in each activated pixel, so increasing the likelihood of exceeding the Medipix threshold. Alternately, the MCPs could be operated at lower gain without a loss of counting efficiency (relative to a larger gap and higher gain). The stages of fabrication of a Medipix vacuum tube are described and shown in Fig. 8. At this point we will have an optical, photon counting, sealed tube imaging device ready for use as the detector head of an adaptive optics wave front sensor (or for other uses).

3.3 Readout electronics and software
We have benefited particularly on readout hardware and software from the developments of the MEDIPIX collaboration. For our lab test detector we have been using a well-proven serial readout system. This system consists of the Medipix2 mounted on a serial test board (designed at CERN) that connects to a “MUROS2” [11] communications box developed by the NIKHEF group. The MUROS2 box interfaces with an acquisition PC via a National Instruments DIO-32HS card. The data acquisition control and image display are through the Medisoft [12] graphical user interface software developed by the Univ. of Naples Federico II.

A high speed parallel interface is under development by members of the MEDIPIX collaboration at the European Synchrotron Radiation Facility (ESRF) to facilitate their high speed x-ray scattering and x-ray diffraction experiments [13]. The interface is designed to have five Medipix chips (bonded to a common ceramic header board) readout simultaneously by a single field programmable gate array (FPGA) via the parallel interfaces of the Medipix chips. The data from each Medipix flows through a pre-FPGA FIFO to prevent the data readout speed being limited by the FPGA processing speed. Implementing the FIFOs allows the FPGA to process the images during the integration of the next image frames. The parallel readout is designed to accommodate ~1 ms frames, 286 µs to transfer the Medipix frames to the FIFOs, the remaining time for integration of the next frame. Once the Medipix frame transfer to the FIFO has begun the FPGA starts processing the data stream (manipulating data from all five chips simultaneously). Manipulation steps include reordering of the data bits (as they get shuffled due to the nature of the 8 x 32-bit read of each 256-bit row); conversion of the pseudo-random counter output into real binary counts (this step can include a dead time correction for extremely high local counting rates); a flat field correction; and finally an optional AO spot by spot centroid calculation (including X and Y centroids and variances, and total counts for each spot based on 7 x 7 pixel regions). Alternatively, full image arrays can be passed to the output.

3.4 Current status and future work
Mechanical design of the sub-components of the vacuum tube and header assemblies is complete. The piece parts for the tube bodies are being fabricated. Brazing of tube bodies will occur after all parts are fabricated and inspected. Fabrication of the ceramic thick film hybrid headers has been completed and these items look very good (Fig. 9). The braze adapter flanges for the header assemblies have been fabricated and are ready to be brazed to the headers.

Fig. 9: Image of as fabricated ceramic headers. The article on the left is at an intermediate stage of fabrication (equivalent to Fig. 7a). The center and right items are final products, showing the interior (cf., Fig. 7c) and exterior (cf., Fig. 7d), respectively.
While the fabrication and brazing is ongoing we have had one Medipix2 die bonded and wirebonded to a ceramic header (without the adapter flange brazed on). The Medipix2 bonded very nicely to the header and the wirebonds are robust (Fig. 10). We have used this “thermal prototype” to verify that the Medipix2 and the die bonding material selected are compatible with the temperatures (~300 °C) needed for GaAs vacuum tube processing. We vacuum baked this thermal prototype for ~ 11 hours at 300 °C, initially at a pressure less than 10⁻⁶ Torr and with a temperature increase/decrease rate of 1°C per minute. The turbomolecular pump used to keep the hot chamber at high vacuum failed during the test, so the last ~6 hours of the bake were done at ~ 30 mTorr, with no visible ill effects to the metalization or bond wires. Though only of “Class C” quality, the Medipix2 chip’s electrical performance was similar both before and after the bake, with no obvious increase in amplifier noise threshold or dead pixels or columns.

Once the header assemblies and tube bodies are brazed we can begin buildup of MCP/Medipix2 imaging tubes as described above and have them sealed with an activated GaAs photocathode window. We may decide to seal a tube in our tube processing facility at the University of California, Berkeley. This device would employ a multialkali photocathode (Fig. 6), as we do not have the capacity in-house to process GaAs, but could be fabricated quickly after the parts are in hand and would provide valuable feedback for the final GaAs tubes. Furthermore, having a working MCP/Medipix2 imaging tube in hand will allow us to investigate other applications for this device.

The Medipix consortium is now discussing the next generation of ROIC using 130nm CMOS technology (“Medipix 3”). Halving the feature size will allow the addition of extra counter buffers in each pixel so the ROIC can integrate while being read out. The front end amplifiers will have higher bandwidth and therefore less deadtime. These changes coupled with faster serial and parallel readouts should result in frame rates up to 10 kHz. The chip will also be designed to be radiation hard. The 55 μm pixel size will probably stay the same, to accommodate the xray and gamma ray imaging applications. This development is likely to start by early 2006.

MCPs are a robust and mature technology and perform well with the Medipix2. Their biggest deficiency with respect to optical photon detection is their dependence on optical photocathodes, and there is no known photocathode that can match the QE of silicon in the optical. Silicon APDs can provide both the QE of silicon and the amplification (> 10⁴) necessary to operate as a noiseless pixel. The development of APD arrays is just beginning using CMOS technology [14] but the QEs are not high and the filling factor is quite low. A thick silicon pn APD design that could be backside illuminated exists [15]. If an array of such devices could be built with the output contact pitch to match the Medipix input pitch, then it is conceivable to use the Medipix as the readout device.

Fig. 10: Images of a Medipix2 ROIC die bonded and wirebonded to a ceramic header. This device is used for thermal prototype testing to verify compatibility of the Medipix2 device and bonding material with the temperatures necessary for vacuum tube processing. During final assembly the ceramic header will be brazed to the adapter ring before the Medipix2 is attached.
of a 256 x 256 counting array with QEs approaching 90%. This would remove the requirement for vacuum tube operation, photocathodes and high voltage. However, the dark rate would be substantial, requiring the need for active cooling and vacuum operation again, though not of vacuum tube quality. If this hybrid APD/Medipix ROIC could be developed, it would be the detector of choice for many high frame rate imaging applications, not just adaptive optics.

ACKNOWLEDGMENTS

The authors wish to thank the Medipix Collaboration for the Medipix2 chips, readout hardware and software and for valuable advice. This material presented here is based upon work supported by AURA through the NSF under AURA cooperative agreement # AST-0132798-SPO#6(AST-0336888)

REFERENCES