MCP-Medipix2 hybrid detector for AO wavefront sensors

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ABSTRACT

A hybrid optical detector being developed at Berkeley has most of the attributes desired for the next generation AO wavefront sensors. The detector consists of proximity focused MCPs read out by a multi-pixel application specific integrated circuit (ASIC) chip developed at CERN (“Medipix2”) with individual pixels that amplify, discriminate and count input events. The detector has 256 x 256 pixels, zero readout noise (photon counting) and can be read out at 1kHz frame rates. We will report on the progress achieved after two years of our three year development effort for this detector technology funded as part of the Adaptive Optics Development Program managed by the National Optical Astronomy Observatory. Details on the first vacuum tube constructed with a Medipix2 ASIC along with the fast kHz parallel electronic readout are presented. We also describe a new hybrid detector design based on HgCdTe APD arrays coupled to a Medipix2 readout that could bring zero readout noise at high frame rates to the near IR regime.

Keywords: adaptive optics, wavefront sensors, MCP, Medipix, GaAs photocathodes, near IR APD arrays

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.

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\textsuperscript{1} or on-chip structures that amplify the collected charge before the readout amplifier\textsuperscript{1}) 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\textsuperscript{2} can have large areas (100 x 100 mm), high spatial resolutions (25 \(\mu\)m 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%).\textsuperscript{3} 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 ASIC\textsuperscript{2}.

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 illustrates the advantage of zero readout noise over detectors with readout noise in determining the centroid of a star with a limited number of photons using many pixels. Fig. 2 is a quantitative 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.

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(“Medipix”) with 37% QE\(^6\). 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. 2 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. 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 reference 6.

![Figure 1. Model simulation of Shack Hartmann spots imaged with detectors of different QE, noise and pixel size.](image)

In each case the FOV remains the same and the star image is centered with the same size in all cases with respect to the FOV (2.5 pixels in the 8x8 format case). The top row assumes 1000 incident photons, the middle 100 and the bottom 10 photons. The first column is a noiseless detector sampled by 8x8 pixels, and the three columns on the right assume a 2.5e- rms readout noise and a QE of 90%, but with different pixel sampling. Note how the readout noise masks the smaller signal in the lower rows while for the noiseless detector a centroid is easily determined, though less accurate than the higher fluence cases.
Fig. 2. 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 a 8x8, 6x6 and quad cell format. Details of the error calculation and weighting functions can be found in reference 6.

2. PHOTON COUNTING ARRAY DETECTOR

The hybrid detector (Fig. 3) 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 QEs of approximately 35% (the photocathode QE mitigated by the open area ratio of the MCP).

2.1 The Medipix2 ASIC

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. 4). 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. 5 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 cm\(^2\) and is 3-side abuttable supporting larger, (512 x \(n\times256\), arrays) with 127 wirebond output/input pads along the inactive edge.

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 \(\mu\)s.

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\(^5\). 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. Tests included response uniformity (flat field), spatial resolution, spatial linearity and dynamic range. We have also used the detector to detect low energy beta particles. Results obtained from this windowless detector have been previously published\(^5,8\). The knowledge acquired has been used to determine the parameters of the optical tube design presented in Section 3. We are now working with a commercial vendor to incorporate the MCPs and Medipix2 into a vacuum tube with a GaAs type photocathode. We expect the first working tubes to be available in the fall of 2006.

The Medipix consortium is now embarking on the next generation ASIC using 130nm CMOS technology (“Medipix 3”). Halving the feature size will allow the addition of extra counter buffers in each pixel so the ASIC 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 \(\mu\)m pixel size will probably stay the same, to accommodate the x-ray and gamma ray imaging applications. Initial analog tests of an 8x8 prototype test structure look promising and delivery of the full 256x256 array is expected in 2008.

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**Fig.4:** 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.

**Fig.5:** 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.
3. OPTICAL MCP/MEDIPIX IMAGE TUBE 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 ºC) 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 (Figs. 6, 7 & 8).

3.1 Medipix ceramic 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 ºC). The interior contact pads need to be compatible with Al wedge wirebonding with spacing close to that of the Medipix 120 µm pad pitch. For

![Fig.6. Ceramic hybrid thick film header design. Header diameter is 27.5 mm. (a) Interior view of the first trace layer and the hermetic vias connecting the interior traces to the exterior connector land pads, note approximately every other via is consumed in this layer. This layer is applied directly to the bare alumina. (b) The second layer of fingers is screened on after the application of an insulating layer of glass and makes contact to the unused ceramic vias through holes in the glass. (c) The header is completed by application of another layer of insulating glass and finally a ground plane layer is screened over this glass. The Medipix2 chip is die bonded to this “upper” ground plane and the signal pads are Al wedge wirebonded to the exposed tips of the header traces (cf. Fig 8). (d) Exterior view, showing the land pads for two 34 contact 0.8 mm pitch connectors and decoupling capacitors.](attachment:image-url)
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. The thick-film technology provides an extremely robust final product that is compatible with active brazing.

While the fabrication and brazing was ongoing we 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. 8). 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 350 °C, initially at a pressure less than 10^-6 Torr and with a temperature increase/decrease
rate of 1°C per minute. Though only of “Class C” quality ( < 2 dead columns), 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.

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. 9. 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).

![Fig.9. Cross-sectional views of the optical image tube fabrication process.](image)

(a) The ceramic header is active brazed to a kovar adapter flange. (b) A Medipix2 chip is die bonded and wirebonded to the header assembly. Electrical testing of the Medipix2 is performed via a serial interface board. (c) This assembly is laser welded to the back flange of the vacuum tube brazed body. (d) The MCPs are installed in the tube, the tube is placed in an ultrahigh vacuum processing chamber and prepared for sealing. (e) The photocathode is activated and the tube is sealed and can be removed from the vacuum processing chamber. (f) Finally the passive components (connectors and capacitors) are bonded to the exterior surface of the ceramic header.

The thick film technology we used on our ceramic headers necessitated the use of an active braze process to fabricate the tube assemblies. Standard brazing that uses a reducing atmosphere (hydrogen) will attack the thick film materials...
used on the chip header. Unexpectedly, this active brazing proved to be difficult, with many brazing attempts resulting in tube bodies that leaked at the 10^-3 std. cc/sec level, many orders of magnitude above what is needed for a sealed tube. Through a process of trial and error, consisting of many high temperature (850deg. C) vacuum baking runs, we effectively had to re-optimize our brazing process to match the materials, coatings, shapes and sizes of our tube parts to get consistent, leak-tight results. We changed the braze material, clamping pressure and surface flatness, finish, coating and treatment. Eventually, we were able to produce tube brazed bodies and headers with the brazed weld rings. Fig. 10 shows both a brazed body side view and a top view with the Medipix header assembly installed but without MCPs or windows.

![Fig. 10. Two images of the brazed tube assembly. The side view on the left shows the stackup of the kovar and ceramic pieces that are brazed together to be vacuum leak tight. The right image looks down into the brazed assembly to show the location of the Medipix2 chip. The MCPs and input window are not installed.](image)

We now plan to seal a tube in our tube processing facility at the University of California, Berkeley. This device would employ a multialkali photocathode 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.

### 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” 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 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. 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.

Our colleagues at ESRF have demonstrated parallel readout at clock rates of 100MHz resulting in data transfers from the Medipix chip to the FPGA board of less than 300 μs from shutter closing. The current firmware simply re-orders the data bits and transfers the entire image to a PC in less than 700 μs from shutter closing through a 2Gb/s optical link. The input FIFOs are specified to work up to 150MHz so tests will be performed at that rate soon. A different set of FIFOs from IDT are available that might operate at 225MHz, increasing the readout rate proportionately.

4. CONCEPT FOR A NOISELESS INFRARED DETECTOR USING THE MEDIPIX CHIP

MCPs are a robust, mature technology and perform well with the Medipix2. Their biggest disadvantage with respect to optical photon detection is their dependence on optical photocathodes; there is no known photocathode that can match the QE of silicon in the optical. Silicon APDs can provide both the high QE of silicon and the amplification (> 10^4) necessary to operate as a noiseless pixel. The development of APD arrays is just beginning using CMOS technology, but the front side illuminated QEs are not high and the filling factor is quite low. A thick silicon pn APD design that could be backside illuminated exists. 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 of a 256 x 256 counting array with optical 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 optical APD/Medipix ASIC could be developed, it would be the detector of choice, not just for adaptive optics, but also for many high frame rate imaging applications. However, our initial review of existing silicon APD arrays has not yet identified a candidate that could easily interface with the Medipix input contacts.

Interestingly, there exists an infrared APD array technology that looks as if it will interface well with the Medipix ASIC. Developed by DRS Technologies, Inc., the APDs are made in short, mid and long wavelength cutoff (λ_c) infrared HgCdTe. The design is based on “high density vertically integrated photodiode” (HDVIP) architecture. It utilizes a cylindrical “p-around-n”, front side illuminated, n+/n-/p geometry that favors electron injection into the gain region (Fig. 11). The reason for the good match to the Medipix ASIC is that the cylindrical APD structure around a wet-etch via can directly couple the output signals to the Medipix input pads underneath the APD array. These APD devices are characterized by a uniform, exponential gain vs. applied bias voltage. Gains of greater than 1000 have been measured in λ_c = 4.3 μm HgCdTe (Fig. 12). At 80°K, λ_c =4.3 μm devices show excess noise factors of close to unity out to gains of 1000.

![Diagram](image_url)  
Fig. 11. Cross section and top view of an HgCdTe HDVIP diode used in avalanche mode (from reference 14)
The lack of excess noise in the amplification process of this type of APD is important for its potential use with the Medipix chip. The input amps of the Medipix2 have an rms input noise of ~75 electrons. If a minimum threshold for counting events is set at ~10 times the rms noise level (i.e. 750 electrons), then the APD must have a gain above this level. There will be a distribution of event sizes about the gain level, and for an amplifier with gain ~1000 and zero excess noise, this distribution will have an rms value of ~32 electrons, so all events will be above threshold and therefore counted. The APD does not need to be operated in the Geiger mode to be counted. The lack of excess noise in this IR APD can be compared to MCPs, where the low gain amplification noise is high, resulting in an exponential output pulse distribution, and loss of events below the Medipix threshold. (For MCPs, this can be overcome by simply increasing the gain of the MCPs by raising the high voltage).

Preliminary discussions with scientists and engineers at DRS Technologies Inc. have led us to believe that both technologies are a good fit. To get the required gain by the Medipix2 chip (> 750) requires a smaller bandgap (λc > 4.3 μm) and therefore we would expect to operate at 77°K. Though designed as a room temperature device, the Medipix2 is expected to be able to function at 77°K as it is a CMOS device. In fact, there is a possibility it might run with less amplifier noise and faster. However, increased speed might interfere with the digital logic, so we plan to test the Medipix2 chip soon at cryogenic temperatures before proceeding to pursue the APD fabrication.

If this device can be made to work, it would lead to similar characteristics as described for the MCP-Medipix hybrid: fast frame rate, zero readout noise, electronic gating. However, it would have high QE in the infrared out to 4.3 μm cutoff. Uses for such an IR imager would be in niche applications where the background flux is low, e.g. fast frame rates like AO wavefront sensors, high dispersion spectrophotometry, or space-based IR imaging.

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