MICROCHANNEL PLATE IMAGING DETECTOR TECHNOLOGIES FOR UV INSTRUMENTS

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Summary

There has been significant progress over the last few years in the development of technologies for microchannel plate (MCP) imaging detectors in the ultraviolet. The nominal configuration of this type of detector consists of a photocathode to convert incoming radiation to photoelectrons, MCP's to amplify the signals, followed by either an optical or electronic image readout scheme. Areas where significant developments have occurred include, enhancements of quantum detection efficiency through improved photocathodes, advances in microchannel plate performance characteristics, and development of high performance image readout techniques. In this paper the current developments in these areas are summarized,.

Photocathodes

The application of an photocathode with high photoemission probability is an effective means of obtaining increased UV quantum detection efficiency (QDE). Commonly used photocathodes for the 50Å to 2000Å UV range are alkali halides such as CsI [1], and KBr [2]. Photocathodes of this type are usually evaporated onto the detector window as a semitransparent layer (<1,000A thick), or onto the MCP as an opaque layer (H10,000A thick) so that material penetrates the MCP pores. Opaque photocathodes are generally more efficient and have better spatial fidelity. Photoelectrons emitted by an opaque photocathode inside the channels are detected by the MCP. Photoelectrons emitted by the cathode on the MCP top surface are also collected when a retarding bias is applied to a grid placed above the MCP. The application of a grid bias often increases the QDE by a factor of 1.5 for efficient cathodes [3]. CsI, KBr, and similar photocathodes are robust enough to withstand atmospheric conditions provided the humidity level is kept low. The QDE achieved by these cathodes is to some extent dependent on the photoelectron detection efficiency of the MCP onto which they are deposited. Our recent results for CsI opaque photocathodes (Fig. 1) on high efficiency bare MCP's are significantly better than those for CsI cathodes made in the past. This can be explained in part by examining the bare MCP QDE performance. We have found that some of the manufacturing steps for MCP's have a critical effect on the bare MCP QDE as shown in Fig. 2. Different batch processes give markedly different results. In addition those MCP's with higher bare QDE also give better photocathode coated QDE's. This and other data indicate that the photoelectron detection efficiency of the poor QDE MCP's is sub-standard, not necessarily their photoemission efficiency. Thus with better MCP process control we should be able to achieve better QDE for many cathodes, as we have done for CsI.

Diamond is a material which holds some promise as a photocathode for the UV regime. Recent investigations [4,5,6,7] have shown that it can be a useful short wavelength UV photocathode with good stability and robustness. Efficiencies of the order 50% have been attained in the 200 – 1200Å band (Fig. 3) and our tests have shown that the exposure stability to air is good, as well as the ability to re-establish high QE on the cathode even after degradation has occurred. Activation and surface treatments may improve the performance further. Diamond may also be used as a direct opaque cathode on the newly developed Si MCP's [7].

Semitransparent RbTe and CsTe are photocathodes with long wavelength cutoffs at ~3000Å for RbTe, and ~3100Å for CsTe have been used in photomultiplier tubes for many years. Opaque RbTe & CsTe photocathodes in PMT's have higher QDE's (40%) (Fig. 4) than semitransparent (15%). So the QDE enhancement is comparable to that obtained for the common UV photocathodes on MCP's. Opaque RbTe and CsTe photocathodes also would provide better spatial distribution than a semitransparent – proximity focus photocathodes. Demonstration as opaque RbTe and CsTe on MCP's has only been done recently due to problems with cathode contamination. We have made several RbTe and CsTe opaque photocathodes on MCP's in sealed tube devices. These cathodes are stable over periods of more than 6 months. The efficiency we have achieved so far is similar to the semitransparent cathode types with QDE, ~12% at 1216Å and 8% at 2537Å for CsTe. Even so the inherent resolution advantage of the opaque cathode geometry makes this attractive. Work to optimize the QDE of opaque RbTe and CsTe cathodes on MCP is currently underway.

Another photocathode which shows promise, for a wider wavelength bandpass is GaN and its associated alloys. GaN has a longer cutoff wavelength (~380nm) than CsTe, while still providing longer wavelength insensitivity. The cutoff wavelength can also be tuned by choice of materials and processing. As a photocathode, as opposed to a solid state device, GaN must be optimized for photoemissive properties. To obtain high yield NEA (negative electron affinity) GaN photocathodes, low resistivity, p-type material is required. In addition surface preparation and activation techniques are very important. Initial work in this area (Fig. 4)[8] has shown that NEA GaN can provide 27% QDE at 200nm, with 380nm cutoff, and further studies are underway.

Microchannel Plates

MCP's are the workhorse amplification step in this kind of detector system. Their performance in terms of gain, pulse height distribution (PHD), background, pulse speed and rate, image fidelity and format size and shape are some of the important properties that define detector performance. Recently a number of developments in channel size, efficiency, background rate, device chemistry and readout requirements have expanded the options for MCP detector systems. Recently MCP's with pore sizes of 5 to 6µm have become available as compared to the 10-12µm sizes previously. Initially these were only available in small formats (18mm), but are now possible for sizes up to >70mm. The small pore MCP's provide a significant spatial resolution advantage as can be seen from the test mask images shown in Figs. 5 & 6. Whether used as single MCP's, or as MCP stacks there are a number of advantages for the smaller pore MCP's. Conventional MCP Z stack configurations provide a narrow pulse height distribution and high gain ($>10^7$) for photon counting imaging applications. Our tests of small pore MCP stacks achieve saturated gains in the region of 1×10^6 with tight PHD's (<50% FWHM) and output pulse widths of <500ps. Some of the developmental image readout schemes (see below), do not require gains as high as some previous schemes. This offers possibilities for improvements in the lifetime (lower overall charge extraction rates) and localized counting rate limits (increased dynamic range) using small pore MCP's.

Considerable efforts have been made over the last few years to provide MCP's for detectors with curved focal planes. This has been done by either grinding, or thermally slumping the MCP's to the correct shape. Typical examples of this are the IMAGE-EUV spherical MCP's (46mm Z stack with 7cm radius, Fig. 7) and the ROSETTA-ALICE cylindrical MCP's (46 x 30mm Z stack with 7cm radius, Fig. 8). Although their performance has generally not been as good as flat MCP's considerable improvements have been achieved recently so that they are close to matching "standard" MCP performance.

MCP background event rates are generally quite low (<1 event cm-2 s-1), with a pulse amplitude distribution of a negative exponential shape. The main background source [9,10] of intrinsic MCP background events is residual radioactivity (beta decay) of the MCP glass, spurring development of MCP glasses without radioactive content [11]. Our results with these MCP's in 80:1 MCP Z stacks demonstrate a significantly lower background rate (H0.03 event cm^{-2} s^{-1}) (Fig. 9). In orbit the cosmic ray interactions increase the background, but anti-coincidence techniques can significantly reduce this contribution.

A new alternative to standard glass MCP's are silicon based MCP's. While still under development we have preliminary results that suggest that Si MCP's may be a good successor to glass MCP's. Si MCP's with square pores and spacings of 8µm have been made in small formats (Fig. 10, 18mm)[7]. Since these MCP's are made by lithographic processes their uniformity is better than conventional MCP's. The materials are also capable of withstanding very high temperatures (>800°C), allowing coatings by CVD processes to give robust secondary electron emission surfaces. We expect that this will lead to enhanced QDE, high event rates and longer lifetimes. Our initial tests have shown that the gain and PHD's for Si MCP's are very comparable to normal glass MCP's. We have used one Si MCP as the input MCP in a stack with two glass MCP's for these tests. The spatial imaging (Fig.11) of UV light on the Si MCP is reasonable, and the gain uniformity is quite flat (Fig.12). The background rates are uniform (Fig.13) and very low, < 0.05 events cm^{-2} s^{-1}, in accord with our expectations since there are no radioactive materials. The QDE's are somewhat lower than good glass MCP's (8% vs 12% @ 584Å, Fig.14), but this is not that bad since the open pore area is only 50% for the Si MCP compared with close to 70% for the glass MCP's. The angular QDE dependence is also similar to glass MCP's. This is in general an encouraging scenario for the future development of Si MCP's.

Image Readout Anodes

There are a large variety of image readout systems for MCP's. These fall into two main classes, optical readout (CCD, PAPA) and electronic readout. The latter being subdivided into discrete anodes and continuous position sensors. Discrete anode schemes include simple multi-anode pad arrays, the CODACON and the MAMA. Continuous position sensors can operate by resistive, or conductive, charge division, or by signal timing methods. Charge division schemes include the resistive anode, the wedge & strip, vernier anodes and the crossed wire encoders. Signal timing methods include the planar, multilayer and wire wound delay lines. We will discuss some of the recent techniques, while details of the others may be found in Ref 12.

Delay Line Image Readout Anodes

Many delay line detector formats and types are possible, they are compact, robust, have high performance imaging, and allow considerable flexibility of design and optimization. A MCP stack with two or three MCP's detects the incoming photons and multiplies the charge signal. The resulting charge cloud is accelerated over a gap (a few mm) and deposited onto the readout anode. Typical charge clouds are H1mm in size and are deposited onto the anode in a few ns. One delay line anode design is the double delay line (DDL) (Fig. 15). The MCP charge pulse is detected on, and divided between, two sets of conductive wedges. The Y event centroid position is determined from the ratios of charge signals on the opposing wedge sets. The wedges are connected to external serpentine delay lines so that the pulse arrival time at each end of the delay line is a linear function of the X position of the original event. Such planar DDL's are produced by photolithographically etching the anode pattern into a conductor layer deposited on a low loss microwave substrate. Anodes of this type have been flown on several rocket [13], shuttle [14], and satellite (FUSE)[15] missions. In the case of FUSE (Fig. 19) we achieve resolution of H20µm FWHM in the dispersion direction to give of the order of 4500 x 200 resolution elements over 94mm x 15mm at rates up to 40 kHz.

For high speed imaging detectors we have designed multi-layer monolithic crossed delay line (XDL) anode schemes. The XDL scheme uses a ceramic substrate coated on both sides with a conductor layer. On one surface the conductor is etched to give a set of fingers approximately 0.5mm wide, and as long as necessary for the image format size. Then a set of insulating fingers is applied in the orthogonal direction such that 50% of the bottom layer is left exposed. This orthogonal set is then coated with a conductor, another insulator layer, and finally another conductor. The middle conductor fingers are grounded to ensure that the top and bottom layers are decoupled. The top layer and bottom layer are used to collect the charge from the MCP's with a 50%/50% sharing. Each set of fingers is connected to a serpentine delay line conductor. Since there is no charge division encoding, and the anode propagation times are usually from 10ns to 100ns, very high counting rates may be accommodated (~1Mhz). This XDL scheme allows the ratio of finger widths, and the size of the active area to be varied independently from the delay. Anodes of this type have been built and tested (up to 72 x 72mm), and provide d25um X & Y resolution [16] with good stability and excellent linearity (Fig. 18). XDL anodes were used successfully on four SOHO [17] instrument detectors (32 x 15mm anode format, 500KHz encoding rate) and the two IMAGE SI detectors (27 x 27mm anode format), and are now being incorporated into the COS (18cm x 1cm), CHIPS (65mm), and GALEX (65mm sealed tube) satellite detectors.

Encoding electronics for XDL anodes can have many forms, but a typical scheme consists of high bandwidth amplifiers for each anode end, followed by timing discriminators. These signals provide start & stop for a time to amplitude converter (TAC), the output of which is converted with an analog to digital converter (ADC) to give the event centroid coordinate in each axis. This scheme provides good performance for event rates up to ~500kHz (SOHO). For higher event rates in future applications we have been developing a high speed interpolator system [18] based on surface mount ECL components. This uses clock cycles and interpolated fractions of clock cycles to provide a high speed encoding method with added benefits of low differential non-linearity, high resolution with small package size.

Intensified CCD/CID's

An intensified CCD (ICCD) or CID is a scheme where a CCD device is coupled to a MCP image intensifier (Fig. 21). In analog mode the input image is read out by the CCD directly sensing the output of the phosphor screen. ICCD's may also be used as photon counting, image centroiding sensors [19]. In this mode the MCP's are used at higher gain producing a localized spot of light for each photon event. If the spot of light from the intensifier is made large enough, event centroid positions on a CCD may be found by calculating the center of gravity of the charge signal levels on adjacent pixels. At high gain ($>10^5$) the statistical variation of the event centroid position is much smaller than the overall event spot size. Event position determination to fractions of the CCD pixel size [20] is possible, and resolving 6μm MCP pores across an 18mm intensifier [20] has been achieved. Fig. 22 shows a segment of an ICCD image obtained by photon spot image centroiding demonstrating that individual MCP pores (6um) are imaged. However, the residual nonlinearities of the image due to position interpolation errors require a compensating algorithm to linearize the image. Overall counting rates of $\sim 10^5$ s^{-1} can be obtained, and counting rates within an interpolation area are H1 event per 10 frames for a 10% deadtime due to position confusion when two events fall in similar positions in the same frame. Charge injection devices (CID's) may also be used [21] in instead of CCD's to enhance local counting rates, although their higher noise may be disadvantageous for low signal to noise situations. Future improvements in CCD frame rates and speed of the interpolation algorithm circuits will result in enhanced counting rates. Large format devices and curved focal planes pose some problems with speed and image registration, although we have built highly curved spherical MCP detectors for IMAGE-WIC [22] and curved detectors with 8cm format are currently being constructed.

Cross Strip Anodes

The cross strip (CS) anode concept (Fig. 23) employs many of the design techniques used for the cross delay line (XDL) anodes (Fig. 16)[23]. CS anode is exactly the same as the XDL except that there are no delay lines attached to the charge collection strips. The CS anode works by direct sensing of the charge on each strip, and the subsequent determination of the charge cloud centroid. The charge collected on individual strips is connected to a charge sensitive amplifier on a chip amplifier array. The charge cloud is matched to the anode period so that charge is collected on several neighboring fingers to ensure an accurate event centroid can be determined. A number of possible methodologies may then be used to encode the event centroid position for each axis. The first task is to determine the strip which corresponds to the center peak of the charge cloud, as determined by the strip with the largest signal. This gives the coarse position. The second task is calculation of the charge cloud centroid to a small fraction of the strip width (nQ_n / Q_n) [Q is charge, n is the strip number] which may be accomplished by a hardware or software sum and division.

We have constructed a test anode by the method described. The anode period is 0.5mm, with 16 X fingers and 16 Y fingers covering a 8 x 8 mm area. The top and bottom strips each have H50% of the overall exposed conductor area and the line definition is extremely good. One preamplifier chip (ICD-2, 16 channel) is used per axis for the first test anode. The preamps are followed by shaping and direct signal digitization, with a centroid position calculated in software from the digitized signals of the charge pulse in each axis. The resolution achieved in pulse bench tests is ~10μm at gains of 5×10^6 using 12 bit digitization (Fig. 24). Our first MCP detector test results achieve <25μm at a gain of 4×10^6 without noise optimization. Combined with high speed FPGA logic and commercial fast ADC's very high rates should be possible at low power consumption levels. The CS anode expected spatial resolution is better than many readouts, with higher photon counting rates (>5MHz) and lower power consumption (H2W) than any of the other readout schemes. The CS anode can achieve this resolution while using low MCP gain (low $x10^6$), thus increasing the local counting rate capacity and overall lifetime of the detector system. In combination with very small electronics packaging, the ability to create many formats, environmental robustness, and inherent long wavelength blindness, the CS anode detector scheme is a significant development for space instrumentation.

Pixel Array Anodes

A different approach to increase the MCP detector performance is by pixelating the anode into an independent array of instrumented charge sensing electrodes. Making each pixel a separate readout channel adds the parallelism that increases the readout speed by orders of magnitude. The basic detector configuration

(Fig. 25) consists of a pixelated plane deposited on a substrate and illuminated by a MCP. Each pixel is connected to a processing chain located on the back side of the substrate. An array of processing chains is integrated in a custom designed integrated circuit or Application Specific Integrated Circuit (ASIC). The illumination of the pixelated plane by the electron cloud generated by the MCP is a circle (or oval). The careful positioning of the MCP above the anode plane optionally combined with a focusing voltage allows one to accurately control the extent of the illumination over a cluster of pixels (Fig. 25). The charge deposited on each pixel in a cluster and the time of the deposition represent all the information associated with an event. Measuring the charge on each pixel as well as the total charge on the cluster allows the centroid of the cluster to be determined with an accuracy of the order of 25 microns for MCP gains in the range $10^5 – 10^6$, at encoding rates of >10 MHz. Linear interpolation schemes such as the determination of the charge centroid are easy to implement. Better spatial resolution may be obtained using more sophisticated algorithms but their implementation in the processing chain and the readout is more difficult. A similar centroiding scheme using events detected with an Intensified CCD demonstrated spatial resolutions better than 3 µm and actually resolved individual microchannel pores [24]. Prototype ASIC chips of this type currently exist (Fig. 26, [25]) and are undergoing tests for this application. Pixel array anodes of this type may eventually provide truly high rate, high fidelity image encoding for MCP’s, with small packaging and low power.

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