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High-performance microchannel plate detectors for UV/visible astronomy

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Abstract

Recent advances in basic microchannel plate detector technology include new photocathodes such as diamond and GaN with high UV efficiency (up to $>50\%$), silicon-based microchannel plates with low fixed pattern noise and background event rates less than 0.02 events $cm^{-2}\,s^{-1}$. In combination with cross-strip photon counting readouts with spatial resolutions of $<5\,\mu m$ at low gain (4×10^5) these advances offer considerable performance improvements in future astronomical instruments.

Keywords: Microchannel plate; Photocathode; Photon counting; Imaging

1. Introduction

Advances in photocathodes (GaN, Diamond, GaAs), microchannel plates (silicon MCP's), and readouts (cross-strip) are poised to make a significant impact on the capabilities of future space instruments. GaN photocathodes have achieved $>50\%$ detective quantum efficiency (DQE) in the UV with a bandpass limit of $\sim 400\,nm$. In addition diamond photocathodes have been made with 40% DQE and sensitivity up to 200 nm. New, silicon-based microchannel plates (MCP's) of 25 mm format with $\sim 7\,\mu m$ pores, have achieved gains of nearly 10^4 for a single Si MCP, with high quantum detection efficiency and very low background (~ 0.02 events $s^{-1}\,cm^{-2}$). Cross-strip anodes have been constructed based on multi-layer metal and ceramic cross-strip patterns to encode the charge cloud centroid for each event. The spatial resolution ($<5\,\mu m$) achieved is sufficient to resolve $6\,\mu m$ microchannel plate pores at low MCP gain ($\approx 5\times10^5$) enhancing the overall lifetime of MCP detector systems and providing image linearity good enough to see distortions in the microchannel plate pore alignment.

2. Photocathode developments

High detection quantum efficiency is essential for the next generation of space astronomy instruments. To obtain improvements over conventional cathodes [1] other materials including diamond, GaN and GaAs derivatives are being investigated. Diamond has a large bandgap (5.47 eV, 227 nm) and shows negative electron affinity when hydrogenated or cesiated. Boron-doped polycrystalline diamond films on Si substrates, and a diamond coated silicon microchannel plate, have been measured (Fig. 1). Hydrogenated diamond DQE's of up to 40% (at 400 Å) have been achieved [2] and Cs activation

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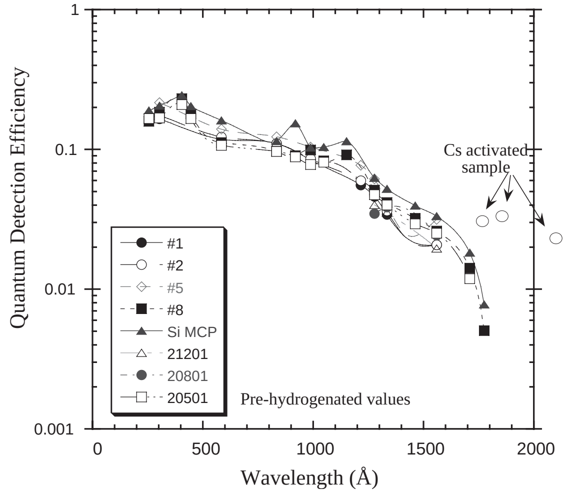

Fig. 1. Opaque DQE vs. wavelength for diamond samples on Si and Si MCP's.

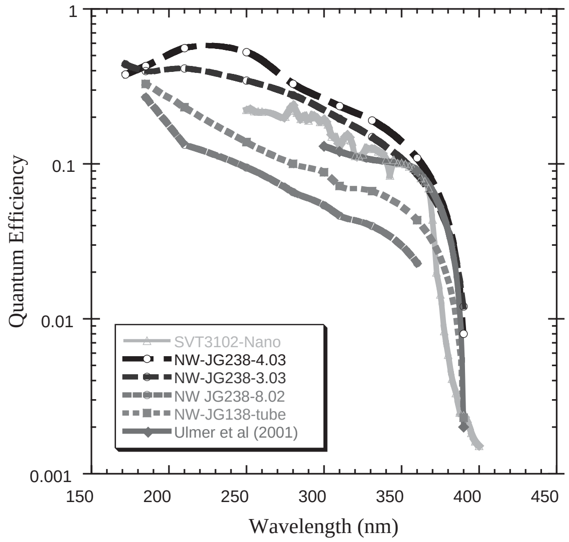

Fig. 2. Opaque GaN DQE vs. wavelength showing advances in activation methods.

shows considerable promise for DQE enhancement at longer wavelengths (Fig. 1). The diamond film is very stable [2], and DQE can be repeatedly restored by re-activation.

Ulmer et al. [3] reported opaque GaN cathodes with efficiencies of up to 30% (Fig. 2) at 200 nm. Our early work with GaN only produced high efficiencies at short wavelengths (Fig. 2). Most recently, we have improved the processing techniques for Mg (*p* doped) GaN material and achieved DQE's $>50\%$ (Fig. 2) with cesium surface activation. These results are slightly better than similar samples processed for us at Nanosciences Inc. The cathodes show a well defined cutoff (380 nm), are relatively stable over a timescale of months and can be repeatedly re-activated.

The QDE of GaAs and GaAsP have been increased to $\sim 50\%$ [4] in the 300–900 nm regime by recent advances in materials and processes. When cooled ($-20°$C) the background rate can be reduced to <10 events/s. High DQE devices with high spatial and time resolution (<500 ps) are possible using these cathodes with MCP's.

3. Silicon microchannel plates

Silicon (Si) MCP's are produced by photolithographic etching of Si wafers and deposition of a secondary electron emissive surface. These Si MCP's (effectively quartz), are thermally robust (800°C) and photocathode compatible. Hexagonal pore Si MCPs with high gain and open area ratios of $>75\%$ have been successfully fabricated. The samples we have tested are 25 mm format with $\sim 6\,\mu$m pores, with square or hexagonal pore shapes. Gain of nearly 10^4 [5] for a single Si MCP has been achieved, and we have achieved gain of 10^6 for a four Si MCP stack. The quantum detection efficiency (Fig. 3) for Si MCP's is the same as glass MCP's but the background rate is very low, ~ 0.02 events s^{-1} cm^{-2} [5]. The flat field images obtained with a cross-delay-line readout are free of any patterned modulation [5], with good gain uniformity. Efforts currently underway are aimed at improving the fabrication process so that the stability and yield are improved and large-area Si MCP's are feasible.

4. Cross-strip imaging readout

The cross-strip (XS) anode is a multi-layer metal and ceramic cross-strip pattern on a ceramic (alumina) substrate. The conductors are fabricated as a set of fingers approximately 0.5 mm wide. Sets

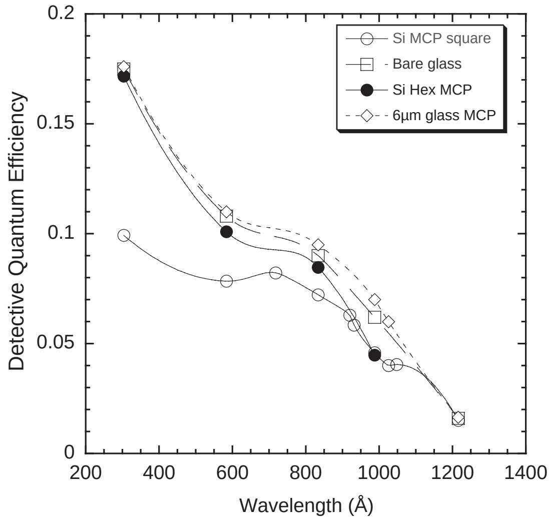

Fig. 3. Square and hex pore Si MCP DQE compared with glass MCP DQE's.

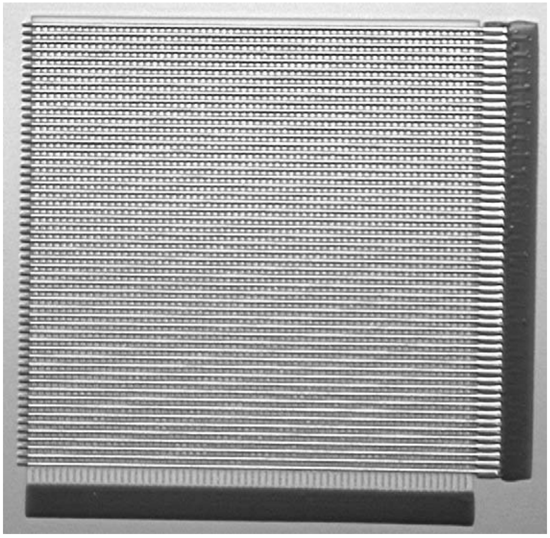

Fig. 5. Photo of a 32 mm × 32 mm cross-strip anode with 0.5 mm strip periodicity.

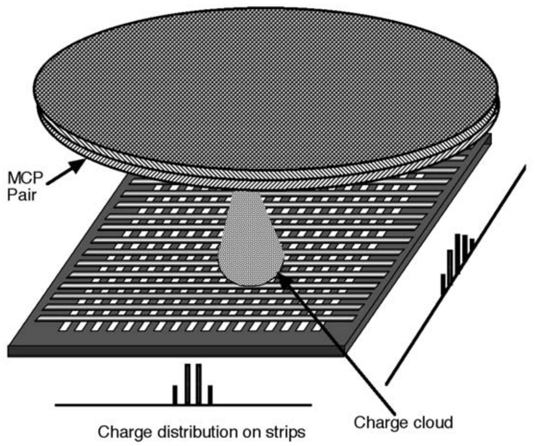

Fig. 4. Schematic of a cross-strip anode readout for an MCP photon counting sensor.

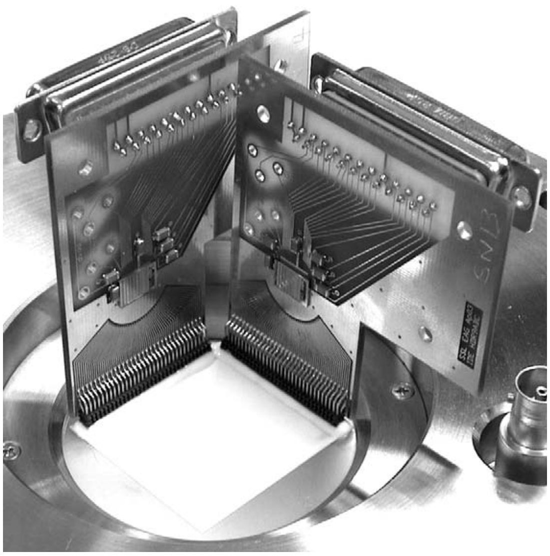

Fig. 6. Photo of IDE ASIC amplifiers mounted directly to the cross-strip anode.

of insulating and conducting fingers are then applied in the orthogonal direction so that 50% of the bottom layer is left exposed. The top and bottom layers are used to collect the charge from the MCP's with a ~50%/50% sharing (Figs. 4 and 5). The charge cloud is collected on several neighboring fingers of each axis to ensure an accurate event centroid can be determined. Signal amplification is accomplished with ASIC preamplifiers (IDE) on small boards (Fig. 6). These are connected to the strips on the anode using small dual in line connectors attached to hermetic conductive vias in the anode substrate. Position encoding is accomplished by analog-to-digital conversion of individual strip charge values and a software or hardware centroid determination.

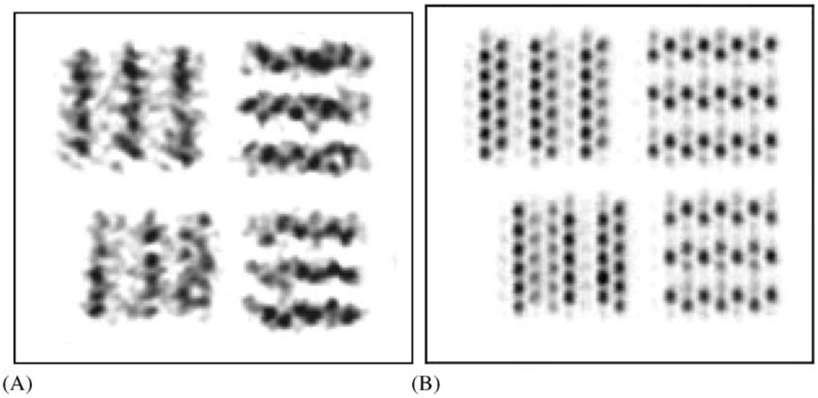

Fig. 7. Cross strip image (A) of Air Force test mask (group 5:5 & 5:6) with a pair of 6 μm pore MCP's at 1.3×10^6 gain compared with an optical photo (B) of the mask on one MCP.

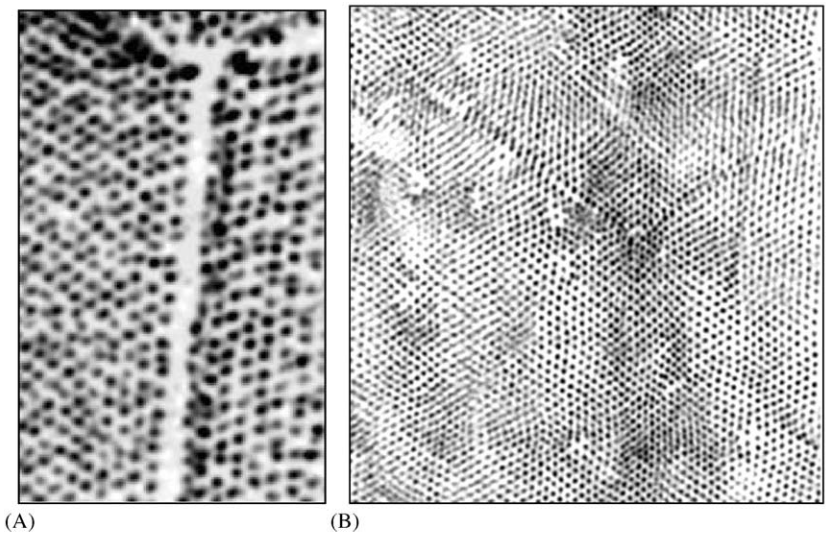

Fig. 8. (A) Cross-strip image of a small section of a single 12 μm pore MCP at $\sim2\times10^5$ gain and (B) an image of a stack of three 12 μm pore MCP's at $\sim2\times10^6$ gain.

The strip which corresponds to the center peak of the charge cloud gives the coarse position. The strip capacitances are small (few pF) and the preamplifier noise is low ($<500e^-$) compared to the MCP signal ($\sim10^6e^-$). Therefore, the calculation of the charge cloud center of gravity can be made to a small fraction ($<1\%$) of the strip size. For the 32 mm × 32 mm anode (Fig. 5) the spatial resolution is high enough (<5 μm) that the pores of a 6 μm pore MCP pair can be resolved (Fig. 7A) at low gain ($\approx1.3\times10^6$) and we can see how the relative position of the MCP pores affect the image fidelity (Fig. 7B). The image resolution and linearity is good enough to enable the MCP pore pattern to be seen even for a single MCP (Fig. 8A) at low gain (2×10^5). This also shows the pore image displacement effect produced at the multi-fiber boundary of the MCP. The distortions produced in a stack of MCP's due to pore misalignments is also observable in the form of displacements in the position of pore images of the first MCP of the stack (Fig. 8B).

The use of low MCP gain will enhance the local counting rate capacity and extend the overall lifetime of a MCP detector system with cross-strip readout. The compact configuration is robust (900°C) and can be integrated into sealed tubes or open face detectors. Furthermore, using high-speed digital logic and fast ADC's, and an anode with custom chip electronics, we envision the position encoding can be accomplished at high photon counting rates (MHz) with low power consumption ($\sim$2 W) for applications in space astrophysics.

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