Next-Generation MicroShutter Array for HWO UV Multi-Object Spectrograph

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We report recent advances in the Next-Generation MicroShutter Array (NGMSA) technology, which enables programmable field selection for the Habitable Worlds Observatory's Ultraviolet Multi-Object Spectrograph with the capability to simultaneously capture over 256 spectra per quadrant (384 × 768 pixels) across various astronomical targets. By replacing the James Webb Space Telescope's flying magnetic actuation system with an electrostatic actuation mechanism, NGMSA achieves scalability to formats exceeding $7.2' \times 7.2'$ with over one million shutters in 2 × 2 mosaic configurations, while maintaining low mass (approximately 1.5 kg per quadrant) and eliminating mechanical complexity and life-limited components. This technology, baselined for LUVOIR, HabEx, and CETUS Decadal Survey mission concepts, is slated for integration into the HWO's UV multi-object spectrograph instrument to enable spectroscopic capabilities for targets ranging from cosmological objects to solar system bodies.

1. Introduction

Multi-object spectroscopy (MOS), designated as a Tier-1 technology gap in the NASA Astrophysics Biennial Technology Report (2024) (NASA 2024), represents a critical technology development priority identified by the Large Ultraviolet Optical Infrared Surveyor (LUVOIR, Roberge et al. (2021)), Habitable Exoplanets Observatory (HabEx, Gaudi et al. (2019)), Cosmic Evolution Through UV Surveys (CETUS, Kendrick et al. (2019)), and the Decadal Survey: Pathways to Discovery in Astronomy and Astrophysics for the 2020s (National Academies of Sciences et al. 2021). While ground-based MOS applications commonly employ robotically configured fibers and punch plates for aperture control, these approaches present significant challenges for spaceflight implementation. The NASA-developed MicroShutter Array (MSA) technology, functioning as a programmable field slit mask, effectively addresses this limitation thanks to its compact size and space-compatible actuation mechanism. This reconfigurable MSA system can generate arbitrary patterns of slits corresponding to sparsely distributed celestial sources and provide functionality analogous to punch plate systems during spaceflight. The first generation of this MSA technology has been demonstrated successfully with the James Webb Space Telescope (JWST) Near Infrared Spectrograph (NIRSpec) instrument (Rigby & *et al.* 2023).

Built upon the success of JWST MSA, the NASA team initiated development of Next-Gen MicroShutter Arrays (NGMSA, Fig. 1), which eliminate the need for heavy and complex flying-magnetic assemblies and enable scalability to large formats with very low mass, no external mechanical complexity, and no life-limited mechanical components. The principal application target for our NGMSA technology is the Ultraviolet Multi-Object Spectrograph of the Habitable Worlds Observatory (HWO), a primary instrument of the new flagship mission in the 2040s. Current science drivers being defined by the HWO Technology Maturation Project Office (HWO TMPO) necessitate the capacity to acquire multiple spectra across diverse astronomical contexts, spanning sparsely populated fields, extended objects, and point-like targets, from cosmological structures to galactic star formation regions, individual extended objects, and solar system bodies. Directly tied to the HWO needs, the technical goal of NGMSA is to advance the Technol-

Fig. 1.— The NGMSA is scalable to meet different field of view needs. Our pilot (FORTIS) and JWST formats are shown on the left. A concept and manufacturing development array is shown in the center; we also produced a ruggedized design of an array mounted on a ceramic carrier with a supporting grid that has been demonstrated through test to general environmental verification standard (GEVS) vibration levels for evolved expendable launch vehicle (EELV) launch, shown on the right.

ogy Readiness Level (TRL) of our electrostatically actuated microshutter arrays in large format from TRL-3 to TRL-5 to enable the MOS capability of the UV Spectrograph Instrument of the HWO. To validate operating the NGMSA in space, we used the Far-ultraviolet Off Rowland-Circle for Imaging and Spectroscopy (FORTIS) sounding rocket program as a flight test platform for the strategic mission application (Li et al. 2020; McCandliss 2021). We demonstrated this technological advancement through successful operations of a 64×128 array on two sounding rocket missions: the Next Generation FORTIS (NG-FORTIS) mission 36.352UG in October 2019, which observed the star-forming spiral disk galaxy Messier 33 (M33), and the Off-Axis FORTIS (OAx-FORTIS) mission 36.384UG in August 2024, which targeted hot horizontal branch stars in the globular cluster M10. A third demonstration is planned for a forthcoming flight in 2026.

2. NGMSA TRL Elevation

This section outlines our strategy to advance NGMSA technology to TRL-5 before the HWO Mission Concept Review (MCR) in March 2029, encompassing our design criteria, fabrication and packaging processes, apparatus development, and final qualification testing. Currently, the NASA Technology Management Board of the Physics of the Cosmos/Cosmic Origins Program Office has assessed our current TRL as 3 for drive electronics and 4 for shutter arrays. The development of rad-hardened drive electronics will occur during HWO phases A-C.

2.1. Design Concept and Criteria

The NGMSA technology revolutionizes microshutter design by implementing purely electrostatic actuation to replace magnetic dependencies, creating an ultra-scalable architecture for substantially larger formats with significant mass reduction. This fully electrical system enables random access to individual pixels in large-format single modules with response times over 100 times faster than JWST MSA, while facilitating an entirely modular array design. Adaptable across UV, visible, and infrared spectra, the current NGMSA specifications are designed to exceed the HWO requirements (Table 1).

Our goal is to enable the capability to simultaneously track 1024 independent objects within a $7.2' \times 7.2'$ field of view using a 2×2 mosaic configuration- quadrupling JWST MSA's capability. The microshutter technology offers a fundamental advantage in high on/off contrast over competing technologies (Kutyrev et al. 2008; Travinsky et al. 2017; Mitchell et al. 2023), minimizing background noise while maximizing signal-to-noise ratio. Current NGMSA arrays deployed on FORTIS flights have demonstrated on/off contrast ratios more than 10^5 in the relevant far ultraviolet (FUV) wavelength range and beam f/#. We anticipate our design specifications to exceed or meet all forthcoming HWO requirements, and will make adjustments once the final specifications are announced.

2.2. Refinement of Fabrication Processes

The NGMSA for HWO is designed on a 150-mm diameter silicon-on-insulator (SOI) fabrication process, which is derived from the 100-mm JWST MSA process with several

Table 1: NGMSA Design Specifications

Attribute	Spec/Attribute Value
Field of View	$7.2' \times 7.2'$ for the 2×2 mosaic configuration
Pixel Numbers	384×768 (294.9K shutters) for each quadrant, more than 1 million total shutters for the 2×2 mosaic configuration
Fill Factor	50% - 60%
Contrast	Higher than 2×10^4 for the diffuse objects and 1×10^5 for the point sources
Source Multiplexing	256 objects simultaneously per quadrant, 1024 for the 2×2 mosaic configuration
Lifetime	More than 10^6 actuations
Wavelengths	Independent within UV/Optical range (100nm – 1000nm)
Size	No larger than $180\ mm \times 180\ mm$ for each quadrant (MSA with fanout circuitry)
Mass	Less than 1Kg for each quadrant

improvements. Aluminum oxide formed by atomic layer deposition is significantly more conformal and uniform than E-beam silicon oxide. This approach drastically enhances the properties of the dielectric used between the electrodes. Dry release using gaseous etchant, such as vapor hydrofluoric acid, prevents membrane stiction caused by Laplace pressure during liquid drying phase and ensures free standing structures. We have manufactured several pathfinder arrays using this new process and with it, we refined the shutter geometry designs for improved performance (Chang et al. 2020; Ke et al. 2022; Kim et al. 2024).

To increase the fabrication yield to meet the HWO requirement, we continue to refine the process on the basis of the metrology and testing results. To minimize photoresist breakage during the contact alignment process, for critical steps in the process, such as blade and torsion bar patterning, we will replace contact lithography with non-contact lithography techniques, such as stepper and direct laser writing. These advanced lithographic techniques also enhance the accuracy of micron feature size and tolerance to the sub-micron range for the blades and torsion bars, and thus increase the uniformity of actuation. Additionally, to improve alignment between the shutter blades and frame structures, we will optimize (1) the wafer de-bowing process to flatten the wafer and fine-tune the thermal process to prevent wafer bond reflow and (2) the etching pressure and temperatures to prevent wafer deformation during the process, both of which will have a positive impact on the shutter operation uniformity and contrast ratio.

The integrity of the shutter frame can greatly affect the UV contrast and requires special attention. We are currently exploring how the surface smoothness of the frame's sidewall, which is affected by periodic sub-micron indentations caused by the Bosch process, affects the scattering or reflection of UV light. Electrically, the surface roughness may affect the coverage of subsequent depositions of dielectric and conductive films. To optimize the roughness property of the frame, the surface can be treated with fluorine plasma to enhance smoothness, thereby ensuring the integrity of subsequent insulation and electrode depositions, and ultimately, operational reliability. Additionally, the surface of the shutter blades and frames can be treated with anti-stiction coating to minimize blade stiction to the frame, and thus prevent stuck-open failures.

2.3. Packaging Designs, Concerns and Resolutions

We conducted a trade study to determine the most rational configuration for a fully operational MSA module, which includes various parameters such as optical, mechanical, and electrical characteristics, fabrication feasibility, and material compatibility. Following instructions from the HWO TMPO, requirements from the LUVOIR and HabEx studies, alongside heritage requirements from the JWST, we have adopted a 2×2 mosaic configuration (Fig. 2) to place four MSA quadrants positioned at the central locus of the instruments. Each MSA module comprises several key components: a microshutter array, a fanout substrate, mechanical support structures, and control electronics. Presently, we adhere to the JWST specification of shutter frame width to ensure that the inter-array gap within the usable viewing areas remains adequately minimal.

We meticulously assessed hybridization options for the MSA-substrate stack construction. While initially choosing aluminum oxide as the fanout substrate with underfill epoxy bonding for the ambient-temperature instrumentation proposed under LUVOIR and HabEx studies, we encountered two significant challenges: the epoxy-underfill method buried front electrodes within the interface, necessitating problematic 3D-printed interconnects or wire bonding across millimeter-thick substrates, and the coefficient

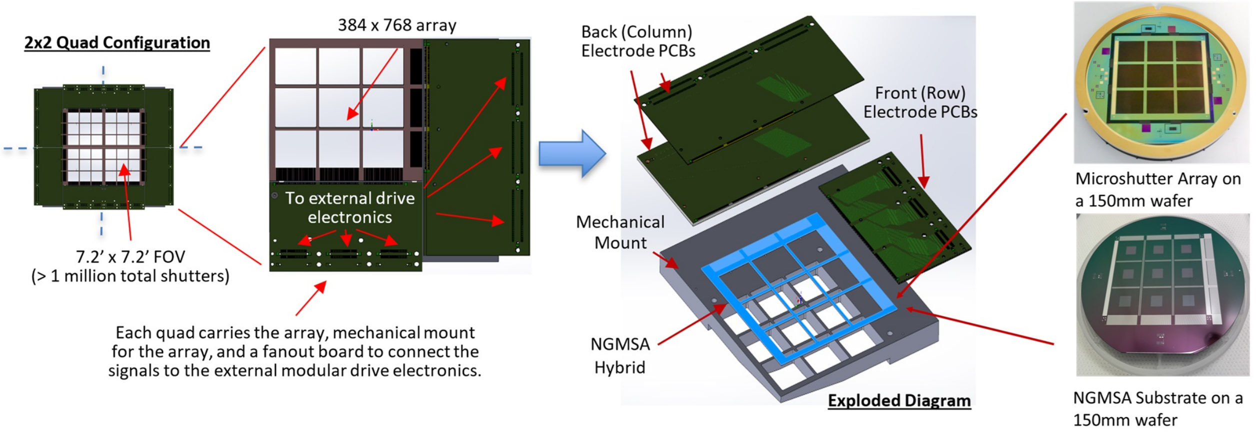

Fig. 2.— A two-side buttable entirely electrically-actuated NGMSA quad will be demonstrated for TRL-5 as a multi-object selector with $> 10^5$ UV contrast through a series of tests demonstrating HWO requirements are met in a relevant environment. This TRL-5 demonstration hardware includes an NGMSA assembly (an array hybridized with a substrate) and PCB fanout boards, all supported by an array mechanical mount. An auxiliary set of drive electronics, not part of the TRL-5 hardware, will be used for array actuation. The current 150-mm large format NGMSA fabrication process, evolved from the established 100-mm JWST MSA manufacturing, functions as a critical pathfinder for producing the large-format arrays for the HWO instrument.

of thermal expansion mismatch between silicon MSA (2.6 ppm/K) and aluminum oxide substrate (8.1 ppm/K) created a 0.55 μm/K discrepancy along the array periphery, potentially causing electrical discontinuities. To address these challenges, we reverted to the JWST MSA configuration, employing indium bump bonding to mount the MSA on a silicon substrate, where bump arrays serve dual roles in electrical conduction and mechanical anchoring. The primary concern with silicon as fanout substrate was the need for additional mechanical support to meet GEVS vibration requirements for EELV launch. After assessing various support structure materials, we found most candidates satisfy the f-number requirement with reasonable structural dimensions. Even titanium, which represents the worst-case scenario with 4.4 mm thickness for required stiffness, offers a minimum f/# = 8.4 and is still well within the LUVOIR requirement (f/#: 18.44 on MSA).

Another key purpose of our planned HWO prototype module is evaluating and optimizing driver electronics designs. Initially, we developed PCBs with all electronics integrated into a single board, which restricted our ability to address design issues and test alternative components. Our current approach implements a fully modular design instead. The HWO demo assembly features fanout PCBs divided into three distinct sections for interfacing with the FOB and driver electronics, allowing easy replacement when design issues arise. Additionally, we have designed the driver electronics as compact daughter board modules that can be readily swapped with different configurations, significantly enhancing testing flexibility and upgrade potential.

2.4. Testing Developments for TRL-5 Validation

Building upon lessons from the JWST era when testing was limited to post-packaging evaluation, we have now developed a ’dual-side’ probing system to enable 2D-addressing tests on unpackaged NGMSA dies (Fig. 3(a) and (b)). This innovation provides essential pre-packaging screening that significantly reduces wasted effort on defective arrays. Such capability is crucial since microshutter array packaging requires multiple specialized engineers and typically produces only two units per month when not performed continuously. Through this early identification of viable arrays prior to the labor-intensive packaging process, we save substantial time and resources while maximizing production efficiency.

To meet TRL-5 requirements, we have designed two vacuum testing systems to evaluate NGMSA operation in space-relevant conditions at NASA Goddard Space Flight Center (GSFC). The 2D-addressing system (Fig. 3(c)), with two 8” windows for full-array viewing through X-Y translational stages, enables comprehensive assessment (yield, operation, lifetime, etc.) of microshutter arrays after initial screening and PCB mounting in the vacuum chamber. The UV contrast measurement system (Fig. 3(d)) evaluates performance across the 115-300 nm wavelength range where light more readily scatters past closed blades. This latter setup incorporates an external vacuum UV monochromator feeding optical elements that produce images captured by a UV camera mounted on an external flange. This system in-

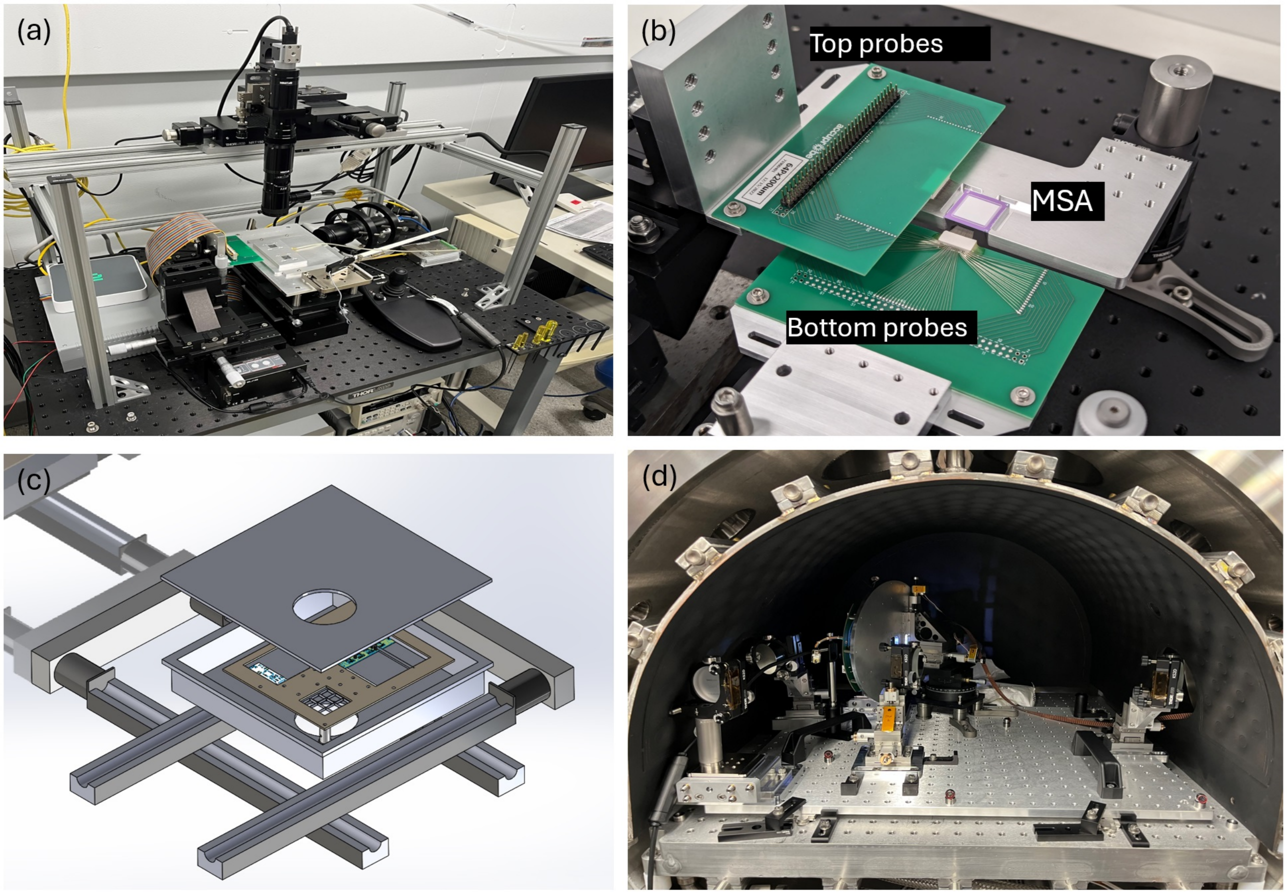

Fig. 3.— Testing apparatus developed for TRL-5 developments: (a) We developed an array actuation system which is capable to screen an array at the die level prior to the packaging process. (b) Based on the actuation system, we are developing a dual-side probing system that will enable 2D-addressing of the arrays prior to packaging. A 64 × 128 test array is shown in the image. (c) The Solidworks model of the vacuum chamber on X-Y stages for 2D-addressing. (d) The vacuum chamber interior showing UV contrast experiment insert platen. Also shown are chamber shroud and plumbing for thermal control.

cludes all necessary components, such as mirrors, mounts, and stages, for integration into a UV-compatible thermal vacuum chamber (TVAC) for testing candidate arrays we have identified.

TRL-5 is achieved once there is "component/breadboard validation in a relevant environment". In our program, the component being demonstrated is a fully functional NGMSA module. Rad-hardened drive electronics are not within the scope of this pre-phase A development or the TRL-5 demonstration and will be developed in phases A to C. A brassboard mosaic carrier with a fully functional MSA will go through: (1) A full mechanical test program followed by a performance test, (2) A thermal survival test, where performance is demonstrated after exposure to the full survival temperature range, and (3) Radiation tests up to a 10-year dose at the second Lagrange point assuming nominal shielding. All environmental tests will be performed using the facilities at NASA Goddard Space Flight Center.

3. Fabrication Results and Testing

Our preliminary process optimization efforts with 64 × 128 arrays fabricated on 100-mm wafers have demonstrated promising results (Fig. 4), achieving near 100% yield in electrical performance without adjacent or electrode-to-ground shorts. The initial scaling to 150-mm wafers for larger arrays has achieved approximately 60% functional yield, though further process refinement is needed to improve uniform actuation. These early results suggest that our targeted approach focusing on fabrication tool upgrades, process parameter optimization, and enhanced contamination control strategies is essential to increase the functional yield to $> 90\%$ to meet the HWO requirement through additional development cycles.

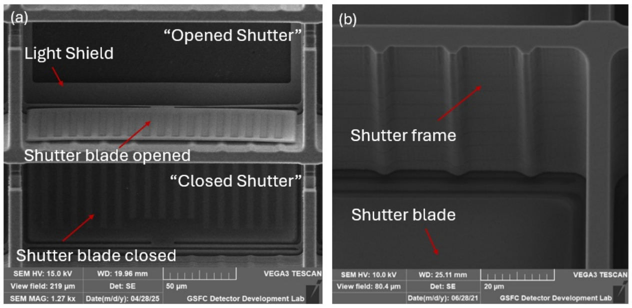

Fig. 4.— The SEM images of microshutters: (a) Open and closed shutters. Light passes through open shutters, while the light-shield adjacent to the shutter blades minimizes leakage through gaps between frame walls and shutter perimeters when shutters are closed. (b) The integrity of the shutter frame's contact surface with the blade during actuation is crucial for ensuring reliable operation over repeated cycles and directly impacts the overall lifetime of the NGMSA system.

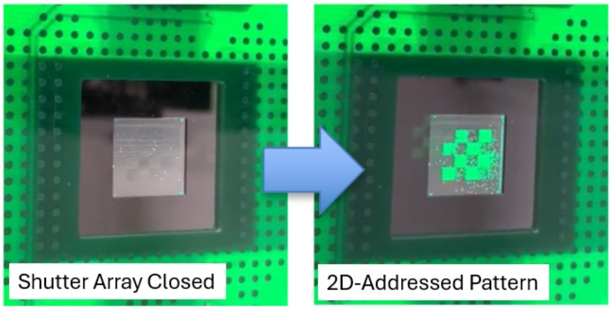

Fig. 5.— Microshutter elements necessitate rapidly rising voltage profiles to generate sufficient actuation momentum for stable operation across the entire array. Among the commercial off-the-shelf (COTS) ICs we have tested, the time domain response of HV3418 with $> 25V/\mu s$ slew rate was found to be adequate for shutter actuation. The right figures show the 2D-addressing pattern of an NGMSA testing device using the HV3418 and HV2801 driver chips with the -40V to 80V operation voltage range.

Actuation testing confirms that NGMSA requires front electrodes to receive fast-rising 120V signals, with voltage rise time correlating directly with electrode capacitance. Our initial evaluation of commercial driver ICs has identified the HV3418 low-voltage serial-to-high-voltage parallel converter as a promising candidate (Microchip 2018), demonstrating adequate slew rate characteristics in early testing. As shown in Figure 5, our first 2D-addressing pattern demonstrations using the HV3418 for front electrode driving and the HV2801 (Microchip 2019) for back electrode management have successfully activated 2D patterns on a 64 × 128 test array. These preliminary tests, while using non-radiation-hardened components suitable only for early development, provide a valuable baseline architecture for future flight-qualified application-specific integrated circuits (ASICs).

Initial contrast measurements at Johns Hopkins University reveal that our NGMSA prototypes can achieve on/off contrast values exceeding 10^5 for 1849 Å, 2537 Å, and 3004 Å, and 5×10^4 for 2214 Å with focal ratios larger than f/12 (Mitchell et al. 2023). More recent experiments using the aforementioned UV contrast measurement system at GSFC demonstrated contrast in excess of 6×10^4 on the external optical bench at optical wavelengths (Fig. 6). The plans moving forward are to optimize the MSA mounting and then move the bench into the UV vacuum chamber to repeat the experiment and transition to point source simulation. Additionally, the study of blade flattening and light-shield designs, a critical aspect for improving NGMSA contrast performance, has yielded preliminary results showing successful reduction of blade bowing to sub-micron levels at room temperature. While these initial results require further verification across broader operating conditions, they already suggest performance superiority compared to alternative technologies like Digital Micromirror Devices, which reportedly achieve maximum contrast ratios of approximately 6,000:1 (Travinsky et al. 2017). These encouraging early-stage results demonstrate NGMSA technology's potential to provide the high-contrast performance essential for HWO's UV multi-object spectrograph and confirm it as the leading UV-MOS candidate to achieve the observatory's science goals.

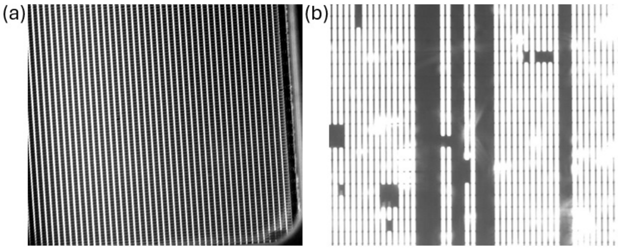

Fig. 6.— Contrast measurements using facilities at GSFC are currently in progress. While we highlight measurements at beam speeds specifically relevant to HWO requirements, we also aim to improve contrast ratios exceeding 10^5 in the low f/# (particularly f/8 - f/12) range to enhance overall device capabilities. (a) This preliminary image shows the MSA under UV light with all shutters closed, where the visible light is glint shining off the light-shields from the side. (b) Measurements of optical band contrast reveal scattered light patterns, providing crucial feedback to the design and fabrication team.

4. Conclusion and Path Forward

To close the technology, engineering, and facility gaps associated with the formulation and implementation of the HWO, our group has submitted a TRL elevation roadmapping plan to the HWO TMPO to advance the technology to TRL-5 by 2029. Currently, our NGMSA project focuses on refining and optimizing fabrication processes and component integration for fully functional devices. We're studying shutter operation to understand how actuation parameters respond to fabrication tolerances. The current NGMSA demonstrates impressive UV contrast exceeding 10^5 in specific FUV wavelengths and beam configurations.

While small-format arrays flown on FORTIS and Off-Axis FORTIS sounding rockets have provided valuable flight performance data, scaling up to meet HWO's large format requirements remains crucial. These larger arrays are now in development under NASA's Strategic Astrophysics Technology (SAT) program, with yield, contrast, and functional shutter count as key metrics. Our experience reveals that process improvements successful with 100-mm small-format arrays often don't translate directly to 150-mm large-format arrays. This difference requires multiple refinement cycles to achieve optimal yield. Despite these challenges, the development of NGMSA is progressing at a steady pace. With pilot devices already validated in suborbital flight conditions, we are confident our NGMSA technology (excluding drive electronics) will achieve TRL-5 before the MCR in March 2029.

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