# Scalable Microshutter Systems for UV, Visible, and Infrared Spectroscopy

Prepared by: Matt Greenhouse (PI; NASA/GSFC) and Meng-Ping Chang (NASA/GSFC)

## Summary

This Strategic Astrophysics Technology (SAT) project started on Oct 1, 2018, with a three-year duration ending on Sep 30, 2021 to develop a large format Next-Generation Microshutter Array (NGMSA). The project website is located at: <u>https://asd.gsfc.nasa.gov/ngmsa/</u> and contains publications and other productivity resulting from this SAT-funded work.

The team at GSFC includes scientists Matt Greenhouse/PI/Code 665, Alexander Kutyrev/Deputy PI/Code 665, Rainer Fettig/Deputy PI – Technical/BeaconGov, and engineers Meng-Ping Chang/PDL, Carl Kotecki/Testing Lead, Regis Brekosky/Fabrication Lead, Frederick Wang/Packaging Lead, Beth Paquette/3D-Printing lead, Tim Miller, Ed Aguayo, Ron Hu, Nick Costen, Samelys Rodriguez, Ming Ke, Kyowon Kim, and Knute Ray in Codes 553, 564, and Newton Inc. Rainer Fettig joined the team in March 2020 as the Deputy PI – Technical. Ming Ke, a PhD student from UCLA, was hired as a pathway intern in May 2020. Our collaborators include Prof. Stephan McCandliss/JHU/Co-I, and his team.

The primary objective of this project is to advance electrostatically actuated microshutter arrays in a large format (736×384, 282.6K total pixels) from Technology Readiness Level (TRL) 3 to 5 in support of the Large UV/Optical/IR Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), and Cosmic Evolution Through UV Spectroscopy (CETUS) Probe Decadal Survey mission concept studies. The microshutter array, utilized as multi-object selectors (MOS), is an enabling optical field mask technology to each of these mission concepts.

COVID-19 impact to this project derives from the protocol requirement for social distancing which remains in effect under Stage 2 of the Agency COVID-19 framework. The fabrication and testing labs at Goddard Space Flight Center (GSFC) were closed and all personnel were under mandatory telework orders from March to September 2020. After October 2020, the labs reopened and operated at less than 50% capacity. This caused 12.5-month delay to our fabrication progress, and to a lesser extent for the rest of the tasks. An additional SAT investment cycle will be necessary to bring TRL maturation to the point where further development can be handed-off to the selected strategic missions (HabEx and LUVOIR) and Probe(s).

Our original SAT goal was to demonstrate a fully functional single-array-module (SAM) assembly at the end of the third year, reaching TRL 5 for LUVOIR, HabEx, and CETUS missions. With completion of vibration testing, the SAM has advanced from TRL-3 to TRL-4. However, due to the impact of COVID-19, further TRL maturation will necessitate a fourth project year.

A breakthrough achievement during the COVID pandemic was the advancement of multi-physics analytical modeling of the NGMSA [1-3]. This modeling has revealed the root cause of a "stuck shutter" problem that was encountered on devices utilizing the JWST microshutter technologies. Our new NGMSA design now incorporates mitigation of this problem.

The milestones this year include progress in fabrication of fully functional large-format SAT microshutter arrays and development of a characterization system to verify the fabricated SAT arrays. This involves development of a SAM that includes a  $736 \times 384$  SAT shutter array packaged to a ceramic substrate, which is fully populated with IC drivers and other passive electronic components for shutter operation.

MOS is a technology development priority of the Cosmic Origins (COR) Program. Aperture-control methods that are popular in ground-based MOS applications (e.g., robotically configured fibers and punch plates) are not practical for spaceflight. Microshutter array technology solves this problem. A microshutter array functions as a slit mask. The array can be programmed to provide any pattern of slits corresponding to sparsely distributed sources on the sky (similar to a punch plate). It can also be programmed to provide shaped slits on extended sources. This SAT technology development is anchored to Astrophysics Division Sponsored Strategic- and Probe-class mission studies: the LUVOIR Ultraviolet Multi-Object Spectrograph (LUMOS), the HabEx Workhorse Camera (HWC) and Ultraviolet Spectrograph (UVS), and CETUS. All of the above studies baseline our microshutter arrays as their multi-object selectors.

As part of our participation in the Far-UV Off Roland-circle Telescope for Imaging and Spectroscopy (FORTIS) project led by Prof. S. McCandliss (JHU), pilot microshutter arrays with 128×64 shutters have been developed for a sounding rocket mission: the Next Generation FORTIS (NG-FORTIS), a pathfinder for developing the technologies necessary to enable far-UV spectroscopic surveys [4, 5]. Two flight assemblies were delivered to JHU for the October 27, 2019 NG-FORTIS launch. This was the first flight mission operating NGMSA and demonstrated electro-pulsed actuation of microshutter arrays, in space. Our latest APRA sounding rocket proposal (FORTIS-3G) was selected in May 2021 and will demonstrate our current electrostatic design including the stuck shutter mitigation discussed above.

# Background

Our first-generation micro-shutter technology enabled realization of the James Webb Space Telescope (JWST) Near-Infrared Spectrometer (NIRSpec). This prior-generation technology involved a combination of electrostatic and magnetic actuation, resulting in a heavy and complex mechanical assembly that does not scale to the larger formats required by strategic mission concepts studied for the 2020 Decadal Survey.

Our NGMSA technology eliminates the magnetic actuation aspect, resulting in a shutter array that is scalable to very large formats with very low mass, no external mechanical complexity, and no life-limited mechanical components. This major breakthrough was demonstrated to TRL 9 in pilot 128×64 arrays of 200- $\mu$ m × 100- $\mu$ m shutter pixels with light shields, under prior APRA and GSFC internal investment funding. This SAT project will advance the above NGMSA state-of-the-art to a 736×384, three-side-buttable format to support strategic mission applications.

NGMSA technology enables an on/off contrast of >10<sup>5</sup> – much higher than what was achievable with micro-mirrors. The ease with which they can be integrated into a wide range of instrument optics designs ensures broad science-community return-on-investment for this technology. The wide range of mission concept studies that are designing around NGMSA illustrates the broad science pull for maturation of this technology. Recognizing the fundamental advantage of microshutters and the need for a technology that can be scaled to large-format arrays to meet the MOS requirements of the Astrophysics Division Strategic Plan, we have anchored development of the NGMSA to multiple mission applications. These missions include LUVOIR and HabEx strategic missions, CETUS Probeclass mission, and the ongoing FORTIS sounding-rocket program as a flight test platform.

# **Objectives and Milestones**

The primary objective of this project is to advance electrostatically actuated microshutter arrays in a large format from TRL 3 to 5 in support of LUVOIR, HabEx, and CETUS. Microshutter devices are an enabling technology for the MOS capability in each of these mission concepts. The milestones of the third year are:

• Integrated module – completing full-scale scalable module fabrication; completing mechanical survival tests to destruction of array module;

- Lot-split testing to determine optimal key-stone shutter blade dynamic clearance; and
- Assembly completing mechanical structure fabrication and two-module integration.

The past performance year has been the most challenging period to this program due to the COVID-19 pandemic. We had to work at a reduced on-site capacity and telework for most of the time, which caused significant delays, particularly in the fabrication progress. At the end of the third year, however, we plan to complete the development of large-format SAT shutter-array design with all electrostatic actuation features. We should complete substrate design and testing, and ready the test facilities. In the fourth year, with completion of the above milestones, we would be able to produce a SAM that includes a large SAT shutter array packaged to a ceramic substrate. The substrate should be fully populated with IC drivers and other passive electronic components for shutter operation.

## **Progress and Accomplishments**

We had made excellent progresses on multiple aspects until COVID-19 started to impact our schedule since March 2020. The pandemic slowed fabrication and lab work. However, it also provided an opportunity to advance analytical modeling which led to a new understanding of the dynamic clearance required by the shutter blades, ensuring reliability beyond what was achieved by the prior JWST-era technology.

## 1. SAT-Array Fabrication

Due to COVID-19 restrictions, array fabrication activities are 12.5 months behind the originally proposed schedule. Fabrication activities partially resumed during late September 2020, and we are currently at 50% workforce capacity in the fabrication facility.

Figure 1 shows a SAT array at different fabrication stages. As shown, the SAT array architecture involves nine subarrays with total 282.6k pixels (736×384, including 240×128×6 for the top and bottom three subarrays; 256×128×3 for the middle three subarrays) that are supported by a ceramic grid structure to provide resiliency to the launch environment (vibration and acoustics). We completed most major process developments, including front electrode and shutter blade patterning, silicon handle layer removal and back deep reactive-ion etch (DRIE). We are currently patterning the back metal and insulation layers on the mechanical model. This mechanical model will be mounted to a substrate for our 3D printing test and used as the test article for a vibration test to destruction. This will enable us to determine the design capability beyond general environmental verification standard (GEVS) as required for flight application (we have already determined through test that the design meets GEVS minimum requirements). We have completed the front-side processing of the fully functional SAT arrays, and are currently performing back-side processing. We expect to complete the fabrication of these fully functional arrays by June 2021.



*Fig. 1.* SAT array at different fabrication stages: (a) after front metal deposition (b) after completion of front-side process (c) after completion of back etch (d) after back metal deposition.

One major hurdle we encountered was the front-to-back alignment runouts. While we were able to perform the alignment on both alignment marks within spec ( $1.5 \mu m$ ), the shutters around the exterior edges of the four corner subarrays showed 2-4  $\mu m$  runouts, as shown in Fig. 2. Several reasons may have contributed this issue, including (1) wafer bowing (2) wax reflow and (3) optical misalignment. To solve this problem, we performed finite element analysis of pre-stress in the silicon nitride, silicon oxide, and aluminum layers to confirm there might exist other factors causing the deformation (bowing and radial) of the wafer. We then adjusted our thermal process parameters to reduce wax reflow during resist baking, and this approach appeared to work on our dummy wafers (Fig. 2). We are currently performing the same improved process on our product wafers and will present our results in the follow up report.



*Fig. 2.* Left: A misaligned microshutter found at the lower left area of the SAT array. Right: Front-to-back overlay measurement using improved thermal processes. The four circled regions are the areas of interest.

Another design improvement we made is to combine all front-side etching processes to improve the dimension precision of the 2- $\mu$ m wide torsion bar. This change would result in significant improvement for shutter actuation as it enhances the critical dimension accuracy of the torsion bar. In addition to process improvements, we also completed design and fabrication of (1) shadow masks (2) device-handling tool (3) array-release jig and masking lid and (4) vapor HF release jig (Fig. 3), all of which will improve process cleanliness and secure sample handling during fabrication.



*Fig. 3.* Tools designed for array fabrication: (a) Shadow mask for back metal pads. (b) Customized array handling tool (c) Array release jig with masking lid. (d) Array holder for vapor HF process and salt-removal baking process.

#### 2. Shutter Electrostatic Actuation Study

We performed finite element analysis to study the electrostatic microshutter operation and associated effects. The goal is to fully understand shutter actuation mechanisms for effective, reliable, and lower-voltage actuation, and further to optimize the microshutter array design in the future. Critical

electrostatic force components were calculated from a recently developed electrostatic model (Fig. 4) to analyze actuation issues. The current shutter design requires a pulsed actuation field to overcome a negative net-torque region. Also, our modeling revealed an undesirable radial pulling force leading to negative dynamic clearance between the shutter blade and its cell. We believe that this phenomenon is the root cause of a stuck shutter problem encountered on the JWST microshutter program. We find that a small (few- $\mu$ m) change in blade width enables stable electrostatic (as opposed to electro-pulsed) actuation as well as better tolerance to fabrication inaccuracies (Fig. 5). We also find that a modification of the blade side shape from rectangular to keystone further reduces possibilities for failed stuck shutters by providing adequate dynamic clearance for all of the degrees of freedom revealed by the model. Detailed information can be found in our latest publication [1].



**Fig. 4.** (a) Torque applied to a shutter blade as functions of angular position and applied voltage. (b) Radial force applied to a shutter blade as functions of angular position and applied voltage. (c)-(d) Electric field lines and normalized field visualized at blade's angular positions of  $0^\circ$ ,  $20^\circ$ , and  $60^\circ$ .



*Fig. 5.* (*a*) Negative and positive y-misalignments. (*b*) Torque and radial force result of y-misalignment cases. (*d*) Electric field lines and normalized field comparison at blade's angular positions of 20°.

Moreover, we explored the electrostatic actuation operation of the shutter blades and torsion bars under different schemes of electrode configuration. We find that it is possible to further reduce the actuation voltage to 50-60 V range (Fig. 6.) when we have 70- $\mu$ m-deep bottom electrodes at the front and back walls. We have submitted a journal article [3] and an NTR [2] to report the new findings. Implementing this finding would require significant changes to our fabrication process. Such changes could be the goal of future projects.



**Fig. 6.** (a) Torque on the blade as a function of  $V_{blade}$  and blade angle when the front and back electrodes are both 70  $\mu$ m long. (b) Torque on the blade as a function of  $V_{blade}$  and blade angle when the front and back electrodes are reduced to 60  $\mu$ m.

#### SAT NGMSA Substrate and PCB Development

During the pandemic, we were able to complete the trace design on the substrate, as shown in Fig. 7. We performed a thermal-mechanical analysis to compare alumina with other substrate material candidates, including silicon nitride, aluminum nitride, and Cesic engineered ceramics during that period. Because the project's requirement of operation temperature to support the above Science Mission Directorate (SMD) mission applications is within the room-temperature range, we decided to stay with alumina as our substrate material even though other materials may have coefficient of thermal expansion (CTE) closer to silicon. Our current alumina substrate has also passed the vibe test in December 2019.



Fig. 7. Left: 1.5-mm thick alumina substrate fabricated by laser cutting. Right: Trace design based on the current alumina substrate design.

The design of the SAM PCB with IC drivers for SAT 2D-addressing with onboard HV power converters and passive parts was delayed due to late distribution of the third year SAT funding, which did not arrive until April 2021. However, this design is approaching completion, and Fig. 8 shows the latest layout. In order to implement the simplest-path approach, row electrode drivers output order on left and right sides are reversed. The output order will be controlled by an operation program.



Fig. 8. Left: SAM PCB layout (design in progress). Right: Layout of the high-voltage card (completed).

## 3. <u>3D-Printing Development</u>

The primary objective of this task is to develop 3D-printed fanout electrodes for large shutter arrays, to replace wire bonding and minimize packaging space to maximize compatibility with science instrument designs. We selected three vendors with different specialties (aerosol jet, syringe micro-dispensing, and pump-assisted micro-dispensing) to demonstrate 3D-printed interconnects on samples representative of an assembly for the front-end and back-end of the array respectively.

We provided test samples where the front end of the array requires 128 conductive interconnects with 100- $\mu$ m width and 200- $\mu$ m pitch from silicon to ceramic over a 1.5-mm vertical step. The back end of the array requires 256 conductive traces of 50- $\mu$ m width with 100- $\mu$ m pitch over a 100- $\mu$ m-height step. Electrical resistivity is required to be no more than 300 ohms/mm, and adjacent trace resistance is to be on the order of giga-ohms.

## (1) Optomec (aerosol jet)

Optomec is a 3D-printer manufacturer specializing in aerosol jet 3D printing. Dielectric fillets and silver interconnects were successfully printed for both front end and back end samples at their research facility. Electrical testing was done at Optomec before and after thermal cycling (Figs. 9 and 10), and so far, this is the most promising technique to print traces to meet our requirements. We are working with Optomec to mature and optimize this aerosol jet 3D-printing technology for our future flight-grade NGMSA interconnects and perform thermal cycling and vibration tests on these 3D-printed test articles.



*Fig. 9.* Left: 3D-printed silver traces on the front end of the array assembly (1.5-mm step height) by Optomec. Right: Electrical measurement before and after thermal cycling. Sample plasma cleaned 15 mins in Argon prior to thermal cycling. 3% new opens after thermal cycling.



**Fig. 10.** Left: 3D-printed silver traces on the back end of the array assembly (100- $\mu$ m step height, 30- $\mu$ m lines on a 100- $\mu$ m pitch. Isolation between the lines measured to be >giga-ohms) by Optomec. Right: Electrical measurement before and after thermal cycling. Sample plasma cleaned 10 mins in Argon prior to thermal cycling. No new opens after thermal cycling.

#### 3D-Flexible (syringe micro-dispensing)

3D Flexible Inc is a small manufacturer of syringe-printing equipment for additive electronics. The syringe printer was used to demonstrate printed traces for representative samples of front-end and back-end electronics. This type of technique requires a very fine-tipped nozzle with very small ID (less than 100  $\mu$ m), and there has to exist a constant gap space (normally tens of  $\mu$ m) between the nozzle tip and the surface that is to be printed. Because of this, 3D Flexible had difficulties printing traces on the uneven ceramic sidewall that had been cut by laser, but they were able to print multiple conductive traces over a 2-mm-height glass slide on a silicon wafer (Fig. 11). It was found that a 30° ramp with 30° dispensing tip angle in combination with a 70- $\mu$ m inner diameter nozzle was the optimal combination to printing over the back end 100- $\mu$ m step (Fig. 12).



*Fig. 11.* (a) 3D-printed silver traces on 2-mm stack glass slide by 3D Flexible. (b) Images of inconsistently printed traces over an uneven sidewall surface with polymer ramps.



Fig. 12. Left: Syringe 3D-printing tool. Right: Silver traces printed at 3DFlexible Inc.

#### (2) nScrypt (pump assisted micro-dispensing)

nScrypt started efforts to print 256 conductive epoxy traces,  $100 - \mu m$  width with 200- $\mu m$  pitch, and 4-6-mm length, over step to a 3-to-4-mm height printed circuit board (PCB) attached to a ceramic

substrate, where traces have an electrical resistivity of no more than 300 ohms/mm, and adjacent traces a resistance on the order of gigaohms. Such a configuration is representative of another portion of the NGMSA assembly. nScrypt was able to print the traces on the printed fillet which had been milled to a  $45^{\circ}$  angle. The printed lines over the fillet were consistent but wider than the requirement at 100 µm (Fig. 13). Process development is still in progress.



Fig. 13. Printed conductive traces over printed and milled fillet. Note the milled surface at the edge of the dielectric ramp and the ceramic substrate.

## 4. <u>Test Facility Preparation</u>

We originally proposed two sets of testing systems for the SAT project: 1) a testing apparatus for the large-format shutter-array characterization before packaging, and 2) testing facility for fully functional 2D-addressing experiment on SAM with 736×384 arrays. In addition, we now plan to build another MEMS mechanical property characterization system to measure the mechanical properties of the torsion bar and shutter blade with involved materials and geometric characteristics. With these three characterization systems, we will be equipped to eliminate low-quality shutter arrays early in the process, saving manpower, packaging materials such as PCBs, electronic components, and most importantly, time.

## (1) Testing system for 736×384 array characterization

Our testing team has completed designing and building the characterization system. The system consists of an automated moving camera and probe cards in X and Y directions respectively, and a motorized stage for the microshutter arrays in the Z direction and theta rotation. Figure 14 shows the completed testing system and a  $7 \times 7$  stitched image of a large SAT microshutter array.



*Fig. 14.* (a) *Characterization system in final installation.* (b)  $7 \times 7$  *mosaic large array imaging to quantifying failed- open and failed- close shutters on a large array.* 

#### (2) Test system for fully functional 2D addressing on a largeformat array

Our original plan was to modify the existing vacuum testing chamber used for JWST MSA quadrants. We later realized the dimensions of the JWST chamber were not sufficient to accommodate all the electronics and circuit boards such that we had to build a new testing setup for SAT fully functional SAM. Figure 15 shows the conceptual diagram of the new system that will be capable of performing 2D-addressing and optical tests. This project is a collaborated effort of Detector Systems and Optics Branches at GSFC.



Fig. 15. A conceptual diagram of the vacuum testing system for fully functional 2D addressing tests.

### (3) MEMS Mechanical Property Characterization System for NGMSA

We will build a system to determine the mechanical properties of MEMS devices using both force probe and resonant excitation. The system will be used to determine the restoring torque of torsion bars of microshutters under various conditions in order to derive the mechanical properties of the involved materials, as well as geometric characteristics and aging properties in conjunction with electromechanical measurements. The system will be another tool to aid in the ever more challenging task of providing input to the design and production of new generations of microshutters.

# **Path Forward**

With reduced labor and lab capacity during the pandemic, we strived to advance every task as much as possible including process development and fabrication of the SAT array, design and fabrication of carriers, shadow masks and wafer handling tools, design and fabrication of alumina substrate with printed traces, PCB layouts, 3D-printing development and optimization, finite element analysis of the electrostatic operation of the microshutters, and design and building the characterization system.

Our proposed TRL maturation schedule was to achieve TRL 5 during project-year three. As a consequence of COVID impacts, an additional SAT investment cycle will be necessary to reach this goal and to mature this technology to the point where further development can be handed-off to the selected strategic mission (HabEx/LUVOIR) and Probe(s).

# **Publications**

- [1] K. Kim et al., "Actuation Force Analysis and Design Optimization of Micro Shutter Array by Numerical Simulation Method," Eng. Res. Express, **3**, 015007 (Jan 2021)
- [2] "Improvement on NGMSA Shutter Performance with Bi-Electrode Modification to Current Row Electrode Design," NASA NTR Case No. GSC-18, 817-1 (submitted to ERX)
- [3] M. Ke et al., "Modelling Results of Microshutters with New Electrode Configuration" (submitted)
- [4] A.S. Kutyrev et al., "Programmable microshutter selection masks in application to UV spectroscopy," Proc. SPIE 11443, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, 114431D (Dec 2020)
- [5] M.J. Li et al., "Successful Demonstration of an Electrostatically Actuated Microshutter System for Space Telescope Flight Missions," Journal of Microelectromechanical Systems, vol. 29, no. 5, pp. 1079-1082 (Jul 2020)

For additional information, contact Matt Greenhouse: <u>matt.greenhouse@nasa.gov</u>

