Microshutter Array System for James Webb Space Telescope

M. J. Li[1], T. Adachi[2], C. A. Allen[1], S. R. Babu[1], S. Bajikar[3], M. A. Beamesderfer[1], R. Bradley[4],
N. P. Costen[3], Kevin Denis[3], A. J. Ewin[1], D. Franz[1], L. Hess[3], R. Hu[3], K. Jackson[5], M. D. Jhabvala[1], D. Kelly[3], T. King[1],
G. Kletetschka[2], A. S. Kutyrev[6], B. A. Lynch[3], S. E. Meyer[1], T. Miller[3], S. H. Moseley[1], V. Mikula[2],
B. Mott[1], L. Oh[3], J. T. Pontius[1], D. A. Rapchun[6], C. Ray[3], S. Schwinger[1], P. K. Shu[1],
R. Silverberg[1], W. W. Smith[3], S. Snodgrass[3], D. Sohl[1], L. Sparr[1], R. Steptoe-Jackson[1],
R. J. Thate[1], F. Wang[3], L. Wang[4], Y. Zheng[1], C. Zincke[3]

[1] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2] The Catholic University of America, Washington D.C. 20064, USA
[3]MEI Technologies, Greenbelt, MD 20771, USA
[4]Sigma Space Co., Lanham MD 20706, USA
[5] Swales Aerospace Co., Greenbelt, MD 20705, USA
[6]Global Space Technology Co., Greenbelt, MD 20771, USA

ABSTRACT

We have developed microshutter array systems at NASA Goddard Space Flight Center for use as multi-object aperture arrays for a Near-Infrared Spectrometer (NIRSpec) instrument. The instrument will be carried on the James Webb Space Telescope (JWST), the next generation of space telescope, after the Hubble Space Telescope retires. The microshutter arrays (MSAs) are designed for the selective transmission of light from objected galaxies in space with high efficiency and high contrast. Arrays are close-packed silicon nitride membranes with a pixel size close to 100x200 μm. Individual shutters are patterned with a torsion flexure permitting shutters to open 90 degrees with minimized stress concentration. In order to enhance optical contrast, light shields are made on each shutter to prevent light leak. Shutters are actuated magnetically, latched and addressed electrostatically. The shutter arrays are fabricated using MEMS bulk-micromachining and packaged utilizing a novel single-sided indium flip-chip bonding technology. The MSA flight system consists of a mosaic of 2 x 2 format of four fully addressable 365 x 171 arrays. The system will be placed in the JWST optical path at the focal plane of NIRSpec detectors. MSAs that we fabricated passed a series of qualification tests for flight capabilities. We are in the process of making final flight-qualified MSA systems for the JWST mission.

KEYWORDS: micro-optics, near infrared, space telescope, indium bump bonding, packaging, microshutter, MEMS, DRIE

1. INTRODUCTION

A Microshutter Array (MSA) system has being developed at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) since 1999. The system will be used as an array aperture for NirSpec, one of the four instruments that will be carried by the JWST to space. JWST is the next generation of space telescope after Hubble Space telescope retires [1]. It is being built-up by a collaborative effort among NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). The JWST launching is scheduled for 2013. The primary mission of JWST is to determine the shape of the universe, reveal the origins of galaxies, clusters, and large-scale structures in the universe, and explain galaxy evolution. To serve the purpose, JWST is designed to detect signals from remote galaxies with an optical resolution of 0.1 arc-seconds in an infrared wavelength range of 0.6 to 28 μm. The NirSpec spectrometer covers the spectroscopic wavelength region, from 0.6 to 5 μm in order to observe galaxies at the peak of the merging and star-forming era. NirSpec is a Multiple Object Spectrometer (MOS) [2] allowing simultaneous observation of a large number of sources in the sky.

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The universe contains numerous stars and galaxies and they are yet remote and scarce. In order to increase the observing efficiency of the NirSpec detector, a multi-object field selector is essential to enable simultaneous selections of multiple targets without spectral overlap on the detector[2]. Traditional field selectors are used in a format of mechanical slits, which are not preferable in general for space flight missions due to their heavy mass and large volume. Applying mechanical slits is not an option for flight missions such as the JWST that will travel 1.5 million kilometers away from the earth. As comparison, MEMS devices are not only light and small but also close-packed so that enables them to reach a high fill factor for viewing targets in sky. MEMS devices also provide the capability and flexibility of programmable addressing. Among various MEMS devices, MSAs are chosen to serve as the object selector for the NirSpec detector. MSAs are transmissive devices so they have the potential to achieve high optical contrast. It is demonstrated in Figure 1 how a microshutter array can be used as an object selector targeting multiple objects in the sky. Each selected shutter is able to open fully to allow signals from targeted objects pass through with minimal scattering of the light. The rest of the shutters can be kept closed, blocking light from unwanted stars and galaxies as well as the entire unwanted dark background in space. Utilizing the MSAs as the multi-object selector increases the instrument efficiency of the NirSpec detector 100 times or more. The MSA assembly is one of five major innovations on JWST and the first major MEMS devices serving observation missions in the space.

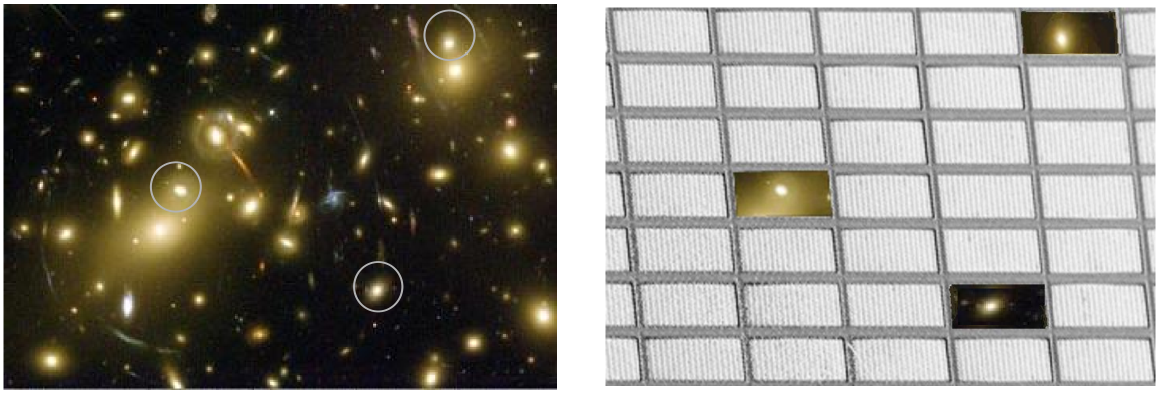

Figure 1. Demonstration of using a microshutter array as an aperture (right) to select multiple objects from the sky (left)

Operating as an object aperture array for the NirSpec detector, the MSA system is designed to meet various instrumental requirements from both scientific and technical aspects. Key instrumental requirements are described as following[3],

- Random Access Addressing: -- must allow the opening of any shutter distribution and equal to or more than 100 objects simultaneously targeted;
- Field of View: -- must cover the field of view of NIRSpec (3.4' x 3.4');
- Contrast: --must have an open to closed transmission ratio of >2000;
- Life Time: -- must operate for 3.0 x 10^4 cycles with minimal failures;
- Operating Environment: -- must operate in the JWST environment, including the temperature ~ 35K, the power dissipation of 40 mW average (at 35K), a volume fitting the envelope in NIRSpec instrument, a mass of 10 kg, and radiation within a life dose of 48 kRad.

We started the MSA development in 1999. Begun from a concept design, we built a 3x3 prototype MSA to demonstrate the concept and the mechanism [4,5]. In eight years, we have fabricated 32x32 mechanical MSAs [4,5], 128x128 functional MSAs [3,6], 64x128 functional MSAs [12], 175x385 large-format MSAs [12], and now the 171x365 flight-format MSAs. Numerous modifications have been made to improve the MSA performance in meeting instrumental requirements. This paper focuses on the MSA development that covers major breakthroughs and milestones in the MSA fabrication. Flight–format MSAs and their packaging are discussed in detail. Various screening testing and qualification testing are also discussed.

2. DEVELOPMENT OF MICROSHUTTER ARRAYS

The MEMS MSA system is designed to have a mechanism of magnetic actuation and electrostatic latching and addressing [7,8]. A magnetic coating is needed on microshutters so that shutters can respond to an external magnetic field for the magnetic actuation. A set of column electrodes is placed on the top of shutters and a set of row electrodes on sidewalls underneath the shutters, so shutters can be electrostatically latched open. A linear permanent magnet aligned with the shutter rows is positioned above a flipped up-side-down array, as shown in Figure 2, and sweeps across the array in a direction parallel to shutter columns (moving towards readers). As the magnet sweeps across the array, sequential rows of shutters are rotated from their natural horizontal orientation to a vertical open position, where they approach vertical electrodes on the sidewalls. When the electrodes are biased with a sufficient electrostatic force to overcome the mechanical restoring force of torsion bars, shutters will remain latched to vertical electrodes in their open state. When the bias is removed or insufficient, shutters will return to their horizontal closed position. As demonstrated in Figure 3, DC voltages applied between shutters (front electrodes in columns) and the back walls (vertical electrodes in rows) are +20V and –20V, respectively. To release a shutter, both the electrode on the shutter and the one on the back wall where the shutter sits in are grounded, like the first and the third shutters in the top row. The shutters with one or both ungrounded electrodes are held open. For example, the second shutter in the top row and the first shutter in the second row are held open with one electrode ungrounded, while the second shutter in the second row and the second one in the third row are kept open with both electrodes ungrounded.

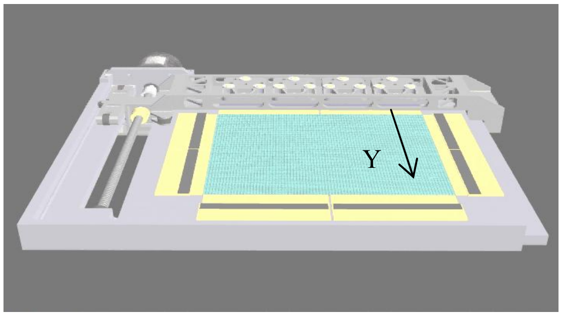

Figure 2. Schematic of an early model for the MSA actuation mechanism. A linear magnet sweeps in y direction across the array

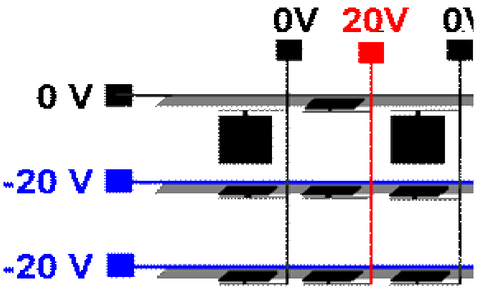

Figure 3. A schematic showing 2-D addressing mechanism for MSAs.

2.1 128x128 Functional MSAs

The first design of functional MSAs is in a format of 128x128 with a pixel size of 100x100μm. Development aspects of these shutter arrays were presented in previous publications [7,8,9], covering the material selection and the fabrication development of mechanical shutter arrays.

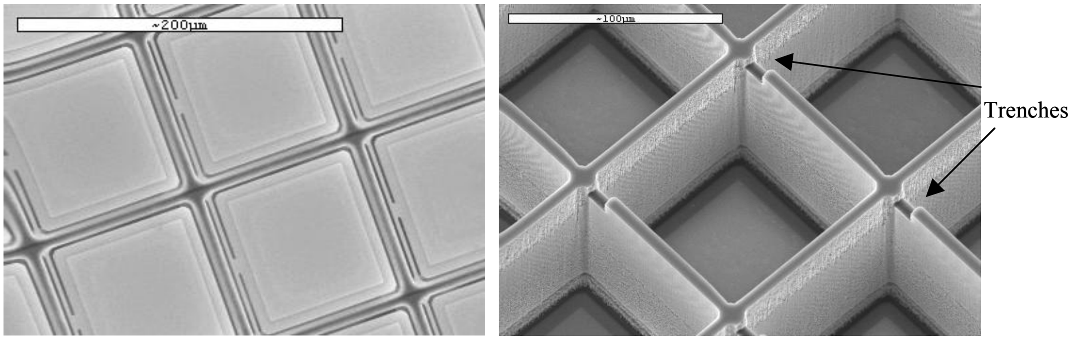

Figure 4. SEM images showing 100x100 um microshutters (left) and grids on the backside of the microshutter array with vertical electrodes fabricated using the Shadow Line technology

Materials were selected through numerical analysis, and various mechanical, thermal mechanical, optical, and electrical tests with the consideration of fabrication capabilities in GSFC. Materials critical to MSA fabrication and function were those for shutter blades and magnetic pads. Silicon nitride was selected for use as shutter blades based on its excellent mechanical and thermal mechanical performances, as well as the maturity in fabrication processes. Cobalt iron alloy was chosen among various magnetic materials as the shutter actuation elements, providing sufficient magnetic response to an external magnet and an ease of processing. 128x128 MSAs were fabricated using bulk-micromachining technology, structured with 0.5μm-thick silicon nitride shutters sitting on a 100μm-thick silicon frame as shown in Figure 4. Each shutter blade is connected to the frame through a hinge and a fine line called the torsion bar. Metal thin films were also deposited covering the front side of shutters as front electrodes, and on the backside frame as well as one side of vertical walls as back electrodes. The torsion bar is a key element in mechanical motion of shutters responding to an external magnetic field and also as an electrical path allowing electrical bias passing through. It was demonstrated that shutters were opened 90 degrees into the frame when a magnetic force was applied on the shutter array. Shutters were selectively latched on back walls as electrostatic forces were applied between the front and back electrodes.

In the fabrication development, a major task was to delineate the metal layer on shutters into columns and that on the frame into rows in order to allow 2-dimensional addressing. The delineation of the front electrodes appeared relatively easy because the involved patterning was conducted on a relatively flat surface of wafers, as illustrated in the left image in Figures 4. The delineation can be seen as narrow gaps between shutter columns that are perpendicular to torsion bars in shutters. The delineation work for the frame electrodes, also called the vertical electrodes, posed a unique challenge. It requires metal layers be deposited and patterned on an 8μm-wide and 100μm-deep frame as shown in the right image in Figure 4. Various approaches were explored in developing a patterning technique. It was a breakthrough when a technique named "shadow line" was developed. It has ever since provided a reliable process for fabricating microshutter vertical electrodes on a wafer-level. The "shadow line" technique consists of a double DRIE process followed by an angle thin-film deposition. The double DRIE process creates trenches on the 8um-wide silicon frame, as shown in the right image in Figure 4. The trenches provide a shadowing effect preventing metal being deposited in the bottom of trenches as an angle thin-film deposition is applied, that completes the vertical electrode delineation. The 1-dimentional and the 2-dimentional shutter addressing, was demonstrated respectively in 128x128 MSAs. The details can be found in early publications [9-11].

2.2 64x128 functional MSAs

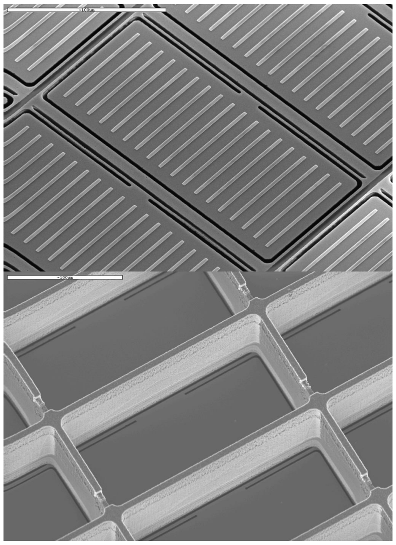

Figure 5: SEM images of the front side (top) and backside (bottom) of a 64x128 microshutter array with zoom-in images of shutter cells.

The 64x128 MSAs was developed later with a pixel size of 100 x 200 μm [10-12]. Shutter elements are shown in Figure 5. In the figure shows the front side (the shutter side) and backside (the frame side) of shutter cells in SEM images. The pixel-size change was made to meet an instrumental requirement regarding the field of view for the NirSpec detector. The change led to increase the MSA fill factor by reducing frames and opening more space for light passing through. These 64x128 arrays were developed for fabrication improvements, functional testing, and reliability testing. The main focuses in fabrication improvements included the torsion bar refinement, magnetic thin-film patterning, and light shield development.

Torsion bar dimensions and geometries are critical to shutter motions when shutters are subjected through the actuation, latching, and releasing processes. Numerical analysis, fabrication testing, and life testing were conducted to optimize torsion bar length, width, thickness, and their geometries. The goal was to have an appropriate design of torsion bars with minimized latching voltages when shutters were selected open and, at the same time, with enough restoring forces when shutters were selected closed. The final design of the torsion bar, as shown in Figure 5, was selected from twelve designs with variations of dimensions and geometries.

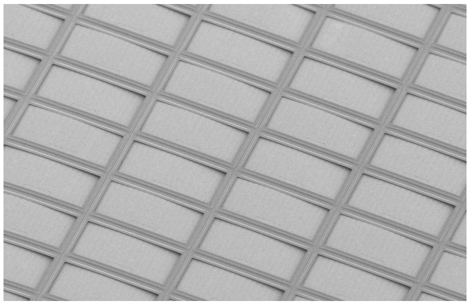

Figure 6. A SEM image shows shutters fabricated with light shields that cover the gaps and the torsion bar features.

Combined with the torsion bar design, work was also carried out to have a modified design for magnetic thin-film patterns. In the magnetic actuation of a shutter array, it is necessary that magnetic domains in CoFe thin films are lined up in a response to an external magnetic field to open shutters 90 degrees into the frames. The magnetic response should ideally subject the shutter blades to a magnetic force that leads the torsion bars under a symmetric shear component over a tensile component as much as possible. The design in Figure 5 consisted of seventeen parallel CoFe magnetic stripes. The design helps to align the most of magnetic domains in the strips parallel to the external magnetic force. Unwanted components are minimized so torsion bars are protected from twisting, bending, or any uneven motion. Shutters are therefore able to function smoothly without touching frames in the actuation, latching, and releasing movements. Numerical design, fabrication testing and actuation testing were conducted leading to the optimized design of the magnetic strips.

Light shields were also modified in the development of 64x128 arrays[12]. Light shields are fabricated to block light from passing through gaps between shutters and frames. Processed with a sacrificial layer, light shields are formed as overhangs covering the gaps. A sufficient overlap between the light shield and the shutter edge must be satisfied to minimize light scattering through. Excessive overlap has to be avoided because it reduces the fill factor of the shutter arrays. Shutters fabricated with light shields are shown in Figure 6. Besides playing the role of light blocking, light shields must be mechanically strong enough so to survive possible physical impacts from shutters. The key is to make smoothly rounded corners at the footage of light shields, which greatly minimizes a stress concentration. New light shields significantly increase the contrast as observed in a series of optical tests.

2.3. 175x384 Large-Format MSAs

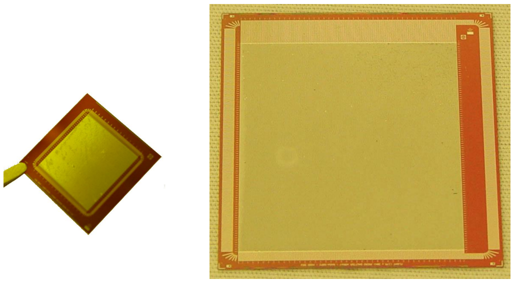

Figure 7. A 175x384 shutter array (right) houses over 65,000 microshutters. It has shutters 8.2 times as those in a 64x128 array (left).

Based on the development of 64x128 MSAs, a close-to-flight-format of MSAs was fabricated with 175x384 pixels[12,13]. These arrays house over 65,000 microshutters with the same pixel size as 64x128 arrays. The number of shutters increased about 8.2 times over 64x128 arrays. The dimension of 64x128 arrays is 19mm x 19mm, and 175x384 arrays 47.8mm x 48mm, as compared in Figure 7. Fabricating large-format MSAs requires an extremely high accuracy of alignments between processing steps in the photolithography. It also demands high etching uniformity over the entire wafer in both wet etching and dry etching processes like DRIE. Successful fabrication of 175x384 MSAs is a milestone that demonstrated our fabrication capability for flight-format arrays.

3. FLIGHT-FORMAT MICROSHUTTER ARRAYS

Recent work has been directed at the development of the flight-format of MSAs[13-15]. These flight-format arrays are designed with 171 x 365 pixels in order to precisely cover the field of view of the NirSpec detector. At the same time, the flight-format of substrates has been designed, fabricated, and populated with all 2-D addressing components. These substrates provide the mechanical support, as well as capabilities of programmable addressing to the flight-format MSAs. A hybridization technique has been developed successfully using single-side indium bump bonding for attaching

MSAs to substrates. We are intensively working on high-level system testing in the process to meet functional, reliability, and various environmental requirements from the instrument, the NirSpec detector.

3.1 171x365 Flight-Format MSAs

As required by the NirSpec instrument, the optical contrast for a flight MSA at an open position over that at a close position must be better than 2000 when the MSA is in operation. It is essential to keep microshutters flat at the operation temperature of the detector, 35 K, so to prevent light leak. The shutters should also maintain nearly flat at room temperatures as subjected to various high-level tests on ground before the JWST launching. It is clear that minimal flatness change can be allowed in the entire temperature range between 35K and 300K. In the MSA fabrication, a metal thin film is coated on shutter blades made of silicon nitride. The thin film should be electrically conductive for the use as shutter electrodes and optically opaque to block light. It should also thermal-mechanically behave as close to silicon nitride as possible in order to minimize thermal stresses in shutters over the temperature range. Intensive experiments were conducted including numerical analysis, film deposition tests, and shutter bowing tests[15]. A metal nitride was selected from a number of candidates as the coating material.

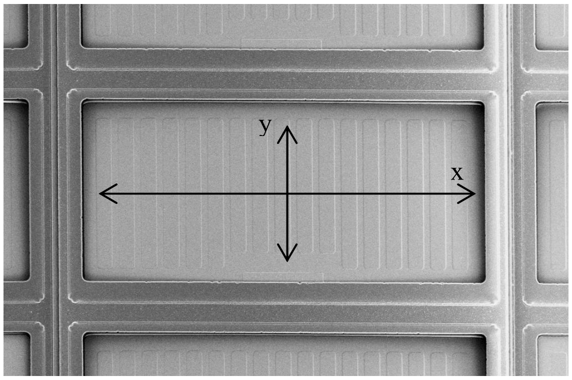

Figure 8. A SEM image shows shutters slightly bowing down on an axis along the long dimension of the shutters.

The metal nitride thin film is coated in a plasma-sputtering deposition system on SOI wafers that has previously deposited with low-stress silicon nitride thin film. The flatness of shutters over temperatures is determined by intrinsic and thermal stresses in metal nitride and silicon nitride layers. The deposition is tuned to the point that the metal nitride film stress, as deposited, is kept lower than the silicon nitride film stress in a certain amount. The tuning provides shutter blades with slight bowing at the room temperatures. The bowing, determined by the stiffness, is sensitive to the stress difference between the two films as 50MPa per micron. The curvature of bowing is defined in the direction parallel to the long dimension of shutters. A shutter image shown in Figure 8 was taken at room temperature, presenting shutters slightly bowing down as expected. Shutters become flat when the temperature decreases to 35K.

Besides the control of the film stress difference between metal nitride and silicon nitride, we also utilize the geometric change of shutter elements over temperature enhancing the control of shutter bowing. Arrows in Figure 8 define the bowing along the long dimension of shutters as the direction of X and the short dimension as the Y. It was observed that the bowing change in X direction is dependent on the initial bowing in Y direction. When the initial bowing in Y direction is set at 0.3um tensile or greater, the bowing in X direction can be reduced to zero over temperature. We control the sputtering deposition of metal nitride so to set the initial shutter bowing as a cylinder with a few microns of compressive curvature (bowing down) in X. With the temperature decreasing towards 35K and the thermal stresses from the mismatch of the thermal expansion coefficients (CTE) between two films playing their role, the shutter bowing in Y direction can reach o.3 to 0.5um tensile and that in X direction changes from compression towards tensile and stops at the flat zero. Variations in metal nitride stress across SOI wafers are also utilized to form the microshutter into the initial cylinder shape. The bowing control for microshutters over a large span of temperature range is a key element in MSA fabrication.

3.2 Flight-format Substrates for MSAs

The NIRSpec instrument requires a total field of view in an area of 7.0 x 7.7 cm^2 covered by the microshutter aperture arrays. With a 105 x 204 μm^2 pixel size, 730 shutter pixels in the dispersion direction by 342 pixels in the cross dispersion direction are needed. To meet this requirement, four 171x365 microshutter arrays are to form a mosaic of 2x2

MSA system. Each array is designed to have its own silicon substrate with 2-D addressing electronics. The advantage is that each quadrant can be made separately and tested independently. If it is necessary, a quadrant can be replaced without affecting other quadrants. The four quadrants will share the same magnetic actuation system together assembled in a mechanical stage.

As the same as MSAs, substrates are fabricated in-house at GSFC. They are made out of single-crystal silicon wafers in the thickness of 2 mm. Utilizing silicon as substrates is to match the material of MSAs that are made of a 120um-thick single crystal silicon. Thermal stresses from the CTE mismatch between MSAs and substrates can be minimized as temperature changing between ambient temperature and 35K. A large aperture is machined in the substrate as shown at the upper-right corner in Figure 9. Surrounded by about 1,080 metal pads the aperture is for housing a 171 x 365 flight-format MSA. It allows light transmit through the MSA to the underlying focal plane of the NIRSpec instrument. Locating the MSA at a corner of the substrate permits close-packing of a mosaic of four flight-format MSAs required for the NIRSpec focal plane. Besides the MSA, each substrate is populated with five customer-designed Application Specific Integrated Circuit (ASIC) multiplexer/address chips as seen in Figure 10. A row of three ASIC chips is to connect to vertical electrodes, and a column of two to front electrodes in the MSA. The substrate also houses twenty capacitors, two temperature sensors, numbers of resistors and all necessary interconnects. All interconnects and bonding pads are first fabricated on a 2mm-thick silicon substrate, followed by fabricating indium bumps on bonding pads (the fabrication of indium bumps is discussed in the next session). The aperture is then machined through a DRIE process prior to the population of all the ASIC drive chips and passive components.

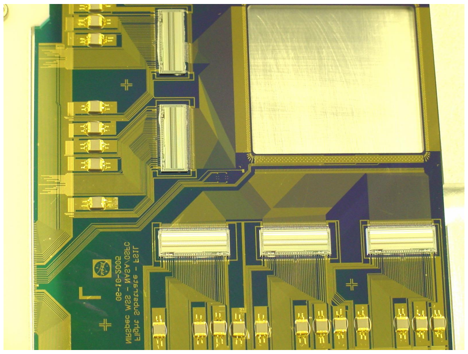

Figure 9. A silicon substrate populated with ASIC chips for multiplexer/addressing MSAs. The aperture at the upper-right corner is for housing the microshutter array.

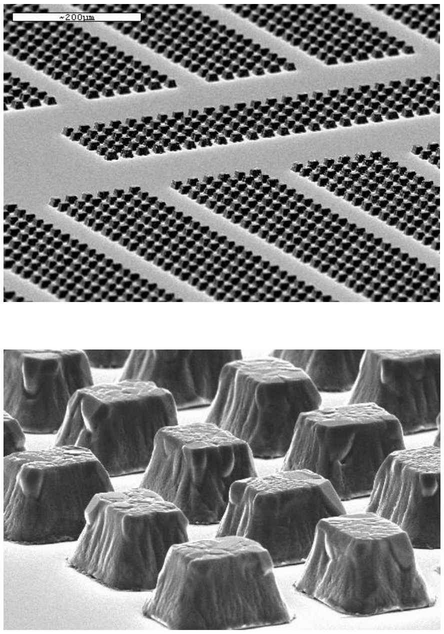

Figure 10. Scanning electron microscope images of clusters of bond pads (top) on the MSA multiplexer covered with small indium bumps (bottom). The height of the bumps in the images is 10 microns.

3.3 Hybridization of MSAs

The hybridization of MSAs to their substrates consists a flip chip bonding and wire bonding processes. The flip chip bonding is conducted to connect front electrodes on shutter arrays to bond pads on substrates. The wire bonding is a standard process that connects vertical electrodes on arrays to substrates.

Previous methodology we had utilized for flip chip bonding was a gold stub ball bonding. After placing gold stubs on metal bond pads around the periphery of the aperture on a substrate, under-fill epoxy was applied in the pad area with gold balls. The MSA was flipped and aligned to the substrate. An adequate pressure was applied to make gold balls contact metal bond pads on the front side of the MSA. The epoxy was then cured at ambient of higher temperature, making tight contacts between the MSA and the substrate at the tip of gold balls. Followed the flip chip bonding process bond pads on the backside of MSA were connected to those on the substrate through a wire bonding process. There are several disadvantages in the use of gold stub ball bonding. Gold stubs with tips taller than others might punch through bond pads on the MSA side upon the bonding pressure, introducing electrical shorts. The contact between gold stubs on the substrate and bond pads on the MSA is a surface contact rather than forming a metallic compound contact, providing a chance of electrically open circuitry in later testing or operation. More concerned, the warping introduced by the epoxy curing leads certain unevenness between the MSA and the substrate that might fail to meet the NirSpec instrument requirement.

Indium bump bonding, on the other hand, provides opportunities to overcome above shortcomings encountered in gold stub bonding. Indium bumps are fabricated through a photolithographic patterning providing even contact surfaces. Even contact surfaces are critical in the mating process in order to eliminate electrical shorting to the substrate. Other advantages include no need for heating and no need for under fill that will be illustrated in later sections. In a traditional indium bump bonding process, the bumps are made on both sides of the mating pair, in our case, the MSA device and the substrate. It is very difficult to pattern indium bumps on delicate MSAs without damaging any components in the devices. A unique single-side indium bump bonding process has successfully been developed at NASA GSFC [14].

Indium bumps are fabricated on substrates through a lift-off process. A thick photoresist mask is patterned on a 2mm-thick substrate, followed by an indium deposition in vacuum. After the lift-off of the photoresist mask, 10µm-high indium bumps evenly sit on bonding pads on the substrate. Indium bumps fabricated on a test substrate are shown in Figure 10. Each bonding pad houses about 150 indium bumps to ensure an enough bonding strength. There are 180,000 indium bumps for bonding a flight-format MSA chip. After a careful cleaning step, the substrate is subjected to a gas plasma treatment to remove a native oxide film formed on indium bumps after the indium deposition. The process also provides a passivation to indium bumps to prevent newly growth of the native oxide. Figure 11 shows a portion of a MSA device (left) and a portion of a substrate near the aperture (right) prior to a bonding process. Both portions hold bonding pads for electrical connection, as well as numbers of mechanical bond pads for evening out bonding force over the periphery of the array chip. Bond pads on the substrate were fabricated with indium bumps ready for the flip chip bonding process.

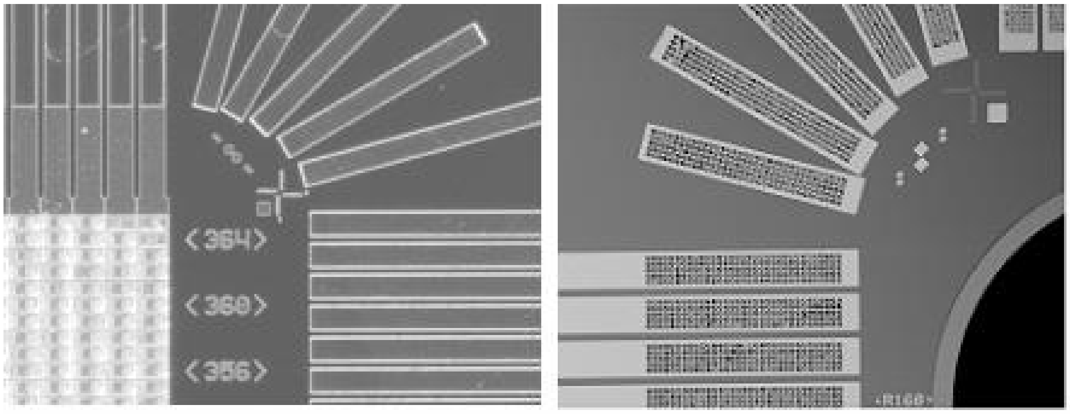

Figure 11. A portion of a MSA device (left) and a portion of a substrate (right). Both portions hold bonding pads for the flip chip bonding. The bonding pads on the substrate were fabricated with evenly spread indium bumps out of a photomask lift-off process.

We use a FC-150 flip chip bonder to perform the bonding between MSA devices and their substrates. A specially designed vacuum tool is used to pick up an upside-down MSA device at its 3mm-wide frame in the periphery of the device chip. The mating pairs are aligned with a 1.0 um alignment accuracy. The bonding is conducted with a bonding force about 0.4 grams per bump. Through the bonding process 10um-high indium bumps are pressed to 5um-high. No heat is applied during the bonding process so to minimize thermal stresses. A typical flatness variation over the entire MSA chip is within 1.0um after the bonding. Unlike the gold stub bonding, there is no need for under-fill epoxy in the bonding area. Eliminating both the heating and under fills enables tremendous deduction of thermal stresses, that is key to obtaining the excellent flatness over entire MSAs.

A series tests were conducted to qualify the newly developed methodology of single-side indium bump flip chip bonding. Mated pairs were subjected to thermal cycling tests between ambient temperature and liquid helium temperature, and vibration tests with loads of a 55 Hertz (Hz) sine burst of 63 G and high -frequency 2-5 kHz sine sweeps. Thermal cycling tests are conducted to test bonds surviving thermal stresses introduced between room temperature and instrument operating temperature 35K, while the vibration tests are to simulate environmental conditions during spacecraft launching. Electrical tests were performed before and after both types of environmental experiments, indicated no loss of any electrical continuity through the mated pairs. Numbers of mechanical pull tests were also executed, providing a tensile rupture strength greater than 100 pounds for each mated pair. No rupture occurred at the interfaces between indium bumps and bonding pads on MSA chips, indicating a reliable adhesion between the two.

3.4 MSA Assemblies

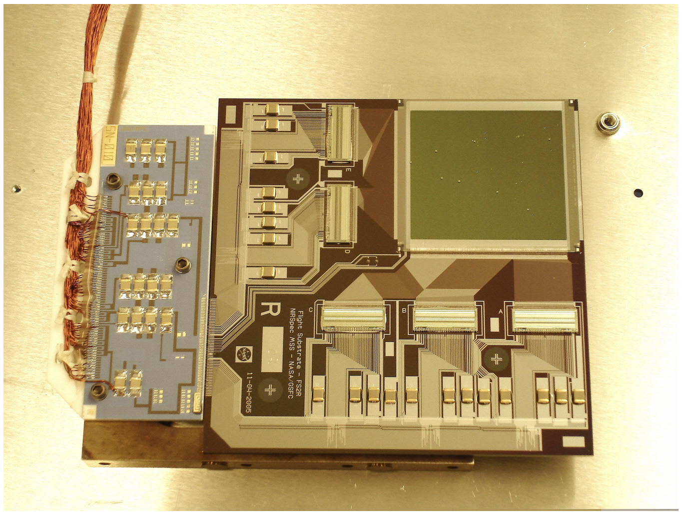

Figure 12. A quadrant of MSA system. A 171x365 MSA was bonded on a silicon substrate at the upper-right corner. The substrate was populated with addressing drive chips and all the passive components

The NIRSpec instrument requires a total field of view close to 7.0 x 7.7 cm^2 covered by the microshutter aperture arrays. With a pixel size of 105 x 204 μm^2, 730 MSA pixels in the dispersion direction by 342 MSA pixels in the cross dispersion direction are needed for the coverage. To meet this requirement, four 171x365 microshutter arrays are assembled to form a mosaic of 2x2 MSA system with four quadrants. Each quadrant is designed to have its own MSA and silicon substrate with 2-D addressing electronics, so that each quadrant can be made and tested separated from others. A quadrant of the 2x2 MSA system is shown in Figure 12. It includes a MSA device bonded to the upper-right corner of a substrate. The array faces down with front electrodes connected to bond pads on the substrate through the single-side indium flip chip bonding and back electrodes connected to the substrate by a standard wirebonding. The substrate is fully populated with 2-dimensional addressing components as described in Session 3.2, and electronically connected to a daughter board. Both the substrate and the daughter board were mounted on a flexure that can be seen underneath in Figure 12.

Flexures are designed with the consideration of protecting silicon substrates from thermal stresses introduced by CTE mismatch between substrates and a large metal plate. The metal plate, as the base of the MSA system, houses all quadrants. A permanent praseodymium quadrupole magnet has been modified for the actuation of all four 171x365 MSA arrays. Arrays are positioned as close at one corner of the substrates as possible, as shown in Figure 12, so that four MSA arrays can be close-packed to form the 2x2 mosaic of MSA system with a minimal reduction of the fill factor for the light.

4. QUALIFICATION TESTING OF MICROSHUTTER ARRAYS

After the fabrication of MSAs and prior to the hybridization of MSAs to their substrates, we subject each MSA to inspections including the pre-screening, actuation testing, bowing testing, and electrical testing. In order to be qualified for the operation in the JWST mission, MSAs are tested to meet various instrument requirements after the hybridization to substrates. Those qualification tests involve the programmable 2-D addressing, life testing, contrast testing, radiation testing, and environmental testing including vibration and acoustic tests.

4.1 MSA Inspection

Prescreening and actuation tests are conducted right after MSA fabrication. Screened out are MSAs with out-of-spec fabrication errors or defects that may affect MSA operations in later functional testing. In the evaluation of microshutter arrays, two failure modes are characterized, the failed open (FO) and the failed close (FC). The former is defined as the light leak through a supposedly closed shutter, while the latter as the light blocked by a supposedly open shutter. In the NIRSpec instrument is required the FC shutters ≤ 3,885 (≤ 6.2%) and the rows with FO shutters ≤10 (≤0.2 %) at the beginning of the life (BOL). It requires the FC shutters ≤7,770 (≤12.4%) and rows with FO shutters ≤20 (≤0.4%) at the end of the life (EOL). There are trade-offs between the numbers of FC and FO. In pre-screening actuation tests, MSAs are exposed to a homogenous magnetic field. Using a software, FC and FO shutters at BOL are respectively counted with an on-and-off the magnetic field. Over thousands of photos are taken, as records, from each MSA with details of individual shutters that will be compared with those taken at EOL. Two images, as shown in Figure 13, present the failed-close and failed-open shutters in a 171x365 MSA. There were 150 failed-close shutters (0.2%) and 3 failed-open shutters (1.8%) in this MSA.. It meets both the FO and FC requirements. Due to a tight requirement for the number of FO, a mitigation methodology has been developed to plug FO shutters. The plugging changes the shutter status from FO to FC.

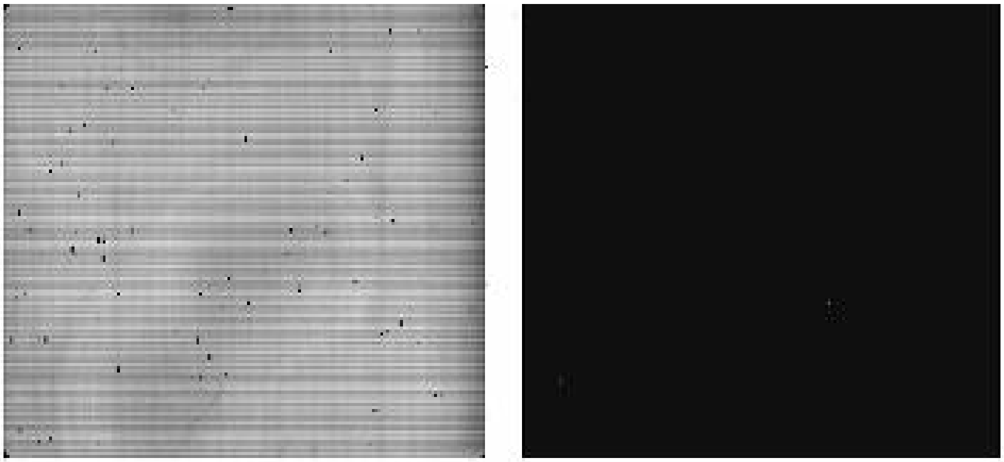

Figure 13. Images of a MSA in an actuation test. A homogenous magnetic force was applied keeping shutters open (left), and withdrawn so to release shutters to a close position (right). Shutters in failed-open/failed-close were enumerated.

Bowing tests are conducted using a confocal imaging system that operates over temperature between ambient and cryogenic. Shutter bowing is monitored over a temperature span typically between 300K to 35K with a resolution of 0.1um. Initial bowing and bowing variation verses temperature are collected from shutters in representative locations in a MSA and recorded as references. Bowings along the short and long dimensions of shutters, as well as shutter tilting are measured.

A standard probe station is utilized to conduct electrical tests as a part of the MSA inspections. Measurements are mainly focused on the continuity of each front and back electrode in the MSA, electrical shorts between every two back electrodes (row-to-row) and every two front electrodes (column-to-column), as well as electrical shorts between every electrode (both front and back) and the MSA silicon substrate.

4.2 MSA Qualification Testing

After the hybridization of MSAs to their 2mm-thick silicon substrates populated with all the addressing components and following-up packaging processes, MSA quadrants are subjected to functional and reliability tests. Custom-designed cryogenic chambers are utilized to conduct these tests with MSA actuation, addressing and monitoring capabilities. Shutters are actuated open in a magnetic field from a praseodymium quadropole magnet sweeping across the array.

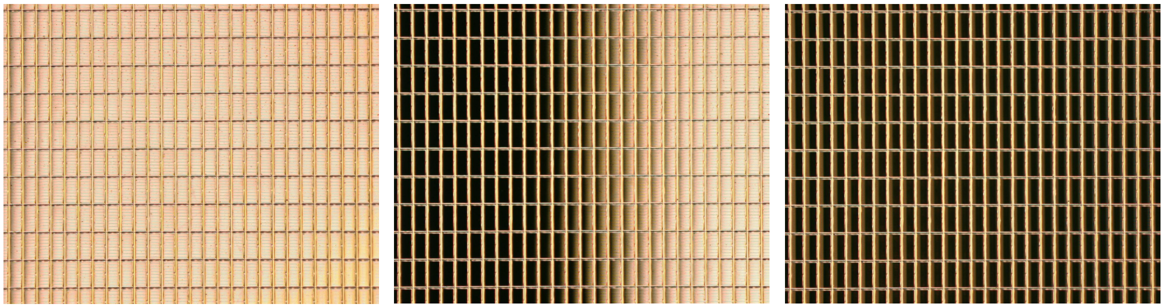
(a) (b) (c)

Figure 14. A shutter array actuated using a praseodymium quadropole magnet. (a) all shutters at a closed position, (b) partial shutters actuated, and (c) all shutters actuated.

During the actuation, the magnet located on the backside of the shutter array (on the grid side) scans across the array. The scan opens shutters, column by column, into the shutter frame by rotating them around torsion bars to the position against back walls. The magnetic force can be controlled by adjustment of the distance between the shutter array and the magnet. Magnetic actuation of MSAs is demonstrated in Figure 14. These images were taken using an optical microscope with a magnet located behind the array scanning from the left to right side. In Figure 14(a), all shutters were closed when the magnet was far on the left side of the array. In Figure 14(b), shutters in the left portion of the view were open when the magnet was approaching the array from the left. Notice columns of shutters in the middle of the region were partially open because the magnetic force was relatively weak. Figure 14(c) shows all shutters in the view were open when the magnet was moved directly under this region of the array. Besides effects of the perpendicular distance between the shutter array and the magnet, shutter actuation behavior also changes when the magnet approaches the array from the opposite direction.

Appling an electrostatic force typically at +/- 20V between front electrodes on shutters and back electrodes on vertical walls in a MSA, shutters are latched against back walls in the windows behind the shutters. A 2-D addressing is fulfilled by keeping typically 20 V to selected shutters to hold them open, and turning off the bias to the rest of shutters with a synchronized sweep of the magnet to gently release them back to their closed position. Various 2-D addressing patterns are programmed into the MSAs to test functional responses of shutters. A 2-D addressing pattern with programmed squares in a MSA is shown in Figure 15. Shutters with transmitted light (bright ones) were latched open, while the rest (dark ones) were released and kept closed. 2-D addressing tests are typically conducted at the cryogenic temperatures where shutters are flat to simulate operating environmental conditions in space. The distance between the MSA and the magnet and the electrical bias are varied to optimize the performance of MSAs. The functions of the electronic drive circuitry are also monitored and modified for their performance.

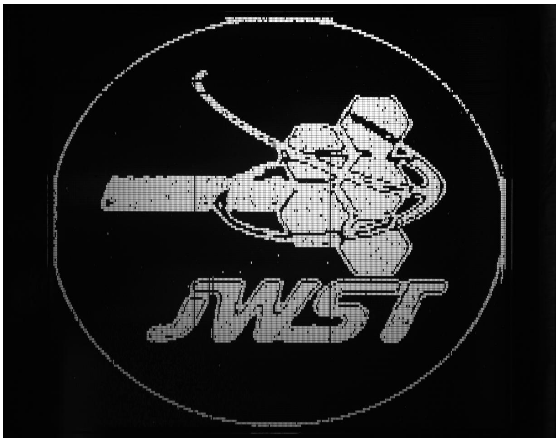

Figure 15. A 2-dimensional addressing pattern in a MSA

Life cycling testing is also conducted in the cryogenic chambers used for 2-D addressing tests[9]. MSA quadrants are subjected to open/close cycles with electrostatic latch at each cycle. A typical cycle rate of 4Hz is utilized, while keeping shutters open for various time durations up to the maximum of 1 week. The extended opening is mainly for the simulation of the durations as the shutters will be open in the JWST mission for signal collection. There were significant increases of failed opens and failed closes in early life tests as an electrostatic latching was added, despite torsion bars were surviving all the life-cycling tests. Investigations in the root causes of the increases of failed closes and opens were led to the well-known culprit in the MEMS field -- stiction. Shutters were found stuck either on back walls or on light shields. The former lead to failed opens and the latter resulted in failed-closed shutters. A few failed closed shutters were shown in the 2-D addressing image in Figure 15. We have developed multiple methodologies and significantly reduced the stiction. The results will be discussed in future publications. Mass tested lately passed 100,000 or more cycles with minimal increase of failed open and failed closed shutters, which satisfied both the BOL and EOL requirements.

Optical tests have been conducted to evaluate MSAs in meeting the instrumental requirements, including transmission testing and reflection testing. The NIRSpec instrument requires the contrast ratio in MSAs to be >2000. Shutter arrays in 64x128 format fabricated with light shields are able to achieve a contrast of 7000 or higher, compared with those without light shields of ~200. The contrast is here defined as the ratio of the transmitted light when shutters are open over the one when they are closed. Light shields make significant differences. The contrast testing were conducted recently on171x365 MSAs with the final designs. The results are 10,000 or better.

Radiation tests are needed to simulate the ionizing particle radiation in space. MSA assemblies are tested by the exposure to gamma rays to a dose up of 200Krad. Flight-format MSAs passed the radiation tests. There was no significant failure in MSAs when subjected to functional tests after the exposure. Other environmental testing being conducted for MSA qualifications are vibration and acoustic tests. These tests are to simulate environmental conditions of the JWST launching. All elements in MSAs and joints in the assemblies are to be tested and qualified through the environmental testing.

5. SUMMARY AND FUTURE WORK

Flight-format microshutter array assemblies have been developed and modified at the NASA Goddard Space Flight Center. The fabrication team has gone through iterations of 32x32, 128x128, 64x128, 175x385, and 171x365 shutter arrays with major breakthroughs. The fabrication capability of wafer-level vertical electrodes enables the MSA's programmable 2-D addressing. The methodology of light shield formation assures MSAs reaching and exceeding the contrast requirement from the NirSpec instrument. A precise control of shutter bowing allows reliable operations at cryogenic conditions. The development of MSA fabrication techniques has resulted in matured processes and increased yields. Flight-format substrates have been fabricated and fully populated with ASIC multiplexer/addressing drive chips. An innovative technology of single-side indium flip chip bonding has been developed for mating MSAs to their substrates with a high uniformity and bonding strength. Complete MSA quadrant assemblies have been demonstrated. MSA fabrication team is now making MSAs for Engineering Test Units and Flight Units. The ultimate goal is providing four-quadrant microshutter systems that meet all the NIRSpec requirements and are ready for flight with JWST into space.

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