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Cryogenic characterization and testing of magnetically-actuated microshutter arrays for the James Webb Space Telescope

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Abstract
Two-dimensional MEMS microshutter arrays (MSA) have been fabricated at the NASA Goddard Space Flight Center (GSFC) for the James Webb Space Telescope (JWST) to enable cryogenic (~35 K) spectrographic astronomy measurements at near-infrared wavelengths. Functioning as a focal plane object selection device, the MSA is a 2D programmable aperture mask with fine resolution, high efficiency and high contrast. The MSA are close-packed silicon nitride shutters (cell size of 100 μm × 200 μm) patterned with a torsion flexure to allow their opening to 90°. A layer of magnetic material is deposited onto each shutter to permit magnetic actuation. Two electrodes are deposited, one onto each shutter and another onto the support structure side-wall, permitting electrostatic latching and 2D addressing. New techniques were developed to test MSA under mission-similar conditions (8 K $\leqslant T <$ 300 K). The 'magnetic rotisserie' has proven to be an excellent tool for rapid characterization of MSA. Tests conducted with the magnetic rotisserie method include accelerated cryogenic lifetesting of unpackaged 128 × 64 MSA and parallel measurement of the magneto-mechanical stiffness of shutters in 'pathfinder' test samples containing multiple MSA designs. Lifetest results indicate a logarithmic failure rate out to $\sim 10^6$ shutter actuations. These results have increased our understanding of failure mechanisms and provide a means to predict the overall reliability of MSA devices.

Introduction

In the quest to reveal the origins of galaxies, clusters and large-scale structures in the universe, scientists and engineers at the NASA Goddard Space Flight Center (GSFC) have begun work on James Webb Space Telescope (JWST) scheduled to launch in 2011. To fulfill its primary mission of observing galaxies at the peak of the star-forming and merging era, JWST will carry the near infrared spectrograph[7] (NIRSpec) which will provide

[7] To be built by the European Space Agency.

the required spectrographic coverage in the near-infrared wavelength region from 0.6 to 5 μm. To increase observation efficiency, simultaneous analysis of multiple astronomical bodies in a single JWST/NIRSpec field of view will be enabled by a programmable aperture mask (PAM) that will select objects to optimally fill the focal plane without spectral overlap [1].

The science requirements on the PAM are that it must cover a large optical field of view in the focal plane (7.7 cm $\times$ 7.0 cm format area) with high resolution (100 μm $\times$ 200 μm pixel dimensions), exhibit high on/off contrast ratio (>2000), and a high fill factor (>70%). Furthermore, to minimize thermal emissions into NIRSpec and since the JWST second Lagrange point orbit will be inaccessible to space shuttle re-servicing missions, the PAM must operate in a cryogenic ($\sim$35 K) vacuum environment reliably over a 10 year mission lifetime without repair after launch. Additionally, any device built to fly in space must, in general, have very tight constraints on mass, volume and power dissipation. In light of these mission requirements, microelectronic mechanical systems (MEMS) technologies are ideally suited for the design and development of the PAM.

Microshutter array design

A team at the NASA GSFC is developing a MEMS-based microshutter array (MSA) for application as the PAM on the JWST/NIRSpec [2, 3]. The MSA will represent the first mission-critical MEMS device to be flown in space. The MSA design has been driven by the aforementioned science and mission requirements and will be verified through extensive characterization and testing under flight-similar conditions. The MSA flight concept consists of a 2 $\times$ 2 format mosaic of four 384 $\times$ 175 arrays of close-packed shutters with a unit cell size of 100 μm $\times$ 200 μm placed in the JWST optical path at the focal plane. Individual shutters are designed with a torsion flexure hinge and are magnetically actuated by scanning a permanent tripole magnet across the MSA and electrostatically held open to allow the high-contrast transmission of light from specific celestial objects into NIRSpec. The selective nature of the MSA is achieved electrostatically via a three-voltage level, cross-point addressing scheme operating on orthogonally oriented column and row electrodes driven by external electronics [4, 5].

The challenges facing the MSA program are (1) the successful fabrication and packaging of the MSA and (2) the development of a comprehensive test plan with MSA-specific test techniques to fully evaluate MSA parts under flight-similar conditions. This paper will highlight the progress achieved in these two areas and discuss recent results.

Microshutter array fabrication

The current MSA development focuses on refining fabrication and testing techniques on smaller 128 $\times$ 64 MSA prototypes before scaling up the design to flight-sized 384 $\times$ 175 MSA dice. Materials selection for the MSA design was based upon a series of previously reported micromechanical tests and numerical analysis [6, 7]. The 128 $\times$ 64 MSA die are fabricated from silicon-on-insulator (SOI) wafers[8]. The SOI wafer consists of a 400 μm silicon handling layer, a 1 μm buried silicon dioxide (oxide) layer, and a 100 μm silicon device layer. A 0.4 μm sacrificial oxide layer and 0.5 μm silicon nitride layer are then pre-deposited onto the silicon device layer of the SOI wafer[9]. Additional depositions of 0.2 μm cobalt–iron magnetic material and 0.2 μm aluminum metal are sputtered onto the silicon device layer (front-side) and are subsequently patterned into magnetic stripes and rows of horizontal shutter electrodes, respectively. Each row of front-side shutters is electrically contiguous through a single front-side strip electrode but electrically isolated from adjacent rows. The silicon nitride shutter and torsion flexure hinge shape is delineated via patterning and reactive ion etching (RIE). An additional front-side metal deposition and patterning step is performed to build aluminum light shields around each shutter for blocking light leaks through the gap between the shutter and the silicon frame. The processing continues on the back-side (the side without shutters) with an anisotropic wafer-thinning back-etch, followed by a deep RIE (DRIE) back-etch to form a silicon frame support structure and to free the shutters from the silicon/oxide substrate. An additional aluminum oxide and metal deposition is conducted to form the vertical electrodes on the inside cell wall of the shutter frame. Each column of shutters is electrically contiguous through a single back-side strip electrode but electrically isolated from adjacent columns by a DRIE trench (8 μm depth) on the back-side frame. The shutters are then released from the silicon substrate by removing the sacrificial oxide layer underneath the shutters. Details of the entire fabrication process of the MSA have been previously described [2, 4, 5, 8, 9]. A schematic representation of an individual shutter cell in cross-section and scanning electron microscope images of a fabricated 128 $\times$ 64 MSA die are displayed in figures 1 and 2, respectively.

Current packaging of 128 $\times$ 64 MSA dice involves bump-bonding the front-side electrode pads, and wire-bonding the back-side electrode pads to gold traces on a 500 μm thick silicon substrate. The silicon substrate is then wire-bonded to a printed circuit board (PCB)[10] equipped with electrical pin connector interfaces to the drive electronics.

Microshutter array lifetesting

An MSA test plan has been developed to evaluate 128 $\times$ 64 MSA parts that are produced to quickly refine the design and fabrication process to meet the PAM science and mission requirements. A host of MSA-specific test techniques and capabilities have been developed and are applied at various stages in the 128 $\times$ 64 MSA development. One important component of the MSA test plan is accelerated cryogenic lifetesting of unpackaged 128 $\times$ 64 MSA dice. The goal of this test is to actuate shutters to 10^6 actuations, one order of magnitude beyond the 100% mission lifetime requirement of 10^5 actuations, in a cryogenic environment and evaluate the resultant failures.

[8] Obtained from MEMS Exchange, Reston, VA 20191, USA.
[9] Deposited through MEMS Exchange, Reston, VA 20191, USA.
[10] Bonding done by the Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.

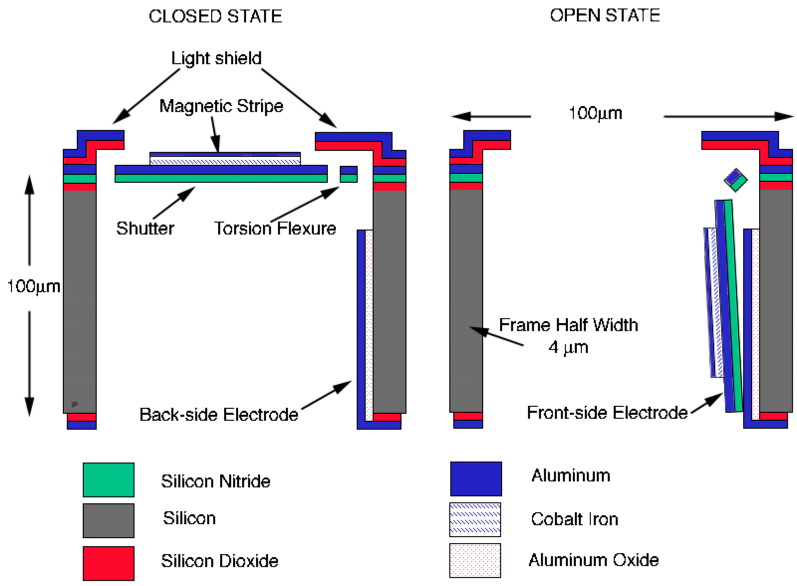
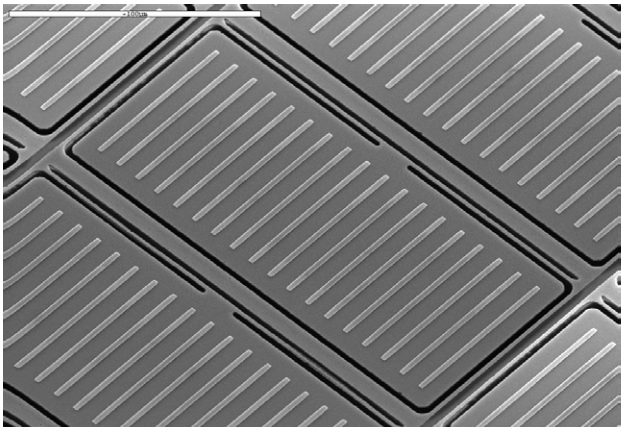
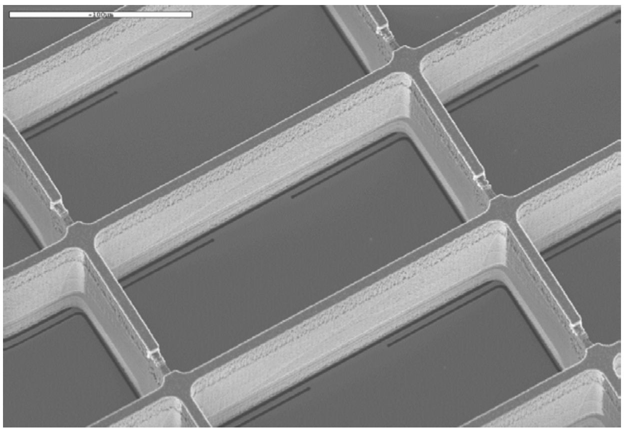


Figure 1. Schematic cross-section of a shutter cell in the closed and open states. Front-side (top) will face light objects in space whose spectra will be determined via NIRSpec placed on the back-side (bottom) of the array.



(*a*)



(*b*)

Figure 2. Secondary electron micrographs of a 128 × 64 MSA die (scale indicates 100 μm). (*a*) Front-side view shown without light shields for clarity. (*b*) Back-side view. Back-side DRIE trench (8 μm depth) provides electrical isolation between columns.

Microshutter array magnetic actuation

In the MSA flight concept, shutter actuation is generated magnetically through the interaction between an external magnetic field provided by a permanent tripole magnet and the cobalt–iron stripes deposited onto each shutter blade. The specific nature of this interaction is dependent upon the tripole magnet geometry. A tripole magnet (and other permanent magnet geometries[11]) has been modeled and constructed such that the magnetic field lines, emanating and terminating from the three poles, assume a carefully prescribed shape as illustrated in figure 3. The microshutter array is positioned in a plane above the tripole magnet tip and is oriented parallel with the tripole magnet travel with the front-side of the array facing away from the tripole magnet (refer to row of schematic unit cell cross-sections in figure 3). As the tripole magnet approaches a shutter cell, the magnetic field intensity and the magnetic field vector in the vicinity of the shutter cell increases and rotates, respectively. Both of these effects are necessary for the shutter blade to magnetically actuate into the open position.

Specifically, the proximity of the flux from the tripole magnet generates induced dipolar fields within each cobalt–iron stripe (denoted by the red arrows in figure 3). The high aspect ratios of the magnetic stripes ensure that the magnetic orientation of each cobalt–iron dipole is aligned with the long stripe dimension because of the presence of a high strength demagnetization field in all other directions [10]. When the external field intensity supplied by the tripole magnet is large enough to affect the cobalt–iron dipoles on a shutter blade, a magnetic torque is generated that encourages

[11] The design of the permanent magnet continues to evolve. Several different geometries have been modeled and tested for use as the magnetic actuator for the MSA. Based upon preliminary results, a permanent quadrupole magnet geometry may offer superior performance in a microshutter array application. However, all tests in this paper were conducted with tripole magnets.

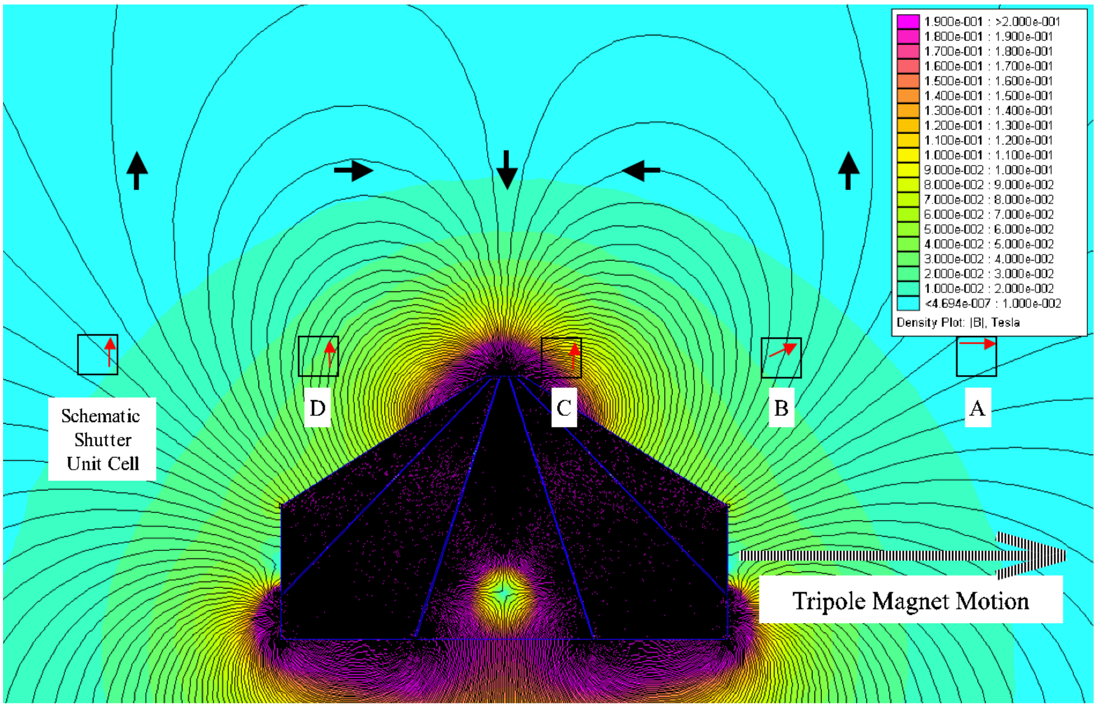


Figure 3. Flux model of the tripole magnetic field. The black arrows indicate the direction of the magnetic field vector along a plane above the tripole magnet. Note that the field vectors rotate as the tripole magnet tip is approached. The horizontal striped arrow shows the direction of tripole magnet motion. The black rectangles are a schematic representation of a row of shutter unit cells in cross-section where the red arrows are the cobalt–iron dipole on each shutter blade pointing towards the torsion flexure.

the cobalt–iron dipoles and thus the shutter blade to align with the flux from the tripole magnet. However, this magnetic torque is counterbalanced by the mechanical stiffness of the torsion flexure, so that at weak magnetic fields the shutter blade will not move (refer to unit cell A in figure 3). As the tip of the tripole magnet is approached along the microshutter array plane, the magnetic field vector begins to rotate downward. If the magnetic torque generated is greater than the torsional stiffness of the flexure then the local cobalt–iron dipoles will likewise rotate downward, opening the shutter blade into the silicon frame (refer to unit cell B in figure 3). The cobalt–iron dipoles continue to follow the rotating magnetic field vector until the shutter blade is fully open against the back-side electrode (refer to unit cell C in figure 3) at which time it can be electrostatically latched and held open (refer to unit cell D in figure 3).

Though the scanning tripole magnet actuation method with electrostatic latching has been successfully demonstrated on packaged and unpackaged 128 $\times$ 64 MSA at room temperature and 30 K and is suitable for the flight MSA design [3], the scanning mechanism required to translate the tripole magnet back and forth operates very slowly: one complete sweep takes $\sim$10 s. At this rate, a single lifetest to 10^6 actuations would require $\sim$116 days to complete; too long given the aggressive MSA development schedule. In order to acquire lifetest data to refine the fabrication process in a timely manner, accelerated lifetesting is necessary.

Magnetic rotisserie accelerated lifetest method

To accomplish accelerated lifetesting, a rapid magnetic actuation method, called the magnetic rotisserie method, was developed. Instead of slowly translating a tripole magnet, the magnetic rotisserie rapidly spins an MSA within a stationary, unidirectional, homogenous magnetic field to simulate the rotating magnetic field vector required to open the shutters. The shutter actuation sequence (top view) is illustrated in the schematic diagram of figure 4 (not drawn to scale). The green arrows indicate the direction of the homogeneous magnetic field generated between two electromagnet poles (green rectangles). The two black lines and black dot represent, in cross-section, the silicon frame support structure and torsion flexure, respectively, of a single shutter cell. The blue and red arrows represent a shutter blade: the color and arrow direction indicate the magnetization direction of the cobalt–iron magnetic material. The actuation sequence begins at 0° with the shutter cell oriented such that the shutter blade is parallel to the homogeneous field direction. The homogenous field, H, is turned on and the cobalt–iron magnetic material is initially magnetized away from the torsion flexure as indicated by the blue arrow. As the shutter cell is spun in a clockwise direction (indicated by the orange arrow), a torque is produced in the magnetized cobalt–iron material which attempts to maintain alignment with the applied homogeneous magnetic field by rotating about the torsion flexure axis against the restoring spring force of the torsion flexure as indicated at 45°. At 90°, the shutter blade makes first contact with the silicon frame support structure: the shutter cell is fully open. As the shutter cell continues to spin, the shutter is pushed along by the silicon frame support structure: the shutter cell is still fully open. At $\sim$180°, the combined effects of the torsion flexure restoring force and a sudden magnetic reversal of the cobalt–iron magnetization direction, now pointing towards the torsion flexure, causes the shutter blade to swing closed as

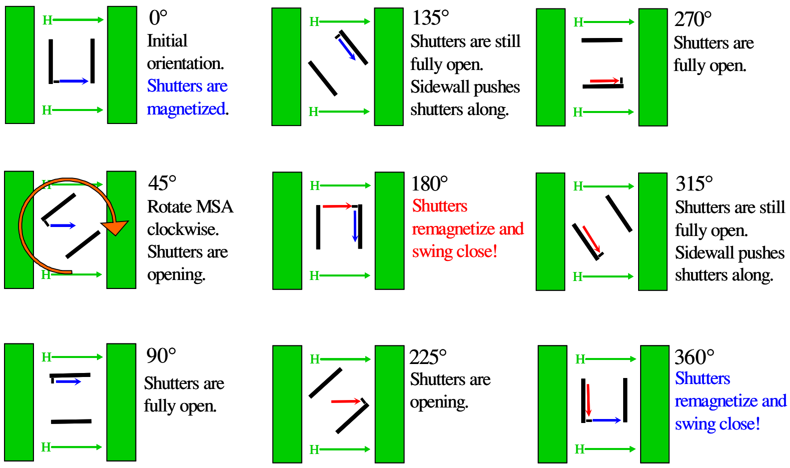


Figure 4. Schematic diagram (top view) illustrating the magnetic rotisserie actuation sequence.

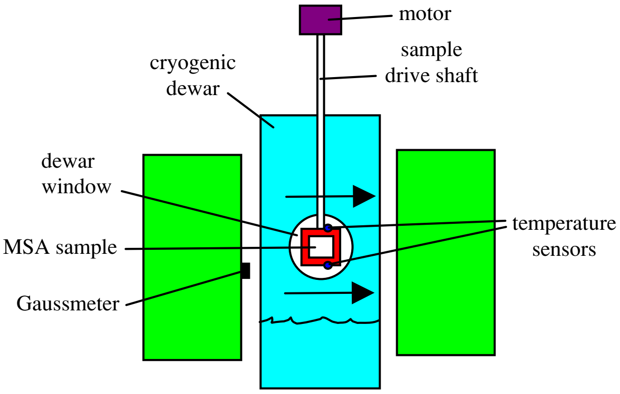
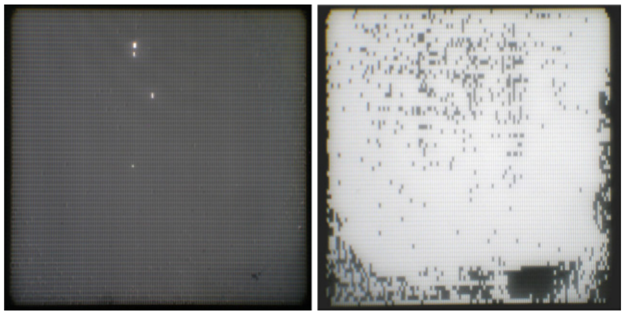


Figure 5. Schematic diagram (side view) of cryogenic magnetic rotisserie.



(*a*) (*b*)

Figure 6. Transmitted light micrographs of a 128 × 64 MSA without light shields in the LHe rotisserie in the (*a*) fully closed position at 0° and, (*b*) fully open position at 180° with $H = 0.4$ T. The active area of the MSA is 1.3 cm across.

indicated by the red arrow. As the shutter cell continues to spin, the remagnetized cobalt–iron again experiences a torque which forces the shutter blade to rotate open (225°) and the entire actuation process repeats itself: 270° fully open, 315° fully open against silicon frame support. At 360°, the combined effects of the torsion flexure restoring force and another magnetic reversal in the cobalt–iron again cause the shutter blade to swing close as indicated by the blue arrow. Thus, one revolution of the shutter cell in the magnetic rotisserie results in two complete shutter actuations.

Two accelerated cryogenic lifetest facilities have been constructed based upon the magnetic rotisserie method: a liquid nitrogen-cooled system (LN_2 rotisserie) and a liquid helium-cooled system (LHe rotisserie). The LHe rotisserie is depicted in figure 5. Unpackaged MSA dice samples are inserted into a non-magnetic, liquid helium dewar and suspended above the surface of the liquid helium coolant. The dewar is situated within a uniform, homogeneous magnetic field generated by a pair of water-cooled electromagnets. The magnetic field strength is adjustable ($-3\ \mathrm{T} \leqslant H \leqslant 3\ \mathrm{T}$) and monitored by a Gaussmeter. The MSA samples are attached to a drive shaft and motor assembly which provides the spinning motion which can attain shutter actuation rates up to 30 Hz. A mechanical counter monitors drive shaft revolutions which are converted to total shutter actuations. The sample temperature is monitored by two silicon diode sensors mounted on the MSA sample holder. The LN_2 rotisserie and the LHe rotisserie are capable of cryogenic testing between $90\ \mathrm{K} \leqslant T \leqslant 105\ \mathrm{K}$ and $8\ \mathrm{K} \leqslant T \leqslant 30\ \mathrm{K}$, respectively.

MSA samples are optically inspected through a set of dewar windows via transmitted light microscopy. Figure 6 displays typical images of an entire 128 × 64 MSA without light shields in the closed (0°) and open (345°) positions that demonstrate the validity of the magnetic rotisserie method for actuating shutters to the open position[12]. Use of fast camera shutter speeds during image acquisition also verifies shutter actuation while the MSA sample is spun at 900 rpm (or 30 Hz shutter actuation rate).

Accelerated lifetests were conducted on five MSA samples with the magnetic rotisserie method to evaluate two failure conditions for individual shutter cells: 'failed open' (light leaking through a supposedly closed shutter cell) and 'failed closed' (light blocked by a supposedly open shutter cell). The as-received, beginning-of-life (BOL), condition of all five MSA samples were imperfect, containing $\leqslant$3% 'failed open' and $\leqslant$11% 'failed closed' failures. Shutter cells exhibiting these BOL failures were excluded from subsequent

[12] This particular MSA sample had known processing imperfections (i.e.: missing and stuck shutters) but was still suitable for verifying shutter actuation.

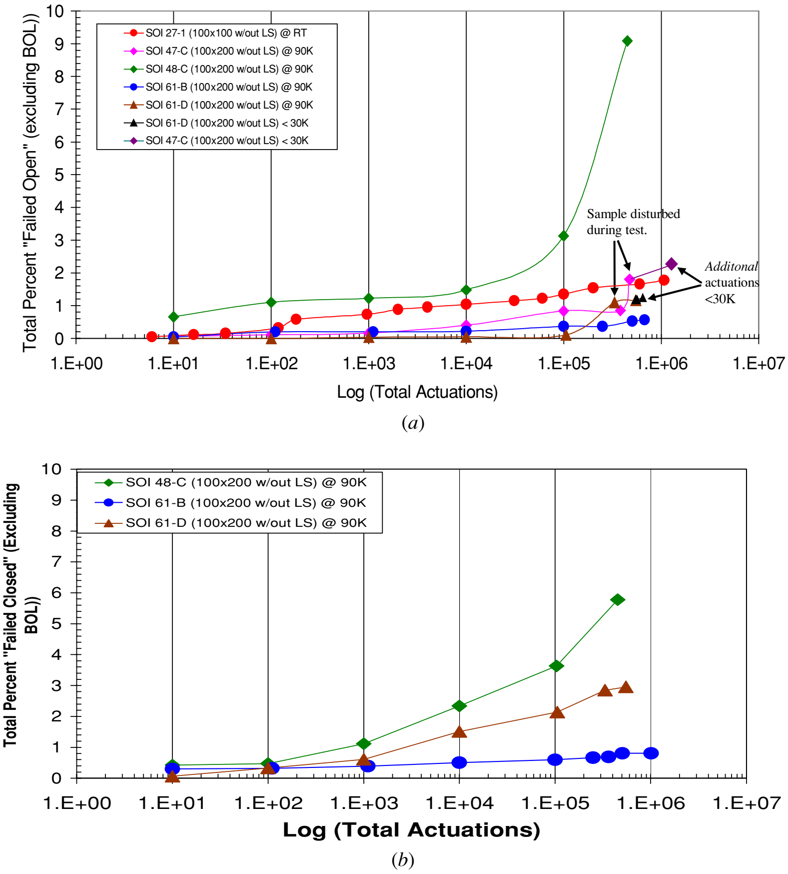


Figure 7. Summary of lifetest results for (*a*) 'failed open' failures, and (*b*) 'failed closed' failures.

lifetest analyses. On average, over 7500 shutter cells per sample participated in cryogenic lifetesting.

None of the rotisserie-tested MSA samples contained light shields (LS). The cobalt–iron on each shutter of all of the MSA samples was of an earlier design, configured as a single square or rectangular pad instead of multiple stripes. One sample, a 128 × 128 MSA from an earlier design with a 100 μm × 100 μm shutter cell size (SOI 27-1), was lifetested at room temperature in ambient air. Cryogenic lifetesting between 90 and 105 K in nitrogen vapor was performed on four 128 × 64 MSA samples of a more recent design with a 100 × 200 μm shutter cell size (SOI 47-C, SOI 48-C, SOI 61-B, SOI 61-D). Two samples (SOI 47-C, SOI 61-B) underwent additional cryogenic lifetesting between 8 and 30 K in helium vapor. The torsion flexure geometry (width and length) of all of the MSAs varied between the samples.

Images of the entire MSA in an open and closed position were recorded at BOL and repeated at a minimum at every order of magnitude of shutter actuation throughout the lifetest. The total change in the number of 'failed open' and 'failed closed' shutters from one inspection to the next was counted and the associated number of shutter actuations was noted. A summary of the lifetest results is presented in figure 7.

For four of the MSA samples lifetested the 'failed open' failure rate increased logarithmically adding <2.3% failures at 10^6 actuations. Scanning electron microscopy (SEM) analysis indicates that the predominant failure mode in these cases was shutters missing due to fracture on the torsion flexure or near the shutter blade neck. The anomalous behavior of the 'failed open' failures of sample SOI 48-C is currently under investigation. The 'failed closed' failure rates also increased with actuations. The primary failure mode was contact between the shutter blades against the silicon frame side-walls preventing shutter actuation. This type of failure would occasionally 'heal' itself: a shutter cell qualifying as a 'failed closed' failure in one optical inspection would not always qualify as a failure in the next inspection. Slight misalignments between the shutter blade and the surrounding silicon frame and out-of-plane shutter blade twisting due to low cobalt–iron coercivity may be the cause of the 'failed closed' failures. Improving the front-to-back alignment with newly acquired fabrication tools and modifying the cobalt–iron magnetic pad into a multiple stripe design with higher coercivity may reduce the number of 'failed closed' shutters in future accelerated lifetests.

Magneto-mechanical stiffness

Since the functional performance of shutter actuation is dependent upon a combination of effects, namely the restoring spring force of the torsion flexure and the magnetic reversal in the cobalt–iron material, the magneto-mechanical stiffness is an important parameter for MSA design purposes. The magnetic rotisserie lifetest method conveniently enables this measurement for all shutters in an MSA in parallel and at cryogenic temperatures.

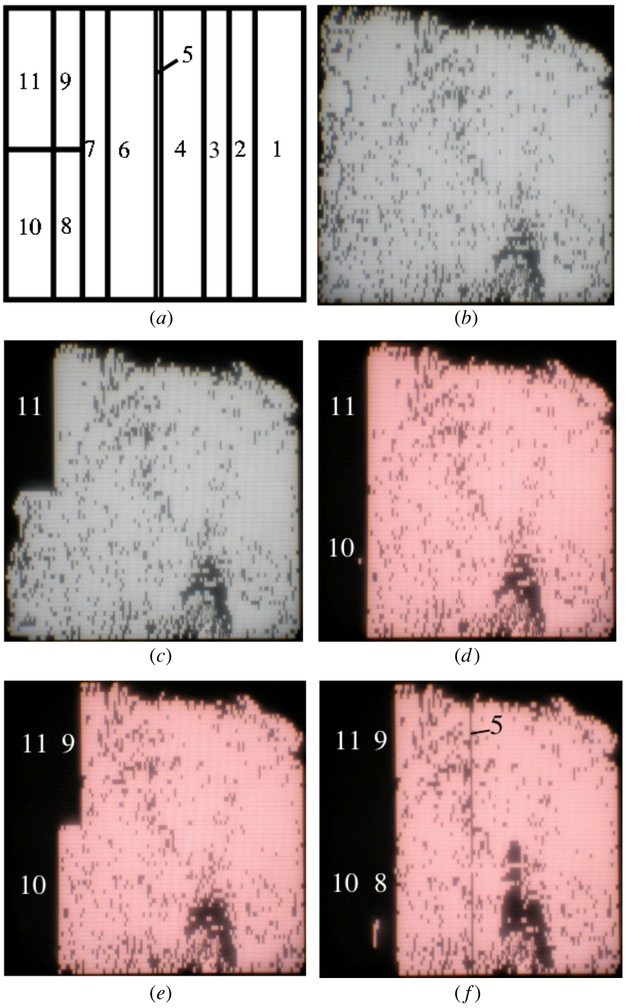


Figure 8. Magneto-mechanical stiffness characterization of 'pathfinder' 128 × 64 MSA. (*a*) Schematic of 11 different test regions, (*b*) all regions open at 0.200 T, (*c*) region 11 closed at 0.160 T, (*d*) region 10 closed at 0.145 T, (*e*) region 9 closed at 0.130 T, (*f*) region 8 closed (95%), region 5 closed (95%) at 0.120 T.

A 'pathfinder' 128 × 64 MSA sample was fabricated containing 11 test regions each with a different torsion flexure geometry (variables were width and length) and/or magnetic stripe design (variables were number of stripes per shutter and stripe width) and is schematically represented in figure 8(*a*). To characterize the magneto-mechanical stiffness, the 'pathfinder' MSA sample was placed in the magnetic rotisserie lifetest apparatus and slowly spun in the magnetic field ($H = 0.200$ T) until all shutters in the array were open. The sample was held at this angle (relative to the applied magnetic field direction), and the magnetic field strength was slowly decreased. As the torsion flexure restoring force and magnetic reversal in the cobalt–iron of a particular test region combined to overcome the applied magnetic field, the shutters within that test region swung close. Shutters within test regions that were magneto-mechanically stiff closed at higher applied magnetic fields than shutters within test regions that were magneto-mechanically more compliant as illustrated in figures 8(*b*)–(*f*). These results have been used to finalize a specific torsion flexure geometry and magnetic stripe design for the next generation of MSA.

Conclusions

The MSA development team at the NASA GSFC has successfully fabricated 128 × 64 MSA devices. A comprehensive test plan has been implemented and MSA-specific cryogenic testing and characterization techniques have been developed. The magnetic rotisserie lifetest method which has been demonstrated at cryogenic temperatures indicates a logarithmic 'failed open' failure rate that adds <2.3% failures at 10^6 actuations. This method has increased our understanding of different failure modes and provides a means to predict device reliability. Near-term efforts include additional cryogenic lifetesting on the next generation 128 × 64 MSA samples with light shields and fabrication of flight-like 384 × 175 MSA devices.

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