CHARACTERIZATIONS OF OPTIMIZED MICROSHUTTER ARRAYS FOR SPACE BORNE OBSERVATORY APPLICATIONS

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ABSTRACT

We report the latest design, fabrication, and characterization results of the Next-Generation Microshutter Arrays (NGMSA) for space borne observatory applications. Our modified blade design aims to improve overall actuation torque by reducing the electrostatic force between free end of the shutter blade and the adjacent silicon frame, which generates counter torque at intermediate travel range, thus enables pure electrostatic actuation for more reliable and stable microshutter operations. This paper presents the experimental performance results of newly fabricated microshutter arrays with varying design parameters and compares the results with simulation predictions.

KEYWORDS

Electrostatic, MEMS actuator, microshutter array, multi-object spectroscopy

INTRODUCTION

A microshutter array (MSA) is a programmable field mask device consisting of a two-dimensional array of individually operable shutters which enables multi-object spectroscopy in the target field of view of a telescope. The shutters allow light only from selected target objects while blocking out all other light. Such a mechanical shutters provides higher optical contrast than other multi-object selection devices [1]. The first generation MSA made for Near Infrared Spectrograph (NIRSpec) instrument on the James Webb Space Telescope (JWST) was designed to operate with magnetic force actuation and electrostatic latching [2].

The NGMSA program at NASA Goddard Space Flight Center (GSFC) is an effort to enable fully electrostatically operable microshutter array based on a modification of the original MSA design, thereby removing heavy and complex magnetic actuation systems used on the JWST [3]. The feasibility of pure electrostatic actuation was demonstrated on the Far-ultraviolet Off Rowland-Circle for Imaging and Spectroscopy (FORTIS) sounding rocket mission in 2019 [4]. Actuation of these

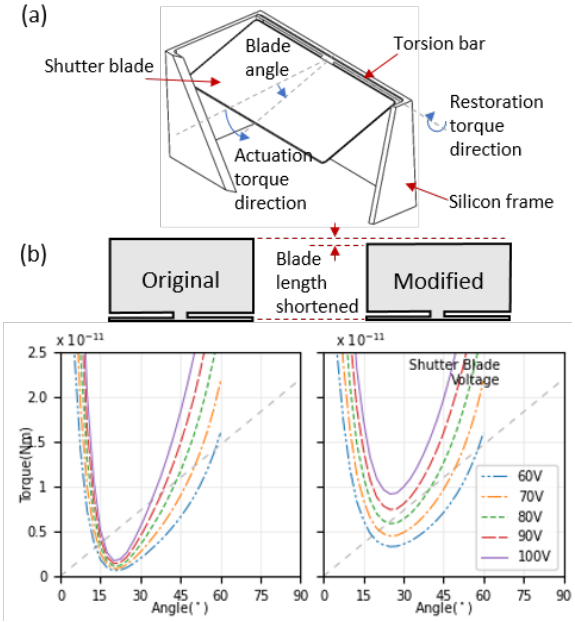


Figure 1: (a) Schematics of a unit microshutter with partial cut-out of silicon frame, (b) Illustration of how shutter blade dimension is modified and the difference in corresponding actuation torque. Original design and 3μm shortened design are compared.

FORTIS-NGMSA relies on fast-rising high-voltage signal (typically called pulse actuation) to gain enough momentum to pass through a range of angles with low actuation torque in the middle of the blade travel span. However, the pulse actuation method often makes fine shutter motion control extremely challenging. The uncontrolled and fast shutter motion causes premature shutter failure, and fast rising voltages induce undesirable blade motions.

In a previous paper, we studied the electrostatic force profile over the angular range of the shutter blade motion using COMSOL Multiphysics finite element electrostatic model, and we found that for the FORTIS design there is a range that the electrostatic actuation torque dips below

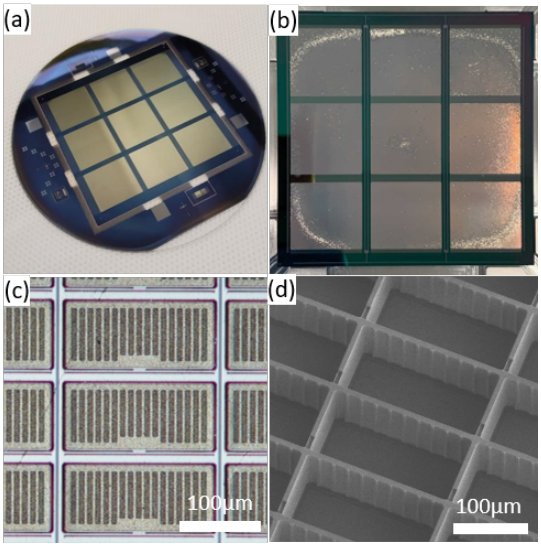


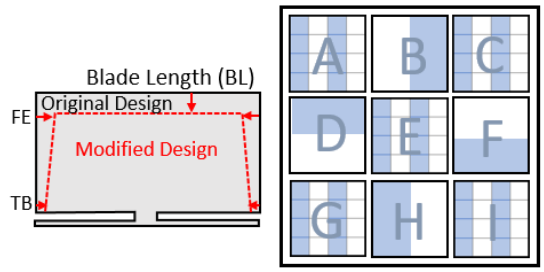
*Figure **2**: (a) A 384×736 format array fabricated on a 6-inch wafer, before being released, (b) Complete array on an array carrier, (c) Top-down view of individual shutters, (d) SEM picture of the back side of an array.*

the mechanical restoration torque, making quasi-static actuation impossible [6]. A brief summary of the study is illustrated in Figure 1. Several variations of shutter blade designs were studied with the simulation model in order to fine designs that enable quasi-static actuation within reasonably low voltage range (100 V or lower). It turned out that shortening the shutter blade by several micrometer effectively increases the actuation torque by reducing unfavorable electrostatic interaction with the adjacent silicon frame. In addition, slight blade width reduction helps avoiding undesirable lateral blade motion.

In the work presented here, we examine the possibility of quasi-static actuation and overall improvement of actuation behavior by fabricating modified shutter blades with varying design combinations. The new designs are implemented into newly developed 384×736 format arrays. Opening angle at low voltage and minimum latching voltages are compared between the new and original designs. Also, an additional finite element electrostatic model is used to understand an unexpected blade behavior observed during electrical testing. We find that stable quasi-static actuation is possible with several different modified blade designs. Further experiments should be performed to identify the most optimal design and understand newly found shutter behavior.

EXPERIMENTAL METHODS

We developed a process to fabricate 384×736 format arrays on 6-inch wafers. Total size of an array is 92 mm×92 mm. The active shutter area is divided into nine sub-arrays separated by 3 mm wide frames to achieve mechanical integrity against vibration. Figure 2(a) and (b) show a fabricated 384×736 NGMSA on a 6-inch wafer before released and a completed array. Individual unit shutters have 200 µm and 100 µm pitches in the in-plane



Design No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
BL (um)	0	-1	-1	-1	-1	-2	-2	-2	-2	-3	-3	-3	-3	-4	-4	-4	-4
FE (um)	0	-1	-1	-2	-2	-1	-1	-2	-2	-1	-1	-2	-2	-1	-1	-2	-2
TB (um)	0	0	-1	-1	-2	0	-1	-1	-2	0	-1	-1	-2	0	-1	-1	-2

*Figure **3**: Illustration of how shutter blade design is modified. Top-right pane shows how different design blades are distributed on an array. Bottom pane shows dimension variations of blade including original design. Each sub-array is labelled as A-I.*

directions. Figure 2(b) and (c) show the front and back side of individual shutters.

Sixteen different combinations of modified blade designs are prepared along with the original design and distributed to multiple sub-arrays. The new designs are modified from previous rectangular blades (design number 0 in figure 3) into smaller rectangular and "keystone" geometry with reduced blade profile (blade length, side gap at free and, side gap at base). The reduction amount ranges between 1 to 4 µm, as shown in Figure 3.

Measurements were performed on an electrostatic test station built in house. Figure 4 shows the setup configuration. The device chuck is mounted on a *y*-axis

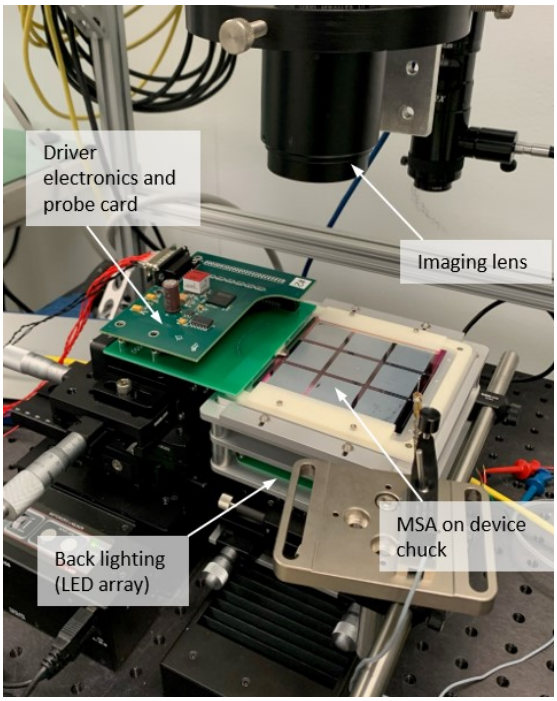
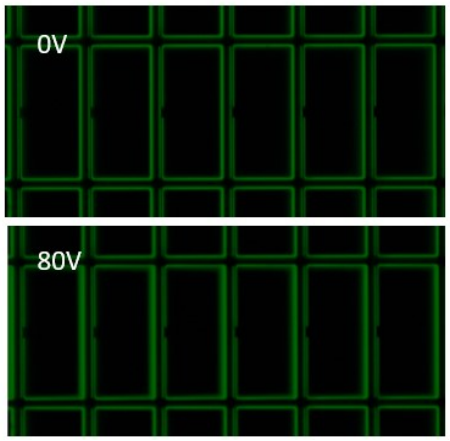


Figure 4: Picture of the electrostatic microshutter actuation test setup.

(a)



(b)

	FE-1μm TB 0μm	FE-1μm TB-1μm	FE-2μm TB-1μm	FE-2μm TB-2μm
BL-1μm	12.5°	12.3°	10.2°	10.6°
BL-2μm	13°	14.8°	12.5°	11.9°
BL-3μm		15.3°	13.6°	12.7°
BL-4μm		16.2°	14.4°	13.7°

Figure 5: (a) Sample low voltage partial opening image data show shutter blades at original position (0 V) and tilted position with 80 V static voltage signal, (b) Averages of 80 V blade tilt angles by different designs.

motorized stage to accurately establish electrical contacts to the electrodes over the whole span of the device. The chuck is equipped with uniform back illumination. Partial or fully open shutters are identified in images captured by a camera mounted above the device. Voltage signals are applied via a multi-contact probe card. Custom driver electronics were developed utilizing a multi-channel high-voltage DAC driver, which is directly mounted on top of the probe card.

Two different test methods are used to verify shutter performance. First, a low voltage partial opening test is performed. In this test, voltages of 0 V–80 V are applied to the shutters and images are taken with back illumination. The images are analyzed to calculate blade tilt angle at a given voltage. This test provides quantitative result of how easily the shutters are actuated at a given voltage. The second method is the latching voltage test. Actuation voltage is slowly increased until the shutters are latched. The number of latched shutters in each design region represents the shutter performance.

During these tests, we observed that some of the shortened blades are pulled toward the torsion bar side and got stuck at partial opening angle. Since the numerical model used in our previous study does not include the torsion bar as a part of the model, but assumes it as a rigid hinge, such a behavior was not predicted. It seems that electrostatic interaction between the torsion bar and its adjacent silicon frame becomes more pronounced by reduced interaction on the free end of the blade. We studied this effect with a revised numerical model with the torsion bar included.

EXPERIMENTAL RESULTS

Low voltage partial opening test

Figure 5(a) shows sample images taken during low voltage partial opening test. At 0 V, the shutter blades are within a perpendicular plane to the viewing axis. When actuation voltage is applied, the blade tilts and the projection of the tilted blade to the perpendicular plane is visible in the image. Blade tilt angle is calculated by comparing the blade length (pixel count) from both images. About 50 shutters are analyzed for each design. Figure 5(b) shows average blade tilt angles at 80 V. As predicted from the previous numerical model study, shorter blades actuate easier than longer ones. As a reference, the original design shutter blade on the same array tilt about 7°–8° at 80 V. This means that modified shutter design effectively improves actuation performance. Note that the tilt angle calculated from this test is less than the value estimated by numerical calculation shown on Figure 1. One possible reason is sub-optimal electrical isolation of electrodes on the device used in this test, which causes current leakage to the silicon frame ground and thus reduce the effective voltage on the blade. There is still a lot of room for improvement in subsequent iterations of fabrication. While the modified side profile of blade may help reduce undesirable blade rotation, narrower blades do not as effectively actuate as wider blade according to this data.

Latch voltage test

A preliminary latching test result is shown in the Figure 6. In this test, the driver electronics apply voltage

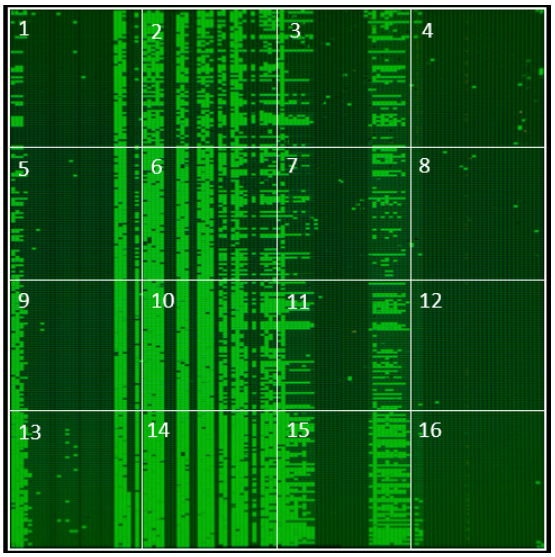


Figure 6: Latch test image of sub-array E (center sub-array) at 120 V. Bright green pixels are latched shutters. Design numbers are marked on each location.

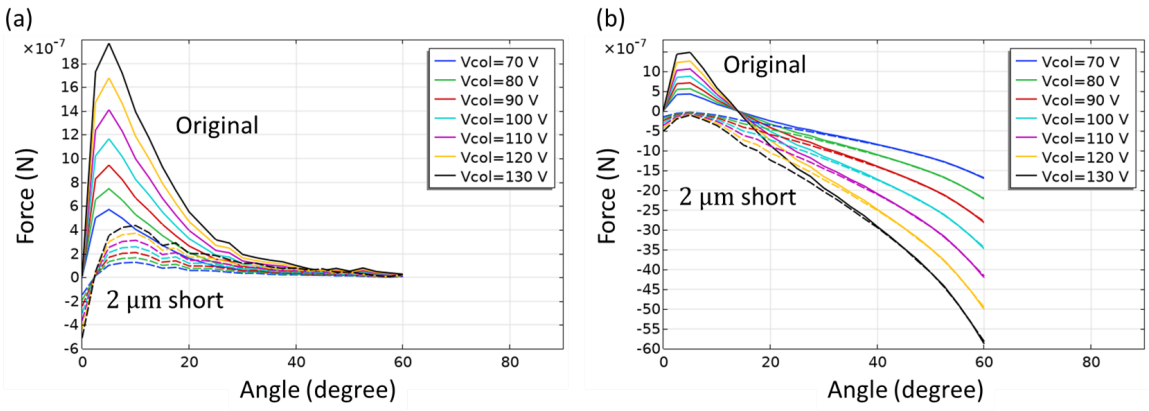


Figure 7: Electrostatic simulation results. (a) Radial force on the shutter. (b) y-direction force on the shutter.

signal to a range of electrodes (25 maximum, which is limited by the number of probe card contacts) simultaneously. Local images of the test area are stitched together to show the entire subarray area result. Note that not all electrodes actuate possibly due to sub-optimal electrode isolation from the silicon frame.

Unlike shutters of the original design, most modified designs can be latched with quasi-static voltage signal. Depending on the design, the shutters start latching from around 110 V. The example shown on Figure 6 is for 120 V. This preliminary result does not clearly show the whole data from an entire array, however, shows a weak trend of actuation performance by design. In the figure, shutters in the bottom left corner (shorter and wider blades) tend to latch better than the opposite side direction.

Of the shorter blades, a number of shutters failed to open. Upon further examination, we found that many of the torsion bars are bent toward the adjacent silicon frame and touch it, and no longer rotate to fully open the shutter. We speculate that the shortened shutter blades experience less forward attraction and as a result, torsion bar side pulling force (backward attraction) becomes more pronounced. It is clear that the balance of electrostatic force between the front and back silicon frame must be considered to optimize the shutter blade motion. In the previous simulation, this phenomenon was not predicted because the torsion bar was assumed to be mechanically stiff enough to withstand the electrostatic forces regardless of the blade design. Therefore, the electrostatic model is updated to include the torsion bar to inspect the test results in more detail.

Electrostatic simulation

Due to the proximity of the torsion bar to the back silicon frame, there is a significant back wall attraction (negative *y*-direction) on the shutter during actuation. The effect of the force is not noticeable in the original shutter design due to the strong attraction between the free end of the blade and the front wall, as shown in Figure 7. When the blade is shortened, the front attraction is significantly reduced. The net force direction on the shutter becomes negative. The small distance between the shutter blade and the torsion bar increases the chance of shutters getting stuck on the back wall.

Simulations suggest that there is an optimum blade shortening of about 2 µm that lowers actuation voltage requirements and maintains *y*-directional force balance on the blade.

CONCLUSION

In this paper we report the improved design of NGMSA such that quasi-static electrostatic actuation is possible. Original NGMSA shutter blade designs are modified by reducing the blade length by 1 µm to 4 µm. Quasi-static partial opening and latching test shows effective actuation performance improvement over the original design. A new shutter failure mode is found during the tests and it is analyzed with an updated numerical simulation. More characterizations on electrostatic operations will be performed as the new processing techniques are being matured.

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