# Design and Fabrication of Electrostatically Actuated Silicon Microshutter Arrays

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**Abstract:**
We have developed a new fabrication process to actuate microshutter arrays (MSA) electrostatically at NASA Goddard Space Flight Center. The microshutters are fabricated on silicon with thin silicon nitride membranes. A pixel size of each microshutter is 100 x 200 μm$^2$. The microshutters rotate 90$^o$ on torsion bars. The selected microshutters are actuated, held, and addressed electrostatically by applying voltages on the electrodes the front and back sides of the microshutters. The atomic layer deposition (ALD) of aluminum oxide was used to insulate electrodes on the back side of walls; the insulation can withstand over 100 V. The ALD aluminum oxide is dry etched, and then the microshutters are released in vapor HF.

Keywords — Microshutters, electrostatic, actuation, rotational, fabrication, ALD, aluminum oxide, breakdown voltage, SOI

## Introduction

We have developed a new fabrication process to actuate MSA electrostatically. In the past, a large microshutter array size of 175x384 had been developed, fabricated, and installed in the James Webb Space Telescope (JWST) as multi-object aperture selectors at NASA Goddard Space Flight Center [1, 2]. The JWST MSAs were magnetically opened and electrostatically held open. The magnetic operation, however, involved moving magnets thus complicated actuation schemes and increased the payload. By solely relying on the electrostatic actuation, the actuation scheme is simple yet the weight of the MSA assembly is reduced. The microshutters were made with silicon nitride membranes with a pixel size of 100 x 200 μm$^2$ and rotate on torsion bars. Fig. 1 (a) shows an optical photo of the microshutter array and (b) shows aluminum light shields above the microshutters. A new electrostatic operation scheme as shown in Fig. 2 is simple, and the array scalability and operation speed are increased. In order to achieve the electrostatic actuation of the microshutters, we need to develop a new fabrication process.

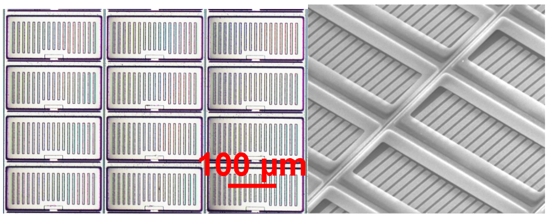


***Fig. 1:*** *A front side image of a (100 x200 μm$^2$) microshutter array (a). On the microshutters, patterned aluminum electrodes and strips of molybdenum nitride are shown. SEM images of microshutters with light shields that prevent light going through the gaps between shutter blade and the frame surrounding the shutters (b).*

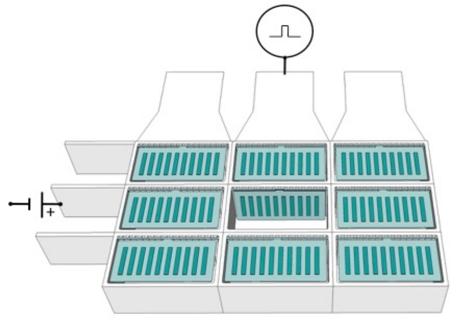

***Fig. 2:*** *An illustration of how the microshutters are individually actuated and addressed by applying a pulsed DC voltage to the front electrodes (top) and a DC voltage to back electrodes (left). Only the microshutters with voltages on both the front and back electrodes latch open by rotating 90° on torsion bars. The front electrodes run vertically while the back electrodes run horizontally.*

## MSA Fabrication

We first grew a layer of thermal silicon oxide on a silicon-on-insulator (SOI) wafer; the buried silicon oxide, device, and handle silicon layers were 3000 Å, 100 μm, and 350 μm thick, respectively. Then, a layer of low pressure chemical vapor deposition (LPCVD) silicon nitride was deposited.

A layer of aluminum was deposited in an e-beam deposition system. Then, the aluminum was etched in an aluminum etchant for the front electrodes. The silicon nitride was etched in a reactive ion etch (RIE) system with tetrafluoromethane ($CF_4$) to form the microshutters. A layer of molybdenum nitride was deposited in a sputter deposition system to make the microshutters flat. The film was photolithographically patterned in strips and etched in a diluted nitric acid (deionized water: nitric acid = 1:1) at room temperature. The stress of aluminum was only around 50 MPa. Even with the low stress of aluminum, the bilayer of the silicon nitride and aluminum would bow ~ 10 μm. Therefore, the strips of the molybdenum nitride corrected the bowing and made the bilayer flat. Also, the molybdenum nitride was used as bonding pads in one of our packaging steps: indium flip chip bonding [1].

After the front side processing was completed, the wafer was temporarily bonded to a Pyrex wafer using an acetone soluble Crystalbond 509 wax; the Pyrex wafer was used to perform a back-to-front photolithography alignment. Then, the handle silicon was thinned down to 100 μm in a lapping system and then completely removed in a deep reactive ion etch (DRIE) system to expose the buried oxide.

On the back side, the buried silicon oxide was photolithographically patterned and dry-etched in a RIE system using $CF_4$. The buried silicon oxide was used to create silicon trenches; the trenches were used to separate back electrodes when the subsequent aluminum was deposited at an angle. Fig. 3 is images showing no aluminum in bottom of the trench. The remaining silicon was first etched in a DRIE system to create walls as shown in the step 1 of Fig. 4. Then, the photoresist used for the DRIE etch mask was stripped and the previously patterned silicon oxide is used as a hard mask to etch the silicon trenches. Fig. 3 is a scanning electron microscope (SEM) image of the back side of the microshutters. The ribs in the back walls were to prevent the microshutter stiction.

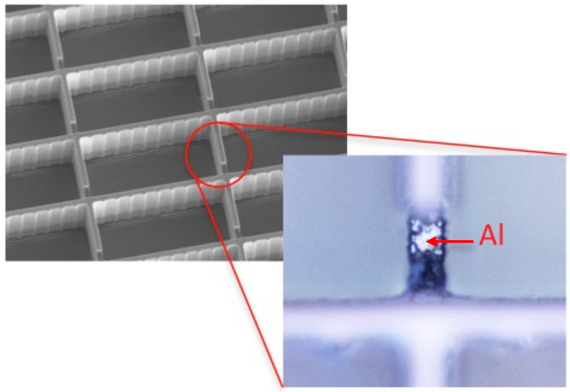


*Fig. 3: A SEM photo of the back walls with trenches. The close-up photo shows that the aluminum is not continuous on the bottom of the trench. Thus, each back electrode running horizontally is separated.*

On the back walls, a layer of plasma-assisted aluminum oxide was deposited conformally using trimethylaluminum and oxygen plasma at room temperature in an atomic layer deposition system to insulate the back side of walls as shown in the step 2 of Fig. 4. We need to keep low temperature because the wafers were still bonded with the wax, which softens around 70 $^{o}$C.

On top of the aluminum oxide, aluminum was deposited at an angle in an e-beam deposition system to create the electrodes only on the back walls as shown in the step 3 of Fig. 4. On top of the aluminum, a layer of silicon oxide was deposited at a different angle in the same e-beam system as shown in step 4 of Fig. 4. The difference in the deposition angles was to cover the aluminum electrode completely with the silicon oxide used as a hard mask for the subsequent dry-etch of the aluminum oxide. We found out that there was a drop in resistance by about half when the silicon oxide was deposited at the same angle and etched in the subsequent etch. The aluminum oxide was only etched behind the microshutter blades with boron trichloride ($BCl_3$) in a RIE system as shown in the step 5 of Fig. 4.

The MSA arrays were first release in acetone, and then all the microshutters were freed by removing the silicon oxide in a vapor HF system; the hard mask of the e-beam deposited silicon oxide was also removed in vapor HF.

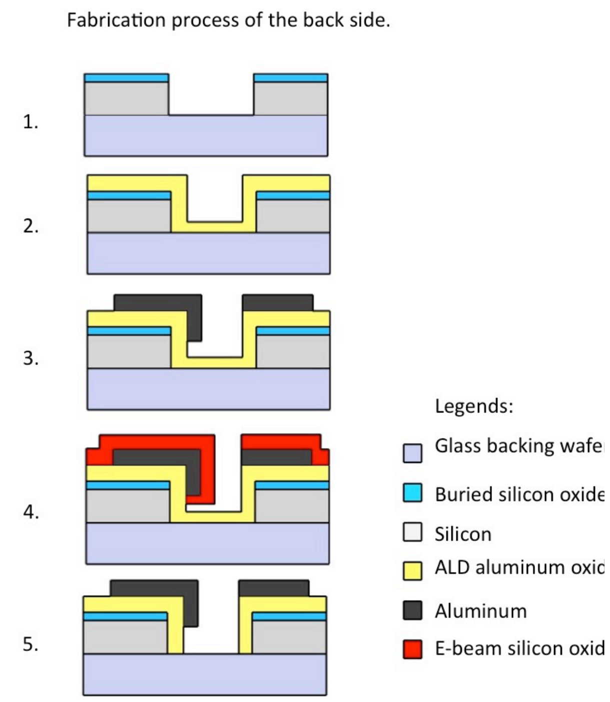


*Fig. 4: An illustration of the back side process of the back side insulator and electrodes. 1: Silicon is etched in a DRIE system. 2: ALD aluminum oxide is deposited as an insulator. 3: E-beam aluminum is deposited at an angle for the back side electrodes. 4: E-beam silicon oxide is deposited at an angle. 5: The ALD aluminum oxide is only etched on the bottom in a RIE system, and silicon oxide is removed in vapor HF.*

**Discussion**

For the electrostatic actuation, we need to keep an operating voltage below 150 V for flight applications. The JWST MSAs were fabricated on 5000 Å thick silicon nitride. Our finite element analysis model using COMSOL and micro-mechanical force measurements agreed that reducing silicon nitride from 5000 Å to 2500 Å results in the reduction of the stiffness of the silicon nitride by the approximate factor of four [3]. Thus, the microshutters opened with a short DC pulse of ~100 V to the front electrode (4). When the microshutters opened with the DC pulse, a DC voltage on the back electrode is applied to bring the microshutters to the back electrode and to keep the microshutters latched. The required back electrode voltage was -25 V [4].

In the new fabrication process, we utilized the ALD aluminum oxide as the insulation layer between aluminum back electrodes and silicon walls to replace the e-beam aluminum oxide that was used in previous JWST MSA fabrication. The e-beam deposited aluminum oxide was not a reliable insulator for the electrostatic actuation of the microshutters; the resistance was low: 1~10 MΩ range, and its breakdown voltage was around 40V. The ALD aluminum oxide is very dense unlike the e-beam deposited aluminum oxide MΩ. Also, the ALD aluminum oxide is conformal unlike directional e-beam deposited aluminum oxide. Thus, the step coverage over the silicon back walls are much better than that of the e-beam aluminum oxide. This explains improved the measured resistance of the ALD aluminum oxide on the back silicon walls etched in the DRIE step: the resistance was over 1GΩ. This also increased the breakdown voltages as shown in Fig. 5. The breakdown voltage of 2340 Å thick of ALD aluminum oxide was around 120 V while 1 µm thick e-beam deposited aluminum oxide was around 40V.

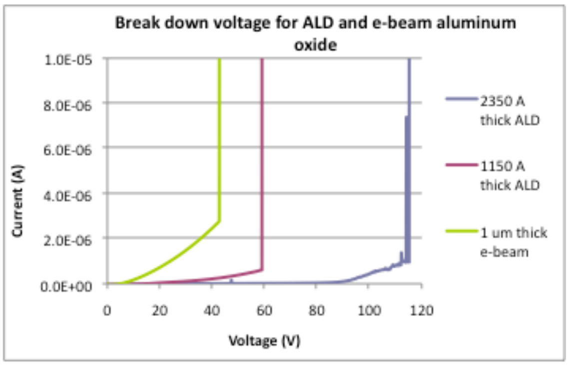


***Fig. 5:** A breakdown voltage comparison of 1 µm thick e-beam deposited aluminium oxide, 1150 Å and 2350 Å thick ALD aluminium oxide. The films were deposited on the flat surface of silicon wafers, and 1x1 mm$^2$ of 5000 Å e-beam aluminium was deposited for this experiment.*

**Results**

With the actuation scheme discussed above, we were able to open microshutters selectively as shown in Fig. 6. The white pixels are where the microshutters were held open while a back illumination was lit; the black background shows that the microshutters stay closed thus block the light.

***Fig. 5:*** *A photo of the microshutters selectively opened with a back illumination.*

**Conclusion**

We successfully fabricated electrostatically acutated microshutter arrays. The array was 64 x 128 pixels. The microshutters opened with a 100 V DC pulse and stayed open with -25 V on the back electrode. In order to achieved the electrostatic actuation, we came up with an optimum thickness of silicon nitride. Also, we used ALD aluminum oxide for the insulation on the back electrodes. The use of ALD aluminum oxide improved electrical insulation by three orders of magnitude.

**Future work**

There are light leaks around the perimeter of each microshutter. We will implement aluminum overhangs over the perimeter of each microshutter. Thus, there will be no light leak around the microshutter blades.

We will make a mosaic of microshutter arrays on a single substrate, such as a printed circuit board (PCB), to increase the field of view for future space telescopes. Also, high voltage driver chips and other electronic components will be installed in the PCB. This will be a complete multi-object aperture selector system for space applications.

**References**


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