

MEMS Deformable Mirror Actuators with Enhanced Reliability

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ABSTRACT

MEMS deformable mirrors with thousands of actuators are under development for space-based operation, which require fault tolerant actuators that will not fail due to electrical overstress. We report on advances made in the development of MEMS deformable mirror actuators with enhanced reliability for space-based, high-contrast imaging instrumentation that eliminate irreversible actuator damage resulting from snap-through.

Keywords: Deformable mirror, spatial light modulators, adaptive optics, MEMS, high contrast imaging.

1. INTRODUCTION

To meet the needs of the astronomical imaging instruments using adaptive optics Boston Micromachines Corporation (BMC) has been developing MEMS deformable mirrors (DMs) with thousands of actuators to allow for precise wavefront control. The BMC MEMS DM architecture is based in the surface-micromachined, polysilicon double cantilever actuator design illustrated in Figure 1 [1]. The device structure consists of actuator electrodes underneath a double cantilever flexure, which is electrically isolated from the electrodes and maintained at a ground potential. The electrostatic actuators are arranged in a square grid and the flexible mirror surface is connected to the center of each actuator through a small attachment post that translates the actuator motion to a mirror surface deformation.

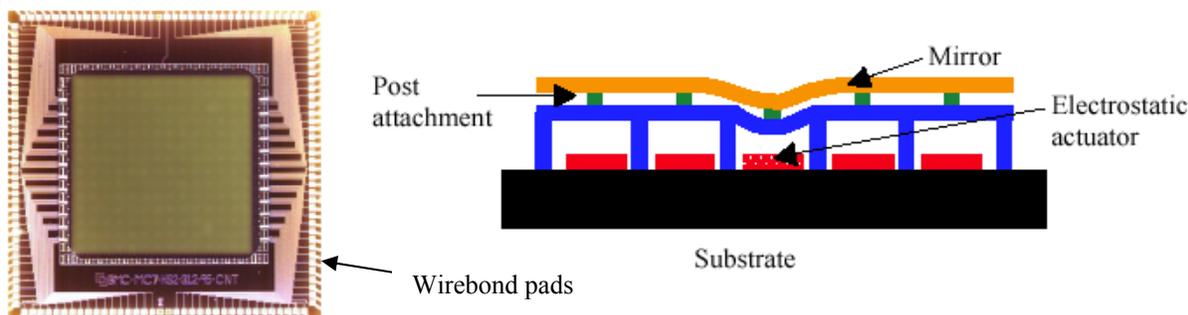


Figure 1. Image of BMC 140 actuator MEMS DM die (Left). A cross-sectional illustration of a 1x5 array of the electrostatically actuated MEMS deformable mirror (Right).

These DMs are extremely attractive for use in imaging instruments due to their ability to provide high-precision, repeatable and hysteresis free wavefront control with high spatial resolution, their relatively low cost, low power consumption, and compact form factor allowing for more compact and light weight optical systems. Using this architecture BMC commercially produces MEMS DMs with 32, 140, 492 and 1020 actuators with up to 6 μ m of mechanical stroke for applications in areas such as astronomy, biomedical imaging, and laser communications. A new class of MEMS DMs has been under development for high contrast imaging applications requiring thousands of actuators, such as the 4092 actuator continuous facesheet DM developed for the Gemini Planet Imager [2], and a 1021 segment, 3063 actuator tip-tilt-piston DM under development for NASA's visible nulling coronagraph. In an effort to enhance the reliability of the DM actuators to increase the probability of success in space based instruments, we have developed improvements to the MEMS DM actuator design and drive electronics.

2. MEMS DMs WITH ENHANCED RELIABILITY

Producing highly reliable DMs is critical, particularly for space-based instruments. For instance, in the high-contrast coronagraphic space-based instruments under development at NASA, failure of even a single actuator in a large array will result in unacceptable performance degradation and loss of the mission. While the excellent long term reliability of BMC MEMS DMs demonstrated in laboratory conditions is reassuring [3], there is good reason to worry that the reliability of the same MEMS DMs in a space environment could be much lower. Space-based instrumentation is subject to ionizing radiation from a variety of sources. The most likely impact of this radiation on DM performance would be to trigger a single event upset in the driver electronics, leading either to a single event transient, or a single event functional interrupt [4]. Of particular concern is a high-voltage (HV) transient that propagates to the actuator electrode resulting in electrical overstress (EOS) of the electrostatic actuator. Though quite robust in other ways, electrostatic membrane actuators are susceptible to damage resulting from such overvoltage, even for short durations due to their fast temporal response. When subjected to voltage above a certain threshold, the actuator suffers from snap-through instability in which its electrostatic attractive forces exceed the actuator flexure's mechanical resisting force, causing rapid collapse of the actuator membrane to the driven electrode. Upon contact, the two electrodes generate an electrical short, generally resulting in permanent actuator damage.

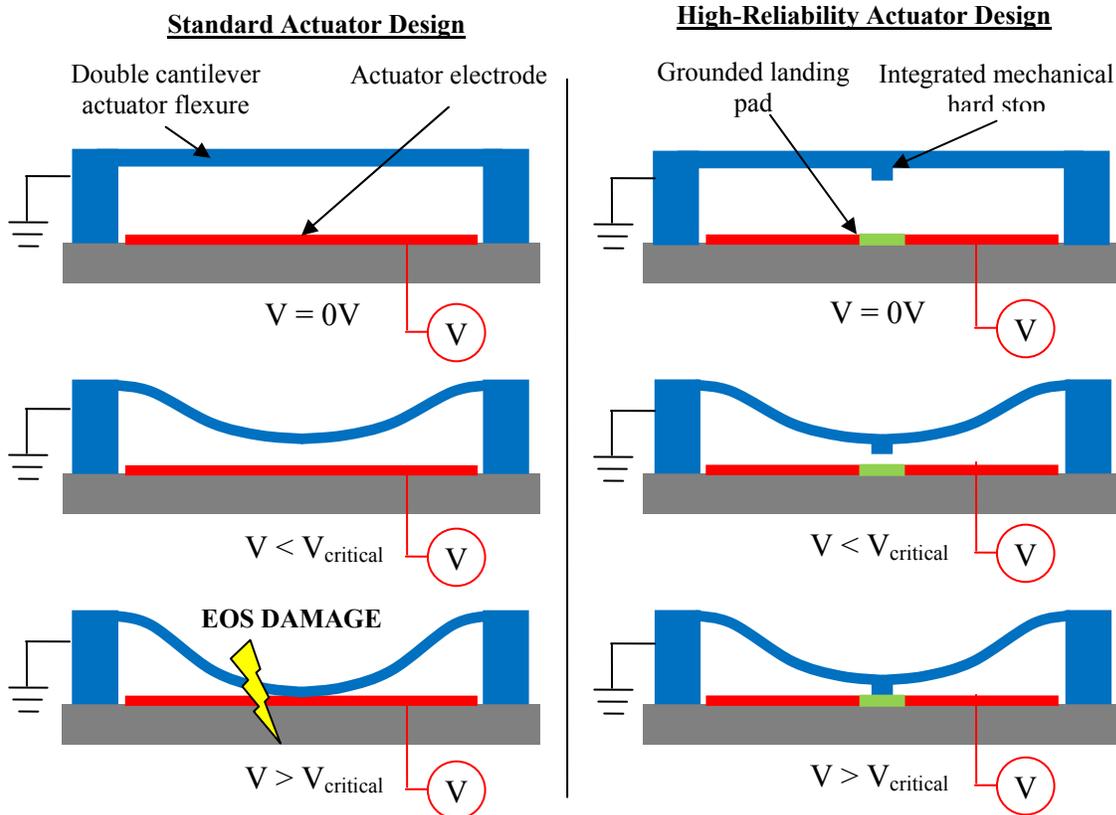


Figure 2. Illustration comparing the standard MEMS DM electrostatic actuator (Left column), and the proposed high-reliability actuator design. EOS-related failure is prevented in the proposed actuator design by placing a mechanical hard stop underneath the flexure that lands on a grounded landing pad embedded in the actuator electrode in the event the applied actuator voltage exceeds the critical operating voltage resulting in actuator snap-through.

These failure modes were mitigated in two ways: 1) by integrating mechanical hard stops into the actuator membrane and 2) by introducing current limiting resistors in-line with high voltage drive signals. As illustrated in Figure 2, the mechanical stops serve to prevent contact between the two electrodes of the electrostatic actuator and reduce the contact area to eliminate the possibility of stiction between the two surfaces. The current limiting resistors represent a redundant

measure to eliminate damage to the electrode in case of an extreme event where the applied voltage in a transient would still result in contact between other areas of the two actuator electrodes.

Since the maximum deflection of the actuator occurs at the center of the double cantilever beam, this is where failure occurs when the critical operating voltage is exceeded. For the new actuator design, however, the hard stops physically prevent further actuator displacement when the critical operating voltage is reached that would otherwise lead to irreversible damage to the actuator as the electrostatic actuator flexure collapses onto the electrode. The hard stops incorporated in the actuator flexure touch down on grounded landing pads embedded in the electrodes before the critical voltage is reached. At this point the mechanical stiffness of the actuator changes since new constraints are created when the hard-stops touchdown, effectively decreasing the span of the actuator by half of its length.

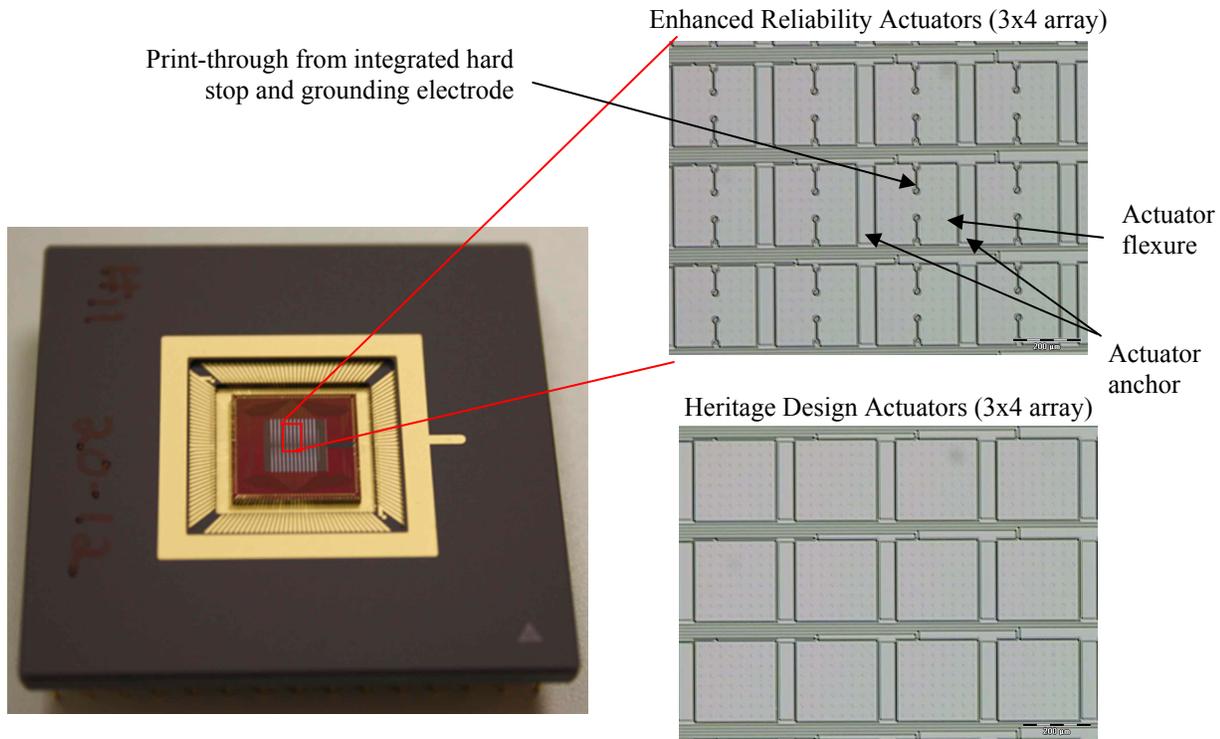


Figure 3. Enhanced reliability actuator array (12x12) mounted and wirebonded into a ceramic chip carrier (Left). A close-up view of a 3x4 sub-array of actuators (Top Right) shows the top of the actuator membrane layer (Poly1) in which the actuator anchors and print-through resulting from the mechanical hard stops and landing pads can be seen. A baseline actuator array is shown for comparison (Bottom Right)

3. VERIFICATION OF ACTUATOR PERFORMANCE

DM actuator arrays with integrated hard stops, shown in Figure 3, were fabricated using polysilicon surface micromachining processes, assembled to a ceramic chip carrier and wirebonded for test.

The electromechanical performance of both the heritage (baseline) actuator and the enhanced actuator designs was measured using BMC laboratory test electronics and a Veeco optical surface profiler. The deflection of the actuators was measured using the interferometer at various voltage intervals and compared to the results of a finite element model constructed to generate the actuator design.

The results of these tests, shown in Figure 4, demonstrate the effectiveness of the integrated hard stops in preventing actuator snap-through by blocking further motion of the actuator flexure as the hard stops touch down on the grounded landing pads at 2.5 μ m of stroke and an applied voltage of 265V. The applied voltage was then increased to 350V, without a significant change in deflection or damage to the actuator. When testing the heritage actuator, irreversible damage occurred after snap-through when a voltage of 267V was applied.

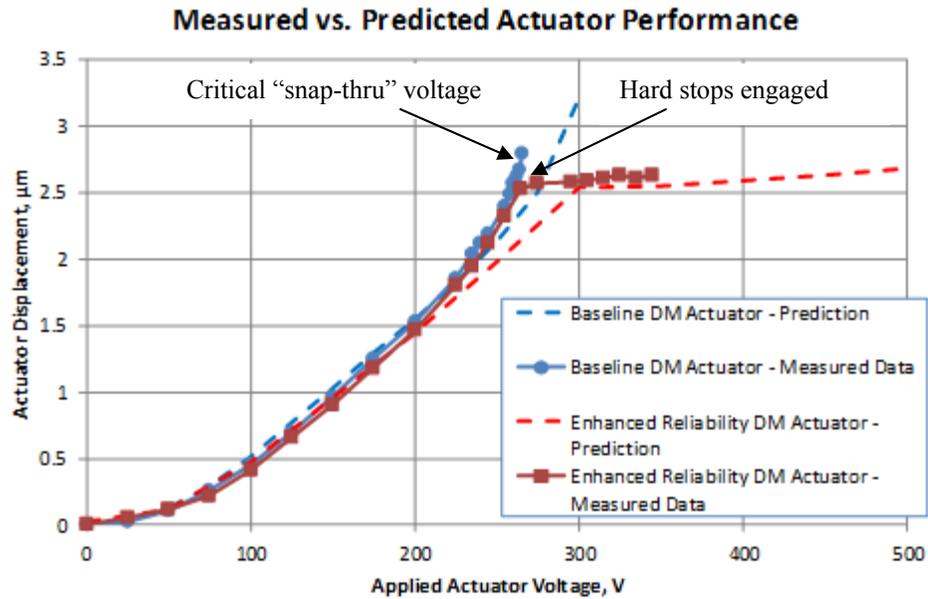


Figure 4. Comparison of the electromechanical performance of the heritage (baseline) and enhanced reliability actuators. This data shows that the hard stops block further motion of the actuator when the critical voltage is reached, preventing snap-through and subsequent actuator failure.

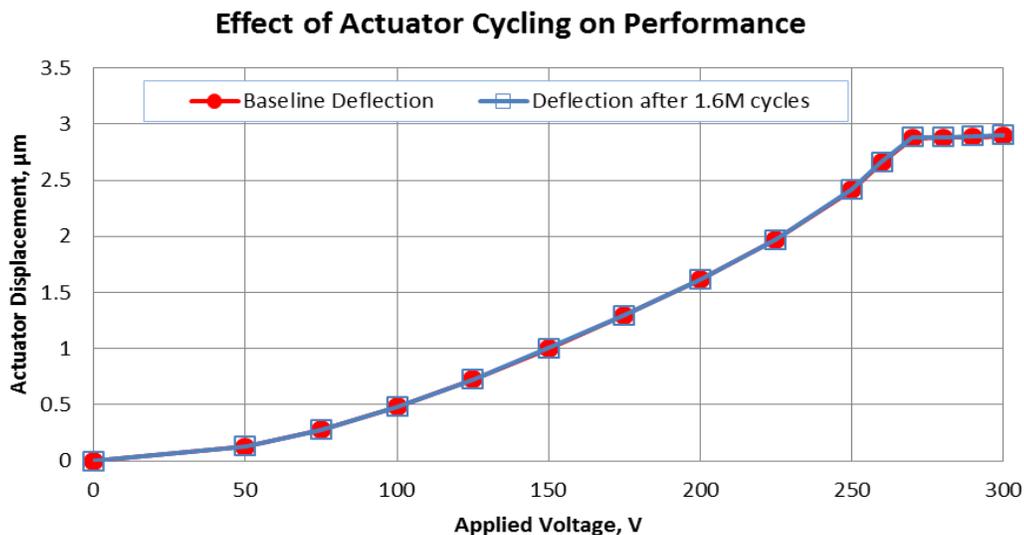


Figure 5. Comparison of actuator electromechanical performance before and after 1.6 million cycles in which the actuator drive voltage was switched between 0V and 300V to investigate the effect of repeated mechanical stop touch down events. The actuator performance was not affected by the repeated actuation beyond the critical voltage of the actuator (critical operating voltage of actuator was 265V).

Comparing the measured actuator data with the predicted performance reveals some divergence between the actuator stroke at applied voltages over 225V which may be explained by slight variations in thin film stresses, and actuator/electrode gap resulting from the fabrication processes, between the modified and heritage test devices. Given that the actuators' voltage versus deflection characteristic becomes more non-linear as the stroke increases (the electrostatic force is proportional to the square of the applied voltage over the square of the electrode-to-actuator flexure gap) the variation between the measured and theoretical data at the high range of the actuator stroke is expected. These

results show that the modified actuator design is effective in preventing damage due to snap-through and does mitigate this single point failure mode of BMC MEMS deformable mirrors.

The enhanced reliability actuators were exposed to a cycling test in which the actuators were cycled between 0V and 300V – an operating voltage 35V greater than the critical voltage that for the baseline actuator design would result in irreversible failure in a single cycle. As shown in Figure 5, these tests showed that the functionality of the actuator was unaffected after 1.6 million actuator cycles.

4. ENHANCING RELIABILITY USING CURRENT LIMITING RESISTORS

As a redundant measure, a second method was used to enhance actuator reliability by using a current limiting scheme to prevent irreversible failures in an electrical over-stress (EOS) event that occurs when DM actuator critical voltage is exceeded. When the critical voltage is exceeded, the actuator flexure collapses onto the underlying fixed electrode resulting in a short-circuit. Due to the upward force exerted by the mirror facesheet at the mirror post the actuator bends in a slight saddle-like shape and therefore the actuator flexure will typically touch on the edge of the electrode in the center of the flexure span. Since contact is made in a very small area, the current density in the location of the short-circuit is very large causing rapid local heating and resulting in significant damage to the structure in this area.

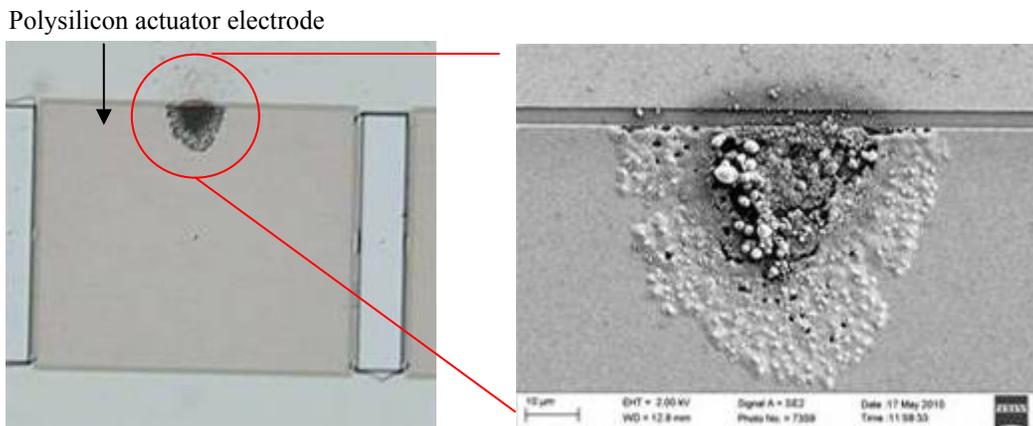


Figure 6. An image (Left) of an electrical over-stress (EOS) damage site on an actuator electrode (DM mirror segment and actuator flexures were removed from the structure after the failure occurred). An SEM micrograph (Right) of the damaged area showing how the polysilicon film and underlying layers are affected by the heat generated by the EOS event – some of the poly has melted and a hole has punched into the underlying dielectric films.

Figure 6 shows an example of the damage resulting from such an event. The figure shows an image of a DM structure with the mirror segments and actuator flexure removed to reveal the actuator electrodes on which an EOS damage site can be observed. An SEM micrograph of this area shows the details of the affected area that resulted in a permanent electrical short between the electrode and the grounded polysilicon films buried underneath the electrode and separated by a number of dielectric insulated films that were also significantly damaged in the EOS event.

To mitigate this failure, current limiting resistors were added on the output of the drive electronics to limit the current that flows when contact is made between the actuator electrode and its flexure. Given that high current densities result in failures caused by local heating, this approach significantly improves the survivability of the DM actuators in case of an electronics fault resulting in a high voltage applied to the actuators. To evaluate the efficacy of this current limiting scheme, a test was set up using a simple electronic breadboard to insert current limiting resistors in-line with the high voltage ribbon cable that runs between the DM drive electronics and the DM mounting board.

For the EOS testing, engineering-grade BMC continuous facesheet DMs were used which were constructed using the standard heritage actuator design. They were tested in 25V increments up to 300V – approximately 50V beyond their critical voltage limit. The voltage was then ramped back down and the actuators were evaluated for damage. This test was performed with varying values for the in-line resistor to determine the threshold resistance at which no damage results from driving the actuator past its critical voltage level. Since the DMs used for the EOS testing were not coated with a reflective metal film, and the rest of the DM structure is constructed of doped polysilicon, IR imaging was used to inspect the devices. The post-test IR inspection focused on the presence of damage sites on the actuator electrode as

shown in Figure 7. The results of these tests concluded that an in-line resistance of $350\text{M}\Omega$, corresponding to a maximum current draw of 830nA at 250V , was the threshold at which no apparent damage resulted from EOS and the actuator performance was unaffected. As shown in Figure 8, with no in-line resistance, significant damage is observed at the electrode level of the DM. At $140\text{M}\Omega$ of in-line resistance there is still some damage observed although it is less severe.

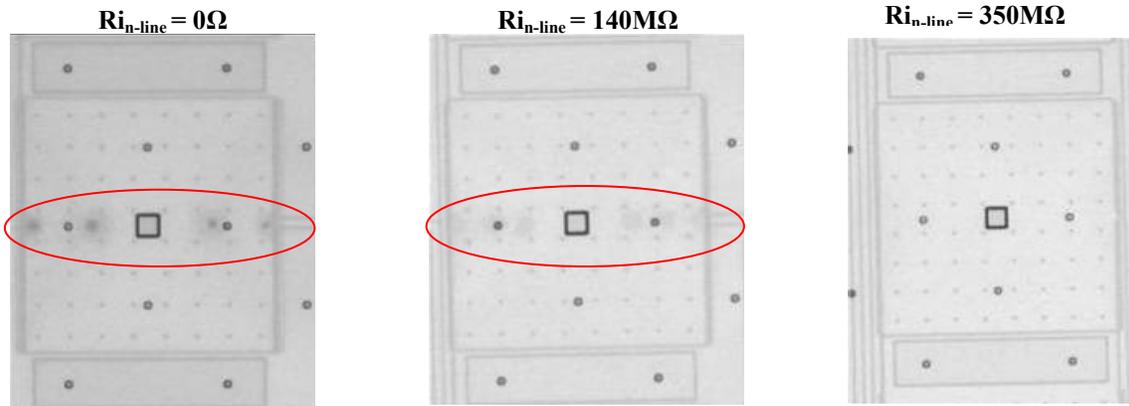


Figure 7. IR microscope images of continuous facesheet DMs exposed to EOS testing with in-line current limiting resistors of 0Ω (Left), $140\text{M}\Omega$ (Center), and $350\text{M}\Omega$ (Right) shows the varying degrees of damage to the underlying actuator electrode. The actuator tested with no in-line resistance (Left) shows significant damage resulting from the EOS; the damage to the actuator tested with $140\text{M}\Omega$ (Center) still shows damage to the electrode although it is less severe; no electrode damage is observed using a $350\text{M}\Omega$ resistor (Right).

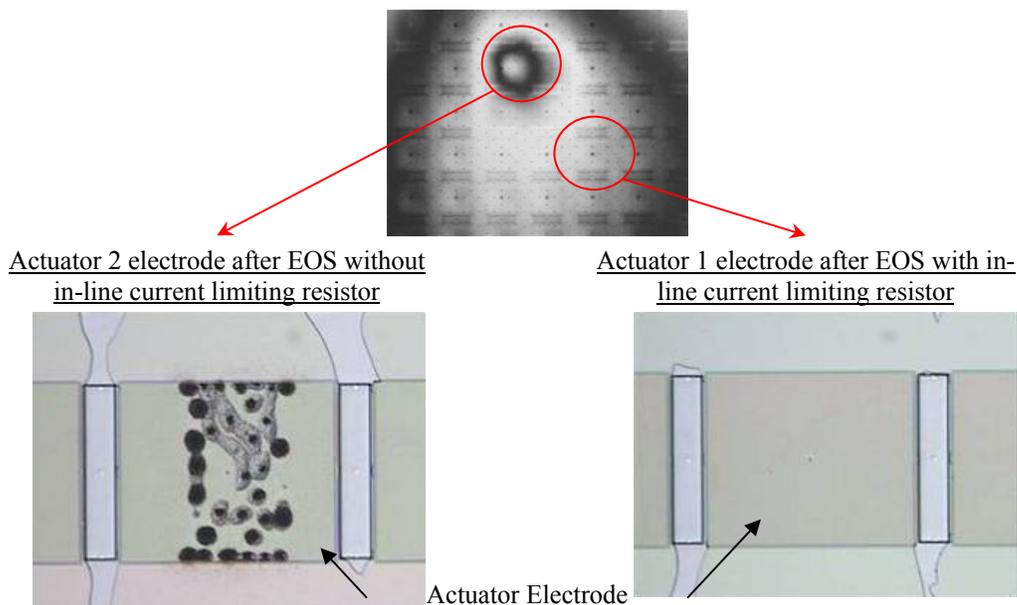


Figure 8. Effects of electrical over stress (EOS) on a MEMS deformable mirror with (test actuator 1) and without (test actuator 2) in-line current limiting resistors are shown on an interferogram of a continuous facesheet DM (Top). A permanent mirror deformation results from the EOS of actuator 2 while there is no damage to actuator 1. Removal of the mirror and actuator flexure layers reveals the actuator electrodes. The damage to the electrode resulting from snap-through are clearly visible at the site of test actuator 2 (Bottom left). There is no snap-through related damage at the electrode of test actuator 2 (Bottom right) due to the use of the in-line current limiting resistor ($350\text{M}\Omega$).

After completion of the EOS testing both the mirror and actuator layers were removed from the DM to allow visual inspection of the actuator electrodes. Figure 8 shows the electrodes of another actuator (test actuator 2) that was subjected to severe EOS conditions without a current limiting resistor in place as well as the electrode of an actuator that

was protected with a 350M Ω resistor. The effect of the current limiting resistor can clearly be seen in these images as there are no signs of damage on the protected actuator electrode. Since the electrostatic actuators draw almost no current, the addition of the in-line current limiting resistor does not have a significant effect on the voltage/displacement characteristic of the actuator (see Figure 9).

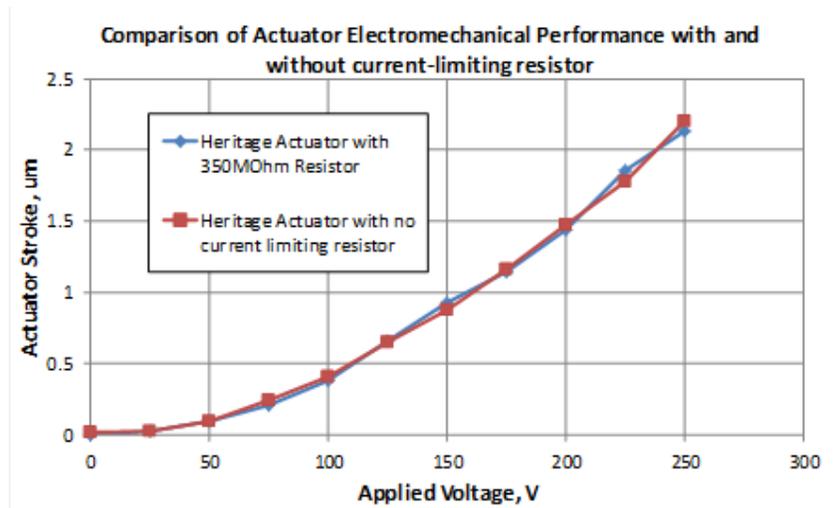


Figure 9. Testing of DM actuator performance with and without in-line current limiting resistor shows no significant effect on the actuator voltage versus deflection characteristic.

5. CONCLUSION

In this paper we have presented the results of the performance of a MEMS deformable mirror actuator design with enhanced reliability that is tolerant to severe electrical overstress conditions. Mechanical stops integrated into the electrostatic actuator prevent snap-through resulting from the application of driving voltages that exceed the critical operating voltage that would otherwise result in irreversible actuator damage. The useable stroke of the DM is also extended by the introduction of the mechanical stops since they eliminate the need for an operating margin on the supply voltage of the electronic drivers over the critical voltage of the actuator to allow for reliable operation. Since the deflection of the modified actuator design simply saturates when the critical voltage is exceeded, the actuator can be operated reliably and repeatably up to its critical voltage.

To provide a redundant measure as required for space-based operation, an electronic drive scheme to limit the current densities, in the case that there is a snap-through event, has also been demonstrated to be an effective measure to eliminate single point failures in high actuator count deformable mirrors.

6. ACKNOWLEDGEMENTS

This work was supported by NASA SBIR Phase I contract NNX11CF40P.

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