Magnetically actuated microshutter arrays

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ABSTRACT

Two-dimensional microshutter arrays are being developed at NASA Goddard Space Flight Center (GSFC) for the Next Generation Space Telescope (NGST) for use in the near-infrared region. Functioning as focal plane object selection devices, the microshutter arrays are 2-D programmable masks with high efficiency and high contrast. The NGST environment requires cryogenic operation at 45 K. Arrays are close-packed silicon nitride membranes with a unit cell size of 100x100 micrometer. Individual shutters are patterned with a torsion flexure permitting shutters to open 90 degrees with minimized mechanical stress concentration. The mechanical shutter arrays are fabricated with MEMS technologies. The processing includes a RIE front-etch to form shutters out of the nitride membrane, an anisotropic back-etch for wafer thinning, and a deep RIE (DRIE) back-etch down to the nitride shutter membrane to form frames and to relieve the shutters from the silicon substrate. A layer of magnetic material is deposited onto each shutter. Onto the side-wall of the support structure a metal layer is deposited that acts as a vertical hold electrode. Shutters are rotated into the support structure by means of an external magnet that is swept across the shutter array for opening. Addressing is performed through a scheme using row and column address lines on each chip and external addressing electronics.

Keywords: microshutter, magnetic actuation, DRIE, silicon nitride, transmissive mask

1. INTRODUCTION

The primary mission of the Next Generation Space Telescope (NGST) is to reveal the origins of galaxies, clusters, and large-scale structures in the universe. In order to observe galaxies in the peak of the merging and star-forming era, NGST operation requires a spectroscopic coverage in the near-infrared (NIR) wavelength region from 0.6 to 5 µm. A Multi-Object Spectrometer (MOS) is proposed for NGST to fulfill the detection of the NIR[1]. An object selector is needed for the MOS to increase instrument observing efficiency by optimally filling the focal plane without spectral overlap. The primary requirements for the selector include: a >1800 x >1800 square element array (scaled appropriately if rectangular elements are used) with an element size (currently 100 µm x 100 µm in our case) to cover the large NGST field of view, a fill factor on the order of 80% or better, contrast >2000, and operation in a cryogenic (around 45 K) environment to assure negligible thermal emission into the spectrometer.

Micromirror array technologies, as developed by GSFC and Sandia National Laboratories, are also candidates for the object selector for the MOS on NGST[2,3]. The disadvantage of using a micromirror array as an object selector is that micromirrors are reflective devices and they diffract and scatter light and therefore provide low contrast. An alternative approach to the micromirror array concept is a device based on microshutters where individual microshutter elements can be actuated to be fully open allowing light to pass through. Microshutter devices have the potential to achieve higher contrast than reflective devices. Besides the NGST and similar applications, microshutter arrays have a great potential for use in laser filtering, eye protection, and mass-spectroscopy, to name but a few.

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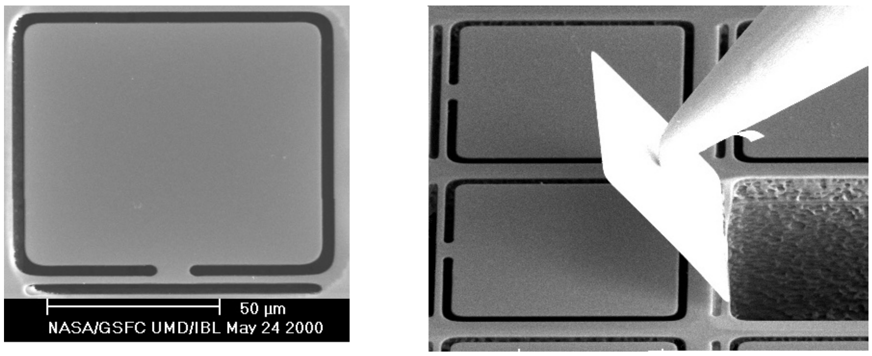
Members of our group have recently reported on the design and initial fabrication tests of microshutter arrays with addressable actuation[4]. We proposed a shutter array design based on a mosaic of 16 512x512 arrays (2048x2048) of transmissive shutters. Each shutter unit cell covers an area of 100 μm^2 and is connected to a frame through a neck region and a torsion beam, as shown in Figure 1. Shutters open 90 degree out of plane through a shutter tilt along the axis of the torsion beam. In previous work, material selection for shutters was carried out through a series of mechanical testing and numerical analysis[5,6]. In addition, mechanical responses of torsion beams were studied to optimize their physical sizes and geometry[6] and shutter array actuation mechanisms were developed and demonstrated using prototype devices with the goal of achieving full programmable addressing and maximizing fill-factor[6,7].



(a) (b)

Figure 1: SEM image of a silicon nitride mechanical microshutter (a) and a shutter opened using a probe (b).

The work presented in this paper, is primarily focused on the fabrication of the microshutter arrays. The challenges are two-fold, first the fabrication of a robust large format shutter array which has mechanical integrity and second, a scheme for addressing and activating individual elements within the array. The requirement of a high fill factor imposes tight tolerances on the shutter frame dimensions on which the addressable actuation circuitry will be fabricated. In order to meet these requirements we have developed fabrication procedures to maximize array sizes while minimizing shutter frame spaces. We have combined conventional semiconductor processing techniques with MEMS technologies to fabricate 32x32 and 128x128 microshutter arrays with a frame width of 8 µm or less. Currently, we are working towards the fabrication of 512x512 arrays. In the following, we will give a description of the architecture of a microshutter element, give the fabrication procedure for producing large format arrays, and discuss the magnetic actuation of the microshutter elements.

2. DESCRIPTION OF MICROSHUTTER ARRAYS

Figure 2 shows a schematic cross-section of a single shutter cell indicating the primary components. The frame of the shutter array is single crystal silicon, 100 µm thick, with frame widths of less than 8 µm between the shutters. The shutter and torsion spring are low-stress low pressure chemical vapor deposition (LPCVD) silicon nitride. Around the perimeter of the shutter cell is an overhanging light shield. This shield blocks light from leaking through the gaps between the shutter and hinge and the array frame when the shutter is in the horizontal closed position. On the structure of the shutter and frame are two sets of strip electrodes used for addressing the array. One set of electrodes cover the bottom surface of the shutter and are connected together via leads on the torsion hinge and array frame in columns (when the array is oriented so that the torsion hinge is at the top of each cell) and connected to bonding pads on the bottom of the outer frame of the array. The second set of electrodes cover the inside wall of the shutter cell aperture on the side next to the hinge. These vertical electrodes are connected via leads on the top of the frame in rows to another set of bonding pads on the top of the outer frame. Currently, connection to the bottom bonding pads is made by conductive epoxy to leads on a transparent substrate that run from under the shutter array to pads outside the perimeter of the array. The electrical interconnection of future runs will made by indium bump bonds. Multiple arrays can then be bonded together to form larger arrays that electrically act as a single array.

Deposited over the column electrode on the shutter is a region of magnetic Co(90)Fe(10) alloy. This allows the shutters to be actuated by an external magnetic field. In the configuration intended for the NGST MOS, a linear magnet aligned to the shutter rows is swept across the array along the columns. As the magnet sweeps across the array, sequential rows of shutters are rotated from their natural horizontal closed orientation to a vertical open orientation in contact with the

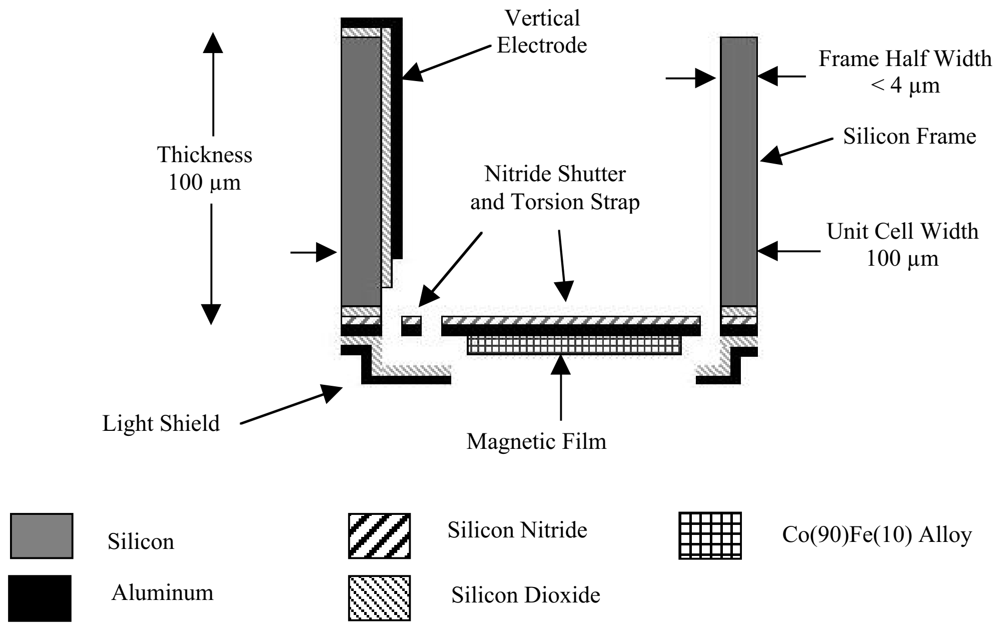


Figure 2: Cross-section of a single shutter unit cell showing the key components.

vertical electrodes. If the electrodes are voltage biased to provide enough electrostatic force to overcome the mechanical restoring force of the torsion spring, the shutter will remain attached to the vertical electrodes in its open state. If the bias is insufficient, the shutter will return to its horizontal neutral closed position.

With this electrode structure, the array can be addressed by using three voltage bias levels V_1, V_2, and V_3, as shown in Figure 3, where $V_1<V_2<V_3$ and the difference between any two voltages is sufficient to hold the shutters open in contact with the vertical electrodes against the mechanical restoring force of the torsion hinge. The shutter column electrodes C_1, C_2, and C_3, in the example, have bias levels V_1 and V_2, the row vertical electrodes R_1, R_2, and R_3 have bias levels V_2 and V_3. When the both electrodes are biased to V_2 is the only state where an open shutter will be released to close. All other combinations result in an open shutter remaining latched open to the vertical electrode.

The addressing sequence begins with all the shutters in their neutral closed position with all electrodes biased at V_2. Then the column electrodes are biased to V_1 and the row electrodes to V_3 and the linear magnet is swept over the array. When the shutters are opened to the vertical position by the magnetic field, the electrostatic force latches the shutters to the vertical electrodes. After the magnet has passed over the entire array, all shutters are latched in their open positions. The array is now addressed row by row. The row to be addressed is selected by changing its bias from V_3 to V_2. The selected row is then addressed by addressing the column shutter electrodes with bias levels V_1 and V_2. Shutters addressed with V_1 will remain latched open, while shutters addressed V_2 will release and return to their closed position. All other rows are not affected by the column electrode addressing since they are held at V3 and thus there is sufficient electrostatic force to hold them open for all values of column electrode biases. The selected row's bias is them changed back to V_3 and the process is repeated for each remaining row until the whole array is addressed. The sequence can be started again with a new pattern by releasing all the shutters into the initial all closed state and starting over, or by addressing all the column electrodes to V_1 and sweeping the magnet again to latch all the shutters to the open state.

Some of our previous microshutter design had integrated high voltage (~40 V) cryogenic CMOS drive electronics based on dynamic random access memory cells. This approach is not currently being pursued due to the fill factor loss resulting from the need to have a large transistor at each unit cell location.

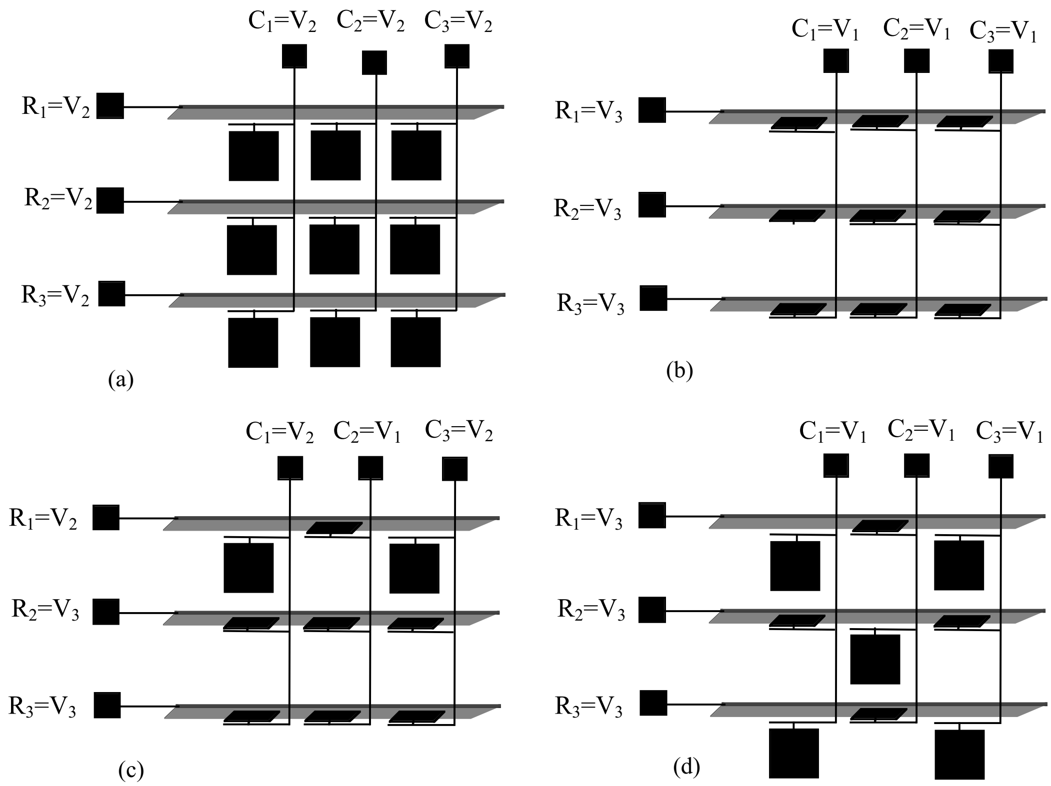


Figure 3: Illustration of the addressing sequence. In the initial state(a) all electrodes are biased to V_2 and all shutters are in the neutral position. During the magnet sweep (b) an electrostatic potential exists between all the shutters (at V_1) and their vertical electrodes (at V_3), latching the shutters into the open position. The addressing sequence (c) begins by selecting a row for addressing (R_1 in this example) by changing its bias to V_2 and then addressing that row by the column biases (V_2 to close a shutter, V_1 to keep a shutter open). This step is repeated for all the remaining rows until the entire array is addressed. During use (d) the open electrodes are latched by keeping a fixed potential difference between the shutters and vertical electrodes.

3. FABRICATION OF MICROSHUTTER ARRAYS

Microshutter array fabrication is carried out through conventional semiconductor processing and MEMS techniques. Mechanical shutter array fabrication is based on bulk processing of the silicon and silicon nitride, which will be described in Section 3.1. The fabrication of the magnetic and electrostatic elements has also been integrated in mechanical shutter array processing and will be described in section 3.2. Deep Reactive Ion Etching (DRIE) is a critical processing step in the fabrication of microshutter arrays, the control of DRIE processing for shutter arrays has been discussed in a previous paper[8].

3.1 Mechanical shutter arrays

100mm single-side polished (100) silicon wafers with thickness' of 300 μm, 400 μm and 500 μm have been used to make microshutter arrays. The processing steps for the fabrication are shown in figure 4. A layer of 250 nm thick low-temperature silicon oxide (LTO) or thermal oxide is first grown on the silicon substrate as etch stops. A layer of low-stress, 500 nm thick , silicon nitride is deposited over the silicon oxide by LPCVD. This is followed by the sputter

Starting Wafer: 100 mm silicon wafer with a 250 nm silicon dioxide (LPCVD or thermal) DRIE etch stop layer and a 500 nm LPCVD low-stress silicon nitride shutter structure layer deposited on both sides. In the future, a buried oxide KOH etch stop layer 100 µm from the device side will be used to better control the thinning etch.

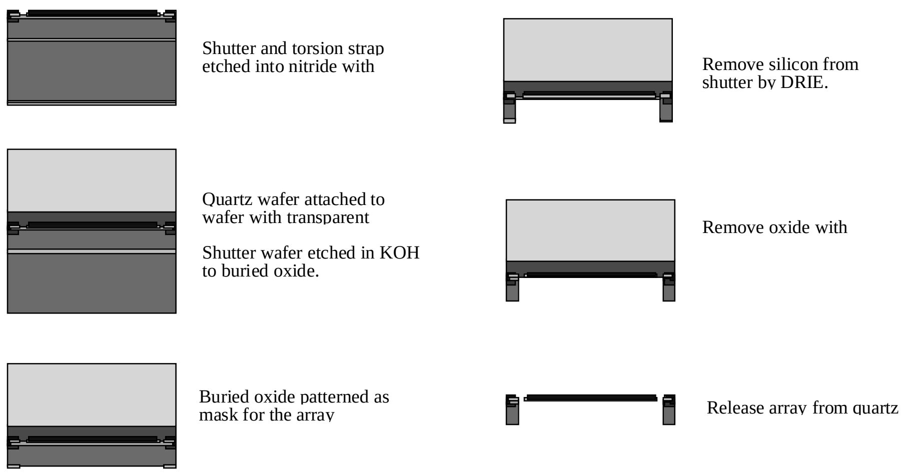
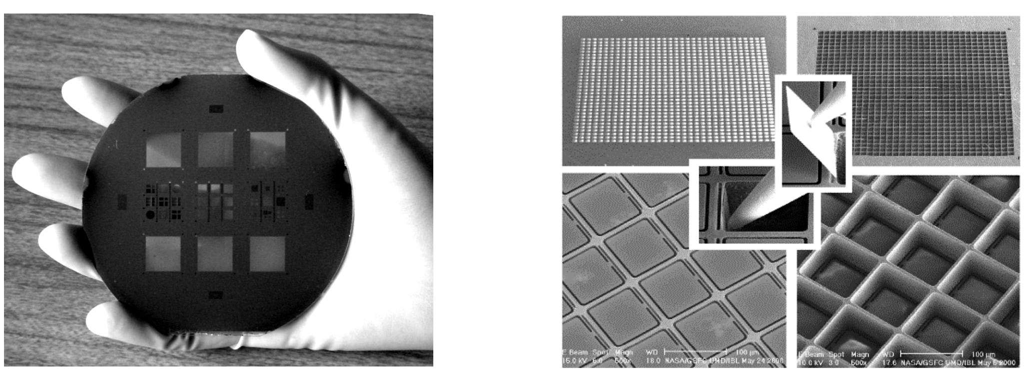


Figure 4. Fabrication procedures for mechanical shutter arrays are illustrated for a single shutter cell.

deposition of an Al/magnet/Al tri-layer, this is discussed more fully in section 3.2. The tri-layer is patterned using positive photoresist Shipley 1811, and the silicon nitride is subsequently etched into the microshutter blade geometries. A single wafer yields six 128x128 shutter arrays, ten 32x32 arrays, and a number of 8x8 arrays, as well as other test structures using the current mask set. The total area combining all these shutter arrays and all test structures in the wafer is equivalent to the area of a 512x512 shutter array. The individual silicon nitride mechanical microshutter unit cells are 100µm x 100 µm as shown in fig. 1. The mask set incorporates shutter array designs with variations in torsion beam widths and shutter frame widths. After patterning and etching of the tri-layer the silicon nitride on the front side of the wafer is etched using a reactive ion etching (RIE) system (MARCH CS-1701) to form the microshutter blades The wafer



(a) (b)

Figure 5. (a) Microshutter arrays and test structures are shown on a 100 mm wafer after DRIE etching. There are six 128x128 shutter arrays, ten 32x32 arrays, and a number of 8x8 arrays, as well as other test structures on the wafer. The total area combining all shutter arrays and all test structures in the wafer is equivalent to the area of a 512x512 shutter array. (b) SEM images of the front side and backside of a 32x32 microshutter array with zoom-in images of a single shutter cell.

is then flipped over and attached onto a quartz carrier wafer with a very thin layer of wax (10~15 µm). Transparent quartz wafers allow for backside-alignment and ease of wafer handling during wafer thinning and subsequent process steps. Silicon nitride and silicon dioxide on the back side of the wafer are etched off using a RIE and a buffered hydrofluoric acid (BHF) etching, respectively. The wafer is then thinned using a 20% potassium hydroxide (KOH) solution at, 65°C. The wafer is etched to the desired thickness of 100µm. Silicon-on-insulator (SOI) wafers have been purchased with a silicon dioxide layer 100 µm below the surface. This oxide layer will be used to improve the uniformity of the thinning etch. The second back etch is performed using DRIE (STS Multiplex ICP System) to create the silicon frame and to free the nitride shutters from the silicon substrate. This is accomplished by patterning shutter array windows on the back of wafer with a thick (5-6µm) positive photoresist (Shipley SJR 5740). The patterned photoresist is used as the mask for the DRIE processing step. Figure 5(a) shows a shutter wafer after DRIE etching. This wafer had no metalization so one can see through the shutter arrays where only 500 nm silicon nitride membranes and shutter frames remain.

After DRIE, the shutter wafer together with the carrier wafer goes through a BHF etch to remove the etch-stop silicon oxide from the nitride shutters. The final step for mechanical microshutter array processing is the separation between the shutter device wafer and the quartz carrier wafer, achieved by solvent soaking. Microshutter arrays are finally released from the carrier wafer and individual microshutter elements are suspended from the shutter frame via the torsion beams. Much effort has been put in on fabricating microshutter arrays with narrow torsion beams in order to achieve reduced torsion stiffness in order to reduce the latching voltages. It is of great concern that thermal oxide may introduce thermal stress that fractures the silicon-nitride membranes. Comparison of the two types of silicon oxide used as the etch-stop revealed that the thermal oxide generated less stress than LPCVD oxide. As a result, the thermal oxide is preferred to protect the shutter membranes in the DRIE process step. A SEM of mechanical microshutter arrays are shown in figure 5(b)

3.2 Magnetic actuated and electrostatically addressed shutter arrays

The magnetic pads and shutter column electrodes are fabricated on the shutter wafers prior to mechanical shutter processing. Metal thin-films are grown on shutter wafers through a sputtering deposition and form a tri-layer metallization. The tri-layer consists of 100 nm-thick aluminum as the shutter electrical electrodes and to provide optical opacity, 200 nm-thick magnetic material as the magnetic pads, and 5 nm-thick aluminum as a passivation film to protect magnetic pads. Magnetic pads are lithographically patterned on all shutters. Microshutters themselves are then patterned starting with an aluminum etch, which defines shutter electrode rows and also microshutter blades and frames. Following is a RIE etching through the silicon nitride, which is the first step of mechanical microshutter processing described in section 3.1. In future processing runs the light shield will be integrated into the process at this point. The light shields will be formed using a sacrificial photoresist process of aluminum over an insulating layer of electron-cyclotron resonance chemical vapor deposition (ECR-CVD) oxide. The wafer is then attached to the quartz substrate and after wafer thinning by KOH and backside DRIE shutter window etching, the vertical row electrodes are formed on the back of the wafer. The vertical row electrodes are E-beam deposited 5 nm-thick Ti and 200 nm-thick Au layers over an insulating ECR-CVD oxide. The metal deposition is done at an angle so that only the back surface of the frame and the side-walls near the hinges of the apertures are coated to form vertical electrodes. The photoresist for the delineation of the electrodes is applied by spray-gun, but otherwise processed normally. The wafers now complete the process with the same steps as the mechanical arrays. The first process run with delineated vertical row electrodes was begun at the time of writing this paper and results will be presented at the conference. Shutter arrays fabricated to test the vertical electrode latching were fabricated with delineated shutter column electrodes and a single blanket vertical electrode. These arrays were successfully operated and addressed as 1-D arrays of lines of shutters.

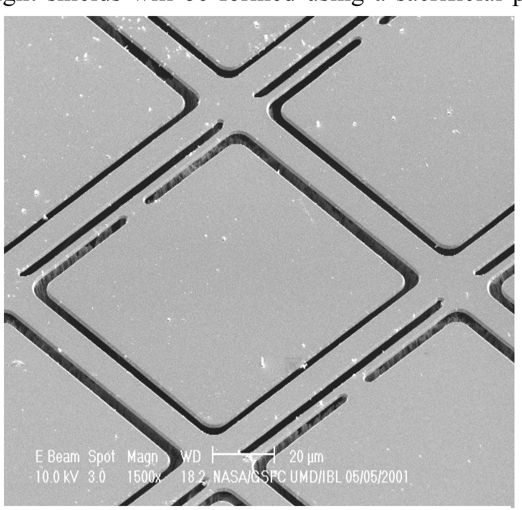
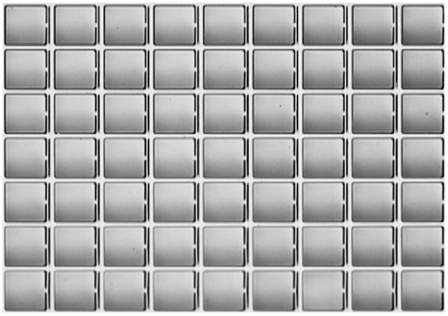
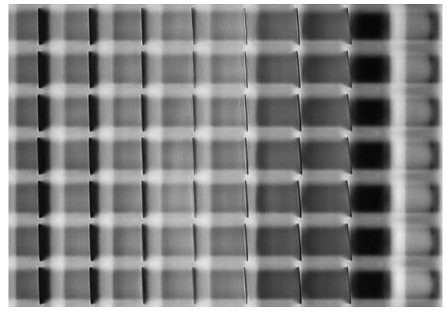


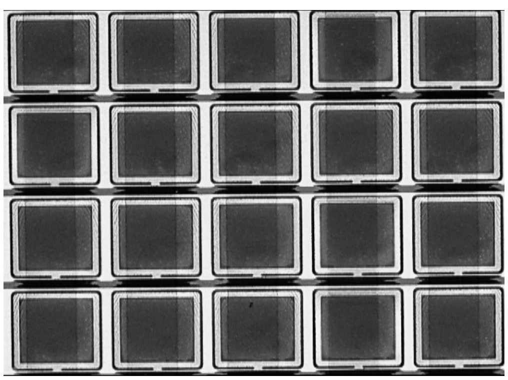
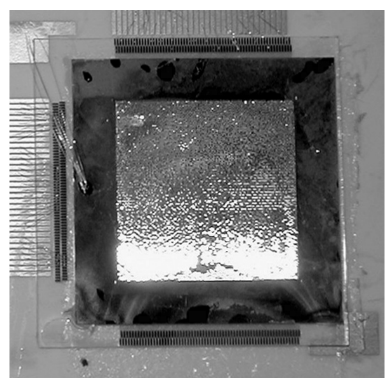
Figure 6: Low-stress 200nm Co(90)Fe(10) film on a silicon nitride mechanical shutter array.

(a) (b)

Figure 7. Shutter arrays with Co(90)Fe(10) magnetic coating, (a) closed shutters, and (b) actuated shutters showing open shutter image (dark) with focus on top edges.

Thermal stress introduced by the in intrinsic stress of deposition and the mismatch of thermal expansion coefficient between the metal and the silicon nitride thin films may cause shutters bowing. Co, Co(50)Fe(50), and Co(90)Fe(10) were tested as the material candidates for magnetic pads. They were deposited on shutter arrays by plasma sputtering. Co(90)Fe(10) films showed the least bowing when inspected at room temperature and 77 K. Optimization of the process via deposition pressure control resulted in less than 0.5 μm bow in the shutter. Figure 6 is a SEM of a blanket coating of 200 nm of Co(90)Fe(10) on silicon nitride shutters used as a structure for stress reduction tests. The effect of magnetic pad sizes and geometry on thermal stresses and magnetic saturation is under investigation. Magnetic actuation was tested by applying a magnetic field to shutter arrays. Figure 7 shows optical images of shutters (a) all closed (no magnet), and (b) a spectrum of open positions with the linear magnet under the array. The dark areas shown in Figure 7(b) are the sides of shutters opening at different angles due to the spatial variation in the magnetic field. The image indicated that the magnet for shutter actuation was moved to the position underneath shutters in the third column from

(a) (b)

Figure 8: Photographs of a section of the completed 1-D addressed shutter array (a) and the entire 128x128 array with its transparent substrate mounted in a ceramic package (b).

right where shutters opened 90 degrees out of plane. The microscope was focused on the open edge of the shutter blades, but due to the small depth of field at this magnification the shutter array frame is out of focus. The test array shown in figure 7 was intended for tests of the magnetic material and does not have addressing electrodes.

Figure 8(a) shows a close-up of one of the arrays with delineated shutter electrodes and a single blanket vertical electrode allowing 1-D addressing of lines of shutters. The photo was taken through the transparent substrate and the slightly darker vertical stripes are transparent electrodes on the substrate. These thin CrSi electrode were used in a test of a technique to electrostatically hold shutters closed in an addressing scheme temporarily abandoned. Figure 8(b) shows the entire 128x128 array mounted on its transparent substrate that is used to bring the bottom shutter electrode leads out from under the array to exposed pads for wire bonding. The critical voltage for latching was found to be on the order of 25 V. Due to limitations in our current electronics, only 32 columns and 32 rows are addressed at this time.

128x128 and 512x512 electronics are being developed. The current drive electronics and future bench-top test electronics will be based on off-the-shelf electronic components, while the NGST flight system will be driven by custom cryogenic CMOS circuits.

4. SUMMARY AND FUTURE WORK

Microshutter arrays were designed as an object selector for the Multi-Object Spectrometer on the Next Generation Space Telescope. Microshutter arrays are transmissive devices minimizing light scattering to provide the high contrast needed for spectroscopy. We have fabricated 32x32 and 128x128 mechanical microshutter arrays with 100x100µm pixels using combined conventional semiconductor processing and MEMS technologies. We have used a combined magnetic and electrostatic approach for actuation and addressing. Materials for shutter membranes, oxide etch-stop, magnetic pads, electrodes and bonding pads have been tested and selected. We are working on the fabrication of microshutter arrays with reduced frame widths and etch gaps to improve the fill factor and light shields to improve the contrast. Larger shutter cells are also being investigated for improvements in fill factor and reduction in operating voltage. The larger shutter cell size improves the fill factor since most of the losses are those around the perimeter of the cell due to the frame and light shield. This perimeter loss increases slower than the open area as the cell size increases, resulting in an improvement in fill factor. The operating voltage decreases as the cell size increases since the electrode area increases and the torsion hinges become less stiff as they increase in length.

Our goal is to fabricate 512x512 microshutter arrays with full actuation and addressing functions. We plan to develop 2048x2048 microshutter arrays as a mosaic of 16 512x512 arrays with a mechanical support and electrical interconnect frame between the arrays. Functional testing will be carried out in a cryogenic environment in the near future.

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