Film Stress of Microshutter Arrays for the James Webb Space Telescope

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ABSTRACT

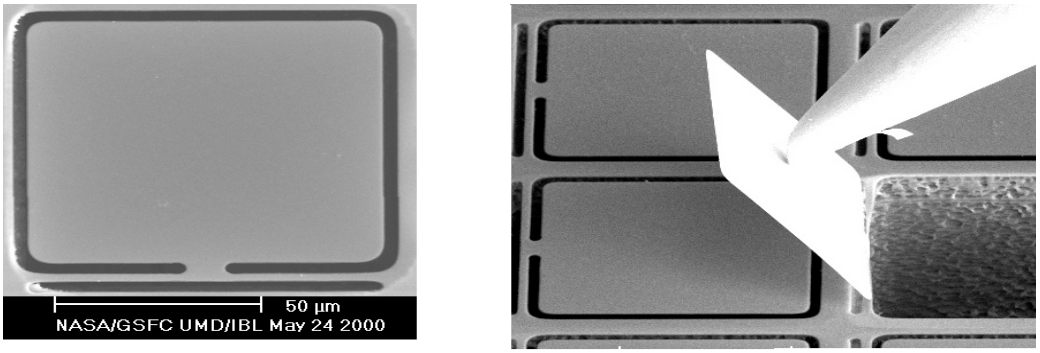
The James Webb Space Telescope (JWST), formally Next Generation Space Telescope (NGST), is one of NASA's challenging projects for advancing the exploration of space. The NGST will be equipped with a Multi-Object-Spectrometer (MOS) that covers the wavelength ranging from 0.6 to 5 micron. To selectively direct light rays from different regions of space into the spectrometer, one approach is to use microshutter arrays serving as the slit mask for the spectrometer. A large format (2Kx1K) individually addressable microshutter array with a lateral pixel size of 100_m x 200_m is being developed and fabricated using MEMS technologies. The microshutter arrays are close-packed silicon nitride membrane cantilevers. A ferromagnetic $Co_{90}Fe_{10}$ film is deposited on the membranes to magnetically actuate the microshutters. During deposition a $Co_{90}Fe_{10}$ film is susceptible to develop large tensile stress that can distort the nitride membranes and affect the contrast of the MOS, especially at cryogenic temperatures. In this paper, we discuss how to minimize the film stress. Stress-test cantilevers are micro machined and used in conjunction with Stoney's formula to determine film stresses. The effects of deposition pressure and power on the $Co_{90}Fe_{10}$ film, aluminum film and multiple-layer film stress are discussed. It is found that sputter-deposition of $Co_{90}Fe_{10}$ at low pressure and power results in favor of low tensile stresses in films.

INTRODUCTION

Background

One of NASA's challenging projects is to replace the exiting Hubble Space Telescope by James Webb Space Telescope (JWST). A primary mission of JWST is to reveal the origin of galaxies, clusters and large-scale structures in the universe[1]. In order to obtain information on star formation and merging in galaxies, JWST will have a Multi-Object Spectrometer (MOS) as one of the three major instruments that covers the near-infrared (NIR) wavelength region from 0.6 to 5micron. Multi-Object Spectrometers are essential tools at most ground-based observatories and are often equipped with a slit mask: an opaque plate with holes punched at the locations of the astronomical sources. Since slit masks implemented with punched plates are not practical for a space mission, a MEMS solution is being developed to enable the JWST science mission. The advantages of near-infrared Multi-Object Spectrometer (NIRMOS) are its combination of wide field of view, of ability to select arbitrary targets while utilizing the NGST's angular resolution, and of relatively high observing efficiency and high spectral resolutions. The primary requirements for the slit mask or selector include: an array size of greater than 2000 x 1000 elements with approximately 100 x 200 microns in dimension; the selector and driving CMOS circuit dissipating less than 35milli-Watts of power and operating at 45 Kelvin to eliminate thermal emission into the instrument; a high fill factor with the total selecting element area over total selector array area more than 80%.

A mosaic of microshutter arrays designed and developed by Dr. Moseley and others[2,3] are the MEMS solution selected for NGST. The proposed design will have a large format of 2048 x 1024 shutter mosaic of sixteen 512 x 256 arrays of transmissive shutters. The current dimension of each shutter is 100_m x 100_m and it will later be increased to 100_m x 200_m. Each shutter is connected to a frame through a neck region and a torsion bar, Figure 1. Shutters are magnetically actuated 90 degree into their silicon support grid and then electrostatically latched open.



(a) (b)

Figure1. SEM image of a silicon nitride mechanical microshutter (a) and a shutter opened using a probe (b)

Each shutter is individually addressable. Magnetic actuation and electrostatic holding are employed to open and latch the shutters. Each shutter consists of a magnetic pad on the front side of the shutter area and an electrode strip from the same column. A second set of row electrodes are located on the wall of a support grid on the backside of the frame to allow cross-point addressing. When a long small tripole magnet aligned to the shutter rows sweeps across the array along the columns, the sequential rows of shutters are rotated 90 degrees from their natural horizontal closed orientation to a vertical open orientation and contact the vertical electrodes. If a bias voltage applied to the electrodes is big enough, the electrostatic force will 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 voltage is insufficient, the shutter will return to its horizontal closed position[4].

There are three layers of metalization on the front side of shutter array (5000Å silicon nitride membrane) and two layers of metalization on the backside frame of the array for the magnetic actuation and electrostatic holding. The front tri-layer metalization consists of a 2000Å aluminum film as the shutter front column electrode, a 2000Å magnetic material film as the magnetic pads and a 150Å aluminum film as a passivation layer to protect the magnetic pads. Ni,

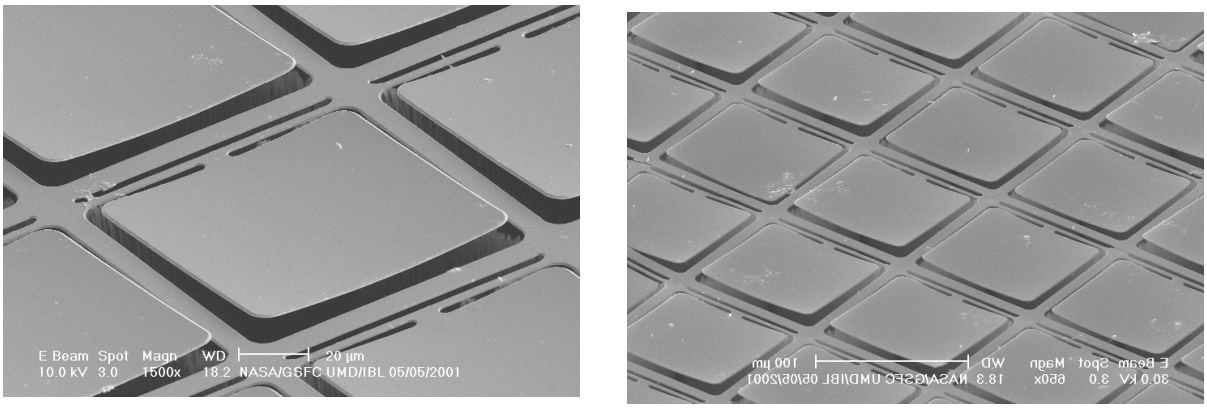


Figure 2. SEM pictures of bowed microshutter arrays result from high film stress

Co, $Co_{50}Fe_{50}$ and $Co_{90}Fe_{10}$ were tested as the candidate materials for magnetic pads. $Co_{90}Fe_{10}$ films showed the best adhesion and the least bowing at room temperature and therefore were our choice material. They also have a high magnetization to provide torque for magnetic actuation. Shutter bowing (figure 2) can be caused by intrinsic or thermal stress of the film, resulting in light leaks into the spectrometer and a reduced electrostatic latching force, which can limit the performance of JWST. In order to obtain high contrast and high fill factor, the shutters need to be flat and therefore the thermal and intrinsic stresses need to be minimized. It is our goal of this study to minimize the film stress to obtain flat shutters. The intrinsic film stress can be reduced by adjusting the deposition conditions since it is known to be a function of the atomic mass of the target material, the sputtering source geometry, sputtering pressure, discharge voltage and atomic mass of the carrier gas. For the space application the microshutter will work at cryogenic temperatures as low as 30 K. Since the films were sputter deposited at ambient temperature, the mismatch of the Coefficient of Thermal Expansion (CTE) between metal and silicon nitride layers and between metal layers will cause thermal stress at the operating temperature..

Stress measurement

There are several film stress measurement methods and commercial equipment to measure film stress. But most of them are used for wafer sizes and cannot work at cryogenic temperatures. A measurement on a large wafer area may not reflect the real stress of the microshutter, which is in 100_m x 100_m size. It is better to measure stress on a sample that is similar to the real microshutter device. It is also important for us to monitor the film stress at different temperatures.

Although the methods that are commonly used to measure stresses in thin films are quite varied, they may be divided into two major categories, structural and mechanical methods. Structural methods investigate the lattice strains on the thin film such as the lattice mismatch between film and substrate in epitaxial growth. Since the stress change is relatively small and the mechanisms for stress variation are on a fine scale, TEM, RHEED and X-ray diffraction are used for this purpose. This method is particularly useful for single crystal films. Mechanical methods include static and dynamic measurements. These techniques can measure relatively large variations of stress. The measured stress is usually the average stress in the film. This method is applied in the present studies.

The principle of static stress measurement is as follows: The presence of a biaxial stress in a thin film on a substrate will cause it to bend. The measurement of this substrate bending is a common method to determine the stress in the film. Substrates in the form of cantilever beams are usually used for in situ measurements. The formulae that have been used in determining virtually all film stress are variants of an equation first given by Stoney in 1909 [5],

$$\sigma = \frac{E_s}{(1-\nu_s)} \frac{t_s^2}{6 R t_f}$$

Where E_s, v_s, t_s, stand for Young's modulus, Poisson's ratio, and thickness of substrate respectively, t_f stands for thickness of film, and R is the curvature of the cantilever beam. For a cantilever of length *l*, where _ = l^2/2R is the free-end displacement, Stoney's formula yields [6].

$$\sigma_f = \frac{E_s}{(1-\nu_s)} \frac{t_s^2}{3 l^2 t_f} \delta$$

All values except R and _ are considered to be intrinsic properties of the cantilever and are independent of stress. The change of the state of stress under a given condition can then be monitored by measuring the variations of the curvature R or the free-end displacement _. Several techniques, such as optic and laser beam measurements can be used for this purpose. In laser beam measurement, the curvature R or the free-end displacement _ of the cantilever beam can be indirectly measured through the deflection of the beam end. This is also called bending cantilever beam technique.

In this paper, we present a film stress measurement method for the microstructure devices. The micro machined cantilever specimen is close to the real microshutter structure, which will help us better understand the microshutter stress. Stoney's formula was used to calculate cantilever stress in this work. The dependences of film stress on the deposition conditions were studied. By optimizing the deposition condition, we are able to produce microshutter arrays with very low stresses for the NGST application.

EXPERIMENTAL PROCEDURE

To measure the stresses of microshutter films, experiments involving the following major steps were carried out at Detector Development Laboratory, Goddard Space Flight Center, NASA and Naval Research Laboratory. (1) Micromaching fabrication of the microshutters and silicon cantilevers by lithographic method. (2) Magnetic material selection and film deposition. (3) Specimen measurement and stress calculation.

Cantilever fabrication

Four-inch single-side polished silicon [100] wafers with a thickness of about 450 um were used to fabricate cantilevers for the film stress measurement. The processing procedure for the fabrication is shown in figure 3. The wafers were cleaned in standard 3:1 H_2SO_4 : H_2O_2 solution. A 2_m thick thermal oxide was grown on the silicon wafers at 1000 ^oC with wet steam flowing into the tube furnace. The wafers were patterned on both sides by using lithographic technique. Buffered HF solution was used to remove oxide from exposed area and then KOH solution was used for silicon etch to thin the wafer in the exposed area. The fabricated cantilever is about 19mm long, 4mm wide and 35_m um thick. There is a layer of about 500nm silicon oxide on top of the cantilever. The cantilever is supported by a thick silicon frame for easy handling.

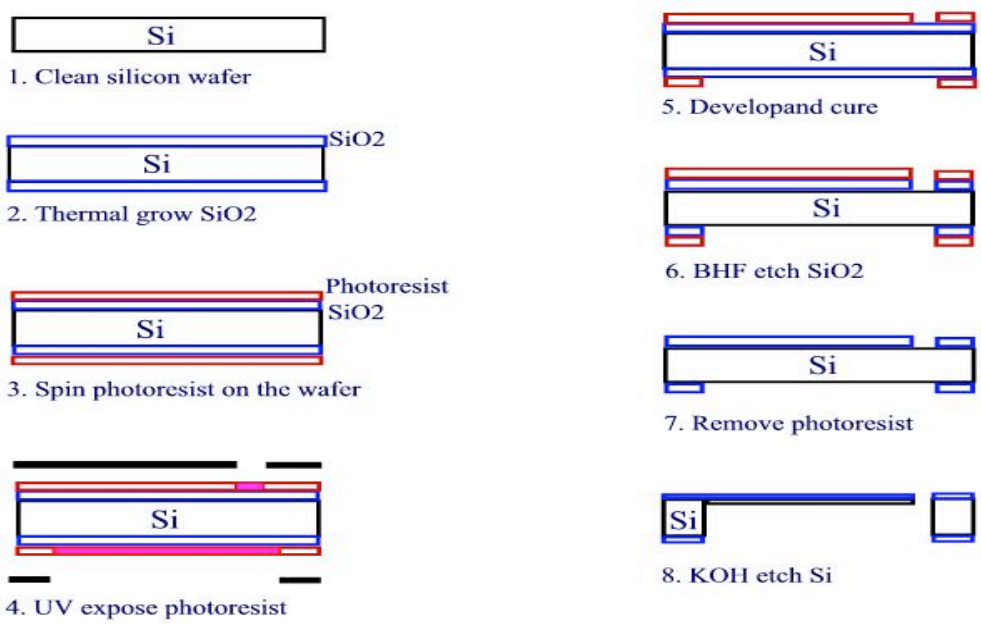


Figure 3. Fabrication process of silicon cantilever

Film deposition

Polycrystalline $Co_{90}Fe_{10}$ (CoFe), Al and Al/CoFe/Al films were made by dc magnetron sputtering at ambient temperature. The base pressure was about $2x10^{-7}$ Torr. Deposition was carried out in a working gas pressure ranging from 0.8 to 4 mTorr of Ar using 60 to 200W of dc power. The distance between the top of target surface and the substrate was about 15cm and was kept constant during our experiments. Since the sputtering rate varied with the working gas pressure, film thickness was measured using x-ray fluorescence (XRF) and a profilometer. Films were deposited on microshutters, micromachined Si cantilevers and polished Si wafers with 2000Å of LPE Si_3N_4 on top.

Film stress measurement

The distance at the free-end of the cantilever between cantilever surface and frame surface and the length of the cantilever were measured by using a Nikon type MM-60 measuring microscope equipped with QUADAR CHEK 200 displayer. The precision of the measuring microscope is 0.5 um. Each cantilever was labeled and measured data were recorded before deposition. After deposition the stress between the metal film and the silicon oxide layer resulted in cantilever bending so that the distance at the free-end of the cantilever was changed. The free-end displacements of the cantilever were measured at the same spots before and after deposition. The film thickness was re-measured by Tencer Instrument alpha step 200 profilometer. The above measured data were used to calculate the film stresses by means of Stoney's formula.

Results and Discussion

Under typical operation conditions for magnetron sputtering it is reasonable to assume that the energy flux into the growing film is only due to the contributions of the kinetic energy of reflected neutrals and ejected target atoms, the heat of condensation and the plasma irradiation[7]. The influence of the thermalization process of particles from the target and the residual contributions of electrons to the substrate heating can be neglected. The energy input is in general increased with increasing pressure and decreasing power and it greatly affects the microstructure and the stress of the films. In addition, the amount of background gas incorporation, a function of gas pressure, can significantly influence thin film structure and density and thus the film stress as well. With a fixed target-substrate distance, the working gas pressure and target power (voltage) are the most important factors for controlling film stresses for a particular target material. It was found that, by carefully adjusting pressure and power; the film stresses can be changed from tension to compression. Therefore it is possible to obtain a film with a near-zero stress.

Since metal films were deposited both on the cantilever and cantilever frame, they were both curved by the film stress. However, because the thickness of the cantilever is much smaller than that of the frame, the frame curvature introduced from stress can be neglected and the free-end displacement of the cantilever can be used to calculate the film stresses. Since there was a tri-layer metalization on the front side of the microshutter, the microshutter bowing was a combined contribution from three layers. However due to the thinness of the third layer (150 Å of aluminum), the film stress contribution from it can be neglected. Figure 4 showed film stress changes with deposition pressure for a 2000Å aluminum film on a cantilever. All of the stress data reported here were measured at room temperature on as-deposited films. In general, the aluminum film has a small negative stress (compression) for pressures ranging from 1 to 3 mTorr. At 4 mTorr and 200 W of deposition power, film stress was changed from compression to tension. One can see from figure 4 that all the aluminum film stresses were small, from –24 Mpa to +17 Mpa.

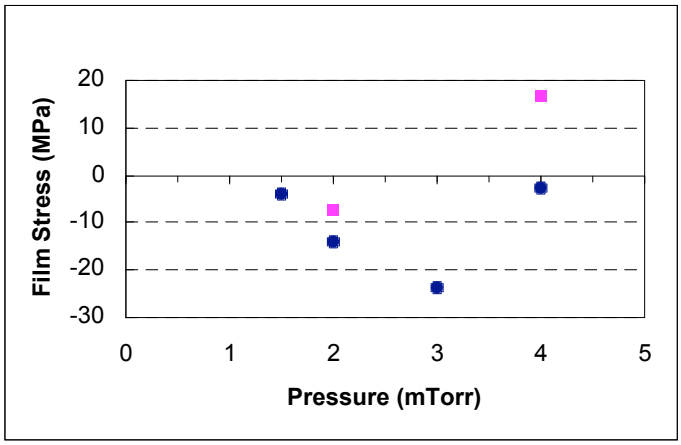


Figure 4. Film stress vs. sputtering pressure for aluminum film. _ 200 W sputtering power. _ 100 W sputtering power

Figure 5 shows the dependence of film stresses on Ar gas pressure for the 2000Å $Co_{90}Fe_{10}$ film on cantilever. For the films sputtered at 200W of power, the film stress was around 140 Mpa at the deposition pressure ranging from 1 to 2 mTorr, but it was increased to 314 Mpa when the pressure was increased to 2.5 mTorr. For the films grown with 100 W of sputtering power, the film stress was also about 140 Mpa at the Ar pressure of 1.5 to 2 mTorr. When the gas pressure was decreased to 1 mTorr, the film stress decreased to 66 Mpa but it drastically increased to 761 Mpa at 3 mTorr. At 60 W of deposition power, the film stress was also around 140 Mpa at the pressure of 1.5 and 2 mTorr. But when the pressure was decreased to 0.8 mTorr, the film stress changed from tension to compression, - 79 Mpa. One can see from figure 5 that the deposition power did not affect the film stress too much for the pressure and power values we studied and that the stress of our $Co_{90}Fe_{10}$ film is mainly affected by the gas pressure.

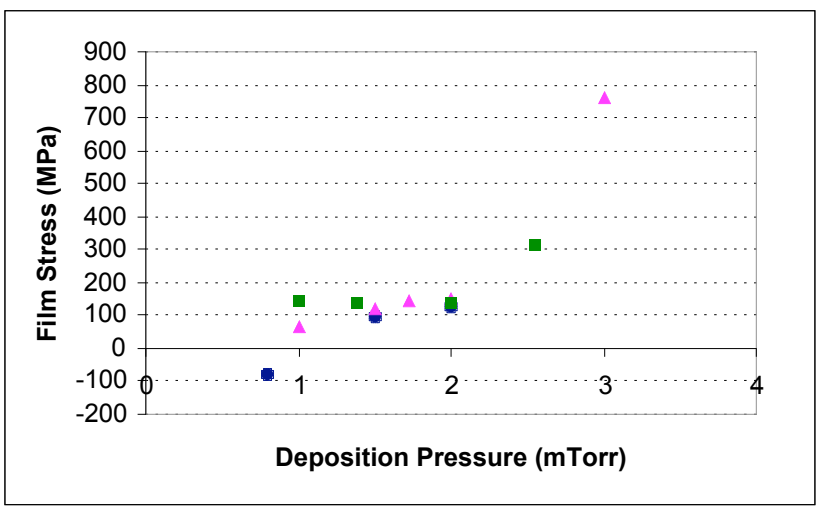


Figure 5. Film stress vs. deposition pressure for $Co_{90}Fe_{10}$ film
_ 200 W sputtering power. _ 100 W sputtering power. _ 60 W sputtering power

In summary, aluminum films did not affect microshutter bowing too much since at the various deposition pressures and deposition powers the film stresses only slightly changed from –24 Mpa to +17 Mpa.. The deposition condition of 3 mTorr pressure and 100 W power may be good for the microshutters since it may compensate some of the

tensile stress from $Co_{90}Fe_{10}$ films. The major contribution for the microshutter bowing was from the $Co_{90}Fe_{10}$ film. The different deposition conditions changed the film stresses from tensile stress of 761 Mpa to compressive stress of –79 Mpa in this experiment. In the $Co_{90}Fe_{10}$ film deposition the deposition pressure is the major contributor for the film stress. In order to obtain a less stressed film the deposition pressure should be lower than 2 mTorr. If we optimize deposition condition, the microshutter bowing may be minimized.

Table 1 shows the total stress of a tri-layer of metal films on cantilevers at the different deposition conditions. The tri-layer consists of a 2000Å thick aluminum film, a 2000Å thick $Co_{90}Fe_{10}$ film and a 150Å of aluminum film. The table also shows that the change of aluminum deposition conditions may not change the total film stresses, but decreases of the $Co_{90}Fe_{10}$ film deposition pressure can decrease the total film stresses. Therefore it may minimize microshutter bowing and fabricate flat microshutter arrays (figure 6).

Table 1: The film stress of three tri-layers deposited at different conditions

Number	Al film deposition condition	$Co_{90}Fe_{10}$ film deposition condition	Total film stress
1	100 W, 3 mTorr	60 W, 1.5 mTorr	90.6 Mpa
2	60 W, 4 mTorr	60 W, 1.5 mTorr	99.8 Mpa
3	60 W, 3 mTorr	60 W, 1.0 mTorr	57.1 Mpa

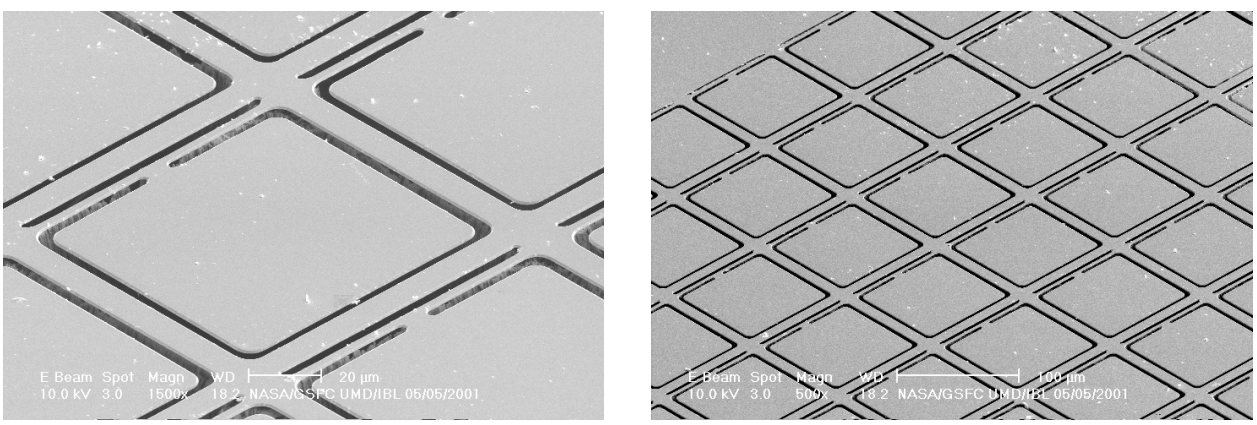


Figure 6. SEM pictures of flat microshutter arrays

CONCLUSION

The bending cantilever beam technique can be used to measure the film stress of microshutter arrays. Micromachined silicon cantilevers can be fabricated to resemble the real microshutter structure and therefore can better reflect microshutter film stresses. This film stress measurement technique can be used for low temperature measurements.

Deposition conditions of the aluminum film only slightly affects film stresses of tri-layers and the aluminum films are in general in a small compressive stress for the gas pressure range we studied. Deposition conditions of the $Co_{90}Fe_{10}$ film can dramatically affect film stresses of tri-layers. With decreasing gas pressure, the $Co_{90}Fe_{10}$ film stress can be changed from tension to compression. The $Co_{90}Fe_{10}$ film stress can be dramatically increased at high gas pressure deposition. For the sputtering power we used, 60W to 200w, the film stress wasn't significantly affected by the power.

By optimizing the deposition conditions we may decrease the total intrinsic stress of the tri-layer film at room temperature and therefore minimizes the microshutter bowing and fabricates flat microshutter arrays. To decrease the total stress at the shutter operating temperature, an intrinsic compressive stress may be desired to compensate for the thermal stress to ensure a flat shutter for the next generation space telescope.

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REFERENCES

1. H. Stockman, the Next Generation Space Telescope: *visiting a time when galaxies were young*, The association of Universities for Research in Astronomy, Inc., 1997
2. S. Moseley, R. Fettig, A. Kutyrev, C. Bowers, R. Kimble, J. Orloff, and B. Woodgate, "Programmable 2 Dimensional Microshutter Arrays, " in Micromachining and Microfabrication, Proceedings of SPIE 3878, 1999.
3. M. J. Li, I. S. Aslam, A. Ewin, R. K. Fettig, D. Franz, C. Kotecki, A. S. Kutyrev, S. H. Moseley, C. Monroy, D. B. Mott, and Y. Zheng, "Fabrication of Microshutter Arrays for Space Application, " in MEMS Design, Fabrication, Characterization, and Packaging, Proceeding of SPIE 4407, 2001.
4. D. B. Mott, I. S. Aslam, K. A. Blumenstock, R. K. Fettig, D. Franz, A. S. Kutyrev, M. J. Li, S. C. J. Monroy, and H. Moseley, D. S. Schwinger, "Magnetic Actuated Microshutter Arrays, " in Micro-machining and Microfabrication, Proceeeding of SPIE, 2001.
5. G. G. Stoney, Proc. Roy. Soc., London, A82, 172 (1909).
6. M. Ohring, in The Materials Science of Thin Film, Academic Press Inc. (1991).
7. T. P. Drusedau, T. Bock, T. M. John, F. Klabunde and W. Eckstein, in J. Vac. Sci. Technol. A17, 2896 (1999).