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Radiation Test Results for a MEMS Microshutter Operating at 60 K

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1. Introduction

The James Webb Space Telescope (JWST), the successor to the Hubble Space Telescope, is due to be launched in 2013 with the goal of searching the very distant Universe for stars that formed shortly after the Big Bang. Because this occurred so far back in time, the available light is strongly red-shifted, requiring the use of detectors sensitive to the infrared portion of the electromagnetic spectrum. HgCdTe infrared focal plane arrays, cooled to below 30 K to minimize noise, will be used to detect the faint signals.

One of the instruments on JWST is the Near Infrared Spectrometer (NIRSPEC) designed to measure the infrared spectra of up to 100 separate galaxies simultaneously. A key component in NIRSPEC is a Micro-Electromechanical System (MEMS), a two-dimensional micro-shutter array (MSA) developed by NASA/GSFC. The MSA is inserted in front of the detector to allow only the light from the galaxies of interest to reach the detector and to block the light from all other sources.

The MSA will have to operate at 30 K to minimize the amount of thermal radiation emitted by the optical components from reaching the detector array. It will also have to operate in the space radiation environment that is dominated by energetic ionizing particles. Because it is located outside the spacecraft and has very little shielding, the MSA will be exposed to a large total ionizing dose of approximately 200 krad(Si).

Following exposure to ionizing radiation, a variety of MEMS have exhibited performance degradation [1-6]. MEMS contain moving parts that are either controlled or sensed by changes in electric fields. Radiation degradation can be expected for those devices where there is an electric field applied across an insulating layer that is part of the sensing or controlling structure. Ionizing radiation will liberate charge (electrons and holes) in the insulating layers, some of which may be trapped within the insulating layer. Trapped charge will partially cancel the externally applied electric field and lead to changes in the operation of the MEMS. This appears to be a general principle for MEMS.

Knowledge of the above principle has raised the concern at NASA that the MSA might also exhibit degraded performance because, i) each shutter flap is a multilayer structure consisting of metallic and insulating layers and ii) the movement of the shutter flaps is partially controlled by the application of an electric field between the shutter flap and the substrate (vertical support grid). The whole mission would be compromised if radiation exposure were to prevent the shutters from opening and closing properly.

A unique feature of the MSA is that, as previously mentioned, it will have to operate at temperatures near 30 K. To date, there are no published reports on how very low temperatures (~ 30K) affect the response of MEMS devices to total ionizing dose. Experiments on SiO_2 structures at low temperatures (80 K) indicate that the electrons generated by the ionizing radiation are mobile and will move rapidly under the application of an external electric field. Holes, on the other hand, that would normally move in the opposite direction through the SiO_2 via a "thermal hopping" process, are effectively immobile at low electric fields as they are trapped close to their generation sites. However, for sufficiently large electric fields (>3 MV/cm) holes are able to move through the SiO_2. The larger the field, the more rapidly the holes move [7].

The separation of the electrons and holes leads to a reduced electric field within the insulating layer. To overcome this reduction in electric field, a greater external voltage will have to be applied that alters the normal operation of the device.

This report presents the results of radiation testing of the MSA at 60 K. The temperature was higher than the targeted temperature because of a faulty electrical interconnect on the test board. Specifically, our goal was to determine whether the MSA would function properly after a TID of 200 krad(Si).

2. Device Description

The MSA is a MEMS device manufactured from a silicon wafer using typical Si processing steps. The device consists of an array of 365 x 171 flaps, each flap having dimension of 100 μm by 200 μm. The flaps are constructed of an insulating layer (Si_3N_4) covered with a thin metal layer that is also magnetic. The flaps pivot about an axis along one of their sides: the remaining three sides of the flaps are separated from the substrate during processing.

All the shutters are forced open in a two-step process. Voltages are first applied to all the shutters and then a magnet is brought close to the array. The combination of the electric and magnetic forces are sufficient to open all the shutters. A positive voltage is applied to the flap and a negative voltage to the substrate through two orthogonal addressing chips (X and Y). The voltages are equal in magnitude but opposite in sign. Once the magnetic field has been removed, the voltages are removed from those shutters that need to be closed.

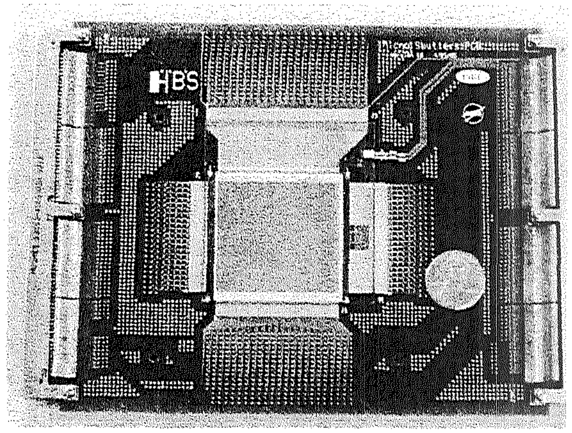

Fig. 1. Microshutter Array mounted on Test Board.

In its open position, the flap has pivoted until it comes into contact with the "vertical" support grid that is part of the silicon substrate, which is also covered with a metallic layer. In that configuration, the electric field across the insulating layer on the flap is a maximum and the shutters would be expected to be most sensitive to the effects of TID.

Fig. 1 is a picture of the shutter array mounted on a test board with all the connections required for controlling the shutters. Fig. 2 shows two adjacent flaps, one open and the other closed.

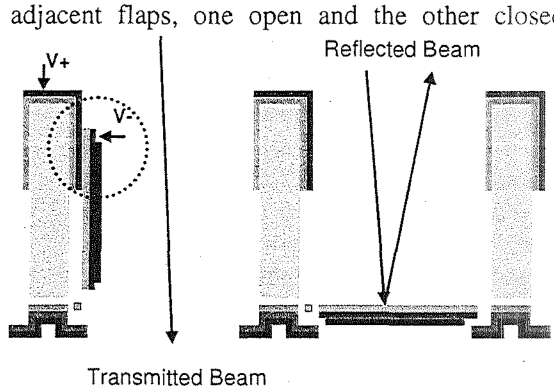

Fig. 2. Two adjacent shutters; the one on the left is open to allow the light to pass through and the one on the right is closed to block the light. The vertical structure is part of the silicon substrate. In the open position, the shutter flap abuts the substrate and the electric field (supplied by V+ and V-) across the insulating layer on the flap is a maximum.

3. Test Setup and Description

The device was mounted inside a dewar under vacuum and cooled to approximately 30 K with liquid nitrogen and liquid helium. The dewar was positioned close to a Co^{60} source where the dose rate was approximately 6 krad(Si)/hour. Measurements were made at doses of 10, 20, 50, 100, 150 and 200 krads(Si).

Prior to commencing irradiation, the shutter array was tested by opening and closing the shutters to determine how many of the shutters were actually operating properly. Random shutters throughout the array were stuck, some open and some closed.

During irradiation all shutters were kept open – this is the worst-case condition for total dose as the electric field is a maximum. Following each incremental dose, the effects of the radiation were determined by capturing an image of the MSA and counting the number of shutters that were stuck open or stuck closed as a function of the applied voltages. Two approaches were used. In one, the applied voltages were decreased in steps, i.e., +23V/-23V, +20V/-20V, +15V/-15V, and +10V/-10V. The idea was to see whether there was any change in the number of stuck shutters as the "holding voltage" was decreased. In the other approach, the voltage on the flaps was decreased in steps of 1 V from 20 V down to 0 V, while the voltage on the substrate was kept constant at 0 V.

4. Results and Discussion

Fig. 3 shows an image of the MSA illuminated from the rear with all the shutters programmed to be open. The dark rectangles are those shutters that were stuck in the closed position. One can see that most of the shutters stuck closed are randomly distributed throughout the array, with a slightly greater concentration on the lower right side.

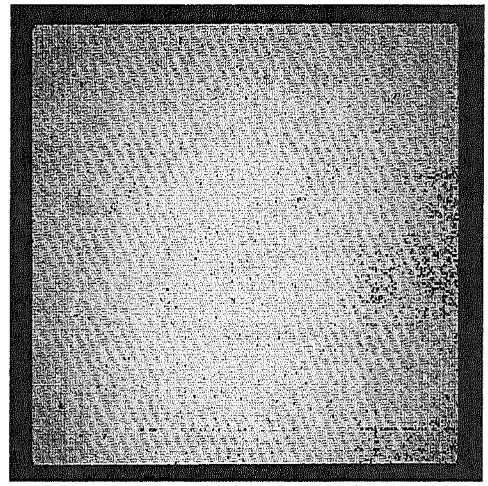

Fig. 3. Image of shutter array. All the shutters are supposed to be open. The shutters that failed to open are seen as dark spots in the image.

Fig. 4 shows the number of shutters stuck closed as a function of TID for four different sets of holding voltages. The figure shows that for high holding voltages (+/-20 V and +/- 23 V) the number of shutters that were closed when they should have been open barely changes with dose. However, at lower holding voltages the number increases quite significantly. In particular, for +/- 10 V, the number of shutters that stayed closed increased from 621 to 1220.

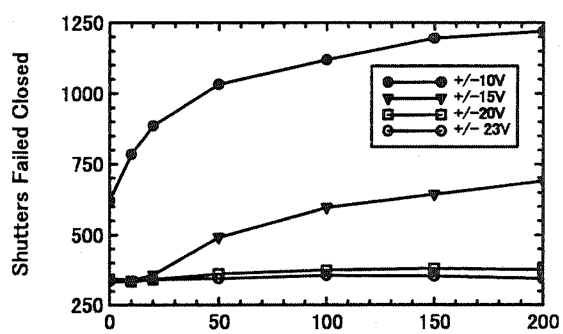

Fig. 4. Number of shutters stuck closed as a function of TID for four different holding voltages.

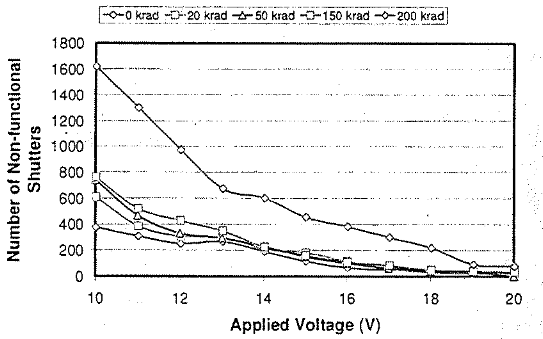

Fig. 5. Number of shutters stuck closed as a function of applied voltage for doses up to 200 krad(Si).

Fig. 5 shows test results for the second test where the voltage applied to the shutters was reduced from 20 V to 10 V in steps of 1 V. The threshold for keeping the shutters open is close to 10 V. There is a pronounced dependence of the number of shutters stuck closed on total dose, particularly for low voltages. At 10 V the number of non-functional shutters is around 400 prior to any radiation dose due to processing, and the number increases to approximately 1600 after a dose of 200 krad(Si).

We attribute the increase in the number of shutters stuck closed in both test procedures to the buildup of charge in the Si_3N_4 insulating layer on the shutter flaps as a result of their exposure to ionizing radiation. The buildup of charge is known to increase stiction in MEMS structures.

5. Conclusion

Radiation exposure appears to cause a buildup of charge in the insulating layer on the microshutter flaps. The charge alters the applied electric field, which has an effect on the opening and closing of the shutters. That effect is very small at high voltages and is confirmed by the data in Fig. 5 showing very little dependence on the number of shutters stuck open with dose. However, at low voltages close to threshold, the number of non-functional shutters increases with dose. Therefore, in the actual application, voltages close to 20 V will be used to mitigate the effect of total dose on the operation of the MSA.

6. References

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