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ELECTROSTATICALLY OPERATED OPTICAL MICROSHUTTER ARRAY FOR A MINIATURE INTEGRATED OPTICAL SPECTROMETER

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ABSTRACT

16x1 programmable microshutter arrays allowing control of the light transmitted through a transparent substrate supporting the array were successfully fabricated using surface micromachining technology. Each microshutter is basically an electrostatic zipping actuator having a curved shape induced by a stress gradient through the actuator thickness. When a sufficient voltage is applied between the microshutter and the actuation electrode surrounding the associated microslit area, the generated electrostatic force pulls the actuator down to the substrate which closes the microslit. Opening the slit relies on the restoring force. High light transmission through the slit area is obtained with the actuator in the open position and excellent light blocking is observed when the shutter is closed. Static and dynamic responses of the device were determined. The pull-in voltage to close the microslit was about 110 V and the response times to close and open the microslit were about 2 ms and 7 ms, respectively.

1. INTRODUCTION

There is a critical need for more comprehensive and definitive analysis of samples for planetary rovers and landers. However, potential instrumentation for landed planetary exploration has relatively severe restrictions on mass, power consumption and data transmission rates, with operational characteristics that are more robust due to the operating environment. Therefore, efforts toward the miniaturization of the instrumentation while maintaining or exceeding the performance of bulk instruments are required to maximize the attainable scientific benefit and provide affordable planetary exploration.

In dispersive spectrometers such as MPB's integrated optical spectrometer IOSPEC⁽¹⁾, high spectral resolution is obtained using narrower input slit widths. However, this limits the optical collection efficiency, reducing the attainable signal to noise ratio (SNR). Using Hadamard transform optical coding techniques^(1,2), the single slit can be replaced by a programmable microslit array. This can provide an

important gain in SNR relative to the single-slit spectrometers due to signal multiplexing and data redundancy.

The approach selected for the shutter array fabrication is based on a zipping actuator to close and open the slit. A stress gradient is introduced in the structural layer used to define the actuator. This stress gradient is obtained by varying the fabrication parameters during deposition of the actuator layer on top of a sacrificial layer. Once the sacrificial layer is removed, the stress in the material relaxes causing the actuator to bend out of the substrate plane. An electrode positioned on the substrate surround the slit. When a sufficiently high voltage is applied between the fixed electrode and the zipping actuator, the generated electrostatic force pulls the actuator down to the substrate which closes the slit. Opening of the slit relies primarily on the restoring force in the actuator.

The design, fabrication and electromechanical characterization of shutter arrays dedicated to the IOSPEC spectrometer are reported in this paper.

2. SIMULATIONS

Information about the zipping actuator behavior was obtained with Intellisuite software. Although some limitations were encountered in term of maximum actuator length that could be simulated and applicability of the contact mode, it was still possible to estimate the actuation voltage needed to close the slit. A zipping actuator was designed with the required curvature radius of about 450 μm , a length of 750 μm and a width and thickness of 100 μm and 1 μm , respectively. For these simulations, the zipper material was a MoCr alloy with a Young Modulus of 300 MPa and a Poisson's ratio of 0.33. No contact between the actuator and the activation electrode was observed for a voltage up to 120V. For a voltage of 140V, a significant deflection of the zipping actuator appeared (Fig. 1). Finally, a voltage of 160V produced an important deflection of the actuator. From these calculations, a voltage around 140-160 V was obtained as a preliminary estimate for the voltage which should be sufficient to fully close the slit.

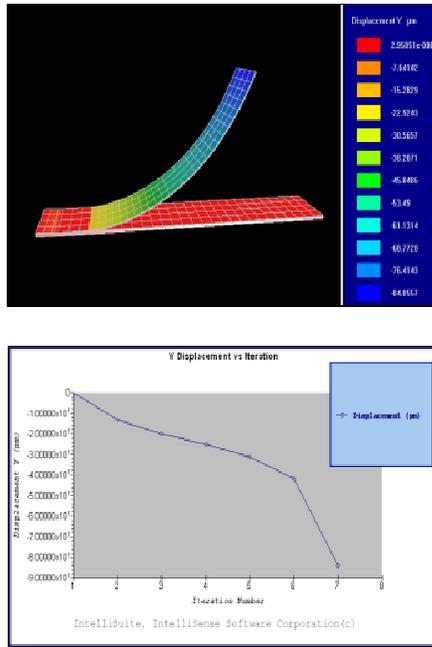


Fig. 1. Deflection of the zipper caused by an actuation voltage of 140V and the corresponding displacement as a function of the iteration number (total number of iterations was fixed to 10).

Additional electromechanical simulations were performed to verify if the actuation voltage applied on a given actuator could affect the operation of the adjacent zipping actuators. The separation distance between the actuators is 40 µm. As can be seen in Fig. 2, the actuation of a zipping actuator with a voltage of 140V does not cause any significant deflection of the adjacent zipper.

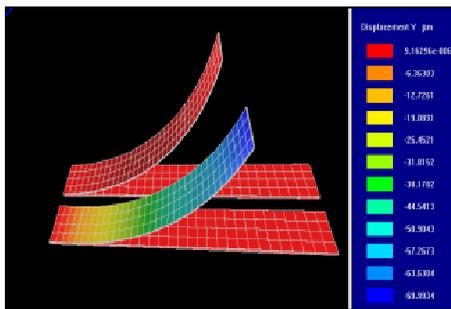


Fig. 2. Deflection of an actuator with a voltage of 140V. No significant effect is observed on the adjacent zipping actuator.

The evaluation of normal mode frequency of the zipper structure was used to estimate the response time of these actuators. This frequency is about 840 Hz (period of 1.2 ms). Therefore, the time required to actuate fully the zipper was expected to be around 1 to 2 ms.

3. FABRICATION

A process flow was developed for the zipping actuator array fabrication (Fig. 3). Sapphire was selected as the substrate material due to its low absorption over the spectral range of interest.

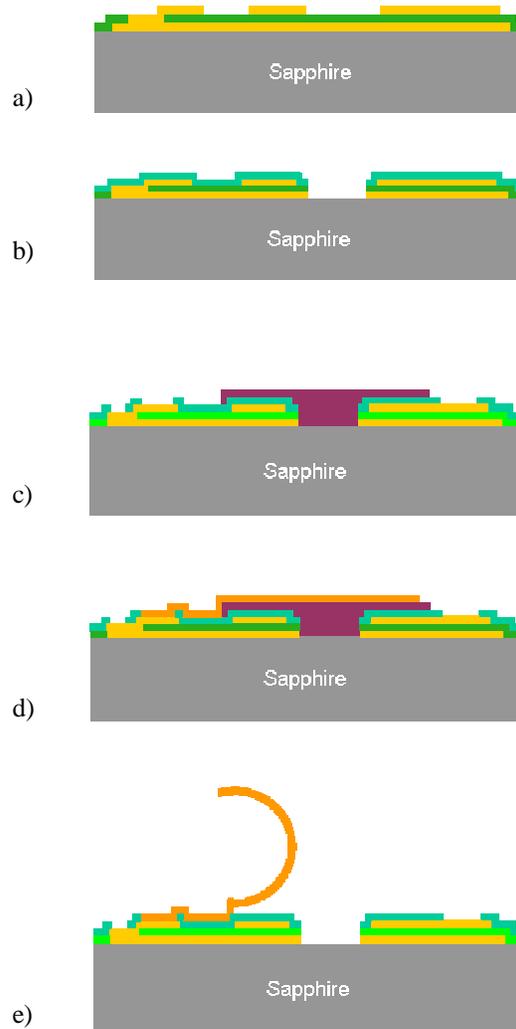


Fig. 3. Summary of the fabrication process for the zipping actuators.

The fabrication process starts with sputter-deposition of an aluminum film (Metal1) on a sapphire substrate (Fig. 3-a). This film provide an opaque material layer in which the transparent slits will be defined. Next, a SiN layer (SiN1) is deposited using Plasma Enhanced Chemical Vapor Deposition (PECVD) for electrical insulation. Windows are opened in SiN1 to provide access to the underlying aluminum layer. These windows are etched using Reactive Ion Etching (RIE) with a CF₄/O₂ plasma. Afterward, an aluminum layer

(Metal2) is sputter-deposited and patterned to produce the activation electrodes (Fig. 3-b). A wet etching step in a typical HNO₃/H₃PO₄ solution is used to define the electrode shape. The electrodes are then electrically insulated with a PECVD SiN layer (SiN₂). Finally, the slits are opened by etching SiN₁, SiN₂ and Metal1. As previously, a RIE process is used to etch the SiN. The Metal1 (aluminum) is etched with the same solution used for the electrode patterning. In Fig. 3-c, a polyimide sacrificial layer is deposited and patterned using a RIE process with Oxygen plasma. This is followed by the definition of contact pads in SiN₂ using RIE. Fig. 3-d, shows the steps of MoCr structural layer deposition and patterning to form the zippers. The MoCr layer is sputter deposited. A stress gradient is induced in the MoCr film by varying the pressure in the vacuum chamber during this fabrication step⁽³⁾. The stress variation required to achieve a given radius of curvature of the zippers can be calculated using the following expression:

$$\Delta\sigma = (Eh)/(R(1-\nu)) \quad (1)$$

where $\Delta\sigma$ is the stress variation through the film thickness, E is the elastic modulus of the material, h is the film thickness, R is the radius of curvature and ν is the Poisson's ratio of the material. The MoCr fabrication step is followed by substrate dicing. Finally, in Fig. 3-e, the polyimide sacrificial layer is removed using an oxygen plasma etch and the zipper structures are released.

Various Zipper array types were included in the layout of photolithographic masks designed for the zipping actuator fabrication. Single and double shutter designs were implemented. For the double shutter design, each slit is closed using two zipping actuators. In this case, the actuators are opposite to each other and each one closes half of the slit. A small region at the middle of the slit is left opaque to avoid the requirement of positioning the zipping structure ends very precisely. Table 1 lists the various types of zipping actuators included on the masks.

Table 1. Shutter types.

Shutter type	Effective slit length (μm)
Single	500
Single	1000
Double	1000
Double	1400
Double	2000

Typical arrays based on single and double shutter structures are shown in Fig. 4. Variation of the radius of curvature from array to array (up to 30 %) was

observed within the 4-inch wafer as a result of some non uniformity in the local deposition conditions.

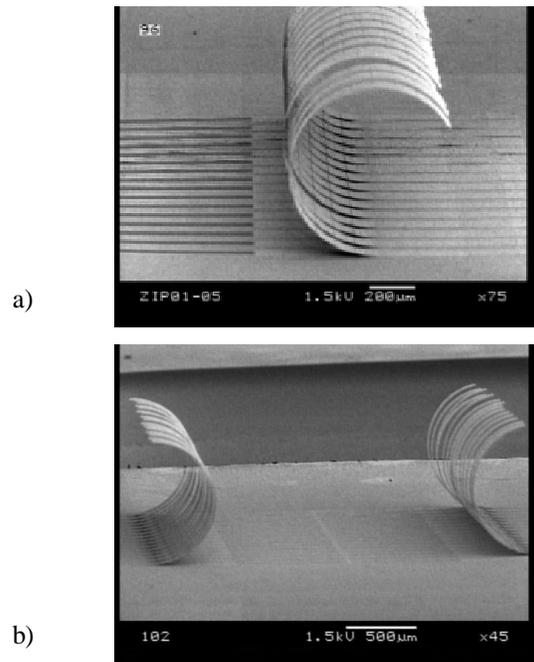


Fig. 4. SEM micrographs, a) 16x1 shutter array based on single shutter structures. Estimated radius of curvature is 370 μm. Effective slit length of 1000 μm. b) 16x1 shutter array based on double shutter structures. Estimated radius of curvature is 360 μm. Effective slit length of 1000 μm.

4. ACTUATOR CHARACTERIZATION

4.1. Static response

Tests were performed on zipping actuators to determine the actuation voltage. This voltage ranges from 100 V to 135 V depending on the zipper position in the array and the array position on the substrate. Fig. 5, shows the static actuation of a shutter with the application of a voltage of 110V between the fixed electrode and the zipper. As can be seen, the slit is fully closed when the voltage is applied, Fig. 5-b). No crosstalk was observed between the actuated zipper and the adjacent zippers. In addition, no stiction problem was observed and the zipping actuator returned smoothly to its original position when the applied voltage was removed.

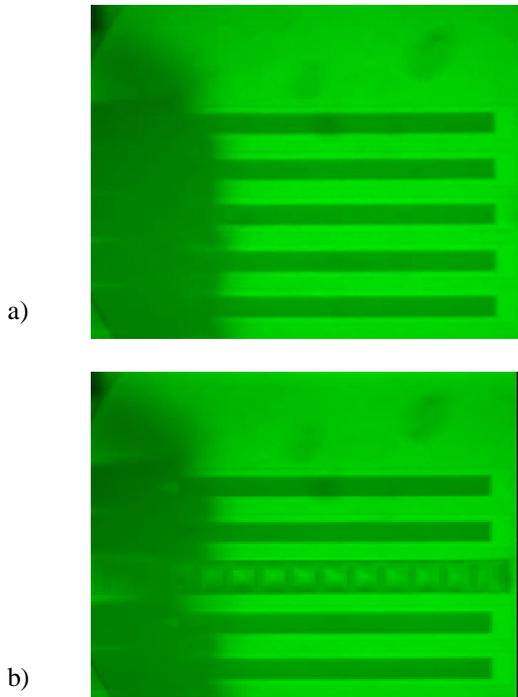


Fig. 5. Static actuation of a single zipper using a voltage of 110 V. a) non actuated state, b) actuated state (the slit was fully closed).

4.2. Dynamic response

An optical test setup was used to characterize the zipper dynamic response. To determine the response time to close the shutter, the upper region of the slit under test was illuminated with a laser beam and the reflected light was recorded with a photodetector (Fig. 6). The photodetector response time was about 10 ns. When the zipper was fully actuated, the intensity of reflected light showed an important intensity variation. The voltage waveform applied to the shutter and the photodetector signal were recorded simultaneously using an oscilloscope. The measured signals allowed characterization of the zipping actuator dynamic response. The response time to fully close the slit is about 2 ms (Fig. 7-a), in line with the estimated 840 Hz natural frequency of the zipper (see section 2 above). This response time is significantly lower than the target time of 30 ms. Opening the slit relies on the restoring force due to the actuator deformation. The response time to open the slit was evaluated to be about 7 ms (Fig. 7-b). This time estimate depends mainly on the oscillation of the zipper around its final equilibrium position. This indicates that by moving the actuator slightly away from the slit, it would be possible to achieve an effective response time of about 400 μ s to open the slit.

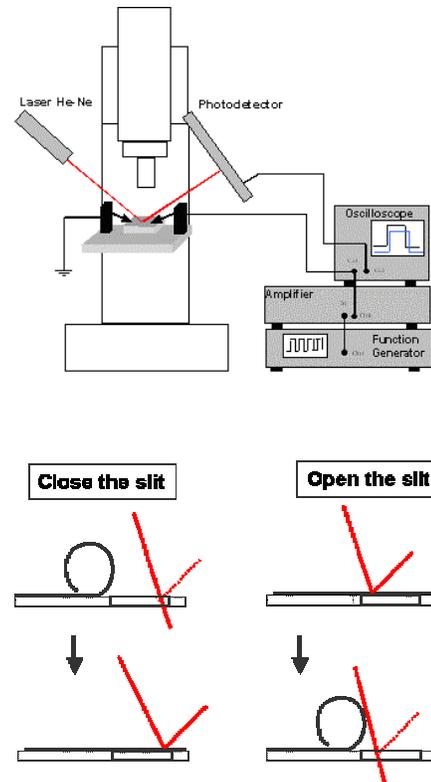


Fig. 6: Simplified illustration of the test set-up for the characterization of the zipper response time for closing and opening.

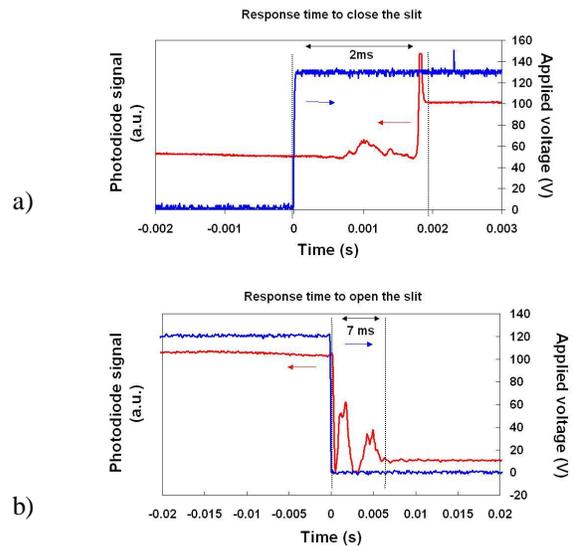


Fig. 7: Characterization of the zipper dynamic response, a) to close the slit and b) to open the slit.

4.3. Slit and zipping actuator transmittance

Optical transmittance of the sapphire substrates was measured before and after processing. These measurements were made with a Lambda 19 UV-VIS-NIR spectrometer and a 1600 FTIR spectrometer, both from Perkin Elmer, to cover the entire wavelength range from 1000 to 5000 nm. No significant change in the optical transmittance was observed after completing all fabrication process steps. As can be seen in Fig. 8, the optical transmittance is 80 % or more for the entire spectral range of interest.

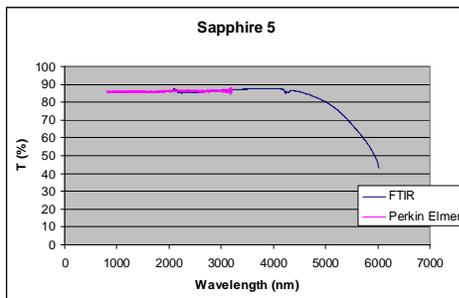


Fig. 8: Optical transmittance measurement of the 1mm thick sapphire substrate after completion of all fabrication steps. The transmittance is 80 % or more in the spectral range of 1000-5000 nm.

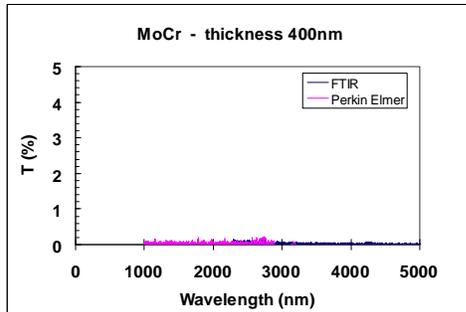


Fig. 9: Optical transmittance measurement of a 400nm thick MoCr layer. The transmittance is lower than 0.2 % in the spectral range of 1000-5000 nm.

Using the same procedure, the optical transmittance of the MoCr film used as the structural layer to form the zipping actuator has been measured over the spectral range of interest. The optical transmittance remains below 0.2 % for the whole range. Therefore, a slit transmission ratio of more than 400 is expected between the open and close states for the 1000 to 5000 nm spectral range.

5. CONCLUSION

The technical feasibility of a 16x1 microshutter array designed for a Hadamard transform miniature

spectrometer was successfully demonstrated. The microshutter operation is based on a zipping actuator approach. Each shutter from the array can be individually and fully closed with an actuation voltage varying from 100 to 135 V. As can be seen in Table 2 below, all initial requirements for the shutter array were fulfilled or exceeded.

Table 2 Compliance with the targeted shutter array specifications.

Parameter	Target	Result
Slit length	1 mm	1 mm
Slit width	60 μm	60 μm
Number of slit in the array:	16	16
Spacing between slits	140 μm	140 μm
Response time to close the slit	30 ms	2 ms
Response time to open the slit	30 ms	7 ms
Slit transmission, on state (Spectral range 1.3 to 5 μm)	> 80 %	> 80 %
Slit transmission, off state (Spectral range 1.3 to 5 μm)	< 5 %	< 0.2 %

Future activities planned to further develop the shutter array include testing of the device against environmental requirements (vibration tests, temperature cycling, etc...) and the characterization and eventual improvement of the zipping actuator lifetime.

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