Large array of 2048 tilting micromirrors for astronomical spectroscopy: optical and cryogenic characterization

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ABSTRACT

Multi-object spectroscopy (MOS) is a powerful tool for space and ground-based telescopes for the study of the formation and evolution of galaxies. This technique requires a programmable slit mask for astronomical object selection. We are engaged in a European development of micromirror arrays (MMA) for generating reflective slit masks in future MOS, called MIRA.

MMA with 100 x 200 µm2 single-crystal silicon micromirrors were successfully designed, fabricated and tested. Arrays are composed of 2048 micromirrors (32 x 64) with a peak-to-valley deformation less than 10 nm, a tilt angle of 24° for an actuation voltage of 130 V. The micromirrors were actuated successfully before, during and after cryogenic cooling, down to 162K. The micromirror surface deformation was measured at cryo and is below 30 nm peak-to-valley.

These performances demonstrate the ability of such MOEMS device to work as objects selector in future generation of MOS instruments both in ground-based and space telescopes. In order to fill large focal planes (mosaicing of several chips), we are currently developing large micromirror arrays integrated with their electronics.

Keywords: MOEMS, MEMS, micromirror, large array, multi-object spectroscopy, cryogenic, programmable slit mask, astronomical instrumentation.

1. INTRODUCTION

Multi-object spectroscopy (MOS) allows measuring infrared spectra of faint astronomical objects that provides information on the evolution of the Universe. In order to optimize the Signal-to-Noise Ratio (SNR), the high precision spectra measurements could be obtained using a MOS. MOS with multi-slits is the best approach to eliminate the problem of spectral confusion, to optimize the quality and the SNR of the spectra, to reach fainter limiting fluxes and to maximize the scientific return both in cosmology and in legacy science. Major telescopes around the world are equipped with MOS in order to simultaneously record several hundred spectra in a single observation run. This technique requires a programmable slit mask for astronomical object selection. Conventional masks or complex fiber-optics-based mechanisms are not attractive for space. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time. Next-generation infrared MOS for ground-based and space telescopes could be based on MOEMS programmable slit masks.

For the near infrared spectrograph (NIRSpec) of JWST, a MEMS-based programmable microshutter array has been developed and fabricated by NASA [1]. During the early-phase studies of the European Space Agency (ESA) EUCLID mission, a MOS instrument based on a MOEMS device has been studied using the capabilities of the largest Digital Micromirror Device (DMD) from Texas Instruments in a space environment [2].

By placing the programmable slit mask in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from other objects and from the sky background is blocked. For example, a MOEMS-based MOS concept where the programmable slit mask is a MMA is shown in Fig. 1. In action, the micro-mirrors in the ON position direct the light toward the spectrograph, while the micro-mirrors in the OFF position are directing the beam back to sky.

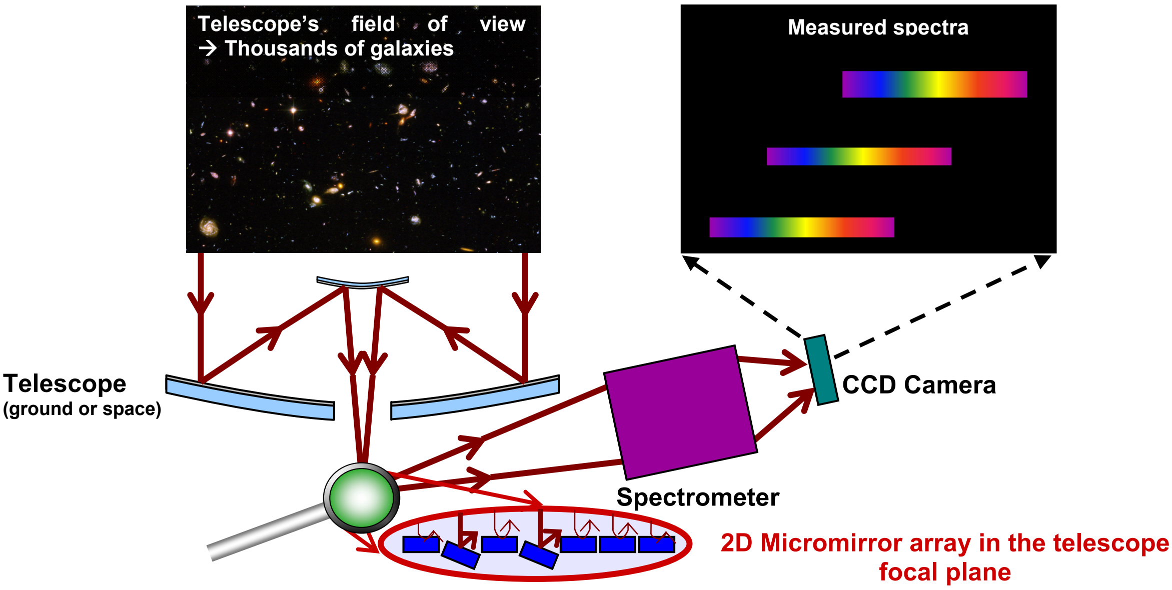

Figure 1: Multi-object spectroscopy requires a slit mask, for object selection, in the focal plane of the telescope.
Object selection avoids overlapping of spectra and remove background signal.

In Europe, collaboration within Laboratoire d'Astrophysique de Marseille (LAM) and Ecole Polytechnique Fédérale de Lausanne (EPFL) has for purpose to develop a European programmable micromirror array (MMA), called **MIRA** [3]. The requirements were determined from previous simulation results and measurements [4]. It has to achieve a high optical contrast of 1000:1 (goal: 3000:1), a fill factor of more than 90 % and a mechanical tilt angle greater than 20°. Furthermore, the mirror surface must remain flat in operation throughout a large temperature range and it has to work at cryogenic temperature.

In this paper, devices composed of 32 x 64 micromirrors are presented. These MMA were characterized optically and in a cryogenic environment. Surface deformation is measured both at room and cryogenic temperatures.

2. CONCEPT

The micromirror is based on the electrostatic double plate actuator. A micromirror is suspended by two polysilicon flexion hinges, which are attached to a sustaining frame (Fig. 2). To generate an electrostatic force, an electrode is placed underneath the micromirror and pillars are placed to set a precise electrostatic gap. A stopper beam is placed under the frame to set precisely the tilt angle of the micromirror after actuation. Finally, two landing beams are placed under the micromirror to avoid the micromirror to touch the electrode and generate short-circuits during the actuation.

When a voltage higher than the pull-in voltage is applied on the electrode, the micromirror is attracted by an electrostatic force towards the electrode. During this motion, it touches its stopper beam (Fig. 2b) and lands on its landing pads. Therefore, after pull-in, the micromirror is electrostatically clamped at a precise tilt angle (Fig. 2c). When the voltage is decreased, the micromirror takes off from its stopper beam. When the restoring force of the flexure beams is higher than the electrostatic force the micromirror returns in its rest position.

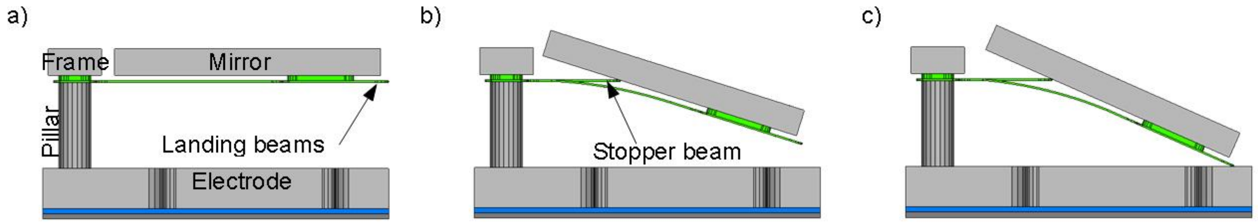

Figure 2: When a voltage is applied on the electrode, the micromirror is attracted towards its electrode by the action of an electrostatic force. During this motion, the mirror touches its stopper beam (b) and at the end of the motion, it is clamped at a precise tilt angle thanks to its contacts with its stopper beam and its landing pads (c).

The micromirrors are addressed of two different ways: line by line or individually. For line addressing, each line of micromirrors are directly connected to the electronics. On the other hand, for individual addressing due to the limited space available, it is not possible to connect each micromirror by an electrical connection. Therefore, individual addressing is implemented based on a line-column algorithm using the property of the tilt angle/voltage hysteresis [5].

3. FABRICATION

Our MMA were microfabricated using bulk, surface micromachining and wafer level bonding. They were made of three wafers: two for the mirrors and one for the electrodes, which were processed separately and assembled by wafer level bonding at the end of the process (Figure 3). A detailed description of the process was provided in reference [5].

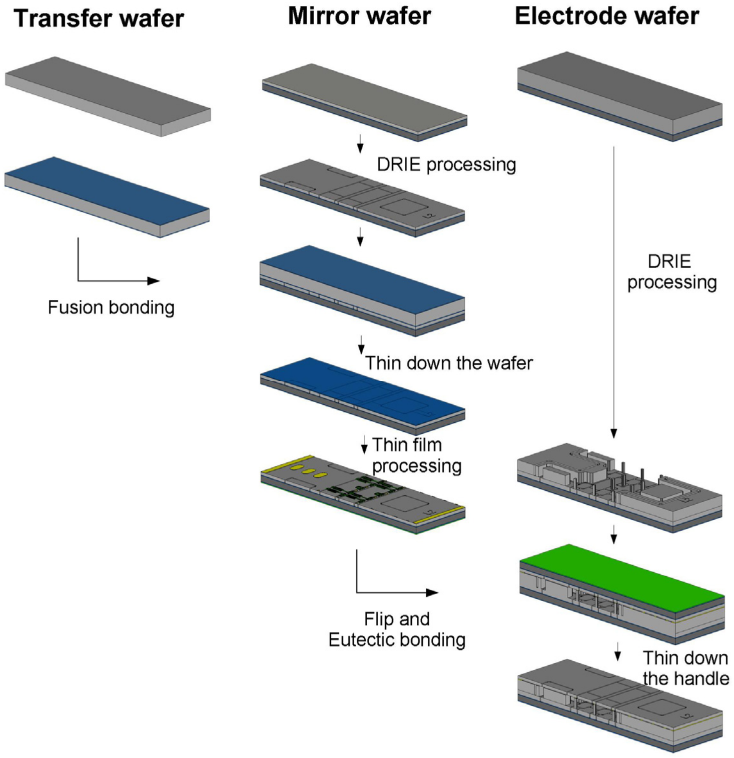

Figure 3: Fabrication process of the MMA involved three wafers and two wafer-level bonds. An oxidized transfer wafer was fusion bonded on top of the trenches of the mirror wafer. The transfer wafer was completely etched by grinding and KOH etching. The polysilicon beams and the gold pads were then patterned on the mirror wafer. Finally, the mirror wafer was bonded by Au-Si eutectic bonding on the DRIE-processed electrode wafer and the handle layer and the BOX of the mirror wafer were completely etched. The parts in grey represented the silicon parts, blue represented the silicon dioxide parts, green represented the polysilicon parts and yellow represented the gold parts.

The trenches surrounding the micromirrors were etched by DRIE in the device layer of the SOI wafer. These trenches were then covered by a 2 µm-thick layer of silicon dioxide by fusion bonding and thinning techniques. For the anchors of the beams, the silicon dioxide layer was etched by RIE. A polysilicon layer was deposited and patterned on the silicon dioxide layer to form the beams. The silicon dioxide layer was thinned down, patterned by RIE and a gold layer was deposited by lift-off technique. Finally, the silicon dioxide layer was completely etched.

For the electrode part, the two levels required on the surface (i.e. pillars and electrodes) were processed by DRIE delay mask process using a mask of silicon dioxide and a mask of photoresist.

The mirror part and the electrode part were then bonded by Au-Si eutectic bonding and the wafer stack was diced. The handle layer of the mirror wafer was then grinded at chip-level. The remaining silicon layer was patterned by honeycomb structures avoiding the bond between the pillars and the micromirror frame to break due to the stress generated by the BOX of the mirror wafer. Finally, the honeycomb structures were removed and the mirrors released by etching the BOX in HF vapor phase etcher.

The 100 x 200 μm^2 micromirrors, made of single-crystal silicon, assuring optical flat surfaces, and coated with a gold thin-film are shown in Figure 4. After optimization of the process, fabrication of MMA was fully successful: no broken mirrors were observed. Moreover, this scalable process using wafer-level bonding was designed to make even larger arrays.

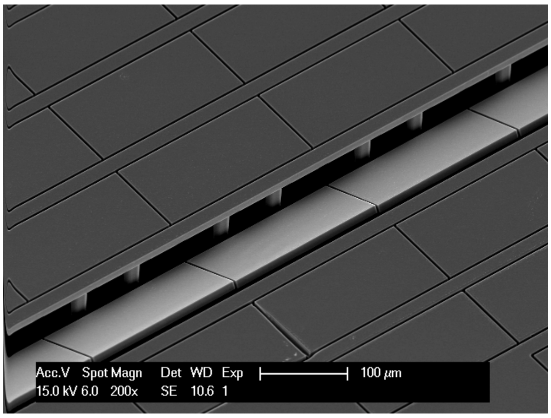

Figure 4: 64 x 32 micromirror array with high fill factor in the vertical direction providing long slits.
Each mirror measures 200 x 100 μm^2.Wafer level bonding steps are required to process these arrays.

Large arrays of 2048 individually addressable micromirrors (64 x 32 mirrors) have been successfully realized and packaged in a Pin Grid Array (PGA) (Fig. 5).

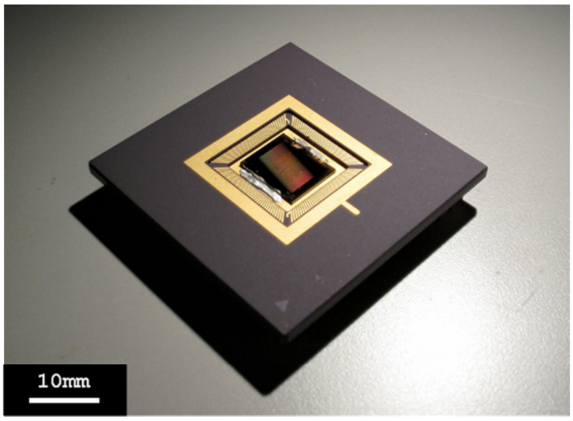

Figure 5: Micromirror array packaged in a Pin Grid Array (PGA).

4. CHARACTERIZATION

The MMA were then characterized electromechanically, optically and in a cryogenic chamber, on bench set-ups dedicated to the characterization of MOEMS devices at LAM.

4.1 Electromechanical characterization

A tilt angle of 24° was measured for an actuation voltage of 130V. Our locking mechanism has been demonstrated and a performance of a few arc-minutes angle difference has been obtained on first prototypes. The fill factor characterized by SEM was 82.3% for the mirror surface and 98% in the direction along the micromirror lines.

Individual addressing of the mirrors is based on a line-column scheme: as a proof of concept, a 2 x 2 sub-part of a MMA of 32 x 64 micromirrors was actuated successfully. [5]

4;2 Contrast measurement

The contrast is the amount of non-selected flux from sky background and bright sources passing through the multi-slit device. The *effective contrast* is the contrast "seen" by the instrument and it has to be measured on elementary MMA mirrors [4]. The contrast of our array was characterized on a dedicated optical bench at LAM. A light source having a diameter of 200 µm has been focused on a micromirror (Fig. 6, top). Two pictures were recorded: for a micromirror at rest (OFF state) and for a micromirror tilted (ON state), see in Fig. 6 bottom. The light intensity of each picture was integrated over the micromirror surface and the ratio between the pictures provided the contrast. **Finally, for a micromirror tilting by 25°, a contrast ratio of 1000:1 was obtained.**

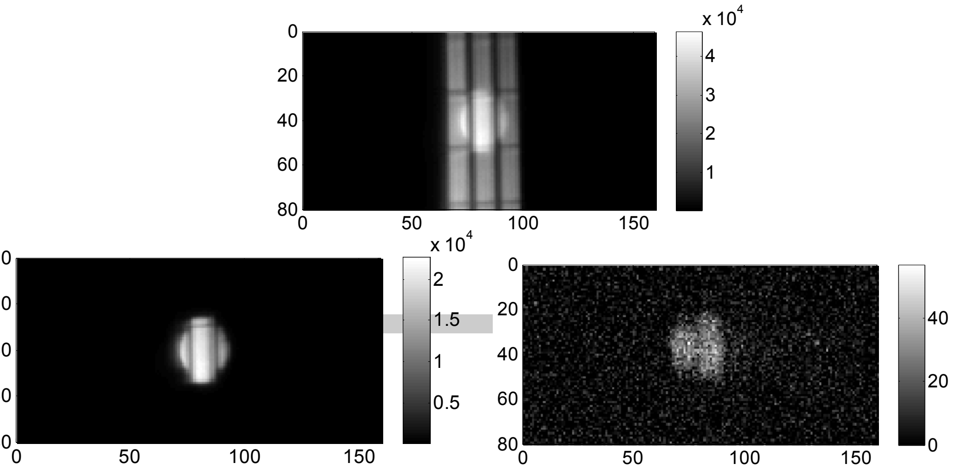

Figure 6: Contrast measurement (top: spot on MMA; bottom: ON and OFF states, displayed on different scales)

A contrast of 1000:1 is large enough for objects and background rejection in the MOS field of view. However, this contrast could be increased in future versions of our array by decreasing the gap around the mirrors and by providing a black coating on the electrodes.

4.3 Surface deformation

To increase the reflectivity for IR application, the silicon micromirrors were coated with gold. Since the micromirror deformation had to be as low as possible at room temperature and at cryogenic temperature, a study was undertaken to determine the coating inducing the smallest Peak-To-Valley (PTV) deformation. Two adhesion layers (Ti and Cr) for the gold layer were investigated. The micromirrors were measured by phase shift interferometry. For the first sample set, 30 silicon micromirrors of 10 x 100 x 200 μm^3 were measured without coating. Then, a coating of 10 nm of Ti and of 50 nm of Au was deposited on a single face of the mirror and the samples were measured. Finally, the surface deformation induced by an adhesion layer of Cr was measured on other micromirrors coated with 10 nm of Cr and of 50 nm of Au.

The silicon micromirrors without coating demonstrated a PTV deformation of 5 nm (mean value). For an adhesion layer of Ti, a PTV deformation of 9.8 nm was obtained and of 11.9 nm for Cr. Therefore, using Ti rather than Cr as an adhesion layer demonstrated a little less of stress.

With a PTV surface deformation of 9.8 nm, with 1nm roughness, these micromirrors demonstrated an excellent quality and although the deformation may increase at cryogenic temperature, it should stay within the limit of 50 nm.

4.4 Cryogenic experiment

In order, to avoid spoiling of the astronomical objects spectra by thermal emission of the instrument, the array has to work in a cryogenic environment. Our MMA is conceived such that all structural elements have a matched CTE in order to avoid deformation within the device when cooling down to the operating temperature.

For characterising the surface quality and the performance of our MMA's at low temperature, we have developed a cryo chamber optically coupled to a high-resolution Twyman-Green interferometer [6]. The interferometer provides a sub-nanometer accuracy, and the cryo-chamber allows pressure down to 10^{-6} mbar and cryogenic temperatures (Fig. 7). In order to get such temperature, the chamber is equipped with an internal screen insulating radiatively the sample from the chamber. Control of the environment is obtained by means of temperature sensors and local heaters. They are wired to the outside environment through a Dutch connector and connected to a custom built control electronics. [7]

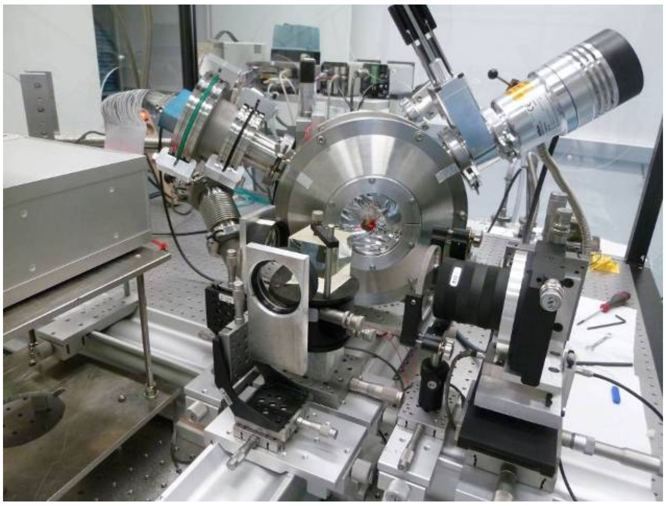

Figure 7: Cryogenic chamber installed on our interferometric setup for characterizing our MMA in space environment. Micromirrors could be successfully actuated before, during and after cryogenic cooling at 162K.

The MMA device is packaged in PGA chip carrier. The PGA is inserted in a ZIF-holder integrated on a PCB board. Large copper surfaces on the PCB facilitate cooling down the system; renouncing the solder-stop layer eases outgassing of the PCB FR4 base material during evacuation of the chamber. The PCB itself is mounted via a fix-point-plane-plane attachment system to a solid aluminum block, the latter being interconnected to the cryo-generator. Thick copper wires between the PCB and the aluminum block further enhance thermal transport between the sample chip and the cryostat. A 100-pins feed-through connector links the chip with a custom built MMA control electronics. Temperature sensors are connected to the aluminum block and to the grid zip connector adjacent to the sample chip.

The micromirrors could be successfully actuated before, during and after cryogenic cooling at 162K. In Fig. 8, micromirrors are tilted when 130V is applied both at room temperature and at 162K. However, this voltage is not large enough for tilting all mirrors; at 148V, an additional mirror could be tilted (Fig. 7d). this effect is due to a combination of a low doping level in the flexion hinges supporting the mirrors and a decrease of carriers speed at low temperature.

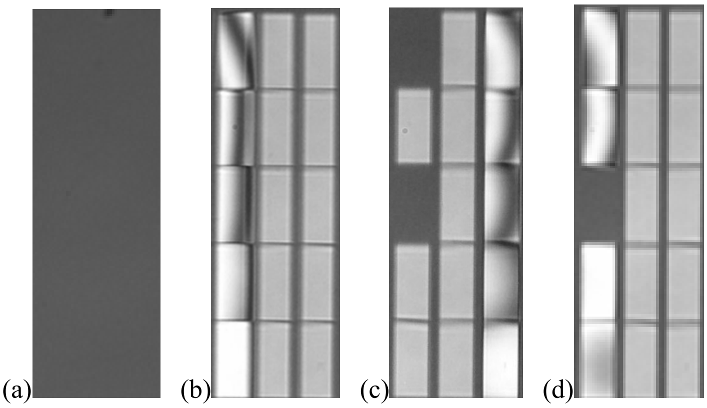

Figure 8: Interferometric observations of the lines of micromirrors during the cryogenic experiment at 162K: (a) micromirrors in OFF state at room temperature (RT); (b) micromirrors in ON state at RT, 130V applied; (c) micromirrors in ON state at 162K, 130V applied; (d) micromirrors in ON state at 162K, 148V applied;

We could measure the surface quality of the gold coated micromirrors at room temperature and at 162 K without large deformation difference. Thanks to the use of a reference plate in the reference arm of the interferometer, identical to the chamber window, we could get a high contrast in our measurements. Interference fringes are clearly visible on the first and last column of actuated mirrors in Fig. 8, and we could then measure the mirror surface deformation when the device was actuated at room temperature and at cryogenic temperature.

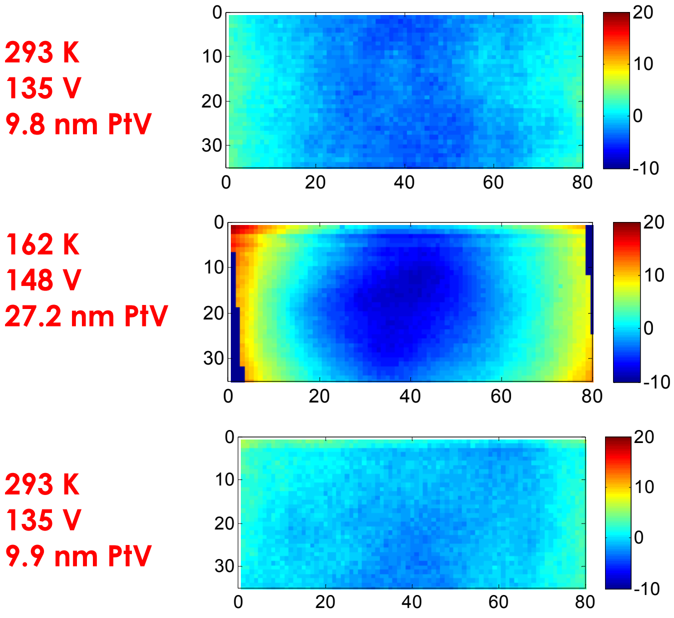

Figure 9: Surface quality of the gold coated micromirrors in actuation, at room temperature before cooling, at 162 K, and at room temperature after cooling. Deformation from 10 nm to 30 nm Peak-to-Valley is measured.

A 9.8nm PTV surface deformation was measured at 293K, increasing up to 27.2nm PTV at 162K. When coming back at room temperature, we measured again the mirror surface deformation and obtained a value of 9.9nm PTV, identical to the value measured before cooling of the array (Fig. 9). The deformation is due to the CTE mismatch between the thick silicon micromirror and the thin gold coating layer on top. However, the surface deformation stays within the limit of 50 nm.

5. CONCLUSION

Micromirror arrays for generating reflective slit masks in future MOS, called MIRA, were developed. Devices with 32 x 64 tilting 100 x 200 µm^2 micromirrors were successfully fabricated using three wafers and two wafer-level bonding steps (eutectic and fusion bonding). No broken micromirrors were observed on the final devices demonstrating the quality of the fabrication process.

The MMA were then characterized electromechanically, optically and in a cryogenic chamber. A tilt angle of 24° was measured for an actuation voltage of 130V. The fill factor characterized by SEM was 82.3% for the mirror surface and 98% in the direction along the micromirror lines. The contrast ratio between the rest and tilted state of the micromirror was 1000:1. The micromirrors coated with 10 nm of Ti and of 50 nm of Au showed a PTV surface deformation at room temperature of 9.8 nm. Several lines of 32 micromirrors were successfully tilted at a temperature of 162K. The micromirror surface deformation was measured at cryo and is as low as 27 nm PTV.

MIRA prototype demonstrates the ability of such MOEMS device to work as objects selector in future generation of MOS instruments both in ground-based and space telescopes. In order to fill large focal planes (mosaicing of several chips), we are currently developing large micromirror arrays integrated with their electronics.

Acknowledgement

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