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## Microfabrication of Optically Flat Silicon Micro-Mirrors for Fully Programmable Micro-Diffraction Gratings

B. Timotijevic<sup>a</sup>, R. Lockhart<sup>b</sup>, R. Stanley<sup>a</sup>, M. Luetzelschwab<sup>a</sup>, F. Zamkotsian<sup>c</sup>,  
P. Lanzoni<sup>c</sup>, W. Noell<sup>b</sup>, M. Canonica<sup>d</sup>, M. Tormen<sup>a</sup>

<sup>a</sup>Centre Suisse d'Electronique et de Microtechnique, Rue Jaquet-Droz 1, 2002 Neuchatel, Switzerland

<sup>b</sup>Ecole Polytechnique Federale de Lausanne – Neuchatel, Rue Jaquet-Droz 1, 2002 Neuchatel,

<sup>c</sup>Laboratoire d'Astrophysique de Marseille, 38 rue Frederic Joliot-Curie, 13388, Marseille Cedex 13, France

<sup>d</sup>Massachusetts Institute of Technology, 77 Massachusetts Avenue, RM 41-317, Cambridge, Massachusetts, USA

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### Abstract

We have fabricated and characterized a Fully Programmable Micro-Diffraction Grating (FPMDG) with 64 silicon micro-mirrors for spectral shaping in the visible and near-infrared wavelength range. The FPMDG arrays of 50  $\mu\text{m}$  and 80  $\mu\text{m}$  wide and 700  $\mu\text{m}$  long silicon micro-mirrors have been fabricated in a process based on anodic bonding of an 8 $\mu\text{m}$ -SOI wafer and a borosilicate glass wafer. The detrimental bending of the micro-mirrors during electrostatic actuation has been minimized through separation of the mechanical and optical sections of the device. Flexures incorporating serpentine structures have been used to reduce the actuation dependence on length and thickness. Independent addressing of the micro-mirrors with negligible cross-talk and with bending of the micro-mirrors smaller than 0.14  $\mu\text{m}$  over 700  $\mu\text{m}$  have been demonstrated.

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*Keywords:* micro-mirror; diffraction grating; optical MEMS; microfabrication

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### 1. Introduction

FPMDGs are used for spectra shaping devices in the visible and near infrared. They can be used for imaging spectrometers and several space missions may require FPMDGs, which operate from the visible to the IR. For IR operation, the micro-mirrors need to move by at least 1 micron. To be efficient, the mirrors need to stay flat. For imaging applications the mirrors need to be long (~1mm). These three constraints make the design and fabrication of FPMDG's challenging. In this paper we present the

microfabrication process for FPMDGs chips containing long and flat micro-mirrors, which can vertically move up to  $1.25\mu\text{m}$ .

## 2. Mechanical design

The FPMDG chip contains 64 micro-mirrors which are actuated electrostatically. Rigid Si micro-mirrors are connected to the centre of the compliant mechanical flexures via linkage arms, as illustrated in Fig. 1. To actuate a micro-mirror voltage is applied between the flexures at either micro-mirror end and the underlying electrodes. The electrostatic force from the potential pulls the flexures towards the substrate. The micro-mirror and its underlying electrode are both at ground to eliminate any attraction between the mirror and the substrate. The mechanical coupling between the optical micro-mirror and the mechanical flexures via the linkage arms permits the micro-mirror to follow the pure vertical displacement of the central point of the flexures, reducing the micro-mirror bending throughout actuation.

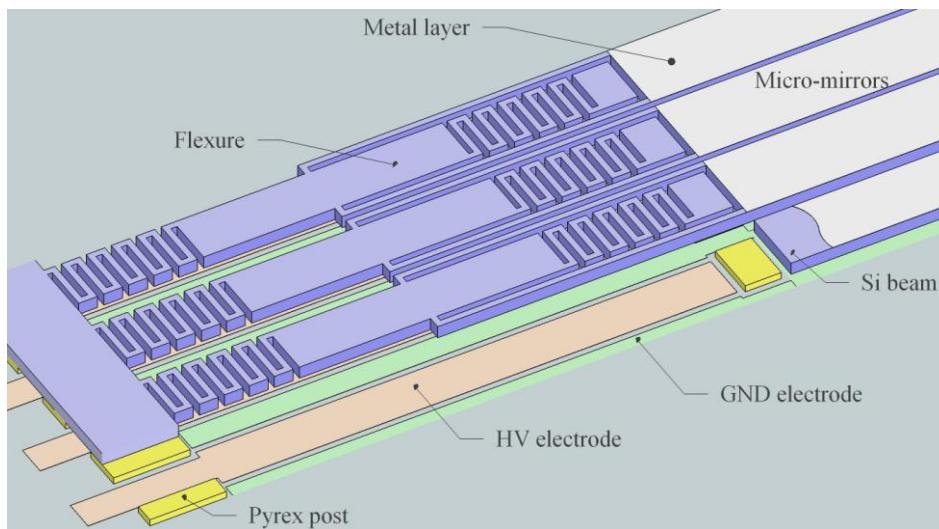


Fig. 1. FPMDG design: 4 micro-mirrors with the corresponding straight-winding flexures and electrodes on one side.

Serpentine flexures are used instead of straight beams to reduce flexure length and increase device layer thickness for the same required actuation voltage. The use of ground electrodes between the high voltage electrodes further limits bending of the micro-mirrors during actuation, thus, distortion of the micro-mirrors is mainly governed by the post-fabrication residual stress.

## 3. Microfabrication

Microfabrication is based on 4 photolithography masks. They are used to process an SOI wafer, the device layer of which is used to pattern the micro-mirrors, and a Pyrex wafer, which is used as a chip support with electrodes.

The process begins with a borosilicate glass wafer (Pyrex 7740), which is etched using a metal hard mask in an inductively coupled plasma reactive ion etcher (ICP-RIE). After etching, the metal mask is removed and electrodes are patterned in the Pyrex trenches using a lift-off procedure. Electrodes consisting of Cr/Pt (10/90 nm) are deposited with e-Beam evaporation.

Anodic bonding is used to transfer the device layer (thickness 8  $\mu\text{m}$ ) of an SOI wafer to the pre-patterned Pyrex wafer. The device layer of the SOI wafer is placed directly on top of the pre-patterned Pyrex wafer. The wafers are placed in a chamber at atmospheric pressure and the temperature is raised to 350°C. A negative electrode contacts the backside of the Pyrex wafer and a positive electrode contacts the centre of the backside of the SOI wafer. A high voltage (700-1200 V) is applied across the wafers driving the positively charged sodium ions towards the cathode and leaving a space charge at the bonding interface. The oxygen diffuses into the silicon to form a solid bond between the two wafers. Once the current flowing through the wafers has decayed back to zero, bonding is complete and the temperature is lowered back to ambient.

The bonded stack is then placed in a bath of potassium hydroxide (KOH) in order to remove the handle of the SOI wafer. Etching of the handle is stopped before arriving at the insulating oxide layer. The thin oxide layer provides an etch stop for the Si handle removal in KOH; however, small pinholes in the thermally grown oxide can allow small amounts of KOH to breach this masking layer causing damage to the silicon device layer. To prevent the damage to the Si device layer, the remaining 20-40  $\mu\text{m}$  of the handle layer is removed using reactive ion etching (RIE).

A final photolithography is done to pattern the micro-mirrors into the device layer of the Si/Pyrex stack. Etching is again performed by RIE using photoresist as a masking layer. The resist is then removed in oxygen plasma. From this step onward, it is crucial to avoid 'wet' steps since the micro-mirrors have already been liberated as a result of the final RIE.

Coating the liberated devices in Parylene C, a polymer deposited at room temperature in a vapor deposition chamber, secures the beams for dicing. The Parylene layer can be subsequently removed via oxygen plasma, liberating the device for final use. Fig. 2 is an example of the fabricated FPMDG with 50  $\mu\text{m}$  wide micro-mirrors.

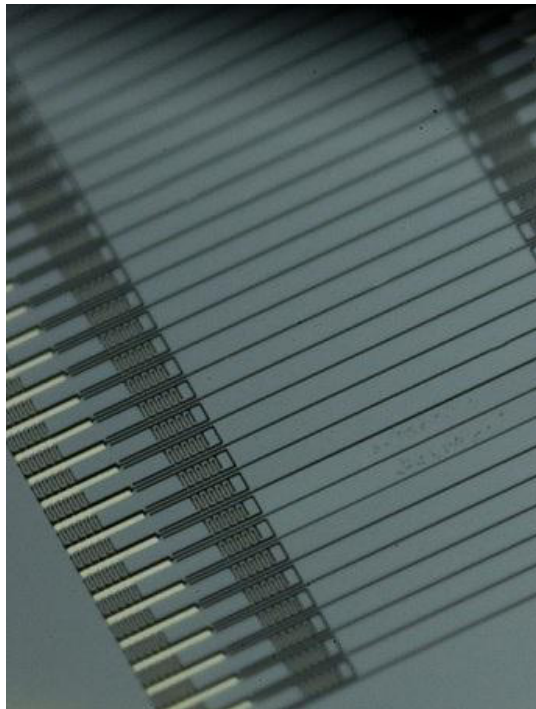


Fig. 2. An image of the fabricated FPMDG with 50  $\mu\text{m}$  wide micro-mirrors and serpentine flexures.

#### 4. Electro-mechanical tests

Electro-mechanical characterization is performed with a white light interferometer (WYKO®) after liberation to inspect the micro-mirror bending and its behaviour throughout actuation. Low bending is crucial for the optical performance of the FPMDG and it is typically required to be smaller than  $\lambda/10$ ,  $\lambda$  being a wavelength. Micro-mirror bowing has been measured on non-biased elements and a typical value of only  $0.12\mu\text{m}$  has been measured over the  $700\mu\text{m}$  total length of the micro-mirrors (Fig. 3). When actuated (displacements up to  $1.25\mu\text{m}$ ), micro-mirror bowing changes insignificantly, less than  $20\text{nm}$ . The cross-talk between the micro-mirrors has not been observed for any actuation voltage. The wirebonded FPMDGs are preliminary tested on the dedicated optical bench [2] and the extinction ratios up to 100 are achieved in the reflected spectrum by adjusting only 3 adjacent micro-mirrors.

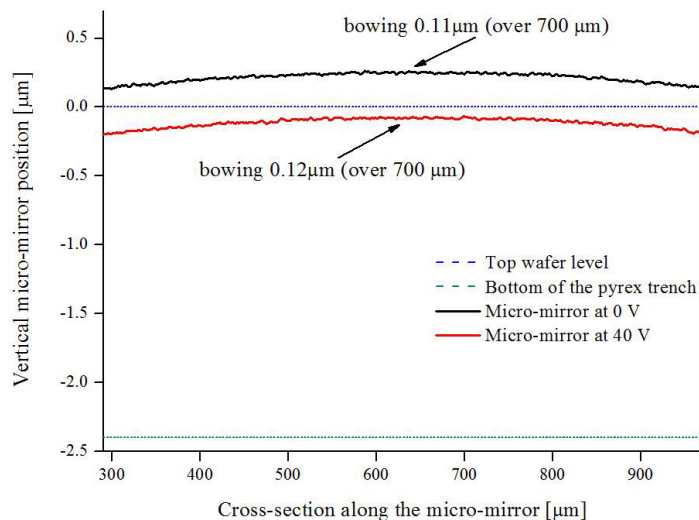


Fig. 3. Cross-section of the non-actuated and actuated FPMDG micro-mirror. Bending negligible and equal in both cases

Displacements up to  $1.25\mu\text{m}$ , negligible bending and independent addressing of the micro-mirrors make the fabricated FPMDGs very good candidates for spectra generators up to  $2.5\mu\text{m}$ .

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