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Segmented Deformable Micro-Mirror for Free-Space Optical Communication

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Abstract— **In this paper we describe a fabrication process for adaptive optics mirrors based on bonding of MEMS structures to electrode chips. This approach allows scaling to large mirror arrays for free-space communication. We demonstrate the process by fabricating pixelated 4 by 4 arrays of micro-mirrors with 1 μm displacement at 200 V actuation voltage.**

I. INTRODUCTION

Free-space optical communications over long distances, e.g. earth to space links, require systems that are able to adapt to changing atmospheric conditions. Adaptive optics (AO), originally developed to correct for atmospheric aberrations in astronomical applications, is well suited for free-space communication, but conventional adaptive mirrors are complex, large in size and expensive [1]. Recently, micro-electro-mechanical deformable mirrors (MEM-DM) have been developed to enable compact and inexpensive adaptive optics mirrors with large numbers of degrees of freedom. Continuous mirrors backed by arrays of actuators have been demonstrated to be particularly well suited for high power laser applications [2] thanks to their good surface quality and good reflectivity. These properties also make them suitable for optical fiber switching applications [3].

Segmented mirrors have speed advantages, due to their small pixel size, and are therefore particularly well suited for high-bandwidth optical free-space communication. MEMS technology enables large micro-mirror arrays (> 1000 x 1000 pixels) that are necessary for the most challenging applications. The operation of such arrays requires integrated electronics for multiplexing and storage. Our approach to the integration challenge is to fabricate the mirror array separately from the electronics, and to bond the two together in a final fabrication step. This approach has been previously demonstrated, using flip-chip bonding and HF oxide release [4]. Here, we describe a process that uses gold compression bonding of the MEMS and electronics and a combination of XeF_2 dry etch of silicon and HF etch of SiO_2 to release the mirror arrays with minimal mechanical and chemical exposure. The feasibility of the process is demonstrated by fabricating AO mirrors with high fill-factor using chips fabricated in a commercial MEMS foundry (MUMPS®)

II. FABRICATION OF BONDED SEGMENTED MIRRORS

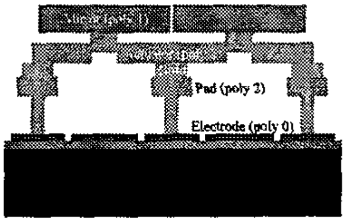

Fig. 1. Schematic cross-section view of 2 pixels showing the layer stack. The vertical scale is 10 times exaggerated.

Figure 1 shows a schematic cross-section of the bonded mirror structure. The mirror is structured in poly 1 and the actuator in poly 2. They are separated by a 750 nm thick oxide layer, which will be limiting the displacement of the mirror. Gold bond pads are deposited on the actuator layer. The mirrors and actuators are made of polysilicon, and are connected so that the complete array is at the same electrical potential. In our first demonstrations, we also used MUMPS to fabricate the electrode chip, i.e. the electrode chip is passive and without circuitry. The electrodes are made in the poly 0 layer and bond pads in poly 0, poly 2 and gold. Figure 2 a) shows the two chips before bonding. The mirror chip is turned upside-down and mechanically bonded to the electrode chip by gold compression bonding. The mirror array is electrically connected to a ground electrode by the bonding pads. A pressure of 100 MPa and a temperature of 300°C is applied using

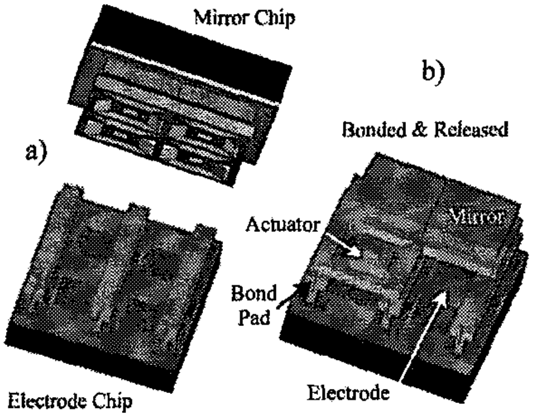

Fig. 2. Schematic 3D drawing of the electrode chip and the mirror chip, a) before and b) after bonding. The vertical scale is 10 times exaggerated.

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a commercial flip-chip bonder. The final bonded stack of layers provides a 5.25 μm spacing between the electrodes and the actuator. Figure 2 b) shows the two chips bonded together. The release of the devices is very critical because the top substrate exerts large mechanical forces on the mirrors and actuators during and just after completion of the release etch. The release is further complicated by the fact that the etch holes, commonly used to speed up the release etch, cannot be used here because they would create unacceptable mirror distortions. To solve these problems, we etch away the top substrate using a dry etch (XeF_2). The oxide layers are then sacrificially etched in 49% HF, and the released chips are rinsed in DI water. In order to prevent device failure caused by sticking, we dry the devices using Critical Point Drying (CPD) with liquid CO_2. Figure 3 is an optical microscope photograph of a released array. Figure 4 is a SEM photograph of one pixel, showing the mirror, the actuator structure, the electrode and one bonding pad. Part of the mirror is broken off to show the underlying actuator and electrode structure.

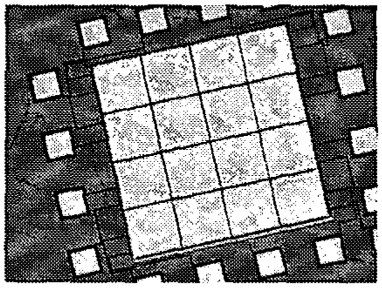

Fig. 3. Optical microscope photograph of a released array. Each pixel is 200 μm x 200 μm.

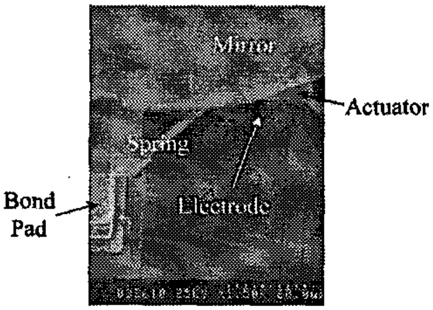

Fig. 4. SEM photograph of the structure of a single pixel, showing top-down: the mirror, the actuator and the electrode layers.

III. MEASURED CHARACTERISTICS OF SEGMENTED MIRRORS

We fabricated arrays with pixel sizes ranging from 100 μm x 100 μm to 400 μm x 400 μm. The radius of curvature of the individual micro-mirrors was measured to be 5 cm in the worst case, and the surface roughness was 40 nm. The fabricated arrays were electrostatically actuated. Figure 5 shows the measured and calculated displacement of a single pixel versus applied voltage on the electrode. The calculated voltage is given by

$$V(x) = (d-x)\sqrt{\frac{2kx}{\epsilon_0 A}}, \tag{1}$$

where d is the distance between the electrode and the actuator, x is the displacement, ϵ_0 is the permittivity of free space, A is the area of the actuator, and k is the spring constant. The spring constant was calculated to be 489 N/m. In Fig. 5, the spring constant was adjusted to 388 N/m, which is 0.8 times smaller than the calculated one. This discrepancy is assumed to be due to differences in the design values and the actual dimensions of the fabricated devices.

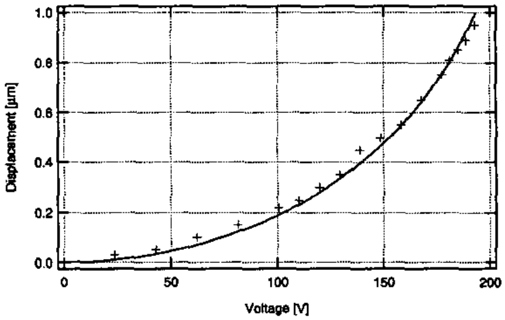

Fig. 5. Measured (crosses) and calculated (plane trace) displacement versus voltage of a single pixel.

IV. CONCLUSION

We developed a bonding and release process for segmented mirrors, which allows separate optimization and fabrication of the MEMS and electrode chips. The motivation for this separation is to be able to scale the devices to large arrays (> 1000 x 1000 pixels) with integrated electronics. We fabricated a segmented mirror, which showed 1 μm displacement for 200 V. We measured the radius of curvature of individual polysilicon micro-mirrors of the array to be down to 5 cm, with a surface roughness of 40 nm. The mirror quality can be substantially improved by using single-crystalline, rather than poly-crystalline, micromirrors.

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