

MIRROR ARRAYS FOR LASER BEAM DEFLECTION

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Design and technology of micro mirror arrays made of monocrystalline silicon are discussed in this paper as well as experimental results characterising the arrays. The technological approaches consist of the use of silicon wet- and dry-etching, wafer bonding (silicon fusion and anodic bonding) and metallization. A novel modified BESOI technology with CMP, wafer bonding with buried refractory metal electrodes and sacrificial layer etching has been developed and will be discussed. The design process is based on analytical calculations of the mechanical behaviour, the fluid flow surrounding the movable mirror and the electrostatic field as well as numerical simulations by means of the finite element method and network analysis. Furthermore, some experimental methods to characterise the electro-mechanical behaviour of micro mirror arrays are discussed. In order to evaluate theoretic models describing the behaviour, the natural frequencies, the damping coefficients and the frequency transfer function are measured.

1. INTRODUCTION

Various movable optical mirrors made of metal [1], polycrystalline silicon [2] or monocrystalline silicon [3] have been presented in the last years. Different mechanical materials for the hinges have been used like aluminium [1], chromium and gold [4], polysilicon [2] or monocrystalline silicon [3]. It has been reported that metal fatigue could occur when metal hinges were used [4]. Monocrystalline micromirrors should be a very

excellent mechanical properties of crystalline silicon.

According to some application ideas a laser beam of some millimetres diameter is to deflect. The moment of inertia is quadratically increased in relation to a quadratic surface area when enlarging the oving mirror surface. Fast movement is impossible. Therefore, a distribution of the mirror surface across a mirror array with small cells of high resonant frequency should be the solution in case of fast deflecting laser light.

2. DESIGN

Fundamentals

The simulation based design process is essentially to meet the application proposal with respect to manifold interactions between physical effects like elastomechanic forces, electric field coupling, and fluidmechanic influence within micromechanic devices. It is possible to take into consideration only a few of the cells when calculating the behaviour to prevent time consuming simulations of large arrays.

A mirror cell consists of a metal coated silicon mirror plate suspended by silicon torsion beams and two driving electrodes. The mirrors are tilted by the electric field in the electrode gap applying voltages between the electrodes and the mirror plate. The electrical force produces an additional translatory deflection of the mirror directed to the driving electrodes,

Equation (1) describes the model of a single mirror cell as a resonator with two degrees of freedom:

$$\begin{pmatrix} J & 0 \\ 0 & m \end{pmatrix} \begin{pmatrix} \frac{\partial^2 \alpha}{\partial t^2} \\ \frac{\partial^2 w}{\partial t^2} \end{pmatrix} + \begin{pmatrix} c_r & 0 \\ 0 & c_t \end{pmatrix} \begin{pmatrix} \frac{\partial \alpha}{\partial t} \\ \frac{\partial w}{\partial t} \end{pmatrix} + \begin{pmatrix} k_r & 0 \\ 0 & k_t \end{pmatrix} \begin{pmatrix} \alpha \\ w \end{pmatrix} = \begin{pmatrix} M_{el} \\ F_{el} \end{pmatrix}, \quad (1)$$

with the mass moment of inertia J , the mass m , the damping coefficient C_r and C_t and the driving electrostatic torque M_{el} and force F_{el} . Due to less mechanic coupling between the motions, the natural frequencies without damping are nearly given by

$$\omega_{or} = \sqrt{\frac{12 G_m I_t}{I_b I_m w_m^3 \text{th} \rho_{si}}}, \quad (2)$$

for rotatory

$$\omega_{ot} = \sqrt{\frac{12 EI}{I_b^3 I_m w_m \text{th} \rho_{si}}}, \quad (3)$$

for translatory motion without any electrostatic field, where the shear modulus is G_m , the torsion moment is I_t , the Youngs modulus is E and the area moment of inertia is I . The electric field of applied voltage U causes a displacement depending torque and decreases the elasticity k of the spring mass oscillators to

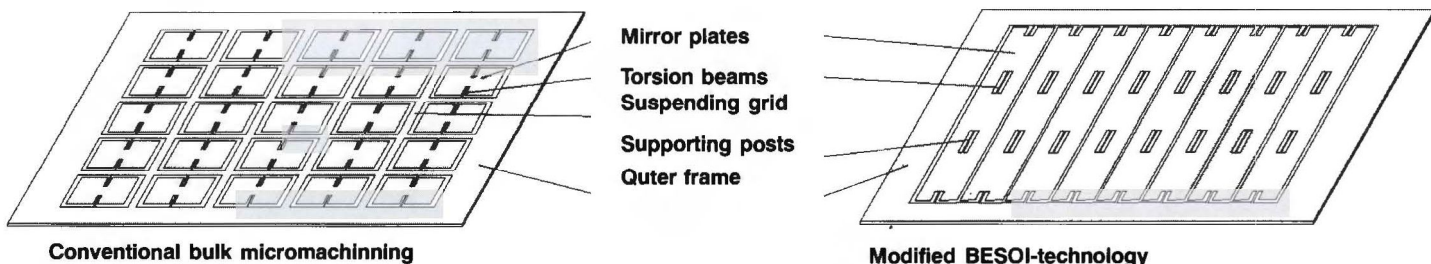


Fig. 1. Schematic view of the mechanically active part of the arrays in conventional bulk micromachining and in modified BESOI technology.

promising approach in the field of scanning actuators because of the well known

which is undesired in some cases. Fig. 1 shows a scheme of two array types, a bulk micromachined one and an array fabricated by using a modified BESOI technology,

$k^* = k - \frac{dC}{d\alpha} \frac{U^2}{2}$. The natural frequency is decreased as well. The electrostatic torque and force are to expressed by

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$$M_{el} = \frac{\epsilon U^2 l_m}{2} \left(\frac{1}{\alpha^2} \ln \frac{d}{w_m/2 \alpha + d} + \frac{w_m/2}{w_m/2 \alpha^2 + d\alpha} \right) \quad (4)$$

and

$$F_{el} = \frac{\epsilon U^2 w_m/2 l_m}{d \left(\frac{w_m/2}{\alpha + d} \right)}, \quad (5)$$

respectively with the tilt angle $\alpha \neq 0$. The angular deflection is of course limited by the mechanical properties but even stronger by an unstable working point caused by the electrostatic field.

FEM analysis

The mirror plates have a high aspect ratio. The width and the length are more than 100 times greater than the thickness. Therefore, the rigid body models are not adequate in this case. The electrostatic force causes a deformation of the mirror plate. It worsens the optical quality. Fig. 2 shows the deformation due to the electrostatic force and the deflection angle. A special suspension and linking of the mirrors to mirror strips reduce the deformation.

A new aspect is the interaction due to

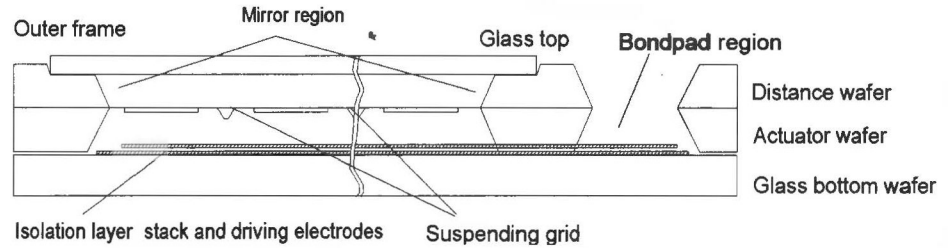


Fig. 4. Cross section of an array in conventional bulk micromachining.

the fluid flow. Fig. 3 shows a vertical view on the bulk micromachining mirror array across the torsion beams and the air flow. The air flow and the pressure below the mirror are calculated by the finite element method. Details are discussed in [5] and [6].

3. TECHNOLOGY

Conventional bulk micromachining technology

A 150 nm Si_3N_4 layer is deposited on the glass bottom wafer by using *Plasma Enhanced Chemical Vapour Deposition* (PE-CVD) in order to fabricate a barrier between the glass and the driving electrodes (1 μm aluminium), which are prepared on top of the nitride. Above these electrodes, a layer stack consisting of PE-CVD Si_3N_4 , PE-CVD

silicon dioxide (SiO_2) and PE-CVD Si_3N_4 insulates the structure against the air, since during the actuator operation a relatively high voltage is applied. The actuator wafer and the upper distance wafer are fabricated in silicon bulk micromachining using double side polished 4" silicon wafers. The silicon membranes situated in the actuator wafer and the frames between them are patterned by anisotropic etching with KOH using SiO_2 and Si_3N_4 as etch mask. The upper distance wafer is etched anisotropically in two steps in order to define spaces for the glass cover and the mirror clearance. *Silicon Fusion Bonding* (SFB) is used to connect the silicon wafers (distance and actuator wafer). A metal (aluminium or gold) is deposited on both sides of the wafer compound using sputter masks. This layer serves as a reflector on the

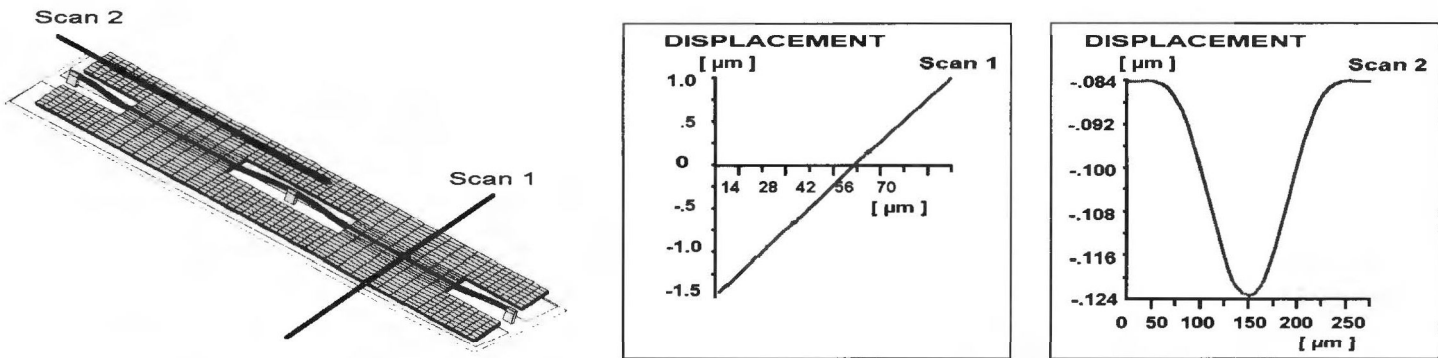


Fig. 2. Calculated mirror deformation, surface plot and line scans.

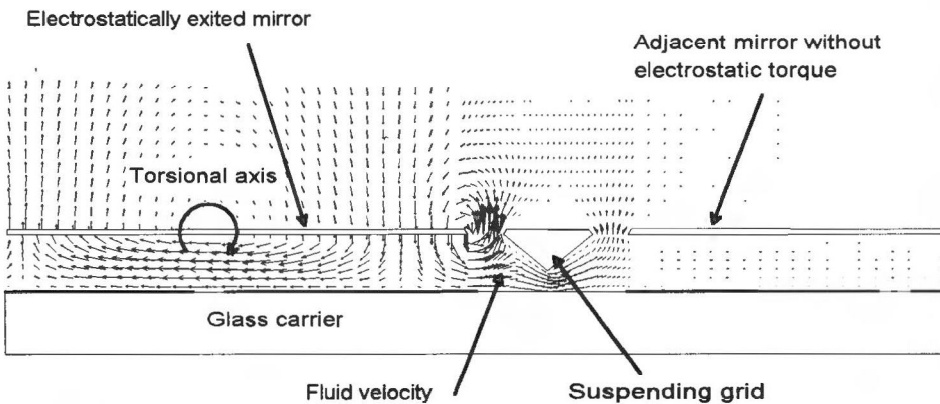


Fig. 3. Fluid velocity field surrounding a moving mirror plate.

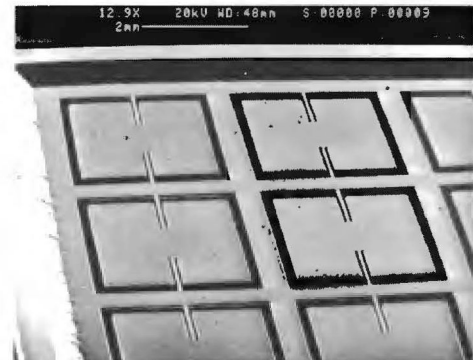


Fig. 5. Top view of a mirror array in conventional bulk micromechanics.

mirror front side and as a conducting and stress compensation layer on the mirror back side. The actuator wafer is attached to the glass bottom wafer by anodic bonding. Fig. 4 and Fig. 5 show a cross section of the array and a SEM-view respectively.

Modified BESOI technology for a micromirror array

Following a thermal oxidation and a deposition of CVD oxide the driving electrodes are brought on and were patterned on the carrier wafer. A further CVD oxide, deposited on this wafer and on an additional blank active wafer serves as sacrificial layer and silicon fusion bondable surface. Before silicon fusion bonding, the wafer containing electrodes must be polished in order to remove the in-oxide-transferred electrode topology. The active wafer is thinned town to 5 μm by KOH wet etching and polished by chemical mechanical polishing. After the coating of the surface with the reflection layer and protecting them, the mirrors are structured and released by plasma etching. A cross sectional view is to be seen in Fig. 6 and SEM-views of a part of the mirror and of a supporting post in Fig. 7. A more detailed discussion of the technology is to be find in [7].

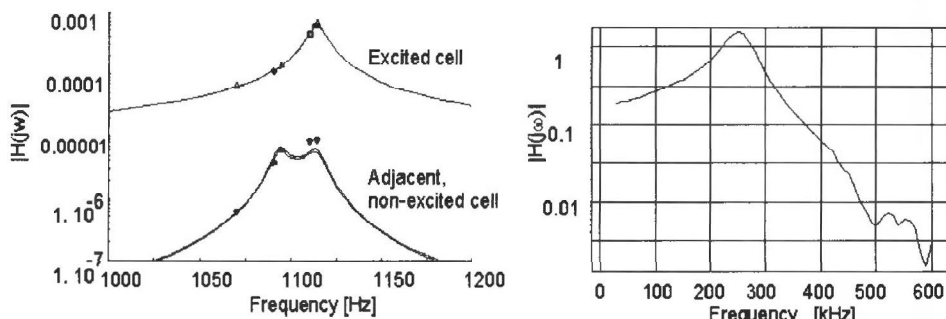


Fig. 8. Simulation of frequency response functions with adapted parameters, compared with measured values (marked) (left); measured frequency response function of an array cell in modified BESOI technology (right).

transfer rates at a frequency near the natural frequencies. The measurement of the mechanical reaction in a range of several nm up to 1 μm is necessary. A Doppler-interferometer is used to separate the rotation concerning the x- or y-axis and the out of plane motion.

Results

The differential equation

$$(-\omega^2 M + j\omega C + K)\phi = u_p F u , \quad (6)$$

describes the experimental model comprising two neighbouring mirror cells. The method of last squares is used adapting the parameter values. The experimental investigation determines very pre-

them at resonant frequencies. Square values of the inherent frequencies correspond to the eigenvalues of the homogeneous part of differential equation (6) without damping. The matrices M, C, K and F of eq. (6) may contain appropriate parameter values (e.g. the mass moments of inertia) and, of course, more discrepant values (e.g. all values of C). A correction algorithm with multiple steps is used. The residual eigenvalues are therefore used to adapt the erroneous part of the K- and M-matrices. Using residual frequency transfer function leads to appropriate values of C. The procedure is described in [7]. Fig. 8 shows the frequency response function of several array cells by using the method of parameter adaptation in order to improve the simulation accuracy and a frequency response function of a mirror array in modified BESOI-technology.

The natural frequencies of the mirror cells are 980 Hz (rotation about the x-axis) and 2.8 kHz (translation in z-direction) with a variation of 100 Hz across the array. The natural damping of the rotation is 0.05. The crosstalk-attenuation between adjacent mirror-cells is more then 26 dB. Angular displacements of about 18° are achievable operating with 700V ac at natural frequency and additional 700 V dc offset.

5. CONCLUSIONS

The design of mirror arrays is based on analytical and numerical calculations of models with parameterized elements and finite element method. The field interaction, like fluid flow and electrostatic field, are involved. It leads to different layouts depending on the technological process. The discussed bulk silicon technology results in mirror arrays with a frequency range up to 2 kHz. Furthermore, a novel modified BESOI-technology with

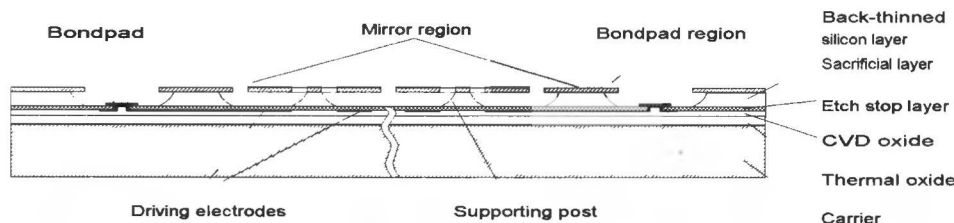


Fig. 6. Cross section of an array in modified BESOI-technology.



Fig. 7. Part of the mirror array in modified BESOI-technology.

4. CHARACTERISATION

Experimental method

Measurement of the frequency transfer functions leads to characteristic values: natural frequencies and damping, eigenfrequencies, dc transfer rates and

cisely natural frequencies of the structure and the damping coefficients. It is required to assign measured frequencies to different oscillation mode shapes. Vibration nodes are detected by observing amplitude and phase shift of the vibration measured at several locations of the structure when harmonically exciting

a back-thinned silicon wafer is discussed. So produced mirror arrays work with frequencies up to 200 kHz. It is demonstrated, that the BESOI-technology offers a promising approach producing high frequency analogue operating mirror elements.

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MICROBOT-BASED ASSEMBLY OF MICROSYSTEMS

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Robots have been a subject of research for almost half a century. In order to make robots more versatile they must be able to operate in a semi structured work place where unforeseen events occur and where sensor data are incomplete. An entire research community has been working on this problem and many unique autonomous and so-called intelligent robots have been conceived and built. Most of these efforts are concerned with robots that operate in the macroworld where they take on chores that could also be handled by humans. However, there is the microworld in which manipulation and handling tasks are very difficult and for which a human has no tools and where the work area is so small that fine manipulation is almost impossible by hand. This paper is concerned with autonomous robots that can operate in a microworld, where microassembly operations, microsurgery or integrated circuit testing and repair is done. As an example of

advanced microrobots, the design and functions of several autonomous microrobots of the University of Karlsruhe are shown; they employ different locomotion and object handling principles. The paper also includes a discussion of future research that has to be done to conceive and build efficient microrobot-based systems.

One of the main problems of today's microsystem technology (MST) is the assembly of a whole microsystem from different microcomponents. Most batch processes are rarely applicable for the production of complex microsystems which consist of microcomponents made of different materials and which are manufactured using different microtechniques. This means that individual components must be accurately assembled in one or more steps to form a desired microsystem. With increasing workpiece miniaturisation, however, it becomes more and more difficult to use conventional manipulation robots for assembling microsystems. The manipulation accuracy is mechanically limited for conventional robots, since disturbing in-

fluences which are often negligible in the macroworld, such as fabrication defects, friction, thermal expansion or computational errors, play an important part in the microworld. Furthermore, these robots are subject to mechanical wearing and must undergo regular maintenance, which makes them expensive. The next point is that the positioning accuracy and the tolerances of the microcomponents lie in the nm range, a few orders of magnitude smaller than in conventional assembly. These accuracy requirements can only be obtained with manipulators having highly precise direct drives. Teleoperated micromanipulation systems depend on the skill of the operator. Although the human hand is a very versatile instrument, and has an almost unsurpassed dexterity, it does not have unlimited abilities to manipulate and to assemble microsystems without suitable aids. So the further development of MST depends on the availability of flexible micromanipulation devices, which allow components to be automatically assembled, reducing production costs and si-