AN ELECTROSTATICALLY EXCITED 2D-MICRO-SCANNING-MIRROR WITH AN IN-PLANE CONFIGURATION OF THE DRIVING ELECTRODES

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ABSTRACT

A novel resonantly excited 2D-Micro-Scanning-Mirror is presented which makes use of an electrostatic driving principle allowing to locate the driving electrodes in the chip plane. The mechanical elements and the mirror plate consist of a 30 μm thick single crystal silicon layer. The mirror plate is suspended by a gimbal mounting and can therefore be deflected along two axes. It is shown that a special isolation technique is suitable to seperate the electrical potentials on the movable elements and therefore allows to excite the two oscillations independently. The isolation technique is based on the oxidation and polysilicon filling of 1 μm wide trenches in the 30 μm thick layer of silicon.

The influence of the surrounding gas on the coupling of the oscillations is examined. No significant influence is observed.

The performance of the novel 2D-Micro-Scanning-Mirror is demonstrated by the generation of various Lissajous patterns by the reflected laser beam. Frequency ratios of 1:1 up to 13:1 are obtained with the presented devices.

INTRODUCTION

Devices for two dimensional deflection of laser beams are used in applications like data capture (stacked barcode, matrix-code), object-identification and -measuring or imaging (display, marking).

In comparison to conventional scanners micromechanical scanners have the potential to achieve high scan frequencies, thereby generating only low acoustic noise and consuming low power. Further micromechanical scanners are suitable to miniaturize existing scanning systems and widening their application area.

Two dimensional scanning systems are either realized by a serial combination of two 1D-scanners with perpendicular scanning direction or by a gimbal mounting of the mirror to enable a deflection in x- and y-direction. In the first case an exact alignment of the incident laser beam is necessary to hit both mirrors. Furthermore, the deflection angle of the first mirror hit by the laser beam is limited by the finite distance to the second mirror and its size. Additionally, this distance is responsible for optical aberrations in the scanned image [1]. Such an arrangement has been used for the demonstration of a micro-mirror raster scanning display [2]. The limited resolution of this system (41 x 52 pixel) is attributed to the static and dynamic curvature of the mirrors.

A very promising approach for the fabrication of 2D-scanners is the use of a gimbal mounting for the mirror plate enabling both the deflection in x- and y-direction. In this case the alignment of the laser beam is as simple as in the 1D-case and the system is free of image distortions. However, most of the devices presented up to now suffer from the fact that the oscillation around the first axis influences the oscillation around the second axis. Especially, when the scanner is acuated electrostatically by driving electrodes placed under the mirror plate [3, 4] it is not possible to deflect the mirror in one direction independently of the perpendicular deflection direction.

An almost independent excitation and control has been realized by magnetic excitation [5]. The mirror is suspended by a gimbal mounting. Because the driving coils for the x- and y-deflection are connected in series the eigenfrequencies of the oscillations must have sufficient difference compared to the width of the resonance curve. However, the main disadvantage of this system in terms of miniaturization is the usage of permanent magnets and the complicated assembly.

These examples show that the realization of a 2D-suspended mirror with an independent excitation of the x- and y-deflection suffers from a suitable driving principle. In this paper a novel 2D-Micro-Scanning-Mirror is presented which makes use of an electrostatic driving principle with an electrode configuration in the chip-plane. This driving principle has already succesfully been demonstrated for the excitation of 1D-Scanning-Mirrors [6, 7] . With this it is possible to fabricate a 2D-suspended mirror where each deflection can be excited independently.

2D-SCANNER-PRINCIPLE

The 2D-Scanner chip is fabricated in a CMOS-compatible process using a SOI-wafer as base material. The movable elements are defined in the top layer of the SOI-wafer. The substrate and the buried oxide layer underneath the movable elements is removed to enable a deflection not restricted geometrically. A schematic view of the patterned top silicon layer of the 2D-Scanner chip is shown in Figure 1.

The mirror plate is suspended by two torsional springs inside a movable frame. This frame again is supended by two springs perpendicular to the direction of the mirrors springs. With this gimbal joint the mirror can be deflected two dimensionally.

The thickness of the heavily boron doped single crystal silicon top layer is 30 μm. In this layer not only the mechanical elements are defined but also the driving electrodes. The mirror plate and the movable frame are excited electrostatically. A more detailed description of the driving principle is given in [8] where its efficiency has been demonstrated on 1D-scanning-mirrors with eigenfrequencies in the range from 0.14 kHz up to 20 kHz.

The actuation principle makes use of a capacity variation during the oscillation. In the case of the mirror of the 2D-actuator this capacitance is formed by the vertical sides of the comblike electrodes of the mirror plate and the movable frame. With increasing deflection angle of the mirror plate the capacitance is decreasing. Applying a voltage between the electrodes an electrostatic torque is generated pulling the plate towards its rest position. Because of small asymmetries of the device which are due to the fabrication process the electrostatical and the mechanical rest position differ slightly.

If a dc-voltage of sufficient magnitude is applied the mirror plate is deflected by an angle of 0.1 mrad, typically. Therefore, an ac-voltage of suitable frequency excites the torsional oscillation of the mirror plate with an amplitude given by the resonance curve.

The movable frame is connected mechanically to the outer frame by two anchors (see Figure 1). These anchors are fixed to the frame only by the buried oxide layer of the SOI-wafer. Therefore, the movable frame and the mirror plate are electrically isolated from the outer frame. Each element, that is the mirror plate and the movable frame, has an eigenfrequency which is defined independently from the other by the width and the length of the respective torsional springs.

To enable an independent excitation of the two perpendicular oscillations filled trenches are used to seperate the different electrical potentials on the movable frame. This isolation technique allows to connect the two anchors of the movable frame to different electric potentials. One anchor is connected to ground and the other is connected to the driving voltage of the mirror plate. The outer frame is connected to the driving voltage of the movable frame, as sketched in Figure 2.

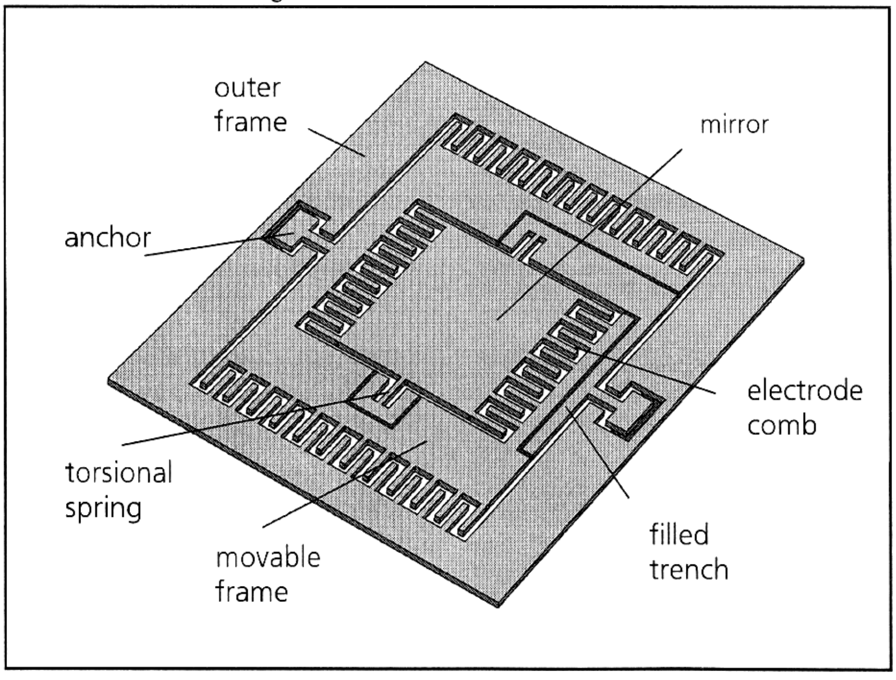

Figure 1: Schematic view of the top silicon layer of the 2D-Micro-Scanning-Mirror

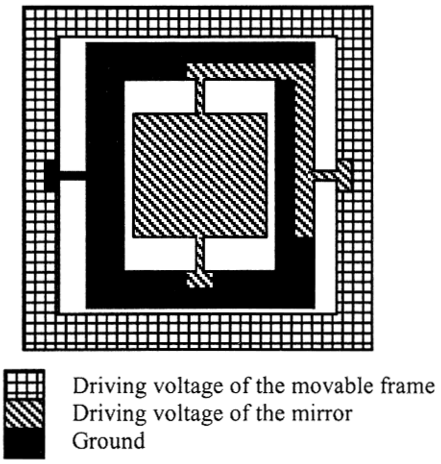

Figure 2: Distribution of the driving potentials enabled by filled and open isolation trenches

The electrical connection of the anchors of the movable frame is done by wire bonding. One anchor of the mirror plate is formed by filled isolation trenches only. To enhance the mechanical stability of the filled trenches they are dovetailed.

FABRICATION PROCESS

The 2D-scanning mirrors are fabricated in a CMOS-compatible process starting with a SOI-wafer with a top layer thickness of 30 μm. The fabrication sequence is detailed in Figure 3.

For the definition of the isolation trenches in the mechanical active areas 1 μm wide trenches with almost perpendicular sidewalls are etched in the 30 μm thick top layer using the ASE^{TM}-process. Due to the selectivity of the process etching stops at the buried oxide layer (Figure 3 a). The sidewalls of the trenches are wet-oxidized at a temperature of 960 °C resulting in a 90 nm thick isolation layer. After that the trenches are filled with LPCVD-polysilicon. The 900 nm thick polysilicon layer on the wafer surface is removed by chemical mechanical polishing. The 90-nm-oxide is etched back in a HF-solution (Figure 3b). As a consequence of this sequence the polysilicon filling is 90 nm embossed on the wafer surface (not shown in Figure 3).

An oxide and a metal layer are deposited for the formation of the wiring (not shown in Figure 3). On the backside of the wafer a hard mask consisting of an oxide and a nitride layer is patterned for the anisotropical etch later in the process. Further, a 50 nm thick layer of Aluminium is deposited on the silicon mirror plate to enhance the reflectivity (Figure 3 c).

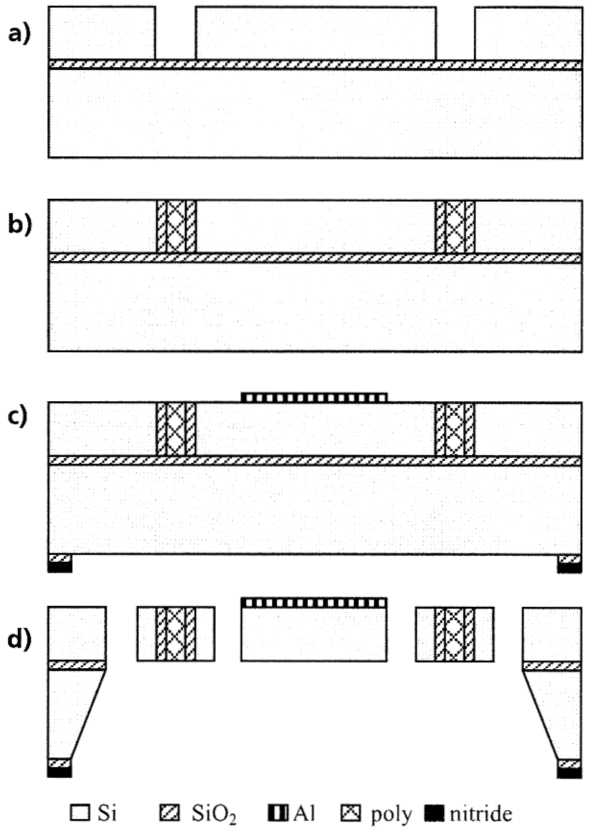

Figure 3: Schematic process flow. The drawings correspond to a cross section parallel to the torsional axis of the mirror plate (compare Figure 1).

The substrate underneath the mechanical elements is removed in a TMAH-solution at a temperature of 75 °C (Figure 3 d). After that the buried oxide is etched in a HF-solution. Finally, the mechanical elements, the electrode comb and the anchors of the movable frame are defined by a deep silicon etch (ASE^{TM}). The width of the electrode gaps is 5 μm.

Figure 4 shows a micrograph of a 2D-Scanner chip. The filled trenches are designed symmetrical to each torsional axis to avoid dynamic instabilities during the oscillation. However, a continuous isolation trench would prevent the necessary contacting of the mirror plate and the respective areas of the movable frame via the torsional springs. Therefore, the respective isolation trenches are interrupted partially (not visible in Figure 4).

Figure 5 shows a SEM-micrograph of a polysilicon filled trench. On the wafer surface the partial interrupt of the isolation trench is visible.

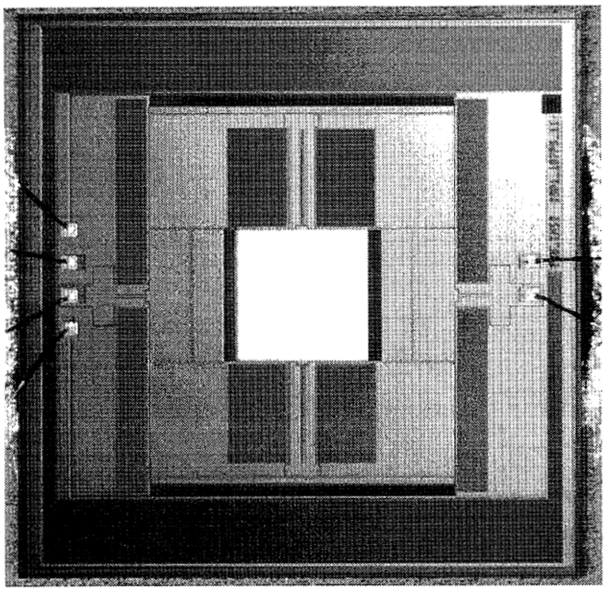

Figure 4: Micrograph of a 2D-Scanner chip. The torsional springs of the movable frame go from left to right. The springs of the mirror plate run perpendicular. On the movable frame the filled isolation trenches are visible. The mirror area is 1.0 x 1.0 mm^2. The chip has a size of 4.2 x 4.3 mm^2.

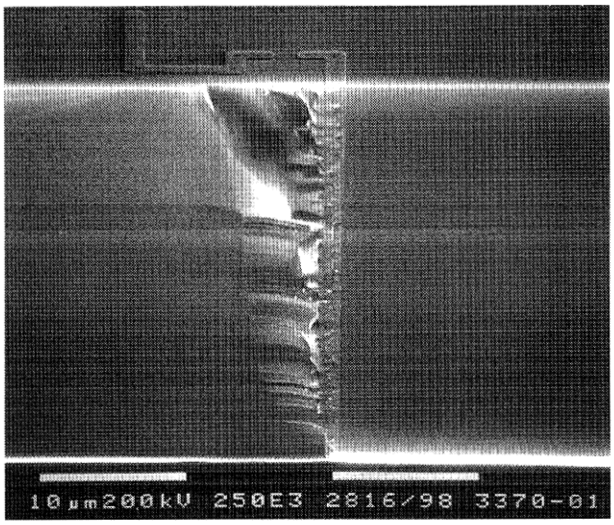

Figure 5: SEM micrograph of a 1 µm wide filled trench in a 30 µm thick single crystal silicon layer. The trench is almost completely filled. Only at the edges of the trenchline significant voids are observable. On the wafer surface the polysilicon is 90 nm embossed.

EXPERIMENTAL CHARACTERIZATION

Three different types of 2D-Scanner devices have been examined. While the size of the movable frame is the same for all of them they have different mirror plate sizes and eigenfrequencies $f_{0,mirror}$ and $f_{0,frame}$ as shown in Table 1.

type	I	II	III
frame-size [mm^2]	2.3 x 2.9	2.3 x 2.9	2.3 x 2.9
$f_{0,frame}$ [kHz]	0.90	0.92	0.61
mirror-size [mm^2]	1.5 x 1.5	1.0 x 1.0	0.5 x 0.5
$f_{0,mirror}$ [kHz]	0.72	0.60	8.3

Table 1: Dimensions and eigenfrequencies of the examined 2D-scanner devices

The frequencies of the mirror plate and the movable frame of type I and II are rather similiar. Taking into account the width of the resonance curve it is possible to examine wether there is a significant energy transfer from the oscillation of the mirror plate towards the frame or vice versa via the surrounding gas (air at atmospheric pressure). Figure 6 shows the resonance curves for type I.

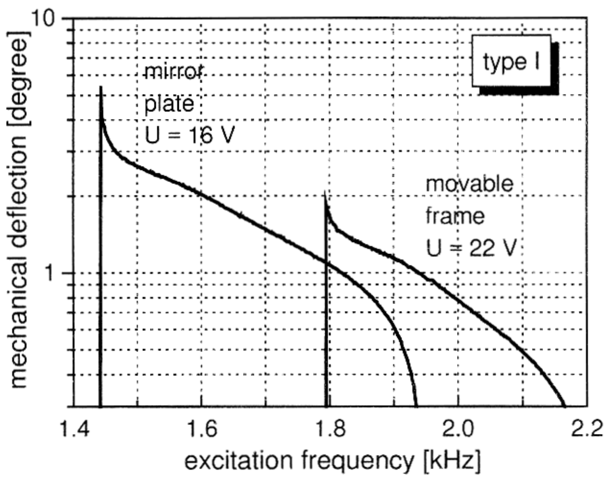

Figure 6: Resonance curve of the mirror plate and the movable frame for decreasing excitation frequency. The oscillation is excited by an ac-voltage of rectangular waveform and a duty factor of 50 %. During measurement each direction of oscillation was excited seperately.

The graph shows the resonance curves for decreasing excitation frequency. Note that the excitation frequency is twice the oscillation frequency. This is because the mirror plate and the movable frame respectively are accelerated towards the rest position twice in each oscillation period. A mechanical deflection angle of ±5.5° giving an optical scan range of 22° is achieved for the mirror plate at a driving voltage of 16 V. Because of the larger moment of inertia the deflection angle of the frame is smaller.

At the peak of the resonance curve any decrease of the excitation frequency results in the breakdown of the oscillation. Sweeping towards high frequencies results in a different resonance curve (not shown in Figure 6). This hysteresis behaviour has already been described for the 1D-scanning mirror [8].

The behaviour in the vicinity of the peak value makes it impossible to stabilize the oscillation amplitude via frequency variation. However, to enable a stable operation with maximum deflection angle the excitation can be synchronized electronically with the oscillation [6].

During oscillation the surrounding gas is moved periodically. The gas movement generated by one oscillation can effect the other one. To test the coupling of the two oscillations via the surrounding gas the following examinations were carried out:

- Excitation of the mirror plate in the vicinity of the resonance frequency of the frame (maximum deflecion angle of the mirror: ±2°)
- Determination of the damping characteristic of the frame for different oscillation amplitudes of the mirror (up to 7.5° mechanical)

With respect to the experimental resolution of the test set-up of 0.02° we observed no coupling of the oscillations.

SCAN PATTERNS

For demonstrating of the functionality of the 2D-Micro-Scanner and especially for demonstrating the possibility to excite the mirror plate and the movable frame independently both oscillations were excited with fixed frequency of various ratios resulting in Lissajous pattern of the reflected laser beam. Figure 7 shows a photograph of a 2D-scanning mirror producing a Lissajous pattern with a frequency ratio of 5:6. The incident laser beam is focused on the 1.5 x 1.5 mm^2 mirror plate. From there the beam is deflected in two directions. The scan pattern is projected on a transparent screen.

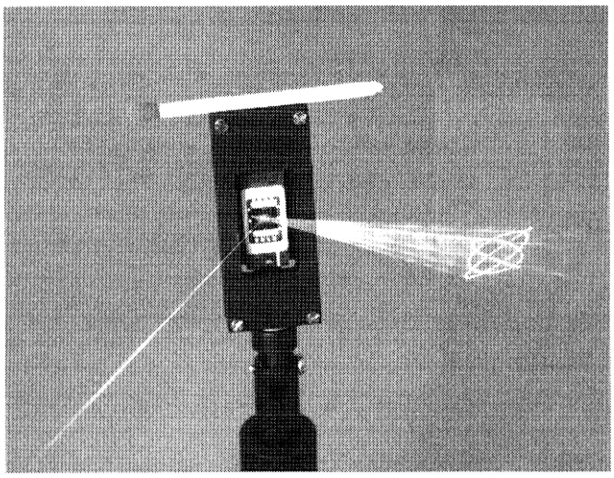

Figure 7: Photograph of a 2D-scanning mirror generating a Lissajou-figure. The mirror plate size is 1.5 x 1.5 mm^2. Both oscillations are excited with a voltage of less than 20 V. The ratio of the excitation frequencies is 5:6.

Despite having almost the same eigenfrequency the mirror can be excited without exciting the oscillation of the movable frame or vice versa as shown in Figure 8a and 8b. The simultaneous oscillation at a excitation frequency ratio of 1 is shown in Figure 8c. The oscillations are displaced in phase by 90°. An area-like scan is achieved with a larger frequency ratio as shown in Figure 8d.

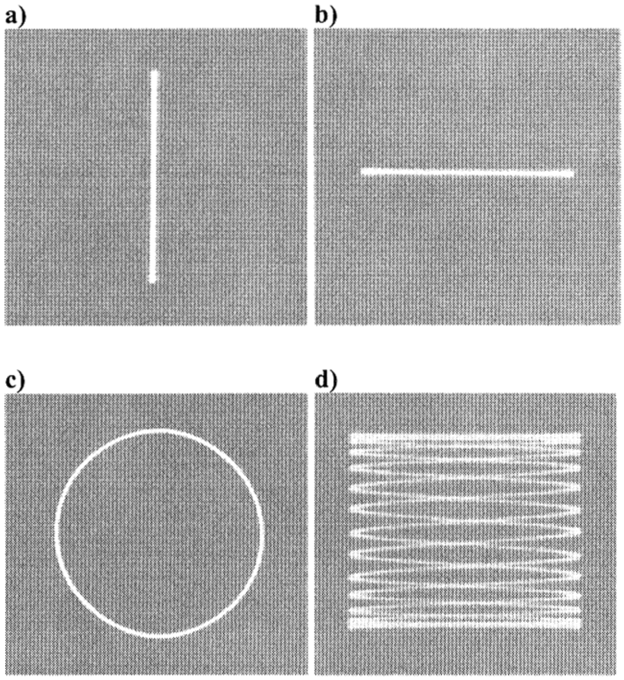

Figure 8: Photographs of different Lissajous patterns generated by the 2D-Micro-Scanning-Mirror:
a) oscillation of the movable frame,
b) oscillation of the mirror,
c) simultaneous oscillation of the movable frame and the mirror with a frequency ratio of 1 and a relative phase of 90° (type I),
d) simultaneous oscillation with a frequency ratio of 13:1 (type III).

SUMMARY AND CONCLUSIONS

A novel micromechanical 2D-scanning mirror has been developed which makes use of an effective electrostatic driving principle. The scanners are fabricated in a CMOS-compatible process. The mechanical elements are made of single crystal silicon. The gimbal mounting of the mirror plate allows the two dimensional deflection of light with a single device. To enable an independent excitation of the movable frame and the mirror plate polysilicon filled isolation trenches are used to seperate the different driving potentials. The filled trenches are located on the movable frame and form the only mechanical connection of electrically isolated areas.

The experimental results obtained by investigations on three different types of 2D-Scanners indicate that the coupling of the oscillations via the surrounding gas can be neglected. The independent excitation of the oscillations has been demonstrated by generating Lissajous patterns with a frequency ratio of 1:1 up to 13:1.

To enhance the deflection angle of the movable frame either its eigenfrequency can be reduced or the scanner can be operated at reduced pressure.

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