Precision Micro-Optical Elements for Manufacturing of Gas Sensors using IR-Absorption

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ABSTRACT

A growing number of micro optical electro-mechanical systems (MOEMS) are used in system applications like IR-detectors, projection displays or LIDAR systems. A new process technology has been developed for manufacturing precise optical components from borosilicate glass by 8-inch wafer batch processing. An improved process technology was applied for the first time for manufacturing of precise spherical mirrors of up to 8 mm diameter. The mirrors are assembled to realize a multiple reflection cell with low outer volume and a large internal optical absorption path. These cells are assembled as IR-absorption gas sensors.

Quantities of precise lenses and mirrors can be produced at low costs by batch processing. The mirrors are covered with a metallic reflective coating. After that processing the optical elements are separated and mounted to realize a multi-reflection cell using two spherical mirrors.

Examples for micromechanically actuated optical components are shown. With piezoelectric driven components a Fourier-Transformation IR-spectrometer might be set-up to be used in combination with the minimized absorption cell.

Keywords: MOEMS, multi-reflection cell, CO2 sensor, micro-mirrors, piezo-electric actuators

1 INTRODUCTION

A growing number of micro optical electro-mechanical systems (MOEMS) are used in system applications like IR-detectors, projection displays or LIDAR systems. For production of MOEMS devices often a number of passive optical components of high precision and high quality have to be used. For miniaturized optical systems passive components need to be manufactured with similar quality and cost specifications as micro sensors and microelectronic devices are produced today. A new process technology has been developed by Fraunhofer Institute Silicon Technology, ISIT for manufacturing precise optical components from borosilicate glass by 8-inch wafer batch processing. Glass forms are produced by a contact-less glass flow process leading to excellent surface qualities with surface roughness in the nanometer range. An improved process technology was applied for the first time for manufacturing of precise spherical mirrors of up to 8 mm diameter. The mirrors are assembled to realize a Herriott-type multiple pass cell with low outer volume and a large internal optical absorption path. These cells will be used as IR-absorption gas sensors.

The method of viscous forming of optical elements has been developed and significantly improved by Fraunhofer ISIT in recent years [1]. The characteristic trait of glasses is used to become flexible and ductile at temperatures far above of their glass temperature. For the technology of micro forming a structured silicon wafer is used as a tool to generate the desired form in a glass wafer tightly attached to the silicon wafer by anodic bonding. By adjusting a suited pressure difference to ambient pressure this method allows production of convex and concave lenses, various forms of optical cap elements and concave mirrors [2], [3]. Due to the specific micro forming process only glasses can be structured that show a very similar thermal expansion coefficient as silicon like borosilicate glass.

Due to the non-contact manufacturing of the optical surfaces very smooth surfaces result with typical roughness RMS values of 1-2 nm. Of even higher importance is the accuracy that is achieved in production of spherical surfaces. Over a complete spherical mirror surface of 8 mm diameter a deviation from the spherical form of below 6µm (peak to valley) can be achieved which corresponds for IR-applications to a value of 1.5λ Peak to Valley (PV), an acceptable value for a mirror surface.

Since the manufacturing process is based on established silicon wafer batch technologies huge quantities of precise lenses and mirrors can be produced at low cost. The mirrors are covered with a metallic reflective coating. After that processing the optical elements are separated. A simple mounting technique was developed to realize a multi-reflection cell using two spherical mirrors.

2 EXPERIMENTAL

Glass Flow Processing is developed and applied for production of various optical elements in Fraunhofer ISIT since more than 10 years [1], [2]. The process flow used for production of micro-mirrors is shown below in Fig. 1. Processing starts with an 8’’ Si-wafer that is patterned by standard lithography. Using an anisotropic deep reactive ion etch process (DRIE) cavities are etched into the silicon with step heights of several hundred microns and vertical side walls (1). After wet cleaning the structured silicon wafer is hermetically sealed to an Alkaline-Borosilicate glass substrate (Schott Borofloat®33)[1] by an anodic bonding process. Since the thermal coefficient of Si and Borofloat glass is almost identical thermal processing of the glass silicon combination does not affect the bond connection. The bonding process is done in an inert gas atmosphere at pressure slightly above atmospheric pressure (2).

Typical bond parameters are T = 400ºC and U = 1200V. Due to the hemerticity of the silicon-glass joint the initial pressure p_i is preserved in the silicon cavities.

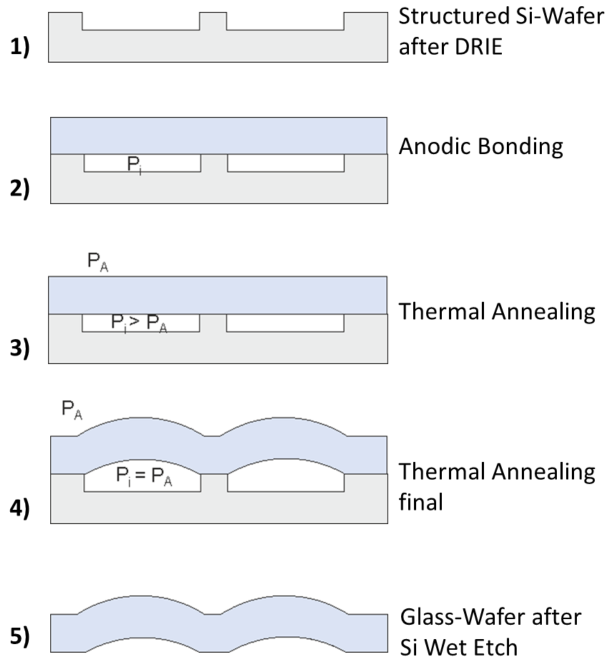

Figure 1: Process sequence for production of concave micro-mirrors.

The wafer bonding process is followed by an annealing process in an atmospheric furnace system (3). The temperature for the glass flow process is in the range of 700ºC to 900ºC which is well above the glass transition temperature of T_g = 535ºC. Thus, the viscosity of the glass is drastically lowered. The higher pressure inside the sealed cavities bends the glass cover upward. This forming process stops when the internal cavity pressure becomes equal to the outer atmospheric pressure p_A. Since the glass cover is firmly bonded to the edges of the cavities a final glass shape results that is determined by the initial dimensions of the cavities, by the glass wafer surface tension and by the initial pressure p_i. In case of a cylindrical cavity with circular top a sphere is formed in the inner surface of the glass cover (4). With a suited cavity pressure at a given cavity diameter perfectly spherical glass forms can be produced. When the temperature is lowered below the glass temperature this form is fixed in the glass wafer. During the cooling of the glass wafer temperature differences between the inside of the cavities and the upper surface of the glass wafer have to be avoided because resulting pressure differences can affect the desired glass form as long as the glass is still in the low viscous state. Especially for larger glass forms this can result in severe form deviations. Finally the silicon wafer is removed by wet etching in Tetramethylammonium Hydroxide (TMAH) or KOH and the backside of the glass wafer is mechanically planarized. Subsequently the mirror surfaces are metallized by a metal evaporation process. For a high reflectivity in the IR range the mirrors are coated with a gold film.

For the set-up of a multiple-reflection cell the design of a Herriott cell with two spherical mirrors was chosen. This is a simple cell design that is relative tolerant against opto-mechanical mistakes in the alignment of the components [4]. For an estimation of the fault tolerances of the chosen cell set-up the optical path was simulated with a ray tracing method (Zemax-EE). For the design used here the incident beam and the detection beam are coupled into the cell from the edge of a mirror at an angle of 8º. The mirrors are produced with a curvature radius of 20 mm, the mirrors are fixed at a distance of 50mm which should result in an eightfold reflection of the incident beam.

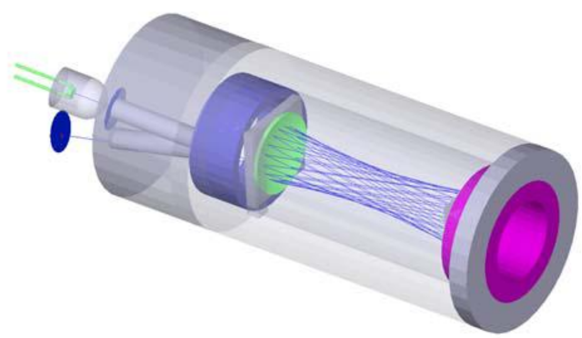

Figure 2: Simulation of the optical ray path in the designed reflection cell.

Initial prototypes of the Herriott cell are manufactured from stainless steel formed parts. For the IR-emitter and IR-detector fittings are prepared that lock into position the required incidence angles of 8º. A later production technology for these multi-reflection cells should make use of wafer bonding technologies between pre-manufactured glass forms.

3 RESULTS

In several trials the glass-flow process with 8''-wafers was optimized for manufacturing of mirrors with a diameter of 8 mm and a radius of curvature (ROC) of 20 mm corresponding to a maximum upward bending of 400 µm. Test mirrors with a diameter of 2 mm could be produced with a surface roughness below 1nm and a maximum deviation from a spherical form of 0.8µm. For

[1] Borofloat®, Trademark of Schott Glas, Mainz, D

mirrors of larger diameter the manufacturing process is more sensitive to process parameter variations. For a diameter of 8 mm and a curvature of 20 mm a curvature uniformity of 3.5% was achieved over an 8''-wafer. Especially the wafer cooling process to fix the generated forms after thermal annealing is critical for the mirror forms. After the glass forming the mirrors are coated with a gold thin film for high reflectivity in the IR-range.

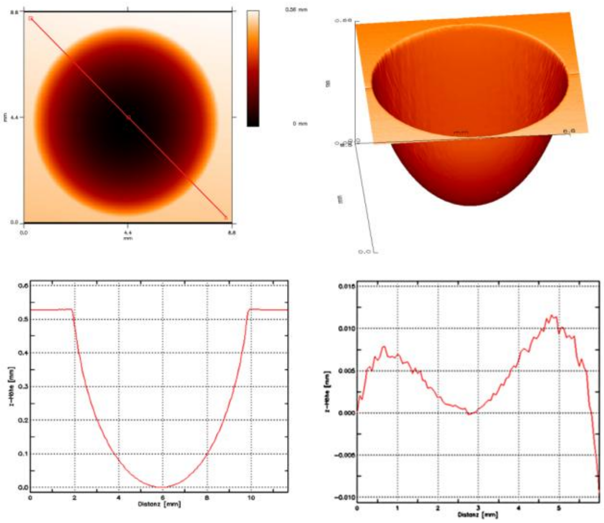

Figure 3: Measurement of profile of an 8 mm diameter reflector surface. Left diagram shows a cross-section, right diagram below shows the difference to a spherical form. Maximum deviation of this example from a sphere is 12 µm. Axis of abscissas is given in mm, ordinate units of right diagram are 5 µm.

Mirrors typically show a deviation from a perfect sphere in the range of 8µm at a diameter of 8mm. Surface roughness is below 1nm due to the contactless production method. For CO2 absorption measurements in the IR-range at 4.2 µm this form deviation is below 2λ and acceptable for application in a Herriott cell.

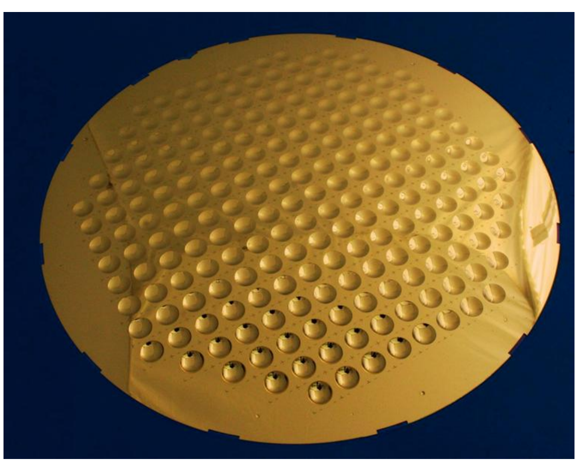

Figure 4: 8'' glass wafer with 8 mm reflectors. The wafer is coated with a gold thin film for optimized reflectivity in the IR-range.

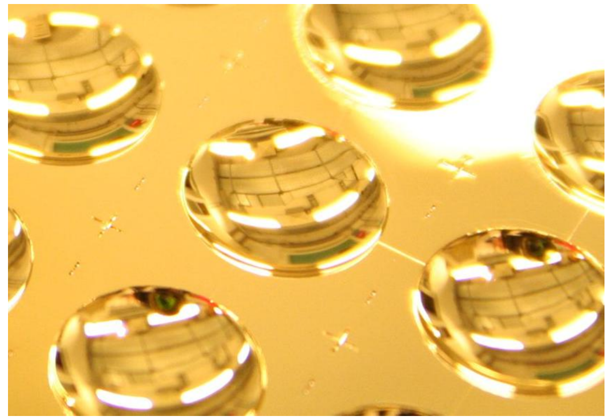

Figure 5: Detail view of gold covered reflector surfaces on 8''-glass-wafer.

First tests of the optical elements were performed using an optical bench. The mirrors were attached to carriers that allowed for a positioning of the components relative to one another. A visible laser beam (635 nm) was used to monitor the optical path. In Fig. 6 the path of rays is made visible by some fog. Laser radiation is irradiated from a small cut-out at a mirror edge at an incidence angle of approx. 8º. As Fig. 6 shows the intended symmetrical light path in the Herriot cell is achieved. Further trials are ongoing to investigate stability of the mechanical set-up and to maximize the path length by optimizing number of reflections.

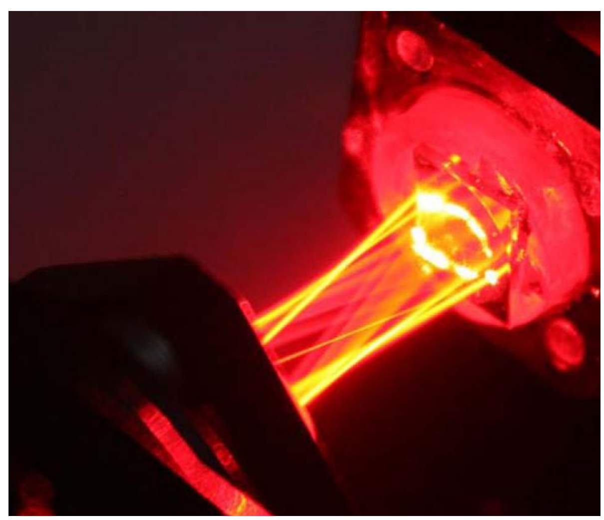

Figure 6: Test of optical path by adjusting two mirrors on an optical bench.

Optical absorption cells have been set up using components of stainless steel. IR-emitter and IR-detector are adjusted by a top frame fixing the incident and escape angle of 8º. In first tests it was observed that the beam divergence of the chosen IR emitting diodes was too large for a strong CO2 absorption signal. Disadvantage of Herriott type cells is that they do not operate with high numerical aperture optical beams [4] due to interfering stray reflections. Therefore for further evaluation of the designed absorption cell IR-emitting laser diodes will have to replace the IR-diodes. Due to the imperfect IR-emitters a CO2 absorption spectrum cannot be shown at present.

The IR-absorption cell described here is designed for continuous measurement of atmospheric CO2 concentration. Initial measurements will determine beam attenuation at the 4.25 µm CO2 absorption line.

In parallel developments are ongoing for micromechanically actuated optical elements using piezoelectric materials [5], [6]. An actuator can be realized by combining a thin film of piezoelectric material (AlN, PZT) on a thin silicon beam. Applying a voltage to the piezoelectric material will bend the beam upward or downward. Using micromechanically adjusted components interferometers can be realized. This will enable e.g. set-up of a Fabry-Perot-Interferometer which can be used to realize a Fourier-Transform IR-spectrometer in combination with the described miniaturized absorption cell. Various designs of actuated micro-optical components have been realized.

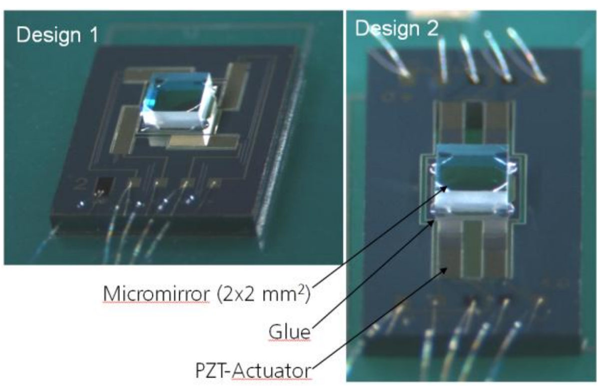

Figure 7: Two design examples of piezoelectrically actuated bending beams with attached optical elements.

Depending on the design linear static movements of 5 µm to 10 µm at 10 V voltage have been achieved for the samples shown in Fig. 7 [5]. Other designs show a static deflection of 20µm at 10 V [7]. The breakdown voltage of the 2µm thick piezoelectric PZT films used in the designs described above is above 50 V/µm.

4 SUMMARY

A new process technology has been developed and improved for manufacturing precise optical components from borosilicate glass by 8-inch wafer batch processing. Glass forms are produced by a contact-less glass flow process leading to excellent surface qualities with surface roughness in the nanometer range. An improved process technology was applied for the first time for manufacturing of spherical mirrors of up to 8mm diameter. The mirrors have been used to build a Herriott type multi-reflection optical cell that is intended to be used for monitoring of atmospheric CO2 content.

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