A novel micromachining technology for structuring borosilicate glass substrates

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ABSTRACT
We present a novel process technology, which enables precision micro machining of glass wafers. With this Glass Flow Process GFP [1,2], which is based on viscous deformation at temperatures above the glass transition temperature $T_g$, any surface topography available on a silicon substrate can be moulded into Borosilicate glasses, especially into bondable glasses like Borofloat¹ or Pyrex². Beside the replication of silicon structures this technique allows the fabrication of optical micro lens arrays with high aspect ratios and minimum spacing. Introducing this GFP technology to MEMS processing enables the deep structuring of glass substrates and opens a wide range of new applications. Optical quality micro lenses with sagittal heights above 100 µm are demonstrated.

INTRODUCTION
Due to superior material properties of glass like transparency, mechanical robustness and chemical resistance the usage of glass for micro mechanical, micro fluidic and micro optical MEMS devices is emerging. Alkaline-Borosilicate glass substrates can easily be joined to silicon substrates by the well known anodic bonding process without additional adhesives [3], whereas these bond seals show good hermeticity and high bond strength. Using prestructured glass substrates with functional elements such as fluidic micro channels or optical micro lenses, the integration level of MEMS devices can be increased whereas the manufacturing process is kept on wafer level. Application and implementation of micro optic devices and their corresponding process technologies are widely described in [4,5,6]. Micro lenses and micro lens arrays are increasingly used for fibre coupling in multi fibre connectors, as collimation devices for LEDs [7,8] and high power laser bars [9]. Further on micro lens arrays are implemented in wave front sensors [10], pixel-based CCD cameras [11], confocal microscopy [12] or direct optical one-to-one imaging [13]. The utilization of movable micro optic elements for beam deflection and modulation in scanners and switches is described in [14].

1 Borofloat®, Trademark of Schott Glas, Mainz, D
2 Pyrex®, Trademark of Corning Inc., NY, USA

At present the available processing technologies for structuring glass substrate are often restricted. Processing brittle glass with computer numeric control (CNC) supported cutting processes like scribing or milling leads to rough surfaces. Because of the small dimensions of microstructures subsequent polishing steps cause exceeding efforts. With reactive ion etching (RIE) photo resist structures can be transferred into the underlying glass substrate. Due to low etch rates the structure depth is limited. In combination with the resist reflow method dense micro lens arrays in fused silica have been fabricated [15].

The new GFP technology offers a cost-effective fabrication technique which is completely based on MEMS processes. The thermal moulding of a silicon wafer preform into the adjacent vacuum bonded glass wafer at elevated temperatures assures almost perfect surface relief replication. Moreover using the GFP in a contactless configuration enables the fabrication of spherical glass structures. The glass wafers structured by GFP can be used as starting material for subsequent MEMS processes. In particular anodic bonding of GFP substrates to silicon is feasible so aligned silicon-glass wafer assemblies with functional structures on both wafers can be fabricated. New types of optical packaging solutions or complete stacked microoptics can be realised in this new process. Using standard MEMS processes makes GFP a very efficient and competitive technology with broad application potential.

Fig.1 Micro fluidic channel structures in borosilicate glass: substrate with channel step height of 150 µm and minimum channel width of 20 µm.
To show the feasibility and the process performance numerous demonstrators like micro fluidic channel structures (Fig.1) or micro optical lens arrays (Fig.2) are fabricated. The surface profiles and the optical properties of these GFP lenses have been systematically examined and the influence of the different process parameters is studied.

**EXPERIMENTAL**

The process sequence of the GFP technology based on standard MEMS processes is shown in Fig.3:

A positive resist layer on 6 inch silicon wafer is patterned by standard lithography (a) and transferred to an underlying 650 nm thick hard mask oxide by dry etching (b). In an anisotropic deep reactive ion etch process (DRIE) cavities with step heights up to several hundreds microns and vertical side walls are etched into the silicon substrate (c).

After elaborate cleaning (plasma, piranha and BOE etch) the silicon wafer is hermetically sealed to an Alkaline-Borosilicate glass substrate (Schott BOROFLOAT®33) by anodic bonding under vacuum (d). Prior to bonding the glass substrates are cleaned with mixture of H₂SO₄ and H₂O₂. The bonding process is done on a Karl Suss SB6 bonder. Typical bond parameters are T = 420 °C and U = 1200 V whereas the bond vacuum is kept below 1 mbar. Due to the hermeticity of the silicon-glass joint the vacuum condition remains preserved in the silicon cavities. The bonding process is followed by an annealing step in an atmospheric furnace system (e). The temperature for this GFP step is typically in the range of 600°C to 800°C and therefore well above the glass transition temperature of Tg = 525°C. Thus, the viscosity of the glass is drastically lowered. The pressure difference between oven atmosphere and cavity vacuum leads to slumping of glass material into the silicon cavity until the silicon structures are completely filled. So the original silicon topography is inversely moulded into glass. The minimum feature size as well as the structure height is hereby limited only by the previous silicon structuring process. Finally the silicon wafer is removed by wet etching in Tetramethylammonium Hydroxide (TMAH) and the backside of glass substrate is mechanically planarized (f).

If the slumping process is stopped before the glass front is reaching the bottom of the cavity (Fig.4), the resulting shape of the glass surface is spherical and can be used as a micro lens. Beside circular lenses also cylindrical or concentric ring lenses have been fabricated.

The resulting lens profile \( h(x,y) \) is characterised by line scan measurements, whitelight-interferometry and scanning electron microscopy (SEM). The effective focal length EFL was measured on a Trioptics Optispheric® system. To determine the wave front aberration an adapted Michelson interferometer was used in cooperation with the university EICN/Le Locle Switzerland.

**RESULTS AND DISCUSSION**

**Moulding of silicon preforms.** Round cavities with different diameter size are etched into silicon substrates with DRIE up to a depth of 150 µm. The GFP anneal step...
is performed at $T = 750^\circ C$ for 2 hours in ambient atmosphere where the viscosity $\eta$ of the glass is lowered down to $\log(\eta) = 7.5$ Pas. After GFP forming the silicon wafer is fully removed in TMAH. In Fig.5 the resulting glass pedestals with 225 $\mu$m diameter, 150 $\mu$m height and a minimum spacing of 20 $\mu$m between the structures are shown:

![Fig.5 SEM image of tall Borofloat glass cylindrical pedestals.](image)

The silicon DRIE process is featured by particular side wall texture in the sub-micron range. This texture is retrieved on the side wall of the glass pedestals. Therefore, a full replication of the silicon topology into glass without detectable degradation is possible. For smaller minimum feature size of the silicon preform a higher GFP temperature has to be chosen for full reproduction.

**Shape of GFP micro lenses.** For the fabrication of spherical glass lenses the slumping of glass into a circular silicon cavity is stopped before reaching the cavity bottom. For this purpose either the process time can be reduced, the residual pressure inside the cavities can be increased or the slumping velocity can be decreased by lowering the GFP temperature as well. A SEM picture of a fabricated micro lens array is shown in Fig.6. Whitelight-interferometrical measurements show that the root mean square values (rms) of the surface roughness are below 2 nm. The superior smoothness of the GFP lenses is due to the contactless fabrication method.

![Fig.6 SEM image of GFP micro lens array (lens radius $r_L = 450 \mu m$, lens height $h_L = 80 \mu m$)](image)

In Fig.7a a line scan measurement of a circle GFP lens is shown. The center of the lens is spherical which is equivalent to a straight line in the first derivative (Fig.7b). Outside a critical lens radius (arrows) an elliptical deviation with respect to a perfect sphere is measured. This deviation in the outer region of the lenses is also visible in the measurements of the wave front abberation. In the total lens area a maximum phase error of 1.2 $\lambda$ is measured which is mainly located in the outer lens region.

![Fig.7 GFP lens profile (a) and first derivative of profile (b) in respect to a perfect sphere (dashed line).](image)

**Influence of process parameters.** A set of lens designs with various radii were sampled with different process conditions whereas the pressure difference was kept constant. The GFP temperature is varied from 660$^\circ$C up to 720$^\circ$C while process time is limited to 8 hours. As seen in Fig.8a the lens height at constant lens radius $r_L = 50 \mu m$ and fixed temperature $T = 700^\circ C$ is linearly raising with increasing process time $t$. Hence the inflow velocity remains constant over several hours and is independent on the actual inflow progress. The lens height is measured for different lens radii and process temperatures and at a constant process time of 2 hours and is graphed in Fig.8b. Typical inflow velocities are in the range of 1 to 10 nm/s. The lens height and thus the inflow velocity are proportional to the lens radius. Since process time and lens diameter scale linearly to the lens height the ratio of inflow velocity to lens radius is only dependent on the GFP temperature.

The observed data matches to a theoretical approach based on the assumption that glass acts as a Newtonian fluid. The linear dependence of the lens height to the lens radius as well as the elliptical deviation of the lens profiles in the outer lens regime are directly caused by the distribution of the velocity field of the inflowing glass liquid. An analytical description of this inflow behaviour is under investigation and will be consecutively published.
Optical Properties. The results of the focal length measurements are summarized in Fig.9. The measured EFL is proportional to the lens radius whereas the slope of the straight line is only defined by the annealing temperature. Therefore, the numerical aperture $N_A$ and the $F$-number ($F#$), which are both directly related to the slope, are only dependent from the physical parameters of the GFP conditions, like temperature, process time or pressure difference and therefore independent of the cavity radius in the silicon substrate. In conclusion for fixed process parameters all GFP lenses have the same optical power.

CONCLUSIONS

In this paper we describe a novel glass micromachining technology which enables the complete replication of silicon structures into bondable Borofloat glass. Furthermore micro lenses can be fabricated with central heights up to 500 µm without costly and time consuming dry etching of glass substrates. This contactless forming of the lenses results in a very low surface roughness. Elliptical deviation in the outer lens regime have been observed. The influence of thermal anneal process parameters are related to lens height and focal length. For fixed process conditions the resulting $F$-number is independent of the lens radius.

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References