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High temperature micro-glassblowing process demonstrated on fused quartz and ULE TSG[☆]

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ABSTRACT

We report, for the first time, a MEMS fabrication process for building atomically smooth, symmetric 3-D wineglass and spherical shell structures, using low internal loss materials, namely fused quartz and ultra low expansion titania silicate glass (ULE TSG). The approach consists of three major steps: (1) a deep fused quartz cavity etch, (2) plasma activated bonding of fused quartz to fused quartz or TSG and (3) a high temperature (up to 1700 °C) micro-glassblowing process. An in-house process capability of 1800 °C glassblowing with a rapid cooling rate of 500 °C/min was developed. Feasibility of the process has been demonstrated by fabrication of fused quartz and TSG micro-glassblown structures. Spherical and inverted-wineglass shells with self-aligned stem structures were fabricated using this process. The approach may enable new classes of TSG and fused quartz MEMS devices with extremely low surface roughness (0.23 nm surface average), intrinsically low thermoelastic dissipation ($Q_{TED} > 5E+10$), and highly symmetric structures (radial error < 500 ppm).

1. Introduction

Maximization of the *Q*-factor is key to enhancing performance of vibratory MEMS devices in demanding signal processing, timing and inertial applications [1]. Current MEMS fabrication techniques limit the maximum achievable *Q*-factor by restricting the material choice to few materials and device geometry to 2-D planar structures. Available materials such as single-crystal silicon have relatively high thermoelastic dissipation and 2-D planar devices are mostly limited by anchor losses. The macro-scale Hemispherical Resonator Gyroscope (HRG) with *Q*-factors over 25E+6 [2] motivates the investigation of 3-D fused quartz micro-wineglass structures for use as vibratory elements in MEMS applications. This paper investigates the intriguing possibility of fused quartz micro-glassblowing as a means to fabricate 3-D shell micro-devices, Fig. 1.

With the emergence of novel fabrication techniques batch fabrication of 3-D wineglass structures are becoming possible. For instance, hemispherical shells fabricated by deposition of polysilicon [3] or silicon nitride [4] thin films into isotropically etched cavities have recently been demonstrated. Alternative fabrication techniques include “3-D SOULE” process for fabrication of mushroom and concave shaped spherical structures [5], as well as blow molding of bulk metallic glasses into pre-etched cavities [6]. MEMS wineglass resonators with atomic smoothness and low thermoelastic dissipation (TED) have not yet been demonstrated in the literature. To take full advantage of the 3-D wineglass architecture, fabrication techniques with low surface roughness as well as materials with high isotropy and low TED are desired.

It has been demonstrated that single-crystal silicon MEMS devices can reach the fundamental Q_{TED} limit by using a combination of balanced mechanical design and vacuum packaging with getters [7]. TED is caused by local temperature fluctuations due to vibration and the associated irreversible heat flow, which results in entropic dissipation. TED can be reduced either by decoupling the frequencies of mechanical vibrations from the thermal fluctuations or by using materials with low coefficient of thermal expansion (CTE). This paper focuses on materials with low CTE, such as fused quartz (0.5 ppm/°C) and ultra low expansion titania silicate glass (0.03 ppm/°C), which can provide a dramatic increase in fundamental Q_{TED} limit (Q_{TED} > 7E+10 for a TSG wineglass structure). When compared to silicon, titania silicate glass and fused quartz dry etching suffers from an order of magnitude higher surface roughness, lower mask selectivity, ∼1 :1 for KMPR® photoresist and lower aspect ratio, <5:1 [8,9].

Pyrex glassblowing at 850 °C on a silicon substrate was previously demonstrated for fabrication of smooth, symmetric 3-D structures [10–13]. However, fused quartz/TSG glassblowing requires temperatures upwards of 1600 °C due to its higher softening point, which prevents the use of fabrication processes that rely on a silicon substrate. This paper explores the hypothesis that high temperature glassblowing (up to 1700 °C), may serve

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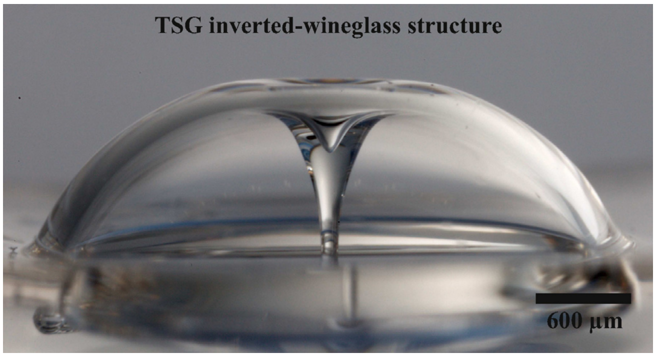


Fig. 1. Optical photograph of glassblown TSG inverted-wineglass structure. Outer diameter is 4200 µm. Glassblown at 1650 °C.

as an enabling mechanism for wafer-scale fabrication of TSG and fused quartz 3-D wineglass structures. The approach consists of a high temperature micro-glassblowing process and an inverted-wineglass architecture that provides self-aligned stem structures. An in-house process capability of 1800 °C glassblowing with a rapid cooling rate of 500 °C/min was developed. Feasibility of the process has been demonstrated by fabrication of TSG and fused quartz micro-wineglass structures and spherical shells [14].

In the following sections, firstly the design parameters for micro-glassblowing is presented. This is followed by details of the fabrication process and the custom-designed fabrication equipment. The paper concludes with analysis of the glassblown structures and discussion of the results.

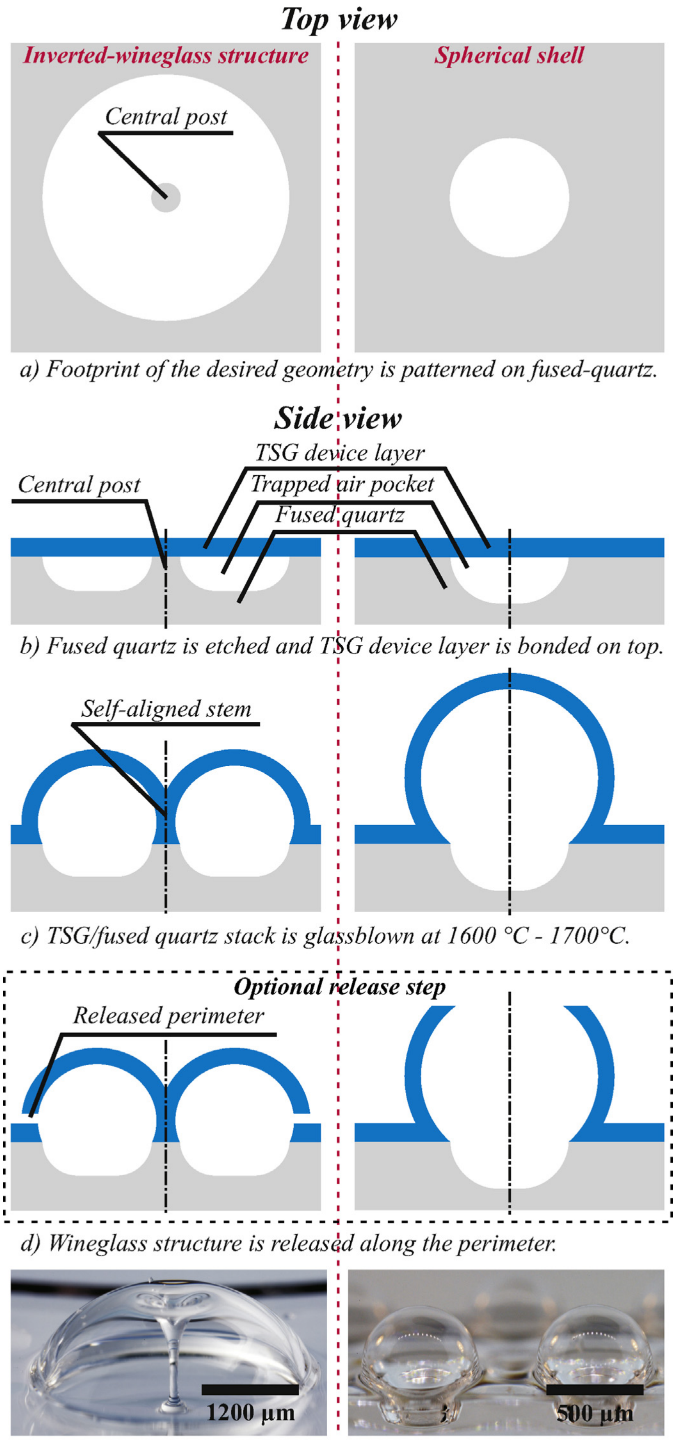
2. Design parameters

This section focuses on analysis of geometric design parameters and the effect of material choice on fundamental Q-factor limits. In order to establish the relationships between material choice, device dimensions and Q-factor, parametric Finite Element Analysis (FEA) was conducted using Comsol® Multiphysics Package [15].

2.1. Geometric design

Micro-glassblowing process utilizes an etched cavity on a substrate wafer and a glass layer that is bonded on top of this cavity, creating a volume of trapped gas for subsequent glassblowing of self-inflating spherical shells. When the bonded wafer stack is heated above the softening point of the structural glass layer, two effects are activated at the same time: (1) the glass layer becomes viscous, and (2) the air pressure inside the pre-etched cavity increases above the atmospheric level. This results in plastic deformation of the glass layer, driven by gas pressure and surface tension forces (glassblowing). The expansion of air (and hence the formation of the shell) stops when the pressure inside and outside of the glass shell reaches an equilibrium, creating a self-limiting process. During this deformation, the surface tension acting on the now viscous glass layer works towards minimizing the surface area of the structure as a result a highly symmetric spherical shell with low surface roughness forms. The process allows simultaneous fabrication of an array of identical (or different if desired) shell structures on the same substrate.

Shape and size of the final glassblown structure can be designed by changing starting conditions such as thickness of the device layer, cavity shape and dimensions as well as environment temperature and pressure during glassblowing [10]. For example, changing the cavity diameter directly affects the diameter of the final glassblown shell, whereas changing the cavity depth (or volume) affects the height of the glassblown structure. It is also possible to fabricate entirely different geometries by changing the initial conditions, for example a circular cavity creates a spherical shell when glassblown, Fig. 2 (right). Inverted-wineglass structures can also be fabricated by defining a central post inside the etched cavity, Fig. 2 (left). When the device layer is bonded to this central post, it acts as an anchor point, which allows the glassblown shell to fold around it, creating a self-aligned stem structure as in Fig. 2(e).



a) Footprint of the desired geometry is patterned on fused-quartz.

b) Fused quartz is etched and TSG device layer is bonded on top.

c) TSG/fused quartz stack is glassblown at 1600 °C - 1700°C.

d) Wineglass structure is released along the perimeter.

e) Fabricated wineglass structure (left) and spherical shells (right).

Fig. 2. ULE TSG/fused quartz micro-glassblowing process, consists of: (a) footprint of the desired geometry is patterned on fused-quartz, (b) fused quartz is etched and TSG device layer is bonded on top, (c) TSG/fused quartz stack is glassblown at 1600–1700 °C, (d) wineglass structure is released along the perimeter, and (e) fabricated wineglass structure (left) and spherical shells (right).