Simulation-Based Approach in Design of 3D Micro-Glassblown Structures for Inertial and Optical Sensors

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***Abstract*—This paper presents a numerical simulation framework for the micro-glassblowing process to design three-dimensional (3D) resonant shells for inertial sensors, and non-resonant cells for optical and atomic sensors. The micro-glassblowing of micro-spherical atomic cells out of Borosilicate Glass (BSG) and micro Hemi-toroidal shells out of Fused Quartz (FQ) are simulated to predict the resulting 3D geometries. Based on the presented simulation framework, strategies to modify the geometry of glassblown shells for improvement of optical and mechanical properties are presented. Micro-spherical BSG cells with $>$97% sphericity and improved thickness distribution for optical transmission, and low-frequency FQ micro-shell resonators with more than 6$\times$ modal separation were designed. The simulation-based approach in this study can be used for the optimization of the 3D shell geometry to achieve higher sphericity, an improved optical light transmission, structural rigidity in micro-spherical cells, and larger modal separation and decoupled mass and stiffness in micro shell resonator.**

I. Introduction

The amorphous and isotropic structural properties of engineered glasses make them an attractive structural material for a variety of sensory application such a biomedical, optics, photonics, and mechanical sensors. A variety of microfabrication techniques have been developed for glass processing in fabrication of microfluidic channels, photonic waveguides, and microlenses, such as laser ablation [1], abrasive-jet blasting [2], Reactive Ion Etching (RIE) [3], and Femtosecond Laser Irradiation and Chemical Etching (FLICE) [4]. The wafer-level micro-glassblowing process was developed for the fabrication of three-dimensional (3D) micro-spherical atomic vapor cells for chip-scale atomic sensors [5]. An array of 3D glass cells was fabricated using Deep Reactive Ion Etching (DRIE) of cavities in a silicon (Si) wafer, an anodic wafer bonding of the Si wafer to a Borosilicate Glass (BSG) wafer, and glassblowing in a high-temperature furnace operating at temperatures higher than the softening point of the glass. The axial symmetry of the glassblown cells enabled an optical multi-port geometry that can be fabricated in batches on a wafer-level, [6], [7].

The micro-glassblowing process was adapted for the fabrication of microspherical [8]–[10], inverted wineglass [11], and dual-shell [12] resonant structures, operating in one of their flexural wineglass modes. A higher Q-factor was achieved using Fused Quartz as the structural material in resonant 3D shells [13]. The material isotropy and the symmetry of the structure, inherited by the surface tension of the viscous glass in the glassblowing, provides stiffness and damping symmetry which are the key characteristics of a precision Coriolis Vibratory Gyroscope (CVG). In 3D shell resonators, the resonant frequency, modal frequency separation, and the energy dissipation mechanisms, such as Thermoelastic Damping (TED) and anchor loss, depend on the shell geometry [14]. However, the final shell geometry in the micro-glassblowing process depends on the process parameters as well as initial glass geometry. In this paper, based on the Finite Element (FE) simulations, strategies to improve the sphericity of cells for increased cell symmetry and light transmission in micro-spherical cells, and modal separation in hemi-toroidal shell resonators are presented and the effect of process modification on the final mechanical and optical properties of the micro-shells are studied using numerical simulations.

II. Finite Element Modeling of Micro-glassblowing

In the micro-glassblowing process, glass undergoes transient and steady-state thermal stages. During the transient process, the temperature would rise to reach the process temperature. At this stage, it was assumed that the glass is in the solid phase and the deformation is negligible. In the steady-state thermal condition, the temperature reaches above the softening point of the material. Thus, activating the viscous flow of the glass. The steady-state thermal stage is assumed as an isothermal process, where the built-in pressure difference initiates the viscous flow, and the surface tension and viscosity control the kinematics of the process.

A Newtonian isothermal fluid flow model was developed to simulate viscous deformation of micro-shells during the steady-state thermal stage [15]. The viscosity, surface tension, and density of BSG and FQ at the glassblowing temperature were extracted from literature to define the temperature-dependent glass properties. A 2D axisymmetric model was built for BSG micro-cell and FQ micro-shell glassblowing simulations, as shown in Fig. 1. In the BSG process, the silicon substrate does not deform at the temperature of glassblowing. Thus, only the glass layer was built, and the glass-silicon boundary was modeled as a slip boundary condition. The cavity pressure and the ambient pressure were applied on inner BGS surface and outer surfaces, respectively. In the FQ process, the substrate deforms during the glassblowing and was modeled as a viscous domain in the simulations. The deformation of the substrate would affect the height of glassblown shells. The cavity pressure drops as shell blows.

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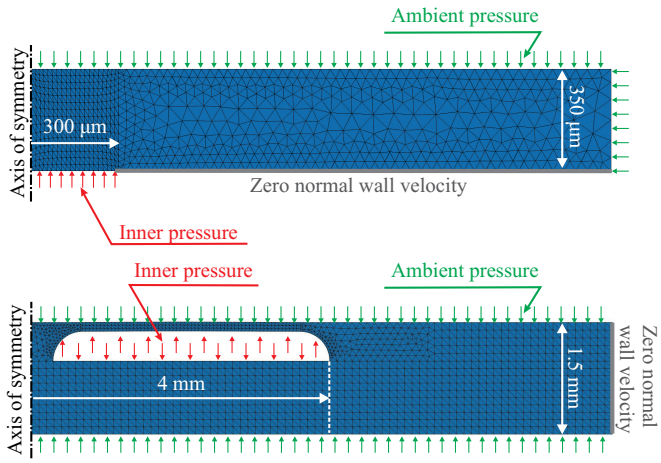

Fig. 1. Finite element model of BSG (top) and FQ (bottom) glassblowing processes. In FQ glassblowing, the substrate deforms and is modeled as a viscous domain. In BSG glassblowing, the Si substrate does not deform and is not modeled to reduce the model complexity.

The pressure re-calculated at each time increment of simulation from the instantaneous glassblown volume using the ideal gas law. Thus, capturing the self-limiting property of the glassblowing process.

III. Micro-Spherical Cells for Atomic and Optical Sensors

The effect of sphericity and non-uniform thickness distribution of micro-cells are studied in this section. In atomic cell applications, the higher the sphericity of cells the higher a through-cell optical transmission and as a result the polarization is maintained and overall cell symmetry is improved. In addition, a non-uniform thickness distribution causes a different portion of the incident beam to diffract at different angles, limiting the performance of atomic cells.

The cell sphericity is defined as the ratio of the effective volume to the surface area of the exposed part of the cell above the glass level [16]. It is calculated as

$$\Psi = \frac{\pi^{1/3}(6V_g')^{2/3}}{A_g}$$

where, V_g' and A_g are the volume and the surface area of the blown part of the cell, respectively. To improve the sphericity, one could reduce the glass thickness, radius of etched cavity r_o, and the ambient pressure, while increasing the etch depth h_e to fabricate a larger cell, Fig. 2. However, glassblowing of

TABLE I
Summary of geometrical parameters of spherical glass cells for 4 different cases presented in Fig. 4.

Case #	a	b	c	d
Ring depth, δ_{etch} (μm)	0	100	200	300
Height (mm)	1.55	1.6	1.72	1.85
Sphericity (%)	91.70	95.49	97.70	97.4

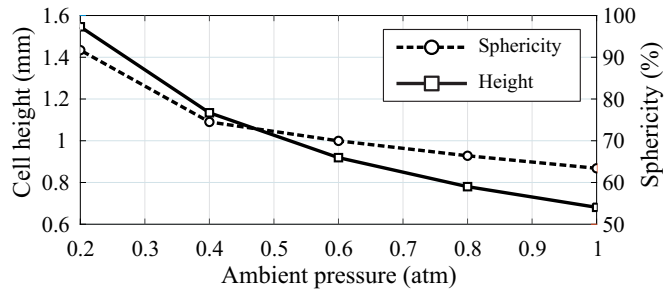

Fig. 2. Cell height and sphericity levels vs. ambient pressure during glassblowing. The glass thickness δ_0= 350 μm, cavity radius r_o= 300 μm, and cavity depth h_e= 700 μm.

a large cell would increase the wall thickness non-uniformity and create a very thin wall ($< 1\mu m$) at the top of cell. As shown in Fig. 4a, the base of a glassblown cell would always have a higher thickness, and the wall thickness would decrease from base to the top of the cell. After cool down, the pressure difference across the cell walls would create a compressive stress that is larger than the compressive strength of BSG glass, breaking the glassblown cell.

A design modification based on the FE model was performed to reduce the wall thickness non-uniformity and increase cell sphericity. An isotropically etched annular ring was added to the initial geometry of BSG glass and the glassblowing simulations were repeated. Fig. 3 shows a schematics of a die cross-section with an etched annular ring in the glass layer with inner radius r_r and depth of $\delta_{g|etch}$. The new design would result in blowing larger, yet more robust, cells and increase cell's sphericity. The simulation results for three different cases are shown in Fig. 4b-d and the results are presented in Table I. Note that, the glass thickness δ_0 =350μm, cavity radius r_o=300μm, and cavity depth h_e= 700 μm are selected for all of the cases.

By controlling the thickness distribution and shifting the thinnest part from the top of cell to the equator of cell would improve the optical transmission through the cell, anticipating an improvement in performance of glassblown atomic cells.

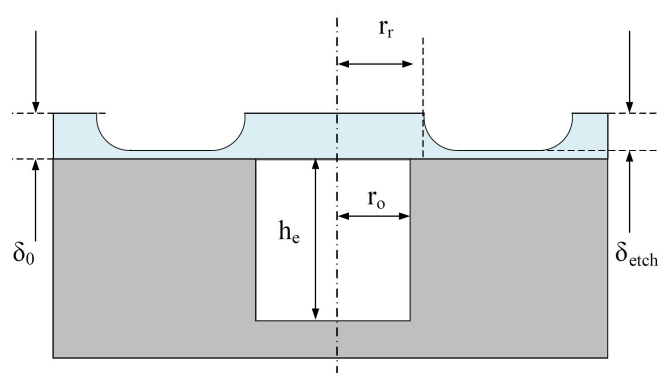

Fig. 3. Schematics of a cross section view of selectively etched annular ring in the BGS glass layer before glassblowing. The r_r and δ_{etch} are the parameters for designing the annular ring, r_o and h_e are the silicon cavity parameters.

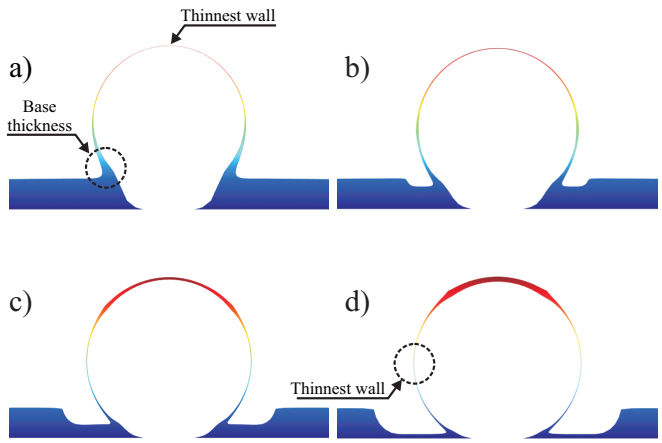

Fig. 4. FEM simulation results showing the cross-section sketches of different cases of annular ring etch depth, (a) an original design without pre-etching, (b) δ_{etch}= 100 μm, (c) δ_{etch}= 200μm and (d) δ_{etch}= 300μm

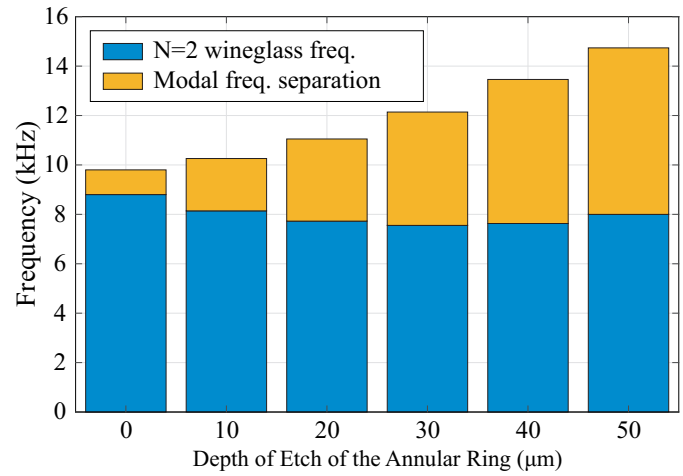

Fig. 6. n=2 wineglass resonant frequency and minimum modal separation in a micro-glassblown FQ shell resonator with different annular ring designs. A 6× improvement in the modal separation was predicted as a result of geometry modification.

IV. Resonant Micro-Shells for Inertial Sensors

In 3D shell resonators, the resonant frequency, modal frequency separation, and the energy dissipation mechanisms, such as Thermoelastic Damping (TED) and anchor loss, depend on the shell geometry [14]. A patterned glass layer before shell formation in blowtorch molding process was demonstrated to control the stiffness and mass distribution of shell resonators [17]. One approach to reducing the resonant frequency of n=2 wineglass modes while keeping the spurious modes at higher frequencies is to pattern the FQ die before glassblowing. Similar to BGS glassblowing, an isotropically etched annular ring was added to the FE model of FQ glassblowing, as shown in Fig. 5a. In simulations, the shell diameter was 7 mm, stem diameter was 1.4 mm, and the depth of cavity etch was 400 μm. The inner radius of the annular ring, r_r, was 3 mm. The depth of annular etch was changed from 0 to 50 μm. The geometry of glassblown FQ shell for the two cases are shown in Fig. 5b-c.

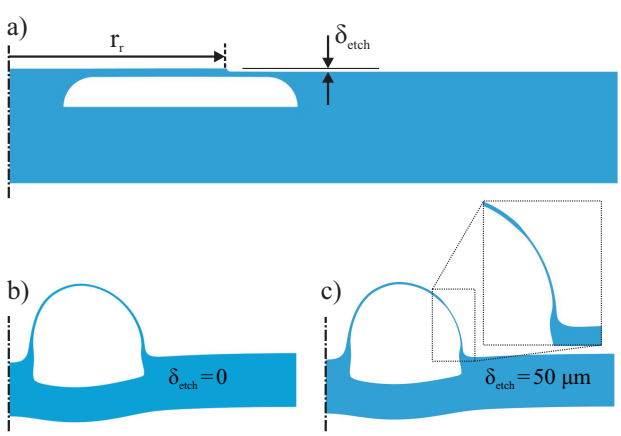

Fig. 5. The modified model of FQ die with added annular pattern (a), the final glassblown geometry without patterning the FQ (b) and pre-patterning with δ_{etch} = 50 μm. The shell thickness distribution changes as the result of pre-patterning FQ prior to glassblowing.

The FE final geometries were transferred to a solid mechanics simulation module, the mesh was trimmed, and the substrate was removed to calculate the modal frequencies of shell resonators. Fig. 6 demonstrates the effect of patterned FQ of the n=2 wineglass resonant frequency and its separation with the closest spurious mode. The selective reduction of shell thickness around the rim area would reduce the wineglass frequency. Moreover, it would change the overall thickness distribution of glassblown shells and stiffen the tilt and out-of-plane modes, which is anticipated to improve environmental immunity of shell resonators operating at low frequencies.

V. Conclusion

A hybrid fluidic-structural multiphysics modeling approach was presented to design spherical cells with increased sphericity and improved thickness distribution, as well as to design low-frequency Hemi-toroidal shell resonators with a large modal separation and improved robustness to environmental vibrations. Based on the simulation results, atomic cells with sphericity of >97% can be fabricated using the glassblowing process. Also, the thin wall thickness at the cell's equator can be achieved for an improved through cell optical transmittance. The design modifications in shell resonators were predicted to exhibit a selective reduction in the operational frequency while stiffening the spurious modes. The simulation framework presented in this work can be utilized to optimize the geometry of three-dimensional glass-based sensors leading to improved performance in timing, optical, and inertial navigation applications.

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