Fabrication and characterization of suspended beam structures for SiO₂ photonic MEMS

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Abstract

This paper proposes a microfabrication process for the reliable release of SiO₂ beam structures. These structures are intended to be utilized in SiO₂ photonic MEMS. A major fabrication challenge is the release of thick (>10 μm) SiO₂ structures with high yield. A single mask process is developed based on temporary reinforcement of the SiO₂ structure. A supporting layer of Si functions as a reinforcing layer during etching and release, thereby enabling a high fabrication yield. Furthermore, the process allows to create structures of which the final Si support thickness is configurable from tens of micrometers to zero, thereby providing additional design freedom.

The fabrication process is tested on a silicon wafer with a ∼15 μm thick thermal oxide layer. The obtained suspended structures are mechanically characterized. Two deformation effects can be distinguished: a curvature of the beam and a slope at the base of the beam. These effects are caused by the compressive mean stress and the gradient stress in the thermal SiO₂. The curvature of the SiO₂–Si beams corresponds to a concave downward profile while the SiO₂ beams without supporting Si reveal a small curvature in the opposite direction (concave upward). The slope at the base is approximately −0.5° for the SiO₂ beams and between −0.5° and 0° for the SiO₂–Si beams. The acquired bending stiffness of long SiO₂ beams is in the newton per meter range (e.g. 0.8 N m⁻¹ for a cantilever measuring 1000 μm in length and 13 μm in width).

Keywords: stress, beam curvature, waveguide, bending stiffness, silicon dioxide MEMS

(Some figures may appear in colour only in the online journal)
waveguide beams can be created, this will open up entirely new possibilities, combining the advantages of MEMS with the preferred optical performance of photonic material systems. In earlier work, we have proposed an alignment concept for the alignment of the waveguides of two PICs, based on suspended TriPleX waveguides and integrated MEMS actuators [3]. This alignment concept and comparable SiO2 photonic MEMS applications require the development of fabrication processes for realizing mechanical structures in SiO2. This paper addresses the challenges in creating such structures and proposes a method for their high-yield fabrication.

The fabrication of structures for SiO2 photonic MEMS is challenging because of the thickness of the layer. The use of SiO2 as a construction material which at the same time has good optical properties requires thick SiO2 cladding layers. A total thickness of approximately 15 μm is required for a Si3N4-SiO2 photonic waveguide with acceptable propagation loss. This thickness differs from the thickness required for other uses of SiO2. For example, when used as a dielectric material or as a (local) doping/etching mask, a thin (<1 μm) layer of SiO2 suffices.

The principle of suspended photonic waveguides has already been demonstrated in literature. Suspended waveguides have been fabricated using various materials, e.g. polymer [4], InP [5], and Si [6]. While some research groups have described the release of SiO2 structures, the obtained structures have different properties than we aim for. Carpenter et al [7] reported on the fabrication of suspended SiO2 cantilevers, but the structures were produced by flame hydrolysis deposition instead of thermal oxidation. Ollier [8] described the fabrication of suspended SiO2 structures made of PECVD SiO2 instead of thermal SiO2. The SiO2 cantilevers fabricated by Chen et al [9] are in the thickness range from 4 μm to 6 μm and therefore do not meet our thickness requirements. It is important to mention that both Ollier [8] and Chen et al [9] included additional lateral beams in their design in order to reduce stress-induced out-of-plane bending of the structure. Wang [10] successfully released 2 μm thick thermal SiO2 with no additional lateral beams. The suspended SiO2 structures were instead supported by a 28 μm–38 μm thick layer of Si.

Reports on suspended structures realized out of SiO2 with a thickness around 15 μm were not found in literature. In our prior work [3], we demonstrated that the release of 15 μm thick SiO2 waveguide beams is hindered by beam failure due to compressive stress. When SiO2 is released from its Si substrate, the compressive stress is converted into strain. If a SiO2 structure is confined (e.g. in a doubly clamped beam situation), the strain will lead to buckling and the resulting stress concentrations can cause beam failure.

This paper offers a robust method to create >10 μm thick suspended SiO2 structures. These suspended structures are an essential element of our proposed alignment concept and the development of SiO2-based MEMS technology in general. The enabling technology and microfabrication process are explained in section 2. Section 3 presents and discusses the results of the proposed Si reinforcement method. Fabricated devices include suspended SiO2 structures with and without Si support. Furthermore, the feasibility of positioning the suspended SiO2 structures with microactuators is evaluated by estimating the beam spring constants and the beam curvature. Section 4 presents the conclusions.

2. Technology

2.1. Fabrication process

The realization of suspended SiO2–Si (henceforth referred to as bilayer) beam structures is accomplished by plasma etching both the SiO2 and the Si. Plasma etching is preferred over wet etching for releasing a suspended structure, to prevent stiction due to surface tension driven adhesion.

In this study, we describe the release of thermal SiO2 structures. The results of releasing suspended TriPleX structures are expected to be comparable to those obtained with thermal SiO2 structures, since the dominant factor leading to beam fracturing is the mean residual stress. Thermal SiO2 has a compressive mean residual stress resembling that of the TriPleX stack.

Figure 1 presents the steps of the single mask fabrication process. The starting material is a Si wafer with a thickness of ~525 μm and a 14.8 μm thick thermal SiO2 layer. A 6 μm-thick spray-coated layer of AZ9260 photoresist was applied on top of the SiO2 and patterned. The design of the photolithography mask allows control over in-plane dimensional parameters like the width and the length of the waveguide beams. The SiO2 was etched using a Drytek Triode 384T with C2F6–CHF3 chemistry (figure 1(b)). After etching through the SiO2 layer, the photoresist mask was not removed but was used once more to etch trenches in the Si (figure 1(c)). From this fabrication step on, an SPTS Omega i2L Rapier deep silicon etcher was used, unless stated otherwise. A trench depth of ~70 μm was realized by deep reactive ion etching (DRIE) and the trench width varied from 30 μm to 100 μm.

After etching the trench in the Si, a ~1 μm thick passivation layer was deposited (figure 1(d)), which was then locally removed from the trench bottom by directional ion bombardment (figure 1(e)). The CF4 passivation layer was deposited using C4F8 gas. SF6 gas and 75 W platen HF power were applied during the trench bottom removal. With the Si sidewalls protected, the Si underneath the beams was then removed by isotropic plasma etching (figure 1(f)). During this etch, SF6 was used without applying any platen HF power. Removal of the passivation layer and photoresist mask by an O2 plasma in a Tepla 300 plasma system resulted in suspended bilayer structures (figure 1(g)). As long as bilayer structures are required, no further processing is needed. In this study, the supporting Si was completely removed by performing additional fabrication steps. Another isotropic plasma etching step with SF6 gas was performed for 60 s, reducing the Si reinforcement (figure 1(h)). All the supporting Si was then removed by a final isotropic plasma etch of 210 s using SF6 (figure 1(i)). Two separate isotropic Si etch steps were performed to enable intermediary measurements.

The advantage of Si reinforcement can be demonstrated by comparing the release of a beam structure with and without Si
reinforcement. Figure 2 illustrates the state at a certain moment during the underetching of a SiO₂ beam structure without Si reinforcement. In this figure, the beam structure is almost entirely suspended. Only at the beam crossings, the SiO₂ is attached to the Si wafer. Due to the geometry of the beam structure, the release of the beams occurs before the beam crossings are released. The three beams, being suspended but also clamped at both ends (at their base and at the beam crossings), are actually doubly-clamped beams. These SiO₂ bridges, no longer supported by any Si, will expand and buckle, leading to stress concentrations and possibly beam failure.

Figure 3 illustrates the state at the same moment during the underetching of a SiO₂ beam structure using Si reinforcement. Again, the beam structure is suspended everywhere except at the beam crossings. However, the created bridges are bilayer structures instead of SiO₂ bridges. The supporting Si limits the expansion of the SiO₂, which results in lower stress concentrations, reducing the chance of beam failure.

Figure 4. Schematic representation of a SiO₂ beam structure during the underetching process without Si reinforcement.

Figure 5. Schematic representation of a SiO₂ beam structure during the underetching process with Si reinforcement.

In addition to the delayed release of beam crossings, another beam failure mechanism can be identified. Although isotropic etching is by definition a process with similar etch rates in all directions, the ‘isotropic’ plasma etch that was used in this study appeared to not be perfectly isotropic. For example, the etching of a rectangular window revealed a lower underetch rate in the corners compared to the underetch rate at the middle of the straight sections. This etch anisotropy caused doubly-clamped beam situations during the underetching of cantilever beams. Si reinforcement reduces the risk of cantilever beam fracturing caused by local etch rate differences. Similar to the situation depicted in figure 3, any doubly-clamped beams formed during underetching will be reinforced by the supporting Si.
2.2. Design

In order to test the effect of Si reinforcement on structures with and without beam crossings, the design included individual waveguide beams and waveguide beams connected at their free ends by a crossbar. The individual beams were designed in sets of one, two, and four parallel beams; the connected structures consisted of two and four parallel beams. All the beam structures were designed with a variety of lengths (250 μm, 500 μm, 750 μm, 1000 μm) and widths (18 μm, 26 μm, 34 μm). These dimensions are a trade-off between having a sufficient cladding thickness (for low propagation loss of future photonic waveguide beams) and obtaining a low bending stiffness (in order to position the beams using micro-actuators). Furthermore, test cantilevers were included with a designed width of 15 μm and a varying designed length. A single wafer contained 72 identical arrays of 60 cantilevers of which the length ranged from 10 μm to 1000 μm with a step size of 16.5 μm.

3. Results and discussion

3.1. Released structures

The realized structures were measured to be approximately 5 μm less wide than designed, resulting in 13 μm, 21 μm, 29 μm wide beams and 10 μm wide test cantilevers. The etch profile had a positive taper between 9° and 10°, resulting in a trapezoidal cross section of the SiO₂ beams. Figure 4 shows an angled view of one of the fabricated SiO₂ beams. The beam widths mentioned above are the mean values of the narrow top and the wider bottom of this trapezoid. The exact cause of the difference between the designed and the obtained width is under investigation. All the final structures had a measured thickness of 14 μm, roughly 0.8 μm less than the SiO₂ thickness at the start of the fabrication. This means that approximately 0.8 μm of SiO₂ was etched from the top surface after removal of the photoresist mask.

Figures 5 and 6 show four parallel suspended beams with and without supporting Si, respectively. The SiO₂ beams in both figures are 1000 μm in length and 13 μm in width.

Furthermore, suspended structures consisting of parallel waveguide beams, connected by a crossbar, were fabricated. Figure 7 shows a suspended SiO₂ structure consisting of 4 connected waveguide beams, each 1000 μm long and 13 μm wide.

The fabrication yield of single cantilevers was determined by counting the number of truncated test cantilevers. Based on a single wafer with 4320 cantilevers in total, an overall yield of 97.8% was observed. Up to a length of 750 μm, all
cantilevers were intact. Above this length, the number of truncated cantilevers increased with the cantilever length. The most affected cantilevers were the longest ones, resulting in a yield of 83% for the 1000 μm long cantilevers.

As opposed to the test cantilevers, the beam structures only showed incidental beam failure. This can be explained by the fact that they consist of beams that are wider than the test cantilevers, making them less fragile. Because of the large variation in beam length and beam width of the structures, the number of implementations of one version was limited. As a consequence, the number of realized beam structures of a specific size was too low to estimate the corresponding yield with any degree of confidence.

3.2. Beam deflection

This section discusses the initial out-of-plane bending of the suspended beams, which was caused by residual stress originating from the thermal oxidation. The profiles of cantilever beams were measured at room temperature using white light interferometric profilometry. A Bruker Contour GT-K 3D optical profilometer was used. Measurements were performed at three different moments during the fabrication process. The first measurement was performed after the release of the bilayer beam, the second after partly etching the supporting Si (i.e. another 210 s of etching), and the third after fully etching the supporting Si (i.e. another 210 s of etching). These three states correspond to steps (g)–(i) in figure 1 and will be referred to as ‘Released’, ‘Si-etch1’, and ‘Si-etch2’, respectively. Figure 8 schematically illustrates the cross sections at the three measured moments during fabrication.

The transverse deflection measurements (of which one example is presented in figure 9) show that the profile of the beam is different at the three fabrication states. The maximum deflection of the free end occurred after Si-etch1, and was almost 100 μm. The beam curvatures were retrieved by curve-fitting the measured profiles with a circle. Only the relevant part of every measurement was used for the curve fitting, indicated by the dashed vertical lines in figure 9. From the measured beam profiles two deformation effects can be distinguished.

3.2.1. Beam curvature. The first effect is an out-of-plane deflection with a constant radius of curvature, which was dependent on the amount of supporting Si. The curvature of the bilayer beams corresponded to a concave downward (r) profile for both the released and Si-etch1 state. However, the SiO2 beams revealed a small curvature in the opposite direction (concave upward, u).

The curvature at the different states during the release process depends on the configuration of and the residual stress in the bilayer beam. Residual stresses originate from the high temperature oxidation and the subsequent cooling down to room temperature in combination with the different thermal expansion coefficients of SiO2 and Si. As a consequence, the bilayer beam will show a curvature.

The amount of curvature is a non-linear function of the Si layer thickness. At the Released state (see figure 9), there will be a certain concave downward curvature, caused by the prevailing Si and SiO2 thickness. Etching of the Si reduces its thickness. In addition, the Si is also etched from the sides, reducing its width and resulting in an irregular cross-sectional shape, defined by the progressing etch fronts. These effects reduce the area moment of inertia of the Si layer and, as a consequence, the concave downward curvature increases during etching (Si-etch1 in figure 9). At small dimensions of the Si layer, the SiO2 layer becomes dominant in the mechanics of the beam, and the curvature decreases with etching of Si. When all the Si is etched, the SiO2 beam shows a small concave upward curvature (Si-etch2 in figure 9), which is caused by the intrinsic gradient stress present in thermal SiO2 [11, 12].

3.2.2. Slope at the base of the beam. The second effect is a negative slope at the base of the cantilever. At this location the Si under the cantilever is removed, leaving a Si sidewall beneath the cantilever base. The compressive and gradient stress in the SiO2 lead to deformation of the SiO2 near this Si sidewall. If a pure SiO2 cantilever is considered, the SiO2 layer is free to expand at its top, but is constrained by the stiff Si, which causes the initial negative slope. For the SiO2 beams, a negative slope of approximately 0.5° was observed. The initial slope of bilayer beams was smaller with increasing thickness of supporting Si.
3.2.3. Mean beam curvatures. The mean curvatures as a function of Si reinforcement of measured beam arrays (consisting of either four separate or connected beams) with a length of 250 μm, 500 μm, 750 μm, 1000 μm are presented in two separate figures. Figure 10 shows the mean curvatures of beams underetched with a narrow trench (∼30 μm), while figure 11 includes the mean curvatures resulting from a wide etch trench (∼100 μm). In both figures, a positive curvature corresponds to a concave downward profile. It is observed that the narrower trench resulted in a lower underetch rate, causing an increased degree of Si reinforcement after the same etch duration.

The curvature of the bilayer beams does not depend on the length. It does depend on the beam width, as can be seen in both figures. This can be explained by the differences in Si support. Different beam widths result in different cross sections of the Si part, affecting the curvature.

An unexpected observation is that the curvatures of the 13 μm wide beams after Si-etch1 (s1-a in figure 11) are much smaller than those of the wider beams (s1-b and s1-c in figure 11). Moreover, the beams with a similar width, but released using a narrow trench, do not show this decrease in curvature (see figure 10). The reason for this inconsistency is that a wider etch trench causes a higher etch rate. The 13 μm wide beams no longer have any Si reinforcement after Si-etch1, if they are released using a wide trench. However, the wider beams (s1-b and s1-c) are still supported by Si after Si-etch1, as well as the beams of similar width that are released using a narrow trench.

3.3. Beam bending stiffness

This section describes the bending stiffness of the SiO₂ beams. In the application of photonic alignment, integrated MEMS actuators will be implemented to position the array of waveguide beams. Because the available force of MEMS actuators is limited, the waveguide array should have a low bending stiffness. In order to obtain a rough estimate of the desired stiffness, one can imagine a microactuator capable of delivering 1 mN. The out-of-plane positioning of a waveguide array over a range of 5 μm requires a maximum array stiffness of 200 N m⁻¹. In case the waveguide array comprises ten parallel beams, this corresponds to an out-of-plane bending stiffness of individual beams of approximately 20 N m⁻¹.

The bending stiffness can be determined using the relation

Table 1. Determined out-of-plane bending stiffness values (mean and standard deviation) of SiO₂ cantilevers.

| Length (μm) | Width (μm) | Stiffness (N m⁻¹) |
|------------|------------|------------------|
|            | mean       | s                |
| 250        | 13         | 53.7             | 1.6       |
| 21         | 93.6       | 0.8              |
| 750        | 13         | 6.9              | 0.1       |
| 21         | 9.5        | 0.1              |
| 29         | 12.2       | < 0.1            |
| 1000       | 13         | 2.1              | < 0.1     |
| 21         | 2.9        | < 0.1            |
| 29         | 3.8        | < 0.1            |
| 13         | 0.8        | n/a              |
| 21         | 1.2        | < 0.1            |
| 29         | 1.6        | < 0.1            |

Figure 10. Beam curvatures measured at the different states during the release process. The error bars indicate the standard deviation from the mean value. This plot only includes the cantilevers with a narrow etch trench (∼30 μm).

Figure 11. Beam curvatures measured at the different states during the release process. The error bars indicate the standard deviation from the mean value. This plot only includes the cantilevers with a wide etch trench (∼100 μm).

Figure 12. Determined out-of-plane beam bending stiffness of SiO₂ cantilevers (not Si-reinforced) as a function of beam length, plotted for different cantilever widths.
\[ k = m_{\text{eff}}(2\pi f)^2, \]  
\[ I = \frac{1}{12}bh^3, \]

where \( k \) is the bending stiffness, \( m_{\text{eff}} \) is the effective mass, and \( f \) is the natural resonance frequency. The out-of-plane natural resonance frequency was measured with laser Doppler vibrometry at ambient conditions. The effective mass was based on dimensions which were estimated from scanning electron microscope (SEM) images.

The determined out-of-plane bending stiffness values of SiO₂ cantilevers (not Si-reinforced) are presented in table 1 and depicted in figure 12. The values for a length of 250 \( \mu \)m are included in the table, but are not shown in the graph, since they are not compatible with the photonic alignment concept. The determined bending stiffness values corresponding to a cantilever of 250 \( \mu \)m in length are greater than 50 N m\(^{-1}\). As seen in the rough calculation above, those stiffness values are outside our range of interest. All cantilevers with a length of 500 \( \mu \)m or more have a derived bending stiffness smaller than 20 N m\(^{-1}\) and therefore satisfy our stiffness requirement.

Figure 12 shows the decrease in stiffness with increasing cantilever length. The stiffness and length are related by the equation

\[ k = \frac{3EI}{L^3}. \]

with \( I \) the area moment of inertia, \( E \) is the Young’s modulus, \( I \) is the length of the cantilever. The data points in figure 12 corresponding to a specific width show a third power relationship, which is in accordance with (2).

For a specific cantilever length, the bending stiffness is expected to scale linearly with the cantilever width, because the area moment of inertia is proportional to the width. For a rectangular beam, the area moment of inertia is

\[ I = \frac{1}{12}bh^3, \]

reinforces the SiO₂ with Si, thereby reducing the risk of beam fracturing. Moreover, the fabrication process allows for a configurable thickness of the final Si support. The advantages of the Si reinforcement are control over the beam stiffness and a greatly enhanced design freedom for suspended SiO₂ structures. The fabrication yield was 97.8% for cantilever beams with a thickness of 14 \( \mu \)m, a width of 10 \( \mu \)m and a length ranging from 10 \( \mu \)m to 1000 \( \mu \)m. In addition to cantilever beams, more complex structures were successfully realized, consisting of parallel beams, connected by a crossbar at their free end.

The bilayer beams were measured to have a concave downward profile with a constant radius of curvature, which was observed to change as a function of Si support. SiO₂ beams without supporting Si were found to have a concave upward profile and a much smaller curvature. A 1000 \( \mu \)m long bilayer beam of 21 \( \mu \)m width was observed to have a radius of curvature of 10 mm after its release. Partly etching the supporting Si resulted in a smaller curvature, corresponding to a radius of curvature of 6.5 mm. After complete removal of the supporting silicon, the cantilever showed a concave upward profile with a radius of curvature of 402 mm.

The measured out-of-plane bending stiffness of the SiO₂ beams ranged from roughly 1 N m\(^{-1}\)–100 N m\(^{-1}\). The long beams (i.e. 500 \( \mu \)m and longer) are compliant enough to be positioned by microactuators. The short beams, however, are probably too stiff to be positioned by microactuators within the required motion range.

4. Conclusion

This paper has presented a robust microfabrication process for the release of SiO₂ structures. This novel process

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