A Novel Buckle-Free Large Rib Microdisk with Submicrometer Thickness

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Thin large microdisks, that are key to dense spectral microcomb generation at visible-to-UV wavelengths, face challenges in fabrication. One of the most difficult issues is the buckling effect that makes comb generation infeasible due to the severe degradation of cavity optical quality factor. Herein, a novel rib disk structure that significantly mitigates the buckling effects is introduced. Using this approach, millimeter-sized buckle-free microdisks with sub-micrometer thickness and high optical quality factor exceeding $10^7$ are obtained.

1. Introduction

Microcavities with high optical quality factors ($Q$) have been one of the most sought-after optical structures for many years. With applications ranging from biosensing and nanoparticle detection to quantum electrodynamics and comb generation, these devices have been at the forefront of many scientific endeavors.$^{[1–9]}$ In particular, cavity-based frequency comb generation has been a research hotspot for more than a decade due to its numerous applications in precision spectroscopy, metrology, and telecommunications.$^{[10]}$

One of the key underexplored areas for microcombs is in vitro precision spectroscopy for biomolecules. As biomolecules usually live in aqueous environments, visible-to-ultraviolet (UV) combs that have larger penetration depth and lower optical absorption in water are necessary. In addition, to discern the complex spectral structure of a biomolecule, the comb should have sufficient high comb tooth density. To emit at visible-to-UV wavelengths, the cavity has to have a submicrometer thickness to meet the anomalous dispersion requirement,$^{[11]}$ while to achieve high comb density, multimillimeter-diameter cavity that has a smaller free spectral range (FSR) is a must. Furthermore, to lower the pump threshold, the cavity should have high optical quality factor ($Q$). Finally, to integrate lab on a chip, comb fabrications on thin-film platforms are highly desirable. Among the thin-film platforms normally used to make microcavities, SiO$_2$ offers unique advantages. The low-loss nature of the thermally grown oxide on top of silicon, and compatibility of the platform with already existing CMOS fabrication technologies, made the silica-on-silicon (SoS) platform a great candidate for comb generation.$^{[12]}$ In this article, we focus on the fabrication of a large thin disk on SoS for visible comb generation, but the discussions are equally applicable to other platforms such as SiN and LiNbO$_3$, etc. due to the same challenges to overcome.

The fabrication of such large thin cavities while maintaining high $Q$ for a dense visible comb is challenging. One of the key obstacles on SoS is the stress build up at the interface between silica and silicon.$^{[13]}$ The stress arises from the fact that the two materials have different thermal expansion coefficients. Hence, when cooling down from high temperatures (exceeding 1000 °C when growing the oxide) to room temperature, significant stress buildup will occur at the oxide interface.$^{[14]}$ This hinders microdisk fabrication by buckling the edges of the disk at high undercuts and deteriorates the $Q$ of the disk. This issue is more severe in large disks, which are necessary for dense microcomb generation. Although large ultrahigh-$Q$ microdisks have been demonstrated without significant buckling problem, these devices were fabricated using thick ($\approx$8–10 μm) oxide layers, accompanied with tedious high-temperature annealing cycles to remove the stress.$^{[15–17]}$ For shorter wavelength, multilayer oxide disks with different wedge angles have been proposed before to provide a limited control on dispersion,$^{[18]}$ but a fabrication procedure for a large thin disk is still missing. To date, even with such a sophisticated procedure, only combs at 778 nm wavelengths and 20 GHz density built on a silica microdisk cavity with a diameter of 3.2 mm and 1.5 μm thickness are demonstrated,$^{[19]}$ while lower-wavelengths higher-density combs for biomolecule spectroscopy are yet to come. It has been shown that, for soliton microcomb generation, the needed anomalous dispersion at shorter wavelengths between 400 and 500 nm can only be satisfied with less-than-1 μm-thin oxides.$^{[11]}$ Thus, the need for thin oxide microdisks cannot be overstated. Our goal in this work is to fabricate a buckle-free ultrahigh-$Q$ large disk with the thin oxide, by introducing a new rib geometry. The approach introduced in this work can address the buckling challenge without limiting the size and the thickness of the disk and does not require any complicated postprocessing. Consequently, the fabricated device maintains a high optical quality factor. This, to the best of our
knowledge, is the first time such a remedy is demonstrated to solve the buckling problem in large thin microdisks.

2. Discussion

The proposed rib disk structure is shown in Figure 1a. The thin silica layer at the edge of the disk is supported by a thicker top part with slightly smaller diameter, which provides sufficient mechanical strength to prevent the thin edge from buckling. Further, we extracted the contour of the rib disk from the scanning electron microscope (SEM) micrograph and exported it to COMSOL for mode simulation. The intensity profile of the fundamental mode is plotted in the inset of Figure 2a, where an intrinsic $Q$ of $2.1 \times 10^{10}$ in the absence of surface scattering is predicted. In our experiment, we fabricated a 1 mm-diameter disk on an SoS wafer with a 4 μm-thick silica thin film. After chemomechanical polishing (see fabrication details in a later section), the thickness of the top part is about 3.2 μm while the rib edge thickness reduces to below 1.0 μm (see Figure 2a). The radius difference between the outer ring and the top support (the rib width) is from 20 to 30 μm (Figure 1e). As shown by the microscope picture in Figure 1c and SEM micrograph, Figure 1e, no evidence of buckling was observed even as we undercut the silicon pillar as far as 80 μm. In contrast, a 1 mm-diameter regular disk fabricated on a 2 μm silica thin film [The disk thickness is around 1.5 μm after polishing] (Figure 1b) with the same undercut displays severe buckling, as shown in the microscope image (Figure 1d) and SEM image (Figure 1f). Further, we measured the surface roughness of the rib disk using an atomic force microscope (AFM) both at the top and at the rib to see the smoothness of the surface. As shown in Figure 1g,h, the surface roughness root mean square (RMS) value of the top is slightly lower, and is about 0.33 nm, whereas the rib part has RMS value of 0.39 nm for surface roughness. This small discrepancy can be attributed to the disk geometry before polishing, where the top surface has more contact with the polishing pad due to the height difference between the top and the rib. It is worth mentioning that both roughness RMS values are close to what was obtained in previous works.[17] The AFM data were obtained on a 2 × 2 μm surface since the rib is not wide enough for large-area scans. Such smooth surfaces in combination with the absence of the buckles are key to maintaining the high $Q$ of such a large thin disk.

The fabrication process starts with defining a ring on a 4 μm-grown SoS wafer. To do so, a Raith 50 e-beam writer is used to define a ring pattern with desired width and diameter, in this case 980 μm inner diameter and 40 μm width, on Poly(methyl methacrylate) (PMMA) resist, followed by a developing step.

Figure 1. A 3D model of a) the proposed rib disk and b) a regular disk. The top-view micrograph c) shows no buckling on the rib disk edge while on d) the regular disk with the same size, thickness and undercut ratio it is severely buckled. e) Plot further shows the top-view SEM of the rib disk. The width of the disk rib is around 20 μm. f) The SEM image of a buckled regular disk. g,h) The AFM images at show the surface roughness of the top part and the rib part of the rib disk, respectively. RMS value obtained for each part is shown in the figure. Roughness RMS is 0.33 nm for the top part and 0.39 nm for the rib part. i–k) The fabrication steps of the rib disk. The white bars on optical microscope and SEM images are 50 μm each.
using MIBK solution. Then the wafer is wet etched using a buffered HF solution (Transene), to etch away the ring to about 1 μm. The PMMA resist is then washed away with acetone (Figure 1i). In this step, a ring-like trench is formed into the silica layer with the depth of around 3 μm. The next step is to define the disk on top of the ring. Note that the disk has to partially cover the ring. The overlap region between the two patterns defines the width of the rib. Disks are made using a photolithography step followed by HF wet etch all the way down to the silicon substrate and a polish-the rib. Disks are made using a photolithography step followed by HF wet etch all the way down to the silicon substrate and a polishing process to reduce the surface roughness of the disk and boost the overlap region between the two patterns defining the width of the rib. Disks are made using a photolithography step followed by HF wet etch all the way down to the silicon substrate and a polish. This also suggests that the regular disk remains mechanically stable, but the regular disk with the same dimensions and undercut buckles, while in the blue coloured region both structures show buckling. The blue “X” sign shows the fabrication condition for the disks in (b), and the white bar in SEM is 20 μm in length.

In this step, a top thicker disk is patterned with a 636.8 nm laser. The disk transmission spectrum of the highest Q at 973.85 nm (red detune) is shown as the blue trace of Figure 2b’s inset, which is fit to a Lorentzian function (red trace of Figure 2b’s inset) to obtain the intrinsic Q of the cavity. The Q degradation at shorter wavelengths can be attributed to more surface scattering at these wavelengths,[17,20] which may be improved through a refined chemomechanical polishing procedure. This also suggests that Q will be higher in the aqueous environments, as the surface scattering (Qss) is inversely proportional to the square of the difference between the two media’s refractive indices square.[20]

where \( \Delta \varepsilon = \varepsilon_r - \varepsilon_{r,0} \) is the relative permittivity difference between the cavity (\( \varepsilon_r \)) and the ambient (\( \varepsilon_{r,0} \)). Assuming a water relative permittivity of \( \varepsilon_{r,0} = 1.77 \) at 632 nm wavelength[21] and a silica relative permittivity \( \varepsilon_r = 2.10 \) at the same wavelength,[22] we expect an increase of \( Q_{ss} \) to \( 2 \times 10^7 \), when the comb is immersed in water. This will greatly lower the pump threshold for comb generation on in vitro spectral analysis of biomolecules.

To investigate the mitigation effectiveness, we conducted mechanical buckling simulations to our rib disk and a regular disk with the same thickness and diameter. To model the mechanical stability of our design, the thermal stress induced
by different thermal expansion coefficients in silica and in silicon is simulated in COMSOL Multiphysics via the finite-element method. The linear buckling study in COMSOL is used to derive the critical load factor (CLF). CLF is defined as the ratio of the minimum load, required for the buckling, to the existing load. A CLF less than 1 means that the structure would face instability under thermal stress. The buckling threshold derived analytically in the study by Chen et al.\textsuperscript{[13]} now can be calculated numerically by doing a 2D parameter sweep on disk radius \( R_0 \) and the undercut ratio \( \xi = 1 - \frac{R_p}{R_0} \) defined as 1 minus the ratio between the pillar \( R_p \) and disk \( R_D \) radii. A boundary between the buckled and unbuckled region can be obtained using numerical simulation on linear buckling for any thickness. This boundary, in our simulations, is defined by the contour of CLF = 1.

Our simulation in Figure 2d displays the unity CLF contour of our rib disk (red curve) and a regular disk with the same disk thickness of 1 \( \mu \text{m} \) (black curve). In general, the left-hand side of the curve shows CLFs higher than 1, which means that the disk remains unbuckled. The right-hand side of the curve shows CLFs below 1; hence, the disks will buckle. Consequently, both rib and regular disks in the blue region will buckle. The yellow region in Figure 2d shows the area in which the rib disk remains stable, but a regular disk will buckle. Further, in the white region, neither the regular disk nor the rib disk will buckle. The cross marker represents the configuration \((R_0 = 0.5 \text{ mm} \text{ and } \xi = 0.17)\) of the regular and rib disk we fabricated (also see Figure 1c,d). In our simulation, we assume that the samples cool down from the growth temperature (1300 K) to room temperature, where fabrication takes place, to determine the stress and associated strain on the silica disks. By doing that, CLFs of 0.503, and 3.826 are obtained for rib disk and conventional disk, respectively. Therefore, the normal disk with the size and thickness specified will buckle (Figure 2b) with a vertical displacement variation of around 5 \( \mu \text{m} \) at disk edge(left). On the other hand, the rib disk with the same size will remain mechanically stable even at high undercuts (Figure 2b) (right) with no observable displacement variation at the disk edge. These simulations are perfectly in par with the experimental results shown earlier. In Supporting Information, we further present two animation videos showing the stress-induced displacement when the disks were cooled down from 1300 to 300 K, one for the rib disk and the other for the conventional disk. As shown, buckling starts to form when the conventional disk is cooled down to 900 K. On the other hand, the rib disk does not show any sign of buckling through the whole cooling process.

In Figure 3, we investigate the dispersion relation of the rib disk in Figure 2a (blue trace) and an unbuckled conventional disk demonstrated in another study\textsuperscript{[17]} (red trace). We assume both cavities are immersed in water. As shown, in a wavelength span of 50 nm between 750 and 800 nm, the fundamental mode in rib structure shows an anomalous dispersion (gray area) at above 775 nm, indicating that generation of soliton even at this mode is possible. In contrast the same mode in conventional disk shows a large normal dispersion as shown by the red curve. It is also worth mentioning that the only soliton microcomb generation at similar wavelengths was reported when the cavity was placed in air.\textsuperscript{[11]} In that case, anomalous dispersion was achieved through a sophisticated hybridization of high-order modes due to the difficulties in making thinner disks without buckling. With our proposed rib structure, the dispersion can be directly controlled by tuning the thickness of the rib in the fabrication process, since thinner ribs have zero dispersion at shorter wavelengths.\textsuperscript{[11]} The insets in the figure further display the fundamental-mode intensity profile of the rib (upper inset) and conventional (lower inset) disks. As shown, when immersed in water, in the absence of scattering loss, an intrinsic \( Q \) as high as \( 1.1 \times 10^8 \) can be obtained for the rib disk and \( 3.6 \times 10^8 \) for the conventional disk at a wavelength of 775 nm. The combined anomalous dispersion and high-\( Q \) properties of the rib disk predict that low-pump-threshold soliton microcomb generation at fundamental mode is feasible in an aqueous environment, which opens a door for future in vitro single-protein spectroscopy.

3. Conclusion

In conclusion, we have demonstrated a novel buckle-free rib microdisk structure with high-quality factors. Using the developed fabrication procedure, a 1 mm-diameter and thinner-than-1 \( \mu \text{m} \)-thick rib disk at a \( Q \) above 10 million was demonstrated. With a refined fabrication, our simulation predicts that the larger and thinner buckling-free high-\( Q \) disk can be made. In future research, such a rib disk will be developed to generate dense soliton microcombs at visible wavelengths, that may enable in vitro label-free single-molecule spectroscopy. In addition, the rib structure can be directly adopted to other material platforms such as SiN, LiNbO\(_3\), etc. to make a large disk with enhanced mechanical rigidity. More importantly, as a novel cavity structure, many photonic properties are yet to be explored.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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