High-Q silica microdisk optical resonators with large wedge angles on a silicon chip

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We experimentally demonstrate high optical quality factor silica microdisk resonators on a silicon chip with large wedge angles by reactive ion etching. For 2-μm-thick microresonators, we have achieved wedge angles of 59°, 63°, 70°, and 79° with optical quality factors of 2.4×10^7, 8.1×10^6, 5.9×10^6, and 7.4×10^6, respectively, from ~80 μm-diameter microresonators in the 1550 nm wavelength band. Also, for 1-μm-thick microresonators, we have obtained an optical quality factor of 7.3×10^6 with a wedge angle of 74°. © 2015 Chinese Laser Press

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1. INTRODUCTION

Whispering gallery mode (WGM) optical microresonators, owing to their high quality factors and small mode volumes, have been widely used in cavity quantum electrodynamics, optical communication, nonlinear optics, chemical/biological sensing, and cavity optomechanics [1,2]. Recently, coupled optical microresonators have attracted more and more attention for their potential applications in coupled-resonator optical waveguides [3,4], analogues to electromagnetically induced transparency [5–7], quantum information processing [8,9], phonon lasers [10], parity-time-symmetric optics [11,12], etc.

So far, chip-based high-Q optical microresonators have been realized using various kinds of materials such as silicon [13,14], silicon nitride [15], silica [16–19], III–V semiconductor [20,21], polymer [22,23], and diamond [24]. Among them, silica optical microresonators, in the forms of toroid [16], sphere [17], and disk [18,19], exhibit ultrahigh optical quality factors on chip due to their ultralow material absorption and extremely smooth surfaces. For the silica microtoroid [16] and microsphere [17] cavities, their quality factors are obtained by reducing the surface roughness down to atomic scale with the help of CO_2 laser reflow. However, this process significantly shrinks the diameters of the microcavities, which limits their applications in device integration and makes it challenging to fabricate two or more microcavities close to each other on the same silicon chip. Recently, a wedge-shaped silica disk resonator (7.5 mm diameter) with a wedge angle smaller than 30° has achieved the record optical quality factor of 8.75×10^8 on chip [19]. However, to boost the optical quality factor of this structure, the silica disk is over etched using buffered HF, which makes the size of the disk smaller than the original pattern on the photomask [18,19]. Also, the small-angle wedge structure pushes the optical WGMs away from the disk perimeter [18,19], which further limits certain device applications in coupled microresonators.

Here, we fabricate a class of high optical quality factor silica microdisk resonators with large wedge angles using the reactive ion etching process. In previous works, dry-etched silica microdisk resonators including single-layer [25,26] and double-layer [27,28] structures have been demonstrated with quality factors of $\sim 5 \times 10^5$ for coupled microresonators [25,26] and with a quality factor of 1.75×10^6 for gradient-force-actuated cavity optomechanics [27,28]. Moreover, these microdisk resonators were fabricated using metal or e-beam resist as a mask for reactive ion etching, which limited the Q-factor or the thickness of the microresonators. In this work, we demonstrate dry-etched silica microdisk resonators on a silicon chip with large wedge angles due to the anisotropic nature of dry etching using photoresist as an etch mask. We have obtained silica microdisk resonators with thickness as large as 2 μm and a record Q-factor of 2.4×10^7 for dry-etched silica microdisk cavities on chip at the wavelength of ~1550 nm.

2. DEVICE FABRICATION AND MEASURED RESULTS

As shown in Fig. 1, the fabrication process for the silica microdisk resonators mainly contains four steps. First, a NSR-1755i7B stepper is used to pattern the photoresist (AZ 6130) on a thermally grown silicon oxide film with a thickness of 1 or 2 μm. After exposure, a post-exposure bake is performed to reduce the sidewall roughness of the photoresist pattern. Then, the reactive ion etching with $SF_6/CHF_3/He$ chemistry is employed to transfer the pattern of the photoresist onto the silicon oxide layer. The residual photoresist after the reactive ion etching is removed using the photoresist remover (AZ remover 700) followed by H_2SO_4/H_2O_2 solution. Finally, the silica microdisk is undercut by the

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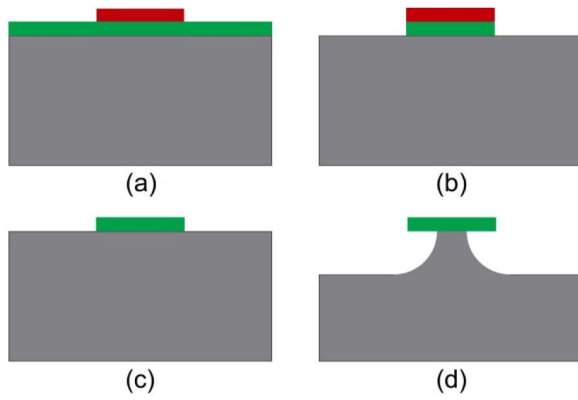

Fig. 1. Fabrication process of the silica microdisk resonator. (a) Photolithography to pattern the photoresist onto a silicon oxide layer. (b) Reactive ion etching to transfer the pattern of the photoresist into the silicon oxide layer. (c) Remove the residual photoresist using photoresist remover and H_2SO_4/H_2O_2 solution. (d) Undercut the silica microdisk resonator using XeF_2 dry etching to form a silicon pillar.

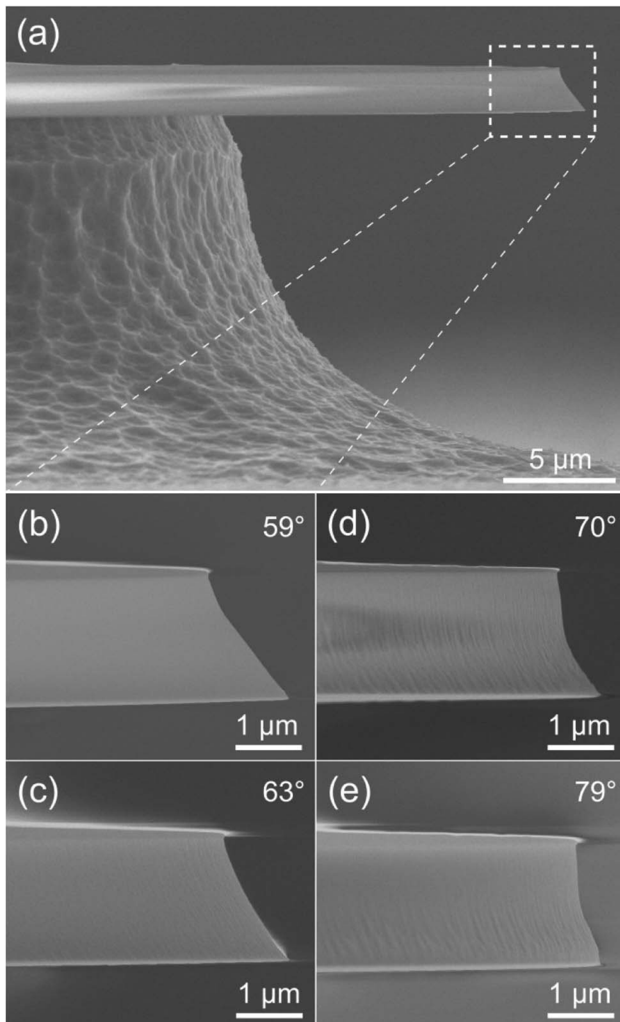

Fig. 2. (a) Side-view SEM image of a silica microdisk resonator with a wedge angle of 59°. (b)–(e) Close-view SEM images of the silica microdisk resonators with wedge angles of 59°, 63°, 70°, and 79°, respectively. The diameter and the thickness of the microdisk resonators are 80 and 2 μm, respectively.

XeF_2 dry etching to form a silicon pillar. Figures 2(a)–2(e) show the typical scanning electron microscope (SEM) images of the fabricated silica microdisk resonators with a thickness of 2 μm. By changing the radio frequency power during the fabrication process, we have obtained silica microdisk resonators with different wedge angles of 59°, 63°, 70°, and 79°, respectively [Figs. 2(b)–2(e)], which are much larger than those of the previously demonstrated silica microresonators fabricated using the buffered HF wet etching process [18,19]. The diameters of the silica microdisks are around 80 μm, which is very close to the size of the patterned photoresist mask.

In order to characterize the fabricated silica microdisk resonator, a tapered optical fiber is used to excite the WGMs of the microresonator via the evanescent wave [29]. A tunable external cavity semiconductor laser (New Focus, model TLB-6328) with a linewidth of less than 300 kHz is coupled into the fiber taper to measure the transmission spectrum of the microresonator by scanning the wavelength of the laser. During the experiment, the measured resonant linewidths of the cavity modes are calibrated by a fiber Mach–Zehnder interferometer, and the silica microdisk resonator is kept in a nitrogen-purged enclosure to prevent unwanted water and particle contaminations.

Figure 3(a) shows the measured transmission spectrum of a fundamental TE-like mode from the 59°-wedge-angle silica microdisk resonator with a thickness of 2 μm and a diameter

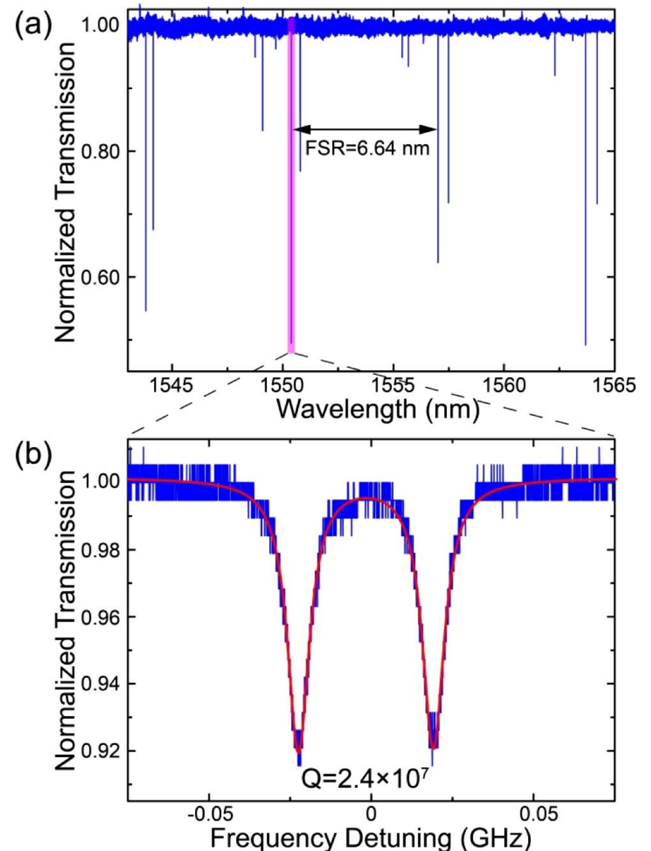

Fig. 3. (a) Normalized transmission spectrum of a fundamental TE-like mode from a 2-μm-thick silica microdisk resonator with the wedge angle of 59°. (b) Detailed scan spectrum of the high-Q cavity mode at the wavelength of ~1550.4 nm.

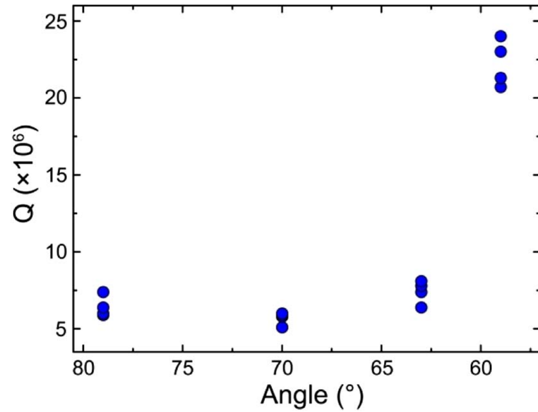

Fig. 4. Experimentally realized quality factors of the silica microdisk resonators with different wedge angles. The diameter and the thickness of the microdisk resonators are kept to 80 and 2 μm, respectively.

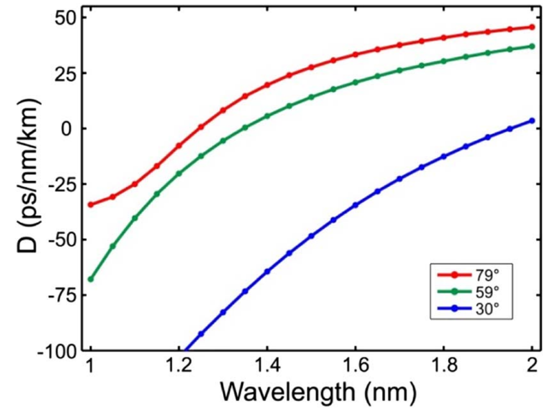

Fig. 5. Simulated group velocity dispersion as a function of wavelength for the fundamental TE-like mode of the silica microdisk resonators with wedge angles of 30°, 59°, and 79°. The diameter and the thickness of the microdisk resonators are kept to 80 and 2 μm, respectively.

of ∼80 μm. The measured free spectral range (FSR) is 6.64 nm, in good agreement with the value calculated from the diameter of the silica microdisk. Figure 3(b) presents the detailed transmission spectrum of this fundamental mode at the wavelength of ∼1550.4 nm. The doublet feature in the transmission spectrum is due to the mode splitting caused by the mode coupling between the clockwise and counterclockwise propagation modes [30]. The measured intrinsic quality factor for this microdisk resonator is 2.4×10^7, corresponding to a finesse of $\sim 1.0 \times 10^5$. This optical quality factor of the dry-etched microdisk resonator is ∼48 times higher than the previously reported single-layer silica microdisk resonators [25,26], ∼14 times larger than the double-layer silica microdisk resonator [27,28], and even closer to the wet-etched silica microdisk resonators with similar diameter and thickness [18,19]. Figure 4 shows the intrinsic quality factors of the experimentally realized silica microdisk resonators with different wedge angles of 59°, 63°, 70°, and 79°. The best quality factors for the 63°, 70°, and 79° microresonators are 8.1×10^6, 5.9×10^6, and 7.4×10^6, respectively. Here, the difference in the quality factors for different wedge-angle microresonators is mainly determined by the roughness of the sidewall induced during the reactive ion etching, as shown in Fig. 2. In addition, in order to get a smaller mode volume for the microresonator, we have also fabricated 1-μm-thick silica microdisk resonators with a wedge angle of 74° and obtained the optical Q-factor to be as large as 7.3×10^6. The optical quality factors of the dry-etched silica microdisk resonators might be further improved by optimizing the fabrication processes, such as the photolithography and reactive ion etching, as well as fabricating disk resonators with larger diameter and thicker silicon oxide layer [19].

3. DISCUSSION

As the dispersion is very important in many nonlinear processes, e.g., parametric oscillation [31], it is worth mentioning that the geometric dispersion and hence the total dispersion can be efficiently controlled by changing the wedge angles. Figure 5 shows the simulated group velocity dispersion of the fundamental TE-like mode for the silica microdisk resonators with wedge angles of 30°, 59°, and 79°, from which we can clearly see that the zero dispersion points shift significantly to shorter wavelengths with the increase of the wedge angles [32]. Also, the dispersion of the microdisk resonators with larger wedge angles moves to the anomalous dispersion region in the 1550 nm wavelength band, which will be helpful for the generation of Kerr frequency combs [33–35].

4. CONCLUSIONS

In conclusion, dry-etched silica microdisk resonators with different large wedge angles have been demonstrated on a silicon chip. A Q-factor as high as 2.4×10^7 is observed from an 80-μm-diameter microdisk resonator with a thickness of 2 μm and a wedge angle of 59°. This kind of high-Q silica microdisk resonator with a large wedge angle will enable monolithic integration of the microdisk resonators coupled to a waveguide and will be useful in coupled-resonator optical waveguides, nonlinear optics, and cavity optomechanics.

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