Silica-based microcavity fabricated by wet etching*

H Long(龙浩), W Yang(杨文), L Y Ying(应磊莹), and B P Zhang(张保平)†

Department of Electronic Engineering, Optoelectronics Engineering Research Center, Xiamen University, Xiamen 361005, *China*

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Silica whispering gallery mode (WGM) microcavities were fabricated by the buffered oxide etcher and potassium hydroxide wet etching technique without any subsequent chemical or laser treatments. The silicon pedestal underneath was an octagonal pyramid, thus providing a pointed connection area with the top silica microdisk while weakly influencing the resonance modes. The sidewalls of our microdisks were wedge shaped, which was believed to be an advantage for the mode confinement. Efficient coupling from and to the 60 μm diameter microdisk structure was achieved using tapered optical fibres, exhibiting a quality factor of 1.5×10^4 near a wavelength of 1550 nm. Many resonance modes were observed, and double transverse electric modes were identified by theoretical calculations. The quality factor of the microdisks was also analysed to deduce the cavity roughness. The wet etching technique provides a more convenient avenue to fabricate WGM microdisks than conventional fabrication methods.

Keywords: whispering gallery mode, wet etching, quality factor

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1. Introduction

In contrast with Fabry–Perot microcavities, distributed feedback (DFB) microcavities and photonic crystal defect microcavities, whispering gallery mode (WGM) microcavities confine light near a circular ring boundary via total internal reflection and exhibit an excellent quality factor ($Q > 10^8$) and a small mode volume.[1] The WGM structure has been successfully applied in sensors, laser diodes, quantum electrodynamics (QED), optical filters, and nonlinear optics.[2–7] Thus far, WGM microcavities have been fabricated from InGaP, GaN, AlGaAs, CaF_2, Si, SiO_2, etc.[8–14] Among these, silica-based microcavities offer the advantages of visible-light transparency, simple processing, efficient coupling, and easy integration with silicon-based electronics. Compared with 3D microcavities (i.e., microsphere), 2D microcavities (microrings, microtoroids, and microdisks) offer benefits such as simpler processing, higher coupling efficiency, and ideality.[1] Currently, most 2D silica microcavities are fabricated by dry etching a silica thin film and a silicon pedestal underneath. Firstly, the silica microdisk pattern is formed by buffered oxide etcher (BOE) etching, and then, the silicon pedestal was fabricated by a dry etching (i.e., XeF_2) process.[15–17] Because of the destruction and degradation caused by dry etching, excess chemical or laser treatments were needed, which increased the fabrication complexity and reshaped the silica microdisk reshape into a microtoroid. In 2003, Kippenberg *et al.* manufactured silica microdisks only by BOE etching and XeF_2 dry etching.[8] Although a quality factor of 10^5 was obtained, a large connection area between the silicon pedestal and the top silica microdisk could not be avoided, which influenced the WGM resonance to a certain extent.[18] In this article, a complete wet etching technique is introduced to fabricate silica WGM microdisks without any subsequent chemical or laser treatment, exhibiting a smooth surface and controllable size. Wedge-shaped sidewalls were also observed, which were believed to positively affect the mode confinement. The WGM modes were coupled from and to the microdisks by utilizing tapered optical fibres, with a quality factor of 1.5×10^4 around a wavelength of 1550 nm. Many resonance modes were observed, including two fundamental transverse electric (TE) modes. A roughness of about 395 nm was deduced from the cavity quality factor.

2. Experiments and discussion

First, a silicon wafer was thermally dry-wet-dry oxidized in a furnace, thus achieving a silica layer with a thickness of about 1.6 μm, as measured by a step profile system. Then, a 360 nm thick Cr metal mask with a nominal diameter of 60 μm was grown by magnetic sputtering to define the microdisk pattern for subsequent photolithography and peel-off processes, as shown in Fig. 1. Next, the silica was etched by a BOE solution. Finally, the microdisk on a silicon pedestal was achieved by wet etching in a 40 wt% KOH solution in a hot bath at 60 °C with ultrasonication.

Figure 2 shows plan-view and side-view scanning electron microscopy (SEM) images of a 60 μm diameter silica microdisk after 45 min of KOH etching. The silica microdisks

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†Corresponding author. E-mail: bzhang@xmu.edu.cn

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exhibit periodic alignment. The diameter of the final fabricated microdisk was 56.64 μm, which is slightly smaller than the designed size. The sidewall of the microdisk exhibited a wedge shape, which was induced by the BOE etching and undercutting of the photoresist pad. The width of the wedge sidewall was about 770 nm (Fig. 2(d)). A similar structure and morphology were also observed by Vahala *et al.*, who utilized BOE to etch silica.[8] According to Bo's calculations, the wedge-shaped sidewalls could be useful in confining the resonance modes into the perimeter of the microdisks, thus enhancing the quality factor and reducing the mode volume.[19] Meanwhile, microdisk optical cavities also require small pedestals,[18,20,21] while the conventional dry etching of silicon (i.e., XeF_2) produces unavoidably large connection areas with silica microdisks. In our wet etching technique, the silicon pedestal formed into octagonal pyramids, which could theoretically be connected with silica by the top point if the etching time is precisely controlled. In the case of the 56.64 μm diameter microdisk, the base length of the octagonal pyramid was about 17.27 μm, while the height of the silicon supporting pillar was about 13.47 μm. The etching ratio between the horizontal and vertical directions was about 3:1. The octagonal pyramid facets were inclined from the flat surface by about 76.2°, which may indicate the (331) silicon crystal facet. A similar anisotropic etching profile was also observed by Minas *et al.*, who reported octagonal pyramids from the anisotropic wet etching of Cr-masked silicon by a KOH and isopropanol alcohol solution.[22]

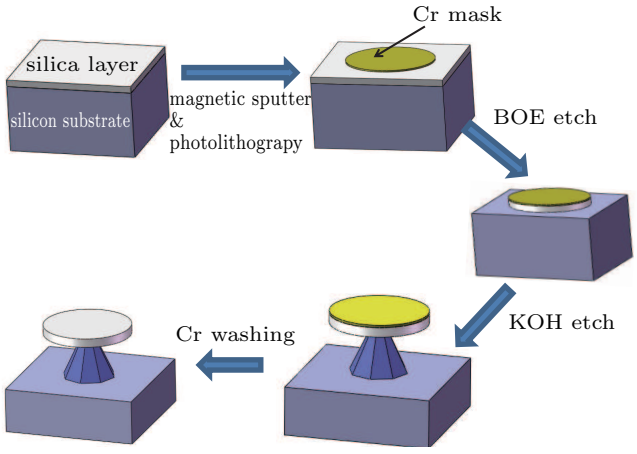


Fig. 1. (color online) Fabrication scheme of a silica microdisk.

To analyse the quality factors and mode spectrum, the transmission spectrum was measured around a wavelength of 1550 nm by coupling the photons of a tapered optical fibre to the disk resonator (Fig. 3(a)). Tapers with diameters of 1–2 μm were used, and efficient coupling was achieved. The tapered fibre was attached to a 3D controlled stage that allows the precise positioning of fibres with respect to the silicon-substrate-containing microdisks. Figure 3(b) shows the taper transmission spectrum after the resonance mode was coupled to the disks. Many WGM resonance frequencies were obtained in the transmission, including high-Q TE-like modes and modes that are higher order in the radial and angular directions. Similarly, various modes were observed in diamond microdisks by Khanaliloo *et al.*[20] and bottle microresonators by Zeravas *et al.*,[23] which may be common phenomena in a high-order resonance region. To further identify the modes, a finite-different time-domain (FDTD) method was applied to calculate the eigen-frequencies of the 56.64 μm silica microdisks. Fundamental TE and transverse magnetic (TM) modes were simulated. The geometry was built based on a 2D silica disk surrounded by air. The electric intensity of the light field obeys Maxwell equations

$$\nabla\times\mu^{-1}(\nabla\times\boldsymbol{E})-k_0^2\left(\varepsilon_{\mathrm{r}}-\frac{\mathrm{j}\sigma}{w\varepsilon_0}\right)\boldsymbol{E}=0.$$

A scattering boundary condition was adopted

$$n(\nabla\times\boldsymbol{E})-\mathrm{j}kn\times(\boldsymbol{E}\times n)=0.$$

Based on the simulation, over the measurement range, two longitudinal fundamental TE modes could be identified, $TE_{168,1}$ and $TE_{169,1}$, which were the 168 and 169 order modes around the angular direction. The experimental results agreed well with theoretical calculations, showing free spectral range (FSR) of about 8.74 nm between adjacent TE fundamental modes.

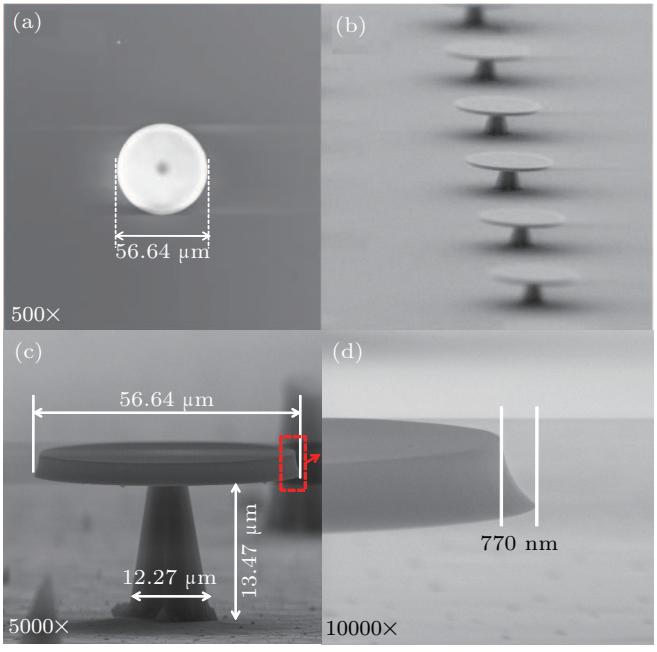


Fig. 2. (color online) Plan-view (a) and side-view ((b), (c), (d)) SEM images of 56.64 μm diameter silica microdisks.

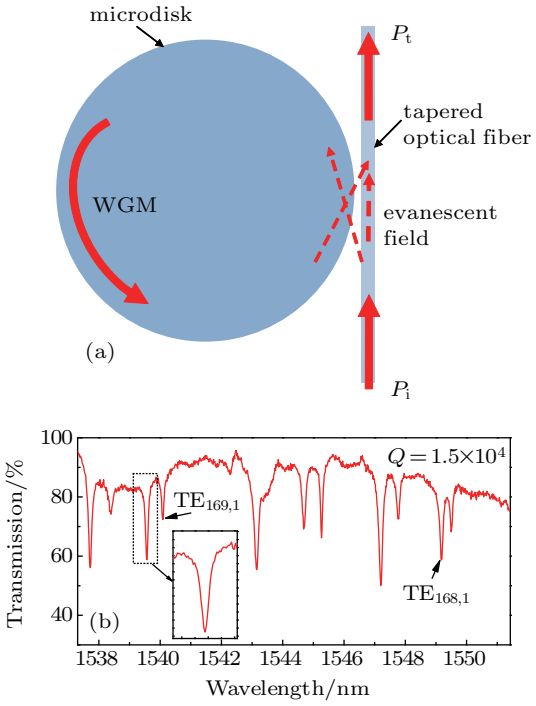


Fig. 3. (color online) (a) Coupling between the microdisk and tapered optical fibre; and (b) mode spectrum of 56.64 μm diameter silica microdisk around 1550 nm.

The highest quality factor of modes around 1550 nm was about 1.5×10^4, which is on the same level of state-of-the-art microdisks.[8,20] The cavity ring-down lifetime τ was 12.25 ps as calculated by: $\tau = Q/\omega$; where ω is the angular frequency of the resonator mode.[21] The quality factor of the microcavity consists of the intrinsic absorption loss Q_i^{-1}, the radiation loss Q_r^{-1}, and the surface scattering Q_s^{-1}

$$Q^{-1} = Q_i^{-1} + Q_r^{-1} + Q_s^{-1}.$$

The intrinsic absorption loss $Q_i^{-1} = \alpha\lambda/2\pi n$, where α, λ, and n are the absorption coefficient, resonant wavelength, and refractive index, respectively. Silica has been widely applied in optical communications at 1550 nm. The absorption coefficient of silica at 1550 nm is only 0.2 dB/km, which induces an absorption loss $Q_i^{-1} = 5\times10^{-11}$.[24] The radiation loss Q_r^{-1} was induced by the light radiation process and was inversely related to the disk diameter. In the 56.64 μm microdisk, the radiation loss Q_r^{-1} should be less than 10^{-11}.[21,24] Generally, the scattering loss dominated the cavity loss mechanism and determined the cavity quality factor, which is related to the square of the roughness

$$Q_{\text{scatt}} = \frac{\lambda^2 R}{\pi^2 \sigma^2 B},$$

where R is the radius, σ is the roughness, and B is the correlation length of surface inhomogeneity, which was reported to be 3 nm for silica.[25] Taking the experimental radius of 28.32 nm, the $TE_{169,1}$ wavelength of 1540.09 nm and the quality factor of 1.5×10^4, a roughness of about 395 nm was obtained.

The roughness calculated from the scattering quality factor comprised the roughness of the top and bottom surfaces as well as that of the sidewalls. The top surface of the silica microdisks was characterized as atomically flat by atomic force microscopy (AFM), as shown in Fig. 4, with a root-mean-square (RMS) roughness of only 0.469 nm. Therefore, the coarse sidewall and bottom surface dominated the 395 nm cavity roughness and therefore limited the quality factor of the microdisks. In our experiment, a 40 wt% KOH solution was utilized, which yielded the fastest SiO_2 etching rate. In future studies, optimizing the KOH concentration and reducing the etching temperature are expected to improve the surface and sidewall roughness, thereby enhancing the quality factors.

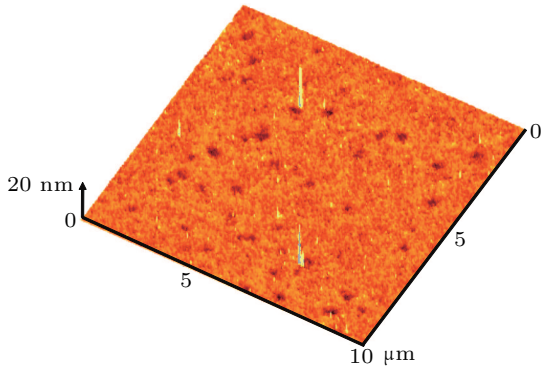


Fig. 4. (color online) AFM image of silica microdisk surface.

3. Conclusion

This paper introduced a convenient, efficient path to fabricate silica WGM microdisks. A periodic array of silica microdisks with diameters of approximately 60 μm was successfully achieved. A smooth surface and wedge sidewall were observed by SEM, which was believed to be beneficial for confining the light field. The WGM resonance field was coupled to the microdisk utilizing tapered optical fibres, showing many resonance modes around 1550 nm. Respective TE modes were identified by theoretical calculations. The quality factor of our silica microdisk was about 1.5×10^4, which was mainly due to the scattering from the bottom surface and sidewall. We believe the KOH wet etching technique could be a novel, facile way to realize WGM microdisk resonance.

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