Fabrication of SiO_2 microdisk optical resonator

Wei Wei (尉 伟)[1], Xiaowei Wu (吴晓伟)[2], Shaojun Fu (付绍军)[1], Yong Wang (王 勇)[1],
Yuanji Pei (裴元吉)[1], Yunfeng Xiao (肖云峰)[2], and Zhengfu Han (韩正甫)[2]

[1] *National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029*
[2] *Key Laboratory of Quantum Information, Chinese Academy of Sciences,*
University of Science and Technology of China, Hefei 230026

Received May 16, 2007

The silica microdisk optical resonator which exhibits whispering-gallery-type modes with quality factors of 9.67×10^4 is fabricated with photolithographic techniques. Reactive ion beam etching (RIBE) is used to get the silica disks with photoresist masks on SiO_2/Si made by standard ultraviolet (UV) photolithography, and spontaneous silicon etching by XeF_2 is used to fabricate the silicon micropillars. This fabrication process can control the microcavity geometry, leading to high experiment repeatability and controllable cavity modes. These characteristics are important for many applications in which the microcavity is necessary, such as the quantum gate.

OCIS codes: 140.4780, 230.4000, 230.5750, 270.5580.

Optical resonators can confine light and storage light energy. They include Fabry-Perot (F-P) cavities formed by two parallel mirrors, travelling wave cavities based on (almost) total internal reflection (TIR), and Bragg cavities based on distributed Bragg reflection (DBR) from periodical structures. Optical microresonators based on TIR can realize small mode volume, sensitivity to surrounding environment, and internal high field intensity which leads to strong coupling between atoms and optical field, so they have fundamental applications in optoelectronics technologies such as cavity quantum electrodynamics (QED) experiments[1], spontaneous emission control[2], nonlinear optics[3], bio-chemical sensing[4], and quantum information processing[5].

In recent years, some theoretical and experimental schemes have been proposed to realize quantum computation and quantum computer, in which the quantum gate is one of the most pivotal devices. Among proposals based on atoms, molecules, quantum dots, super conduction and linear optics[5], the proposal based on cavity QED is one of the most potential ones to realize quantum gates. According to the demand of the realization of QED quantum gates, optical resonators should have high mode quality factor (Q factor), small modal volume, large free spectral range (FSR), and controllable cavity modes[6]. So the fabrication of high quality optical microresonators is the fundamental process.

Optical microresonators which work in the form of whispering gallery mode (WGM) are motivated by the pioneering work of Ilchenko *et al.*[7]. Some of the high quality optical microresonators such as microcylinders, microdisks, and microspheres to date have been achieved. The combination of their ultrahigh Q factor, very small mode volume, and relatively easy fabrication, makes them become potential means for cavity QED experiments. Although with lower Q factor than microsphere and toroid cavities, microdisk cavities which can achieve Q factors higher than 10^5[8] are now being studied too. Compared with microspheres which support $(2l+1)$ azimuthal modes, this kind of resonator supports very few radial and azimuthal modes, so in principle this cavity system is allowed for single mode operations with smaller mode volume, which lead to high coherent coupling factor $g(r)=(\mu^2\omega_c/2h\varepsilon_0 V_m)^{1/2}$ between an individual atom and a WGM field of interest[6], where r is the lifetime, ω_c is the cavity resonance frequency, h is the scattering-induced coupling between the two counter-propagating modes of the microcavity, μ and ε_0 are atom coefficients, V_m is the mode volume. Compared with other kinds of microresonators, microdisk resonator can achieve controllable geometry and high experiment repeatability, which indicates the controllable cavity modes. Furthermore, with the assistance of tapered waveguides, microdisk resonators allow integration of a lot of quantum logic components on a silicon chip, which enhances the physical capability of the realization of quantum computation and quantum computer[6,9,10].

The object of our research was to fabricate the microdisk resonators for quantum gates. In the fabrication experiments of circle microdisk resonators, the effects of various technical parameters on microcavities' quality were investigated.

The fabricated microdisk cavities were SiO_2 disks, which were supported by silicon micropillars to form edges divorcing from silicon so as to avoid circumjacent disturbing. So the following fabrication steps were adopted: silicon wafers coated with certain thickness SiO_2 were painted with photoresistant (PR); mask patterns were transferred to PR over silica with standard photolithograph; PR patterns were transferred to silica layer with ion beam etching (IBE); silicon under the silica disk was etched with isotropic silicon etching to form mushroom-like microresonators.

The processes of fabrication experiments were as follows:

1) Wafers preprocessing.

2) PR painting. AZ1400 photoresist was painted on wafers with rotation painting.

3) Photolithograph including exposal and developing.

4) Etching of SiO_2. In this research, SiO_2 was etched

with reactive ion beam etching (RIBE) with Ar+CHF_3 mixture gases to ensure the transfer of PR figures to SiO_2 layer, as well as satisfying SiO_2 etching rate[11].

5) Etching of Si under SiO_2 microdisk. To protect the formed SiO_2 microdisks, the XeF_2 silicon etching was chosen to form silicon micropillars. Optical microresonators fabricated with this etching method could be easily controlled with high precision and little pollution[12].

6) Removing residual PR.

Every fabrication step was important to achieve microcavity with excellent performance, so the parameters of each step have been optimized through experiments. In the fabrication, to confirm the fabrication quality, the result and status of every step should be examined and analyzed to find feasible parameters. RIBM in LKJ-1C-150 IBE system (Spacefight Ministry 23rd Institute) with 1:2 flux ratio Ar/CHF_3 mixture gases and 3×10^{-2} Pa working pressure was performed to form the SiO_2microdisks. Wafers were inclined according to some special etching purpose, and rotated during etching process to achieve uniform etching rate in various directions. The cooling system of etching device could help to control wafers temperature to avoid the PR deformation caused by ion bombardment during etching. In real etching process, SiO_2 etching rate of 25 nm/min was achieved with 40-mA ion beam, 500-eV ion energy, 280-V acceleration voltage, and 48-mA neutralization current.

Selective silicon etching with XeF_2 was performed in XeF_2 etching system which had been designed and constructed in house, as shown in Fig. 1. The silicon etching rate of 0.3 μm/circle has achieved with the etching pressure of 200 Pa.

Optical microscope (OM) photo and scanning electron microscopic (SEM) photos of a 60-μm-diameter SiO_2 microdisk are shown in Figs. 2 and 3. In both figures, the microdisk has smooth edge without obvious roughness and deformation. As shown in Fig. 2, the intersection curve between silica microdisk and silicon micropillar is not smooth and has anomalous distortion, which is caused by the XeF_2 etching of silicon, but this distortion hardly has effect on the performance of microcavity. Measured by SEM, the microresonator's diameter was the same as that of the mask and PR figure in the former step, which indicated that the geometry factor of mask figures could be held in the fabrication process and there were little negative effect on microresonator sidewall and surface during RIBE to form silica microdisk and XeF_2 etching to form silicon pillar.

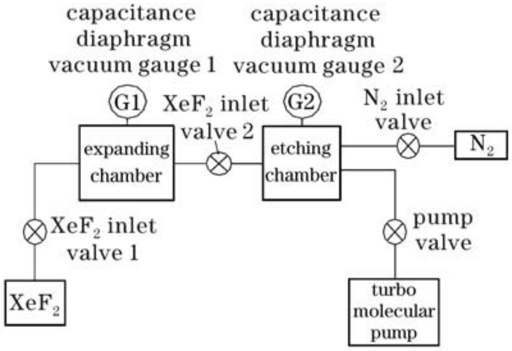

Fig. 1. Diagram of XeF_2 etching system.

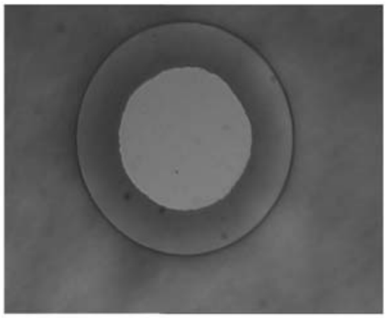

Fig. 2. Optical microscope photograph of a 60-μm-diameter circle microdisk resonator.

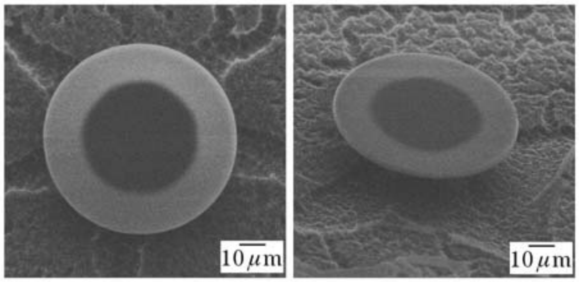

Fig. 3. SEM photograph of a 60-μm-diameter circle microdisk resonator.

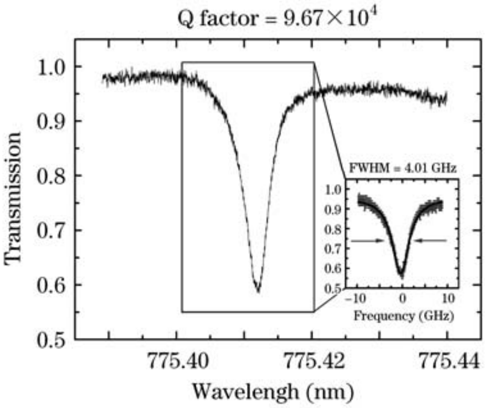

Fig. 4. Q factor of a 60-μm-diameter microdisk resonator.

To measure the Q factor of microdisk resonator, a tapered fiber was used to couple microdisk, and a laser was used to excite resonance at 780-nm band[13]. By measuring the full-width at half-maximum (FWHM) of the Lorentzian-shaped resonance in the undercoupled regime, the Q factor of 9.67×10^4 was observed, as shown in Fig. 4.

In summary, the microdisk optical resonators have been fabricated with optical microfabrication, which can achieve high Q factor and be free from negative characteristics of microsphere cavity. Fabrication process with standard photolithography and dry etching can achieve geometry control and repeatable fabrication of high Q factor microdisk cavity. Mask figures can be transferred to SiO_2 layer to form silica microresonators with RIBE accurately. There are little negative effect on microresonator sidewall and surface during RIBE and XeF_2 etching processes. The repeatable and controllable microresonators fabrication process can provide the favorable elementary technical basis of the development of quantum gates.

This work was supported by the National Natural Science Foundation of China (No. 60537020 and 60121503), the Science and Technology Ministry of China (No. 2006CB921900), and the Knowledge Innovation Program of the Chinese Academy of Sciences. Z. Han is the author to whom the correspondence should be addressed, his e-mail address is zfhan@ustc.edu.cn.

References

1. D. W. Vernooy, A. Furusawa, N. Ph. Georgiades, V. S. Ilchenko, and H. J. Kimble, Phys. Rev. A **57,** 2293 (1998).
2. S. M. Spillane, T. J. Kippenberg, and K. J. Vahala, Nature **415,** 621 (2002).
3. R. E. Slusher, Semicond. Sci. Technol. **9,** 2025 (1994).
4. T. Aoki, B. Dayan, and E. Wilcut, Nature **443,** 671 (2006).
5. M. A. Nielson and I. L. Chuang, *Quantum Computation and Quantum Information I: Quantum Computation* (in Chinese) (Q. Zhao trans.) (Tsinghua University Press, Beijing, 2004) pp.256—318.
6. Y.-F. Xiao, Z.-F. Han, and G.-C. Guo, Phys. Rev. A **73,** 052324 (2006).
7. V. S. Ilchenoko, X. S. Yao, and L. Maleki, Opt. Lett. **24,** 723 (1999).
8. T. J. Kippenberg, S. M. Spillane, D. K. Armani, and K. J. Vahala, Appl. Phys. Lett. **83,** 797 (2003).
9. D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, Nature **421,** 905 (2003).
10. S. M. Spillane, T. J. Kippenberg, and O. J. Painter, Phys. Rev. Lett. **91,** 3902 (2003).
11. Y. Liu, D. Xu, X. Xu, X. Zhou, Y. Hong, and S. Fu, Journal of University of Science and Technology of China (in Chinese) **37,** 536 (2007).
12. W. Wei, X. Wu, F. Lu, Y. Xiao, S. Fu, Y. Pei, and Z. Han, Journal of University of Science and Technology of China (in Chinese) (to be published).
13. X. Wu, Y. Xiao, Y. Yang, C. Dong, Z. Han, and G. Guo, Chin. Opt. Lett. **5,** 668 (2007).