FABRICATION OF ELECTROSTATICALLY-ACTUATED, IN-PLANE FUSED QUARTZ RESONATORS USING SILICON-ON-QUARTZ (SOQ) BONDING AND QUARTZ DRIE

Young-Suk Hwang[1], *Hyoung-Kyoon Jung*[1], *Eun-Seok Song*[1], *Ik-Jae Hyeon*[2], *Yong-Kweon Kim*[1], *and Chang-Wook Baek*[2,*]
[1]Seoul National University, Seoul, KOREA
[2]Chung-Ang University, Seoul, KOREA
[*]Corresponding author: cwbaek@cau.ac.kr

ABSTRACT

This paper reports a novel process to fabricate *electrostatically-actuated*, in-plane micromechanical resonators made of *fused quartz* for high-*Q* microsensor applications. Two key processes – low temperature plasma-assisted Silicon-on-Quartz (SoQ) direct bonding and quartz DRIE using C_4F_8/He plasma – have been used in combination with thin metallization to fabricate fused quartz resonators driven by electrostatic force. The proposed method enables wafer-level fabrication of fused quartz resonators readily mounted on the substrate, which is advantageous over the conventional fabrication method of quartz crystal resonators. By using the proposed process, 40-μm-thick laterally-driven fused quartz cantilever resonators have been successfully fabricated. The measured *Q*-values of the metal-coated fused quartz cantilevers are 21,700~48,900 according to the length of the cantilever.

INTRODUCTION

Quartz material has been applied to resonators in time keepers, oscillators and high-frequency filters, as well as to microsensors such as piezoelectric micro gyroscopes and quartz crystal microbalances (QCM), because of high quality factors, low aging rates and good temperature stability of quartz [1-3]. In these classical applications, quartz devices are usually manufactured from a single crystal quartz wafer of proper cuts such as X, Z, or AT. Orientation-dependent anisotropic etching property of single crystal quartz in an ammonium bifluoride solution has been used to make quartz microstructures [4]. Also, piezoelectricity of single crystal quartz is suitable for driving/sensing of quartz resonators and sensors.

On the other hand, fused quartz is also a very good resonator material which has a high quality factor, and has been used for bulk hemispherical resonator gyroscopes (HRG). Especially, fused quartz is known to have a very low thermoelastic damping, which is a dominant loss mechanism in microscale, compared to silicon or single-crystal quartz [5]. However, fused quartz has not been frequently used for micromechanical resonators because high aspect ratio, precise anisotropic etching is difficult since wet etching technique does not work anymore, and piezoelectric properties for actuation/sensing are lost.

Recent advances in SiO_2 DRIE technology make it possible to fabricate high aspect ratio, thick glass or quartz microstructures with good sidewall profiles [6, 7]. Therefore, DRIE technique is a useful tool for micromachining of fused quartz, which has no specific crystal orientations. In addition, low-temperature wafer bonding between dissimilar materials such as silicon, SiO_2, or quartz have been reported [8, 9]. If quartz DRIE is properly combined with wafer bonding techniques, fused quartz resonant microstructures can be fabricated in a similar way to produce silicon resonators using the anodically-bonded SiOG wafer, as reported in our previous result [10]. In this case, by conformal coating of fused quartz with a very thin metal film, quartz resonators *actuated by electrostatic force* with high *Q*-factors due to the excellent properties of fused quartz can be realized.

In this paper, a novel process to fabricate laterally-driven electrostatic fused quartz resonators is proposed by using Silicon-on-Quartz (SoQ) bonding and quartz DRIE. A low temperature, plasma-assisted SoQ bonding is developed, and the bonded silicon wafer is used for both a quartz DRIE mask and a handling wafer of quartz devices. Fused quartz is used as the device layer for resonators, and patterned by DRIE using a C_4F_8/He gas mixture with the bonded silicon mask. By bonding a trench-formed silicon wafer with a fused quartz wafer, and coating a thin metal film on the fused quartz, wafer-level fabrication of electrostatically-actuated fused quartz resonators is possible. In order to demonstrate the usefulness of the propose method for high-*Q* resonant quartz devices, fused quartz cantilever resonators have been fabricated and their resonant frequencies and *Q*-factors have been evaluated.

FABRICATION PROCESS DETAILS

SoQ (Silicon-on -Quartz) direct bonding

In this study, SoQ direct bonding process has been developed for two purposes. A silicon wafer bonded with a quartz wafer can be used as an excellent etch mask for quartz DRIE. In DRIE of glass or quartz, metal masks (e.g. aluminum or nickel) are general due to their superior etch selectivity (~10) over resist masks. However, in order to etch quartz more than tens of microns, a thick metal layer is needed, which in turn requires an additional process like electroplating [6]. The wafer-bonded silicon is a good alternative for an etch mask of quartz: it has a high etch selectivity (>15), the thickness of silicon can be easily adjusted within a full range of wafer thickness, and silicon is precisely patterned by DRIE. In addition, the wafer bonded silicon can also be used as a handling substrate for the fabricated quartz devices. In contrast to the conventional fabrication process of quartz crystal resonators, in which each resonator is separately etched from quartz crystal and mounted to the package individually, wafer bonding approach enables to fabricate quartz resonators self-mounted on the handing substrate in wafer level. Also, it can provide an opportunity for wafer-level packaging of quartz devices.

In this work, an oxygen plasma-assisted bonding process is used to keep the bonding temperature as low as possible. Low temperature bonding is important since thermal expansion coefficients of silicon and quartz are quite different. The process details are summarized in Fig. 1. First, 4-inch, 500-µm-thick double-side polished silicon and fused quartz (VIOSIL-SX, ShinEtsu) wafers are cleaned by standard RCA1 solution. RCA1 cleaning removes surface contaminants and makes the surface hydrophilic with OH$^-$ terminations in order for spontaneous bonding to occur [8]. Then the wafers are exposed to oxygen plasma in RIE mode to activate the wafer surfaces. It is known that the physical/chemical effects of plasma treatment increase surface energies, which help to obtain higher bonding strength at a relatively low annealing temperature [9]. After plasma treatment, the wafers are rinsed in DI water and brought into contact at room temperature for the spontaneous bonding to be occurred. Finally, the wafers are annealed at a temperature of 300 °C for 8 hours to increase the bonding strength.

Bonding experiments under different plasma treatment conditions have been performed using the proposed bonding procedures. As a typical result, photograph of the SoQ wafer, where a quartz wafer is bonded onto a silicon wafer with 5-µm-deep trenches, is shown in Fig. 2. Shear strength of the bonded wafer for each condition has been measured by System 522 universal bond tester. The highest bonding strength of 10 MPa is obtained at a minimal oxygen plasma treatment time of 15 seconds. The measured strength is about half of the nominal strength of anodic bonding (~20 MPa), but is sufficient to sustain subsequent chemical thinning or mechanical polishing processes.

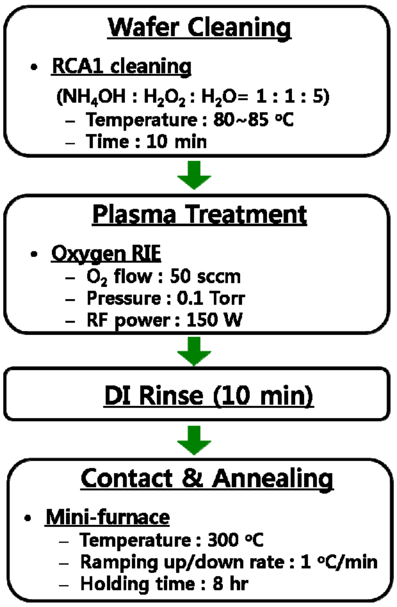

Figure 1: Process flow of SoQ bonding.

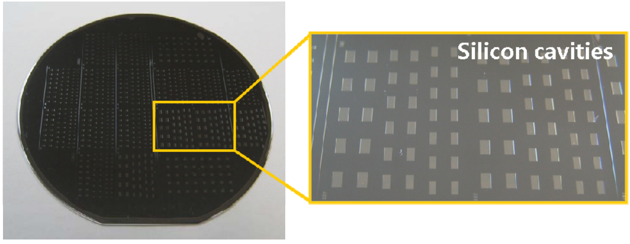

Figure 2: Photograph of the bonded SoQ wafer. Fused quartz wafer is bonded onto the silicon wafer with 5-µm-deep trenches.

Quartz DRIE using wafer-bonded silicon mask

Quartz DRIE process has been studied using an AOE (Advanced Oxide Etcher, STS) system with a gas mixture of C_4F_8 and He due to its excellent selectivity for silicon mask. A single crystal silicon wafer is bonded with the fused quartz wafer using the developed process, thinned down to 30 µm by lapping and CMP, and patterned bysilicon DRIE. Using this silicon mask, DRIE of fused quartz has been performed. Process conditions are summarized in Table 1.

Table 1: Process conditions for quartz DRIE.

Process parameters	Values
Gas flow	C_4F_8 = 18 sccm He = 25 sccm
Chamber pressure	4 mTorr
Antenna power	1300 W
Bias power	500 W

The SEM image of the etched 50-µm-thick fused quartz microstructures is shown in Fig. 3. Almost vertical profile angle is achieved by using the above process conditions. Etch rate and selectivity are measured to be 0.38 µm/min and 15:1, respectively. Effect of He flow rate on the etch rate of quartz is negligible, but etch selectivity is improved as He flow rate is increased. However, too much increase of He flow is not effective to eliminate so-called a cusping effect, which is the distortion of etch profile at the bottom of the structure [10]. Since the thickness of silicon mask is sufficiently large to overcome the decrease of etch selectivity, He flow rate was reduced in our experiment. Deep etching of quartz more than 50 µm will be possible using this bonded silicon mask.

Fabrication of electrostatic fused quartz resonators

Based on the developed SoQ bonding and quartz DRIE techniques, a simple two-mask, wafer-level process to fabricate electrostatic fused quartz resonators has been designed. The fabrication process flow is illustrated in Fig. 4. It starts with forming 5-µm-deep trenches by DRIE in a single-crystal silicon wafer. This silicon wafer becomes a supporting substrate of quartz devices. The trenches are

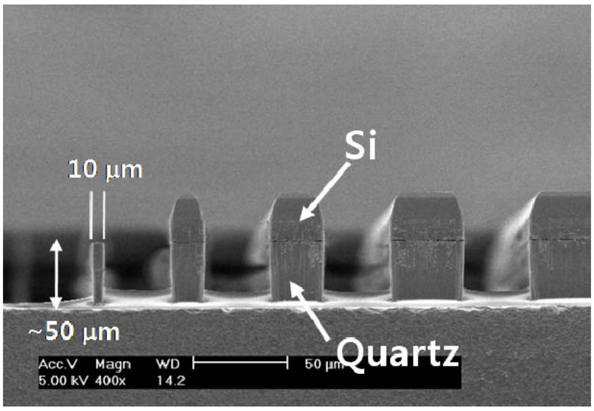

Figure 3: SEM image of 50-µm-thick quartz microstructures etched by DRIE using the bonded silicon mask layer.

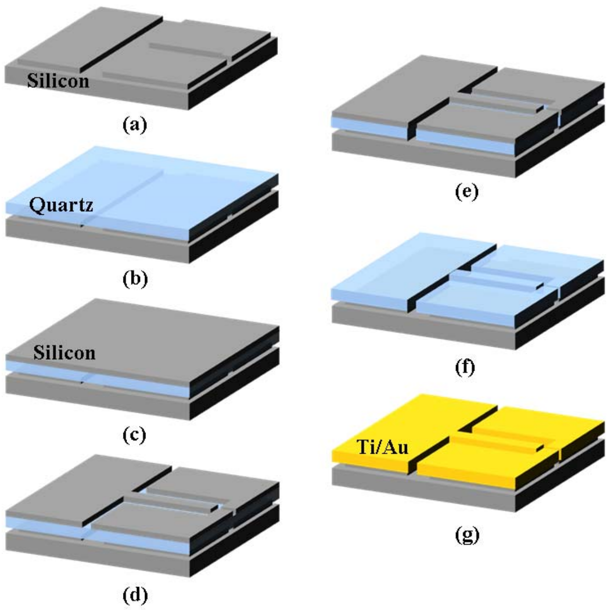

Figure 4: Fabrication process of electrostatic fused quartz resonators: (a) trench formation by Si DRIE, (b) 1st SoQ bonding and quartz thinning, (c) 2nd SoQ bonding and Si thinning, (d) Si mask formation by Si DRIE, (e) Quartz DRIE, (f) Si mask removal, and (g) sputtering of thin metal films.

formed to electrically isolate driving electrodes from the resonator through the silicon substrate, as well as to release resonators automatically at the moment quartz DRIE is finished. This trench-formed silicon substrate is bonded to a fused quartz wafer. After reducing the thickness of the quartz wafer down to the target value of 40 µm by lapping and CMP, another silicon wafer is bonded onto the surface of quartz. The second silicon wafer is also thinned down to 30 µm and patterned by DRIE to form silicon etch masks for quartz DRIE. After quartz DRIE using C_4F_8/He plasma, the silicon mask is removed by DRIE. Finally, the exposed quartz surface is metallized with a conformal coating of Ti/Au (5/50 nm) by sputtering to make the quartz layer conductive for electrostatic actuation.

In order to show the feasibility of the process, cantilever resonators having beam lengths of 900~1200 µm have been fabricated. Photographs of the fabricated fused quartz resonator wafer and the die attached on the PCB board are shown in Fig. 5. Due to the pre-etched trenches, individual cantilevers and two neighboring electrodes are kept electrically disconnected after sputtering. SEM images of the fabricated fused quartz cantilever are shown in Fig. 6. The width of the fabricated beam is 12.8 µm, which is reduced from the designed value of 20 µm due to the lateral overetching during the process.

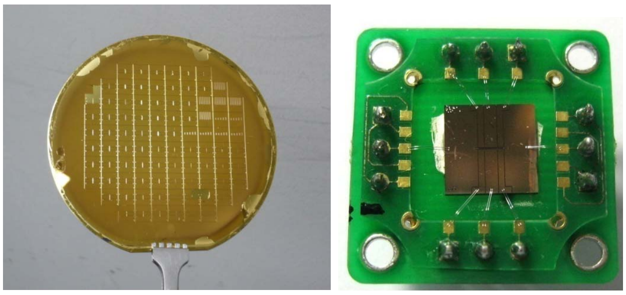

Figure 5: Photograph of the wafer-level fabricated fused quartz resonator and the resonator die attached on the PCB board.

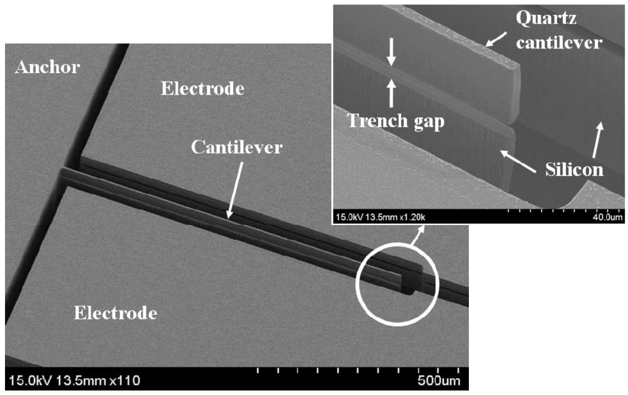

Figure 6: SEM images of the fabricated fused quartz cantilever resonator.

EXPERIMETAL RESULTS

Resonant frequencies and quality factors of the fabricated fused quartz cantilever resonators have been measured using Micro System Analyzer (MSA-400, Polytec) under a vacuum level of < 2 mTorr. The resonator wafer is placed in the SUSS vacuum chamber, and the DC bias voltage of $V_P = 7$ V and ac driving voltage of $v_{pk\text{-}pk} = 1$ V are applied between one of the electrodes and the DC bias voltage of $V_P = 7$ V and ac driving voltage of $v_{pk\text{-}pk} = 1$ V are applied between one of the electrodes and the cantilever. The fundamental mode resonant frequency is determined first using the out-of-plane laser Doppler vibrometry. Fast, broadband sweeping is possible in this mode because of the extremely high sensitivity of the system. Then the in-plane motion of interest is analyzed using stroboscopic video microscopy by narrowband sweeping around the resonant frequency.

A typical measured frequency response curve of the cantilever resonator is shown in Fig. 7. Quality factors are evaluated from the frequency response using the equation $Q = f/\Delta f$, where f is the resonant frequency and Δf is the 3-dB bandwidth. The measured resonant frequencies and quality factors are summarized in Table 2. The resonator

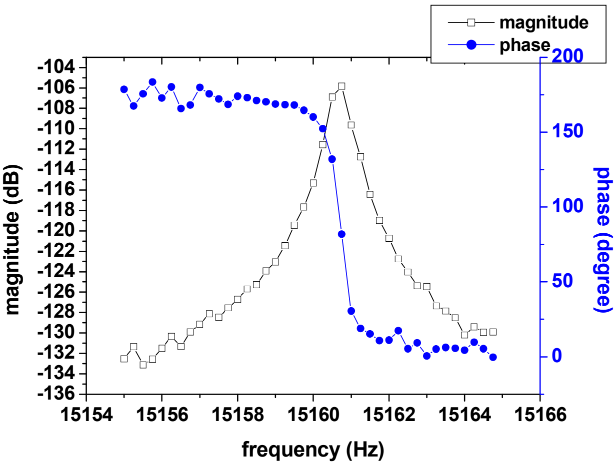

Figure 7: Typical measured frequency response of the fabricated fused quartz cantilever (length of the beam L = 900 µm, width of the beam w = 12.8 µm, thickness of the beam t = 40 µm). Measurement is performed at a vacuum of 2 mTorr.

Table 2: The fundamental resonant frequencies and quality factors of the fabricated fused quartz cantilever resonators.

Beam length [μm]	**Measured resonant frequency [kHz]**	**Quality factors**			
		Measured Q	**$Q_{support}$ (calculated)**	**Q_{TED} (calculated)**	**$Q_{support+TED}$ (calculated)**
900	**15.16**	**33,100**	753,300	907,300	411,600
1000	**12.16**	**38,100**	1,033,000	830,800	460,500
1100	**10.11**	**48,900**	1,375,000	793,500	503,200
1200	**8.33**	**21,700**	1,786,000	784,800	545,200

Q-values from 21,700 to 48,900 are obtained according to the beam length of the cantilever. Support quality factor ($Q_{support}$) and thermoelastic damping quality factor (Q_{TED}) of the quartz cantilever calculated from the analytic models given in [11] are also included in Table 2 for comparisons. The measured quality factors are lower than those from the analytic models by an order of magnitude. Degradation of quality factors might be attributed partially to the surface loss due to the defects and absorbed contaminants at the quartz surface during and after quartz DRIE process. Another possible reason is internal energy loss in the thin metal film deposited on the quartz surface for resonator actuation. According to our FEM simulation results, the resonant frequency of the cantilever is not significantly changed by coating of very thin metal film. However, it is reported that even very thin metal coating of 100 nm may reduce quality factors by more than an order of magnitude [12]. It is expected that further reduction of the metal thickness or partial removal of metal unnecessary for actuation will increase quality factors of fused quartz resonators further.

CONCLUSIONS

In this work, a novel process combining SoQ direct bonding and quartz DRIE has been proposed to demonstrate electrostatically-actuated fused quartz resonators for high-Q microsensor applications. Two processes of plasma-assisted SoQ bonding and quartz DRIE using wafer-bonded silicon masks are utilized, and these approaches enable us to fabricate resonator arrays supported on the handling substrate in wafer level. Fused quartz cantilever resonators with a thin film metal coating have been fabricated and their resonant frequencies and quality factors have been measured. The measured quality factors are from 21,700 to 48,900. The proposed technique will be very useful to develop quartz-based high-Q microsensors, taking advantages of extremely low thermoelastic damping of fused quartz and simple electrostatic actuation mechanism.

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