PIEZOELECTRICALLY OPERATED ACTUATORS BY QUARTZ MICROMACHINING FOR OPTICAL APPLICATION

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ABSTRACT

We report the new type of a monolithic quartz actuator which is fabricated by anisotropic etching and operated through piezoelectric effect at resonant frequency. The quartz actuators with large displacement have not been developed because quartz has small piezoelectric constants compared to other materials such as PZT. However, we proved that a smart mechanism enabled us to have a large displacement up to 200 microns with a millimeter size suspended actuator using the piezoelectricity of quartz. As examples, we fabricated bellows type actuators and optical choppers, and measured their mechanical characteristics. We also showed that the bellows type actuator could displace a small object statically by hitting it repeatedly. This woodpecker motion can be applied to move the small optical component such as a mirror and prism to switch the path of light.

1 INTRODUCTION

One of the most promising applications of MEMS in near future is micro-optics. Micromachined devices such as an interferometer [1] and a display [2] were reported. Our research interest is to change the path of light mechanically for micro-optics. In order to regulate the beam of light, the optical component such as a micro mirror and prism should displace at least greater than the diameter of beam. Considering the core diameter of multi-mode optical fiber for example, we need the component and displacement greater than 20 μm .

Quartz is a suitable material for our purpose because of following reasons: Quartz is (1) transparent, (2) chemically inert and stable. (3) Wafers of wide range in thickness are available. (4) Vertical surface of high aspect ratio can be formed by anisotropic etching. (5) It has piezoelectricity. Recently many researchers have developed the passive devices such as a pressure sensor [3] and a gyroscopic sensor [4] with quartz, converting the mechanical strain into polarization through direct piezoelectric effect. Also, converse piezoelectricity can generate mechanical strain with applied electric field, thus we can use it for active devices such as quartz oscillators. However, the quartz actuator with large displacement has not been developed because the piezoelectric constants are very small compared to those of other materials such as PZT.

In this paper, we propose a simple and smart mechanism to obtain large displacement with resonant type quartz actuators operated through piezoelectricity. As examples we fabricated bellows type actuators and monolithic optical choppers. Their measured and theoretical characteristics are reported.

2 PIEZOELECTRIC OPERATION

In order to activate the piezoelectric strain, the orientation dependence of piezoelectric effect should be carefully considered. The piezoelectric constants are written in tensor form as follows:

$$\{e_{ij}\} = \begin{pmatrix} e_{11} & e_{12} & 0 & e_{14} & 0 & \\ 0 & 0 & 0 & 0 & e_{25} & e_{26} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \qquad (1)$$

$$\begin{aligned} e_{11} &= -e_{12} = -e_{26} = 0.17 \quad \mathrm{C/m^2}. \\ e_{14} &= -e_{25} = 0.04 \quad \mathrm{C/m^2}. \end{aligned}$$

$$\boldsymbol{T} = -e^{t}\boldsymbol{E}. \qquad (2)$$

where $\boldsymbol{T}$ is mechanical strain and $\boldsymbol{E}$ is applied electric field. These show that the electric field along ±X generates expanding or shrinking strain along Y-axis via piezoelectric

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constant e_{12}. Therefore, if direction of applied electric field is alternatively distributed in a quartz Y-rod, the distribution of excited strain deflects the rods like a stretched letter of "S".

In order to distribute the direction of electric field alternatively in the rod, we have three choices to arrange electrodes as shown in Fig.1. In scheme (a), electrodes exist on top, bottom, and side surfaces. Therefore, the electric field penetrates inwards on section A, and outwards on section B as illustrated in the same figure. Thus, the piezoelectric strain is alternatively distributed.

Note that only electric field along X-axis is concerned to set the strain, *i.e.* the field along Z-axis does not have any effect because the piezoelectric constant $e_{31} \ldots e_{36}$ are all null. The similar effect as (a) is expected with scheme (b) and (c). They are easier to fabricate than (a) because they have no pattern on the side wall, but have meandering electrodes on top and bottom. Because scheme (b) has cross junction of electrodes, we adopted (c) for the simplicity of fabrication.

Figure 2 shows the result of FEM (Finite Element Method) piezoelectric simulation by ANSYS^{TM} (revision 4.4). The model used was a quartz Y-rod of 2 mm long, 50 μm wide, and 100 μm thick with the electrodes arranged as scheme (c). Elastic constants used are shown in Table 1. The bottom end is fixed to the ground, and top end is restricted to rotate around Z-axis. The calculated static displacement A_S at the top is as small as 0.1 μm along X-axis under the applied voltage of 100 V. However, if we have a large quality factor Q, we can expect a large resonant amplitude A_r because A_r is Q times as large as A_S.

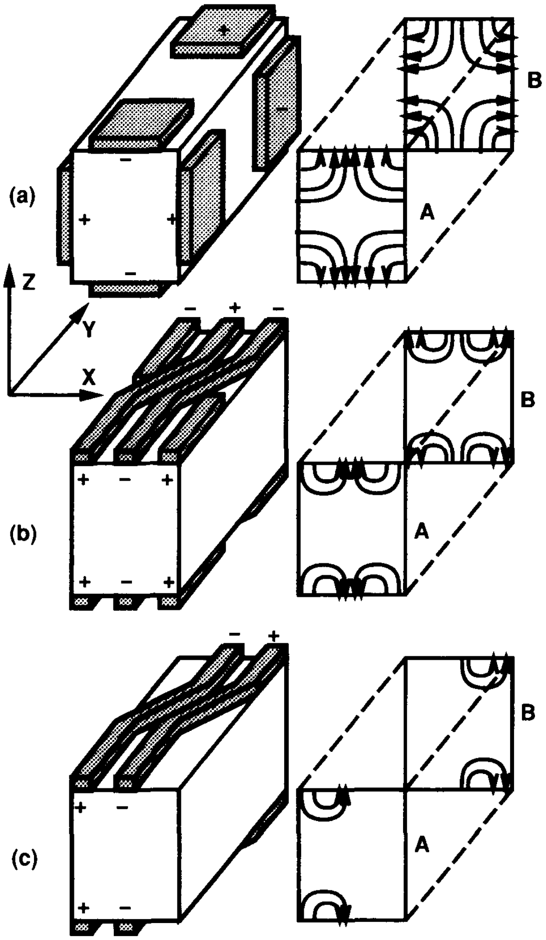

Figure 1: Arrangement of electrodes on quartz Y-rod

(a) Electrodes are located on top, bottom and side surfaces. (b) Meandering electrodes on top and bottom surfaces have similar effect as (a). Scheme (c) is the most simplified arrangement.

Young's modulus	E_x	8.67×10^{10} Pa
	E_y	8.67×10^{10} Pa
	E_z	10.7×10^{10} Pa
Poisson's ratio	ν_{xy}	0.154
	ν_{yz}	0.130
	ν_{zx}	0.130

Table 1: Elastic constant of quartz

3 FABRICATION PROCESS

Quartz belongs to the trigonal trapezohedral class (32) of the rhombohedral subsystem. The axes are usually chosen so that Z is the axis of three-fold symmetry, and X is that of two-fold. We use Z-cut quartz substrate because the piezoelectric strain is effectively set up as discussed in §2. Another reason is that the etching rate along Z-axis is the fastest in this crystal, and that vertical side walls (X- and Y-surface) can be formed with a Z-cut wafer. The etching profile can be precisely predicted [5], and many devices have been fabricated by this method [6][7].

Figure 3 shows fabrication sequence of quartz micromachining: (1) After cleaning the 100 μm thick z-cut quartz substrate, we deposit chromium (500 Å) and gold (2000 Å) successively on both surfaces by sputtering. (2) A set of Photoresist is put on the metal layer and patterned by photolithography. (3) With this photoresist as a mask, the metal layer on each side is patterned by ion milling of argon. (4) After removing the photoresist, we put another set of photoresist on the metal and pattern it. (5) Quartz is anisotropically etched in 82 °C saturated solution of ammonium bifluoride (NH_4HF_2). (6) With the photoresist formed in step (4) as a mask, the metal layer is patterned again by ion milling to form the electrodes, and then photoresist is

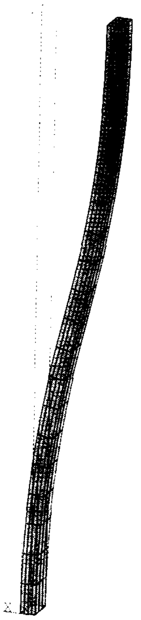

Figure 2: FEM simulation of piezoelectric strain

Quartz Y-rod (2 mm long, 50 μm wide, and 100 μm thick) is deflected through piezoelectric effect. Estimated static displacement at the top is 0.1 μm at 100 V.

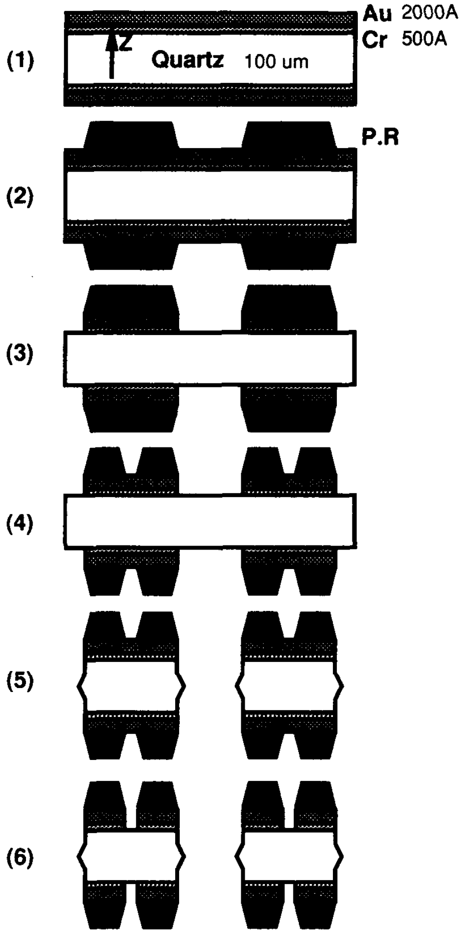

Figure 3: Fabrication process of quartz micromachining

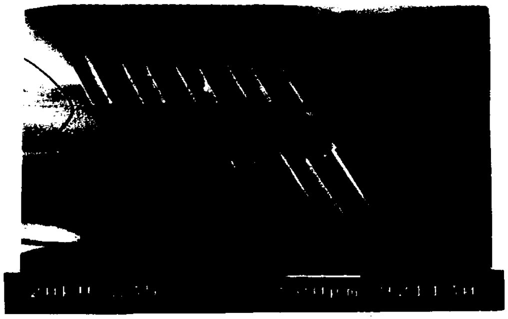

Figure 4: SEM view of bellows type actuator

The chip is 7 mm × 5 mm in area, and 100 μm in thickness. Each folding suspension is 2.5 mm long and 50 μm wide.

removed to complete the precess. Note that metal layers are used as etching resist in step (5), and as electrodes after fabrication.

Crystallographic transition (α-quartz $\leftrightarrow$ β-quartz at 573 °C) does not undergo during the fabrication because both sputtering and ion milling are low temperature processes.

In addition, since quartz is an insulator, no leakage current exists between the metallizations. Therefore, we can expect small power consumption in operating devices.

4 ACTUATORS

Two examples have been fabricated to verify our operation scheme: bellows type actuator and optical chopper. This section shows their structures and mechanical characteristics.

4.1 BELLOWS TYPE ACTUATOR

Figure 4 shows a SEM (Scanning Electron Microscope) view of the fabricated bellows type actuator. It has four pairs of folding suspensions which were described in §2. Total size is 7 mm × 5 mm in area, and 100 μm in thickness. Each suspension is 2.5 mm long and 50 μm wide. Figure 5 is a close view of electrodes on the suspension.

In Fig.6 we show the frequency response of the actuator in the vacuum chamber of SEM (10^{-4} Torr). The resonant frequency is 2.64 kHz. The measured peak to

Figure 5: Meandering electrodes

Each electrode is 5 μm wide, and located with 10 μm clearance on 50 μm wide suspension.

peak amplitude is 140 μm at 100 V in vacuum as shown in Fig.7.

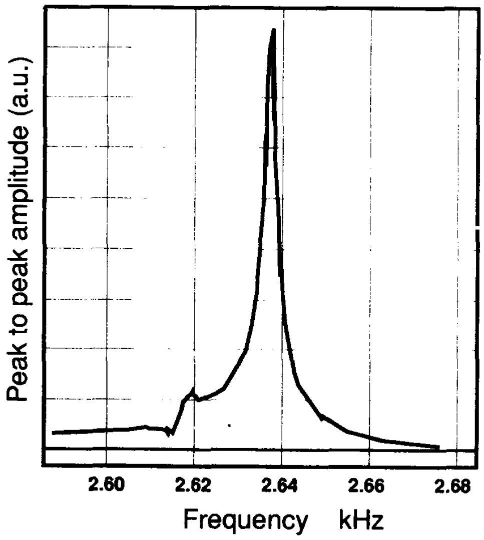

Figure 6: Frequency response of bellows type actuator

Measured in vacuum (10^{-4} Torr).

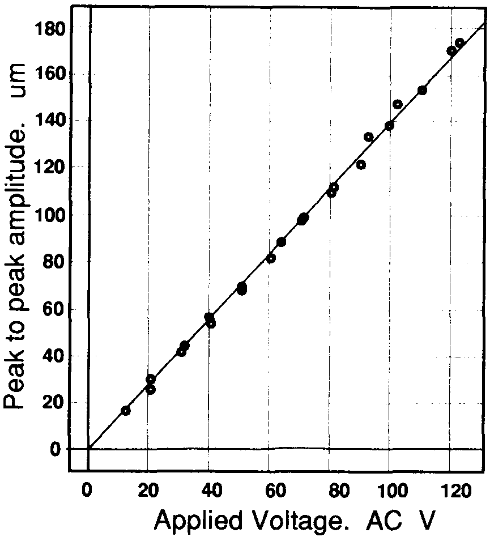

Figure 7: Peak to peak amplitude versus applied voltage

Measured in the SEM vacuum chamber (10^{-4} Torr) at the resonant frequency.

Quality factor Q is written in the form $Q = \sqrt{\frac{km}{c}}$, where m, c, k are the mass of the structure, the viscosity coefficient of oscillating system, and the elastic constant of the suspensions, respectively, which appear in the quadratic equation of motion, $m\ddot{x} + c\dot{x} + kx =$ force. Because a usual quartz device oscillates to change the thickness, it has very large k, therefore, large Q. On the other hand, since our actuator has very flexible suspensions, the quality factor is as small as 600 in vacuum.

Some researchers proposed the method to get static displacement with resonant actuators [8][9]. Because our actuator has a large peak to peak resonant amplitude, large static displacement is expected. Our test shows that oscillation of the actuator is large and strong enough to hit a small object many times just like a woodpecker, and displace it statically. Figure 8 shows the actuator hitting a small piece of silicon substrate (2 mm square, 250 μm thick), which was consequently displaced by 200 μm after 5 second woodpecker action. Although the resonant frequency during this motion shifted to a higher value than that of free oscillation, the resonance was maintained by choosing appropriate frequency of the excitation.

Based upon this result, we are going to apply this woodpecker mechanism to change the path of light statically as shown in Fig.9. In this scheme, a mirror plate is assembled between two pins, and the left actuator hits the mirror at the left side to turn it clockwise around Z-axis, and the right one for the counterclockwise motion.

Designing the masks of photolithograhy properly, we can also form the bevel surfaces besides vertical walls by anisotropic etching of quartz. We are also going to fabricate the micro mirror and prism and to drive them with the actuators in the same substrate.

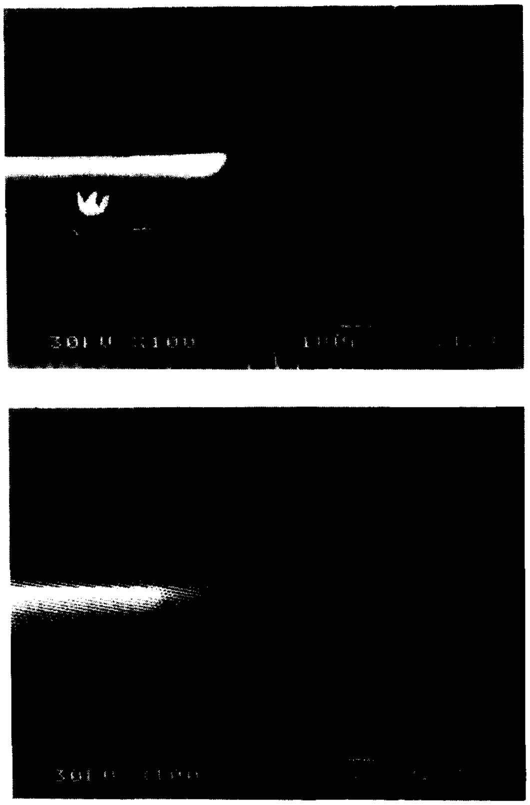

Figure 8: Woodpecker motion of the bellows type actuator

The tip of actuator hits the object (a piece of silicon substrate) to displace it by 200 μm after 5 second woodpecker action.

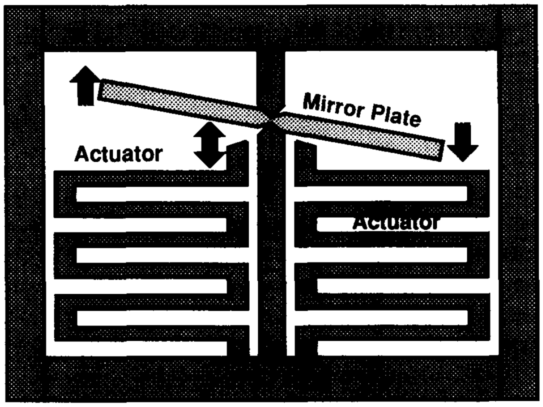

Figure 9: Static displacement by bellows actuators

The left actuator hits the mirror to turn it clockwise, and the right one counterclockwise.

4.2 OPTICAL CHOPPER

Choppers are usually employed in optical sensors to regulate the incident light into alternating signal so that the signal is amplified without DC drift. The conventional chopper is composed of a disk with some windows and a motor to turn it.

Figure 10 shows a SEM view of fabricated optical chopper by quartz micromachining. This monolithic chopper is composed of three parts: a chopper plate with through holes, four folding suspensions, and a frame. The chip is only 7 mm × 7 mm in area, and the suspension is 2 mm long and 50 μm wide. Each suspension has electrodes on both top and bottom surfaces as discussed in §2, and it drives the chopper plate along the arrow in the figure. As the chopper plate oscillates, the incident light is regulated through the holes.

The characteristics as a optical sensor are under investigation, and will be reported in other paper.

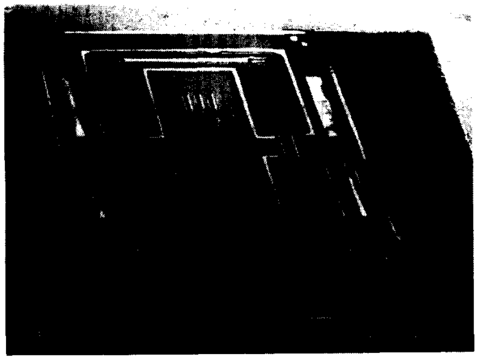

Figure 10: SEM view of optical chopper

The chip is 7 mm × 7 mm in area, and 100 μm in thickness. The suspensions (2 mm long and 50 μm wide) support and drive the chopper plate placed inside the frame.

5 CONCLUSION

We proposed a new mechanism of piezoelectric operation to have a large displacement with a microfabricated actuator. Quartz was employed to make the actuators because of its piezoelectricity and anisotropic etching profile. Two types of actuators were reported with their mechanical characteristics and the future application for micro-optics.

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REFERENCES

[1] J.H.Jerman, D.J.Clift and S.R.Mallinson, "A Miniature Fabry-Perot Interferometer with a Corrugated Silicon Diaphragm Support", *IEEE Solid - State Sensor and Actuator Workshop"*, Hilton Head Island, South Carolina, June 4 - 7, 1990, pp. 140 - 144.

[2] K.E.Petersen, "Silicon as a Mechanical Material", *Proc. IEEE* **70**, No.5 (1982), pp. 420 - 457.

[3] M.Dufour, M.T.Delaye, F.Mechel, J.S.Danel, B.Diem and G.Delapierre, "A comparison between micromachined pressure sensors using quartz or silicon vibrating beams", *Proc. 6th. Int. Conf. Sensors and Actuators (Transducers '91)*, San Francisco CA, 1991, pp. 668 - 671.

[4] J.Söderkvist, "Design of a solid-state gyroscopic sensor made of quartz", *Sensors and Actuators* **A21 - A23**, (1990) pp. 293 - 296.

[5] T.Ueda, F.Kohsaka, T.Iino and D.Yamazaki, "Theory to predict etching shapes in quartz and application to design devices", *Trans. Soc. Instrum. Contr. Eng.* **23** (1987), pp. 1 - 6 (in Japanese).

[6] T.Ueda, F.Kohsaka and D.Yamazaki, "Quartz Crystal Micromechanical Devices" *Proc. 3rd. Int. Conf. Solid-State Sensors and Actuators* (Transducers '85), Philadelphia, PA, I.S.A., June 11-14, 1985, pp. 113 - 116.

[7] J.S.Danel, F.Michel and G.Delapierre, "Micromachining of Quartz and its Application to an Acceleration Sensor", *Sensors and Actuators, A21-A23* (1990), pp. 971 - 977.

[8] A.Lee, P.B.Ljung and, A.P.Pisano, "Polysilicon Micro Vibromotor", *Proc. IEEE Micro Electro Mechanical Systems*, Travemünde, Germany, Feb. 4 - 7, 1992.

[9] T.Higuchi, Y.Hojjat, and M.Watanabe, "Micro Actuators Using Recoil of an Ejected Mass", *Proc. IEEE, Micro Robots and Teleoperators Workshop*, Nov. 9 - 11, 1987.