

Surface electrode configurations for quartz MEMS double-ended tuning fork resonator

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The quartz double-ended tuning fork (DETF) resonator is well known to be sensitive to longitudinal force and is widely used as the sensing element in modern accelerometer, force and pressure sensors. The quartz DETF resonator works in-plane, with anti-phase flexural mode vibration, which is driven into oscillation by internal strains created by AC voltages applied to electrode patterns on the beams. The DETF vibration modes and vibration characteristics are determined by the electrode pattern and its electromechanical coupling efficiency. Presented are three kinds of electrode patterns for different applications, and the effect of electrode patterns on the vibration performances are investigated experimentally. With the fundamental frequency at 65 KHz, the DETF resonator is designed and fabricated using the wet etching-based quartz MEMS technique. The vibration characteristics including Q -value, and equivalent parameters, are evaluated using a 4294 A impedance analyser. Experimental results demonstrated that the vibration characteristics of quartz DETFs are affected by the electrode patterns including pattern location and widths. These results are expected to be useful for designing quartz DETF based devices.

1. Introduction: The double-ended tuning fork (DETF) resonator has been widely used as a force transducer to measure acceleration, force and pressure [1–6]. The DETF resonator is composed of a pair of substantially parallel beams, a slot between the two beams and two mount pads at the ends of the beams. When used as force transducer, the DETF works in-plane with anti-phase flexural mode vibration, which cancels the forces and torques produced at the roots of beams. These structural behaviours reduce the vibration energy leaking into the mounting support structure, maintaining the DETF resonating with a high mechanical quality factor (Q -value). Fig. 1 shows the schematic diagram of the typical DETF structure and its vibration motion. The fundamental resonating frequency of the DETF is sensitive to longitudinal forces, in a way that increase upon a tensile force and decrease upon a compressive force. Many materials could be used for fabricating a DETF resonator, such as quartz, silicon, steel and so on. Among these materials, crystal quartz draws more attention because of the excellent mechanical properties, such as high Q -value and temperature stability. Furthermore, the quartz-based DETF transducer promises a simple and miniaturised structure because of its own piezoelectric effect, which could be used for exciting and detecting the desired flexural mode vibration by arranging a metal electrode pattern on the beam structure. This should be an obvious advantage when compared with other materials, where additional structures should be added to perform the excitation/detection of flexural mode

vibration, such as electrostatic excitation/capacitive detection, magnetic excitation/magnetic detection, electrothermal excitation/piezoresistive detection, optothermal excitation/optical detection and dielectric excitation/capacitive detection [7]. The design rules of a DETF resonator structure have been extensively studied for gaining a high-quality factor, and high-force-frequency sensitivity [7, 8], and for avoiding spurious mode vibrations [9]. However, studies on the designing and fabrication of the quartz DETF excitation electrode have been reported by very few, which has hindered the development of microquartz DETF transducer applications. The electrode pattern should be able to not only excite the DETF resonator working in a determined vibration mode, but also achieve high electric–mechanical coupling efficiency resulting in friendly acceptable equivalent circuit parameters by the detecting oscillating circuit. Furthermore, the fabrication process should be simple and compatible with the process of the DETF-based sensor's full structure.

For a quartz crystal DETF, the beam length is designed along the quartz crystal Y -axis, the width along the X -axis and the thickness along the Z -axis. At least two metal electrodes are coated on the beams, which produce an electric filed component in the direction of the X -crystallographic axis coupling to extensional stress in the Y -direction through the piezoelectric stress coefficient e_{12} to excite the in-plane flexural mode vibration [10]. Ideally, for exciting the fundamental frequency vibration, the two electrodes are arranged on the top, bottom and two side walls and the electrical polarity is changed two times at the nodal points as in Fig. 2b. The changing of electrical polarity corresponds to the stress distribution induced by flexural mode vibration, and the changing position is located at the zero-stress positions (0.22, 0.76) as in Fig. 2a. The curve of Fig. 2a is obtained from the beam vibration equations [11]. Fig. 2 suggests that the electrode patterns should be formed surrounding the cross-section and on the whole length of the beam. To fabricate such a pattern, nowadays there are two micro-fabrication methods. One is using the three-dimensional photolithography process, in which a photoresist spray-coating system and incline exposure equipment are needed to pattern the metal electrode on the side wall, causing a high-cost process. The other

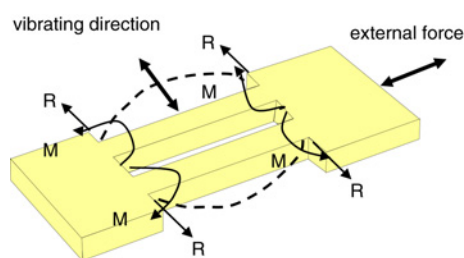


Figure 1 Schematic diagram of DETF structure and its vibration motion

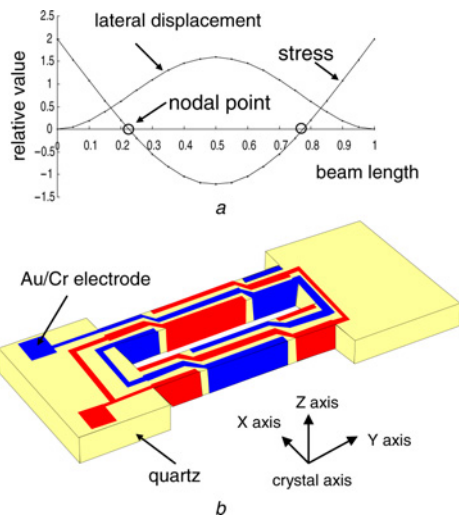


Figure 2 Ideal electrode configuration of quartz DETF resonator
 a DETF vibration mechanical motion distribution
 b Surrounding electrode configuration

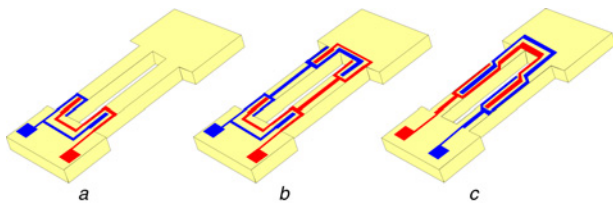


Figure 3 Schematic diagram of designed three kinds of electrode patterns
 a Scheme 1
 b Scheme 2
 c Scheme 3

method is using a stencil mask to shadow the metal-unwanted area, which is theoretically sound and simple. However, it is very difficult to align the stencil mask with the quartz wafer in the micro-level, yielding poor production. Furthermore, when the DETF resonator is integrated into a complex monolithic structure, such as a typical ‘push–pull’ structural accelerometer [12], in which structure the beam thickness is thinner than the proof mass, the forming surrounding electrode pattern will become more difficult using the above two methods.

However, to drive the beam to deflect in-plane, it is not always necessary to form the electrode on the side wall and on the whole beam length. Toshiyoshi *et al.* [13, 14] have successfully fabricated quartz beam microactuators by using the partial surface electrode, which is very easy for fabrication. In this Letter, three kinds of surface electrode patterns are designed and investigated for different applications as in Fig. 3, all of which could be fabricated by a simple process. Fig. 3a shows an electrode pattern on only one end of the beam, and this design is for an application where the detection electrode is designed on the other end and a feedback could be performed into the driving circuit as previously reported [15]. Fig. 3b shows an electrode pattern designed on one partial end portion and a full central portion beam, which is maximally taking advantage of the beam surface without the wire jumping linking. Fig. 3c shows an electrode pattern designed for the DETF with variable cross-sections, in which the central width of the beam is reduced and it is difficult to form an electrode pattern [12, 16]. The effect of these electrode patterns on a given DETF resonator’s performance are experimentally compared by measuring the vibration characteristics by measuring the resonating

conductance using an impedance analyser 4294 A. Further, the electrode width of each type electrode pattern is investigated and optimised according to the measured equivalent circuit parameters.

2. Experimental

2.1. Design of DETFs and electrode configurations: The dimensions of the designed DETF are 4 mm length, 190 μm width and 100 μm thickness. For all three kinds of electrode patterns (Fig. 3), in the beam length direction (*Y*-direction), the locations of electrical polarity change are set to be 890 μm from two joining ends, respectively, according to the zero-stress nodal calculated as Fig. 2a. In the beam width direction (*X*-direction), two pairs of electrodes are designed to produce tensile stress and compressive stress, respectively. The side two electrodes have the same width and same electrical potential, and the width of the central electrode is two times that of the side electrode. In this experiment, the side electrode varies from 10 to 40 μm , consequently the gap between the side and central electrode changes accordingly.

Further, a DETF with variable cross-sections is designed, which is reported with enhanced force sensitivity [12, 16]. The width of the beam is reduced from 190 to 100 μm and to 50 μm and the corresponding lengths are 1.3 mm, 500 μm and 400 μm , respectively. For these kinds of applications, it is difficult to form an excitation electrode pattern on the reduced central beam. The surface electrode patterns of schemes 1 and 2 (Fig. 2) were designed, and the electrode length was designed to be 890 μm (nodal point of conventional DETF) and 1170 μm (taking advantage of the widest beam as is possible), respectively.

2.2. Fabrication process: The designed DETFs were fabricated using a well-established quartz wet-etching process [17]. This fabrication process starts from a 100 μm -thick Z-cut quartz wafer. The process flow is as follows: (i) wash quartz wafer using piranha solution ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2 = 3:1$) at 110°C for 15 min; (ii) sputter Au/Cr (150 nm/50 nm) metal films on the double sides of the wafer; (iii) coat and pattern photoresist for creating basic DETF structure, followed by Au/Cr etching; (iv) remove photoresist; (v) coat and pattern photoresist for creating electrode configuration, followed by 150°C hard-baking for 30 min; and (vi) etching quartz in saturated ammonium bifluoride solution at 85°C, followed by etching Au/Cr and photoresist removal.

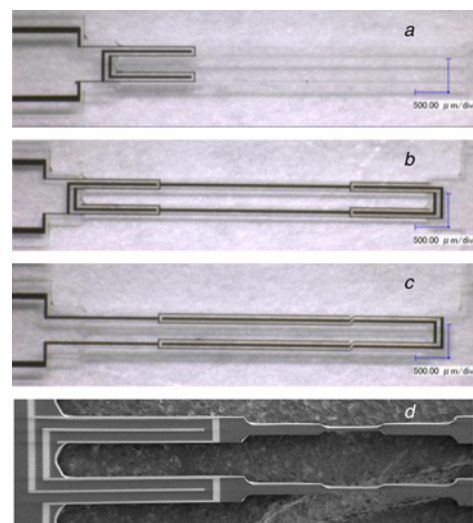


Figure 4 Pictures of fabricated quartz DETFs
 a Coated with electrode pattern 1
 b Coated with electrode pattern 2
 c Coated with electrode pattern 3
 d Close-up picture of modified DETF beam

2.3. Evaluation: After fabrication, the DETF resonator was cut from the wafer. The vibration characteristics of the fabricated DETFs were measured using an Agilent 4294 A impedance analyser with the aid of a 42 941 A test fixture. The head of the 42 941 A is equipped with a standard two-pin probe, and the space between the two electrode pins is adjusted to match the two pads of the DETF resonators. The resonant frequency, Q -value and equivalent circuit parameters were measured by scanning the conductance performance. For precise evaluation, the measurement precision was set to be level 5, the sweep number was 800 and the scanning span was set to be 60 Hz.

3. Results and discussion: Fig. 4 shows pictures of the fabricated DETFs. Figs. 4a–c show the conventional DETFs with different electrode patterns. Fig. 4d shows the DETF with the modified beam. All of the DETFs were measured using an impedance analyser under the same conditions. Fig. 5 shows example pictures of the measured results, which are coated with the designed pattern 3 and the electrode widths are 20 μm (Fig. 5a) and 30 μm (Fig. 5b), respectively. The summarised important vibration characteristics are shown in Fig. 6. Fig. 6a gives the dependence of motional resistance and capacitance ratio on the electrode width of conventional DETF, and Fig. 6b gives these

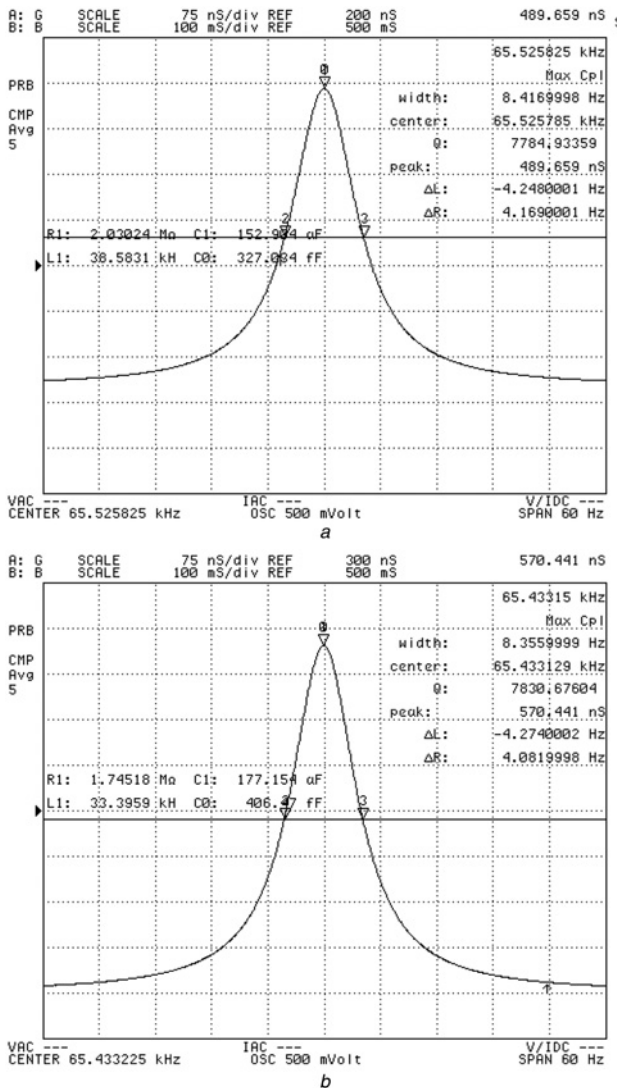


Figure 5 Measured vibration characteristics of DETF coated with electrode pattern 3
a Electrode width 20 μm
b Electrode width 30 μm

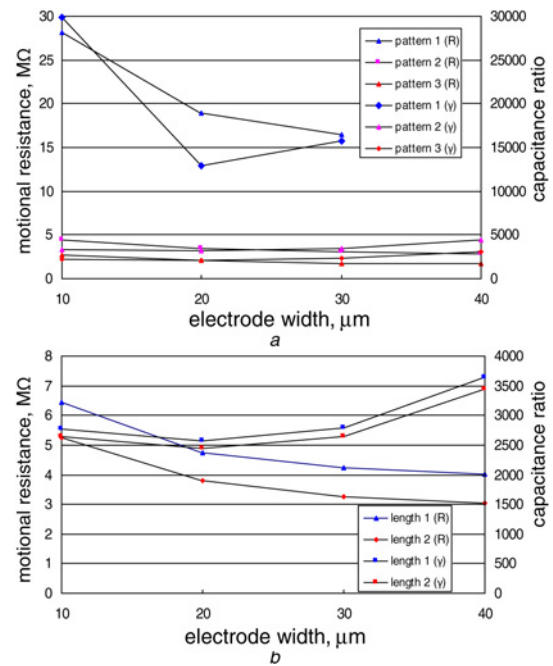


Figure 6 Summarised measurement results

a Dependences of motional resistance (R) and capacitance ratio (γ) on the electrode width of conventional DETF

b Dependences of motional resistance (R) and capacitance ratio (γ) on the electrode width and length of DETF with variable cross-sections

values of the modified DETF coated with designed pattern 2. The measured Q -values of the fabricated DETFs are about 8000, 5000 in air for all of the conventional DETFs and the modified DETFs, respectively, which are mainly determined by the mechanical structure (dimensions of the beam, slot and joining ends).

Generally speaking, high Q -value, low motional resistance (R) and small capacitance ratio ($\gamma = C_0/C_1$) imply a good resonator [18]. Further, for the flexural mode vibration, the piezoelectric coupling factor is approximately inversely proportional to the capacitance ratio. In actual applications, a small capacitance ratio is also desired for easy designing of the driving circuit. From Fig. 6a, we can learn that the simple one-side surface electrode pattern 1 produces very large motional resistance (few 10 M Ω) and capacitance ratio. Except for special requirements, for example, feedback information is needed, this kind of pattern should be adopted for driving and the other side is left for detecting pattern. Patterns 2 and 3 give relatively small motional resistance and capacitance ratio, which is considered acceptable for actual application because usually the fundamental frequency of flexural mode vibration is low (< 100 kHz), and it is not a big problem to design an oscillator circuit to match it. For example, Traon *et al.* [12] realised very small output noise despite of the large motional resistance at 2.5 M Ω . For all of the pattern schemes, we can find that the motional resistance is gradually reduced with the increase of electrode width. However, we can also find that a smallest capacitance ratio (high piezoelectric coupling factor) exists at the mediate electrode width (it also means a mediate gap between the two electrodes). A trade-off should be made by considering between the motional resistance and capacitance ratio when designing a matching driving circuit. From Fig. 6b, we can learn that for a modified DETF, the effect of electrode width on the motional resistance and capacitance ratio appeared in the same tendency (different value). It can be learnt that the electrode length 2 (1170 μm) worked better than the length 1 (890 μm). This result demonstrated that for the modified beam geometry, the zero stress location (nodal point) would also move, and a detailed analysis and optimisation should be made for these applications.

Finally, two important points should be noted about this experimental research. In this Letter, we aim to investigate the possibility of designing simple surface electrodes, and so the experimental conditions were strict. First, all of the experiments were performed in air; so the air damping would greatly degrade the flexural mode vibration. Second, the electrode pattern is only set on one surface of the beam. Depending on the actual application requirements, if the resonator is packaged in vacuum and both the top and bottom surfaces are coated with electrode patterns, the performance of the DETF would be further improved.

4. Conclusion: For simplifying the fabrication process and widening the application field, a high-quality quartz MEMS DETF resonator with a surface electrode was designed, fabricated and evaluated. Three kinds of surface electrode patterns are proposed and experimentally demonstrated for effectiveness, which could be easily realised using the conventional planar photolithograph process. High Q -values about 8000 were achieved for the 65 kHz fundamental frequency DETF with all of the electrode patterns and the highest piezoelectric coupling efficiency was found on pattern type 3. The motional resistance below 2 M Ω was achieved even in air and excited with only one side surface electrode. Furthermore, the motional resistance and capacitance ratio were greatly affected by the electrode pattern type and electrode width, which should be optimised by considering the oscillating circuit. The effect of electrode length on the modified DETF was also investigated. These results are expected to contribute to the design and realisation of quartz MEMS DETF-based microdevices.

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