A HIGH-SPEED BATCH-MODE ULTRASONIC MACHINING TECHNOLOGY FOR MULTI-LEVEL QUARTZ CRYSTAL MICROSTRUCTURES

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ABSTRACT

This paper describes recent advances in batch-mode micro ultrasonic machining (μUSM) and its application to quartz crystal (QC) microstructures. Acoustic emission sensors are used for close monitoring of this batch process. Multi-level AT-cut QC microstructures have been successfully fabricated at a cutting rate >24 μm/min, which is substantially faster than available options for plasma-based etching. Arrays of disks, H-shaped and tuning fork structures are demonstrated with a cutting depth up to ≈105 μm on the 110 μm-thick QC substrate. Micromachined QC structures are also mounted on interconnection substrates. Preliminary electrical tests have been performed for resonance characteristics. A low-thermal-expansion glass ceramic, ZERODUR®, has also been micromachined at a cutting rate >18 μm/min.

I. INTRODUCTION

Quartz crystal (QC) is widely used for timing reference and control in watches as well as oscillator circuits and filters. It is also extensively used in sensing applications such as microgravimetry with quartz crystal microbalance (QCM), high-sensitivity gyroscopes and sensors for viscosity, infrared radiation, etc. [1-3]. This is mainly because of its piezoelectric property with high quality factors (Q), which results in low mechanical energy dissipation and thus high-sensitivity sensors. Among various quartz cuts along different crystalline directions, the AT-cut QC offers high temperature stability around room temperature and high Q even in a viscous fluid [4,5], and is commonly chosen for QCM and other sensing applications.

Currently available options for lithography-compatible batch-mode microfabrication of QC and integration with microsystems are somewhat limited. The profile and machining rate of wet etching with solutions such as $HF:NH_4F$ or NH_4HF_2 depend heavily on the crystalline orientation of QC, greatly limiting possible micromachined geometries. Furthermore, it is usually favorable only for Z-cut QC, for which vertical sidewalls and faster etch rates (typically <2 μm/min) can be obtained [6], leaving out other QC orientations such as AT-cut that is of more interest for sensors. Laser-assisted wet etching has been demonstrated on QC, however, it results in a melted zone that undesirably changes the crystalline structure, reducing its piezoelectric properties [7]. Heavy ion induced wet etching has also been developed to enable anisotropic etching along arbitrary directions in QC. However, complex equipment is necessary to generate the high-energy heavy-ion beam, the etching rate is similar to typical wet etchings and relatively slow, the etching profile shows heavy signs of ion tracks, and the disorder in the crystalline lattice caused by ion bombardment can affect the material properties, especially in a so-called ion stopping layer [8]. Deep reactive ion etching (DRIE) with nickel masks has been used for micromachined QCM arrays, etc., but the etch rate (≈0.4 μm/min) needs improvement for thick structures [9].

We have previously reported batch-mode micro ultrasonic machining (μUSM) for PZT and Macor® ceramics with a lateral feature size of 25 μm and a machining rate of >18 μm/min [10]. However, for QC microstructures with multi-level features, close process monitoring is necessary to optimize parameters like vibration amplitude and feeding speed. This paper describes the application of acoustic emission (AE) sensors for batch-mode process monitoring, and successful fabrication of multi-level QC microstructures. Micromachined QC structures are also mounted on glass substrates with metal interconnections, and the electrical measurement results are reported.

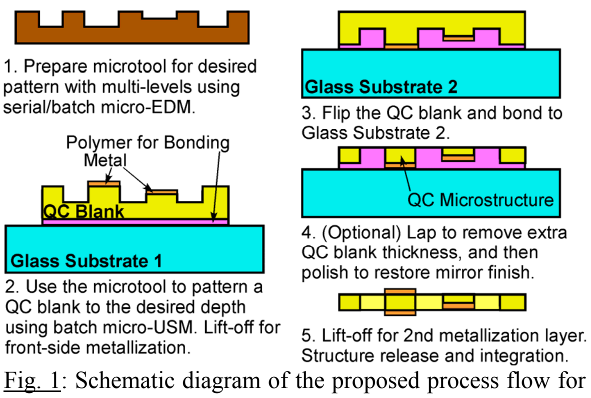

Fig. 1: Schematic diagram of the proposed process flow for quartz crystal microstructure with multi-levels.

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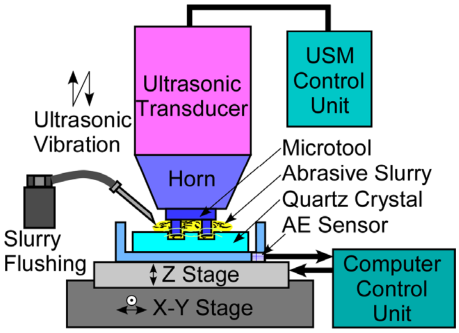


Fig. 2: Schematic diagram of the μUSM setup for batch-mode pattern transfer onto quartz crystals. Acoustic emission (AE) sensor is used for dynamic process monitoring and control.

II. PROCESS DESCRIPTION

The proposed process flow is shown in Fig. 1. Hard-metal (such as steel) microtools with desired patterns are made by micro electro-discharge machining (μEDM). This can be performed in serial mode for rapid prototyping of simple patterns, or batch mode for compatibility with lithographic methods [11]. Multi-level structures are also defined in the microtools. For batch mode operation, electroplated copper structures can be formed using SU8 or LIGA molds with lithographically-defined patterns. These copper structures are then used as an electrode on the Panasonic μEDM machine MG-ED72W to transfer the patterns onto hard metal substrates for microtools. Non-lithographic rapid-prototyping can be performed for simple patterns by a similar process, in which the original serial EDM function of the MG-ED72W machine is used to define the pattern on the microtool by running a program on a computer to control the "writing" movement of the rotating EDM electrode wire on the microtool substrate as well as different cutting depths for multi-level structures.

The patterns on the microtools are then transferred onto commercially-obtained AT-cut QC blanks (International Crystal Manufacturing, Inc., OK, USA) on a new custom-designed batch μUSM setup shown in Fig. 2. Abrasive slurry, which consists of water and fine abrasive powders, is supplied between the tip of the microtool and the QC workpiece. The vibrating tip of the microtool is fed into the workpiece. The ultrasonic motion of the microtool imparts velocity to the abrasive particles on its downward stroke. These particles, in turn, are responsible for the erosion of the workpiece, thus creating the desired cavities in the shape of the microtool. In the previous batch μUSM setup reported in [10], the dynamic force detection method based on wideband piezoelectric sensors is inadequate for process monitoring. This is because the sensor output is dominated by the 20 kHz vibration component generated by the ultrasonic transducer, and is an averaged value over the entire cutting area of the microtool, due to presence of the slurry. In contrast, the AE sensor (HD15 miniature sensor, Physical Acoustic Corporation, NJ, USA) used in the new setup detects the transient elastic waves (>100 kHz) generated by the microchipping that occurs in the workpiece during μUSM, which is a measure of the actual machining. The dominant 20 kHz vibration component is simply filtered out by the band pass filtration that occurs over 100 kHz - 400 kHz. The use of the AE sensor also improves the effectiveness of the machining in feedback control mode with constant machining load because the obtained feedback signals provide a clearer indication of the machining status. AE sensors have been previously used to monitor serial μUSM hole drilling with a rotating wire [12], but their application to the batch-mode (parallel) μUSM has not been previously reported.

After pattern transfer onto the QC blank, metallization is carried out by a lift-off process with an evaporated or sputtered Cr/Au layer as one of the electrodes. The QC blank is then flipped and polymer-bonded to another glass substrate which is used as a carrier. Lapping from the backside to reduce the extra thickness of the blank is optional; polishing is necessary if lapping is performed, in order to restore a mirror finish and retain the high Q characteristics. Finally after a second metallization step the structure is released by dissolving away the bonding polymer.

III. PROCESS DEMONSTRATION

The process parameters for the batch μUSM demonstrated on QC are summarized in Table I. The ultrasonic transducer generates vibrations with a frequency of 20 kHz and variable amplitudes. In

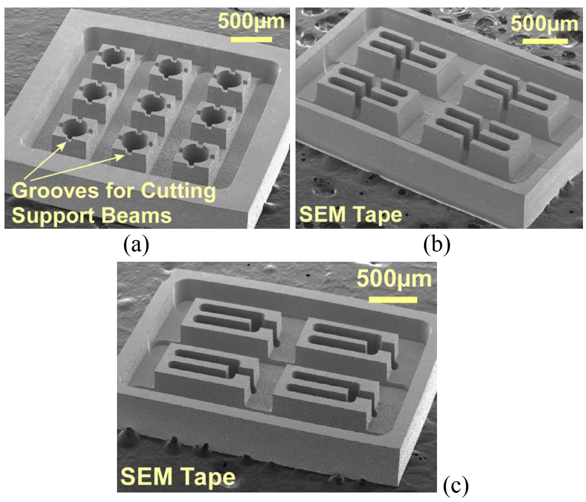
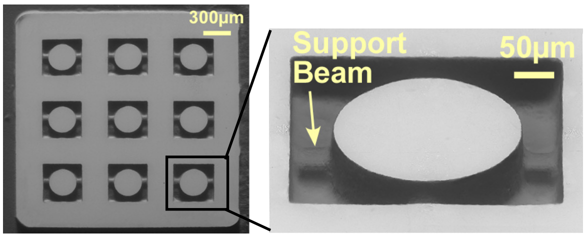


Fig. 3: SEM images of microtools made by serial mode μEDM for: (a) 3×3 array of disks; each supported by four 50 μm-wide beams formed by the grooves; (b) 2×2 array of H-shaped structures; (c) 2×2 array of tuning fork resonators.



(a) (b)

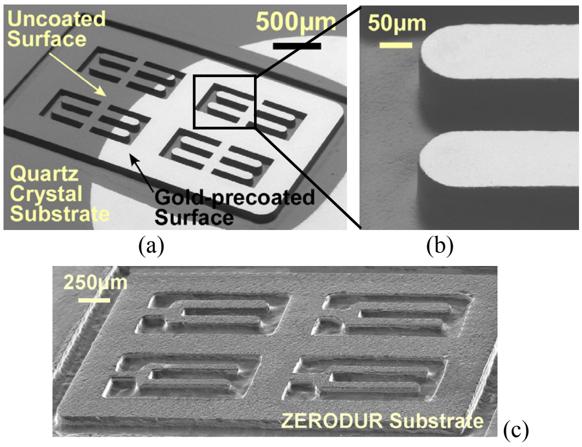
Fig. 4: Photos of: (a) PZT disc array batch fabricated by SEDUS process using batch µUSM to transfer a pattern defined by serial µEDM. (b) Released PZT disc. Diameter: 200 µm. Thickness: 50 µm.

previous experiments on PZT, a vibration amplitude of 15 µm was adequate to sustain machining rate >50 µm/min. However, for QC micromachining, a higher vibration amplitude of ≈20 µm is necessary to reach machining rates of 40-50 µm/min for features >300 µm. Smaller features can be formed at a machining rate of ≈24 µm/min with a vibration amplitude of ≈15 µm without cracking the QC or chipping the structure edges. The abrasive slurries are tungsten carbide powers with average diameter of 0.5~1 µm, mixed in water with a volume ratio of 1:2. In the demonstration machining on QC, the tool wear on the stainless steel microtools is measured as <1-2%, taking as the ratio of tool height worn *vs.* cutting depth.

Fig.3 shows the µEDM'ed microtools for three patterns used for the demonstrations. These tools were made by serial µEDM with a cutting depth of ≈400 µm. Fig.3(a) shows the stainless steel microtool for a disk-array pattern (e.g., for a multi-channel QCM array). Each 300 µm-diameter disk is supported by four beams (50 µm wide and long), with half the thickness of the disk to reduce anchor loss. The depth of the grooves on the microtool for the support beams is, therefore, set to half of the target cutting depth of the whole QC structure. This is used to demonstrate the multi-level micromachining capability of batch mode µUSM, which cannot be easily performed using other current technologies. Fig.3 (b) and (c) show the microtools for arrays of H-shaped and tuning-fork microstructures, respectively. The H-shaped structures have a 100 µm beam width,

Table I: Process parameters of batch-mode µUSM used for quartz crystal micromachining.

Transducer frequency	20KHz
Vibration amplitude	15-20 µm
Abrasive powders	WC (0.5~1µm)
Machining monitoring mode	Acoustic emission
Machining rate	>24 µm/min. (40-50 µm/min possible for large features >300 µm)
Tool wear ratio (height)	<1-2% (Stainless steel)



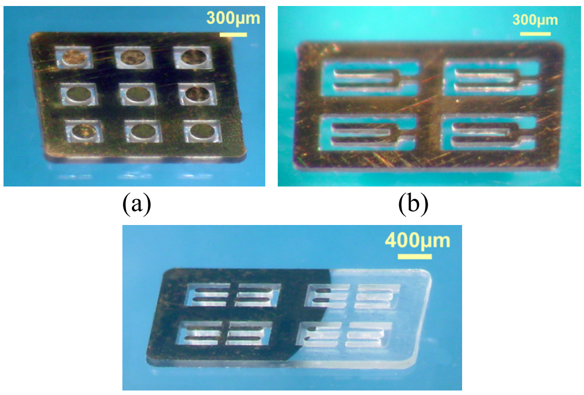
(a) (b) (c)

Fig. 5: ESEM images of: (a) an array of H-shaped patterns transferred onto a quartz crystal substrate by the process; (b) close-up view of the structure, showing the vertical sidewall formed in the batch mode µUSM. Cutting depth: ≈105 µm. Note that the machining did not remove the gold layer pre-coated on quartz. (c) SEM image of an array of tuning fork patterns transferred onto a ZERODUR substrate. Cutting depth: ≈100 µm.

and the tuning-fork structures have either 100 µm or 80 µm beam width.

The patterns transferred onto QC blanks using batch µUSM are shown in Figs. 4 and 5. The multi-level structure (Fig.4b) has a ≈90 µm thickness for the disk and a ≈40 µm thickness for the support beams. Fig. 5(a) shows the H-shaped structure array on a QC blank partially pre-coated with Cr/Au layers, indicating that the µUSM process does not remove the metal layers, while Fig.5(b) shows the vertical sidewall of the machined structure. The released structures after lapping are shown in Fig.6. Note that the scratches in Figs.6 (a) and (b) are only on the metal layer and formed during cleaning steps following µUSM and lapping.

The process was also tested on ZERODUR® glass ceramic (Schott North America, Inc.), which has a very low thermal expansion coefficient and is



(a) (b) (c)

Fig. 6: Photos of the released quartz crystal structures. (a) Disk array (≈85 µm thick); (b) H-shaped structure array (≈100 µm thick); (c) tuning fork array (≈75 µm thick). Note the scratches in (a) & (b) are only on the metal layers.

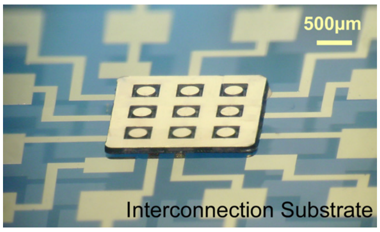


Fig. 7: Photo of the disk array mounted on a substrate with metal interconnections using silver epoxy, showing the concept of on-chip integration with other MEMS and circuit devices. The top common electrode is to be wire bonded.

promising for resonator applications. Fig. 5(c) shows a turning-fork pattern transferred onto the ZERODUR substrate, with a machining speed of ≈18 µm/min and a vibration amplitude of 20 µm.

The QC disk array structure is then mounted on a glass substrate with metal interconnections to show the concept of on-chip integration with other MEMS and circuit devices (Fig.7). The patterned bottom electrodes of the QC structure are bonded to the metal pads on the substrate using silver epoxy in this demonstration. The top common electrode is then wire-bonded. Fig.8 shows the measured impedance spectrum of one of the disks, with a typical piezoelectric resonance peak at ≈19.17 MHz.

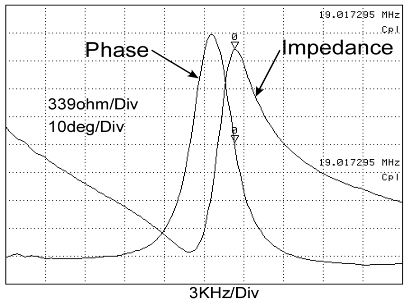


Fig. 8: Screen print of Agilent 4395 impedance analyzer, showing the measured impedance of a quartz disk in the array with a typical piezoelectric resonance peak in air at atmospheric pressure.

V. DISCUSSION

The measured resonance peak shows a modest *Q* that is likely reduced by a relatively large parasitic resistance at the lead transfer between the QC structure and the interconnection substrate. A better lead transfer approach would help to improve the *Q* factor.

As shown in Figs.4 and 5, the machined sidewalls of the QC microstructures do not appear to have a mirror-finish. However, this should not significantly affect the *Q* factor in the electrical measurement since the resonance frequency is determined by the top and bottom surfaces of the AT-cut QC disc in the thickness shear mode.

VI. CONCLUSIONS

Recent advances in batch-mode µUSM process are reported, including the utilization of acoustic emission sensors for process monitoring. Multi-level QC microstructures are successfully fabricated on AT-cut substrates, which are of most interest for sensing applications, though other crystal cuts are expected to work with the process as well. The process provides a high machining speed, >60× higher than reported for DRIE. The three patterns demonstrated in the paper are of interest for sensing or resonator applications, and will be pursued in future efforts. Additional tests showed that ZERODUR zero expansion glass ceramics can also be micromachined by the process.

ACKNOWLEDGEMENT

This work was supported primarily by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866. Facilities used for this research include the Lurie Nanofabrication Facility (LNF) operated by the Solid-State Electronics Laboratory (SSEL) at the University of Michigan.

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