Precision Grinding of Ultra-Thin Quartz Wafers

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For bulk acoustic wave quartz resonators, the central resonant frequency is inversely proportional to the wafer thickness. The tolerance of the resonant frequency is directly proportional to the total thickness variation of the quartz wafer. To increase the operating frequency while preserving a high tolerance on frequency, thinner quartz wafers with better thickness tolerances are needed. This paper describes the design and implementation of a precision grinding apparatus capable of producing ultra-thin quartz wafers to better thickness tolerances than previously achieved. A distributed-stress fixturing method that permits machining of ultra-thin, brittle substrates is described. The machine's precision has been achieved through a high stiffness structural loop and real-time position feedback control. Optical interferometry is used in a new technique to measure thickness variation over the entire wafer. This research will enable production of quartz crystal oscillators with higher frequencies and better quality for the resonator industry.

Introduction

Quartz wafers are ideally suited for use as high-frequency mechanical resonators. Their piezo-electric properties permit an efficient transfer from electrical energy to mechanical energy (and vice-versa). Such resonators are used for virtually all electronic timing functions in computers and clocks. The frequency and quality of mechanical resonance are determined by the wafer's geometry and surface quality: very thin wafers of uniform thickness are needed to obtain high frequency resonance with minimal frequency broadening (Bottom, 1982). Producing wafers from brittle materials is a technology that was developed for the semiconductor industry. Semiconductor microelectronics, however, do not usually require wafers with uniform thickness. Typically, semiconductor wafers are lapped flat and then polished, providing damage-free surfaces with little control of overall flatness or parallelism between opposing faces. Both variables must be controlled precisely in the production of quartz resonators, requiring advances in existing fabrication technology. The brittleness of quartz makes it a difficult material to machine accurately. Etching, grinding, polishing, and lapping are potential material-removal techniques, and each presents difficulties with respect to the resonator fabrication. Chemical etching can reduce the wafer's overall thickness, but cannot improve its thickness tolerance (Salz, 1990). Grinding is a deterministic contouring process that could be used to grind quartz wafers, though no currently available commercial grinder is capable of producing damage-free quartz wafers with sub-micrometer thickness tolerances (Youden, 1992). Some commercial wafer grinding systems do exist. Developed for the semiconductor industry, these machines typically achieve thickness tolerances no better than 5 μm[1]. Also, grinding of quartz usually involves material removal through brittle fracture, making it difficult to machine thin wafers without breaking them.

Recent advances in grinding technology have led to processes known as "ultra-precision" grinding or "micro-grinding," in which subsurface damage is sharply reduced by controlling the diamond abrasive grain depth-of-cut to tolerances below 1 μm. Ultra-precision grinders are now commercially available[2], though to date none have been adapted to the more difficult task of ultra-precision wafer grinding (Youden, 1992).

In some cases, brittle materials can be micro-ground without inducing any subsurface damage, in a process known as *ductile-regime* grinding (Bifano et al., 1991). The transition from brittle-regime grinding to ductile-regime grinding has previously been characterized for quartz micro-grinding. Figure 1 illustrates the transition for a plunge grinding experiment described by Bifano et al. (1991).

In this figure, the area percentage of post-grinding surface damage, as measured from SEM photographs of the ground surface, is plotted as a function of the measured plunge grinding infeed rate. It can be seen from this figure that for quartz to experience less than 10 percent surface fracture requires machining tolerances (e.g., grinding grain depths-of-cut) in the 10 nm range.

Polishing and lapping also remove material though a *ductile* process, but they cannot be used to control wafer thickness to tolerances better than a few micrometers (Salz, 1990). Compounding the difficulties in machining accurate, damage-free surfaces in quartz wafers is the fact that these wafers are usually so thin (~ 100 μm) that they defy standard fixturing techniques.

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[1] For example, Strasbaugh Automatic Wafer Back Grinding Machine Model 7AA, manufactured by Strasbaugh Inc., San Luis Obispo, CA.

[2] For example, The ASG2500, manufactured by Rank Taylor Hobson/Rank Pneumo, Keene, NH.

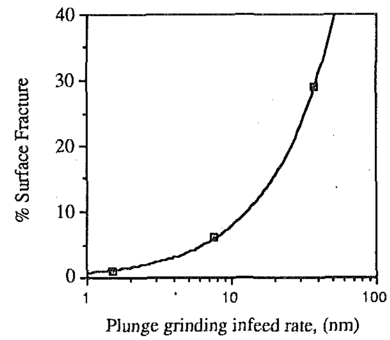

Fig. 1 Brittle-ductile transition in micro-grinding of quartz (Bifano et al., 1991)

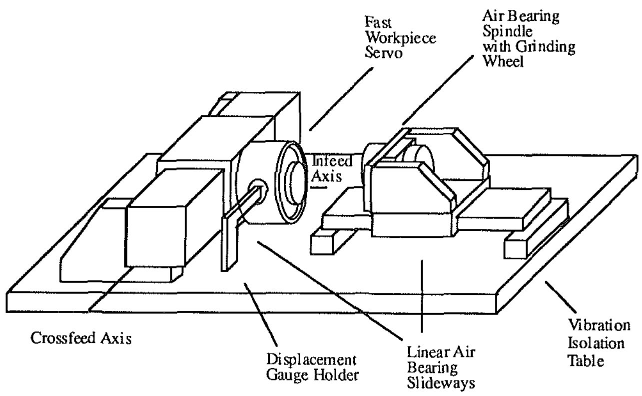

Fig. 2 Wafer grinding apparatus

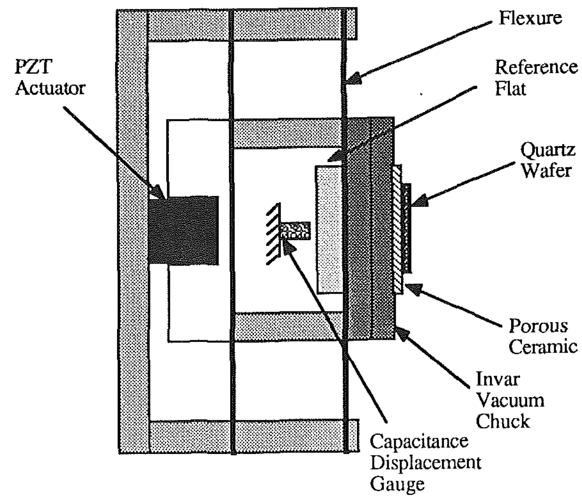

Fig. 3 Workpiece servo-mechanism cross-section

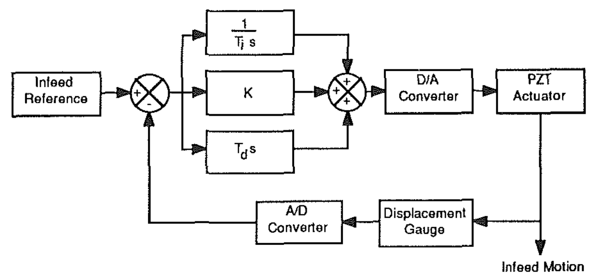

Fig. 4 Position feedback control system schematic

Any mechanical or adhesive bonding of the wafer to the machine will induce local deformations that will limit the achievable accuracy of the machining process. New processes for manufacturing quartz resonators will require precise control of the machining parameters. Moreover, novel mounting and material removal processes are required to guarantee uniformity of wafer thickness and minimal subsurface damage. These goals can be achieved by integrating three precision engineering technologies: ultra-precision grinding, distributed-stress vacuum fixturing, and closed-loop, real-time, precision infeed control.

Wafer Grinding Test Bed

A two axis ultra-precision grinding apparatus has been constructed to serve as a test bed for wafer grinding experiments. This apparatus incorporates two linear air bearing slideways in a T-base formation. A rotary air-bearing is used as the grinding spindle. Figure 2 is a schematic of the apparatus.

By using the air bearing slideways and spindle in this configuration, high stiffness (~ 50 MN/m) and precise open-loop performance have been achieved (Hosler, 1992). A flexure-based, closed-loop, servo-controlled workpiece mounting system has been developed to hold the wafer and provide infeed motion with a 10 nm resolution and a 14 μm range. This mechanism, called the *fast workpiece servo*, is attached to the linear slideway that acts as a crossfeed mechanism. The crossfeed axis is translated by a piezoelectrically actuated "inchworm" device[3] with 5 nm resolution and a 50 mm range. The grinding wheel outside diameter is 100 mm. It is cup-shaped, and the active cutting surface is on the face of the cup.[4] It is mounted to the air bearing spindle, which is driven by a DC servo motor.

The grinding apparatus is temperature controlled to +/− 0.03 K. This is accomplished using a one pass air shower, based on a system developed by Luttrell (1990). The air temperature is controlled by mixing two air streams: one heated and one cooled. Using a microprocessor-based closed-loop integral controller, an in-line damper is adjusted to regulate the temperature of the mixed air stream entering the grinding enclosure. The temperature control figure (+/−0.03 K) is based on one-minute averages of a thermistor-based temperature measurement in the mixed air stream.

Fast Workpiece Servo. To achieve the precision needed to machine quartz wafers to the flatness, surface quality, and parallelism required, a flexure based electromechanical servo-controller has been designed and built. Figure 3 is a cross-sectional view of the cylindrical fast workpiece servo. The actuator for the servo is a piezoelectric stack (25 mm diameter $\times$ 20 mm long), which has a maximum range of 14 μm.

Preloading the piezoelectric stack is accomplished through the use of two annular plate-like flexures, which are attached at their inner diameter to an Invar™ chuck plate and at their outer diameter to a hollow cylinder fixed to the crossfeed slide. The dual flexures ensure straightness and repeatability of infeed motion. For infeed control, a fixed capacitance gauge (50 μm range, 5 nm resolution) senses displacement, in the infeed direction, of a reference flat mounted directly behind the chuck plate. The gauging axis is collinear with the actuation axis, and passes through the cutting point. By configuring the system in this way, Abbe offset errors are eliminated. To achieve 25 nanometer accuracy, closed-loop position feedback control is used on the infeed axis. A high speed proportional-integral-derivative controller has been used. The control system schematic is shown in Fig. 4. The control algorithm is written in Turbo C and assembly languages on an 80286 micro-computer

[3] Burleigh Inchworm, Burleigh Inc., Fishers, NY.

[4] The wheel configuration is similar to that used in "blanchard" grinding. However, the grinding procedure used on this apparatus closely resembles that used in "surface" grinding, with a fixed downfeed and constant velocity crossfeed.

platform. The computer uses a commercially available data acquisition board (Data Translation DT2823) with 16 bit resolution that includes four A/D channels and two D/A channels.

Using the controller described above, the workpiece servo has achieved a positioning resolution of 10 nm over a bandwidth from 0-300 Hz. The servo loop bandwidth is limited by resonant frequencies of the mechanical structure.

Vacuum Fixturing of Wafers. Distributed-stress vacuum fixturing is used to secure the thin wafers during machining. The objective is to hold the wafers in such a way that deformations caused by fixturing are insignificant with respect to the thickness tolerances required for the wafer. A vacuum-actuated porous ceramic chuck was chosen for its ability to provide a uniform holding force over the entire wafer surface. The porous ceramic surface behaves as if it were a large collection of vacuum ports, with each port having a very small diameter. An average pore diameter of 25 μm was used. With this pore size, the fixturing forces are distributed evenly enough over the wafer surface so that the wafer deflection over any individual port is infinitesimal compared to the thickness tolerances desired (e.g., calculations for a 25 μm thick wafer indicate a maximum vacuum induced deflection of less than 1 nm).

The porous ceramic surface must be machined in place on the same apparatus that is used to machine the quartz wafers. Grinding the chuck flat is perhaps the most difficult operation in the proposed wafer grinding process, since porous ceramic actively erodes the grinding wheel bond. The similarities between a porous ceramic chuck and a ceramic "dressing stick" used to resurface a grinding wheel make deterministic grinding of such a chuck complicated: the wheel wear rate is of the same order of magnitude as the chuck wear rate. Nevertheless, the success of the proposed process relies on the creation of a flat base upon which wafers can be mounted. Through careful, iterative grinding steps, the vacuum chuck has been successfully ground to a peak-to-valley flatness of approximately 300 nm. This was done using a bronze bonded wheel with a large diamond grain size (~ 80 μm).

Wafer Grinding

Once the vacuum chuck has been machined under controlled grinding conditions, the wafer can be mounted and ground. Since the wafer is very thin, its back surface conforms closely to the chuck surface. The front surface is then ground as flat as possible, again using real-time feed-back control and a reference flat.

Sources of Error. The errors in thickness that are left on the wafer after grinding can be attributed to one or more of the following sources:

- *Porous chuck flatness errors*—Since the goal of the proposed grinding is to produce a flat surface on the front of the vacuum-supported quartz wafer, and the rear of the wafer conforms to the chuck contours, chuck flatness errors will be directly transferred to the wafer. These errors were measured using an inductance-type contact displacements gauge, and are typically ~ 300 nm.
- *Control system errors*—Any error in the control loop will result in workpiece servo positioning errors, which will be directly imprinted on the wafer surface. Possible control system errors include:
  - Errors in reference flat—The reference has been measured and is flat to a tolerance of 25 nm over its surface.
  - Gauging errors—The capacitance gauge sensor is noise-limited at 5 nm. It is mounted on a stable support in a temperature controlled ($+/-0.03°$C) environment. Measured thermal drift for the gauge mounting system in the temperature-controlled environment is 50 nm over a 1 hour period.
  - System model errors—A simple PID control loop was chosen for control of the system, and the open-loop system step response was used to set the three independent gains. Although primitive, this algorithm is successful at limiting control errors to 10 nm for disturbance frequencies up to 300 Hz.
- *Uncontrolled position errors*—The control loop is closed around the workpiece holding flexures, the crossfeed slide, and the fixed capacitance gauge, but does not include the capacitance gauge support bracket, the grinding wheel, or the grinding spindle. Thermal and spindle-mount drift errors outside of the control loop were measured independently and were found to be less than 50 nm over the course of a grinding test (1 hour).
- *Grinding errors*—This category includes error sources that have not been completely characterized to date. Most significant is probably wheel wear, which was measured and found to be less than 125 nm per 5 μm of material removal. It is unclear at this time if dull diamonds are pulled out of the bond matrix by increasing grinding forces or if they remain stuck in the bond matrix. Based on similar grinding studies carried out on this machine in ceramic grinding, it seems likely that over the duration of the wafer grinding experiments, diamonds remain in the bond, but get increasingly dull (Yi and Bifano, 1991).

Some errors described above are random, while others are systematic. The square root of the sum of the squares for these error sources is 333 nm, which is a reasonable first-order estimate of the best thickness tolerances that could be realized on this micro-grinding at present. For 5 μm of material removal depth, then, it is expected that the best possible thickness tolerance that could be obtained on this apparatus is 333 nm. These errors are dominated by deviations in the porous ceramic chuck flatness.

Grinding Procedure. The wafer grinding procedure involves a fixed infeed of the workpiece, followed by a slow crossfeed of the workpiece across the face of the rotating grinding wheel. Because the infeed is very small compared to the face runout of the grinding wheel, it is expected that only a small number of grinding diamonds contact the workpiece[5]. Each diamond that contacts the workpiece cuts an arc-shaped groove of uniform depth across the wafer surface. The spacing between adjacent grooves is determined by the crossfeed motion per revolution of the grinding wheel. When the face of the grinding wheel has completely passed across the wafer surface, the wafer is retracted along both its infeed and crossfeed axes. The entire cycle is then repeated with an additional infeed step.

The wheel is re-trued and redressed before each grinding test. Quartz wafers received for grinding are already lapped and deep-etched, and represent tolerances that are the best commercially available. These wafers have been measured with a contact thickness gauge at give places to determine their thickness tolerances. The "five point" measurements were later found (through interferometry) to underestimate total thickness variation on the surface by as much as a factor of two. The total thickness variation (TTV) measured for as-received wafers using the five-point gauging was always ≥ 2 μm. The grinding conditions that were used to grind wafers are described in Table 1.

[5] This model of a single "high-spot" on the grinding wheel has been verified experimentally for ultra-precision grinding (Fawcett and Dow, 1990).

Table 1 Wafer grinding conditions

Wheel Geometry	100 mm diameter cup wheel, 6.3 mm wide face
Wheel Composition	10-20 μm natural diamond, 100 conc., bronze bond
Configuration	Air bearing spindle and cross slide
Infeed	100 nm/pass, 50 passes per sample
Crossfeed	40 μm/sec
Wheel speed	1.5 m/sec
Wafer size	32 mm x 32 mm x 0.10 mm
Cutting Environment	Water

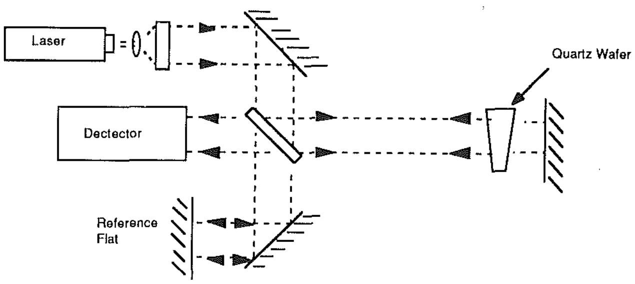

Fig. 5 Interferometer schematic

Wafer Thickness Measurement Technique

A technique to measure the thickness variation of thin quartz wafers has been implemented using optical interferometry. The measurement set-up is illustrated schematically in Fig. 5. A modified Green-Twyman interferometer is used to generate an interferogram corresponding to wafer thickness variation. A collimated plane wave generated by a helium neon laser source passes through the quartz wafer, reflects from a flat mirror, and returns through the wafer to a detection system where it interferes with a reference plane wave. If the wafer is not of uniform thickness, light passing through a thicker section has a longer optical path distance, *opd*, than light passing through a thinner section of the wafer. The optical path distance of coherent laser light passing through several different media can be written as:

$$opd=\sum_i n_i x_i \quad (1)$$

where n_i is the index of refraction of the medium and x_i is the distance traveled in the medium. For the setup under consideration, light travels through only two materials; air and quartz. The difference in optical path distance (Δopd) for two sections of the wafer that differ in thickness by an amount Δt is given by:

$$\Delta opd=2\Delta t(n_{\text{quartz}}-n_{\text{air}}) \quad (2)$$

(the factor of two is due to the light traveling through the wafer twice). A difference in optical path distance (Δopd) equal to one wavelength of light (λ) will result in one interference fringe on the interferogram. From Eq. (2), it can be seen that the wafer thickness variation per interferogram fringe is:

$$\Delta t=2\lambda(n_{\text{quartz}}-n_{\text{air}}) \quad (3)$$

The total thickness variation of the wafer is then given by:

$$TTV=2\lambda N(n_{\text{quartz}}-n_{\text{air}}) \quad (4)$$

where N is the number of fringes in the interferogram.

The optical phase difference between measured and reference wave fronts is analyzed using a 80386 desktop computer that digitizes and evaluates the interferogram. The interferometer and the imaging software are commercially available[6]. Using the technique discussed above, we were able to measure the thickness variation of the wafers before and after machining. The best "as-received" wafers (which has already been double side lapped to the tolerance limits achievable in conventional BAW wafer processing) were typically in the range of 2 μm thickness variation over a 32 mm × 32 mm wafer. Figure 6 shows a contour plot of the thickness variation of a typical 100 μm thick quartz wafer prior to machining on the wafer grinding apparatus. The "five-point" thickness measurement technique indicated a total thickness variation of 2.0 μm. The contour of this wafer measured by interferometry showed a total thickness variation of 2.2 μm. This value represents the typical TTV limitation of current BAW wafer production processes (i.e., lapping and etching).

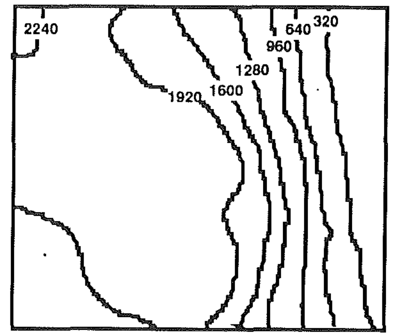

Fig. 6 Contour plot of thickness variation in a quartz wafer that has been double-side lapped and etched to best effort in the existing commercial BAW wafer fabrication process. Contour intervals are 320 nanometers. Total thickness variation: ~2200 nanometers.

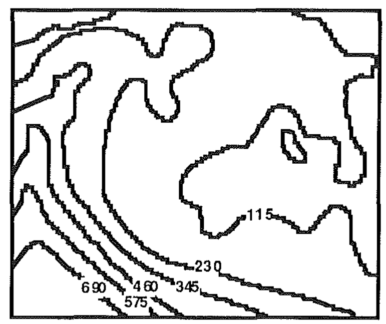

Fig. 7 Contour plot of thickness variation in a quartz wafer that has been ground on the previously described ultra-precision grinding apparatus (one side only). Contour intervals are 115 nanometers. Total thickness variation: ~700 nanometers.

Using a bronze bonded grinding wheel with a diamond grain size of 10–20 μm, a wafer was ground on the wafer grinding apparatus using the grinding conditions described in Table 1. Total depth of material removed was approximately 5 μm. Figure 7 shows the thickness variation contour plot for the machined part. This is not the same wafer that was shown in the previous figure; however, its original thickness variation measured by the "five-point" contact measurement technique was initially the same as that given for that wafer (i.e., 2.0 μm). The sample shows an overall thickness variation of about 0.7 μm on the contour map, representing an improvement in thickness tolerance by a factor of three over the lapped and etched wafer surface. The total thickness variation achieved is two to three times larger than the estimated random errors measured for this grinding process, which seems reasonable.

The lower-limit on achievable total wafer thickness for this process has not been established. To date, the minimum thickness achieved is ~80 μm. Further reductions in wafer thickness will be limited primarily by the extent of grinding-induced subsurface damage, which can be controlled by modifying the abrasive grain depth-of-cut for the process.

[6]Breault Research Organization Inc.

Summary

By integrating three current technologies of precision engineering: *ultra-precision grinding*, *distributed-stress vacuum fixturing*, and *closed-loop*, *real-time*, *precision infeed control*, a new process for manufacturing thin wafers has been developed and tested for its feasibility. The process permits fabrication of quartz wafers with thickness tolerances that improve the current state-of-the-art by a factor of two. It has been demonstrated that quartz wafers with thickness variations of < 1 μm can be produced by a deterministic grinding process.

Also, a technique for measuring the thickness variation of micro-ground quartz wafers has been demonstrated.

This new technology is not restricted to the resonator industry. It is anticipated that by the year 2000, the semiconductor industry will begin production of ultrahigh density one giga-bit D-RAM for the computer industry. For these devices, thickness variations on the order of 0.1 μm over an area of 20 mm $\times$ 20 mm will be required (Abe, 1991). The present work describes a fabrication strategy that might achieve such tolerances in production.

Acknowledgments

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