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A study on the optimal fabrication method for micro-scale gyroscopes using a hybrid process consisting of electric discharge machining, chemical etching or micro-mechanical milling

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ABSTRACT

For productive manufacturing of an accurate small-scale wine-glass gyroscope, a hybrid fabrication process consisting of either electric discharge machining, chemical etching, or micro-mechanical milling have been proposed. A comparison of silicon cavity fabrication processes has been conducted in terms of productivity, quality and geometrical accuracy, aiming at the use of the cavity as a mold for creating a thin wall diamond hemisphere, which is the main component of a wine-glass gyroscope. The results have shown that the EDM process, combined with chemical etching, can yield the highest productivity but with limited shape accuracy. The use of mechanical micro-milling, while less productive than EDM and etching, produces a superior quality and geometric accuracy.

1. Introduction

In order to reduce the dependency on conventional MEMS fabrication methods for 3D freeform feature fabrication in silicon wafers, traditional manufacturing technologies offer a compelling alternative due to their ease of use and fabrication capabilities for complex geometries. While MEMS technologies, such as X-ray LIGA and micro-stereolithography, are capable of creating 3D features in silicon, their productivity is poor and accessibility is limited due to high operational costs. For many MEMS applications which require 3D features, such as micro-lenses, sensors, and actuators, the key stage of fabrication is the creation of a high quality, geometrically accurate freeform mold, which is then used for structural layer deposition, etching, polishing, etc. Fig. 1 shows one such application, which is a CVD diamond shell for a micro-scale rate integrating gyroscope (MRIG) based on a hemispherical "wine-glass" resonator, with a cross sectional view of the shell's typical dimensions shown in Fig. 2. For this device, radial deviation and geometric symmetry are of utmost importance in order to optimize device performance. While past feasibility studies have shown that traditional manufacturing processes, such as electrical discharge machining (EDM) and mechanical micromachining are capable of producing such freeform shapes [1,2], there is a lack of knowledge in terms of comparing the performance characteristics for these processes.

EDM is an ideal material removal process for hard/brittle materials such as silicon since there are no cutting forces involved, which eliminates the tendency of crack propagation due to localized pressure on the workpiece [3]. While this process has been shown to be highly productive while using low discharge energies to avoid micro-cracking [4], it requires post processing in order to achieve the desired surface quality, which is achieved here through chemical etching. Mechanical micro-milling, under ductile mode machining conditions, is also effective in creating 2D and 3D shapes in hard/brittle materials [5–7]. Due to the presence of cutting forces, however, the productivity may be limited by the need to achieve defect free machining results.

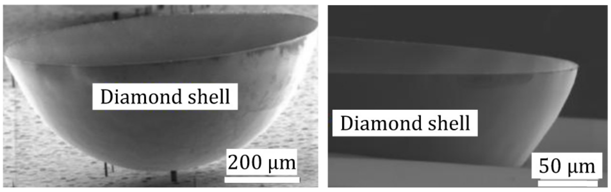

Fig. 1. SEM images of fabricated CVD diamond fully released shell for a hemispherical gyroscope.

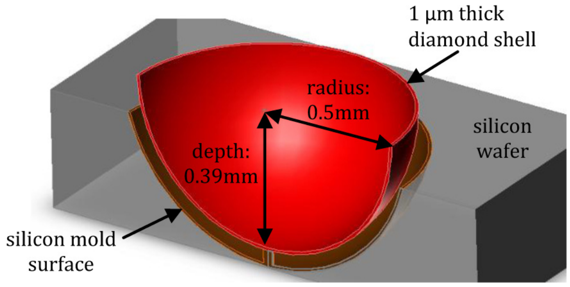

Fig. 2. Cross section of CVD diamond shell and dimensions for hemispherical gyroscope fabrication prior to release from silicon mold.

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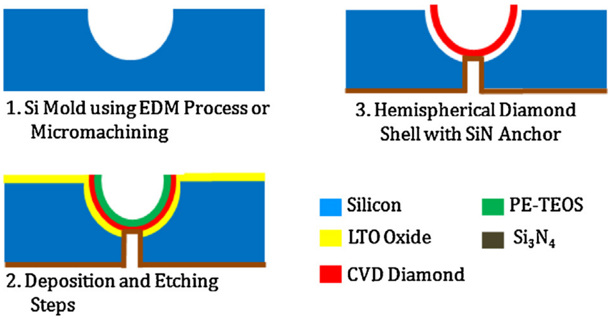

Fig. 3. Fabrication process flow using EDM and etching or mechanical micro-milling for hemispherical structures on silicon.

In order to compare the achievable productivity, quality, and geometric accuracy of traditional manufacturing capabilities for 3D feature fabrication in silicon, two processes will be examined: EDM roughing with chemical etch finishing and mechanical micro-milling. The process flow for hemispherical shape fabrication is shown in Fig. 3. While the MRIG device requires additional post processing via various MEMS fabrication steps, this paper focuses on a direct comparison of the two traditional manufacturing processes with the goal of observing which processes are most suitable to achieve either the best productivity, surface quality and/or geometric accuracy possible.

2. Study on a fabrication process consisting of EDM with chemical etching

2.1. Experimental setup

An EDMing process is to be developed in conjunction with chemical etching for wine glass resonator mold fabrication. After forming the EDMed hemispherical silicon mold, wet isotropic etching will be conducted using HNA (HF/nitric/acetic acids) to efficiently obtain a smooth and highly axisymmetric mold. For the EDM process, careful selection of electrode material, number of operations, cutting conditions and wafer resistivity must be conducted in order to create a large number of hemispherical mold features on a single wafer with good productivity and stability while minimizing electrode wear.

From past research, it was found that by using a diamond-based electrode material such as PCD, wear can be largely eliminated when EDMing common materials such as steel or tungsten carbide [8,9]. From this, PCD was selected as a suitable electrode material to achieve minimal wear through proper selection of EDM cutting conditions for EDMing of silicon. A 1 mm diameter hemispherical PCD electrode was fabricated using a single pass profile cut at high speed rotation using a 6-axis wire EDM. For EDMing of the silicon wafer, a die-sinker EDM is used with high speed electrode rotation capability (300 rpm) for good shape concentricity. Standard 100 mm diameter, ⟨1 0 0⟩ silicon wafers doped to a resistivity of 0.2 Ω cm are used for experimentation.

Two different EDM processes are tested in order to observe the balance between productivity and quality. First, only a roughing EDM operation is tested using a *Z*-axis plunge motion with the goal of optimizing productivity and electrode wear without considering surface quality. In order to reduce the effects of wear, a positive polarity is applied to the electrode with an adequately long discharge ON time. The adverse effect of such EDM conditions, however, is that the surface roughness will also be relatively large.

Second, the same roughing operation will be followed by a finishing operation, which makes use of *X*–*Y* plane orbital motion and negative electrode polarity in order to optimize surface quality without considering productivity and/or electrode wear. The use of a negative polarity, unfortunately, results in higher electrode wear rates and the need to re-condition electrodes frequently to maintain shape geometric accuracy.

2.2. Experimental results

EDM roughing experimentation was completed for 200, 1 mm diameter, hemispherical features at a constant feature depth of 390 μm using a single electrode for all features. All EDM conditions were held constant except for the discharge ON time, which was set at 1 μs and 5 μs for trials 1 and 2, respectively. Table 1 lists the cycle time, electrode wear and surface roughness results while Fig. 4 shows the PCD electrode before and after each EDMing. The first trial resulted in a cycle time of 47 min and wear rate of 150 μm per 200 features. The second trial's cycle time was slightly longer at 55 min but remarkably resulted in a wear rate of only 2 μm per 200 features. This corresponds well with the application of a larger discharge ON time for the second trial, and the increase in cycle time contributed to greater volume removal since the electrode did not wear considerably, thus, EDMs more material than that of the first trial.

Table 1
Experimental results comparison for silicon wafer EDMing of 200 hemispherical features with a single electrode.

Trial	Discharge ON time (μs)	Cycle time (min)	Electrode end wear (μm)	Surface roughness
1	1	47	150	15–20 μm, R_z
2	5	55	2	15–20 μm, R_z

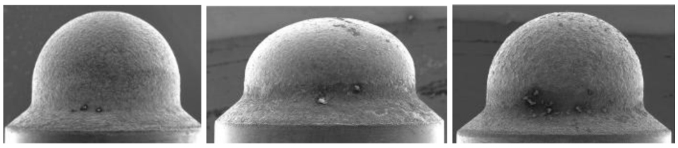
(a) New electrode (b) Trial 1 used electrode (c) Trial 2 used electrode

Fig. 4. PCD electrode comparison before and after EDM roughing.

Using the EDM roughed hemispherical features, HNA etching was attempted in order to efficiently improve the surface roughness. HNA has a relatively aggressive etch rate of 6–8 μm/min at 31 °C, which results in an etch time of less than 2 min to simultaneously etch all 200 features.

In order to further improve the surface roughness and shape accuracy of the hemispherical features, two-step EDM rough and finishing trials were conducted, which use an orbital finishing motion of 20–40 μm per side with low discharge energy settings and negative electrode polarity. Due to the negative polarity condition, electrode wear increases severely, thus, only a single feature will be EDMed per electrode. Eight different trials were conducted, each using different discharge parameters, which vary orbital distance, discharge current, servo voltage and discharge ON time. The resulting feature upper rim radial variation and eccentricity numerical data are plotted in Fig. 5 along with a feature that was rough EDMed only for reference.

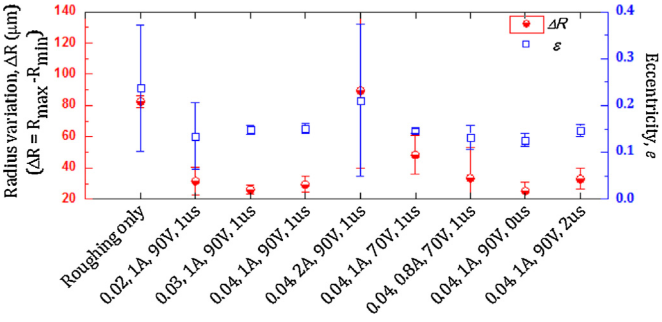

Fig. 5. Feature characteristics after EDM finishing for various orbital distances, current, voltage and discharge ON time settings. Measurements were collected from 3 samples for each trial.