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DESIGN AND FABRICATION OF A SILICON-BASED MEMS ROTARY ENGINE

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ABSTRACT

Design and fabrication of a Silicon-based MEMS rotary engine are discussed in this paper. This work is part of an effort currently underway to develop a portable, autonomous power generation system potentially capable of having an order of magnitude improvement in energy density over alkaline or lithium-ion batteries. Central to the development of this power generation system are small-scale rotary internal combustion engines fueled by high energy density liquid hydrocarbons capable of delivering power on the order of milli-Watts. The rotary (Wankel-type) engine is well suited for MEMS fabrication due to its planar geometry, high specific power, and self-valving operation with a minimal number of moving parts. The smallest "micro-rotary" engine currently being fabricated has an epitrochoidal-shaped housing under 1 mm^3 in size and with a rotor swept volume of 0.08 mm^3.

This paper discusses some of the fabrication issues unique to MEMS fabrication of a rotary engine at this small scale. High precision, high aspect ratio structures are necessary to provide adequate sealing for high compression ratios. Effects such as footing and lateral to vertical etch rates must be minimized for proper engine operation. A fabrication process is necessary for the complex, multi-height geometry of the housing and rotor assembly. Finally, a repeatable and simple assembly technique must be developed in order to mass-produce these engines.

Fabrication of a Silicon-based micro-rotary engine is being conducted in U.C. Berkeley's Microfabrication Laboratory. The engine system is composed of three main components: rotor, housing, and shaft. The engine and rotor housing must be entirely fabricated from Silicon without embedded oxide to prevent thermal mismatch or structural weakness at the Si-oxide interface. In order to meet this requirement, the fabrication processes for the housing consists of a two-mask two-etch process of a solid Silicon wafer. The fabrication of the rotor follows a similar process, utilizing deposited oxide as a release layer. Using Silicon Dioxide and photoresist for masking, housing and rotor structures are etched from solid Silicon using timed Deep Reactive Ion Etching (DRIE). A unique feature of these processes is the self-masking of the spur gear in the housing and the shaft thru hole in the rotor during the second DRIE steps, which give the necessary multi-level, cross-sectional profile.

INTRODUCTION

A growing area of research within MEMS (MicroElectroMechanical Systems) is energy conversion and generation. As electrical and mechanical systems are being miniaturized, components used to power these systems limit the size and weight of the device. Thus, there is a need for a compact, portable power generation system with a high energy density. Improvements and innovations in MEMS manufacturing techniques and materials have provided the opportunity to produce MEMS-scale thermal devices such as engines, fuel cells or thermoelectric devices [1]. Power generated from a MEMS scale engine could be applied directly via output torque or converted electrically by an electrical generator. Specific applications include mobile electrical power supplies necessary for electronic systems or mechanical torque necessary for robotic.

The ultimate goal of the present work is to fabricate a micro-rotary engine which produces ~10-100 mW of power. A rotary engine was selected for development as the basis of a MEMS-scale power generation system due to several factors: planar design of the rotor and housing, design simplicity due to its "valveless" operation, and power from a rotary engine can be extracted mechanically or electrically.

The chamber of this engine is approximately 1 mm in size with an engine displacement of 0.08 mm^3. A 20% efficient power generation system using this engine could potentially have 5 times to 14 times the energy density of a primary battery (such as lithium or alkaline batteries). This would lead to a potential savings in system weight or an increase in the total system lifetime in comparison with a battery. Table 1 shows the anticipated operating and design parameters of the micro-rotary engine.

Research into the combustion and design issues of engine miniaturization began with the design and testing of a centimeter-scale "mini-rotary" engine. These engines were fabricated from steel using electron discharge machining (EDM). Testing of the mini-engines with H_2-air mixtures produced combustion as well as power output of approximately 3 Watts at 10,000 RPM. The ultimate goal of the mini-rotary engine is to produce ~30 W at 40,000 RPM [2,3].

During the design and testing of the "mini-rotary" engines, precision fabrication was identified as a key parameter limiting performance. Without adequate tolerances, compression is severely

Table 1: Micro-rotary engine design parameters

Est. Power (mW)	30
RPM	40,000
Displacement (mm^3)	0.08
Fuel Consumption (μL/hr)	19
CO_2 Output (mL/min)	0.6
Heat Output (W)	0.1
Rotor Diameter (μm)	900
Rotor Thickness (μm)	300

limited which subsequently decreases the power output of the engine. Consequently, fabrication tolerances generated in the manufacturing of a MEMS-scale engine will be important to the overall operation of the engine.

Currently, research is centered on the fabrication of the individual components of the engine such as the rotor and housing. The overall dimensions of these components and their interaction with each other will be an extremely important first step toward an operational power generation system. This paper discusses the design, development, and fabrication of a Silicon-based rotary engine parts for pick and place assembly.

ENGINE DESIGN AND FABRICATION ISSUES

A rotary engine operates on a 4-stroke cycle, which can be modeled as either the Otto or Diesel cycle, depending on the ignition source. Otto or Diesel cycle efficiency is a function of the engine compression ratio. In a rotary engine, the fuel-air mixture is compressed between the rotor and the chamber wall. The typical leakage paths in the rotary engine are past the rotor apexes and the rotor face. Engine sealing in the rotary (and piston) engine relies on the rotor and housing faces staying in contact and forming a seal. Typically, a fluid (fuel and/or oil) is used to seal the micropores that inevitably exist between two sliding surfaces. In large-scale rotary engines, the apex and face seals are spring-loaded, forcing contact between the housing wall and rotor, aiding the sealing of each chamber.

The primary assumption in the rotary sealing system is that the housing and rotor are straight and parallel, which is essential to obtain good sealing and, in turn, a high compression ratio. In MEMS, typical deep reaction ion etching (DRIE) processes can produce an aspect ratio of 20:1 to 100:1. One of the first tasks after fabrication of the individual micro-rotary parts is to quantify the wall straightness.

Currently, the micro-rotary engine is being fabricated in separate

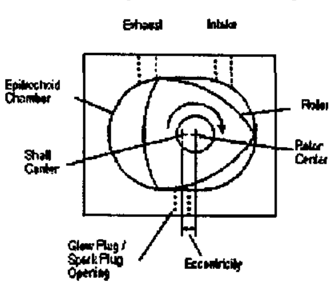

Figure 1. Rotary engine schematic

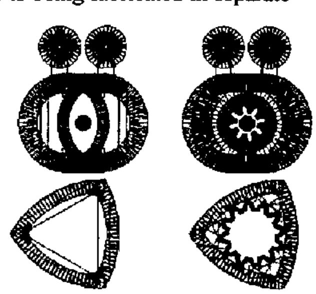

Figure 2. Micro-rotary engine housing rotor mask designs

parts to simplify the fabrication process and explore methods of increasing wall straightness and minimizing the fabrication tolerance. In addition, fabricating the engine components separately allows for the testing of various rotary engine parameters and designs. The current micro-engine mask design consists of a 5x5 matrix that varies spur / annular gear design and rotor and housing offsets. Different spur gear designs are being investigated to determine the appropriate number of gear teeth based on fabrication tolerance and engine operation. As the number of gear teeth increase, the accuracy of the rotor placement during engine increases. Increased rotor placement leads to improved sealing, as the rotor apexes are in contact with the engine housings. However, gears require an involute profile to accurately mesh and disengage during operation [4]. During the housing fabrication process, the spur gear is required to self-mask, so that the gear is at a different height than the housing walls. Without a mask protecting the gear profile, the involute profile will inevitably degrade as the etch continues. An important issue is to determine the maximum number of gear teeth that can survive the self-masking process.

The other design parameter being investigated with the first generation micro-rotary engine is the maximum housing offset required for sealing. In a rotary engine with a true epitrochoidal housing, the tips of the rotor do not continually touch the housing sides during operation. If apex seals are installed, the apex seals are forced to move slightly in and out during engine operation. An offset reduces this effect, leading to longer engine life and improved sealing in large-scale engines [5]. The first generation micro-rotary engine rotor does not have apex sealing; therefore, the rotor / housing clearance is minimized by the increased rotor housing offset.

In the design matrix, the number of housing spur gear teeth step from 2, 8, 12, 24, to 36 [6] gear teeth, with the corresponding rotor annular gear teeth count from 3, 12, 18, 24 to 54. The 'Wankel-type' rotary engine being fabricated in this project requires a 3:2 gear ratio between the annular and spur gears [7]. The housing offset ranges from 0, 5, 10, 25 to 50 μm. Accordingly, the rotors have been increased in size to fit within the housing. An advantage of the pick-and-place method is that during assembly, rotors of varying size can be tested in any housing to determine which size rotor is the most useful for practical operation.

ENGINE HOUSING DESIGN AND FABRICATION

The micro-rotary engine epitrochoidal housing is dictated by the following equations [5]:

$$x = e\cos 3\alpha + R\cos\alpha + a\cos(\alpha + \Theta_e) \quad (1)$$

$$y = e\sin 3\alpha + R\sin\alpha + a\sin(\alpha + \Theta_e) \quad (2)$$

$$\cos\Theta_e = \frac{R + 3e\cos 2\alpha}{9e^2 + R^2 + 6eR\cos 2\alpha} \quad (3)$$

where e is the eccentricity, R is the generating radius, x is the epitrochoid horizontal position, y is the epitrochoid vertical position, α is the rotor angle, and Θ_e is the polar angle of apex. An AutoCAD LISP program was written to draw the eptirochoid housing shape as a series of rectangles with a <1 μm tolerance to the epitrochoidal shape.

Figure 2 shows the engine housing mask for the first generation micro-rotary engine. The inlet and exhaust port positions are similar to the designs of the mini-rotary engine, with the inlet and exhaust designed to accept gauge 22 syringe needles. The engine housing cross-section is shown in Figure 3 and consists of a 300 μm high

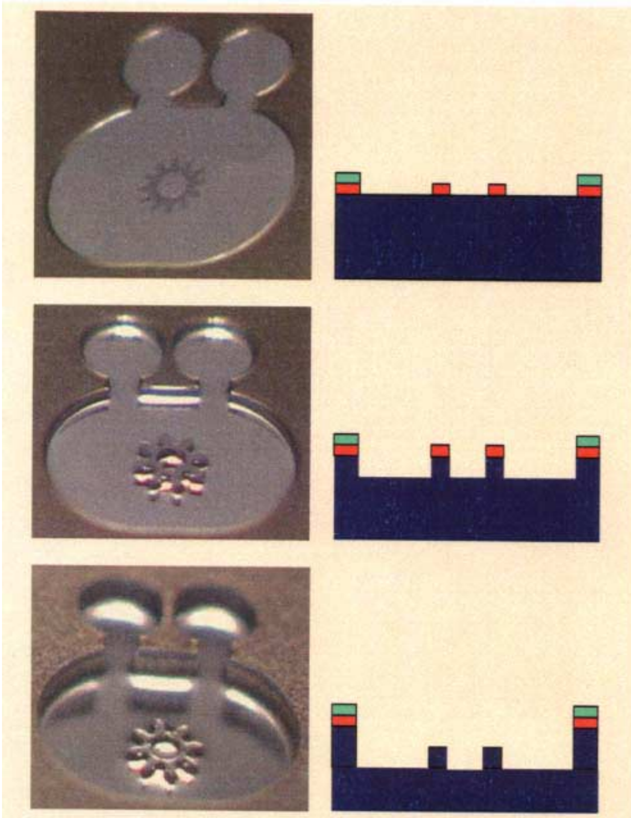

Figure 3. Micro-rotary engine housing fabrication process.
Top. 1.5 microns of SiO_2 and 9 microns of thick resist have been applied and patterned. The oxide mask is identical to the thick resist mask, except for the spur gear, where no resist is present.
Middle. After first ~100 micron etch. The inlet / exhaust port, epitrochoid housing profile, and spur gear have been etched into the Si substrate.
Bottom. The oxide is etched away and a second DRIE is performed. The housing is etched a further 200 microns. Gear is self-masking.

housing with a spur gear ¼ to ½ the overall height of the housing wall (75 μm to 150 μm tall). This two-height cross-section requires a two-mask, two timed etch process shown in Figure 3.

The micro-rotary engine housing fabrication process begins with a 500 μm thick Silicon (Si) wafer. The depth of the completed housing will be 300 μm. A series of different engine depths will be investigated in the future to study heat losses from the micro-engine. A 1.5 μm thick Silicon Dioxide (SiO_2) layer is deposited using Low Pressure Chemical Vapor Deposition (LPCVD) and acts as mask 1 for the etching process. The SiO_2 is patterned and etched, as shown in Fig. 3. This SiO_2 etch defines the epitrochoidal housing, inlet / exhaust ports, and spur gear. Thick photoresist (~9 μm) is applied and patterned. The thick photoresist pattern is identical to that of the SiO_2, except the housing spur gear is not covered by photoresist. Notice that the deep bulk Si etches occur after the two masks (SiO_2 and thick photoresist) have been applied and patterned. This method ensures that the photoresist mask is as accurate as possible.

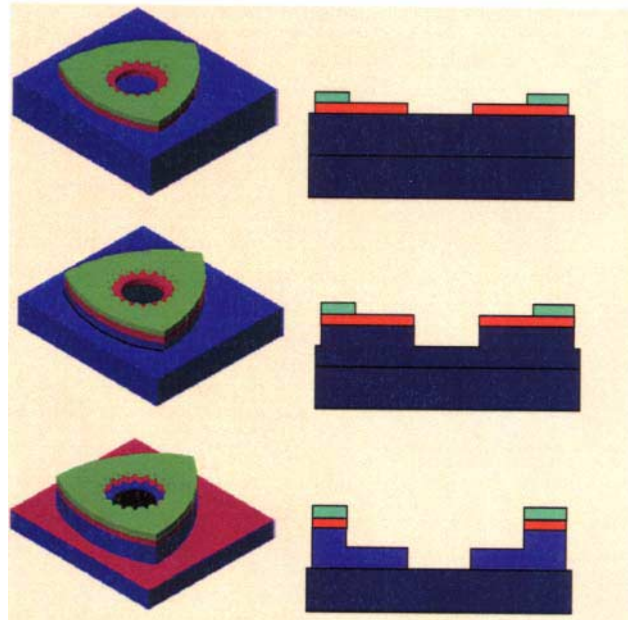

Figure 4. Micro-rotary engine housing fabrication process.
Top. 1.5 microns of SiO_2 and 9 microns of thick resist have been applied and patterned. The oxide mask is identical to the thick resist mask, except for the spur gear.
Middle. After first ~125 micron etch. The inlet / exhaust port, epitrochoid housing profile, and spur gear has been etched into the Si substrate.
Bottom. The oxide is etched away and a second DRIE is performed. The housing is etched a further 175 microns.

A timed (~100 μm) deep reactive ion etch (DRIE) defines the design patterned by the oxide. The wafer is then exposed to an anisotropic oxide etch, which strips off the spur gear patterned oxide. However, the thick photoresist is still intact. Another timed (~200 μm) DRIE is then performed. During the second DRIE, the spur gear is also being etched, because it is no longer protected by the Silicon Dioxide (SiO_2). However, the engine housing floor is also being driven down, resulting in a ~100 μm high spur gear, which is self-masked during the second DRIE. The dimensional details will be described later in the paper.

MICRO-ENGINE ROTOR DESIGN AND FABRICATION

The design of the first generation micro-engine rotor does not incorporate apex or face seals. Sealing tests with this rotor will provide a baseline for comparison with future rotor designs incorporating seals. It is also important for the basic rotor fabrication to be optimized prior to integration of further apex and face seal designs. The rotor fabrication process is also a two-etch, two-mask process with SiO_2 and thick photoresist used as the masks. The rotor design consists of annular gear sets ranging from 3 teeth to 54 teeth,

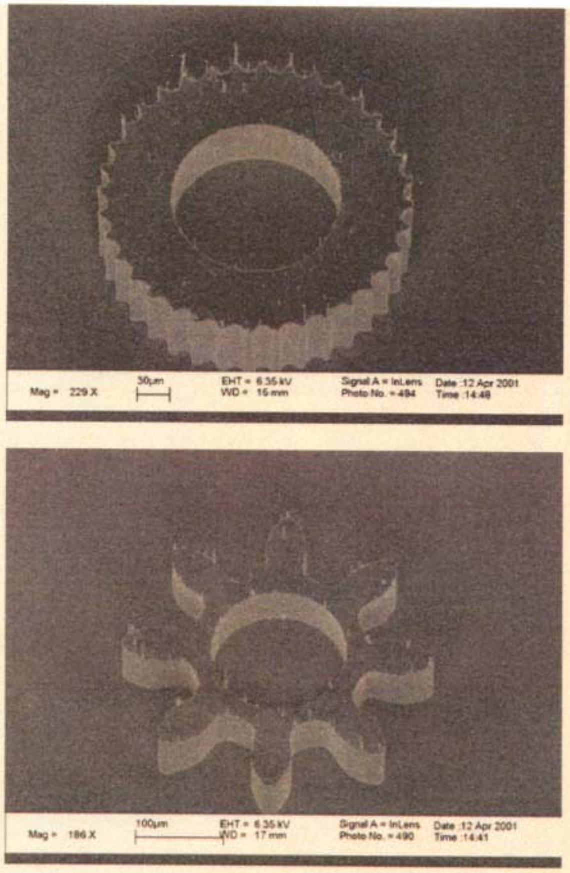

Figure 5. SEM images of 36-tooth (above) and 8-tooth (below) spur gears in the micro-rotary engine housing

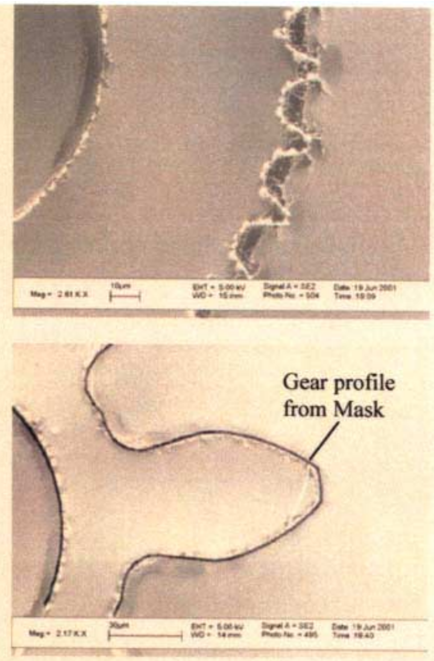

Figure 6. SEM images of 36-tooth gear profile (above) and 8-tooth gear profile (below). The mask design for the 8-tooth has been overlaid the SEM

matching the spur gear set in the housings. In addition, the rotor diameters also correspond to the housing offsets (0 μm to 50 μm).

The micro-rotary engine rotor fabrication process begins with a 300 μm thick Si wafer. A 1.5 μm thick SiO_2 layer is deposited using LPCVD and acts as the release layer for the rotors, as well as the first mask for the etching process. The SiO_2 is patterned and etched. This SiO_2 etch defines the rotor shape and shaft through hole. Thick Photoresist is applied and patterned to define the rotor outer shape and spur gear. A timed (~125 μm) deep reactive ion etch (DRIE) defines the design patterned by the oxide. The wafer is then exposed to an anisotropic oxide etch, which strips off the shaft through hole oxide, allowing the annular gear patterned in the thick PR to be the mask during the next DRIE Si etch. However, the thick photoresist is still intact. The rotor device wafer is then attached to a handle wafer via hardened photoresist for the second DRIE Si etch. The second Si timed etch (~175 μm) is then performed. During the second DRIE, the annular gear is masked by the thick photoresist, while the shaft through hole is self-masked. The housing spur gear is ~100 μm high, while the annular gear is ~175 μm tall, ensuring that there is no interference during assembly. After the second DRIE etch, the device wafer is separated from the handle wafer in a 85°C PRS-3000 photoresist etchant. The rotors are released from the SiO_2 layer by a HF dip and collected for assembly on filter paper.

HOUSING AND ROTOR FABRICATION ANALYSIS

Analysis of the housing and rotor fabrication process consists of visually inspecting the housing and rotor with a LEO 1550 Scanning Electron Microscope (SEM) and dimensional measurement with a Veeco Wyko NT3300 white light interferometer (Wyko). Initial measurements of the housing and rotor indicate issues with gear teeth profile accuracy, cross-wafer etch uniformity, and sidewall straightness. However, these initial observations do indicate that it is possible to fabricate a micro-rotary engine.

Gear Tooth Profile Accuracy

Figures 5 and 6 show a series of SEM pictures of housing spur gears. Figure 5 shows images of the 36-tooth and 8-tooth gears in the micro-rotary engine housing. From measurements with the Wyko, these spur gears are 75±5 μm in height. The vestigial Si "stringers" are a product of residual oxide remaining after the SiO_2 removal etch. A close-up of the 36-tooth gear profile and 8-tooth profile is shown in figure 6. The 8-tooth single gear profile has the mask design overlaid as a black line. Measurements of the gear tooth profile were taken using SEM and compared with the mask involute profile. For the 8-tooth gear profile, there is no discernible bilateral etch along the gear side and a <1 μm etch along the top of the gear tooth. This is a tolerance of 100% for the gear edge and a 99% tolerance for the gear tooth tip. In contrast, the 36-tooth gear lost the upper 50% of the entire gear tooth during the self-mask etching process.

From these measurements, the 8-tooth spur gear can be used for testing of the micro-rotary engine. The 12-tooth spur gear retained 85% of the mask profile along the gear side and 92% along the top of the gear. The 12-tooth spur gear will be tested to determine if the spur gear is usable. The fabrication recipes and etch recipes can also be

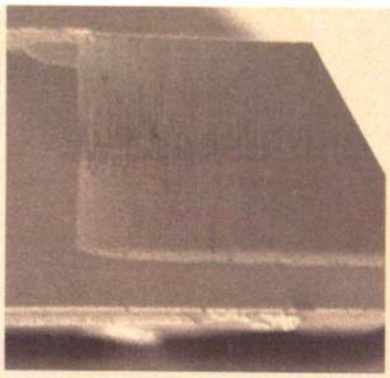

Figure 7. SEM of cleaved housing wafer. Si DRIE results in 46:1 aspect ratio.

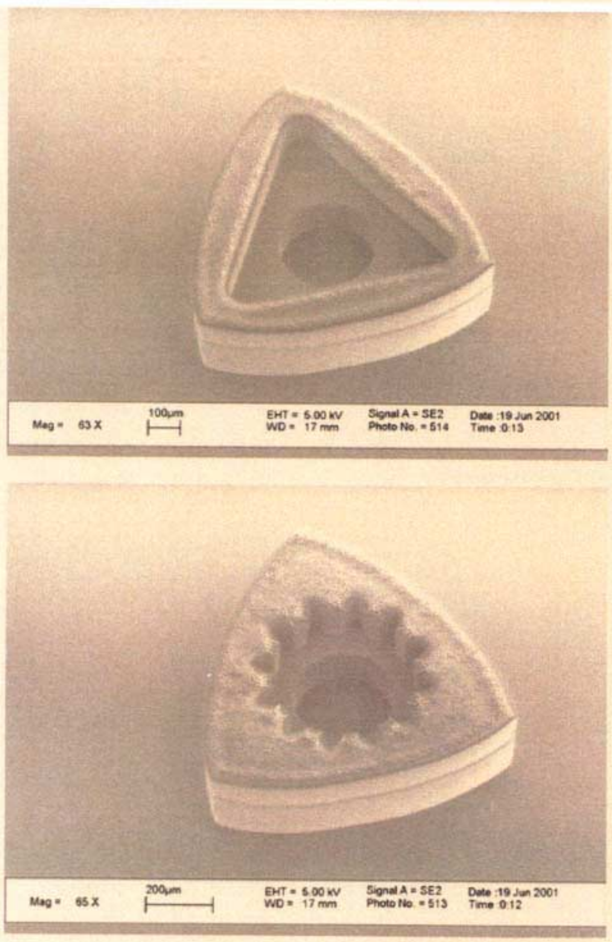

Figure 8. SEM of first generation micro-rotary rotor
Top: 3-tooth rotor prior to release.
Bottom: 12-tooth rotor prior to release
The amorphous pebbly material on the rotor top is photoresist. The line visible partway down the rotor side is due to the second SiO_2 etch.

modified to reduce the lateral etch in the 12-tooth spur gear. The effect on rotor placement and sealing will be determined during the leakage testing process.

Si Cross-Wafer Etch Uniformity and Sidewall Straightness

The DRIE performed for the rotor and housing are both timed. The Silicon Technology Systems (STS) Advanced Silicon Etch system etches Si at approximately 2.7 µm/min utilizing current recipes. However, the etch rate can vary depending on trench size, depth, and wafer temperature. Thus, it is difficult to accurately control the depth of the two Si etches. Furthermore, cross-wafer etch depth uniformity is also difficult to maintain, resulting in ±25 µm etch uniformity from wafer edge to wafer center when etching 300 µm deep on a 100 µm diameter wafer as measured by the Wyko. Cross-wafer etch non-uniformity lowers the yield of the fabrication process, because the rotors must be used in engine chambers with 300 µm deep trenches to minimize face leakage.

A SEM image of a cleaved housing wafer shows an aspect ratio of 46:1 (see Fig 7). To date, this is the most critical and difficult issue to overcome in the micro-rotary engine fabrication process. A series of options are being investigated to overcome this issue. Fine tuning the DRIE etching process of the STS is currently underway. It is believed that a 100:1 is possible with a more advanced DRIE etcher. With the introduction of a lubricating fluid in the micro-engine to aid in sealing, initial tests can be conducted. Parameter ramping will also be introduced to reduce surface roughness and increase the etch rate as the features are etched deeper [8]

CONCLUSIONS AND FUTURE WORK

Silicon housings and rotors for a micro-rotary engine have been fabricated at the UC Berkeley Microfabrication Laboratory. Initial measurement of the fabricated engine pieces indicates that the fabrication process has produced viable engines parts for an initial investigation into sealing and material characteristics. The housing spur gear and rotor through holes have been fabricated using a self-masking method to produce structures 150 µm in diameter and 75-100 µm in height.

Issues still remain with the fabrication process. Significant lateral etching of the spur gear profile and non-uniform etch rates across the wafer reduces the number of useable parts fabricated during the manufacturing process. The spur and annular gear tooth profile is important for engine operation; however, the gear tooth profile for gears with a smaller number of teeth seem adequate for engine operation.

Fabrication process and STS etch recipe modifications are being implemented to reduce the Si etch uncertainties. A low frequency platen for Silicon-on-Insulator (SOI) etch processes has been installed in the STS. STS etches with the low frequency platen result in increased cross-wafer uniformity with the cost of a lower Si etch rate (~1.5 µm/min). In addition, a method for obtaining real-time DRIE etch depths using a Fourier Transformed Infrared (FTIR) spectrometer is currently being investigated and installed.

DRIE timed etch depth and cross-wafer uniformity are issues for the micro-rotary engine housing fabrication and, to a lesser extent, the rotor fabrication. The current fabrication process can produce acceptable engine parts, but at the expense of low yield. Changes to the DRIE etching process and minor engine design changes will be made to minimize the effects.

After fabrication of micro-rotary engine housings and rotors with a 50:1 aspect ratio, the rotor and housing will be manually assembled.

This first generation micro-rotary engine will be initially tested by compressed air and an electric motor to determine engine leakage and wear characteristics. The Si engine will first be tested, followed by SiC coated Si pieces [9] and then Silicon Nitride (Si_3N_4) coated parts. The objective of these tests will be to investigate the long-term wear, lubricity, and toughness of the materials.

ACKNOWLEDGEMENTS

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