ABSTRACT

New results are presented for the development of a micro, internal-combustion engine fabricated in a process that achieves 900 µm deep features via deep reactive ion etching (DRIE). A single-sided 900 µm deep etch process with high mask selectivity is used to generate straight sidewall structures with low sidewall roughness. This research is part of an effort to create a portable, MEMS-based Rotary Engine Power System (MEMS REPS) capable of producing power on the order of milliwatts with an energy density better than that of a conventional battery. The MEMS REPS is based on the planar geometry and self-valving operation of a Wankel engine with an integrated electrical generator. A generator and stator co-located within the engine rotor and housing eliminates the need for any external shafts, couplings, or seals.

The rotary internal combustion engine is composed of 5 major components: a 900 µm deep rotor with soft magnetic poles and 25 µm wide in-plane cantilever beams which act as apex seals, a 900 µm deep epitrochoid housing with intake and exhaust ports, rear plate with spur gear, a top plate, and a shaft. This configuration was chosen in order to eliminate the effect of beaching during timed DRIE etches and to minimize engine leakage while maximizing spur gear teeth resolution, and simplifying engine fabrication. However, this configuration requires some assembly and optimization of DRIE parameters for each component.

The rotor and epitrochoid housing are co-fabricated on the same wafer to minimize deviation in thickness and match etch behavior between mating components. This approach forces the generation of a mask with narrow, deep trenches (to define the cantilever apex seals on the rotors) in proximity to large “tub” etches (to define the engine housing). High etch cycle pressures improved etch selectivity to over 350:1 with respect to oxide and 150:1 to photoresist which is necessary for 900 µm deep features. High pressure also improved sidewall profile of the etched structures. Engine cross-sections show an 8 µm wall deviation on either side of a 250 µm trench through an etch depth of 867 µm. In addition to good sidewall straightness, these etch parameters give a low sidewall roughness through the generation of small size scallops on the sidewalls. However, the side effects of these etch parameters include silicon “grass” at the bottom of the trench, poor etch uniformity across the wafer, and increased effect of aspect ratio dependent etching. Some strategies to overcome these effects are discussed.
INTRODUCTION
Recent advances in microfluidic and microfabrication technology have allowed for the development of more complex, integrated microsystems consisting of fluidic, electrical, and mechanical components. Of particular importance is the development of anisotropic Deep Reactive Ion Etching (DRIE) processes used for the fabrication of high aspect ratio structures from silicon with high etch rates and robust mask selectivity. This process has been integral to the development of microfluidic and micro-mechanical devices such as small-scale pumps, valves, coolers and tweezers. Typically, DRIE is used to define silicon structures such as microchannels, comb drive teeth, or cantilever beams of a few hundred microns in thickness. As the range of possible applications for micro-fabricated systems grow, demands are increasing for thicker device substrates with higher aspect ratios to be etched with a greater degree of precision.

A growing area of interest within the Micro Electromechanical Systems (MEMS) field concerns the development of portable, autonomous power generation devices [1]. One system with high aspect ratio structures which integrates microfluidic, mechanical, and electrical components is the MEMS Rotary Engine Power System (MEMS REPS). The goal of the MEMS REPS is a portable, autonomous power generation device based on a rotary internal combustion engine capable of power output on the order of tens of milliwatts. A conceptual prototype of the MEMS REPS is shown in Figure 1.

Applications for such a device include supplying power to cellular phones, remote sensors, or to other MEMS-based devices. Typically, commercial primary and secondary batteries are used to power portable electronic devices. However, batteries suffer from low energy densities which burden the application with excessive weight or short battery lifetime. In comparison, a liquid hydrocarbon fueled internal combustion engine operating at 10% efficiency would provide a 2.6 times energy density of the best primary or secondary batteries [2].

The basis for the MEMS REPS is a liquid hydrocarbon fueled rotary internal combustion engine. Engine torque is converted to electricity via an integrated electrical generator. The engine-generator assembly is located within a thermally insulated package shown in Figure 1. Figure 2 shows a schematic view of the engine with an integrated electrical generator. This paper focuses on the fabrication of the internal combustion engine central to MEMS REPS.

The engine design is based upon a Wankel rotary combustion engine. The Wankel design is advantageous for fabrication using MEMS techniques due to its planar geometry, few moving parts, and self-timed operation. This approach does not require valves or pumps for fuel delivery or injection, but rather the fuel and air input is controlled through the sweeping of the apexes by the intake and exhaust ports. With an anticipated power output on the order of tens of milliwatts, the use of valves and pumps becomes prohibitive for a truly autonomous portable power generation system.

The basic operation of a conventional Wankel engine is illustrated in Figure 3. The engine rotor turns within a housing chamber called an epitrochoid. The engine rotation is controlled through an eccentric cam shaft and a gearing between the housing (spur gear) and rotor (annular gear). The rotor partitions the combustion chamber into 3 portions within which 3 different cycles take place simultaneously. As the leading apex crosses the intake port, a fresh fuel/air mixture is drawn into the engine. When the trailing apex covers the intake port, the fuel/air mixture is compressed until the rotor reaches top dead center. At this point or just prior, a spark plug or a heated catalytic wire ignites the compressed mixture. The rapidly expanding gases act on the rotor through an eccentric
The core of the engine is made up of a rotor and epitrochoid housing which are highlighted in Figures 6-7. The generating torque. Eventually, the leading apex uncovers the exhaust port releasing the combustion products.

**PROCESS DESIGN**

There are three key parameters which influence the design of the Wankel rotary engine used in the MEMS REPS: system integration, fabrication, and assembly. One of the key driving features of the design is the integrated electrical generator. Typically, electric generators are coupled to an engine via a shaft. Electricity is generated through the rotation of an external component coupled to the shaft of the engine. On the microscale, this configuration would require ultra precise alignment between the engine and generator shafts. Such a setup would result in increased frictional losses, and new fluidic leakage paths which could compromise engine compression. Alternatively, these problems are averted if the generator is incorporated within the rotor of the engine itself. Soft magnetic material can be electrodeposited into holes in the rotor and serve as the rotating component of the generator. As the rotor rotates, the soft magnetic material varies the flux through a conductive coil. The disadvantages of this design lie in merging the magnetic components into the rotor in terms of fabrication, thermal, and mechanical design.

An important consideration of the engine design with respect to the generator is the engine size. For the purpose of this research, the size of the engine is defined by the length scale of the minor axis of the epitrochoid or the widest portion of the rotor. As engine size increased, the electrical generator will more closely able to match to the torque characteristics of the larger displacement engine. However, the engine size must not be increased such that use of batch fabrication via MEMS is prohibitive. In order to produce meaningful power from the electrical generator, the size of the engine was set to 2.4 mm with a thickness of 900 µm and eccentricity of 185 µm. These dimensions keep the same ratio between the minor axis and thickness as previously developed working prototype engines with a size scale of over a centimeter [3].

Two different approaches can be undertaken in the design of the rotary engine for MEMS fabrication. In one approach, the spur gear plate and the epitrochoid housing can be combined into one piece in order to minimize leakage from the engine chamber. One difficulty in extending this design to MEMS fabrication is its reliance on timed DRIE etches and the “beaching” effect. Figure 4 shows the floor of an epitrochoid rising up to the epitrochoid wall like sand due to a non-uniform trench bottom. Beaching can cause the rotor to seat improperly opening up wider leakage paths across the rotor faces. Beaching can be minimized by lowering etch cycle pressure in the DRIE process. Unfortunately, these more uniform etches incur both low selectivity to masking materials and low etch rates which would limit engine thickness. Another difficulty in this configuration is that the fabrication process would require a self-masking etch step. Lateral etching of the outer walls of gear teeth would limit tooth involute resolution such that high spur gear teeth counts would not be possible [4]. The number of spur gear teeth used is important since fewer teeth will lead to less accurate rotational control of the rotor within the epitrochoid. Subsequently, the apexes of the rotor would track the outer wall of the housing less accurately.

From a fabrication standpoint, a simpler approach is to separate the fabrication of the spur gear from the epitrochoid housing by making them separate components. The spur gear can then be fabricated in a one mask process with high precision. The epitrochoid can be fabricated via a through wafer etch without the effect of beaching. However, this engine configuration would require assembly. Figure 5 shows the cross-section of the rotary engine implemented in this design.
rotor has 3 important features: integrated in-plane cantilever apex seals, high accuracy annular gear teeth, and holes for electrodeposition of soft magnetic material. The epitrochoid housing features the intake and exhaust channels and the epitrochoid. This paper focuses on the fabrication of the rotor and housing. The engine is assembled via flip chip bonding of the rear plate, middle housing and a cover plate. Prior to final enclosure of the epitrochoid housing, the rotor and shaft are inserted via a precision pick and place method.

A critical factor to the engine operation is maintaining compression and minimizing leakage across the apexes and over the rotor faces. These flows are generated via large pressure gradients between different sections of the engine. A simplified flow model has shown that gap sizes must be less than 1 µm between the engine housing and the rotor apexes [5]. However, fabrication of MEMS devices with that degree of accuracy and with the thickness of the rotary engine would be impossible. Previous research on a centimeter scale prototype engine has shown that the majority of engine leakage arises from blow-by around the rotor apexes rather than across the rotor faces [3]. In order to maintain compression and minimize engine assembly, an apex sealing system consisting of pre-compressed in-plane cantilever beams are integrated into the rotor apex (Figure 7).

Mechanical modeling of the apex seals indicates that the apex seal width in the plane of the wafer and the corresponding trench size behind the seal are important to engine performance. The width and length of the apex seal dictate the stiffness of the cantilever beam and its ability to track the curve of the epitrochoid. However, a stiffer beam will lead to greater frictional losses if the length of the beam is not extended. The trench size behind the cantilever beam is important because it adds to the dead volume of the combustion chamber. Increasing the size of the combustion chamber decreases the compression ratio thereby degrading performance [6]. From a fabrication standpoint, the narrow width of the apex seal increases the demands on the DRIE etching process. For a 900 µm deep etch, a 25 µm wide apex seal backed by a 25 µm must maintain 30:1 aspect ratio (height to width ratio) on a relatively small trench in comparison to other structures on the rotor and engine housing.

FABRICATION

The objective of this fabrication process is produce highly accurate engine components which will minimize leakage. A variety of different methods for fabrication were examined in order to obtain this objective. One large constraint on the fabrication process is the relatively large thickness and high aspect ratio of the engine in comparison to typical MEMS devices fabricated from Deep Reactive Ion Etching.

Instead of utilizing wafer bonding, the rotor and epitrochoid housing are co-fabricated on a single 900 µm thick wafer. Misalignment of a rotor fabricated using wafer-to-wafer bonding could exceed 1 µm which would adversely affect compression and increase leakage. Two different strategies could be employed in order to etch through an entire 900 µm wafer. One method would be to etch half way through the wafer from the frontside. Subsequently, the backside of the wafer is patterned and etched until the rotors and housings are released. A similar approach was taken in the fabrication of a 1 mm thick combustor for a microfabricated gas turbine with one of the etches being isotropic [7]. The advantage of this strategy is that the vertical sidewalls of the DRIE would only need to be maintained through 450 µm rather than the entire
900 µm. However, frontside to backside lithography steps suffer from at least 1 µm of misalignment which could cause similar problems as wafer bonding. Preferably, a frontside 900 µm deep silicon etch will generate the most accurate pattern with a minimal amount of misalignment.

The fabrication process begins with 925±25 µm thick double-side polished 4 inch Silicon wafers. The first masking step is performed using 2.0 µm g-line photoresist. Labeling and die-scale flip chip alignment crosses and verniers for a FC150 die bonder are patterned on the wafer using a short (1-3 min) SF6 plasma etch.

After stripping and cleaning the wafer, a 1.5 µm thick LPCVD SiO2 is deposited on the wafer. The oxide layer serves as part of a dual mask etching process and as a release layer. The oxide layer is patterned with a 2.0 µm thick g-line photoresist and an anisotropic, dry oxide etch. This lithography step patterns the features which will be etched through the entire wafer as seen in Figure 8. After the photoresist is stripped, a 10 µm thick layer of Shipley SPR220 photoresist is coated on the wafer. The wafer is soft-baked for 10 minutes for 10 minutes and hard baked for 2 hours at 80°C. This type of resist exhibits a superior selectivity to normal photoresists during plasma etching. The resist is exposed to a pattern that includes both the through wafer features and the features which are only partially etched through the wafer such as the annular gear.

The 900 µm wafer is then attached to an oxide encapsulated handle wafer for the subsequent DRIE steps. Prior to performing any etching, a short chamber clean was performed on the STS chamber to improve etch profile and rate consistency from run-to-run. A timed etch via DRIE of approximately 320 µm in depth is performed to define the depth of the intake and exhaust ports without removing the exposed oxide regions entirely (Figure 9). The wafer is then exposed to an anisotropic oxide etch which removes remaining the exposed oxide. The exposed oxide is the difference between the hard oxide mask and the photoresist mask. The anisotropic oxide etch does not significantly attack the exposed photoresist. Finally, the photoresist pattern is driven down through the rest of the wafer thickness via DRIE.

The rotors and housings are released from the handle wafer by an acetone dip. The wafer is then cleaned in piranha to remove any residual adhesive that remains from the handle wafer attachment. A 1-2 minute dip in concentrated HF releases the rotors and housings from the underlying oxide layer. Figure 10 shows a released rotor with in-plane cantilever apex seals and holes for integrated soft magnetic material deposition placed on top of a penny.
DRIE CHARACTERIZATION

The most common method utilized for deep anisotropic etching of Silicon for MEMS devices is based on a patented process developed by Robert Bosch [8]. The Deep Reactive Ion Etching process relies on fluorine radicals generated in a SF₆ plasma to remove silicon. High density SF₆ plasma is provided via Inductively Coupled Plasma in order to obtain a sufficient number of free radicals for etching. sidewall passivation is provided by a conformal deposition of a fluorocarbon generated by a C₄F₈ plasma. Cycling of etch and passivation steps generates high rate, anisotropic etching of a silicon substrate. The ability to use Silicon oxide, Silicon Nitride and photoresist as masking materials for this etch process allows for compatibility with typical MEMS processes.

The UC Berkeley microfabrication laboratory uses a Surface Technology Systems (STS) Advance Silicon Etch (ASE) machine for deep silicon etch processing. The STS DRIE tool features an inductively coupled plasma at 13.56 MHz with impedance matching and power control on a coil above the chuck. An electrostatic chuck is used to secure a 4 inch substrate within the chamber after loading through a manual loadlock. Independent energy control is provided a 13.56 MHz biasing of the platen via impedance matching and automatic power control. Wafer cooling is provided by a chiller and aided by a Helium flow across the backside of the wafer. The chamber lid temperature is maintained at 45°C.

Three parameters are examined for the characterization of the STS ASE machine for 900 µm thick etching: vertical sidewall profile, trench wall roughness, and mask selectivity. As discussed earlier, a vertical sidewall profile is necessary to minimize leakage paths around the apex seal. For the purposes of this analysis, sidewall profile is defined as the difference between the widest portion ($L_w$) of the trench width and the trench width at the top ($L_m$) as seen in Figure 11. Similarly, large scallops or exceedingly rough sidewalls could also act as a leakage path. High mask selectivity allows the oxide and photoresist mask to not erode significantly during the long etch duration. A number of previous studies have indicated that four process parameters control these effects: platen power, pressure, process gas flows, and etch and passivation cycle times [9,10].

This study examined the effect of three parameters: pressure of the etch step, platen power, and the cycle times etch and passivation steps. Process pressures were examined between 25 mTorr and 45 mTorr via control of a fixed pressure control valve angle (APC). High-pressure recipes have been shown to improve mask selectivity [9]. Platen powers were varied between 10 and 15 Watts. Platen power was used to adjust the sidewall profile to improve verticality. Sidewall surface roughness is highly dependent on the ratio of etch to passivation flows.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pressure ↑</th>
<th>Platen Power ↑</th>
<th>Time Ratio ↑</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selectivity</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Etch Rate</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Sidewall profile</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>less reentrant</td>
<td>+</td>
<td>more reentrant</td>
<td>more reentrant</td>
</tr>
<tr>
<td>Scallop size</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Uniformity</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Grass Formation</td>
<td>+</td>
<td>-</td>
<td>-</td>
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</table>

Table 1: General gas flow and RF power parameters

Table 2: Summary of observed effects for high thickness etching

Figure 10. Released 900 µm thick rotor placed upon a penny.

Figure 11. Sidewall profile definition for a reentrant trench profile (left) and a bowed trench profile (right).
passivation cycle times. Table 1 summarizes the DRIE process parameters used for this study.

Table 2 shows a summary of the primary effects of these parameters on the goals of the 900 µm DRIE. It should be noted that uniformity is improved with increasing platen power at high process gas flows. This is a second order effect [10].

FABRICATION ANALYSIS

The first objective of the 900 µm etch characterization is to obtain etch parameters which would have a sufficient mask selectivity. An analysis of the effect of pressure on selectivity was performed and the results are shown in Figure 12. High pressure DRIE recipes produced maximum oxide selectivity in excess of 350:1 and photoresist selectivity greater than 150:1. Resist and oxide thicknesses were measured optically. Trench depths were measured using a white light interferometer. These results indicate pressures greater than 35 mT are necessary for 900 µm deep etches with sufficient mask selectivity. Scanning Electron Micrographs were taken of cross-sections which showed that high pressure recipes gave a more vertical sidewall profile. Low pressure recipes resulted in trapezoidal shaped, reentrant cross-sections and extreme undercuts of the structures (Figure 13). A high process pressure showed bowed sidewall which is widest at a trench depth of approximately 450 µm. Results for sidewall profile are summarized in Figure 14.

One effect that can be seen clearly in Figure 13 is the phenomenon is “grass” or black Silicon. Grass is defined as thin stalagmites of Silicon which are located on the bottom of an etched trench. It has been established that the phenomenon of grass is dependent on pressure with the re-deposition of masking material within trenches causing local masking. Some research has shown a cutoff in APC angle of 75 above which grass is formed [9]. However, an absolute cutoff in APC may not accurately define the process space within which grass is developed. Grass growth also depends on process gas flow, platen power, and cycle time ratio. In addition, the pressure of a particular recipe can vary with the amount of Teflon and other

Figure 12: Effect of pressure on selectivity with a platen power of 12 W, 10 second etch cycle time, and 6 second passivation cycle time.

Figure 13: Examples of two different sidewall profiles dependent on the etch pressure. Above, a reentrant profile results from an etch performed at 25 mT. Below, a slightly bowed trench results from a high etch pressure of 43 mT.

Figure 14: Effect of pressure on sidewall profile with a platen power of 12 W, 10 second etch cycle time, and 6 second passivation cycle time.
deposits on the sidewall of the chamber. The formation of grass was found to be most significant in the center of the wafer and generally moved out radially due to etch rate non-uniformity called the “bullseye effect”. The bullseye effect is characterized by outer portions of the wafer etching at a faster rate than the wafer center. For features etched through the entire wafer, grass formation at the bottom of a trench is not significant. However, some grass that forms near the sidewalls can develop into large wall growths. The grass formed on the features such as the annular gear or the intake and exhaust ports could be a potential source of silicon debris inside the engine. This is due to the fact that these trenches are not etched through the entire wafer so the grass is not eliminated. Increasing pressure also increases the non-uniformity across the wafer. Figure 15 shows etch rate as a function of pressure with non-uniformity. Etch rate was measured during the first 300 mm of the etch. Accurate measurements during the later portions of the etch with the white light interferometer were not possible due to scattering from the grass.

In order to remove the slight bowing of the vertical profile, adjustments to the platen power and cycle time ratio were made. Table 3 shows that a 2W reduction in platen power resulted in a 38% improvement in sidewall profile over the results shown in Figure 14. Reduction in the cycle time ratio did not produce a marked effect on the sidewall profile. The final objective for this process optimization is improved surface roughness. Figure 16 shows the sidewall of the epitrochoid etched. Scallops formed on the sidewall of the trench were well less than a 1 µm in size.

One difficulty in the etch process which still arises even with improved sidewall profile is the resolution of the 25 µm wide apex seals. Figure 17 shows a partially etch profile of a rotor with a reentrant apex seal. This effect arises due to the large (500 µm) trench adjacent to the apex seal. While this particular recipe etches ~250 µm wide trenches very straight, larger trenches exhibit an increasing reentrant profile. This results in an undercut of the apex seal which eventually leads to the outer trench merging with the trench behind the apex seal. Currently, the deepest apex seal resolved is 500 µm. However, the trenches around the rotor could be standardized to 250 µm in width making sidewall profiles across the mask more uniform. In order to accomplish this, dummy structures will be designed around the rotor to generate more uniform width trenches.

Table 3: Summary of the effect of platen power and cycle times

<table>
<thead>
<tr>
<th></th>
<th>Reduced Cycle Time Ratio</th>
<th>Reduced Platen Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sidewall Profile (µm)</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>Oxide Selectivity</td>
<td>303</td>
<td>368</td>
</tr>
<tr>
<td>Photoresist Selectivity</td>
<td>124</td>
<td>125</td>
</tr>
</tbody>
</table>

Figure 15. Etch rate analysis showing uniformity for a platen power of 12 W, 10 second etch cycle time, and 6 second passivation cycle time.

Figure 16. Wall roughness of engine housing etched at 43 mT etch pressure, 12 W etch platen power, 10 second etch cycle time, and 6 second passivation cycle time.

Figure 17. Example of a reentrant 25 µm wide apex seal.
A more important issue in successful fabrication of the integrated apex seal is the effect of Aspect Ratio Dependent Etching (ARDE). ARDE is characterized by wider trenches etching at a higher rate than narrower trenches. This effect is even more pronounced at higher pressures where lag between trenches has been as much as 100 µm. One method that can be used to overcome this effect would be to utilize a backside etch to help the more narrow trenches overcome ARDE. Since the narrow trenches do not define the exterior of the rotor but rather the apex seal interior, any backside lithographical misalignment will not cause undue mismatch between the rotor and the epitrochoid housing. However, the backside trench will affect the stiffness of the apex seal if there is any misalignment.

CONCLUSION

The development of 900 µm deep MEMS rotary engine components with a high degree of accuracy has been realized. Using a three mask process, rotors and housings for a rotary internal combustion engine for use in MEMS REPS have been fabricated with smooth sidewalls, high mask selectivity and straight sidewalls. A high pressure DRIE recipe was utilized which allows for high rate Silicon etching. This recipe produced 900 µm deep trenches with a sidewall profile deviation of 11 µm with an oxide selectivity beyond 350:1 and photoresist selectivity beyond 150:1. The tradeoff of high selectivity is a decrease in cross wafer etch depth uniformity and the development of Silicon grass on the bottom of the etch trenches. Poor cross wafer uniformity will limit the yield of such an etch process but should not affect the overall success of the components. Silicon grass at the bottom of the through wafer features only retards the etch rate of the process but does not adversely affect the straightness or the roughness of the sidewalls. Some concerns still lie in the etching of the high aspect ratio features such as the 25 µm wide apex seals in proximity to larger or lower aspect ratio features and lower etch rates due to the effect of ARDE. However, proper mask design will eliminate these effects.

ACKNOWLEDGEMENTS

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