

Evaluation of Undercut and Applicability of a Batch HF Vapor Etching System in MEMS Release Etch Processes

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ABSTRACT

The release etch is one of the most critical processing steps in MEMS device manufacturing. Many single-wafer solutions have been utilized to date, but these processes are typically not attractive for high-volume manufacturing due to the long process times requiring a prohibitively high number of process chambers. A batch HF and IPA vapor process has been developed to meet the needs of device manufacturers. This offers relatively high throughput in a small footprint while maintaining a controlled undercut in order to achieve the desired release etch. The process has been characterized to demonstrate the impact of the process variables and has been demonstrated on various MEMS devices including three-level polysilicon microengines with yield and reliability results comparing favorably to more traditional processes.

INTRODUCTION

While there are numerous challenges in the manufacture of MEMS devices, one of the most critical is performing the release etch. Various process solutions have been developed, including wet processing, dry processing, the use of supercritical fluids and vapor phase processing. However, most of these schemes have been implemented primarily on single-wafer process platforms. Although these have provided satisfactory results from a process performance perspective, the relatively long process times required in many release etches has rendered them unacceptable from a throughput and cost of ownership perspective. Consequently, there is a need for a controllable, predictable release etch capable of achieving throughput necessary for volume production. Of paramount importance is control of the undercut. The undercut must be achieved so that specific device features are free to move, but this must be accomplished in such a manner that these features do not adhere to either underlying or adjacent materials in the phenomena known as “stiction.” An HF – isopropyl alcohol (IPA) vapor etch process was developed some time ago for FEOL surface preparation processes in the manufacture of integrated circuits. This patented process has obvious application for the purpose of undercutting an releasing MEMS devices (1).

This paper will explore the various parameters which control the etch characteristics of a batch HF vapor processor. We will then examine whether the blanket film etch rate may be used as a predictor of the lateral etch rate underneath device structures. We investigate whether the diffusion path becomes an inhibitor to the exchange of reactants and products at the oxide interface underneath the device structure, with the objective of being able to achieve an undercut of >40 microns (per side) in a

uniform and predictable manner. Results demonstrating reliable functionality of three level polysilicon micro-engines, released in this optimized etch, are also included to reinforce viability of this process.

EXPERIMENTAL

Experiments were performed on a Semitool Spray Acid Tool (SAT) configured to perform HF vapor etching. The system was equipped with two proprietary vapor generators, one for HF (49% by weight) and the other for isopropyl alcohol (IPA). Both use a passive vapor generating system which passes a specific volume of nitrogen or other carrier gas through a mass flow controller (MFC) and across the surface of a temperature controlled liquid in the vapor generator, thereby entraining the evolved vapors into the gas streams. These two vapor streams may be further diluted by mixing with an additional MFC controlled flow of pure nitrogen. Vapor mixing occurs prior to delivery into the process chamber. A simplified flow diagram is shown in Figure 1. The vapor generator itself is key to the process. The generator is of a “passive” design, meaning that we do not actively bubble a carrier gas through the liquid nor do we heat the liquid in order to vaporize a given quantity. Such methods tend to produce aerosol droplets in conjunction with the vapor. The aerosol droplets can lead to non-uniform etching, spotting and stiction issues. Figure 2 shows the vapor generator configuration.

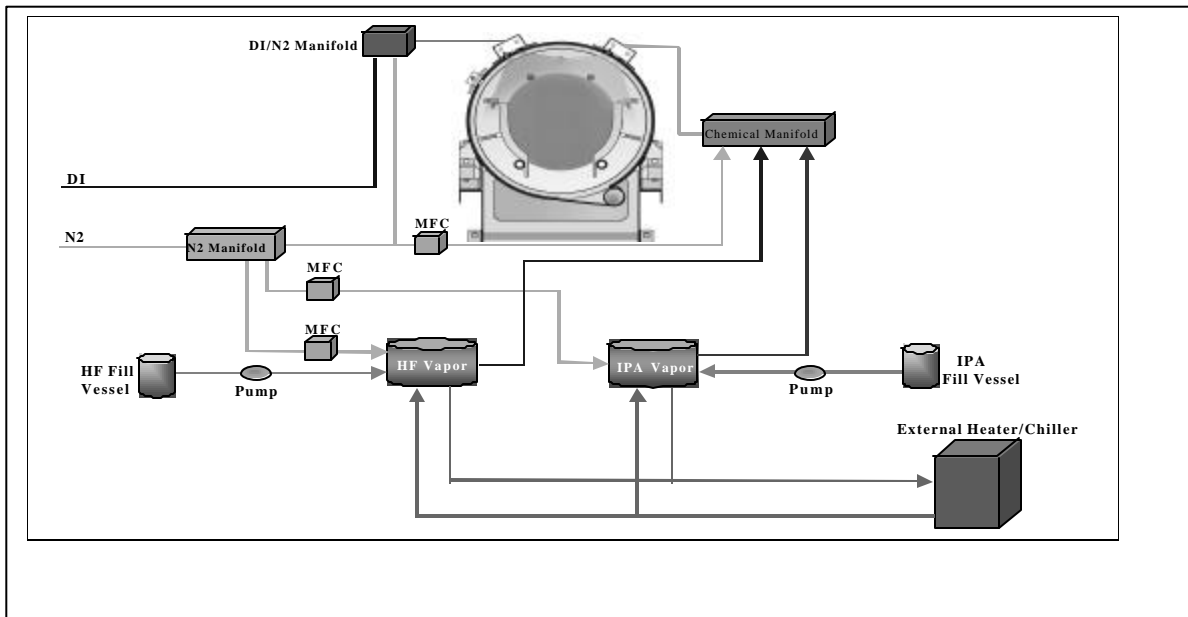


Figure 1: HF vapor etch system fluid flow

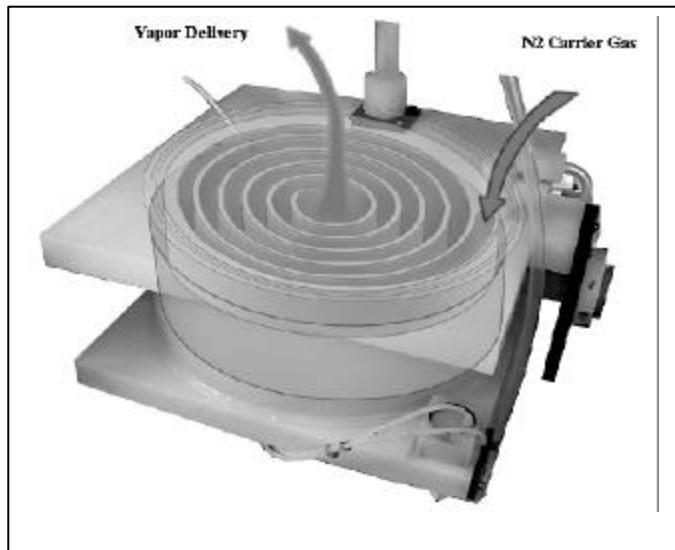


Figure 2: Vapor generator schematic

The vapor generator incorporates a spiral baffle in the design. Gas flows into one end of the spiral and is constrained to flow through the spiral path, thus increasing the contact time between the gas and the liquid interface. Thus the gas is approaching saturation by the time it exits the vapor generator.

An external heater/chiller circulates fluid through Teflon® coils installed in the vapor generator to provide a means of temperature control. Evaporative cooling within the vapor generator would otherwise create

unacceptable temperature variation and process instability. Care is taken to ensure that vapor does not condense in the lines upon exiting the vapor generator.

The process chamber itself is made of high density polyethylene (HDPE). This is preferred to Teflon® as it is relatively inexpensive, light weight and has a low porosity and low affinity for HF adsorption. The system can process a batch of up to 25 substrates at one time, with sizes ranging up to 200mm in diameter. The series of experiments reported in this paper were performed on 150mm wafers, processed in a conventional Entegris A190-60M Teflon® cassette.

Three of the primary variables affecting etch rate are the MFC flow rates through the HF and IPA vapor generators and the N₂ dilution flow with which these are mixed. After performing screening experiments, these variables were characterized using a central composite model in a DOE. Two of the more significant results are represented in Figures 3 and 4. Film thickness measurements were performed on a Tencor UV-1250 ellipsometer. While a number of variables were evaluated, we found that the vapor composition has the greatest impact on the silicon dioxide etch. The vapor composition is controlled by use of the N₂ gas flow through the MFCs. Two of these flows are passed through the vapor generators. The vapor flows are then blended with an N₂ dilution flow to ensure that the vapor as delivered to the process chamber is not approaching the dew point, which could otherwise lead to the formation of a macroscopic condensate film resulting in stiction on released devices.

In Figure 3 we see a very strong relationship between the HF and the IPA vapor flow rates with regard to the etch. It should be noted that the changes in the IPA flow, and the overall IPA flow itself are much smaller than the HF flow conditions. Again, this is reasonable because the IPA vapor pressure at near ambient conditions is approximately 33 mmHg while the vapor pressure of 49% (weight) HF is approximately 14 mm Hg. As a result, the volume of IPA in the mixed vapor is higher than the volume of HF, even though much lower N₂ flows are delivered to the IPA generator.

The role of the IPA may be envisioned as that of a surfactant or wetting agent. While HF vapor alone has a tendency to form a microscopic boundary layer

preferentially on hydrophilic surfaces, The IPA forms a more uniform film on all surfaces, thereby promoting a more uniform etch, especially in regards to generating undercut on device structures. At the same time, the IPA also provides the advantage of reducing surface tension in the microscopic boundary layer on the wafer surface. While this is undoubtedly one of the mechanisms through which etch uniformity is improved, it is also of benefit as device structures are released, as there is less tendency to generate the force necessary to create displacement which leads to stiction. Silicon beam structures two microns wide and 1500 microns in length were consistently released without problem. In the rare instances where stiction was observed on silicon beam structures, we found that a physically probing the structure would allow it to spring back to its operational position. This is contrary to observations made on structures which had been released in a wet-etch process where it appeared that stiction on similar structures was irreversible.

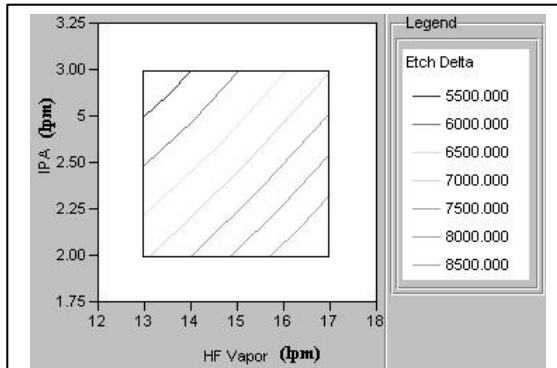


Figure 3: HF and IPA Vapor Flow Effect on Etch Delta (Å)

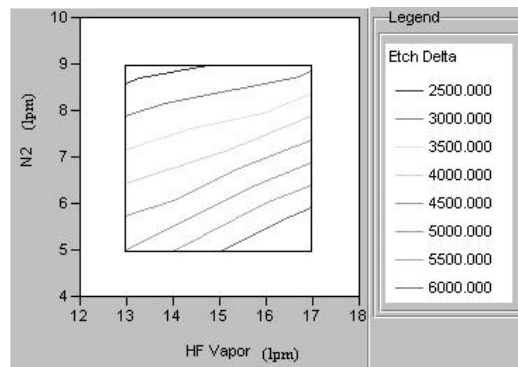


Figure 4: N₂ Dilution and HF Vapor Flow Effect on Etch Delta (Å)

The impact of the N₂ dilution gas is shown in Figure 4. It should be noted that the use of N₂ as a diluent is not required, and various hardware configurations have been incorporated in order to eliminate this. However, we have found it convenient to retain this variable as it allows us to make fairly simple and predictable adjustments to the etch process without altering the gas flows through the vapor generators.

While a carrier gas is used to deliver the etchant vapor to the process chamber, the primary mechanism for getting the reactants to the oxide surface is diffusion of the gas and vapor species within the process chamber. In order to evaluate the ability of the reactant species to diffuse into the small device geometries, test structures were prepared consisting of a polysilicon film over an oxide layer. Various size contact or via openings were etched through the polysilicon film using an RIE plasma. The photoresist was then stripped and the test structures were etched in an HF vapor process. Afterwards the samples were cross-sectioned and imaged using an SEM. Figure 5 shows images from two different samples

The experiments represented in Figure 5 are of interest on a couple of points. First, we achieved confirmation that vapor was able to diffuse through the submicron

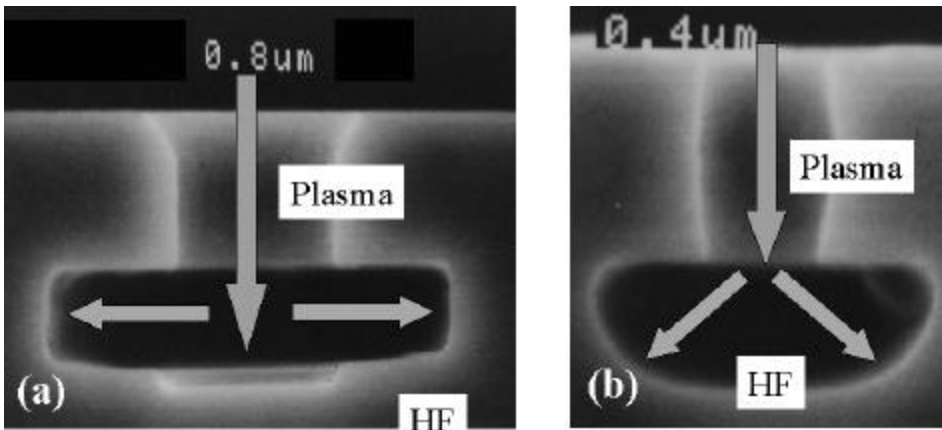


Figure 5: HF vapor etch through submicron vias. (a) Plasma etch through the oxide layer. (b) Plasma etch to the top of the oxide interface

features, react with the oxide and the reactants were able to diffuse back out without apparent inhibition. Figure 5(a) shows the retention of the vertical sidewall profile which was produced by the plasma etch going all the way through the oxide. Figure 5(b) shows the generation of a typical isotropic etch profile, the result of the plasma etch being stopped at the interface between the polysilicon and oxide layers. This was some of the earliest work showing the potential of an HF vapor etch process for MEMS release applications.

While the early experiments focussed on the ability of the HF vapor to enter small geometries and successfully react, it was recognized that successful implementation of the process would require the ability to undercut structures distances from a few microns to perhaps 40 microns or more. The undercut evaluation was continued using test structures which had a five micron wide slot etched through a polysilicon layer one micron thick. The underlying oxide was two microns thick, and there was another oxide film on top of the silicon approximately one micron thick as shown in Figure 6.

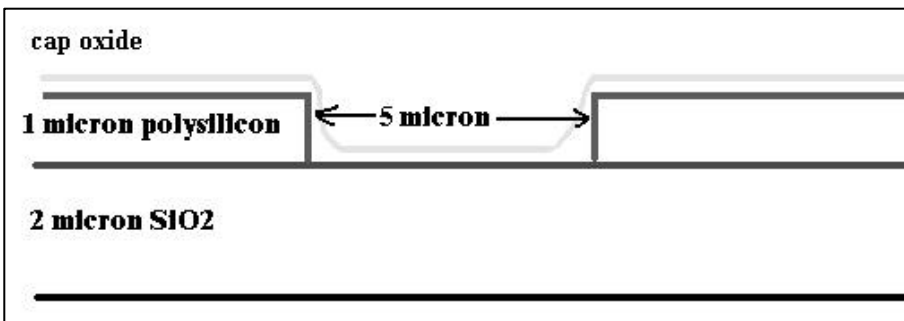


Figure 6: Undercut Test Structure

Using this structure, a series of progressively longer etch processes were run in order to correlate the etch time with the amount of undercut achieved. The objective was to determine the linearity, and therefore the predictability of the etch. We also needed to determine if the etch became limited by the length of the diffusion path through which the vapor reactants and the reaction products must diffuse in order to maintain the process at the continuously receding oxide face. Figure 7 is a visual depiction of the results of this series of tests. The images were taken through an IR microscope and show the progression of the etch at 4, 12 and 24 hours. In figure 8 see the progression of the

measured undercut depicted graphically with the y-intercept constrained to pass through the origin, as no etch is theoretically possible prior to the start of the process. While the three data points are not intended to be comprehensive, they do give a good indication of the process predictability.

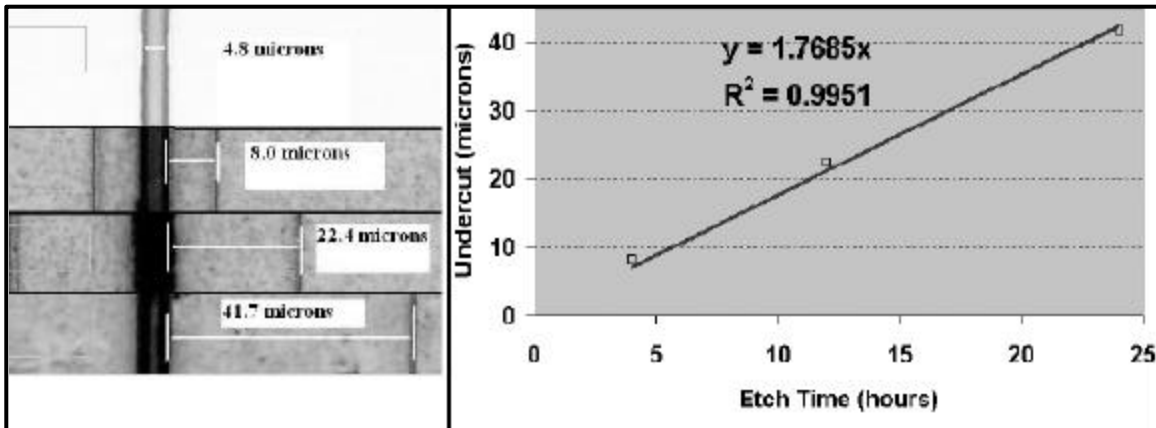


Figure 7: IR image of etch undercut (a) opening – no etch (b) 4 hour (c) 12 hour (d) 24 hour

Figure 8: Etch undercut linearity

SEM cross-sections were then taken of each of the etch samples in order to verify the IR microscope data and to evaluate the cleanliness of the etch. In order to view the actual undercut cross section, a Focussed Ion Beam (FIB) was used to cut through the polysilicon layer perpendicular to the etch slot, thereby revealing the undercut gap. These images are shown in Figure 9.

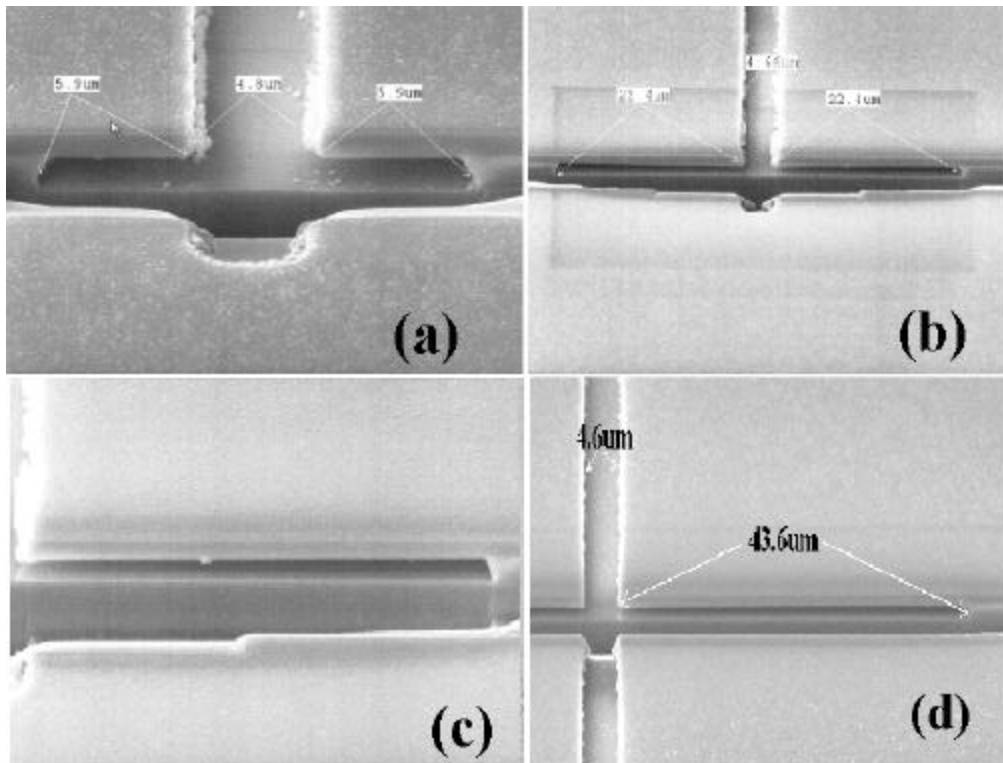


Figure 9: FIB cut to expose vapor etch undercut (a) 4 hour, 6 micron, (b) 12 hour, 22 micron (c) detail of 12 hour etch to show terminal slope (d) 24 hour, 44 micron

There are several items of interest in regards to the images in Figure 9. First, we note that the plasma etched opening in all cases showed some degree of polymer build-up along the edge. It appears that a more aggressive photoresist strip and polymer removal process may have been in order on these samples. Second, the HF vapor etch appears to have left an essentially clean, residue free surface. While the four hour etch sample shows some kind of contamination in the plasma etched opening, the undercut surface is quite clean, other than some very slight residue which may be attributed to the FIB process which was used to mill away the silicon and expose the vapor etch undercut. The location of the slight residues seen in the plasma etch opening suggest that this may have come from the polymer residue noted along the sidewall, as none of the residue is seen in the center of the trench. Third, the etch profile was not what we had anticipated based on the images shown in Figure 5(b). This image suggested a very isotropic etch profile. However, figure 5(b) is an image of a relatively short etch with a small amount of undercut. It appears that diffusion mechanisms may eventually limit the vapor access to the oxide interface underneath the polysilicon structure, until the etch profile actually becomes re-entrant. The amount of negative slope is, however, quite minimal and did not appear to change appreciably between the six micron and 44 micron undercut samples. Lastly, we note that the rate of undercut appears to be undiminished even when the amount of undercut exceeds 40 microns, indicating a predictable, linear etch capable of undercutting very large MEMS device structures.

In order to further explore the potential limitation on vapor diffusion through a one micron gap, another sample was etched for a period of time to target an undercut of about 18 microns. The image of this sample is shown in Figure 11(a). A second sample was etched for a similar period of time, and is shown in Figure 11(b) with an undercut of 22 microns. The sample shown in 11(a) was re-etched along with the sample in 11(b). The image of this sample is shown in Figure 11(c), having been etched twice. Note that the second etch on sample 11(c) corresponds nicely with the initial etch on 11(b), both

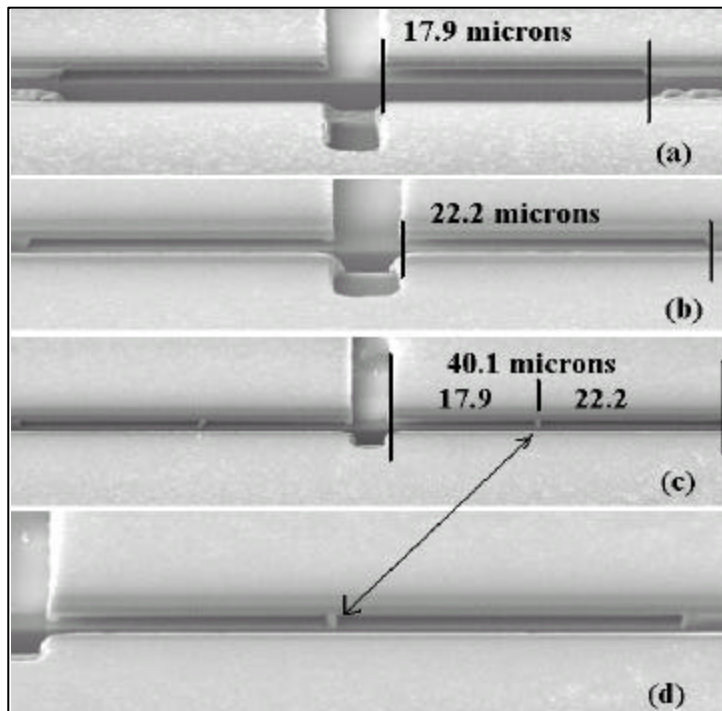


Figure 11: Two-stage etch. (a) initial etch control (b) second etch control (c) two-stage etch (d) detail of artifact shown in two stage etch

showing 22 microns of undercut. This is significant because sample 11(b) commenced etching right at the trench wall, while sample 11(c) commenced etching at a distance 18 microns in from the trench wall, thus requiring the vapor to diffuse for that distance through a one micron gap. This was achieved apparently without inhibition.

One anomaly of some significance was noted on the sample which was etched twice. Inspection of the sample using an IR microscope distinctly showed the etch boundary, the same as seen in the images in Figure 7.

After the second etch, one could still clearly discern the original etch boundary as well as the final etch bound. This was thought to be a staining or stress effect on the polysilicon layer. However, the SEM image shown in Figure 11(c) and (d) indicate the presence of some kind of artifact in the gap created between the HF vapor etch. In 11(c) one can see the artifact on both sides of the etch gap. Attempt to image the artifact at higher magnification were not successful. Further work will be required to determine what this is, but in the meantime all we can say is that it does not appear to inhibit the diffusion of vapor underneath the structure. We have not seen this feature on device wafers, even though we frequently etch in stages in order to record the progression of the release etch and to ensure that devices are not over-etched. So it is not clear whether or not this artifact is actually present on device wafers and if it is, if it is capable of inhibiting movement of released structures.

As a final test, the HF/IPA vapor etch process was used to release a fully functional micro-engine designed and used at Sandia National Laboratories. This device is a relatively complex 3-layer device and is shown in Figure 11. The device includes structures such as gears, combs and linkages, all of which must be free to move in order for the device to function. A 12 hour etch process was performed, targeting an undercut of >20 microns. The undercut was verified using optical measurements on an IR microscope. Functionality testing was performed on several devices at over 1000 cycles per second. Device performance was similar to the process of record on all parameters tested, though comprehensive testing has yet to be completed.

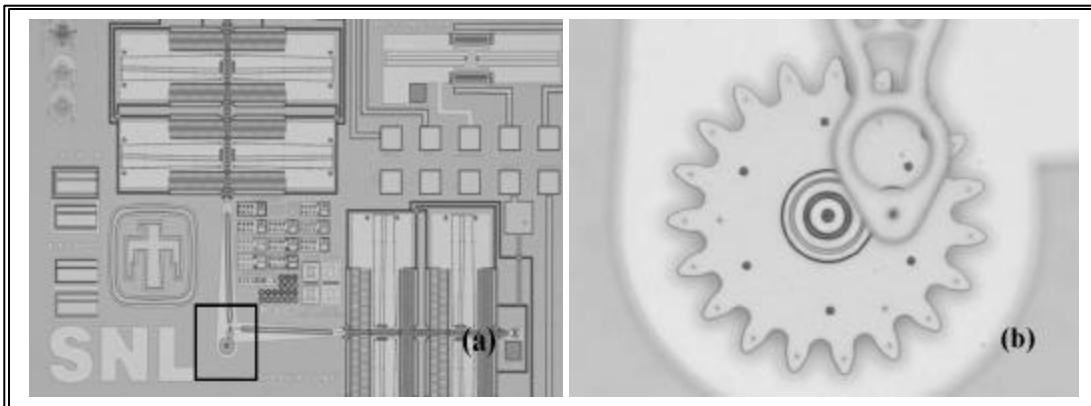


Figure 11: Sandia National Laboratories Micro-Engine (a) engine (b) gear detail

On-going studies are being performed in order to more fully characterize the process in various applications. While it does not appear to affect undercut, which is the focus of this paper, we have noted the appearance of etch residues on certain features. On etch processes which are performed for several hours, there is a moderate change on exposed silicon nitride surfaces. The extent of the change appears to be strongly affected by the type and composition of the silicon nitride in conjunction with the time of HF vapor exposure. Preliminary studies indicate that the HF may be reacting with the nitride to form ammonium fluoride crystals. These are water soluble, but water rinsing is generally not desirable following the MEMS release etch. The crystals can also be readily sublimated, with the amount of time required to sublimate the crystals inversely proportional to the temperature used. Typically, a temperature of 160C for 2:00 minutes is adequate to removed the residue, though this should be done in a controlled

environment as the ammonium fluoride vapors can be hazardous and form an acidic solution when mixed with water. A heating step has been used after completion of the release etch and appears to remove the material from the silicon nitride surface without adverse impact to the device.

A second issue has been noted with etch residue. This has only been seen in areas where silicon dioxide has been fully removed in order to expose a hydrophobic surface such as silicon or polysilicon. As mentioned previously, the etchant vapor forms a thin condensate film on the surface of MEMS device. The chemical reactions primarily occur in this microscopic condensate layer. However, as the surface converts from the hydrophilic to the hydrophobic state, surface tension can cause the microscopic condensate film to pull the liquid into isolated, macroscopic droplets. Because this typically occurs before any structures have been released, it has not been seen as a stiction issue, but it is cosmetically undesirable. The key to controlling the spotting issue is to control and slow the etch rate at the time that the bulk oxide clears. Slowing the etch rate generally corresponds to a reduction in the amount of microscopic condensate formed. Thus there is insufficient liquid to be pulled into visible droplets as the surface becomes hydrophobic. This has never been seen as an issue during undercut, as the amount of exposed oxide, and hence the amount of microscopic condensate formed, is so small as to prevent droplet formation.

CONCLUSIONS

The batch HF/IPA vapor etch process has proven to provide a viable means of performing a MEMS release etch. The process is able to provide a fairly linear etch rate while undercutting features to a distance of greater than 40 microns per side, thereby allowing the release of structures up to 80 microns in width. The progression of the undercut has been repeatable and predictable when process parameters are suitably controlled.

This process provides a significant advantage over single-wafer processing platforms in high-volume production applications. Load sizes of up to 25 wafers can be accommodated while etching at a rate to undercut device features at a rate of two to three microns per hour. Process feasibility has been shown on various types of test structures as well as on a relatively complex 3-layer polysilicon micro-engine. Process results indicate that the HF vapor release etch is capable of producing devices with performance characteristics similar to the process of record.

ACKNOWLEDGEMENTS

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