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Characterization and Modeling of Wafer and Die Level Uniformity in Deep Reactive Ion Etching (DRIE)

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ABSTRACT

Wafer and die level uniformity effects in Deep Reactive Ion Etching (DRIE) are quantitatively modeled and characterized. A two-level etching model has been developed to predict non-uniformities in high-speed rotating microstructures. The separation of wafer level and die level effects is achieved by sequentially etching wafers with uniformly distributed holes. The wafer level loadings range from 0.06% to 17.6%. Resulting wafer maps reflect the transition from an ion-limited region to a neutral-transport limited region. Additionally, long-range die-level interactions are also evaluated. Resulting die-level etching non-uniformities have a comparable magnitude to wafer-level effects. A model taking into account both the diffusion and reaction rate of neutrals is applied to predict the etching of up to 21 dies. Agreement between measurement and prediction support the hypothesis that the depletion of radicals is the main cause of die-level etch variation. The characterization and prediction methods are applied to etching a micro-scale turbine engine.

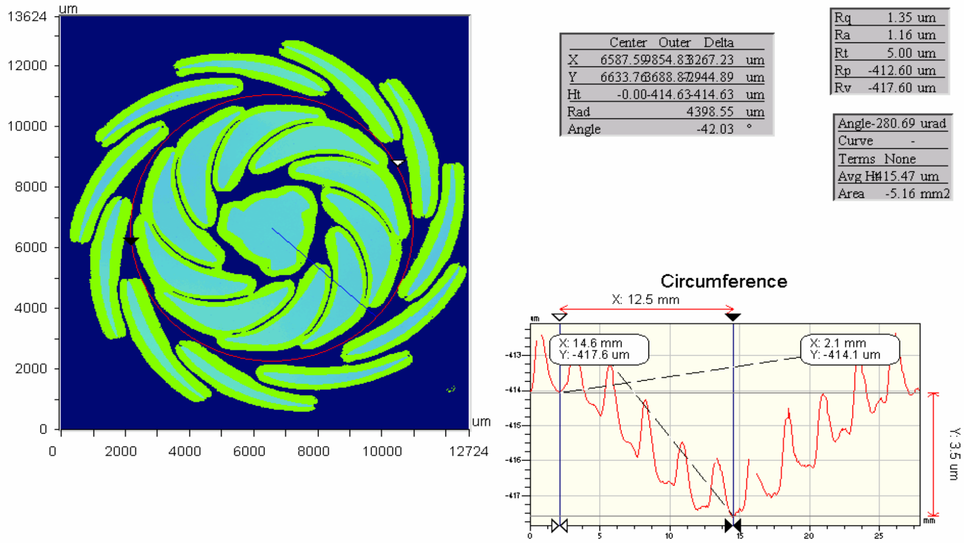
INTRODUCTION

With etch depth variations on the order of 10 microns being regularly observed, DRIE nonuniformities are an extremely pertinent issue in MEMS fabrication. Our experiments show that the sources of non-uniformity in plasma etch can be sorted into three levels and characteristic lengths: wafer level, die level (millimeter scale), and feature level (micron scale). Extensive studies have described uniformity issues for plasma etching in integrated circuits, mainly focusing on feature-level effects. For MEMS, however, the die-level effects have a more prominent role due to large open area layouts. Etch depths for microengine turbine blades are plotted in figure 1. The peaks reflect a phenomenon known as RIE lag, while the sinusoidal variation results from a combination of global and die-to-die interactions. In this study, the wafer level uniformity maps are obtained by etching a series of masks under low aspect ratio conditions (<1.0). The loading densities ranged from 0.06% to 17.6%. Loading is defined as the ratio of etched to un-etched areas on the wafer surface. Then, masks are designed to capture the range and magnitude of die-level effects. Finally, a model based on neutral diffusion is used to simulate the etching for a twenty-one die layout.

EXPERIMENT

Sample preparation and measurement methods

The experiments were conducted on a standard ASE etcher made by Surface Technology



	Center	Outer	Delta	
X	6587.59	9854.83	3267.23	um
Y	6633.76	3688.87	-2944.89	um
Ht	-0.00	-414.63	-414.63	um
Rad			4398.55	um
Angle			-42.03	°

Rq	1.35 um
Ra	1.16 um
Rt	5.00 um
Rp	-412.60 um
Rv	-417.60 um

Angle	-280.69 urad
Curve	-
Terms	None
Avg Ht	-415.47 um
Area	-5.16 mm2

Figure 1. Measurement results of etching depth for rotor blades represented by green color taken along the radius of 4.0 mm, which shows the etch variation cause by feature, die and wafer levels.

Systems (STS), employing a Time Multiplexed Inductively Coupled Plasma (TMICP) technology that was patented by Robert Bosch Gmbh. The Bosch process features alternating cycles of SF_6 gas etching and C_4F_8 polymer deposition. A 0.5 µm thick silicon dioxide layer was thermally grown on six-inch wafers, which were then coated with a 5 µm thick layer of AZ4620 photoresist at 3500 rpm. After a 30 minute prebake at 90 C, the wafers were exposed using an EV aligner for 12 seconds (λ=320 nm, energy=6 mW/cm^2) and developed (AZ440). The wafers were then baked again for 30 minutes at 90 C before being etched in a 7:1 Buffered Oxide Etch (BOE) solution for 7 minutes. Following the DRIE step, the wafers were put in a Piranha (H_2SO_4: H_2O_2 3:1) bath for 10 minutes to strip off the photoresist. Finally, the wafers were placed in an oxygen plasma asher for 30 minutes to remove any remaining polymer film from the etch process. Depths were measured using a WYKO profilometry system. For the global etch maps, depths were obtained by averaging values from a line drawn across the center of each hole.

Mask design

Two sets of masks were designed to characterize wafer and die level etch variation. The wafer-level masks feature uniformly sized and spaced holes. The loading was varied by changing the spacing between holes. Sidewall area is not considered in the loading calculation, since the directionality of the process results in a much slower etch rate as compared to the trench bottom. We suggest that the 0.06% loading mask reflects the charged ion distribution in the chamber. According to ion-neutral synergism theory, fluorine neutrals will be abundant for each trench at these conditions [2]. The die-level masks feature both concentric rings and monitor points (also small holes). The monitor points, which have a negligible loading effect, are uniformly distributed around the die composed of concentric rings. The concentric rings have uniform spacing while changing diameter to keep the loading density constant over an arbitrary local area of interest. The monitor points are used to draw conclusions about the perturbation in etch rate a die can cause at various distances. The local loadings are 10%, 50% and 90% respectively with corresponding wafer level loadings of 0.17%, 0.8% and 1.7%.

Experimental results and discussion

The wafer level loading effect on etching is studied by plotting inverse etch rate versus etchable area as shown in figure 2. The linear relationship that exists between them is consistent with Mogab's theory [3]. Additionally, the maximum etch rate using this recipe is about 2.5 microns/min. The rate is governed by the equilibrium point between neutral generation and consumption rates.

All maps are normalized by the highest etch rate point on the wafer. Roughly, about 10% etch rate variation exists across the wafer. For the maps with loading of 0.06%, 1.1% and 4.4% a 'hot spot' having a higher etch rate exists. It is located 40 mm left of the wafer center for 0.06% loading. A similar trend is found from ion flux measurement of the same etching system [4]. As the loading increases, the 'hot spot' shrinks and moves off of the wafer. This phenomenon can be explained as follows. The hot spot under 0.06% loading reflects the ion distribution above the wafer surface since neutrals are abundant. The neutrals start showing their effects with loading increasing from 0.06% to 1.1% and 4.4%. The etch rate is determined by both ions and neutrals. With the loading further increasing, the neutrals become the dominant factor, and the resulting map would now reflect the neutral distribution. Therefore, as seen in figure 3, the map at 17.6% loading is dramatically different from the low loading case. In fact, it features a 'cold spot' on the right of the wafer which has the lowest etch rate (84%).

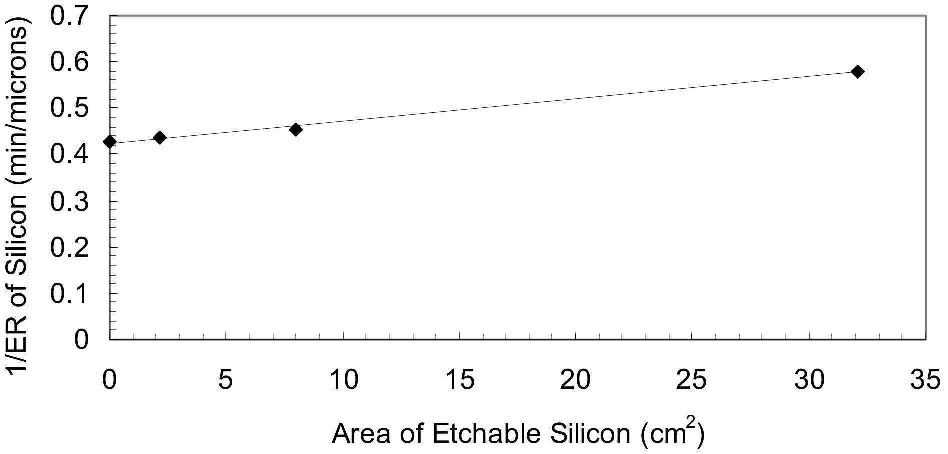
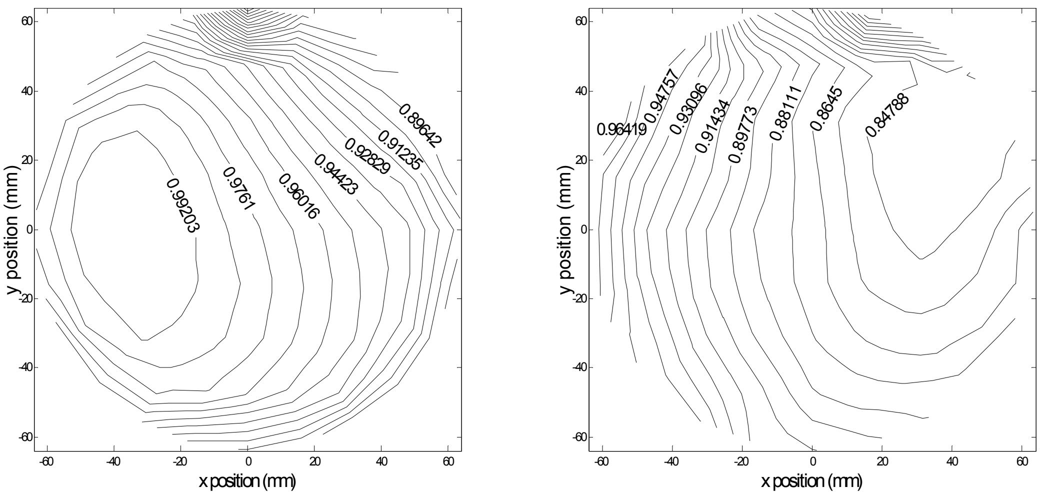


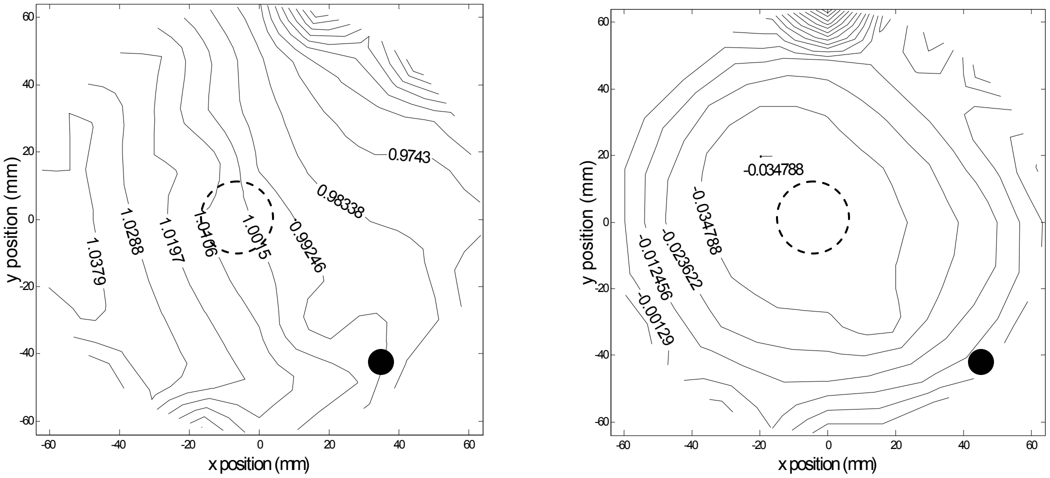
Figure 2. Inverse of etch rate vs. loadings for masks A, B, C and D (0.06%, 1.1%, 4.4% and 17.6% loading).



(a) Etching variation map for mask A

(b) Etching variation map for mask D

Figure 3. Wafer level etching maps under loadings of (a) 0.06 and (b) 17.6%. All data are normalized by the highest etch rate in the map. The primary flat of the wafer is at the bottom.



(a)

(b)

Figure 4. (a) Die level etching map for loading of 10% before extraction. (b) Extracted map after subtracting corresponding wafer level map from (a). The dashed line represents the die location and the solid point represents the reference point during subtraction.

Die-level etching non-uniformity is determined by subtracting the corresponding wafer level map from the experimental results. Figure 4 shows a die level etch map for local loading of 10% and total wafer loading of 0.4%. The contour of the die level map is not perfectly concentric due to the fluorine flow in the chamber. The upper part of the wafer has a higher slope than the lower part. The effect of the die on peripheral area is apparent in spite of some flow effect.

SIMULATION

Single die prediction

As an exercise, one wafer with only one compressor blade die (local loading: 85%; total loading: 1.6%) on the top-left was etched to check uniformity without die-to-die effects. The etching duration is 30 minutes. The etch depth was measured at radii of 8 mm and 6 mm on the rotor. The normalized etch depth on two radii show similar trends. Meanwhile, 8 mm shows higher etch variation than 6mm due to its larger diameter. Setting the aspect ratio well below 1.0 minimizes feature-level effects. A comparison between prediction and experimental data on 6mm radius is plotted in figure 5. Data from the 1.1% wafer level mask was used to model the wafer level effects in the case. The good agreement between them suggests that the uniformity maps can provide a good prediction for the etching of single compressor blade die as long as we use the appropriate wafer level loading map.

Multiple die simulation

A model based on neutral diffusion was built to explain the etch variation. An etch with 21 main pump dies on the wafer is simulated. The layout is shown in figure 6. A circular measurement was taken at a 2.2 mm radius from the die center. It should be noted that the 90% loaded die is replaced by 90% loaded annular rings to simplify the simulation. The wafer was rotated by 90 degrees four times during etching to mitigate wafer-level effects. The total etching time was 90 minutes. Feature level effects are evident immediately following etching. However, since we measure the etch depth at a uniform radius, the feature openings are the same for each point. Thus feature level (aspect ratio) effects are eliminated from the data. As expected, the center die shows the best etch uniformity, which is below 0.2%. The center die is the most uniform because it has symmetric die-to-die interaction from all sides.

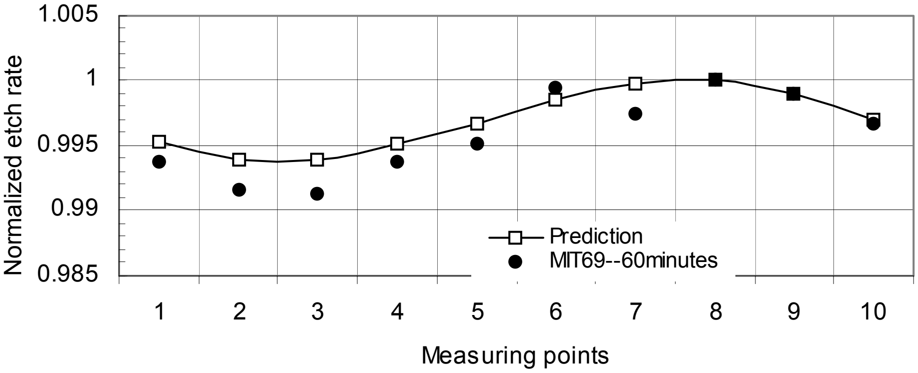
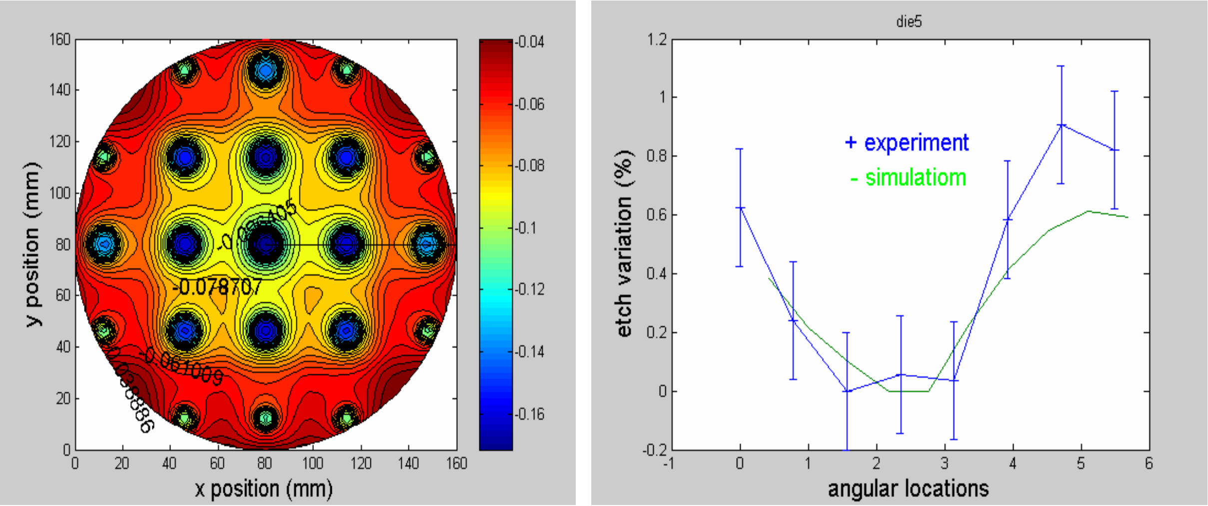


Figure 5. Comparison of prediction with measurement on radius of 3.0mm of compressor blade. The prediction is based on wafer level etching map with loading of 1.1%.



(a) (b)

Figure 6. (a) Simulated etching variation contour of 21 dies layout based on the neutral diffusion. The negative values mean the etching rate is slower than that outside wafer. (b) Comparison with measurement for die 5 which is on the top left corner of the layout.

CONCLUSIONS

This paper focuses on experimental methodology to quantitatively characterize etching uniformity on both wafer and die level of MEMS structures. The wafer level uniformity maps reflect clearly the transition from ion-limited region to neutral-transport limited region. These maps can be useful tools to predict etch uniformity. The consumption of a large amount of neutrals results in a local density gradient near the die which is also detected using different masks. The range of this effective region depends on both the diffusivity and reaction rate of neutrals with silicon. With the above analysis, a model based on neutral diffusion is established to predict etch variation due to die-to-die effects. Agreement between experiment and simulation support the hypothesis that neutral diffusion is the main source of etch variation. Further work will involve simulation of time dependent etching, as this will allow us to consider the effect of increasing sidewall loading.

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REFERENCES

1. Epstein et al., “Micro-heat engines, gas turbines and rocket engines,” *AIAA paper*, *28th AIAA Fluid Dynamic Conference*, Snowmass Village, CO, June 29-July 2, (1997).
2. R. Gottscho and C. Jurgensen, *J. Vac. Sci. Technol.*, B 10(5), 2133-2147 (1992).
3. C. Mogab*,* *J. of Electrochemical Society*, 124 (8), 1262-1268 (1977).
4. *4Th USA ASE User Meeting*, San Francisco (2000).