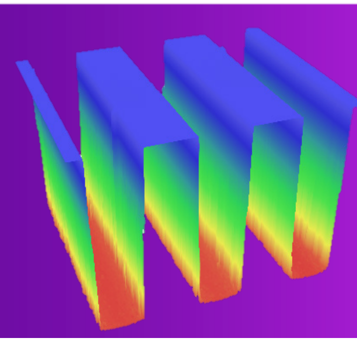
Measurement of Deep Trenches to Study the RIE Lag Effect

Zeta™ Optical Profilers



Introduction

The demand for accurate characterization of high aspect ratio geometries such as narrow gaps, deep trenches or deep holes arises in many technologies and industries. A variety of metrology techniques have been utilized to accommodate these needs. Among the candidates for this type of metrology, 3D optical profiling characterization is becoming more and more prevalent in process control. Due to its non-destructive measurement method and excellent data accuracy, optical profiling is especially advantageous for delicate samples.

In this application note, deep trenches of varying width were etched into silicon using reactive ion etching (RIE). RIE processes are widely used in industry, but the development of these processes can be highly complex. Critical dimensions, aspect ratio and position all impact the etch rate, which is core to process development. An example of how the RIE etch depth can vary as a function of feature dimension is illustrated in Figure 1. This phenomenon is called RIE lag or ARDE (aspect ratio dependent etching), and it occurs frequently in the microfabrication process.

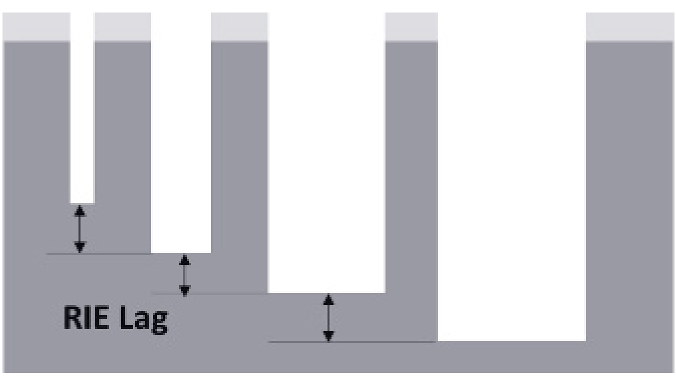


Figure 1. Reactive Ion Etch (RIE) lag is highly influenced by device geometry.

The common way to characterize the RIE lag is to use a Scanning Electron Microscope (SEM) to characterize the cross-section of the device structure. However, sample preparation of the cross-section for SEM analysis is both destructive and time-consuming. The Zeta™-20 optical profiler utilizes the proprietary ZDot™ measurement technique to non-destructively characterize deep trenches with varying width and aspect ratio. The example discussed here illustrates the RIE lag effect and provides guidelines to further optimize the fabrication steps during process development.

Deep Trench Measurement Considerations

When measuring deep trenches, it is important to understand the aspect ratio limit of the metrology tool. It is challenging for some types of profilers to measure high aspect ratio structures, especially for features with narrow openings. When selecting the type of profiler and measurement technique, the scope of applications and capabilities must be considered. For example, a stylus profiler generally works best for samples with aspect ratio < 1:1, due in part to the included angle of the stylus tip. White light interferometry (WLI) is favorable for its excellent z resolution, but the performance may be unsatisfactory for samples with high surface roughness.

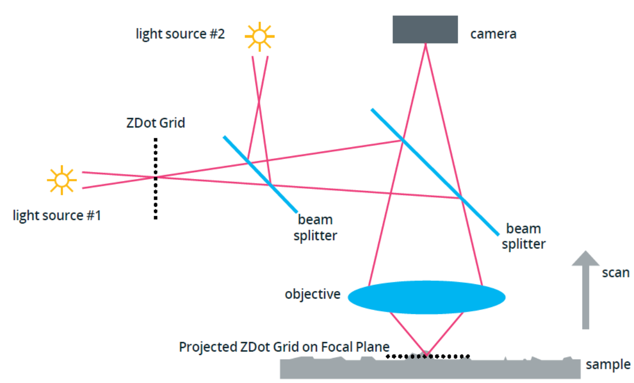


Figure 1. Schematic of the ZDot™ measurement technique

The Zeta optical profiler's unique ZDot^{TM} technology is chosen here to showcase its excellent performance for deep trench measurement. ZDot technology, shown in the Figure 2 schematic, utilizes a structured illumination technique to optimize the vertical resolution of the objective lens. This optimization is achieved by enhancing the focus across the

ZDot grid, which can be thought of as an array of pinholes. One light source goes through the ZDot grid as a projector, projecting the grid on to the sample surface. The grid is only in focus when the optics are in the correct z position, and the true vertical position is easily determined based on the peak optical signal from the ZDot grid. The best contrast position of each pixel is then collected to generate the 3D topography of the sample. A second light source is used to collect the True Color image of the sample, while the first light source measures the topography of the surface at each z position.

When measuring high aspect ratio trenches, it is recommended to use low-magnification objectives with smaller numerical aperture (NA). Because the top of the trench surface acts as an aperture stop, light hitting the top of trench with a high angle of incidence is blocked from reaching the bottom of a deep trench, as shown in Figure 3. Only light with a small angle of incidence relative to the direction perpendicular to the surface can reach the bottom of the trench. Therefore, lower NA (0.45 for 20x) objectives have a smaller portion of blocked reflected light as compared to higher NA (0.8 for 50x) objectives. The lower NA measurements enable higher light intensity with increased signal-to-noise ratio. In addition, Zeta's advanced software algorithms further optimize the high aspect ratio trench measurement.

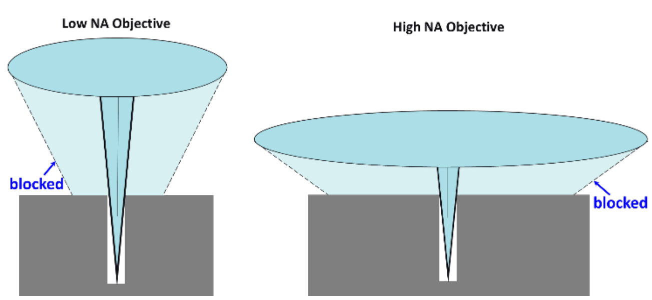


Figure 2. The reflected light in a deep trench is shown for low NA (left) and high NA (right) objectives.

3D Optical Profiling to Study the RIE Lag Effect

For this study, deep trenches were etched simultaneously using RIE and exposed, and were then measured by the Zeta-20 3D optical profiler. The 3D scanning results shown in Figures 4-6 were all measured using the ZDot technique. Figure 4 is the top-down True Color image of a 200µm wide trench. The 3D representation, shown in Figure 5, enables measurement of the dimensions of the 200µm wide trench, the depth of which is measured to be 228.09µm. The trench slope and trench shape are displayed in Figure 6. The slope at the trench corner indicates a slower etching rate as compared to the trench center.

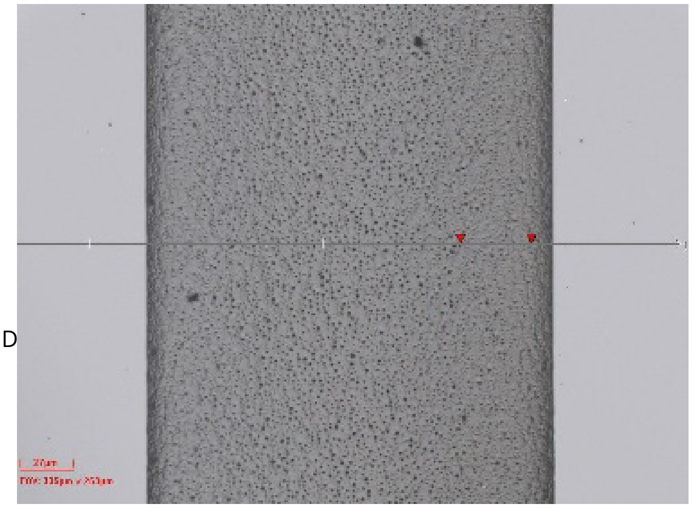


Figure 3. Top-down True Color image of a 200µm wide trench captured using ZDot technology.

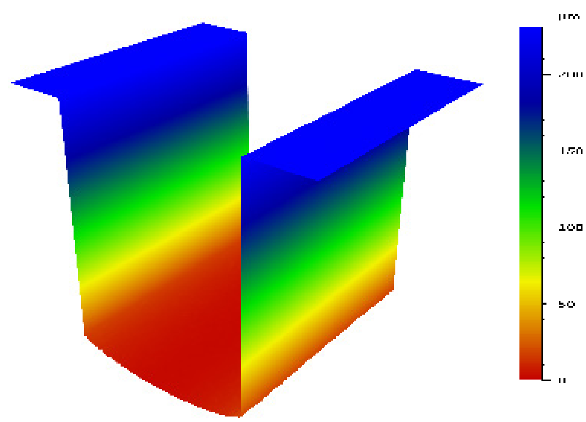


Figure 5. 3D measurement of the trench also captured using ZDot technology, where the color scale represents the Z height.

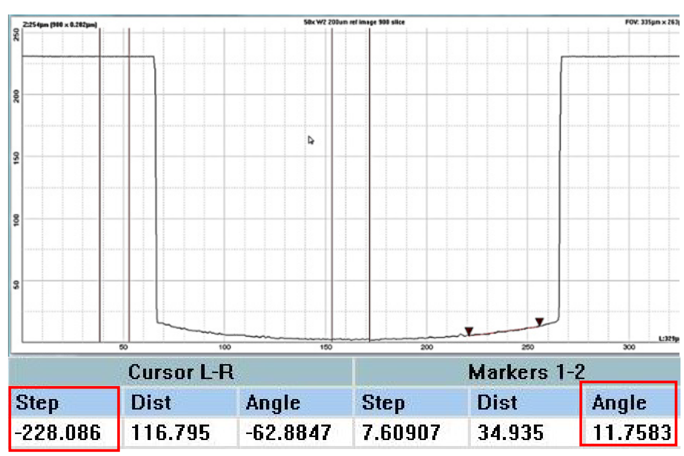


Figure 6. The 2D profiles extracted from the 3D scan reveal the trench geometry, including Step height (trench depth) and trench Angle.

The narrower etched trenches were examined next: for the 100µm wide and 60µm wide trenches, the measured depth decreased to 217.10µm to 204.92µm, respectively. Figure 7 shows data from a set of 60µm wide trenches. By plotting the measured depth as a function of width, shallower depths are observed for narrower trenches. The fact that wider features are etched deeper is not surprising; this depth variation is due to the anticipated RIE-lag-induced slower etch rate for narrower trenches. When a trench has a wide opening, fluorine radicals transport to the bottom of trenches easily, and can be processed at a high Si etch rate, resulting in deeper trench fabrication. Near the trench wall or for narrower trenches, the diffusion rate of fluorine radicals is lower, resulting in a lower etch rate. Adjusting the bias and other parameters can allow the RIE etch rate to be tuned for the specific pattern.

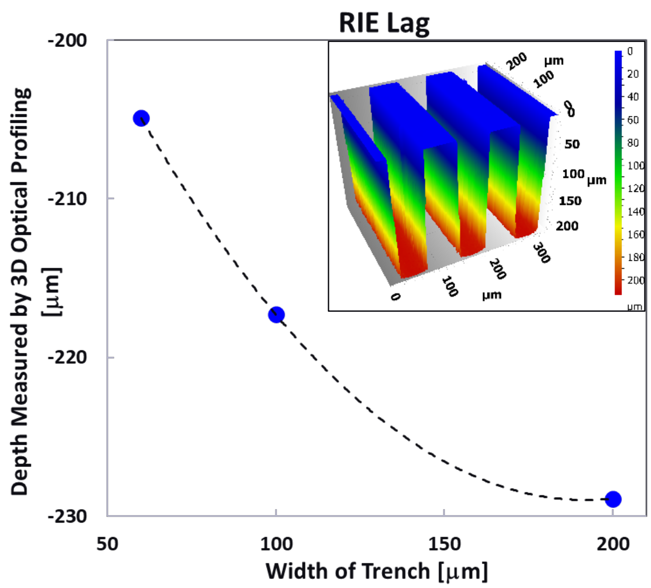


Figure 7. Optical profiling of trench depth as a function of trench width quantifies the effect of RIE Lag, where shallower depths are observed for narrower trenches. The inset shows the 60µm wide trenches.

Lastly, we compared the Zeta optical profiler results to SEM results collected from the same wafer, where excellent correlation was observed, as shown in Figure 8. Note that the offset between SEM and optical profiler can be attributed to the different measurement locations on the wafer. These correlation results recommend the use of the Zeta measurements to complement those from the SEM. The Zeta 3D optical profiler is suitable to characterize deep trenches and can be used as a quality control tool to monitor the trench geometries, including RIE lag effect, during the microfabrication process.

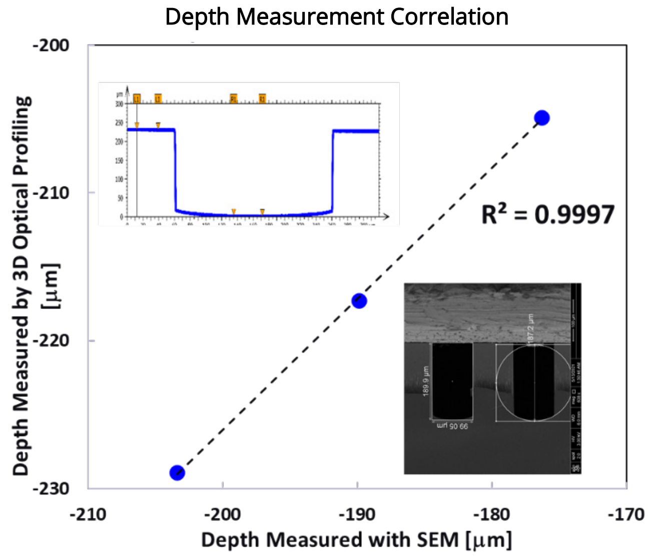


Figure 8. Correlation of the Zeta optical profiler result (profile shown at top left) and SEM result (profile shown at lower right).

High Aspect Ratio Trench Measurement

Additional assessment was performed on even narrower trenches with higher aspect ratios ranging from 5:1 up to 15:1. For the reasons discussed previously, a 20X objective with smaller NA was used for this kind of study. Figure 9 shows a top-down image of three sets of trenches with widths of 40µm, 20µm and 10µm. The measured depth of these trenches, shown in Figure 10, ranged from 190.0µm for the 40µm wide trenches and 152.2µm for the 10µm wide trenches. It was observed that, as expected, the wider trenches were deeper than the narrower ones, where the depth difference between nearby trenches with different width is approximately 20µm.

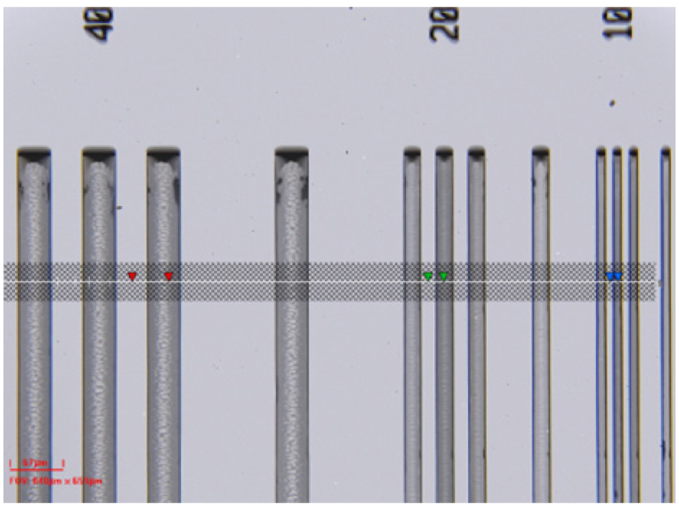
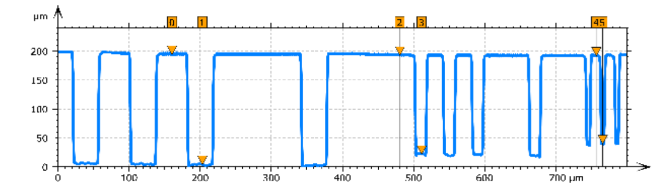


Figure 9. A top-down Zeta True Color image of three sets of high aspect ratio trenches, with nominal widths of 40µm, 20µm and 10µm.



Parameters	Unit	0-1	2-3	4-5
Height difference	μm	-190	-170.8	-152.2

Figure 10. 2D profile taken from the 3D scan shows high aspect ratio trench depth measurements for the three different trench widths.

Additional Characterization of Trench Topography

Full characterization of a deep trench is important, because the surface roughness and shape of the trench edge has a large influence on device performance. Zooming in to the bottom of the 200μm wide trench, as shown in Figure 11, highlights both the shape of the bottom surface as well as the radius of the curvature. The curved shape is typical for the RIE process because the etch rate slows down at the edges. It is therefore necessary to quantify the difference in curvature between different trenches. The radius of curvature, shown in Figure 12 and defined by ISO 12181, was calculated to be 372.1μm.

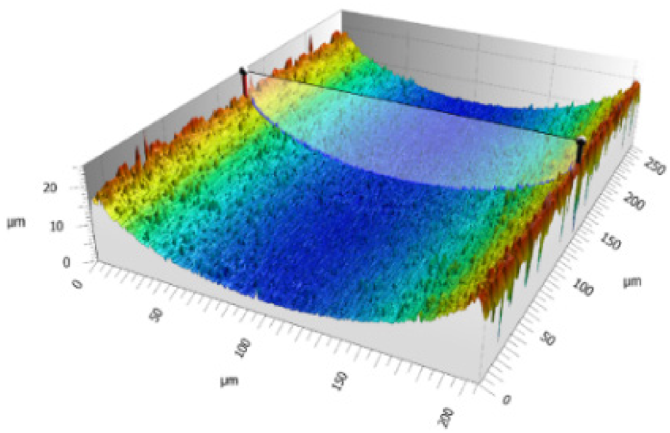


Figure 11. A zoomed-in area of the 3D scan illustrates the curvature and roughness of the bottom of the trench; the 2D scan position is indicated.

The roughness of the etched silicon surface is another key parameter for further process development. The unique feature detection function of the Zeta tools enables automatic detection of areas of interest within the field of view (FOV) and can also measure the bottom roughness of all trenches collectively. Measurement results are based on the appropriate threshold settings (height, pixel intensity, image RGB, size, shape, etc.). In this case, the areas of interest are the center regions of the trench bottoms. Both size and depth are used as thresholds, and the middle region is detected and highlighted by the software, as shown in Figure 13. The height difference

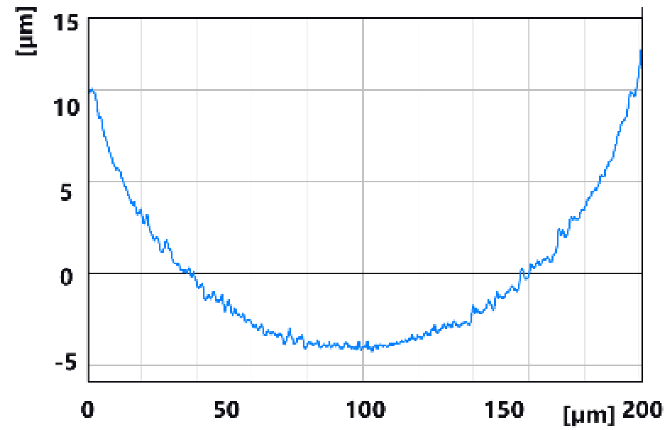
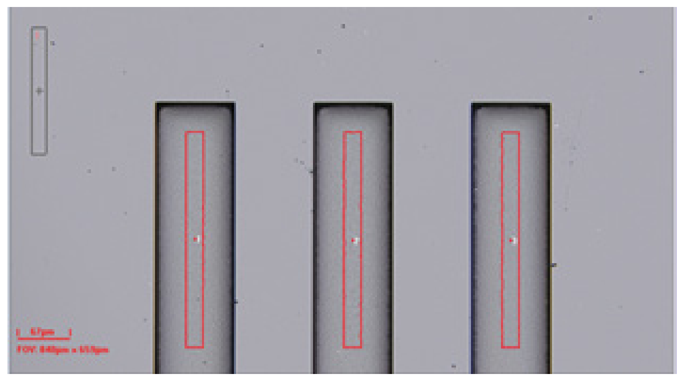


Figure 12. A 2D profile from the 3D scan in Figure 11 is used to calculate the radius of curvature at the trench bottom as 372.1μm.



Index	CenterX	CenterY	MajorAxis	MinorAxis	AvgDia	Sa	Sq	Spv	Sz	AvgHeight
1	233.583	480.200	285.719	22.638	154.178	0.625	0.773	5.499	4.308	-75.849
2	433.552	481.915	285.407	22.841	154.124	0.855	1.034	6.736	5.682	-74.767
3	633.521	481.572	285.033	22.981	154.007	0.533	0.666	5.087	4.155	-74.476
Min	233.583	480.200	285.033	22.638	154.007	0.533	0.666	5.087	4.155	-75.849
Max	633.521	481.915	285.719	22.981	154.178	0.855	1.034	6.736	5.682	-74.476
Mean	433.552	481.229	285.386	22.820	154.103	0.671	0.825	5.774	4.715	-75.031
SD	163.274	0.741	0.280	0.141	0.072	0.136	0.155	0.701	0.687	0.591
Var%	37.660%	0.154%	0.098%	0.617%	0.046%	20.222%	18.750%	12.141%	14.569%	-0.788%

Figure 13. The Zeta software automatically detects the measurement areas based on user-defined threshold settings. The depth and roughness measurements are displayed in the output report.

was calculated against the user-defined reference area at the upper left of the image. Three trench centers within the FOV were detected, and the areal roughness statistics (Sa, Sq, Spv, Sz) and height difference were automatically generated in the result report.

All analysis settings can be saved as part of a measurement recipe and applied to multiple measurement locations as part of a sequence. In sequence mode, the XY stage automatically moves to the next measurement location once the previous measurement is complete. A final report that includes results from all sequence measurements is then generated. Because this measurement method is automated, the Zeta software is ideally suited to characterize arrays of trenches to provide measurement statistics for the whole wafer or for multiple wafers measured in production mode.

Conclusion

The Zeta optical profilers from KLA Instruments, incorporating the patented ZDot™ technology, can measure deep trenches with widths ranging from 10μm to 200μm and even larger. High performance automated measurement of high aspect ratio trenches was also demonstrated, and excellent correlation was observed between optical profiler and SEM results. In conclusion, the Zeta optical profiler offers a comprehensive, non-destructive solution for the measurement of deep trenches and to quantify the RIE lag effect associated with high aspect ratio device microfabrication.

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