SPIE 2005 #5752-97

Dual Side Lithography Measurement, Precision and Accuracy

Daniel Schurz, Warren W. Flack, Robert L. Hsieh
Ultratech, Inc.
San Jose, CA 95134

Advances in micromachining (MEMS) applications such as optical components, inertial and pressure sensors, fluidic pumps and radio frequency (RF) devices are driving lithographic requirements for tighter registration, improved pattern resolution, and improved process control for pattern placement on both sides of the substrate. Consequently, there is a similar increase in demand for advanced metrology tools capable of measuring the Dual Side Alignment (DSA) performance of lithographic systems.

The requirements for an advanced DSA metrology tool include the capability of measuring points over the entire area of the substrate, and of measuring a variety of different substrates and film types and thicknesses. This paper discusses the precision and accuracy of an advanced DSA metrology system, the UltraMet 100. This system offers DSA registration measurement at greater than 90% of a wafer's surface area, providing a complete front to back side registration evaluation across a wafer. The system uses top and bottom cameras and a pattern recognition system that allow simultaneous target capture and measurement on both substrate surfaces.

Because no industry standard has been established to determine the accuracy of dual side pattern metrology, an accuracy gauge was designed for this study that allows both top and bottom cameras to simultaneously measure offsets between two targets on one substrate surface. In this paper, an accuracy gauge is measured on the UltraMet 100 and the results are compared to measurements taken on a reticle X/Y pattern placement metrology tool calibrated to a NIST traceable standard. In addition, tool performance is analyzed in terms of system repeatability and reproducibility.

Key Words: Dual side alignment, lithography tool performance, precision, accuracy, repeatability, reproducibility

1.0 INTRODUCTION

Dual side wafer lithography is becoming a common method used to manufacture both microelectronic and MEMs devices. These include such diverse applications as high frequency devices when dual side patterning is employed to minimize signal attenuation by thick metal deposition [1], and ink jet heads where backside channels convey ink to front-side nozzles [2]. Dual side lithography is also used to build three-dimensional system-on-chips containing silicon-on-insulator (SOI) device layers bonded together [3]. It is also widely employed to fabricate inertial accelerometers, pressure sensors, variable optical attenuators (VOAs), magnetic and optical-networking components and microshutter arrays [1]. As manufacturing processes improve the capability to produce smaller features on both wafer surfaces, front to back surface alignment becomes more critical. It is anticipated that by 2006, alignment requirements will be on the order of 1.0 μm. Consequently front to back alignment verification metrology will be increasingly important.

To meet the more challenging lithography requirements for advanced devices, a number of companies are transitioning to projection lithography from full wafer aligners for volume production. Manufacture of these advanced devices frequently requires using statistical process control (SPC) methods to monitor production. Alignment inspection data can be fed back to provide in-line process corrections to the lithography module. As companies look for yield improvement opportunities, all linear overlay errors will need to be evaluated and minimized. While two point metrology at the edges of the wafer is typically used in less stringent manufacturing environments, it cannot give complete front-to-back registration information. Determining the linear error components (scaling, rotation, and orthogonality), requires a minimum measurement of six points across a wafer [4]. To meet this growing market requirement, Ultratech, Inc. has developed the UltraMet 100 dual side alignment metrology tool that provides simultaneous measurement capability on approximately 90 percent of a substrate's top and bottom surfaces [5].

In this case, performance is based on the ability to measure the displacement between a front side and back side feature with repeatability and reproducibility. The tool must be able to make repeated measurements within a specified tolerance relative to the mean, with no adjustments to the tool or movement of the device being measured (repeatability). It must also be able to reproduce a set of measurements within a given tolerance over time, and with the measurement artifact removed and reloaded onto the tool (reproducibility). A reproducibility measurement must encompass all contributing errors inherent in the tool and in the measurement process, including operator error caused by substrate reloading [6,7]. The precision of a set of measurements (σ_{MS}) can be obtained from the root mean squared sum of the variation in the repeatability (σ_{repeat}) and the reproducibility (σ_{reprod}) [7]:

$$\sigma_{MS} = \sqrt{(\sigma_{repeat})^2 + (\sigma_{reprod})^2} \qquad (1)$$

where σ_{repeat} is the sigma of repeatability and σ_{reprod} is the sigma of reproducibility.

Repeatability and reproducibility for the UltraMet tool are specified at 0.10 μm 3σ and 0.30 μm 3σ respectively. Consequently, the performance capabilities of the DSA tool are evaluated against these specifications for repeatability and reproducibility.

The third critical component of metrology tool performance is system accuracy. The alignment of front-to-back features in MEMS devices is often difficult to determine accurately until the end of the process. Accurate in-line measurements are needed to verify and correct alignment. Accurate measurements made across a wafer can also be used to adjust the linear errors of scaling, rotation, and orthogonality of the stepped pattern on the wafer. This can significantly improve the registration performance across a wafer if processing introduces distortions in the wafer patterns. Stresses from thick films and thermal processing can produce errors of several parts per million (ppm) or more in MEMS applications. For most cases, a measurement accuracy of 0.20 μm is adequate for characterizing the errors and for making adjustments to the scaling, rotation, and orthogonality of the stepped pattern on the wafer.

Tool accuracy is a combination of random and systematic sources of error, and may be determined by comparison to an established reference [7]. One method to achieve accuracy is by careful calibration of each imaging subsystem. Another is to use a standard or gauge that provides a fixed distance between two features that can be measured on the tool, and is traceable to a NIST standard. Currently, there are no widely accepted standards available that provide referenced distances between points on opposite surfaces of a thin substrate [5]. Therefore, for this study, a gauge to determine tool accuracy was designed, manufactured, and measured on multiple DSA tools. Measurement results from the DSA tools are compared to measurement results from a Leica 2020, an industry accepted X/Y pattern placement tool that is calibrated to a NIST standard. Accuracy is expressed as the average of alignment offset measurements between the two systems. Because the Leica 2020 is NIST traceable, it is considered the reference tool.

2.0 EXPERIMENTAL METHODS

2.1 Wafer Processing

Reproducibility and repeatability measurements are performed on etched silicon wafers. The test wafers are SEMI-Standard, dual-side polished, 6 inch silicon. These substrates are 650-700 mm thick with 1500 Å of thermal oxide and a total indicated range (TIR) and total thickness variation (TTV) of less than 1 μm. They were patterned on both top and bottom surfaces using an Ultratech NanoTech 160 Wafer Stepper™. The optical specifications for the NanoTech 160 are shown in Table 1. The NanoTech 160 uses broadband gh-line illumination with DSA alignment capability for backside exposure. The photoresist for both top and bottom lithography was Shipley S1808 coated to 1.2 μm thick on both sides of the wafers using the process and equipment described in Table 2. The resist thickness was measured on a Nanometrics 8100X.

2.2 Accuracy Gauge processing

A chrome on quartz wafer design of the accuracy gauge allows measurement on both a Leica 2020® X/Y pattern placement tool and the UltraMet 100. Target features were digitized as two differently shaped patterns placed 40 μm apart in X with zero Y separation (Figure 1). The gauge was manufactured by first generating 10X reticles on a TRE 220 Mask Pattern Generator®. The reticles were imaged onto a 4 x 4 x 0.060 inch chrome coated quartz wafer using an ASET 645 Step & Repeat camera®. The wafer was coated with 5300 Å of AZ1518 photoresist and developed in Microchrome's PPD455 developer. The chrome was etched for 30 seconds at ambient temperature in Micorchrome CEP200 etchant.

The target features, imaged in chrome on one side of the quartz substrate, provided sufficient line edges for measurement on the Leica 2020. Differently shaped targets enabled simultaneous capture by the top and bottom cameras on the UltraMet using Cognex's Patmax® image processing software [8].

2.3 Measurement

The UltraMet 100 uses two microscopes to measure offsets between targets located on both sides of a substrate (Figure 2). As a result, a Tool Induced Shift (TIS) measurement component must be evaluated and included in the final offset calculation [9]. This component is determined as follows: a substrate is loaded on the tool in a 180^o rotated orientation, moved to the first target site, focused and measured. The substrate is then removed and reloaded at a 0^o orientation, moved to the original site and re-measured. Then the substrate is moved to each of the remaining selected target sites and measured. The X and Y offsets and rotational differences from the first site measured at 0^o and 180^o are used to calculate TIS correction offsets that are applied to all measurement sites by the tool software at the end of the measurement routine. The TIS measurements add approximately one minute to the measurement routine for each substrate.

2.4 Experimental Data

Repeatability was calculated at two sites on a test wafer which were each measured thirty times in succession with no movement between measurements. TIS measurements were made at 0^o and 180^o orientations as described in section 2.3. The wafer was removed and reloaded (cycled) and the entire measurement procedure repeated thirty times. After TIS correction of the thirty successive site measurements, a 3σ value was calculated for each site in both X and Y axes. The highest 3σ values were recorded.

Reproducibility was calculated using the same TIS corrected measurements used for repeatability. A 3σ value was calculated for the entire set of thirty measurements times thirty cycles at one site on a test wafer.

Accuracy was determined using one pair of target features at five target sites (center, top, bottom, left, right) on the chrome on quartz gauge to compare the measurements taken on the LMS 2020 and the UltraMet 100. The LMS 2020 measurement value is the average value of twenty scans taken at a single site. The repeatability of the LMS 2020 was confirmed by measuring the same site twenty times over the course of four days. Each UltraMet 100 measurement value is the average of thirty repeated measurements taken at a single site with TIS correction values applied.

The accuracy gauge was measured through ten cycles on an UltraMet 100 to determine accuracy and stability over time. Measurement values from the center location (only) of the artifact were calculated. To determine tool-to-tool performance, the same five target sites (center, top, bottom, left, right) on the gauge were measured in a single cycle on each of four different systems.

3.0 RESULTS AND DISCUSSIONS

3.1 Repeatability

Tool repeatability can be seen in the box and whisker plots in Figures 3a and 3b. These plots represent measurement data from a single wafer measured through thirty cycles on a single tool as described in section 2.4. Each cycle consists of thirty repeatability measurements taken at a site without any wafer movement. The top, bottom and middle line of each box corresponds to the 75th percentile (top quartile) 25th percentile (bottom quartile) and 50th percentile (median) of the thirty measurements [10]. The whiskers extend from the 10th percentile (bottom) to the 90th percentile (top). The diamond symbol within each box represents the mean for the data range. The mean of all thirty cycles has been normalized to zero to clearly show the variation.

In each cycle, the data range is consistently below 0.10 µm which translates to 3σ values below the repeatability specification of 0.10 µm. These results indicate reliable image capture of the optical system and software in both X and Y axes. Similar results that meet all system specifications were obtained on six additional tools.

3.2 Reproducibility

Reproducibility test results for a single measurement session of thirty cycles are also shown in the same box and whisker plots in Figures 3a and 3b. Nearly all the measurement data is within a range of ±0.10 µm. This translates to 3σ values well below the specification of 0.30 µm. The mean values of each cycle, with the exception of cycle one, are all within ±0.10 µm. These results, combined with similar results obtained from six additional UltraMet 100 DSA measurement tools, indicate a consistent ability to exceed the system specifications.

3.3 Accuracy: Alignment Offset Measurement

Accuracy of the UltraMet is determined by measuring alignment offsets on the accuracy gauge and comparing the results to those obtained from measuring the same gauge on the Leica 2020. The graphs in Figures 4 through 6 show the UltraMet offsets plotted against the Leica 2020 reference measurements which have been normalized and shown as the horizontal line at Y equals zero. When the accuracy gauge was measured through ten cycles on the UltraMet 100 (Figure 4), all values at the center point of the gauge were within 50 nm of the X offsets, and within 150 nm of the Y offsets obtained when measured on the Leica 2020. Measurement consistency is indicated since 90% of the measurements of each axis are within a 50 nm range. The test was duplicated to confirm that a small bias exists in the X results. It should also be noted that the 100 to 150 nm difference from the Leica 2020 measurements is only 0.04% of the X target separation of 40 µm. The use of a 40 µm target separation magnifies errors such as camera scale or rotation calibration, that are proportional to the size of the offset. For product wafers, the optimum separation of front to back alignment marks is zero which minimizes error.

One possible reason for the offset difference in UltraMet to Leica measurements is that the Leica views both targets with a single top down optical system while the UltraMet uses two optical systems; one views top down, the other bottom up. When measuring the accuracy gauge, the target captured by the bottom optical system is viewed through the 60 mil thickness of the gauge glass. Imaging through this extra layer of glass may be distorting the image of the bottom camera, possibly affecting both the mean bias and scale. These effects are not present when viewing product wafers with targets on both top and bottom substrate surfaces.

Offsets across the gauge were evaluated by measuring three points in each axis. Figure 5a shows a 40 to 60 nm range of differences from the Leica 2020 measurements in the Y target offsets at each point moving across the gauge in X. The X target offsets also measure within a 60 nm range, but differ from the Leica 2020 results by 120 to 180 nm. Similar results are seen in the target locations across the gauge the Y axis (Figure 5b). Point to point differences range from 20 to 30 nm for both X andY target offsets.

Tool-to-tool accuracy was evaluated by measuring the same gauge on four different UltraMet 100 systems. Figure 6 shows the X target offsets from five measurement locations across the gauge for each tool. Each measurement is compared to the same results from the Leica 2020. Tool numbers 003 and 008 measure within 50 nm of the Leica 2020 reference measurements. Tool numbers 005 and 001 are each within 100 nm across the gauge, however each shows some bias relative to the Leica values. These results show that the UltraMet 100 has a sufficiently small alignment offset (accuracy), as verified by a NIST traceable standard, to meet the alignment requirements for current and future DSA applications.

4.0 CONCLUSIONS

The precision of the UltraMet 100, as calculated by repeatability and reproducibility, is sufficient to meet most of the current and future dual side alignment metrology requirements of the nanotechnology and MEMS markets.

An accuracy gauge has been designed that allows calibration of DSA tools that utilize opposing optics to view two sides of a substrate. The gauge can also be measured on an X/Y pattern placement metrology tool for correlation to NIST standards. The gauge has been used to determine that the accuracy of the UltraMet 100 is sufficient for dual side devices with 1.0 μm front-to-back alignment requirements.

Future work will include the redesign and manufacture of additional accuracy gauges that can be used to characterize offset bias on individual DSA metrology systems.

5.0 ACKNOWLEDGEMENTS

The authors would like to thank Hai Nguyen for his contribution in measurement and data collection.

6.0 REFERENCES

1. L. Chen, H. Neves, T. Kudrle, “Process Development for the Integration of MEMS and RF Devices”, *Cornell Nanofabrication Users Network*.
2. C. Cheng, J. Hu, Y. Lai, H. Wang, C. Cheng, “Monolithic thermal ink jet print head combining anisotropic etching and electroplating”, *Input/Output and Imaging Technologies II Proceedings*, SPIE **4080**, 2000.
3. R. Reif, A. Fan, K. Chen, S. Das, “Fabrication Technologies for Three-Dimensional Integrated Circuits”, *International Symposium on Quality Design Proceedings*, IEEE, 2002.
4. M. van den Brink, C. de Mol and R. George, “Matching Performance for Multiple Wafer Steppers Using an Advanced Metrology Procedure,” *Integrated Circuit Metrology, Inspection and Process Control II Proceedings*, SPIE **921** 1988.
5. D. Schurz, W. Flack, D. Anberg, “Dual Side Metrology for Micromachining Applications”, *Metrology, Inspection, and Process Control for Microlithography XVIII Proceedings*, SPIE **5375**, 2004.
6. *Metrology Tool Gauge Study Procedure for the International 300 mm Initiative (I300I)*, Technology Transfer # 97063295A-XFR.
7. *Evaluating Automated Wafer Measurement Instruments*, Sematech, Technology Transfer 94112638A-XFR.
8. http://www.cognex.com/products/PatMax/default.asp, January 2004
9. K. Hoshi, E. Kawamura, H. Morohoshi, H. Ina, T. Fujimura, H. Kurita, J. Seligson, “TIS-WIS interaction characterization on overlay measurement tool”, *Metrology, Inspection, and Process Control for Microlithography XVI Proceedings*, SPIE **4689**, 2002.
10. G. Box, W. Hunter, J. Hunter, “Statistics for Experimenters,” *John Wiley & Sons* (1978).

Parameter	NanoTech 160
Reduction factor	1X
Wavelength (nm)	390 - 450
Numerical aperture (NA)	0.31
Partial coherence (σ)	0.58
Wafer plane irradiance (mW/cm^2)	1200

Table 1: Optical specifications of the NanoTech 160 stepper used in this study.

Process Step	Parameters	Equipment
HMDS	Vapor Prime, 20 minutes at 150^{o}C	YES oven
Frontside Coat: Shipley S1808	2750 RPM for 30 seconds	ACS200 track
Softbake	Hotplate, 30 seconds at 105^{o}C	ACS200 track
Backside Coat: Shipley S1808	2750 RPM for 30 seconds	ACS200 track
Softbake	Convection Bake, 30 minutes at 105^{o}C	Blue-M Oven
Exposure Frontside (first layer)	Focus: 0 Exposure: 100 mJ/cm^2	NanoTech 160
Develop: Arch OPD262	1 minute puddle, DI water rinse	ACS200 track
Exposure Backside (second layer)	Focus: 0 Exposure: 100 mJ/cm^2	NanoTech 160
Develop: Arch OPD262	1 minute puddle, DI water rinse	ACS200 track
Hardbake	Convection Bake, 30 minutes at 110^{o}C	Blue-M Oven

Table 2: Process conditions for Shipley S1808 for 1.2 μm thickness on silicon substrates.

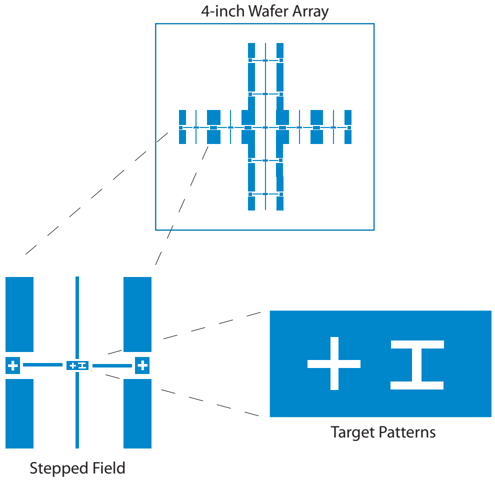


Figure 1: Digitized patterns shown for the accuracy gauge are clear (glass) patterns on the wafer.

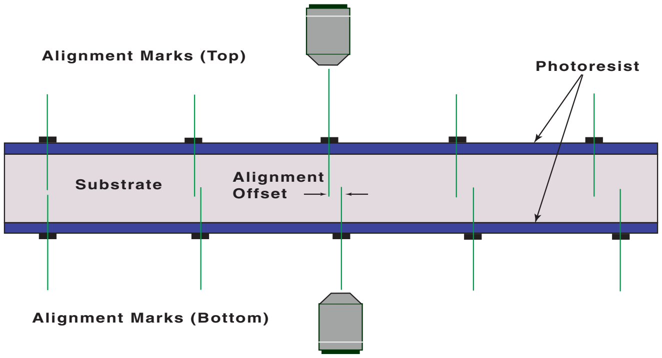


Figure 2: Cross section of a substrate with front and back side patterns in photoresist. The DSA metrology is performed using top and bottom microscopes. The alignment offset is determined by comparing alignment targets on the top and bottom of the wafer.

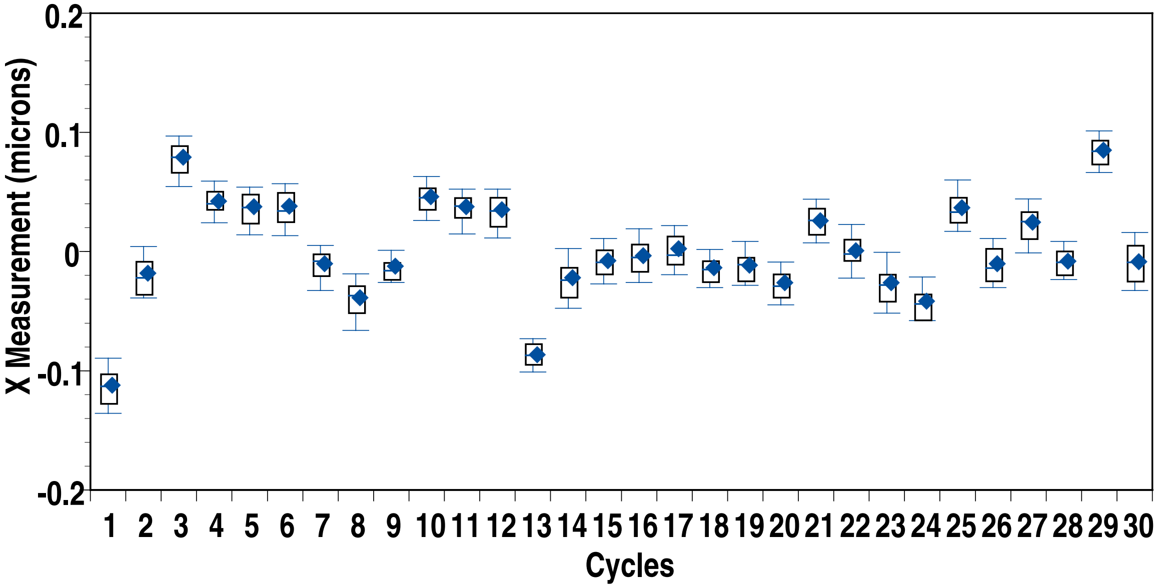


Figure 3a: Box and whisker plot of X reproducibility over thirty wafer cycles. Each cycle consists of thirty repeatability measurements as shown by the box (25 and 75% of data) and whiskers (10 and 90% of data).

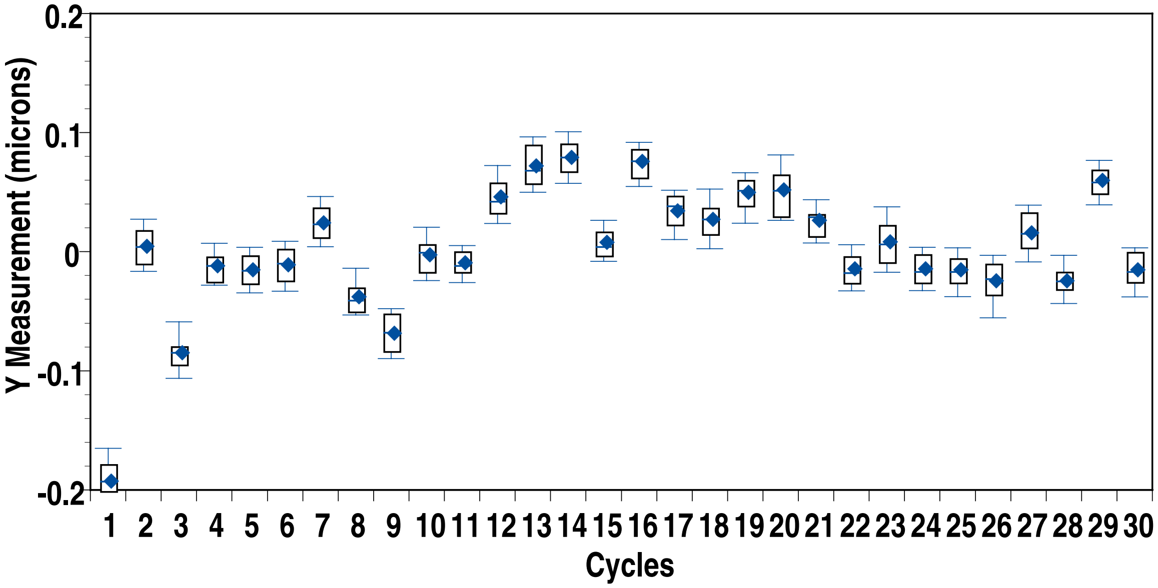


Figure 3b: Box and whisker plot of Y reproducibility over thirty wafer cycles. Each cycle consists of thirty repeatability measurements as shown by the box (25 and 75% of data) and whiskers (10 and 90% of data).

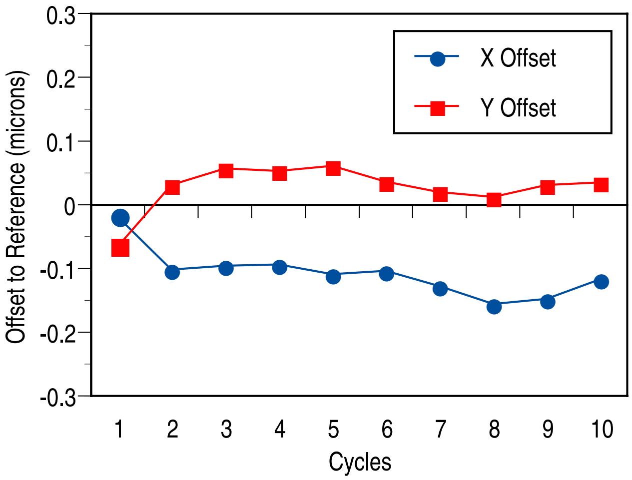
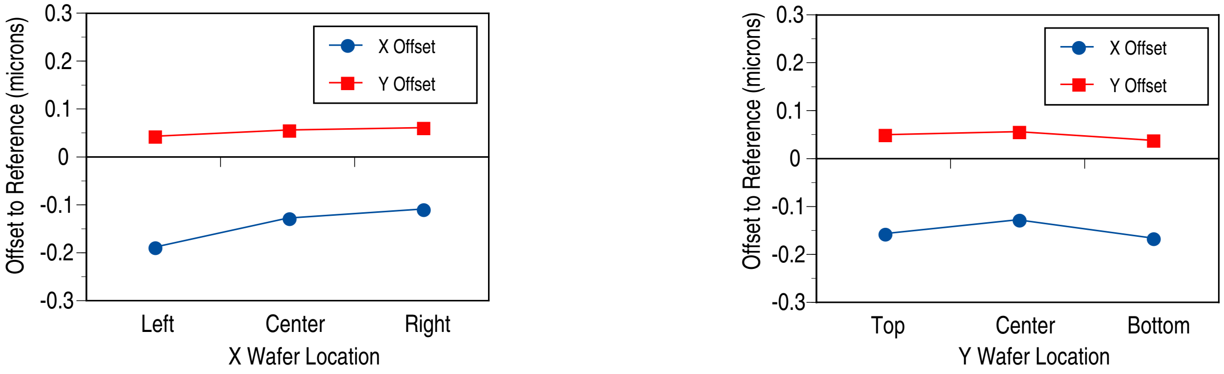


Figure 4: Accuracy in X and Y repeated over ten cycles at the center of the chrome on quartz gauge. The zero line represents the normalized Leica 2020 reference measurements.



(a) Wafer Left to Right

(b) Wafer Top to Bottom

Figure 5: Accuracy in X and Y across the chrome on quartz gauge from left to right and top to bottom. The zero line represents the normalized Leica 2020 reference measurements.

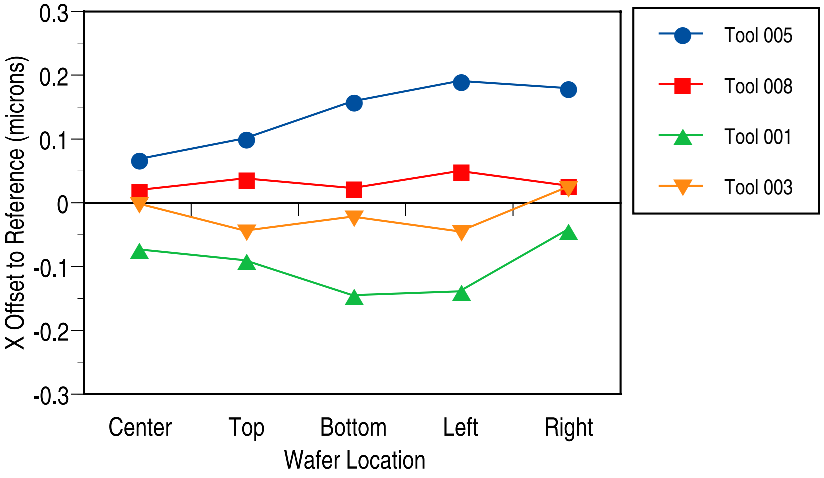


Figure 6: X Accuracy for four different UltraMet 100 systems measured at five points across the chrome on quartz gauge. The zero line represents the normalized Leica 2020 reference measurements.