Dual Side Wafer Metrology for Micromachining Applications

Daniel Schurz, Warren W. Flack, Doug Anberg
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 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 the lithography systems.

There are a number of requirements for an advanced DSA metrology tool. First, the system should be capable of measuring points over the entire area of the wafer rather than a narrow area near the lithography alignment targets. Secondly, the system should be capable of measuring a variety of different substrate types and thicknesses. Finally, it should be able to measure substrates containing opaque deposited films such as metals.

In this paper, the operation and performance of a new DSA metrology tool is discussed. The UltraMet 100 offers DSA registration measurement at greater than 90% of a wafer's surface area, providing a true picture of a lithography tool's alignment performance and registration yield across the wafer. The system architecture is discussed including the use of top and bottom cameras and the pattern recognition system. Experimental data is shown for tool repeatability and reproducibility over time.

Key Words: Dual Side Alignment, DSA, lithography tool performance, repeatability, reproducibility

1.0 INTRODUCTION

1.1 Dual Side Alignment

In the expanding MEMS and nanotechnology markets, a number of device types require alignment and exposure between the front and back surfaces of a substrate. For example, DSA is used in creating system-on-chips in three-dimensional integrated circuits for successive bonding of silicon-on-insulator (SOI) device layers [1] and for Radio Frequency devices to minimize attenuation by metal deposition [2]. DSA is also used for ink jet heads to align backside channels for ink flow to front-side nozzles [3]. Other devices requiring dual-side alignment are inertial accelerometers, pressure sensors, variable optical attenuators (VOAs), magnetic and optical-networking components and microshutter arrays [2].

Until recently, the resolution requirements and alignment tolerances for DSA have not been critical, therefore, metrology to verify alignment has not been widely utilized. Now, with shrinking geometries, DSA alignment is becoming more stringent and metrology becoming more important. Figure 1 shows an Ultratech customer survey of predicted DSA requirements. The maximum and minimum curves represent the range of customer DSA requirements over time. A requirement for 1.0 µm occurs as early as 2006. As the resolution and alignment requirements have become more challenging, a number of companies are moving to projection lithography rather than full wafer aligners for volume production. Sample inspection is becoming more widespread, providing the feedback needed to implement statistical process control (SPC) in DSA process steps. In order to determine the linear error components (scaling, rotation, orthogonality and mean), the alignment should be checked at a minimum of six points across a wafer [4]. This is especially critical for warped or bonded wafers, since two point metrology at the edges of the wafer cannot give accurate or complete alignment information. And, as companies look at continuing improvement in yield, linear overlay errors will need to be more stringently evaluated.

Since advanced MEMS devices are not yet in high production volume, automated DSA metrology is not a requirement for most manufacturers. A lower priced manual metrology tool that can be upgraded in the future is sufficient. However, the tool needs to allow multiple points to be measured across the wafer. It is also necessary for the data to be analyzed automatically. It is anticipated that in the future, a fully automated metrology tool will be required.

This paper will discuss the design and performance of a DSA metrology tool. It will provide measurement data showing alignment repeatability and reproducibility for multiple sites across the wafer.

1.2 Performance Requirements

The performance of any metrology tool is based on the ability to measure a feature (or its relative position) with repeatable accuracy under two conditions. 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 measure within a given tolerance over time with the measurement feature removed and reloaded onto the tool (reproducibility). The results obtained in reproducibility encompass all contributing errors inherent in the tool and in the measurement process, including operator error caused by substrate reloading [5,6]. Because a tool's precision (P) is the total measurement variation, it can then be calculated as [6]:

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

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

Tool accuracy is a combination of random and systematic sources of error compared to an established reference. At this time, there are no widely accepted standards available that provide referenced distances between points on opposite surfaces of a thin substrate. Therefore, the DSA metrology system must achieve its accuracy by careful calibration of each imaging subsystem as described in section 2.1.

The first generation of the UltraMet system is designed to measure alignment where process tolerances are 1.0 µm or greater. Accordingly, to achieve a precision to tolerance ratio less than 30%, repeatability and reproducibility for this tool are specified at 0.10 µm 3σ and 0.30 µm 3σ respectively. The precision to tolerance ratio is calculated as follows:

$$\frac{P}{T} = \frac{100 \times 6\sigma_{MS}}{T} \qquad (2)$$

where σ_{MS} is the precision of the measurement system.

1.3 Tool Description

The UltraMet 100 DSA tool provides the capability to measure the alignment between patterns printed on the top and bottom of a substrate as shown in Figure 2. The tool’s basic configuration is shown in Figure 3. The X-Y substrate stage is located on a granite block for stability. The metrology is performed by two optical microscopes with 12.5X magnification. One views the top of the substrate and is movable in the Z-axis, while a second microscope simultaneously views the bottom of the substrate and is stationary in X, Y, and Z. Because two microscopes are used, the tool is capable of measuring a wide variety of opaque and transparent substrates and film types.

The substrate holder is a glass material that is transparent at the operating wavelength of the microscopes. This allows measurement of the bottom surface of a substrate at nearly any site within the six inch holder diameter. It is easily reconfigured for substrate sizes ranging from 2 inches to 6 inches, round or square, and is capable of handling substrate thickness up to 2 mm. A substrate can be rotated to 0^o and 180^o orientations for Tool Induced Shift (TIS) correction [7].

The computer system for controlling and operating the tool includes a video frame grabbing board for capturing images from the Charge Coupled Device (CCD) cameras using Cognex's Patmax® image processing software. Patmax identifies key features in an object and correlates their spatial relationships to match a trained image to the image on the substrate, and is unaffected by the objects angle, size or appearance [8]. Patmax's tolerance of changes in an object's orientation allows for rapid target acquisition. The computer is located on a separate cart from the stage and measurement units. The computer system provides a monitor for visual display of the video image from both top and bottom cameras simultaneously.

The pattern recognition system, or Machine Vision System (MVS), provides a high degree of precision and versatility in registration measurement using a wide range of target shapes and sizes. Nearly any unique feature within an approximate 300 µm viewing window, ranging from 20 to 100 µm in size and with line-width greater than 4.0 µm can be successfully acquired by the MVS, including existing metrology or device features within any die on the substrate [9]. The top and bottom CCD cameras can be trained to acquire different target shapes simultaneously which provides more flexibility in job setup. A reference fiducial consisting of a grid of measurement structures for CCD pixel calibration is embedded in a peripheral area of the stage.

2.0 EXPERIMENTAL METHODS

2.1 Ultramet 100 Operation

2.1.1 Calibration:

After initial system setup, there is a single calibration routine required on daily or weekly intervals, depending on the tool usage. Pixel calibration is needed to translate pixel space (camera coordinates) that the computer uses to calculate physical space (microns). The single sided calibration process “learns” the mapping from the camera's pixel plane to the image plane on the wafer surface. It is used to account for subtle differences in optical magnification, position, rotation, and camera tilt between the top camera and the bottom camera.

Pixel calibration is performed using an array of reference fiducials spaced 100 µm apart embedded in a peripheral area of the substrate stage. Two images are taken simultaneously, one with the top camera and one with the bottom camera looking at the same array of fiducials. The bottom camera is used as the base point of reference (the exact center of the image is considered the XY plane 0,0 point). The bottom image is compared to the top image, looking for differences in translation, rotation, tilt, and spacing between fiducials. A Cognex software algorithm is utilized to calculate and store these differences. Calibration is complete and any further measurements will have the stored algorithm applied [10]. On screen instructions guide the operator through the calibration procedure, which takes less than 5 minutes.

2.1.2 Measurement:

Job files are created by the operator that specify the desired number of measurements to be repeated at a single site. Any number of repeated measurements can be set depending on the user's requirements for a statistical analysis confidence level [11]. The system software provides a text file containing each raw measurement point at each site, as well as a mean value and 3σ value for the site. The operator also selects a “step list” of the number and order of sites to be measured. Step lists are written as text files and placed in a directory for attachment to a job file. The system software uses the step list to guide the operator through the measurement routine. The system supports importing a bitmap file that depicts the sites to be measured from any commercial graphic software program. The bitmap file can be attached to the job file and used to guide the operator.

The operator has the option of using a target feature from an existing target library, or training on a new device or metrology feature on the substrate. The training process creates an image file that is placed in a directory and then attached to the job file.

Because the UltraMet 100 uses two microscopes to measure offsets between targets located on both sides of a substrate, a Tool Induced Shift (TIS) calculation must be made and included in the final offset calculation. When the completed job file is selected for the measurement routine, 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 the remaining designated sites and measured. 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.

2.1.3 Data Analysis:

An ASCII measurement file containing all raw measurement results, TIS correction values and all TIS adjusted measurements for each site can then be viewed on-screen. Values are calculated in both the X and Y-axes. The data files can be loaded into any spreadsheet or statistical software package for statistical analysis.

2.2 Wafer Processing

The test wafers were SEMI-Standard, dual-side polished, 6 inch silicon wafers. These substrates are 650-700 µm thick with 1500 Å of thermal oxide and a TIR/TTV < 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 and the wafers were coated with 1.2 µm thick on both sides using the process and equipment described in Table 2. The resist thickness was measured on a Nanometric 8100X.

2.3 Experimental Data

Repeatability was calculated at two sites on a test wafer which were each measured thirty successive times with no movement between measurements. TIS measurements were made at 0^o and 180^o orientations as described in section 2.1.2. The wafer was removed and reloaded (cycled) and the entire measurement procedure repeated 30 times. After TIS correction of the 30 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 30 measurements times 30 cycles at one site on a test wafer.

3.0 RESULTS AND DISCUSSIONS

3.1 Repeatability

Tool repeatability can be seen in the box and whisker plots in Figures 4a and 4b. These plots represent measurement data from a single wafer measured through 30 cycles on a single tool as described in section 1.2. Each cycle consists of 30 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 30 measurements [11]. The whiskers extend from the 10th percentile (bottom) and the 90th (top). The symbol within each box represents the mean for the data range. The mean of all 30 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 0.10µm. These results indicate reliable image capture of the optical system and software in both X and Y axes. Results that meet all specifications were obtained on two additional tools.

3.2 Reproducibility

Reproducibility test results for a single measurement session of 30 cycles are also shown in the same box and whisker plots in Figures 4a and 4b. Nearly all the measurement data is within a range of ±0.10µm. This translates to 3σ values well below the specification of 0.30µm. The mean values of each cycle, with the exception of cycle one, are all within ±0.10µm. These results, combined with similar results obtained from two additional UltraMet 100 DSA measurement tools, indicate a consistent ability to exceed the system specifications.

3.3 Reproducibility Over Time

Reproducibility over time was tested on a second tool in five measurement sessions over a 12 day period. The results are shown in Figure 5. The data was collected using the previously described method. Each box and whisker set includes all 30 reproducibility cycles taken each of the five days. The mean of all five measurement sessions has been normalized to zero to more clearly show the variations. Similar data from a second tool shows that all of the measurement data falls within ±0.15µm. The range of mean values of each measurement session is only 0.10µm. Y-axis results are not shown since they are similar to the X-axis.

4.0 CONCLUSIONS

The UltraMet 100's precision, calculated by repeatability and reproducibility, is sufficient to meet current and future dual side alignment metrology requirements of the nanotechnology and MEMS markets. The precision to tolerance ratio (P/T) for this tool meets alignment tolerances in the processes typically employed in current applications and those expected in the near future. Second and third generations of the UltraMet will include substrate handling automation, 200mm wafer handling capability, and improved measurement capability for tighter DSA alignment specifications expected to be required in the future.

Future work will involve tool to tool performance characterization and working with the MEMS industry to establish reference standards for determining tool accuracy.

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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.

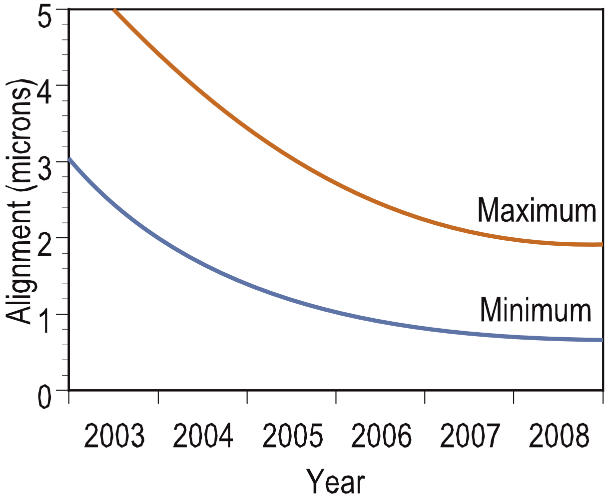

Figure 1: DSA overlay requirements as a function of time. The maximum and minimum curves represent the range of customer DSA requirements.

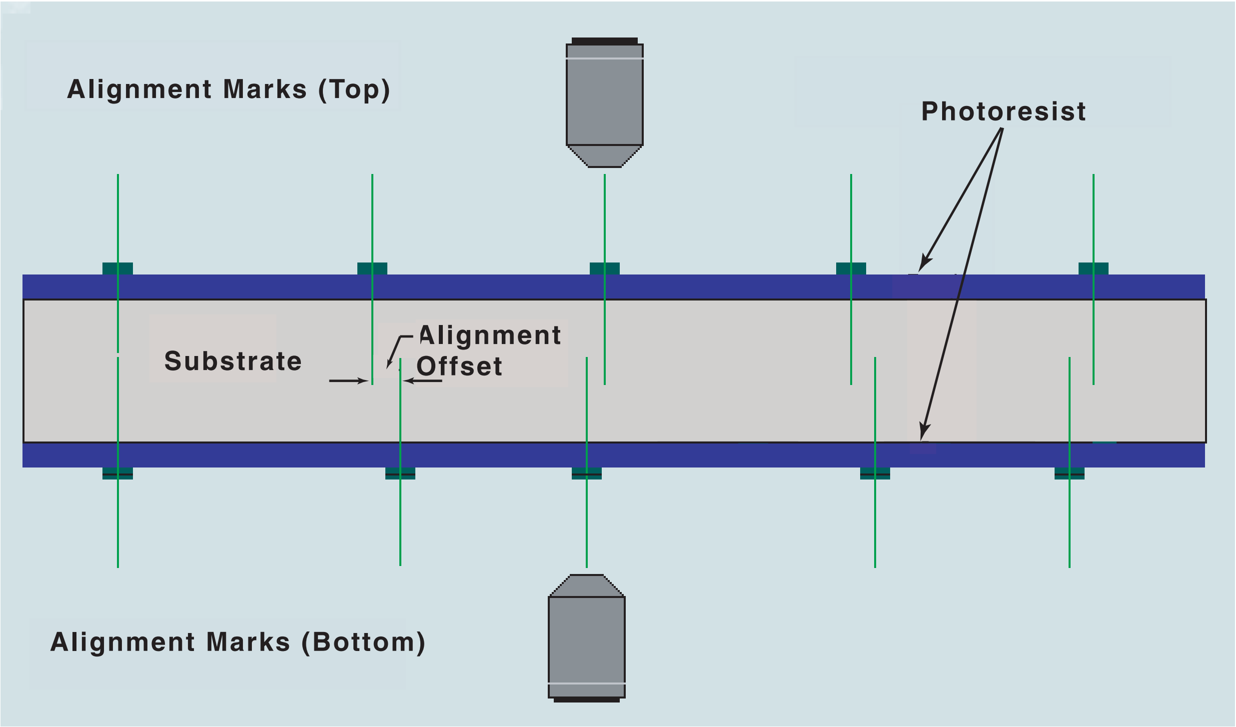

Figure 2: Cross section of a substrate with front and back side patterns in photoresist. The DSA metrology is performed using top and bottom microscopes. The alignment offset is determined by comparing alignment targets on the top and bottom of the wafer.

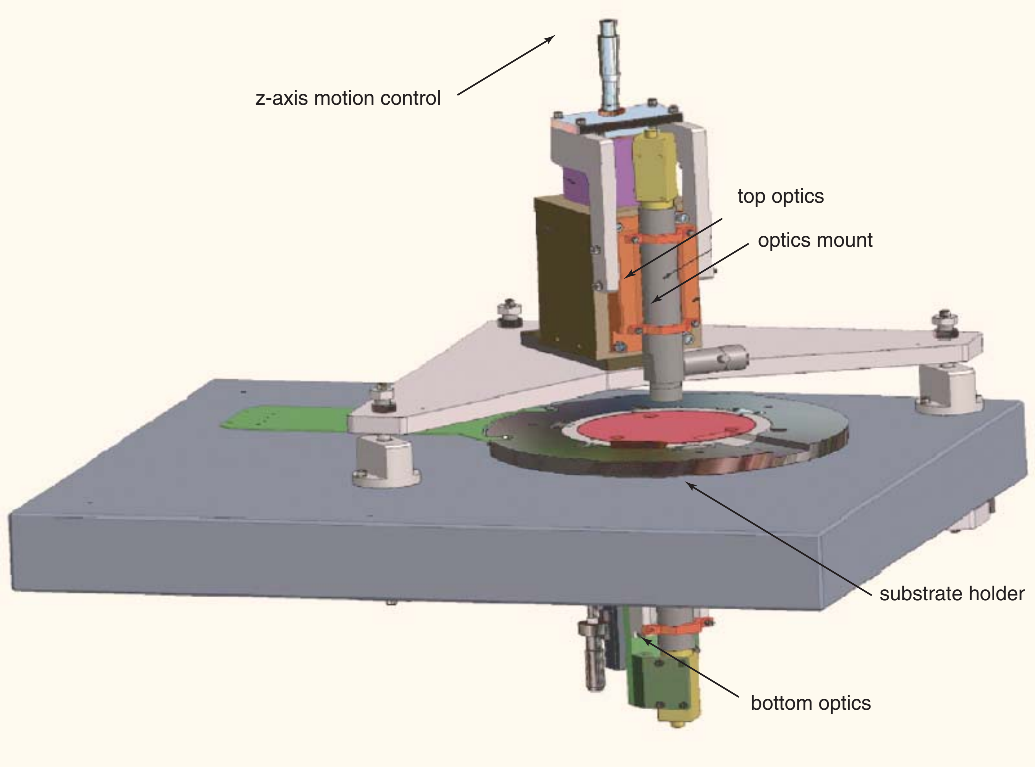

Figure 3: Drawing of UltraMet 100 optical and stage subsystems.

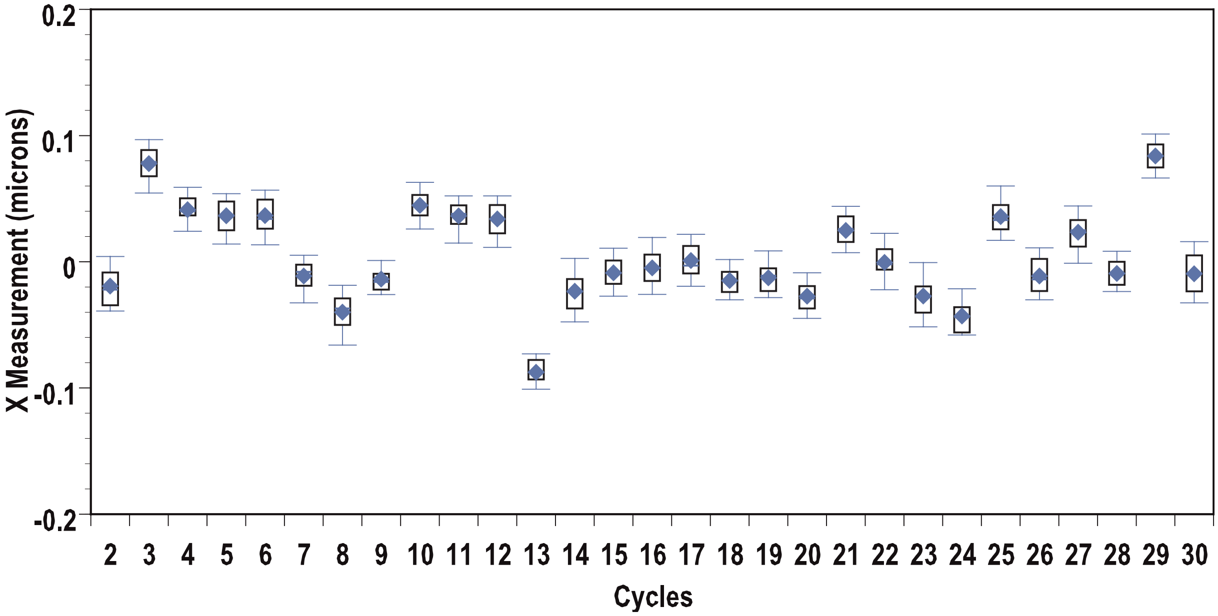

Figure 4a: Box and whisker plot of X reproducibility over thirty wafer cycles. Each cycle consists of thirty repeatability measurements as shown by the box (25 and 75% of data) and whiskers (10 and 90% of data).

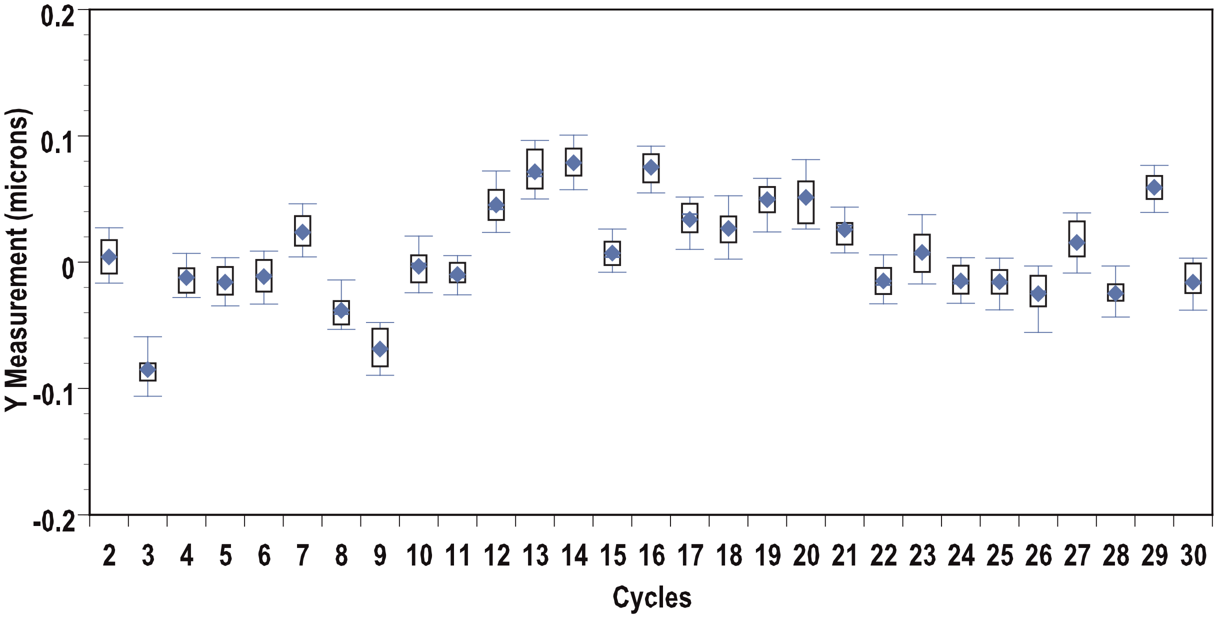

Figure 4b: Box and whisker plot of Y reproducibility over thirty wafer cycles. Each cycle consists of thirty repeatability measurements as shown by the box (25 and 75% of data) and whiskers (10 and 90% of data).

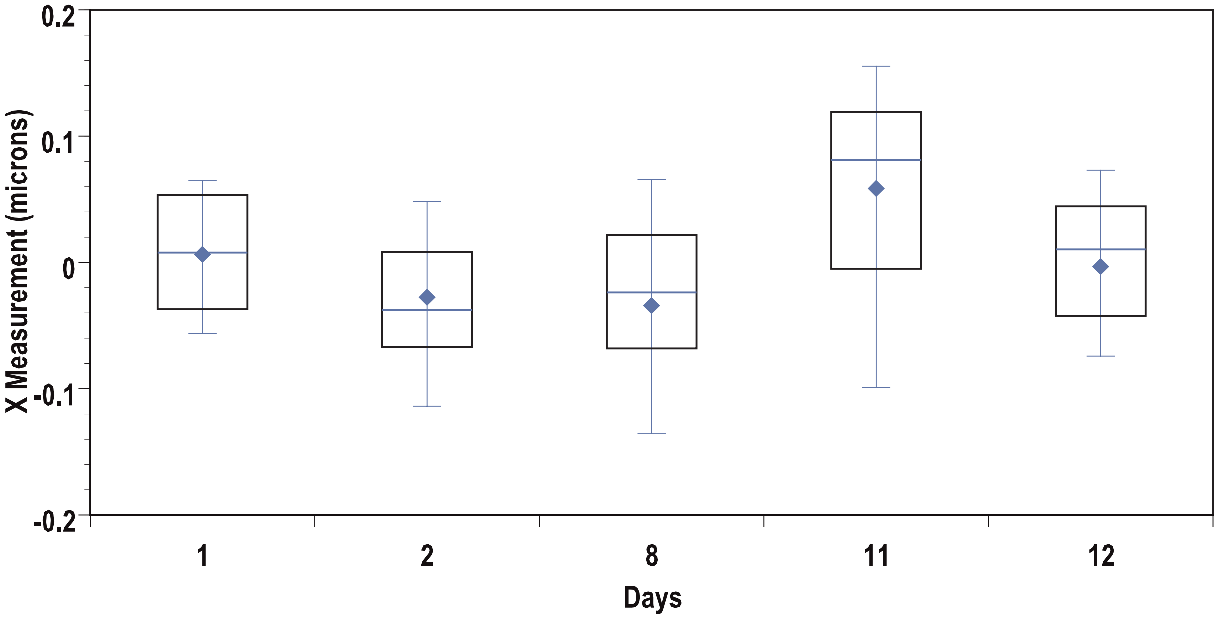

Figure 5: Box and whisker plot of X reproducibility over five days. Each cycle consists of thirty reproducibility cycles as shown by the box (25 and 75% of data) and whiskers (10 and 90% of data).