Metrology for Characterization of Wafer Thickness Uniformity During 3D-IC Processing

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Abstract

There is a constant desire to increase substrate size in order to improve cost effectiveness of semiconductor processes. As the wafer diameter has increased from 2" to 12", the thickness has remained largely the same, resulting in a wafer form factor with inherently low stiffness. Gravity induced deformation becomes important when using traditional metrology tools and mounting strategies to characterize a wafer with such low stiffness. While there are strategies used to try to reduce the effects of deformation, gravitational sag provides a large source of error in measurements. Furthermore, glass is becoming an important material for substrates in semiconductor applications and metrology tools developed for use for characterizing silicon are inherently less suitable for glass. Using a novel mounting strategy and a measurement technique based on optical interference provides an opportunity to improve on the methodologies utilized to characterize wafer flatness (warp, bow) and total thickness variation (TTV). Not only can the accuracy of the measurement be improved, using an interference based technique allows for full wafer characterization with spatial resolution better than 1 mm, providing substantially more complete wafer characterization.

Introduction

Historically, use of glass wafers in the semiconductor industry has been primarily for MEMs and CMOS image sensor applications. These applications typically had loose specifications for TTV and warp. Using glass as a carrier wafer for precision thinning of silicon in 3D-IC applications requires that the thickness uniformity and warp are tightly controlled since non-uniformities in the carrier directly impact the accuracy of the silicon TTV.

Another challenge is given by the fact, that over the past several years, wafer diameters have increased dramatically; resulting in the requirement to accurately characterizes extremely high aspect ratio wafers (300 mm diameter and thickness < 1 mm). High aspect ratio parts have inherently low stiffness and characterizing the flatness of such a component is extremely challenging due to gravity effects. Conventional mounting methods, e.g. three/four-point mounts, are less suitable for flatness characterization of such high aspect ratio parts due to a great deal of deflection of gravity and sensitivity to how the wafer is placed on the mount. This leads to erroneous results when trying to characterize warp and bow.

Corning® Tropel® has developed a novel distance measuring interferometer based on a frequency stepping laser that is well-suited to characterize the flatness and TTV of glass wafers. In fact, several commercial interferometers capable of characterizing the flatness, thickness, and TTV of 300 mm diameter glass wafers have been installed. In addition to novel mounting strategies that substantially avoid errors given by historical techniques; this metrology tool has extremely high accuracy and a tight pixel density. A 300 mm diameter wafer would have millimeter-level lateral resolution as compared to profile based resolution given by existing techniques. This greater data density provides extremely valuable information to the quality of the wafers.

We will compare and contrast different metrology techniques and their relative attributes and discuss additional developments in using this technology. The significant advantages provided by this approach for precision characterization of wafers and wafer stacks will also be provided.

Background

In the beginning the semiconductor industry was just an emerging market. Lithography as it is done today was beyond the imagination of even the people at the leading edge of this new technology revolution. Wafers were small, first 1 inch then 2 inches in diameter. The industry was looking for consistent characterization of these small thin wafers to establish standard quality.

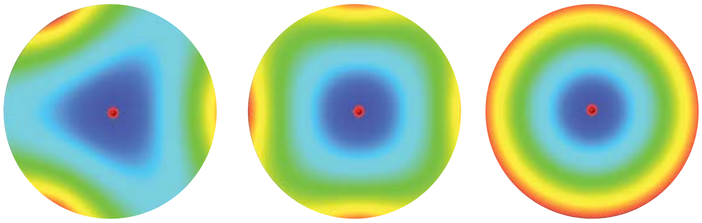
What was it they wanted to characterize? They were looking for a measure of the degree of convex/concave shape in the wafer, and an overall wafer flatness measurement.
With the wafer sizes of the time, it was desirable to support the wafer in a simple manner that was easily reproducible, so the three-point mount was perfect. It is a kinematic support, so any three-point support should result in the same deflections. A small misalignment of the part would result in a relatively small reproducibility error.

However, measuring the concave/convex magnitude becomes trivial in this fixture. You can simply measure the center point and compare the measurement to the measurement of an optical flat supported by the same three points. This then becomes a measure of the sag of the wafer. There is a small amount of gravitational influence, but this should remain relatively constant from wafer to wafer for the same nominal geometry. The beauty of this measurement is that you can measure bow with a single point probe on a fixed jig. Film stress could be correlated directly to the magnitude of the change in this bow measurement (e.g. see Stoney's equation) after the application of the film.

Measuring warp still requires full surface information, but the three-point support allows the measurement to be made directly without the complication of calculating the least squares plane, making it convenient back when these types of analysis were limiting factors.

Over time the diameter of the wafer grew, but the thickness did not increase proportionally, 3 inch, then 4 inch, 5 inch for a while, then 6 inch, 8 inch, and now 300 mm (12 inch) with 450 mm (18 inch) just over the horizon. This seems like no major concern, but all those small errors associated with minor alignment errors start to become very significant relative to the target values of bow/warp.

Another challenge arises from variation from how the wafer is mounted on the metrology tool. Often times a three-point mount is used with characterizing a wafer, but four-point mounts, ring supports and others are also utilized. Deformation from gravity will significantly differ in shape and magnitude depending on how the wafer is held during characterization. Figure 1 shows the shape of a theoretically perfect (TTV and flatness = 0 μm) wafer if it is held at the perimeter by a three-point (1a), four-point (1b), or ring support (1c). The magnitude of the total deflection (sag) is also strongly related to the mounting strategy. As indicated in Figure 1, the calculated deflection through finite element analysis (FEA) modeling of a 300 mm diameter, 0.7 mm thick supported at the perimeter by three-point, four-point and ring support is 206 um, 160 um and 130 um respectively.


(1a) Three-point mount at perimeter Sag: 206 μm

(1b) Four-point mount at perimeter Sag: 160 μm

(1c) Ring support at perimeter Sag: 130 μm

Figure 1. FEA showing shape of deformation with different support levels

The effect of how the wafer is supported on the total sag of the wafer was discussed above. There can also be substantial changes in variation by small changes in the wafer properties, mounted under the same conditions. Let's consider a few simple cases:

Wafer diameter: 300 +/- 1 mm
Wafer material: Silicon
  Density: 2.33 g/cm3,
  Elastic modulus: 141 GPa
  Poisson's ratio: 0.22
  Wafer thickness: 0.7 mm +/- 0.01 mm
  Three-point support radius: 147 mm
Glass Material: Corning SGW3
  Density: 2.38 g/cm3,
  Elastic modulus: 74 GPa,
  Poisson's ratio: 0.23
  Wafer thickness: 0.7 mm +/- 0.01 mm
  Three-point support radius: 147 mm

The first thing to note is that for these material properties, the magnitude of the gravitational sag from a three-point support at -3 mm from the edge is 206 microns, which is certainly not negligible. Compare this to the results for a 0.4 mm thick, 50 mm diameter Si wafer, which has a sag of just over 0.35 microns. This, you can argue, is negligible, the variation from loading is almost certainly negligible, and the variation from different wafer thickness is also negligible.

If you consider our 300 mm wafer case, simply varying the thickness of the wafer from 0.69 mm to 0.71 mm changes the gravitational influence by over 12 microns.

Clearly for getting a meaningful measurement with a three-point support requires compensating for the influence of gravity. However as we can see from the sensitivity to the wafer thickness, the compensation is highly sensitive to variations from wafer to wafer. Even with constant wafer geometry and properties, measuring a wafer with this kind of magnitude from gravity becomes unnecessarily complex, and incredibly sensitive to load orientation. For wafers with relatively loose tolerances, 10 μm TTV and 200 μm warp for example, this may appropriate. However, gravity compensation is a questionable strategy to obtain accurate measurements for 300 mm wafers with 2 μm or 3 μm of TTV and 40 μm or 50 μm of warp. Efforts underway to increase the diameter of the semiconductor wafers will exacerbate the issue. For the purpose of illustration, consider the same 0.7 mm thick wafer, with a 450 mm diameter. This will sag more than 1000 um.

Different materials such as glass, typically have stiffness lower than silicon and the influence of gravity becomes even greater. For example, a glass wafer with the same geometry as our 300 mm silicon wafer will sag by 404 microns instead of the 206 microns described previously. Table 1 summarizes the sag as a function of wafer diameter, thickness and material. With larger and thinner wafers, a three-point support is likely to introduce as much uncertainty in the measurement as the magnitudes of the real wafer flatness. Using other non-kinematic support methods will not allow for accurate compensation either.

Material	Diameter (mm)	Thickness (mm)	Support Radius (mm)	Sag (μm)
Silicon	50	0.40	22	0.35
Silicon	300	0.69	147	212
Silicon	300	0.70	147	206
Silicon	300	0.71	147	200
Silicon	450	0.70	222	1060
SGW3	300	0.70	147	404

Table 1. Summary of wafer sag variability with wafer dimension/material

Ultimately, what needs to be considered is what attribute is being characterized, and what is the best approach. For non-silicon substrates, many users have changed from a three-point supported warp measurement to what is known as *Sori*, which measures the wafer as it would sit in its free state on a flat plate. Naturally the wafer will still bend under the influence of gravity, but this will represent the same condition this wafer will "see" during its useful life. Also this does not require a compensation for gravity, as the gravity is a part of the measurement condition. This is especially beneficial for very thin very large diameter wafers as they no longer have rigidity, so errors in the gravitation correction can be bigger than the real "flatness". If the gravity compensation is 90% correct, for these cases that would still represent a 30-40 micron error, which in most cases is probably larger than the free state flatness, and certainly larger than the Sori.

Some studies around Sori measurement have also highlighted the errors introduced when using a three-point mount for measuring silicon wafers. In one case, supports positioned incorrectly by 2 mm caused 10 um of error in the Sori measurement.[3]

Challenges discussed above are highlighted in industry standards that discuss methods for measuring warp and TTV for silicon wafers.[4,5] Among the limitations listed are:

- If there are substantial differences in diaeter, thickness, fiducials, or crystal orientation from that used for gravitation compensation procedure, the results may be incorrect.
- Different methods of implementing gravitional compensation give different results.
- Different geometric configurations of wafer holding (e.g. three-point, four-point, ring support, etc.) will yield different results.
- The quantity of data points and their spacing may affect the measurement results. Results obtained with different data point spacing using the same tests may be different.
- TTV and warp are determined using partial scan patterns; thus, the entire surface is not sampled and use of another scan pattern may not yield the same results.
- Certain test methods do not completely separate TTV from warp.
- Running probes off the test specimen during the scan sequence gives false readings.

A New Method for Wafer Characterization

A new interferometric measurement technique has been developed to overcome the limitations described above.1 The FlatMaster® MSP-300 (Multi-Surface Profiler) System (see Figure 2) is based on a new frequency scanning technology. This system has a field of view of >305 mm and measures absolute height, flatness and parallelism of multiple surfaces. It is well-suited to quickly (~ 1 minute total measurement time) characterize wafer flatness (warp, bow) of silicon and glass wafers with vertical accuracy of < 1 um. The system utilizes a 2k x 2k camera, which gives sub-millimeter lateral resolution in wafer characterization. Each pixel of the camera represents a point of direct measurement on the wafer – means that on a 300 mm diameter wafers there is on the order of 3 million actual direct measured data points. Contrast this to current methods which are frequently hundreds or maybe a few thousand points, with extensive interpolation, which means much of the wafer remains uncharacterized. For glass wafers (transparent at operating wavelength) the FlatMaster® MSP-300 enables simultaneous measurement of flatness, thickness, and TTV. The system provides the ability to characterize up to 1 mm of bow with micron level accuracy. Thickness and TTV accuracy are < 1 um and < 0.1 um respectively. This production worthy system has several units already installed.

This interferometer design is based on a novel frequency-stepping laser that is tunable over 30 nm. Conventional tunable lasers provide continuous tuning over a range of wavelengths without any mode transitions. An interferometric image is collected at consecutive laser mode frequencies making it very easy to perform Fourier transforms. The modulation frequency of the interference on each pixel is directly proportional to the optical path difference between the reference and test arms of the interferometer as well as the laser mode spacing. The inherent stability of the frequency stepping laser results in a very accurate conversion from the modulation frequency of the pixel to its optical path difference (OPD). A Fourier transform is performed on each pixel to determine the height difference between the reference and measurement arms independent of its neighboring pixels. The laser mode spacing combined with conventional phase measuring interferomer (PMI) techniques give the ability to achieve sub-nanometer resolution. This technique can be applied to both rough and smooth parts making it possible to perform metrology on 300 mm glass and silicon wafers to measure flatness, thickness, and TTV..

Figure 2. Picture of the FlatMaster® MSP-300 interferometer

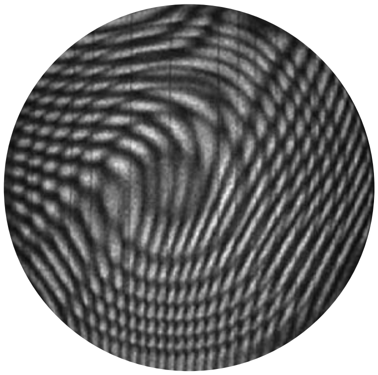
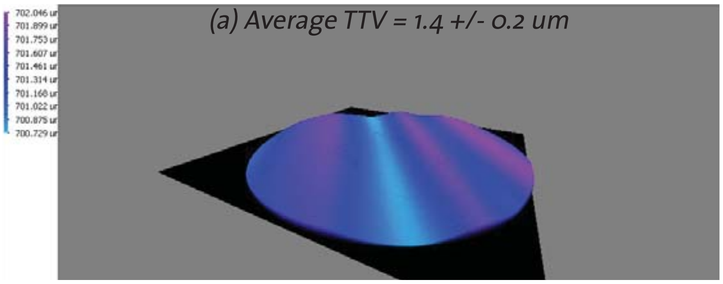


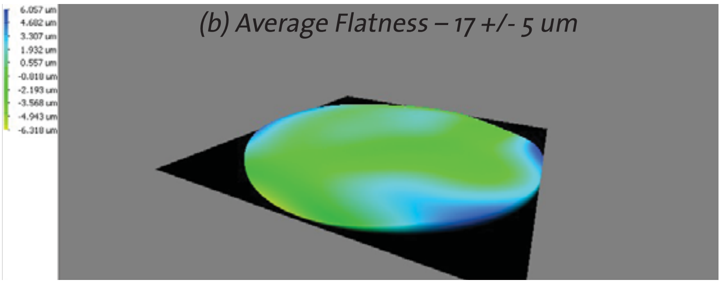
Figure 3. Interferogram of a 300 mm glass wafer. The interferogram shows interference fringes for both flatness and TTV.

Figure 3 shows the interference fringes from a glass wafer being measured on the FlatMaster® MSP-300. Note that the interferogram consists of fringes due to both variations in flatness and TTV. The software used in the FlatMaster® MSP-300 can separate these fringes and allow for simultaneous characterization of flatness (bow, warp) and TTV. Figure 4 shows typical output maps of the TTV (1.4 +/- 0.2 um) and flatness (1.4 +/- 0.2 um) from a glass wafer (error represents 1 standard deviation). The high data density gives substantially more data fidelity as compared with scan based techniques typically used today.

The method of support used in the FlatMaster® MSP-300 is a series of very thin wires as shown schematically in Figure 5. Notice the faint vertical lines seen in the interferogram in Figure 3. This level of support prevents the large gravitational deflections given by more traditional techniques discussed above. Finite element models show that the same wafer (300 mm diameter, 0.7 mm thick) that gives 100's of um of deflection using three-point or four-point mounts discussed above, would have < 1 um of deflection due to gravity effects. This means that flatness measurements would be insignificantly affected by gravitational effects.



(a) Average TTV = 1.4 +/- 0.2 um



(b) Average Flatness – 17 +/- 5 um

Figure 4. Data maps showing (a) TTV (~1.4 um) and (b) flatness (~17 um) of a glass wafer with sub-millimeter lateral resolution.

Results

A series of tests were done to evaluate the ability of the FlatMaster® MSP-300 to characterize glass wafers. The first test was to evaluate the repeatability of the wire support mount relative to the three-point mount. For this test the three-point mount was placed at a location at ~60% of the wafer radius to minimize the total deflection (assuming minimal variation at minimum sag). Figure 6a shows a glass wafer being measured on the FlatMaster® MSP-300 using the three-point mount support and Figure 6b shows a wafer mounted on the wire support.

A test was then done where the same wafer was measured 10 times using both mounting methods. The bow and warp for each mounting method is given in Figure 7. It is clearly seen that not only does the wire support substantially reduce warp and bow induced by gravity, the variation in measured warp and bow is much higher for the three-point mount. Given that the measurement system was identical in each case, this increased variation can be attributed to non-repeatability from the mounting strategy. Figure 8 shows the thickness and TTV results from this test. Note first that the wire support method gives thickness repeatability better than 0.03 um and TTV repeatability < 0.003 um. The relatively large sag given by the three-point mounting method degrades repeatability of thickness and TTV measurements, but it is still quite good at 0.1 um and 0.01 um respectively.

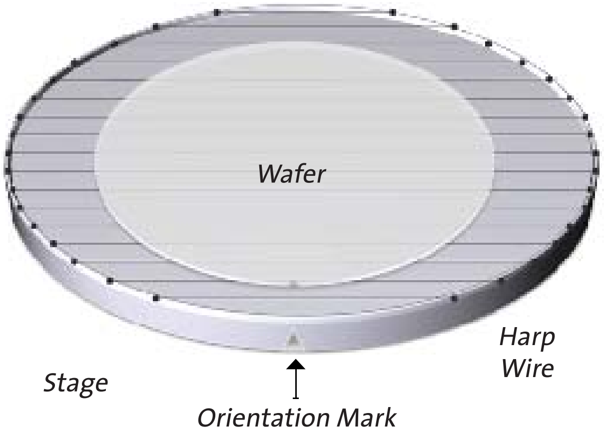


Figure 5. Schematic Showing wire support methodology to support wafers in the FlatMaster® MSP-300

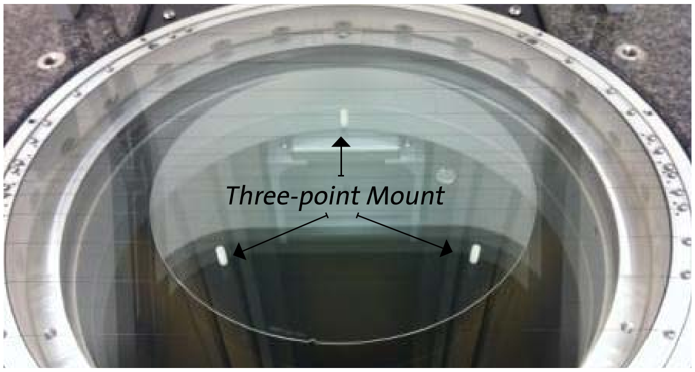


Figure 6a. Glass wafer on FlatMaster® MSP-300 using a three-point mount

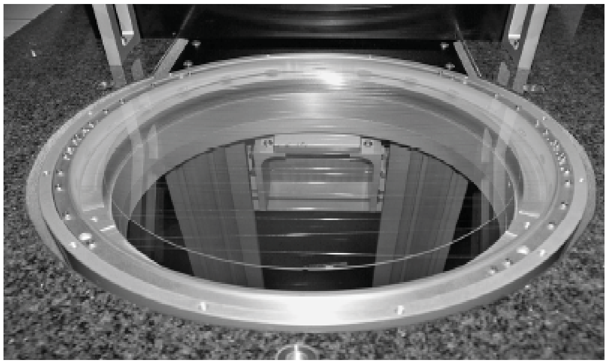


Figure 6b. Glass wafer on FlatMaster® MSP-300 on wire support

Commercially available FlatMaster® MSP-300 tools operate at visible wavelengths. It is possible to outfit the system using light sources and cameras that operate in the infrared, where silicon is transparent. A FlatMaster® MSP-300 system was modified to enable characterization of a silicon wafer that had been mounted to a glass carrier and thinned. Figure 9 shows the interferogram of this wafer and Figure 10 shows the resulting TTV map. The error in the TTV map after thinning was ~0.75 um. The high lateral resolution of the camera gives high density data that even allows you to see the grinding marks in the silicon, giving the possibility for substantial process knowledge to be gathered.

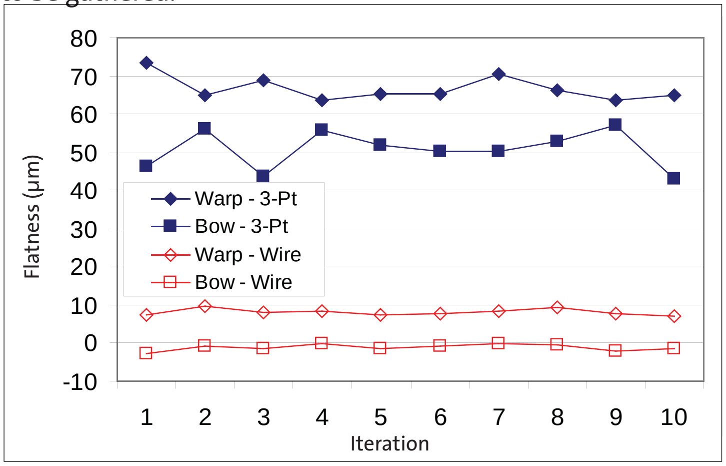


Figure 7. Resulting warp and bow for wire support and three-point support methods.

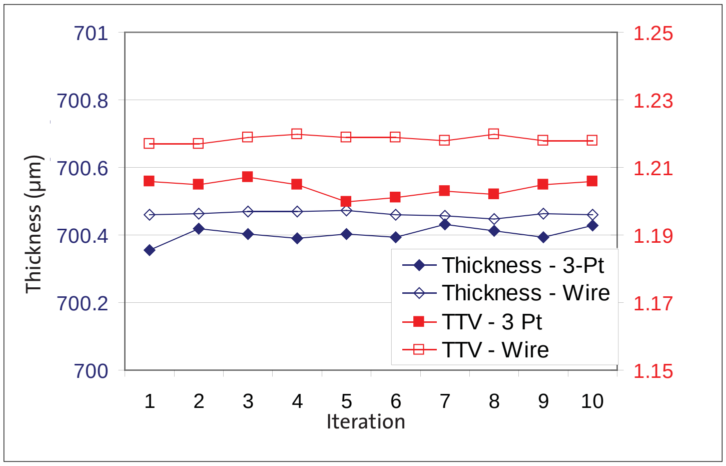


Figure 8. Resulting average thickness and TTV as measured by wire support and three-point support methods.

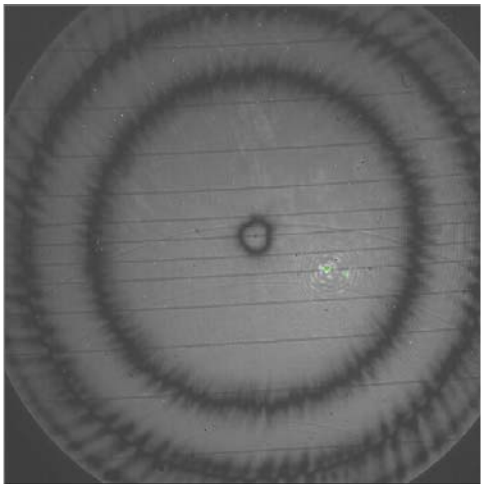


Figure 9. Interferogram of a thinned silicon wafer characterized using a FlatMaster® MSP-300 in the infrared regime.

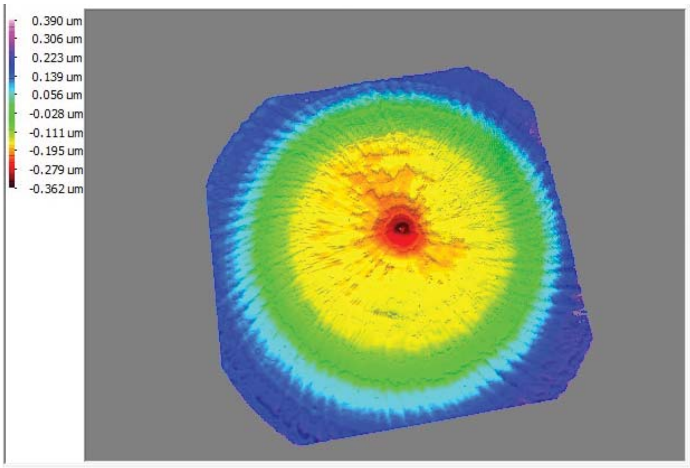


Figure 10. Data from characterizing a thinned silicon wafer using showing ~ 0.75 um deviation, and grinding marks are clearly seen.

Conclusions

As the diameter of semiconductor wafers continues to increase, gravity induced deformation becomes important. Traditionally used metrology tools and mounting strategies to characterize a wafer with such low stiffness can lead to large source of error in measurements. Furthermore, glass is becoming an important material for substrates in semiconductor applications, making metrology tools developed for use for characterizing silicon less suitable for the overall need to characterize semiconductor wafers to high precision. Gravity compensation of 300 mm diameter wafers is documented in this paper unsuitable for today's tightest wafer specs of 1.0 µm TTV and 20 µm of warp. Using novel mounting strategies and measurement technique based on interferometry provides significant improvements on the methodologies utilized to characterize wafer flatness (warp, bow) and TTV today. Not only can the accuracy of the measurement be improved, using an interference based technique allows for full wafer characterization with spatial resolution better than 1 mm, providing complete wafer characterization. Extending the tool to work in infrared wavelengths would provide even more benefits for characterization of silicon wafers.

Acknowledgements

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