Interferometric Thickness Calibration of 300 mm Silicon Wafers

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Abstract: The “Improved Infrared Interferometer” (IR^3) at the National Institute of Standards and Technology (NIST) is a phase-measuring interferometer, operating at a wavelength of 1550 nm, which is being developed for measuring the thickness and thickness variation of low-doped silicon wafers with diameters up to 300 mm. The purpose of the interferometer is to produce calibrated silicon wafers, with a certified measurement uncertainty, which can be used as reference wafers by wafer manufacturers and metrology tool manufacturers. We give an overview of the design of the interferometer and discuss its application to wafer thickness measurements. The conversion of optical thickness, as measured by the interferometer, to the wafer thickness requires knowledge of the refractive index of the material of the wafer. We describe a method for measuring the refractive index which is then used to establish absolute thickness and thickness variation maps for the wafer.

Keywords: 300 mm silicon wafers, wafer thickness, wafer thickness variation (TTV), Inteferometry, Infrared interferometer

INTRODUCTION

The International Technology Roadmap for Semiconductors (ITRS) [1] projects an exposure site flatness requirement of $\leq$ 51 nm and a nanotopography requirement of $\leq$ 13 nm by 2010. Nanotopography is the component of flatness error with spatial frequencies smaller than 0.05mm^{-1}. These stringent requirements for wafer flatness at the exposure site are imposed by the physics of the photolithography process. For diffraction limited exposure objectives, the smallest achievable linewidth, *L,* is determined by the exposure wavelength and numerical aperture, *NA,* of the objective:

$$L = k_1 \frac{\lambda}{NA}. \tag{1}$$

k_1 is a lithography process dependent factor which depends, for example, on properties of the resist. Creating smaller integrated circuit features compels moving to shorter wavelengths and larger numerical apertures. When the depth of focus,

$$D = k_2 \frac{\lambda}{NA^2}, \tag{2}$$

is reduced, this - in turn - limits the allowable flatness variation at the exposure site. Again, k_2 is a process dependent factor. The tight limits on flatness and nanotopography create new challenges at two stages of the integrated circuit (IC) manufacturing process. Wafer manufacturers must improve the polishing processes to meet the requirements for wafer flatness and nanotopography. Manufactures of wafer testing equipment need tools which allow measurement of flatness and nanotopography with sufficient accuracy and spatial resolution. Optical tools are beginning to replace wafer flatness metrology tools based on capacitance gages or airflow gages. Our research addresses the needs of both wafer manufacturers and wafer testing equipment manufacturers for 300 mm silicon reference wafers with a calibrated thickness and thickness variation, which are measured with low uncertainty, and can be used for calibration and validation purposes.

In the following sections we will describe the “Improved Infrared Interferometer” (IR^3) of the National Institute of Standards and Technology (NIST). IR^3 was developed to measure the thickness and thickness variation of low-doped silicon wafers with diameters up to 300 mm.

THE IR^3 INTERFEROMETER

Undoped silicon is transparent to light at wavelengths larger than approximately 1100 nm. The thickness and thickness variation of wafers made from silicon, or other infrared optical materials, can be characterized using the well established methods of optical interferometry, which achieve very low measurement uncertainties. NIST’s IR^3 interferometer is a multi-configuration interferometer that can be used as a Twyman-Green interferometer, a

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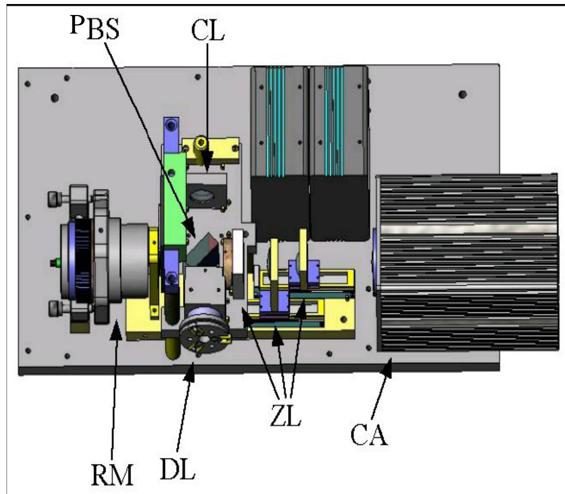

Figure 1. NIST Improved Infrared Interferometer (IR^3). The main components of the interferometer are: collimator lens (CL), polarizing beam splitter (PBS), phase-shifting reference mirror mount (RM) for the Twyman-Green configuration, diverger lens (DL), zoom lens system (ZL), and camera (CA). The footprint of the interferometer is 250 mm x 410 mm.

Figure 2: Test end of the IR^3 setup for thickness variation measurements of 300 mm wafers. Shown are the collimator lens together with a silicon wafer and a return flat.

Fizeau interferometer, or a Haidinger interferometer. Precursors to the current instrument have been described by Parks *et al.* [2] and Schmitz *et al.* [3]. Figure 1 shows a solid model of the interferometer. Light from a tunable external cavity diode laser is delivered to the interferometer through a polarization-maintaining fiber. The interferometer operates at a wavelength of 1550 nm. At this wavelength, which is within the C-band of fiber-optics communication, laser sources are readily available. The plane of polarization is inclined by 45° with respect to the plane of the interferometer. After collimation by a lens (CL) a polarizing beam splitter (PBS) creates two beams with orthogonal polarization, one traveling to the diverger lens (DL), the other to the reference mirror (RM) for the Twyman-Green configuration. Both beams are circularly polarized by precision λ/4-plates. For measurements of 300 mm wafers, the test beam must be expanded. This is accomplished with an f/3 diverger objective (DL) and the large collimator lens shown in Figure 2. A zoom lens system (ZL) images the wafer under test on the camera (CA). Commercial phase-shifting software is used to make phase measurements either by shifting the wavelength of the laser or by electro-mechanical shifting of the reference mount. The polarization optics of the interferometer prevent unwanted coherent reflections from reaching the camera and thus eliminates “ghost fringes”.

MEASUREMENT SETUPS

IR^3 is a flexible tool, which is configurable in several ways. Figure 3 indicates two of its configurations, the Fizeau (A) and Tywman-Green (B) configurations. Either can be used for measuring the thickness variation of wafers.

In the Fizeau configuration the interferometer test beam is expanded to 300 mm by the collimator lens. The wafer itself becomes the Fizeau cavity of the interferometer. Reflected light from both wafer surfaces returns to the interferometer’s camera where interferograms are measured. The laser wavelength is varied to implement phase shifting interferometry, and the resulting height maps directly represent the optical thickness variation of the test wafer. To obtain the physical thickness variation of the wafer this must be divided by the refractive index of the wafer material. The Fizeau configuration has many advantages for thickness variation measurements. The interferometer cavity is a solid and is unaffected by vibration and turbulence is absent. In addition, the coherence length of the laser source can be reduced because the distance between the wafer surfaces is small. This completely eliminates coherent reflections from optical

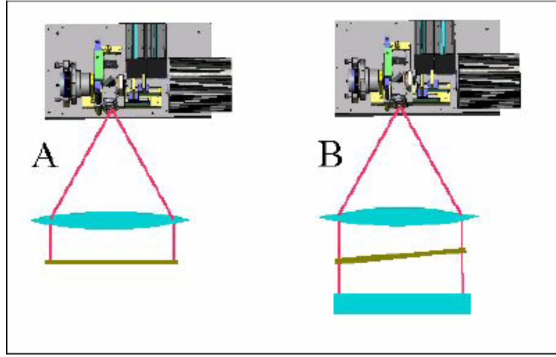

Figure 3. Two configurations of the IR3 interferometer for wafer thickness variation measurements. A is a Fizeau configuration with the wafer as interferometer cavity, B is a Twyman-Green configuration.

surfaces in the interferometer which otherwise lead to measurement errors.

Sometimes measurements cannot be made in Fizeau mode, for example when a wafer is not polished on both sides or if the free spectral range of the wafer cavity exceeds the tuning range of the laser source. The Twyman-Green setup B, shown in Figure 3, must then be used. The wafer is tilted slightly to prevent the light reflected by the wafer surfaces from returning to the interferometer. Instead, the test beam, after having passed through the wafer, is returned to the interferometer with a return flat after passing through the wafer a second time. Phase shifting is implemented by mechanically moving the Twyman-Green reference mirror with a piezo-electric phase shifter. Now two measurements are required, one with the wafer in the interferometer cavity and one without. The optical thickness variation Θ of the wafer is then calculated as follows:

$$\Theta = \frac{1}{2}\frac{O_e - O_w}{n_{Si} - n_{air}}, \qquad (3)$$

where O_e is the optical path difference for the empty interferometer and O_w is the optical path difference with the wafer inserted. As in the case of the Fizeau configuration, the refractive index n_{Si} must be known to determine the thickness variation. n_{air} is the refractive index of air which is about 1.00027 for normal laboratory conditions at 1550 nm.

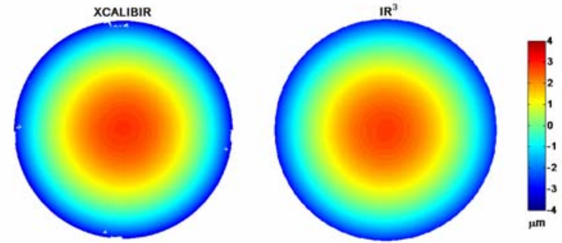

Figure 4. Thickness variation of a 300 mm diameter, 2 mm thick fused silica wafer measured with NIST's XCALIBIR interferometer at 633 nm (left) and with the IR^3 interferometer at 1550 nm (right).

TEST MEASUREMENTS

To validate the performance of the IR^3 interferometer we measured the thickness variation of a 300 mm diameter, 2 mm thick fused silica wafer with IR^3 and compared the results with thickness variation measurements made with NIST's XCALIBIR interferometer which is a 300 mm aperture, phase-shifting Fizeau interferometer working at a wavelength of 633 nm. Fused Silica is a stable and well-characterized material that is transparent at 633 nm and at 1550 nm. For the XCALIBIR measurement, a Fizeau cavity was set up with two 300 mm diameter reference flats and the empty cavity was measured. Then the silica wafer was inserted into the cavity and another measurement was made. The thickness variation was calculated from these two measurements in the manner described in the previous section and Equation 3. In IR^3 the same silica wafer was measured in Fizeau configuration with wavelength phase-shifting. For the determination of the physical thickness variation of the wafer the measurement of the refractive index of fused silica by Malitson [4] was used. Both measurements of the thickness variation of the fused silica wafer are shown in Figure 4 side by side. A careful comparison of the measurements shows essentially no difference between the two.

REFRACTIVE INDEX

When an interferometer is used to measure thickness and thickness variation of a wafer, an additional measurement of the refractive index of the wafer material must be made to determine the physical thickness of the wafer. In this section, we describe a method for measuring the refractive index of the wafer material using the

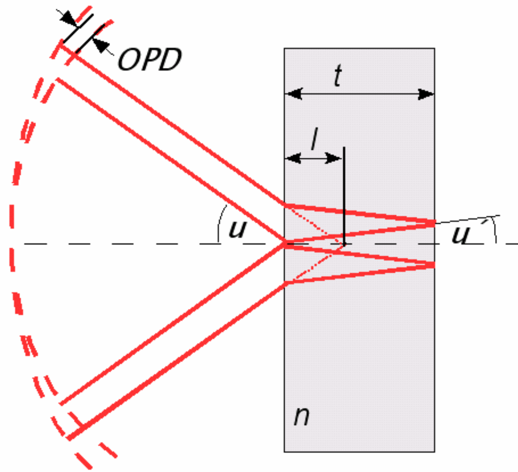

Figure 5. Reflection of the converging light cone with half cone angle u from the diverger objective by a wafer near the focus.

IR[3] interferometer. Parks *et al.* [2] have described a Haidinger interferometer for thickness variation measurements of wafers in a diverging beam. We use a variant of this method to measure the refractive index of the wafer material at one point of the wafer. The wafer is placed into the interferometer at the focus of the diverger lens as shown in Figure 5. Figure 6 shows the fringes, and the resulting height map, that are seen when a silicon wafer is placed in the interferometer. No additional optics is needed for the measurement. Light from the wafer front surface is reflected back into the interferometer. This is the reference beam. The beam passing through the wafer is reflected back into the interferometer by the wafer's back surface. The optical path difference (OPD) between the two wavefronts at the margin of the light cone is given by [5]:

$$OPD = \frac{1}{2} l \sin^2 u \ , \qquad (4)$$

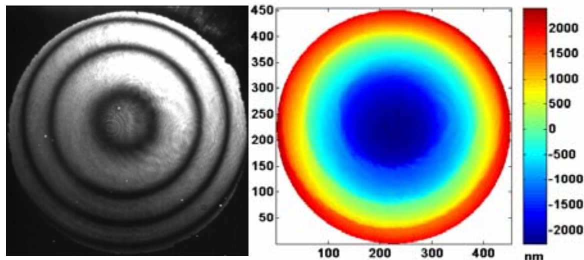

Figure 6. Interferogram and height map for a wafer inserted near the focus of the diverger objective.

where l is the focus separation of the reference and test light cones, which is given by:

$$l = \frac{2t \tan u'}{\tan u} \ . \qquad (5)$$

u is the half angle of the light cone created by the diverger objective and u' is the half angle of the refracted light cone inside the wafer. These two angles are related by Snell's Law:

$$\sin u' = \frac{\sin u}{n_{si}} \ . \qquad (6)$$

It follows from Equations 4 to 6 that the refractive index of the wafer material can be calculated once the OPD for the marginal ray, angle *u*, and wafer thickness *t* are known. To confirm this method yields accurate results for the refractive index, we have measured the refractive index of the fused silica wafer mentioned in the previous section because the refractive index of fused silica is well known ([4]). For the measurement of the half angle of the light cone made by the diverger objective an f/3 return sphere with a radius of about 1m was set up confocal with the diverger. The return sphere was then moved a small distance, *l,* and the resulting defocus was measured with the interferometer. A light cone half angle of 8.115(6)° was calculated using Equation 4[1]. Next, the fused silica wafer was placed in the interferometer near the focus, the resulting height map was measured with the interferometer, and the Zernike coefficient a_{20} (focus shift, or power) for this map was calculated. Its value was 28.283(1) µm. The physical thickness of the wafer at the same location was determined with a mechanical contact measurement and found to be 2062(1) µm. Using Equations 4 to 6 one can calculate the refractive index of fused silica, which is 1.442(3) at 1550 nm. This is in good agreement with Malitson's value of 1.444 [4].

WAFER THICKNESS VARIATION

The thickness calibration of a silicon wafer is a two-step process. First, the refractive index of the wafer material is measured at one (or more) locations of the wafer with the procedure outlined above. For these measurements the

[1] Combined standard uncertainties in the least significant digit of a value are stated in brackets.

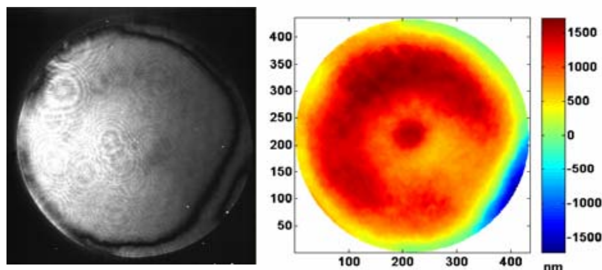

Figure 7. Interferogram and optical thickness variation of a 300mm diameter silicon wafer. The height unit is nm and the x and y coordinates are pixel numbers.

silicon wafer was placed in the interferometer so that the diverger objective focus illuminates a small area about 10 mm from the wafer notch in the radial direction. Figure 6 shows the interference fringes and the resulting height map. The OPD of the meridional ray was determined by measuring the "focus shift" Zernike term of the height map in Figure 6 with phase-shifting interferometry. The thickness at the illuminated point of the wafer was measured with an electro-mechanical indicator and it is 770(1) µm. Using Equations 4 to 6 it follows the refractive index of the wafer material is 3.471(8) at 1550 nm. The refractive index measurement was repeated at the center of the wafer to detect any radial changes in the refractive index. The refractive index at the wafer center is 3.492(8). These values are in good agreement with those reported by Primak [6] and Villa [7]. We observed a statistically significant difference between the index at the center and at the periphery of the wafer which warrants further investigation. The optical thickness variation of the wafer is depicted in Figure 7, and Figure 8 represents the physical thickness variation of this low-doped 300 mm double-side polished silicon wafer. The repeatability of the measurements is 5 nm peak-to-valley. The physical thickness variation of the wafer is within 1000 nm peak-to-valley. It is clear, this variation in physical thickness cannot be due to a change in refractive index of the magnitude we measured. A reduction of the uncertainty of the refractive index measurement will be necessary before we can determine with certitude which fraction of the optical thickness variation is due to index variation and which is caused by physical thickness variation.

CONCLUSION

Measurements with the "Improved Infrared Interferometer" (IR^3) of the National Institute of Standards and Technology (NIST) show that the interferometer is a promising tool for the thickness characterization of 300 mm silicon wafers with total thickness variation below 1µm.

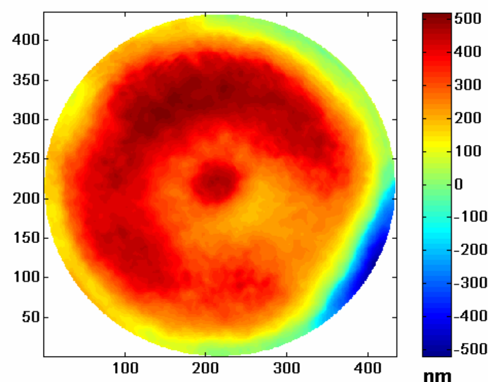

Figure 8. Physical thickness variation map of a 300mm diameter silicon wafer. The height unit is nm and the x and y coordinates are pixel numbers.

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REFERENCES

1. The International Technology Roadmap for Semiconductors 2004 (*http://public.itrs.net*), Section "Front end processes", Table 69a;
2. R. E. Parks, L.-Z. Shao, A. Davies, and C. J. Evans, "Haidinger interferometer for silicon wafer TTV measurements" in *Metrology, Inspection, and Process Control for Microlithography XV, Proc. SPIE* **4344**, 496-505 (2001)
3. T. L. Schmitz, A. Davies, C. J. Evans, and R. E. Parks, "Silicon wafer thickness variation measurements using the National Institute of Standards and Technology infrared interferometer", *Opt. Eng.* **42**, 2281-90 (2003)
4. I. H. Malitson, "Interspecimen comparison of the refractive index of fused silica", J. Opt. Soc. Am. **55**, 1205-1209 (1965)
5. W. J. Smith, "Modern Optical Engineering", 2nd edition, p. 328, McGraw Hill (1990)
6. W. Primak, "Refractive Index of Silicon", App. Opt. **10**, 759-763 (1971)
7. J. J. Villa, "Additional data on the refractive index of silicon", App. Opt. **11**, 2102-2103 (1972)