Measurement of Step Height by Traceable Interference Microscope

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Abstract. A Traceable Interference Microscope (TIM) to calibrate the step height standards is presented. The construction of the TIM includes an interference microscope, a stabilized He-Ne laser, and a rotated ground glass. The instrument’s original white light source is replaced by the stabilized laser through an optical fiber. The step height is measured by calculating the phase difference of two fringe patterns both on the upper and lower surfaces of the specimen. A new methodology called Double-Tilt Imaging (DTI) method is proposed to determine the Numerical Aperture Correction Factor (NACF). The wavelength of the light source and the difference both in angles and in spatial frequencies between the positive and negative tilts would reveal sufficient information to allow for the determination of the NACF directly. The light source used is a stabilized He-Ne laser traceable to the definition of the meter and the angle measurement to the angle standards by an autocollimator. The calculation of the aperture correction factor for the interference microscope with a 10X Mirau-type objective lens yields a traceable average value of 1.01936 with a relative standard uncertainty of about 5.74×10^{-4}. The expanded uncertainty of this step height calibration system is determined to be approximately 3 nm.

1. Introduction

Surface topography of small features on MEMS devices or semiconductor chips is usually measured by profilers with high vertical and lateral resolutions. The measurements of the surface topography are performed by instruments with the stylus method [1], scanning probe microscopes [2], or optical methods such as confocal or interference microscopes. For determining the accuracy of these instruments, step height standards are popular artifacts for vertical scale calibrations [3].

An Interference Microscope (IM), as an instrument to measure the step height, is a powerful tool with high sensitivity and vertical resolution of below 1 nm because of its non-contact and non-destructive advantages. This paper describes the development of a Traceable Interference Microscope (TIM) to calibrate the step height standards at National Measurement Laboratory (NML) in Taiwan. The TIM was built based on a commercial interference microscope with a stabilized laser as the replacement to the originally-equipped white light source. Due to light focus by objective lens of the interference microscope, the optical path projected onto and reflected from the sample surface are not equal to twice of the difference in height. A correction factor for the numerical aperture should be considered to amend the value [4]. Conventionally, the determination of the correction factor could rely on derivations from approximation equations or numerical computation against predetermined specifications of standard specimens. Nevertheless, neither method could practically suffice the
establishment of measurement traceability for the values under investigation. A Double-Tilt Imaging (DTI) method is developed for determining this correction factor with direct traceability [5]. According to the ISO “Guide to the expression of the uncertainty in measurement”, the combined standard uncertainty of a nominal height value of 329 nm for the Traceable Interference Microscope is 3 nm with 63 effective degree of freedoms.

2. Traceable Interference Microscope and Step Height Measurement

Figure 1 shows the traceability of the step height standards. Users usually calibrate the displacement sensors periodically by utilizing step height standards for stylus instruments, scanning probe microscopes, or interference microscopes. The step height standards can be calibrated by the TIM with stabilized laser source traced to the length standards. Based on the DTI method to determine the Numerical Aperture Correction Factor (NACF), two tilted angles are measured by an autocollimator, which is calibrated by the angular standards and traced to the circle closure principle.

Figure 2 illustrates the construction of the TIM which includes an interference microscope, a stabilized He-Ne laser, and a rotated ground glass. The light passes through the ground glass before entering the fiber to eliminate the spackle noise. The lenses expand the light spot size and the Mirau-type objective lens focuses the light on the sample surface. The reflected light coming from the sample interferes with the reflected light from the reference mirror inside the objective lens. Subsequently, high-resolution CCD cameras are used to detect the light intensity of the interference pattern and to transfer the image to the computer.

The step height defined in ISO 5436-1 [6]. The definition is shown in Figure 3. A line or plane is drawn to be parallel with A and B portions of upper surface and another line is drawn for C portion of lower surface. Both of lines have to be fitted by the least-square algorithm. The height value is calculated based on the average distance between the two lines. An example of the step height interference image is shown in Figure 4. The dash lines, representing the edges of the upper and lower surfaces, are determined by image analysis software. From the phase difference of two fringe patterns both on the upper and lower surfaces of the
specimen, the step height value could thus be determined. The height value of the standards would be calculated and traced to the definition of the meter via the stabilized laser source.

Figure 5 reveals the relationship between the spatial wavelength $L$ (or pitch) of the interference fringes and the height difference. When the incident light is perpendicular to the sample surface, the height difference of a single fringe interval is $\lambda/2$, where $\lambda$ is the light wavelength. Due to the effect of focus by objective lens, the height difference has to be corrected by multiplying a factor $k$, which is the NACF. Thus, the inclined angle $\theta$ is expressed by the trigonometric function as:

$$\bar{\theta} = \tan^{-1} \left( \frac{k \cdot \lambda/2}{L} \right) \equiv \frac{k \cdot \lambda/2}{L}$$

To easily determine the angle, relative angle measurement is designed as opposed to absolute angle measurement. Using the proposed method, the flat surface is measured twice at different inclined angles ($\theta_1$ and $\theta_2$). Simultaneously, two spatial frequencies ($\omega_1$ and $\omega_2$) of the fringe patterns are also calculated. The spatial wavelengths are $L_1 = 2\pi/\omega_1$ and $L_2 = 2\pi/\omega_2$. Thus,

$$\theta_1 \approx \frac{k \cdot \lambda/2}{L_1} = \frac{k \cdot \lambda \cdot \omega_1}{4\pi}, \quad \theta_2 \approx \frac{k \cdot \lambda \cdot \omega_2}{4\pi}$$

Assuming that $\theta = \theta_1 + \theta_2$ and $\omega = \omega_1 + \omega_2$, the correction factor is obtained as:

$$k = \frac{4\pi \cdot \theta}{\lambda \cdot \omega}$$

Here the values of $\theta$ and $\lambda$ must be traced to the angle standards and the definition of the meter respectively, and $\omega$ can be obtained by the sine curve fitting algorithm [7] after the view field of CCD image is calibrated by the line-scale standards.

3. Results and Uncertainty Evaluation

According to the expression of measurement uncertainty defined in ISO GUM [8], the mathematic model of measurement uncertainty for step height measurement would be listed as:

$$Y_c = \left[1 + \alpha \cdot (20 - t_d)\right] \frac{\lambda}{2} (i + \xi) \cdot k$$

In this equation, $Y_c$ is the measurement value. $\lambda$, $t_d$ and $\alpha$ represent the wavelength, the temperature during calibration and the thermal expansion coefficient, respectively. Whereas, $i$, the integer part of the optical path difference divided by $\lambda/2$, would be decided by the nominal size or closed size of the step height. Lastly, $\xi$ is the fraction part of the optical path difference divided by $\lambda/2$.

Table 1 lists the uncertainty budge of NACF for the 10X objective lens. The measurement of NACF is affected by the laser wavelength, angles and spatial frequencies, etc. The calculation of NACF for the TIM with a 10X Mirau-type objective lens yields a traceable average value of 1.01936 with a relative standard uncertainty of about 5.74×10^{-4}. Table 2 lists the uncertainty budge of the TIM. The combined standard uncertainty is approximately 3 nm and the effective degree of freedom obtained by the Welch-Satterthwatte formula is determined to be 63.
Table 1. Uncertainty budget of NACF

| Quantity | Estimate | Type | Distr. | Std. Uncertainty | Rel. Std. Unc. | k |
|----------|----------|------|--------|-----------------|---------------|---|
| \( \theta \) | 1600° | - | - | 0.11° | 6.9\times10^{-3} | 115 |
| \( \theta_1 \) | | | | | | |
| \( \theta_2 \) | | | | | | |
| \( \theta_3 \) | | | | | | |
| \( \Delta R \) | | | | | | |
| \( \Delta i \) | | | | | | |
| \( \Delta \mu \) | | | | | | |

Table 2. Uncertainty budget of TIM

| Quantity | Estimate | Standard uncertainty (x) | Sensitivity coefficient (ci) | Uncertainty contribution | Degree of freedom |
|----------|----------|--------------------------|----------------------------|--------------------------|------------------|
| \( \lambda \) | 632.82 nm | 0.01 nm | \( \frac{D}{632.82}\times10^{10} \) | 1.6\times10^{-7} nm | 50 |
| \( i \) | integer | 0 | \( \frac{63282\times0.001936}{2} \) nm | 0 nm | \( \infty \) |
| \( \zeta \) | = 1 | \[0.0641]^{2} + [0.009\Delta \lambda]^{2} \] | \( \frac{63282\times0.001936}{2} \) nm | \[0.45]^{2} + [0.029\Delta \lambda]^{2} \] nm | 31 |
| \( k \) | 1.01936 | 5.85\times10^{-1} | \( \frac{D}{1.01936} \) \times10^{-1} | 0.574 \times D mm | 61 |
| \( \Delta \mu \) | 20 °C | 0.173 °C | \(-2.55\times10^{-2} \Delta \mu \) | 4.4\times10^{-2} \Delta \mu \) mm | 12.5 |

4. Conclusion

A TIM was constructed for height measurement in nanometer-scale. The measurement system consists of an IM with a stabilized laser and a rotated ground glass. For the determination of NACF with viable traceability, the DTI method was applied. The combined standard uncertainty was 3 nm for a sample with a nominal height value of 329 nm. Further investigations include developing an aperture-less IM and extending the measurement range to 100 μm.

References

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