Measuring of the maximum measurable velocity for dual-frequency laser interferometer

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There is an increasing demand on the measurable velocity of laser interferometer in manufacturing technologies. The maximum measurable velocity is limited by frequency difference of laser source, optical configuration, and electronics bandwidth. An experimental setup based on free falling movement has been demonstrated to measure the maximum measurable velocity for interferometers. Measurement results show that the maximum measurable velocity is less than its theoretical value. Moreover, the effect of kinds of factors upon the measurement results is analyzed, and the results can offer a reference for industrial applications.

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Dual-frequency laser interferometers have advantages of high resolution, high speed, long range capability, multi-axis measurement and so on. So they are widely used in the advanced manufacturing and the fast growing nanometer techniques, such as real-time position control systems in the step-and-scan photolithography tools for manufacturing integrated circuits. Laser interferometers have been incorporated into such manufacturing equipments as lithographic systems, precision cutting machines, and precision measuring machines[1−4]. This has led to the production of higher density integrated circuits, precision mechanical components. In the semiconductor industry, the technique for measuring smaller features with faster throughput time is required as the circuit integration becomes denser and the wafer size becomes larger. The need for a high measurement velocity is a result of the increasing throughput requirements of these systems[5,6].

In the step-and-scan photolithography systems, the measured objects, such as wafer stage and reticle stage, move fast. Moreover, the measurable velocity of objects is always variable. For example in the photolithography systems, the wafer stage and reticle stage scan along y-axis and step along x-axis at one time (see Fig. 1), and the velocities of wafer stage and reticle stage are variable constantly, as shown in Fig. 2. This requires that the measurable velocity of interferometer can keep up with the increasing requirements of these stages.

Maximum measurable velocity is an important performance for a high speed measurement system with high precision. The maximum measurable velocity of dual-frequency laser interferometer depends on the combination of the frequency difference between the two components of the He-Ne laser beam, the optical configuration, and the electronics bandwidth. According to the theory of relativity, the Doppler frequency shift can be given as

$$\Delta F = -\frac{1-u/c}{\sqrt{1-(u/c)^2}}, \tag{1}$$

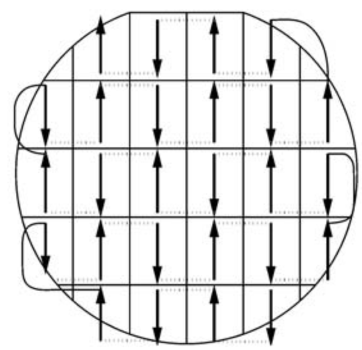

Fig. 1. Scan-and-step process for wafer manufacturing.

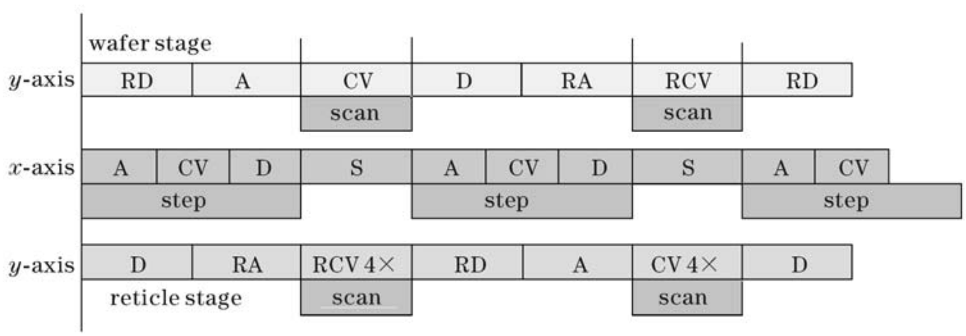

Fig. 2. Scheduling of wafer stage and reticle stage. A: accelerating; RA: reverse accelerating; D: decelerating; RD: reverse decelerating; CV: constant velocity; RCV: reverse constant velocity; S: static; CV 4×: four-fold constant velocity; RCV 4×: reverse four-fold constant velocity.

where ΔF is the Doppler frequency shift, u is the velocity of measurement object, and c is the velocity of light in vacuum. Using binomial theorem and omitting the high-order item of u/c, Eq. (1) can be expanded as

$$\Delta F = f \cdot \frac{u}{c} = \frac{u}{\lambda}, \tag{2}$$

where λ is the vacuum wavelength of measurement beam, which is 632.991354 nm typically for the dual-frequency He-Ne laser. Because the laser beam can be thrown back from the measurement object, the relative velocity v is amount to $u/2$. According to Eq. (2), the measurable velocity for a single-pass interferometer can be given as[7]

$$v = \frac{\lambda}{2}\Delta F. \tag{3}$$

The frequency received by photo-detector for dual-frequency interferometer is

$$f' = f_1 - f_2 + \Delta F = \Delta f + \Delta F, \tag{4}$$

where Δf is the frequency difference of laser source. In order to avoid the low-frequency noise, the received frequency f' must be more than zero. Therefore the value of Doppler frequency shift ΔF must be less than frequency difference of laser source Δf. So the maximum measurable velocity $V_{\max}$ can be shown as

$$v_{\max} = \frac{\lambda}{2}\Delta f. \tag{5}$$

Two different methods of generating the frequency split are used in industry: Zeeman technology and acousto-optic modulating method. The Zeeman technique produces two frequencies by applying an axial magnetic field to the laser tube. Laser sources using Zeeman technique are typically limited by a frequency difference of 3—4 MHz, which corresponds to approximately 1200 $\text{mm}\cdot\text{s}^{-1}$ with a simple-pass interferometer. The acousto-optic modulating method uses a frequency shifter, such as a Bragg cell, to produce the frequency difference. Laser sources using acousto-optic modulating method have a 20-MHz frequency difference. However, the signal processing electronics system is usually designed in a frequency range of 20 ± 13.3 MHz[6], corresponding to approximately 4200 $\text{mm}\cdot\text{s}^{-1}$ with a single-pass interferometer. It is the theoretical maximum measurable velocity. Actually, the maximum measurable velocity is limited by optical configuration and electronics bandwidth at the same time, especially the latter. In order to test actual maximum measurable velocity for an interferometer, an experimental setup based on free falling movement has been developed.

The experimental setup is shown in Fig. 3, which is separated into two parts: interferometer system and measurement system. The optical single-pass interferometer system is composed of a dual-frequency He-Ne laser, a photo-detector, a polarization beam splitter (PBS), a reference corner cube (RCC), a measurement corner cube (MCC), electronics and screen. The dual-frequency laser uses Zeeman technique to produce two frequencies and the frequency difference is about 3.4—4 MHz[8]. The measurement system consists of a mirror mount, a pin, a slide, a slippy guide, and a base. The MCC is attached on the mirror mount.

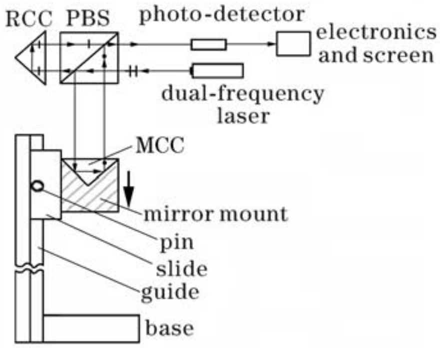

Fig. 3. Setup for measuring the maximum measurable velocity of interferometer.

The dual-frequency laser emits two orthogonal linearly polarized beams with frequencies f_1 and f_2 respectively. And the two beams are sent to the PBS, in which they are separated into the measurement beam f_1 and the reference beam f_2. The reference beam f_2 goes to RCC which is fixed with respect to the PBS and the measurement beam f_1 goes to MCC which is attached on the mobile mirror mount. When the MCC moves, the returned frequency from MCC is $(f_1 \pm \Delta f)$ due to the Doppler effect. It interferes with f_2 and is sent to the photo-detector, generating an electronic signal carrying the information of displacement. Then the electronic signal is sent to electronics system and processed. At last the displacement value of MCC is displayed on the screen. When the velocity of MCC is overrun, the displacement value of MCC can no longer be measured by interferometer system and also no longer be displayed on the screen.

The mirror mount is fixed to the slide which is assembled to the guide. The guide and the slide are both precisely machined and lubricated, moreover the guide is sternly upright to the horizontal line. The course that MCC moves along the guide can be taken for the free falling movement without considering the air resistance and friction. It is well known for a free falling body that[9]

$$v = \sqrt{2gh}, \tag{6}$$

where g is the acceleration of gravity that is little different in different places all over the world, the value of g is 9794.0 $\text{mm}\cdot\text{s}^{-2}$ in Shanghai; h is the displacement value of MCC displayed on the screen.

When the measurement began, the pin was pulled out fleetly. In this instant the MCC began to free fall, and its initial velocity was zero. The screen displayed the displacement value of MCC until the velocity of MCC was overrun. The maximum displacement value $h_{\max}$ was measured for 5 times, and the mean value $\overline{h}_{\max}$ can be calculated. According to the mean value and Eq. (6), the maximum measurable velocity $v_{\max}$ can be calculated. In our experiment, without considering the air resistance and friction, the mean value $\overline{h}_{\max}$ is 60.3584089 mm for the single-pass interferometer system, so the actual maximum measurable velocity is $v_{\max} = \sqrt{2 \times 9794.0 \times 60.3584089} = 1087.3\ \text{mm}\cdot\text{s}^{-1}$. The measurement results are shown in Table 1. The

Table 1. Results of Maximum Measurable Velocity (g = 9794.0 mm·s^{-2})

No.	1	2	3	4	Mean
$h_{\max}$ (mm)	61.0680161	61.3062401	57.9912987	61.0680807	60.3584089
$v_{\max}$ (mm·s^{-1})	1094.0	1096.3	1066.1	1093.7	1087.3

actual maximum measurable velocity is less than its theoretical value which is 1200 mm·s^{-1} mentioned above.

In repetitious measuring experiments, the measurement results are a little different from each other. The errors come from the following aspects[10]: 1) the guide is not sternly upright to the horizontal line for misalignment error; 2) the friction coefficient between the guide and the slide is not zero absolutely; 3) the air resistance cannot be ignored completely; 4) the influence of the acceleration of MCC.

In conclusion, the maximum measurable velocity of interferometers is limited by many factors, such as frequency difference of laser source, optical configuration, electronics bandwidth and so on. An experimental setup based on free falling movement has been demonstrated to measure the maximum measurable velocity for interferometers. Results show that the maximum measurable velocity is less than its theoretical value. Moreover, the measurement results of the maximum measurable velocity can offer a reference for industrial application.

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