A Laser Measurement System for Fast and Precise Positioning*

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Recently, there has been an increase in the positioning accuracy required in the production processes for ULSI. For instance, in a wafer stepper for a 4-Mbit DRAM, the required positioning accuracy is said to be more than 0.04 μm . There is also a requirement to reduce the positioning times in such processes. To meet these needs, a new laser measurement system which can accurately measure high speed displacement has been developed. When the target's speed is low, its displacement is measured by comparing the phase change of light reflected by the object with the phase modulated by an electro-optic crystal. When the target's speed is high, its displacement is measured using a fringe counting technique. The system achieves an accuracy of ± 4 nm and a maximum allowable measurement speed of 1 000 mm/s.

Key Words: Measurement, Accuracy, Sensor, Laser, Displacement, Electro-optic crystal, Phase, Modulation

1. Introduction

In the production of ULSI, accurate wafer positioning to several tens of nanometers is required. For instance, it must be ± 40 nm in the stepper for a 4-Mbit DRAM. Production accuracy depends on the accuracy of the positioning sensors, because closed-loop control is generally used in these accuracy levels. In the future, the higher the density of the ULSI, the higher the positioning accuracy will need to be. To meet these requirements, a new laser measurement system measuring displacement with high accuracy and high measurement speed has been developed.

2. The Current Status of Laser Measurement Systems

Laser measurement systems commercially available are shown in Table 1; our system is included as

the last line. These systems can be divided into two groups according to principle.

2.1 Types detecting doppler shift

As a laser beam irradiates an object to be positioned, the frequency of the reflected beam is shifted Δf by the Doppler effect in proportion to the velocity v of the object as shown in the following equation.

Table 1 Laser measurement systems

Principle	Manufacturer	Specification		Notes
		Resolution (nm)	Velocity (mm/sec)	
Doppler-shifted frequency detecting method	A	5	2 0 0	Double path
	B	1 3	9 0 0	Double path
Phase shift detecting method	C	4 0	2 0 0	Double path
	D	4 0	1 5 0	Double path
	E	4 0	6 0 0	Double path
Phase modulation method		1. 3	1 0 0 0	Single path

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$$\Delta f = \pm \frac{2}{\lambda} v \quad (1)$$

where λ is the wavelength of the laser beam.

In this system, displacement is measured by integrating the detected Δf . To obtain the Doppler shift Δf requires a laser oscillating in two frequency modes. The maximum velocity of the object $V_{\max}$, to which a sensor can respond is given by the following equation.

$$V_{\max} = \frac{\lambda}{2} \Delta F \quad (2)$$

where ΔF is the split frequency of a two-mode laser. The optical resolution of this system is $\lambda/4$.

2.2 Types detecting phase-shift of laser beam

The phase of a reflected beam changes in proportion to the displacement of an object. The relationship between the displacement D and the phase shift ϕ of a reflected beam is given by the following equation.

$$\phi = \frac{4\pi}{\lambda} D \quad (3)$$

In these types of laser measurement systems, displacement is measured by detecting the phase shift of a reflected beam. Although manufacturers use various phase detection methods, the resolution in all phase shift measurements is $\pi/2$ (rad). This corresponds to $\lambda/8$ converted into displacement. The responsiveness of the sensor is limited only by the frequency characteristic of the electrical circuits, but theoretically, no limits exist to the measuring speed of an optical system. The advantage of this type is that a laser oscillating in only one frequency mode can be used.

2.3 Comparison of types

In each type, measurement resolution is improved by both optical and electrical methods, but it is difficult to improve the resolution and the responsiveness simultaneously because resolution is inversely proportional to responsiveness.

3. Operation of the System

The newly developed sensor measures the displacement of an object by detecting a phase shift in the measurement beam using an optical interference method. High accuracy and high measurement speed are achieved by switching between two measurement modes. The switching depends on the speed of the object; i.e. when its speed is low, the movement is measured by comparing the phase change of the measurement beam with the phase modulated by an electro-optic crystal⁽¹⁾⁽²⁾. When its speed is high, the movement is measured by merely counting changes in the intensity of the interference signal between the reference beam and the measurement beam. A schematic diagram of the system is shown in Fig. 1.

In Fig. 1, a laser beam is split into a measurement beam B1 (dotted line), and a reference beam B2 (solid line), by a polarizing beam splitter (PBS). B1 is reflected by an object and B2 is reflected by a reference surface. They travel to the beam splitter (BS) and are divided into two pairs of beams; BT1 and BT2 (transmitted beams), and BR1 and BR2 (reflected beams). BT1 is perpendicular to BT2, and BR1 is perpendicular to BR2.

Fig. 1 Schematic diagram of the laser measurement system

3.1 Operation in the low-speed mode

The operational mode when the object moves slowly is called the low-speed mode. The phase difference ϕ_x immediately before the electro-optic crystal is shown in following equation:

$$\phi_x = \frac{4\pi}{\lambda}(X - l_0), \quad (4)$$

where l_0 is the optical path length from the splitting surface of the PBS to a reference surface.

X is the optical length from the splitting surface of the PBS to an object. The electro-optic crystal⁽³⁾ is a key element in the phase modulation method. Crystal 1 and crystal 2 are identical, but crystal 2 is rotated 90° around the Y -axis as illustrated in Fig. 2. The phase difference ϕ_f , between BT 1 and BT 2, grown in the crystal is shown in the equation below if the polarization direction of BT 1 matches the X -axis of the crystal and that of BT 2 matches the Z -axis.

$$\phi_f = \frac{2\pi}{\lambda}(n_e^3\gamma_{33} - n_o^3\gamma_{13})\frac{l}{d}E^{(4)}, \quad (5)$$

where n_e and n_o are refractive indexes of the crystals.

γ_{33} and γ_{13} are Pockels constants.

d is the thickness of the crystal. (2 mm)

l is the length of the crystal. (40 mm)

E is the voltage applied to the crystal.

λ is the laser wavelength.

We used lithium niobate (LiNbO₃), and each constant is shown in Table 2⁽⁴⁾.

The next equation reads the same as Eq. (5) except that these constants have been calculated.

$$\phi_f = \frac{2\pi}{\lambda}(4.68 \times 10^{-9})E, \quad (6)$$

where $\lambda = 632.8$ nm.

The voltage $E_{\lambda/2}$ (called the half-wave voltage) when $\phi_f = \pi$ (rad) and $\lambda = 632.8$ nm is shown in the following equation.

$$E_{\lambda/2} = 67.5 \text{ (V)} \quad (7)$$

Table 2 Constants of LiNbO₃

n_e	n_o	γ_{33}	γ_{13}
2.220	2.286	30.8×10^{-12} m/V	8.6×10^{-12} m/V

Fig. 2 Constitution of the E-O modulator

The AC voltage given by the following equation is applied to the crystal.

$$E = E_{\lambda/2} \sin \omega t, \quad (8)$$

where $E_{\lambda/2}$ is the voltage generating a phase difference (π rad) in the crystal.

Then the value of ϕ_f changes as follows.

$$\phi_f = \pi \sin \omega t \quad (9)$$

Therefore, the phase difference, ϕ_t , between BT 1 and BT 2, after they have passed through a crystal, is given by

$$\phi_T = \frac{4\pi}{\lambda}X - \frac{4\pi}{\lambda}l_0 + \pi \sin \omega t. \quad (10)$$

A beam through the crystal is split by BS 2 into two beams of equal intensity. One beam is guided to detector 2 through polarizer P2 and an optical fiber. The through axis of polarizer P2 is set at +45° against the page, and the intensity I_T of the interfering beam at detector 2 is given as

$$I_T = I_{T1} + I_{T2} + 2\sqrt{I_{T1}I_{T2}} \cos \omega t, \quad (11)$$

where the intensity of BT 1 at detector 2 is I_{T1} , and the intensity of BT 2 at detector 2 is I_{T2} .

Another beam is led to detector 3 through polarizer P3 and an optical fiber. The through axis of polarizer P3 is set at -45° against the page. The intensity I_T'' of the interfering beam at detector 3 is given as

$$I_T'' = I_{T1} + I_{T2} - 2\sqrt{I_{T1}I_{T2}} \cos \omega t. \quad (12)$$

Thus the output e of the differential amplifier is shown as

$$e = K(I_T' - I_T'') = 4K\sqrt{I_{T1}I_{T2}} \cos \phi_T, \quad (13)$$

where K is constant.

ϕ_x changes with object movement and ϕ_f changes cyclically, so the output e of the differential amplifier crosses the zero level when Eq. (14) is satisfied. This is called phase-compensated time.

$$\phi_T = (n + 0.5)\pi, \quad (14)$$

where $n = 0, \pm 1, \pm 2, \dots$

We can pinpoint this moment with a compensated time detector and by sampling the applied voltage to the crystal at that moment. We can then determine ϕ_f from Eq. (6) and obtain ϕ_x . The relationship of the object position X and the sampled applied voltage E at the compensated time is shown in Fig. 3.

The applied voltage increases in proportion to the displacement from X_0 and jumps at X_1 . After that, these jumping points are found to occur every $\lambda/4$ ($= 158.2$ nm) movement. When the object moves in a positive direction and jumps from $E_{\lambda/2}/2$ to $-E_{\lambda/2}/2$, the low-speed pulse generator generates positive pulses. When the object moves in a negative direction and jumps from $-E_{\lambda/2}/2$ to $E_{\lambda/2}/2$, the low-speed pulse generator generate negative pulses. At this time, the direction memory memorizes the direction of the

movement.

Displacement X from X_0 to X_a is given by the following equation.

$$X = X_a - X_0 = \frac{\lambda}{4}N + \frac{\lambda}{4E_{\lambda/2}}(E_a - E_0) \quad (15)$$

Therefore, the up-down counter counts the number N of low-mode pulses generated through the mode switching circuit, and the total displacement is given by the addition of N multiplied by $\lambda/4$ and the difference in the applied voltage translated to displacement as equation above.

3.2 Operation in the high-speed mode

When the speed of the object increases, operation in the low-speed mode becomes unstable because of electric circuit characteristics. So the system switches the operation mode from the low-speed mode to the high-speed mode automatically by sensing the velocity of the object. In the high-speed mode, this system measures the displacement using the beam reflected by BS 1 in Fig. 1.

The measurement beam BR 1 and the reference beam BR 2, reflected by BS 1, interfered with by polarizer P 1, and caught by detector 1, change in intensity each time the object moves $\lambda/4$. A pulse (high-speed pulse) is generated every time the output voltage of detector 1 changes. By counting the number of high-speed pulses through the mode switching circuit, the high-speed movement of the object is measured with a resolution of $\lambda/4$ where the direction of the movement is determined by that just before the system switched from the low-speed mode to the high-speed mode. Total displacement in the high-speed mode is given by counting the number N multiplied by $\lambda/4$. The mode switching operation is concerned with the interval T of the low-speed pulses. The mode switching circuit switches automatically from the low-speed mode to the high-speed mode at $T=20\ \mu\text{s}$ (8 mm/s translated to velocity) and from the high-speed mode to the low-speed mode at $T=40\ \mu\text{s}$ (4 mm/s translated to velocity), where the hysteresis of the switching velocities is set to avoid

Fig. 3 Relationship between position and applied voltage

mode chattering.

4. Characteristics of the System

The movement of objects is measured from the phase difference between the measurement beam and the reference beam as described in section 3. It is impossible to accurately determine the displacement at the nanometer level, so the system must be calibrated by generating optical pseudo displacement with a Babinet-Soleil Compensator (BSC) and using a different electro-optic crystal for calibration.

However, the pseudo displacement generated by the electro-optic crystal is no more than a few micrometers. Hence, three types of tests are performed:

- (1) measurement accuracy,
- (2) maximum allowable measurement speed,
- (3) mode switching.

The performance of the system is tested according to the experimental setup shown in Fig. 4.

4.1 Measurement accuracy

As shown in Fig. 4, accuracy in measuring a position is tested by generating static pseudo displacement with a BSC. This produces a pre-determined phase difference between B 1 and B 2. The retardation accuracy of the BSC, in terms of the measurement of the system, is within 0.7 nm. The results of the test are shown in Fig. 5. In this figure, the horizontal axis represents pseudo displacement, and the vertical axis represents measurement error. The maximum measurement error is ± 4 nm. Most of that is due to the retardation error of the BSC itself.

4.2 Maximum allowable measurement speed

The testing process is illustrated by Fig. 4 and Fig. 6. When the AC voltage shown in Fig. 6(a) is applied to the electro-optic crystal for calibration in Fig. 4, the intensity of the interfering light at detector 1 changes as in Fig. 6(b). This is the same as the intensity of the interfering light when the object

Fig. 4 Schematic diagram of performance test

moves as in Fig. 1.

The maximum allowable measurement speed is determined by counting the high-speed pulses during a constant interval τ with a system counter, counting with a standard counter the number of times the applied voltage crosses the zero point during the same interval and by then comparing those numbers.

The counted pulses have been compared and the counts coincide up to 3.5 MHz, corresponding to a speed of 1 100 mm/s.

4.3 Mode-switching operation

In a mode-switching circuit, one kind of pulse (high-speed or low-speed) is selected from among those generated in every $\lambda/4$ of movement. Switching these pulses at the wrong time causes double counting or the missing of pulses leading to discontinuous increments or decrements in the measurements. The new system is designed to switch its operating mode from low-speed mode to high-speed mode at a speed of 8 mm/s, and from high-speed mode to low-speed mode at a speed of 4 mm/s.

A pseudo-displacement with a peak-to-peak amplitude of 2 849 nm and a frequency of 1 kHz was fed into the system and the output was recorded in a

digital memory. The result is shown in Fig. 7. Around the maximum and minimum points, when the speed is low, the displacement is measured precisely in the low-speed mode. Around the midpoint, when the speed is high, it is measured roughly in $\lambda/4$ steps in the high-speed mode. No skip is observed in the measurements, which means the mode-switching operation was performed accurately. The configuration of our system combined with the XY stage is shown in Fig. 8.

5. Conclusions

Accuracy of wafer positioning to within ten nanometers is required more and more as LSI pattern densities increase. There is also a requirement to reduce the positioning time in such processes. To meet these needs, the authors have developed a new laser measurement system which can measure displacement with extremely high accuracy and measurement speed. The high accuracy and measurement speed are achieved by their system's ability to switch automatically between two measurement modes. The capabilities of the system are:

- (1) measurement accuracy: ± 4 nm,

Fig. 5 Measurement error for position

Fig. 6 Timing charts for assessing measurement speed

Fig. 7 Measurement of pseudo displacement

Fig. 8 Configuration of the laser measurement system

- (2) maximum allowable measurement speed : 1 000 mm/s,
 (3) resolution : ± 1.3 nm.

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