Vibration insensitive interferometer using sinusoidal phase-modulation and feedback control

Osami Sasaki, Hidetaka Iwai, and Takamasa Suzuki

Faculty of Engineering, Niigata University, 8050Ikarashi 2, Niigata-shi 950-2181, Japan
Fax 81-25-262-6747 E-mail: osami@eng.niigata-u.ac.jp

ABSTRACT

It is easy to extract a signal proportional to a phase fluctuation from a sinusoidally phase-modulated interference signal. This fluctuation is caused by mechanical vibration or air turbulence. In a sinusoidal phase-modulating interferometer using a laser diode (LD) the phase fluctuation is reduced by changing the injection current of the LD with a feedback control system. This control is very useful to a Fizeau type interferometer for surface profile measurement of a large size object. IC wafers of 100 mm diameter are measured with an interferometer insensitive to mechanical vibration and air turbulence. The phase fluctuation with nearly constant amplitude which corresponds to 30nm in surface height is reduced by about 10%. However the reduction in the phase fluctuation is not performed well for an instantaneous and large phase fluctuation. In order to be insensitive to all kinds of phase fluctuations the feedback signal is always observed, so that the interference signal is captured when the amplitude of the feedback signal is less than a specified level during the capturing time of 0.53 s. Thus surface profiles of the IC wafers can be measured with a high repeatability of a few nm even when any kind of vibration exists.

Keywords: interferometer, vibration compensation, surface profile measurement, sinusoidal phase modulation

1. INTRODUCTION

Laser interferometers are widely applied to surface profile measurements in high-precision manufacturing. However, since interferometers are generally very sensitive to mechanical vibrations, the measurements become difficult when there are vibrations around the interferometers, for instance, in production fields. In order to use interferometers in the unstable environments, the sensitivity of the interferometers to vibrations must be reduced by some techniques.[1] Common-path interferometers are the most known technique for reducing the sensitivity to vibrations. However, special polarizing optical devices are required to introduce phase-shifting interferometry to a scatter plate interferometer[2] and a point diffraction interferometer[3]. Another technique is to make the detection time of the interference signal so short that the vibrations are frozen. Single-shot phase-shifting interferometers have been proposed in which multiple phase-shifted interferograms are produced at the same time and detected with a short time.[4,5] Optical system to produce the multiple interferograms becomes complicated and expensive. In an interferometer with a simple optical system a single interferogram with numerous tilt fringes are detected with a short time.[6] Although a surface profile of an object is calculated from the single interferogram through its Fourier transform, the accuracy of the measurement by the method is not so high as that by the single-shot phase-shifting.

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In this paper a feedback control system for reducing the effects of vibrations is installed in a sinusoidal phase-modulating Fizeau interferometer.[7-9] A signal proportional to a phase fluctuation caused by vibrations is easily extracted from the interference signal. Using a laser diode (LD) the phase fluctuation is reduced by changing the injection current of the LD with a feedback control system. Since the reduction in the phase fluctuation is not performed well for an instantaneous and large phase fluctuation, the feedback signal is always observed so as to capture the interference signal when the amplitude of the signal proportional to the phase fluctuation is less than a specified level during the capturing time. Thus surface profiles of the IC wafers can be measured with a high repeatability of a few nm even when any kind of vibration exists.

2. PRINCIPLE

2.1. Sinusoidal Phase-Modulating Interferometry

A laser diode (LD) is used as a light source of an interferometer in which a small change in the wavelength of the LD is generated by changing the injection current. When the wavelength of λ_0 changes by $\Delta\lambda$, the phase of the interference signal is given by

$$\alpha_L=2\pi L/(\lambda_0+\Delta\lambda)=2\pi L/\lambda_0-2\pi(\Delta\lambda/\lambda_0^2)L, \qquad (1)$$

where L is optical path difference, and $\Delta\lambda^2$ is neglected in the expansion of the equation. The first tem of phase α_L is denoted by $\alpha=2\pi L/\lambda_0$ that is produced with the wavelength of λ_0. When $\Delta\lambda=-b\cos(\omega_c t+\theta)$ is generated by changing the injection current, the following interference signal in sinusoidal phase-modulating interferometry is obtained:

$$\begin{aligned} S(t) &= A+B\cos[Z\cos(\omega_c t+\theta)+\alpha] \\ &= A + B\cos\alpha\,[J_0(Z)-2J_2(Z)\cos(2\omega_c t+2\theta)+\cdots] \\ &\quad -B\sin\alpha\,[2J_1(Z)\cos(\omega_c t+\theta)-2J_3(Z_b)\cos(3\omega_c t+3\theta)+\cdots], \end{aligned} \qquad (2)$$

where A is a constant, B is amplitude of the time-varying component, and $J_n(Z)$ is the n-th Bessel function. The modulation amplitude is $Z=2\pi b\beta L/\lambda_0^2$, and β is the modulation efficiency of the LD. Denoting Fourier transform of S(t) by $F(\omega)$, the modulation amplitude Z and the modulation phase θ are obtained from $F(\omega_c)$ and $F(3\omega_c)$. The phase α is obtained from $F(\omega_c)$ and $F(2\omega_c)$ with known values of Z and θ. A two-dimensional CCD image sensor (hearafter it is called CCD) is required for measurement of surface profile. The output of the CCD is an integration of the time-varying signal S(t) over the storage period of the CCD. Fourier transform $F(\omega)$ is obtained from the output of the CCD.

2.2. Elimination of Vibration

The fluctuation in phase of the interference signal caused by mechanical vibrations is expressed by $\eta(t)$. The constant component A in the interference signal is eliminated with an electric circuit of a high-pass filter. By sampling the signal of $B\cos[Z\cos(\omega_c t+\theta)+\alpha+\eta(t)]$ when $\cos(\omega_c t+\theta+\eta(t))$ is equal to zero, a phase-detected signal

$$S_F(t)= B_F\cos[\alpha(t)+\eta(t)] \qquad (3)$$

is obtained. This signal is used as a feedback signal with which the injection current of the LD is controlled. When the injection current changes by i_C, the phase α of the interference signal changes by $\alpha_C=-2\pi(\beta i_C/\lambda_0^2)L$. The effect of the mechanical vibrations is eliminated by controlling the injection current so that $S_F(t)$ becomes to zero with proportional and integral feedback controller. Then the phase of $\alpha(t)+\eta(t)$ becomes to a constant of $\pi/2$.

If the mechanical vibration is instantaneous and strong, the elimination by the feedback control mentioned above is not enough. The fluctuation in the $S_F(t)$ is observed whether the magnitude A_F of the fluctuation exceeds a specified value H_F. When A_F is smaller than H_F, the interference signal is fed to a computer. If it is fed to a computer continuously for a specified period, the capture of the interference signal is completed. This operation is called the automatic capture without vibration.

3. SETUP OF THE INSTRUMENT

3.1. Optical System

Figure 1 shows a configuration of a laser diode interferometer free of vibration for surface profile measurement. Wavelength of the laser diode is 685 nm and its maximum output power is 60 mW. Light from the LD is collimated with Lens L0. The elliptic pattern of the beam is converted to a circular pattern with an anamorphic prism pair APR. Objective lens L1 diverges the beam to be 100 mm-diameter in the front of lens L2 whose focal distance is 500mm. The diameter of pinhole PH1 is 50 μm. The collimated beam is incident to glass plate wedged by 1 degree GPW and IC wafer of 100 mm-diameter. Object light reflected by the surface of the IC wafer and reference light reflected by one side of GPW are turned by 90 degrees by beam splitter BS1. The light reflected by another side of GPW is blocked by pin hole PH2 of 100 μm-diameter. An image of the object is made on CCD by lens L2, L3, and L4 with a magnification of 1/45. An image of the object on the photo diode is also made by lens L2, L3, and L5. Beam splitter BS2 is a polarizing one, and its reflectivity is about 90 % for the polarization angle of the light adjusted by rotating LD and APR. The pixel size of the CCD is 10 μm-square, and number of the pixel used is 239×239.

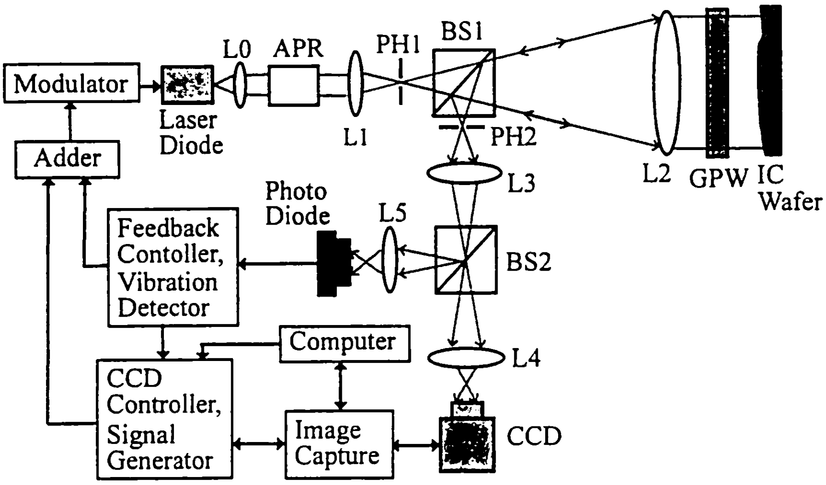

Fig.1 Laser diode interferometer free of vibration for surface profile measurement.

3.1. Interference Signal and its Detection with CCD

Figure 2 shows the relations among the modulation signal of $\cos(\omega_c t+\theta)$, the shutter pulse of the CCD, and the interference signal $S(t)$. The exposure time T_A is equal to$T_C/8$ and its position is specified by the shutter pulse, where $T_C=1/f_c=2\pi/\omega_c$.[10] One period of signal $S(t)$ is divided into the eight regions according to the exposure time. The frame period T_F is set to be equal to $nT_C+(1/8)T_C$ so that each of the eight regions is recorded sequentially in one frame, where n is a positive integer. In the interferometer constructed $T_F=1/200$, $n=3$, and $f_c=375$Hz, however $n=2$ in Fig.2. Since the signal $S(t)$ is captured during the period of 64 frames, the capturing time T_P of $S(t)$ is $64T_F=0.53$ s.

The modulation signal and the shutter pulse are produced from the vertical synchronizing signal of the CCD with electric circuits. The modulation signal is used as the injection current of the LD to generate the wavelength change $\Delta\lambda$ of $-b\cos(\omega_c t+\theta)$. Since the optical path difference L caused by the distance between the object surface and the surface of GPW is about 30 mm, the phase-modulation amplitude $Z=2\pi b\beta L/\lambda_0^2$ is 2.6rad.

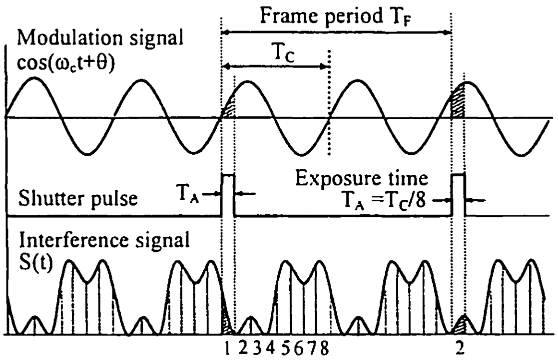

Fig.2 Detection of interference signal with CCD.

4. MEASUREMENT RESULTS

4.1. Automatic Capture without Vibration

Figure 3 shows the feedback signal $S_F(t)$ when the feedback control worked well. The small motor gave mechanical vibration to the interferometer. Since the amplitude of this vibration was constant with time, the amplitude of the fluctuation $\eta(t)$ in phase of the interference signal caused by the vibration is reduced to about one-tenth of that observed when the feedback control did not work. The reduced amplitude was slightly smaller than H_F as shown in Fig.3. The amplitude of H_F causes fluctuations in a measured surface profile of the object with a magnitude of 3 nm. In addition to the vibration produced by the motor, instantaneous vibration was given by tapping the floor. In this case the amplitude A_F of $S_F(t)$ exceed to the amplitude of H_F as shown in Fig.3 because the feedback control did not completely reduce the effect of the instantaneous vibration. The interference signal was captured when the amplitude A_F is less than H_F. In Fig.3 the signal capture stopped before the capturing time became T_P because the amplitude A_F exceeded H_F due to the instantaneous vibration. The signal capture automatically restarted when the amplitude A_F fell to H_F. The amplitude A_F was less than H_F during the capturing time T_P of 0.53 s, and the signal capture finished.

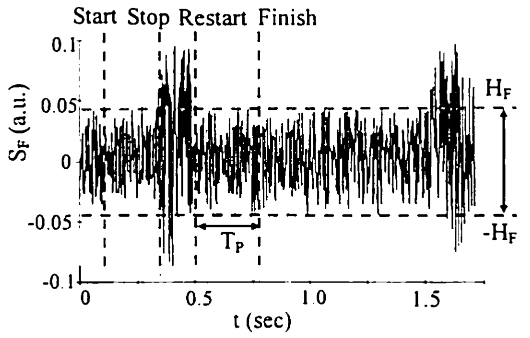

Fig.3 Capture of interference signal by detection of vibration-free period.

4.2. Measured Surface Profiles

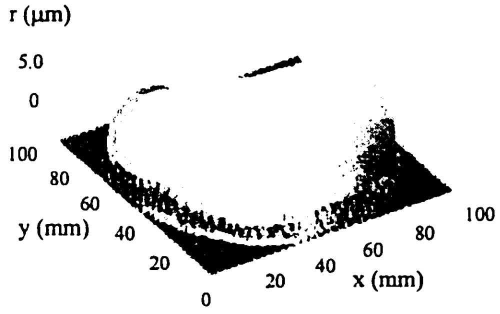

Fig.4 Surface profile measured when there was almost no vibration.

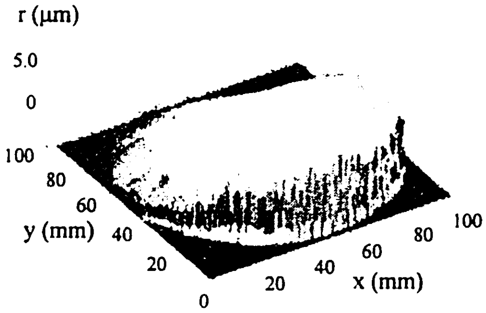

Fig.5 Surfaced profile measured when the automatic capture without vibration did not work.

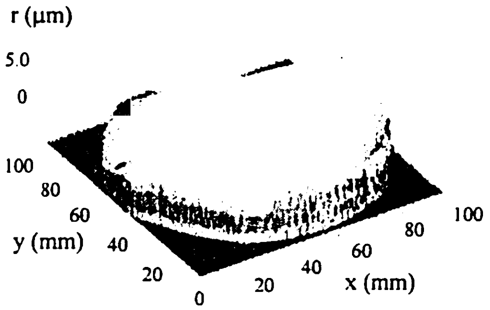

Fig.6 Surfaced profile measured when the automatic capture without vibration worked well.

Surface profiles of a IC wafer of 100mm-diameter were measured. Figure 4 shows a surface profile measured when there was almost no mechanical vibration. Peak-valley (P-V) value of the measured surface profile was 7.022 μm. Next mechanical vibrations were given to the interferometer with the motor and by tapping the floor. Figure 5 shows a surfaced profile measured when the automatic capture of the interferences signal did not work. Since the measured result contained the effect of the vibration, root-mean-square (RMS) value of the difference between the surface profiles of Figs.4 and 5 was 509 nm. Figure 6 shows a surfaced profile measured when the automatic capture of the interferences signal worked well. RMS value of the difference between the surface profiles of Figs.4 and 6 was about 5 nm, and P-V value of the measured surface of Fig. 6 was 7.024 μm. The repeatability in the measurement was a few nm when the automatic capture without vibration worked.

5. CONCLUSION

In the sinusoidal phase-modulating interferometer using the LD the phase fluctuation caused by mechanical vibration and air turbulence was reduced by changing the injection current with the feedback control system. The phase fluctuation with nearly constant amplitude which corresponded to 30nm in surface height was reduced by about 10%. However the reduction in the phase fluctuation was not performed well for an instantaneous and large phase fluctuation. In order to be insensitive to all kinds of phase fluctuations the feedback signal was always observed, so that the interference signal was captured when the amplitude of the feedback signal was less than a specified level during the capturing time of 0.53 s. Thus surface profiles of the IC wafer of 100 mm diameter could be measured with a high repeatability of a few nm even when the instantaneous and large vibration existed.

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