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Grating Pitch Measurement Beyond the Diffraction Limit with Modified Laser Diffractometry

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The demand for accurate measurements of nanostructures is increasing for the microprocesses and nanotechnology used in the semiconductor industry. In this study, we present an improved method for measuring gratings with a pitch size lower than one-half of the laser wavelength by using a modified laser diffractometer (LD). In experiments, the modified LD with a 633 nm laser is used to measure a grating with a 288 nm pitch size. This result is compared with results measured by both a metrological atomic force microscope and the traditional LD with a 543 nm laser. The validity of this method is demonstrated. The difference between the pitch size of 288 nm obtained by these three methods is approximately 0.17 nm. © 2011 The Japan Society of Applied Physics

1. Introduction

Concerning the microprocesses and nanotechnology used in the semiconductor industry, the demand for accurate nanostructure measurements is becoming more important. Furthermore, nanotechnologies are being transferred from research laboratories into industry. In order to improve the quality of products, inspection instruments are very important for calibration and traceability. Atomic force microscopy (AFM),1,2) scanning electron microscopy (SEM),3,4) and transmission electron microscopy (TEM)5) are well-known techniques for nanostructure topography measurements. However, the instruments used in these techniques need standards to calibrate the accuracy of measurement capability. Therefore, a one-dimensional (1D) grating is commonly used to calibrate the accuracy of the axis and to support the specifications in the nanometer features. Several studies have been reported on the inspection methods used for the grating pitch.6–11) Interlaboratory comparisons (NANO 4, 5, and APMP.L-S2) were carried out for measuring pitch sizes,12–15) and the metrology laboratories involved used metrology atomic force microscopy (MAFM) and a laser diffractometer (LD).

In this study, an alternative method for the precise measurement of grating pitch lower than the optics limit measured with the LD method is presented. The measured grating pitch is 288 nm by using a modified LD with a 633 nm laser and a traditional LD with a 543 nm laser. To validate the accuracy of the LD method, a high-resolution MAFM system was used to measure the grating size of 288 nm. Both methods are described in the following.

2. Experimental Methods

2.1 LD method

As schematically presented in Fig. 1, the LD method is also developed for measuring the grating pitch lower than the optics limit. The experimental setup of the LD method consists of a He–Ne polarization laser (Melles Griot/25 LGR 193-249), a precision rotary table (PRT; Aerctech/ADR 240), a four-quadrant position sensitive detector (PSD), a polarization beam splitter (PBS), a quarter-wave plate (Q), and a one dimensional (1D) grating (Advanced Surface Microscopy 1D300). The grating with a nominal 300 nm pitch is manufactured using a silicon wafer substrate coated with a polymer material.

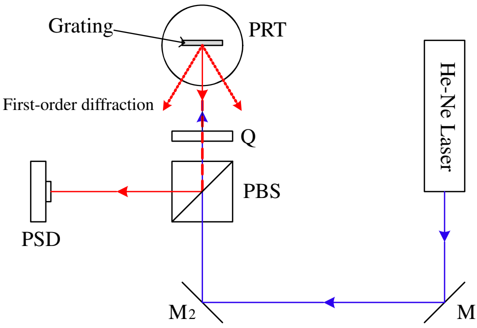

Fig. 1. (Color online) Schematic diagram of optical path design.

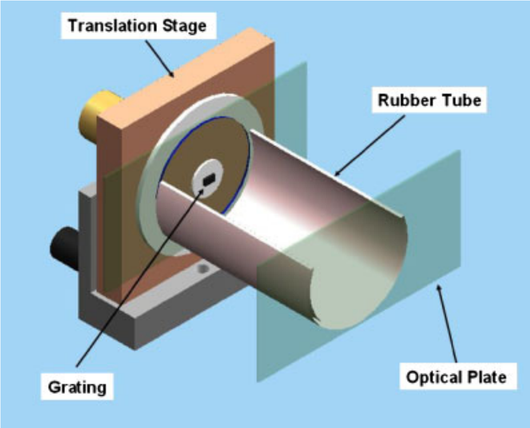

Fig. 2. (Color online) Experimental apparatus of the OD method.

To measure grating pitches lower than the optics diffractive limit, the LD method needs an apparatus with a vessel that contains an investigated liquid and a reflection grating. The vessel has a volume along the front side and is fabricated from an optical plate that is mounted on a six-degrees-of-freedom translation stage. The front face of the optical plate is mounted on a grating, which is aligned to be coincident with the spindle axis of rotation, and the normal light of the grating surface is aligned such that the laser beam retro diffracts upon itself. The middle part of the vessel is a semicircle tube and the tube material is rubber. The tube

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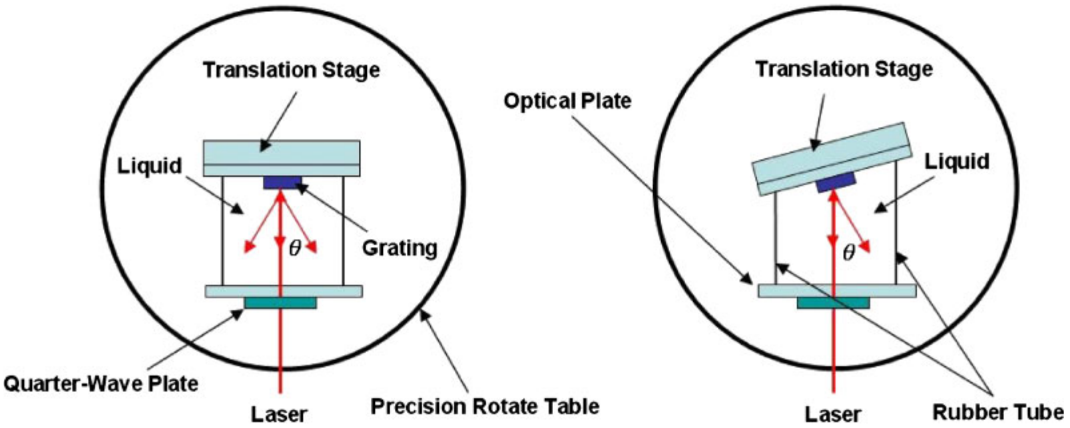

Fig. 3. (Color online) Device for measuring refractive index of liquid based on Littrow configuration.

is easily filled up with the investigated liquid. The front side of the semicircle tube is mounted on an optical plate that is necessarily transparent over the wavelengths of interest. The apparatus with a vessel that contains the investigated liquid and a reflection grating is mounted on a six-degrees-of-freedom translation stage, as depicted in Fig. 2.

Figure 3 depicts a device for measuring the refractive index of a liquid based on the Littrow configuration.16) The optical plate connects with a quarter-wave plate. The optical plate is a transparent glass and the incidence angle of laser light on the plate is 90°. Hence, the refractive index of the optical plate does not affect either pitch value or diffraction angle. Because diffraction appearance occurs in the liquid, the reflective index of the immersed liquid can be determined by a known grating size and a diffractive equation17,18)

$$P = \frac{m\lambda}{2n_{\mathrm{s}} \sin\theta}, \qquad (1)$$

where n_{s} is the refractive index of the experimental liquid, m is the diffractive order, θ is the diffraction angle, λ is the vacuum wavelength of the laser, and P is the grating pitch value.

In this study, the PRT is returned to the origin and the PSD is adjusted. The reflective zero-order diffraction beam coincides with the center of the detector, which is treated as the reference position. Rotating the PRT counterclockwise makes the positive first-order diffraction beam coincide with the center of the detector, and the diffraction angle θ is measured. As a consequence, the immersion liquid raises the refractive index of the environment, and the diffraction angle is relatively reduced. The experimental setup of the LD method is shown in Fig. 4.

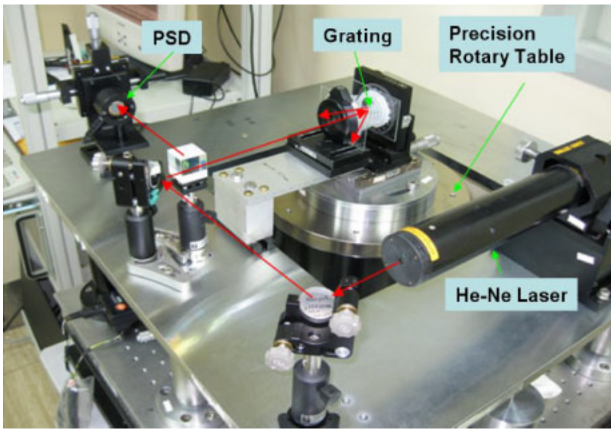

Fig. 4. (Color online) Experimental setup of LD method.

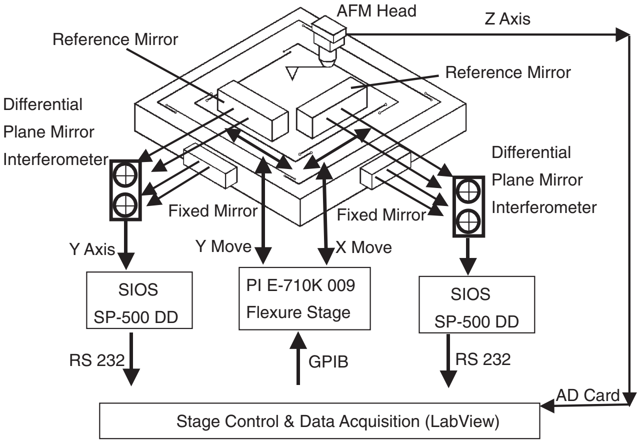

Fig. 5. Schematic diagram of MAFM.

2.2 MAFM method

AFM is a powerful technique for measuring nanometer-scale line pitch and nanostructure topography.19–23) Figure 5 shows the principle of pitch measurement and a schematic diagram of MAFM. The system uses a custom-built LabView program in an industrial computer to servo control the two-dimensional scan of the flexure stage, to read the voltage of the Z-axis capacitance sensor of the AFM apparatus, and to read the displacements of the flexure stage relative to the reference mirrors from the differential plane mirror laser interferometers (SIOS AE SP 500 DD E). The displacements of the X- and Y-axes of the flexure stage from laser interferometers via RS232 interfaces and the voltage of the Z-axis of the AFM apparatus via an AD card are obtained simultaneously while the AFM probe is scanning. Finally, in this study, we use LabView software to carry

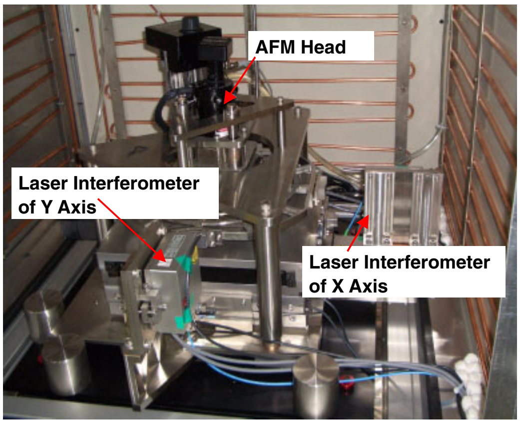

Fig. 6. (Color online) Photograph of MAFM.

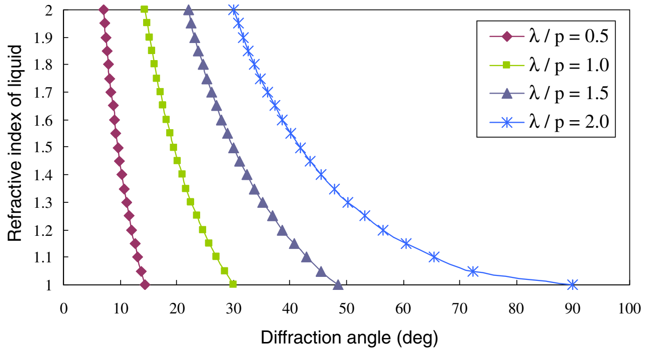

Fig. 7. (Color online) Refractive index of liquid n_s and the diffraction angle θ.

out the interpolation in the X- and Y-directions, and use the SPIP software to estimate the pitch value.[24)] A photograph of the MAFM setup is shown in Fig. 6. The MAFM system is installed inside a thermostat where the temperature is maintained at $20 \pm 0.1\,°\mathrm{C}$. To carry out the proposed measurement method, the measurement range should be larger than 10 times P, where P is the mean pitch. For example, a size of $3 \times 3\,\mu\mathrm{m}^2$ and 512×512 steps are used to measure the 288 nm pitch size in a grating.

3. Results

Figure 7 shows the relationship between the refractive index of a liquid n_s and the diffraction angle θ. Using a known laser wavelength and pitch value P, in this study, we compare four different wavelength-to-pitch ratios λ/P. The results reveal that a higher λ/P corresponds to higher measurement sensitivity.

In this study, two He–Ne laser sources of 543 and 633 nm wavelengths are used to measure the grating pitches. Therefore, using the LD method, we can determine that the refractive index of water is 1.3318 for a λ of 633 nm at 20 °C. Figure 8 shows the relationship between pitch-to-wavelength ratio λ/P and the diffraction angle θ for a λ of 633 nm. The two curves depict the grating immersed in air and water. Immersion can not only measure the refractive index of liquids, but also the grating pitch, which is less than one-half of the laser wavelength.

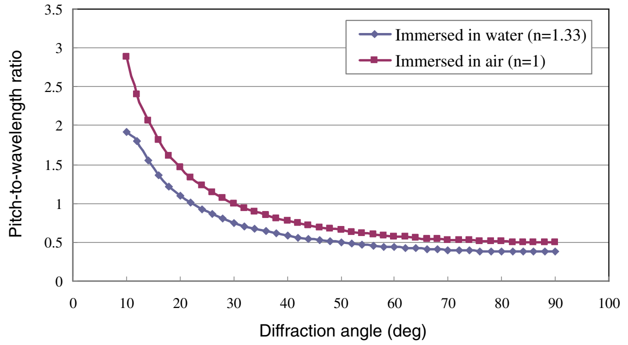

Fig. 8. (Color online) Pitch-to-wavelength ratio λ/P and the diffraction angle θ.

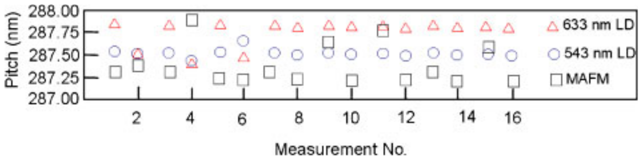

Fig. 9. (Color online) Measurement results of LD and MAFM methods.

Table I. Measurement results (unit: nm).

Method	Grating pitch (288 nm) Measurement result	Grating pitch (288 nm) Standard deviation
LD (λ 543 nm)	287.591	0.003
LD (λ 633 nm)	287.577	0.004
MAFM	287.422	0.338

In this study, we measure 288 nm pitch size using the LD method with 543 and 633 nm wavelengths. Measurement results are compared with those of the MAFM method and the LD method, as shown in Fig. 9. The squares represent results obtained by MAFM, triangles represent an LD of λ equal to 633 nm, and circles represent an LD of λ equal to 543 nm. Pitch values are the average of 16 measurements, and measurement results are shown for comparison in Table I.

4. Conclusions

In this study, an alternative method for the precise measurement of the grating pitch lower than the optics limit measured with the LD method is presented. The method has many merits such as simple optical configuration, high measurement accuracy and rapid measurement. To validate the accuracy of the LD method, the 288 nm pitch size has been measured using the LD method with 543 and 633 nm wavelengths, and measurement results were compared with those of the MAFM method. The grating pitches among the three different methods obtain a maximum deviation of approximately 0.17 nm. The deviation of LD measurements between 543 and 633 nm wavelengths is 0.014 nm, which is larger than their standard deviations of 0.003 and 0.004 nm, respectively. The error sources include laser stability, angle measurement, reproducibility of the rotary table, refractive index, and thermal expansion. The measurement accuracy can be further improved if these errors are decreased.

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