Nanometer scale grating evaluation with small angle X-ray scattering

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Gratings shrink to nanoscale in order to meet fast progress for advanced semiconductor industries at 22 nm or 15 nm technology node. The characterizations of the nanoscale gratings are difficult to obtain accurately and nondestructively. An advanced metrology solution for precision grating characterization becomes critical for improving the production yield. Transmission small angle X-ray scattering (SAXS) is an emerging dimensional metrology platform to quantitatively characterize gratings including pitch, linewidth, line height, sidewall angle and line edge roughness with sub-nm precision. In this study, a transmission SAXS method for extracting grating information from the scattering intensity with respect to X-ray wavenumbers was demonstrated. The averages of pitch sizes and depth of gratings were obtained from the model-fitted evaluations to the measured X-ray scattering intensity, which is described by the Fraunhofer diffraction. The SAXS measurements were performed at the BL23A station of the National Synchrotron Radiation Research Center (NSRRC), Taiwan. The measurements of side wall angles and pattern widths were carried out with the sample rotating from -60 to 60 around the axis perpendicular to the grating direction. Diffraction peak intensities I(Q) and the corresponding reciprocal space wavenumbers Q(1/Å) were measured by a 2D image detector for pitch sizes. The pitch sizes of 141 nm, 273 nm, and 413 nm were obtained though the analysis of the slopes from the linear fitting of the diffraction peaks and wavenumbers.

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1. Introduction

According to the International Technology Roadmap for Semiconductor, metrology with capability of providing nanoscale information of the pattern cross-sections is critical to the development of practical high-volume nanofabrication. The nanofabrication requires quantifying the statistically averaged feature dimension as well as variations from the average in nanoscale precision, as the minimum feature size in integrated circuits approaches 32 nm and smaller. However, conventional characterization methods such as scanning electron microscopy (SEM), optical scatterometry and atomic force microscopy are approaching their sensitivity limits at this size scale especially for patterns with dense and high aspect ratio features.

A technique based on small angle X-ray scattering (SAXS) has been introduced as an alternative to current measurement methods for characterizing patterns with critical dimensions (CD) on the scale of nanometers. Critical dimension- small angle X-ray scattering (CD-SAXS) has several potential advantages over existing inspection metrologies such as an increased sensitivity for smaller features including side-wall angles, side-wall roughness, and dense and high aspect ratio patterns either by grazing incident SAXS (GISAXS) or transmission SAXS.

In this paper, we demonstrated that transmission SAXS can provide a fast and accurate measurement of averaged pitch sizes and pattern widths of gratings from the positions and relative scattering intensity of diffraction peaks of the measured spectral profiles. Furthermore, analysis of the measured data suggests that more details in pattern shapes and side wall roughness can be extracted with more accurately modeling methods. The SXAS results were compared to cross-sectional SEM and AFM images of the same patterns for confirmation.

2. Measurement system and experimental processes

2.1 Measurement system

The SAXS measurements were performed at the BL23A station of the National Synchrotron Radiation Research Center (NSRRC), Taiwan. The layout of the station BL23A beamline is shown in Fig.1. Synchrotron X-ray source at NSRRC was used to provide high brightness and power to perform transmission SAXS measurements for the critical dimension of nanoscale gratings. Gratings on the rotating stage for the experimental setup are shown in Fig. 2.

The SAXS instrument, located in an experimental hutch, consists of a collimation system, a sample stage and a post-sample section. For the transmission SAXS measurement, the sample stage was modified for incident X-ray penetrating the sample perpendicularly.

This beamline is equipped with double Si(111) crystals with high energy resolution ($\Delta E/E \sim 2 \times 10^{-4}$) in the range of 5-23 keV, or by a double Mo/B4C multilayer monochromators for 10-30 times higher flux (~10^{11} photons s^{-1}) in the 6-15 keV range. A Si-based plane mirror was used to selectively direct the beam downwards. A beam collimation system was implemented for the X-ray beams with pinholes and slits positioned apart for ~5 m. The post-sample section consists of a 1 m Wide Angle X-Ray Scattering (WAXS) section with two linear gas detectors, a vacuum bellows (1-4 m), a two-beamstop system and the SAXS detector system, all sit on a motorized optical bench for motion in six degrees of freedom.

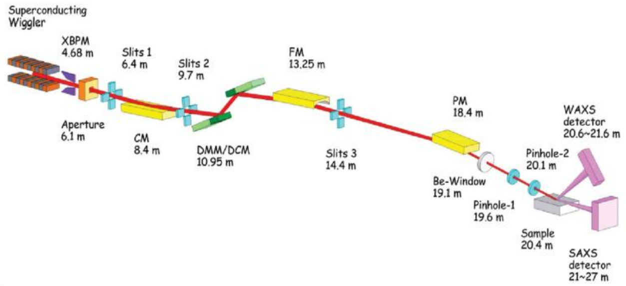

Fig. 1 schematic drawing of the BL23A SAXS beamline layout.

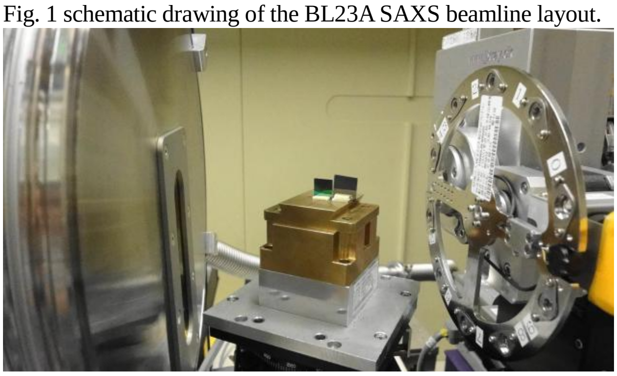

Fig. 2 SAXS sample stage.

A dedicated small-angle X-ray scattering (SAXS) beamline with the in-achromat superconducting wiggler insertion device (IASW6) hard X-ray source can provide a low-divergence beam of relatively high flux density and high energy resolution for nanostructure studies. The characteristic parameters for the X-ray source are summarized in Table 1. The monochromatic beam is focused by a toroidal mirror with 1:1 focusing for a small beam divergence and a beam size of ~0.9 mm x 0.3 mm (horizontal x vertical) at the focus point located 26.5 m from the radiation source.

Number of poll	16
Magnet period	6.1 cm
Peak magnetic field	3.1 T
Deflection parameter	17.7
Photon beam size	0.37 mm
Total power	2.0 kW

Table. 1 Characteristics of IASW6 (with 300 mA beam current)

2.2 Experimental processes

In our study, the nano-patterned silicon gratings with nominal sizes of 139 nm, 278 nm and 416 nm (LightSmyth technology) were measured by transmission SAXS method at the energy of 17k eV. The AFM images of the gratings are shown in Fig. 3, in which the consistency of the average pitch sizes and the side wall roughness were confirmed. The samples, shown as Fig. 3(1), were assumed to consist of a series of equally spaced parallel lines through the whole 15 x 15 mm^2 single crystal silicon squares. According to AFM scanned images, the line direction was marked backside of the sample as a reference for sample and measurement alignment.

The side wall roughness of the gratings can be analyzed from SAXS measurement, as well. The transmission SAXS measurements were conducted by rotating the grating from -60° to 60° with step size of 2°. In each measurement, the counting time is 250 seconds. Each sample takes around 4 hours for completion except for the time spent for the sample setting and test run. All measurements were performed at controlled room temperature (23.0 ± 1.5 ℃) and in air.

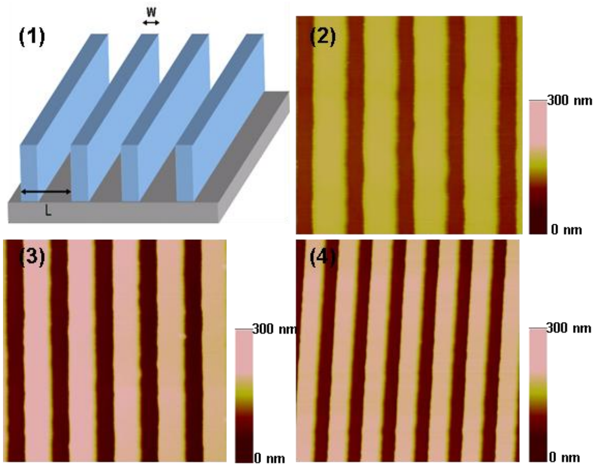

Fig. 3 (1)The ideal 3D structure of silicon line gratings; and the AFM images of line grating with pitch sizes of (2) 139 nm, (3) 278 nm, and (4) 416 nm.

The measured SAXS data was corrected with background scattering intensity with consideration of the transmission rate. The transmission rate of the patterned silicon for each rotating angle is different. As a result, the transmission measurement (tm) is required along with the transmission SAXS measurement. In this experiment, the tm measurements took the same amount of time as that of the transmission SAXS. The SAXS measurements were collected by the 2D images detector, as shown in Fig. 4.

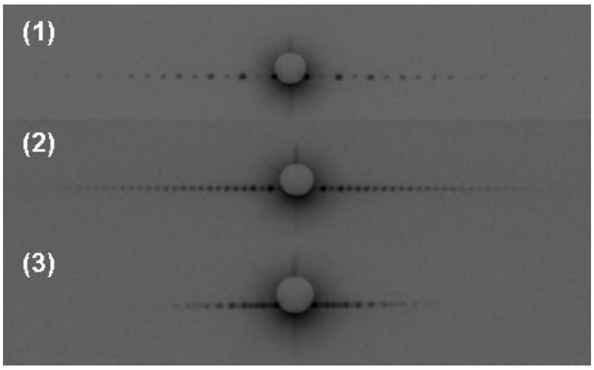

Fig. 4. SAXS 2D images of silicon line gratings of (1) 139 nm,(2) 278 nm, and (3) 416 nm.

The scattering intensity and the position of the diffraction spectrum for grating measurements were reproduced and shown in Fig 5. As it can be observed, clear diffraction peaks can be easily identified for small pitch sizes (139 nm and 278 nm). However, as the pitch size increases, it becomes more difficult to indentify the shape and peak positions of the diffraction peaks. Higher angle resolution for the detector is required for large gratings.

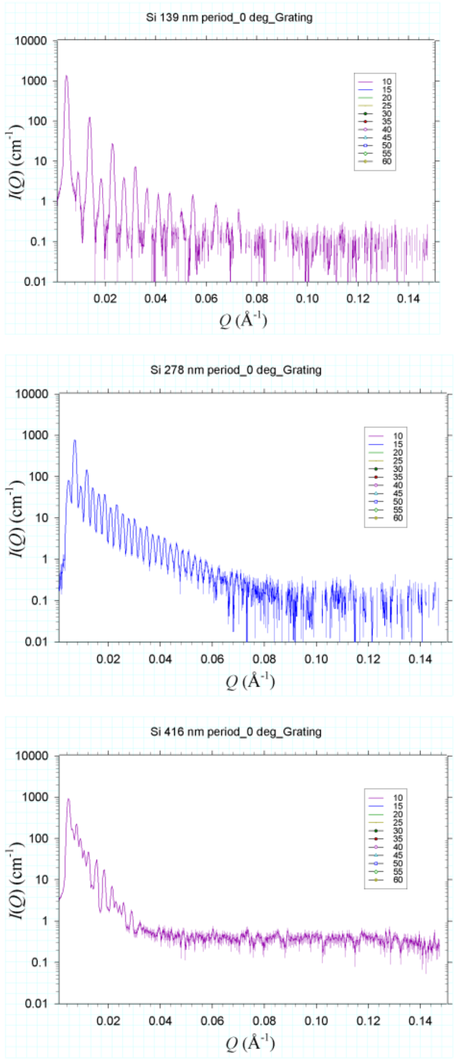

Fig. 5. SAXS 2D images of silicon gratings of (1) 139 nm, (2) 278 nm, and (3) 416 nm.

3. Results and discussions

In term of theory, we constructed a model for analyzing the periodical structure based on data-fitting process for Fig. 5. First, a grating can be constructed as a periodic structure, as shown in Fig. 6 and Fig 7. The grating generally is a 1D periodic structure. The mathematical model can be described by the following Equation (1):

$$\sum_n \delta(q_x - \frac{2n\pi}{L}) \quad (1)$$

In Figure 6 and in the Equation (1), ρ(x) is the function of electron density in X direction (2nπ/L), and the period of grating is 2π/L. However, the Equation (1) was described from periodic grating function, it also called structure function. Furthermore, the structure function was also provided some information about the grating such as pitch.

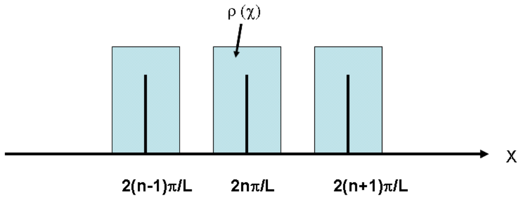

Fig. 6. The scheme diagram of a periodic grating.

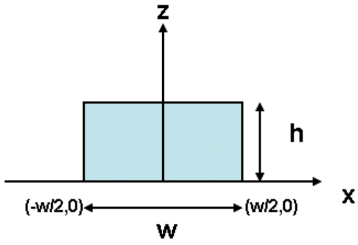

Fig. 7. The 2D scheme of a periodic structure.

Second, in the Equation (2) was described that when a synthetic wave induced by X-ray incidents into an atom in 3D space, and it also called the form factor.

$$F(q_x, q_y, q_z) = \iiint_V \rho(x, y, z) e^{-i(q_x x + q_y y + q_z z)} dxdydz \quad (2)$$

$$F(q_x, q_y, q_z) = \rho(x, z) \int_0^h \int_{-w/2}^{w/2} e^{-iq_x x} e^{-iq_z z} dxdz \quad (3)$$

In this theoretical model, at first, we use 2D space to simplify these equations. In Fig. 7, we define the height (h) and width (w) in this grating, so the equation is simplified as shown in Eq. (3).

Second, the Equation (3) is described as a synthetic wave induced by X-ray through out an atom in 2D space. However, the function is a vector. The datum from the experiments is a scalar. In order to analyze the data, we need to rewrite the function to the square absolute value of Equation (4). Besides, A is the structure function. Finally, the intensity I (Equation (5)) combines the Equation (4) with the A.

$$\left|F(s)\right|^2 = \left|\rho(x, z) \int_0^h \int_{-w/2}^{w/2} e^{-iq_x x} e^{-iq_z z} dxdz\right|^2 \quad (4)$$

$$\mathrm{I} = \mathrm{A} \times \left|F(s)\right|^2 = \sum_n \delta(q_x - \frac{2n\pi}{L}) \times \left|\rho(x, z) \int_0^h \int_{-w/2}^{w/2} e^{-iq_x x} e^{-iq_z z} dxdz\right|^2 \quad (5)$$

Based on above equations, a theoretical model is constructed to describe X-ray diffraction intensity for the gratings measured by the transmission SAXS. Consequently, the pitch sizes, line width, and height of the grating can be obtained. According to Equation (1) and Fig. 5, the orders of the diffraction peak are plotted with respect to wavenumber Q. Then, the slop 2□ /L can be obtained, where the L indicates the sizes of pitches. The calculation of the slopes and the fitting process for the pitch sizes of 139 nm, 278 nm and 416 nm are shown in Figure 8-10.

From these plots, we can obtain the relations for the slopes and the pitch sizes of gratings, as shown in Fig. 11. When the value of the pitch sizes increases, the slope decreases. The slope is 0.0044, 0.0023, and 0.00152 respectively. Based on the fitted slopes, the measured pitch sizes of the grating are 141 nm, 273 nm, and 413 nm respectively. Comparing with the nominal values of the gratings provided by the manufacturer, there are small discrepancies between the measured values and nominal values. The discrepancies, -2 nm, 5 nm, and 3 nm, are in reasonable range when two different measurement methods (SEM and SAXS) were applied to measure the pitch sizes of gratings.

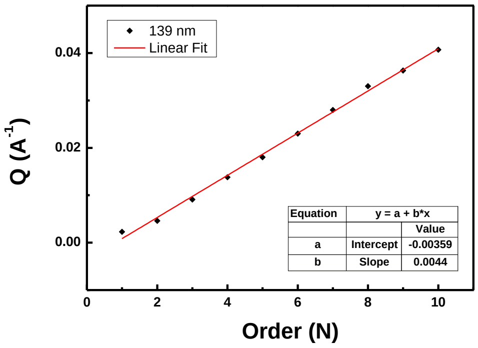

Fig. 8. The linear fitting for obtaining the slope (139 nm).

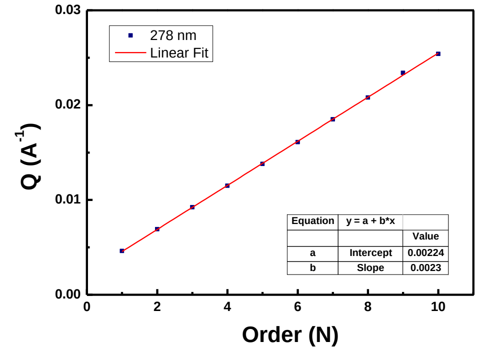

Fig. 9. The linear fitting for obtaining the slope (278 nm).

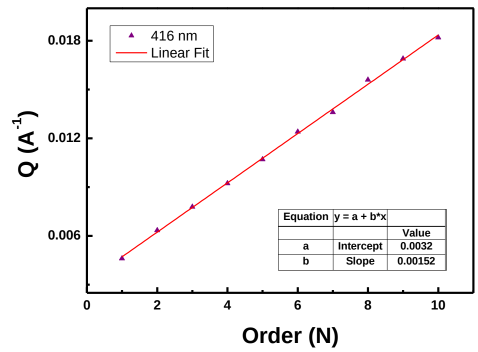

Fig. 10. The linear fitting for obtaining the slope (416 nm).

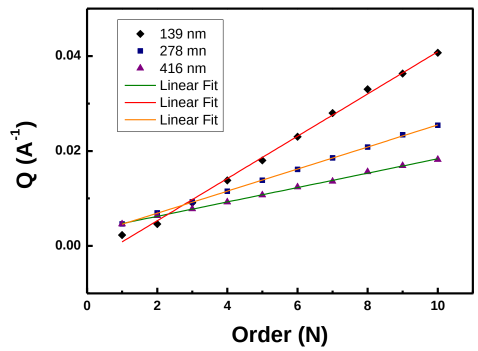

Fig. 11. The Q-Order chart of three different grating.

Additionally, the background intensity for SAXS measurements was another possibility to cause the discrepancies. In Fig. 5, high orders of the peaks for this grating (139 nm) are much sharper. As a result, the Q values are obtained precisely. However, if the pitch size is larger, the positions of the peaks are harder to obtain. Thus, the counting time and background intensities are apparently important. To obtain more accurate values, we should increase the data counting time and correct for the background intensities.

4. Conclusion

Small angle X-ray scattering (SAXS) is a non-destructive measurement tool. It is a metrology tool for advanced semiconductor process when the technology node progress towards 22 nm and below. With the shrinkage of size, the feature sizes of the grating are hard to obtain through the traditional optical scattering tool due to the diffraction limit. However, with a short X-ray wavelength when the SAXS technique is applied, it can detect nanoscale CD features easily and correctly. The measurement results from SAXS scattering provide accurate evaluations for pitch sizes, line width, roughness, and side wall angle. Accordingly, for CD measurements in nanoscale range, this technique is an appropriated metrology tool in semiconductor industry. The validation experiments were performed at the National Synchrotron Radiation Research Center (NSRRC) with a small-angle X-ray scattering (SAXS) instrument. In this experiment, we obtained the pitch sizes of the grating based on slopes from the linear fitting of the plots of the diffraction peaks and wavenumbers. The obtained pitches are 141 nm, 273 nm, and 413 nm respectively.

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