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Optimization of Nano-Grating Pitch Evaluation Method Based on Line Edge Roughness Analysis

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Pitch uncertainty and line edge roughness are among the critical quality attributes of a pitch standard and normally the analyses of these two parameters are separate. The analysis of self-traceable Cr atom lithography nano-gratings shows a positive relevance and sensitivity between LER and evaluated standard deviation of pitch. Therefore, LER can be used as an aided pre-evaluation parameter for the pitch calculation method, such as the gravity center method or the zero-crossing points method. The optimization of the nano-grating evaluation method helps to obtain the accurate pitch value with fewer measurements and provide a comprehensive characterization of pitch standards.

Keywords: Pitch evaluation, nano-grating standard, line edge roughness, atomic force microscope.

1. INTRODUCTION

Lateral pitch standards, such as one-dimensional or two dimensional nano-gratings, are widely used as transfer standards to calibrate the nonlinearity or image magnification for all kinds of microscopes [1]. Many nanofabrication methods have been utilized to fabricate lateral pitch structures, including e-beam lithography, multilayer gratings [2], [3], atom lithography [4]-[6], atom-based rulers [7]-[9], and so on. Before the nanoscale pitch structures can be used as transfer standards, pitch uncertainties need to be measured with metrological AFMs and estimated with the effective pitch evaluation methods [10].

Effective pitch evaluation method is one of the key factors to lower the calculated pitch uncertainty, thereby increasing the calibration accuracy [11], [12]. The Gravity Center (GC) method [1], [13], [14], Zero Cross Points (ZCP) method [11] and Fourier Transform (FT) method [1], [15], [16] are the most commonly used pitch evaluation methods for one/two dimensional nano-grating standards. As a kind of pitch calculation method based on the real nano-grating profiles, the uncertainty of measurement results with GC or ZCP method relies on the selection of effective profiles. Therefore, optimization of effective profile selection for GC or ZCP methods offers a new way to increase the calibration accuracy of pitch standards.

Normally, line edge roughness (LER) refers to the randomly varied edges of critical dimensions (CD) of grate patterns [17]. Previous study has noted the importance of LER as a critical quality attribute of the pitch: a reference line with lower LER can achieve the same accuracy with fewer measurements [18]. Motivated by this concept, in this paper, we have introduced LER as a reference evaluation parameter for the pitch evaluation of one-dimensional self-traceable Cr atom lithography nano-gratings. The analysis shows that there is a positive correlation between LER and evaluated standard deviation of pitch of AFM measurement data, which provides key evidence for the effective profile selection during the pitch evaluation process and further increases the pitch calibration accuracy.

2. THEORIES

A. *Pitch evaluation method with LER*

Two profile-based methods are utilized in this paper: GC method and ZCP method, which are illustrated in Fig.1.a). First, a threshold line is set to divide the nano-grating profiles into two parts. For the GC method [1], [11]-[13], the geometrical center above the threshold line is treated as the gravity center; the distance of two neighboring gravity centers is defined as the pitch. For the ZCP method [11], [12], zero cross points are the intersection points between the threshold line and profile curves of the nano-grating pattern. The middle point of a pair of zero crossing points on each nano-grating pattern is treated as the geometric center point. Then the pitch values of the ZCP method are defined as the distance between neighboring middle points.

The profile cutting proportion (p), which is the profile below the threshold line, plays a critical role in pitch uncertainty estimation. Generally, the profile cutting

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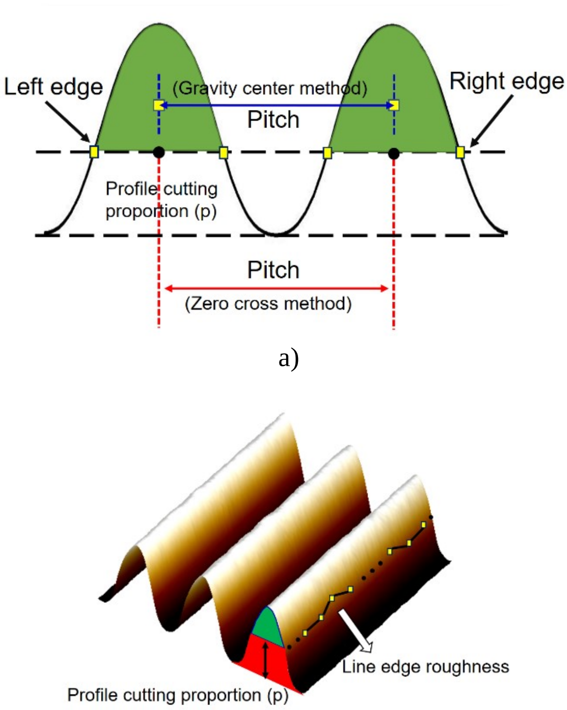
proportion is set to be 50 % of the peak to valley height (PTVH) as a tradition, but whether 50 % is the best or not has not been elucidated clearly yet. If we expand the threshold line to a plane at the same height, then we get intersecting lines along the nano-grating edges, as demonstrated in Fig.1.b).



a)

b)

Fig.1. a) Schematic of the Gravity Center method and the Zero Cross Method; b) Definition of line edge roughness of Cr atom lithography nano-gratings.

The LER describes the variation of the crossing points, which will provide effective information to select the best profile cutting proportion and, thereby, minimize the evaluated standard deviation of pitch. The average edge and the standard deviation (σ) of the line edge are defined as follows [18]:

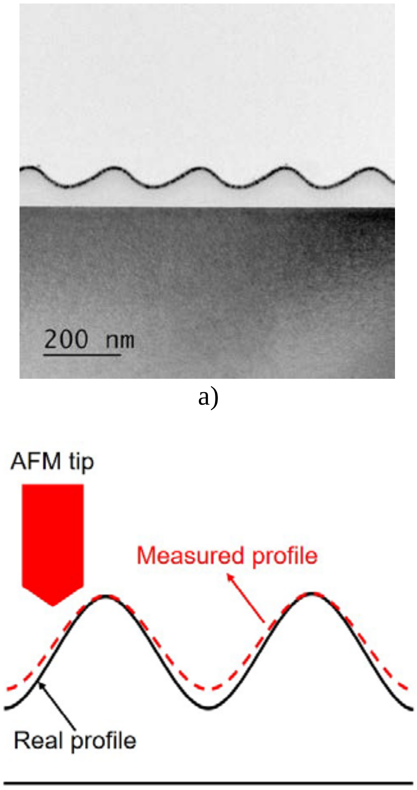
$$\begin{cases} \bar{x} = \dfrac{\left(\sum_{i=1}^{N} x_i\right)}{N} \\ 3\sigma = 3\sqrt{\dfrac{\sum_{i=1}^{N} \Delta x_i^2}{N-1}} = 3\sqrt{\dfrac{\sum_{i=1}^{N} (x_i - \bar{x})^2}{N-1}} \end{cases} \qquad (1)$$

Where x_i is the position measured of the *i*th point along the line edge. Normally, LER must be reported as 3 σ of the total, and in our case, we will investigate the LER of both edges over a length of L, and every time L is divided into 20 spacings apart. Then we obtained 21 measured positions to calculate the LER. The length L is assigned to be 0.5P, 1P, 2P, 3P, 4P, respectively, where P is the nominal pitch (212.8 nm).

B. Cr atom lithography nano-gratings

The nano-gratings used here are fabricated by laser focused Cr atomic deposition [4], [5], [19], i.e., the so-called Cr atom lithography nano-gratings. The detail experimental setup is described elsewhere [20], [21]. During the Cr nano-grating fabrication process, collimated Cr atoms are focused to the nodes or antinodes of a standing wave grazing across the substrate surface. So, the period of the Cr nano-gratings (212.8 nm) is directly traceable to the half of the laser light wavelength, which is strictly locked to specified atomic level transitions. In this way, the Cr atom lithography nano-gratings can be used as self-traceable calibration length standard in nanotechnology.

The profile of Cr nano-gratings has an advantage of reducing the image distortion caused by the tip effect, which offers great convenience for the LER analysis. The images obtained by the AFM normally are a combination of tip geometry and sample surface. The linewidth is normally broadened due to the resulting dilation of the tip. Fig.2.a) is the cross section TEM image of Cr atom lithography nano-gratings, the height to width ratio is relatively low, so the measured profile can reduce the tip effect and reveal the real profile to the full extent, as illustrated in Fig.2.b).



a)

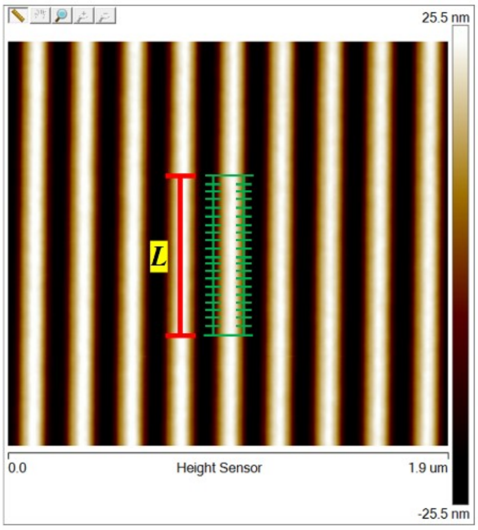
b)

Fig.2. a) Cross section TEM image of Cr nano-gratings; b) The discrepancy between measured profile and real profile of AFM measurement for Cr nano-gratings.

3. LINE EDGE ROUGHNESS ANALYSIS

A. *Line edge roughness of Cr nano-gratings*

Fig..3 shows the AFM image and grating profile of Cr nano-gratings used for the line edge roughness analysis. The selected PTVH is around 50 nm with very smooth and uniform parallel lines in Fig.3.a) and Fig.3.b). The original pixel size of the image is 488×450, we did the data interpolation and low pass filter to eliminate the imaging noise [1]. As mentioned before, the LER is calculated over left and right edges of a length L which is divided into 20 spacings apart (Fig.3.a)). The LER analysis results of this AFM image are typical and representative in similar image calculations.



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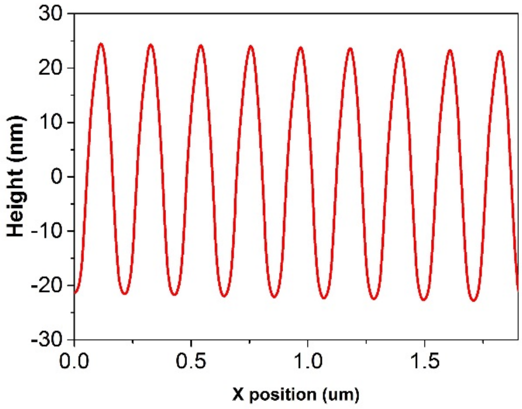
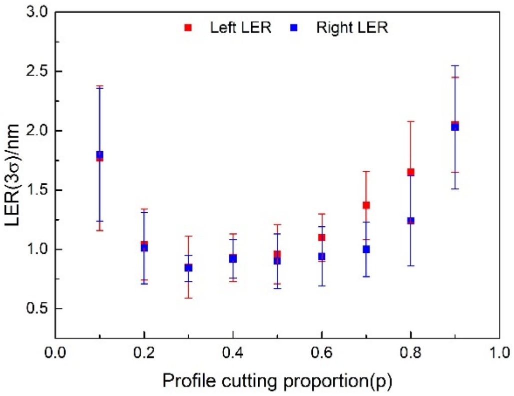


b)

Fig.3. a) AFM image of Cr nano-gratings (1.9 µm×1.75 µm); b) AFM profile of Cr nano-gratings with a peak to valley height of around 50 nm.

Fig.4.a) shows the 3 σ LER of left and right edges as a function of profile cutting proportion (p), and the calculation length L of the LER is P (212.8 nm). Here the profile cutting proportion (p) is the profile below the threshold line in Fig.1.a). It is obvious that the LER keeps at a very low level (below 1 nm) when p ranges from 0.2 to 0.6 and the minimum LER appears at p=0.3 of these discrete value assignments, which verified the speculation about the best p selection. The LER will increase when p decreases to 0.1 due to increased randomness of the laser focused Cr structures at the top. The same trend appears when p increases to 0.9, together with the increased discrepancy between left LER and right LER, which are highly possibly caused by the AFM scanning distortion induced by the tip effect. In addition, it should be noted that the LER of p<0.5 of left and right edges are almost identical even with a slightly asymmetric structure, which may be an evidence to explain why the self-traceable Cr nano-gratings have an advantage of low uncertainty.



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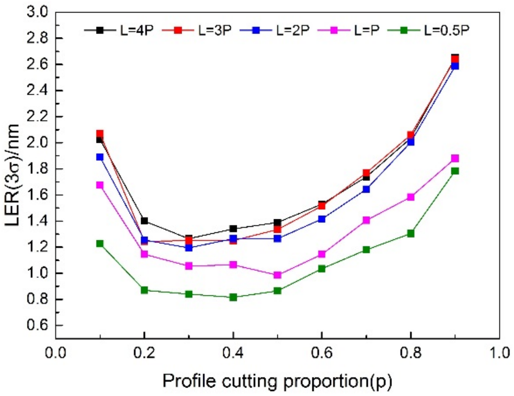


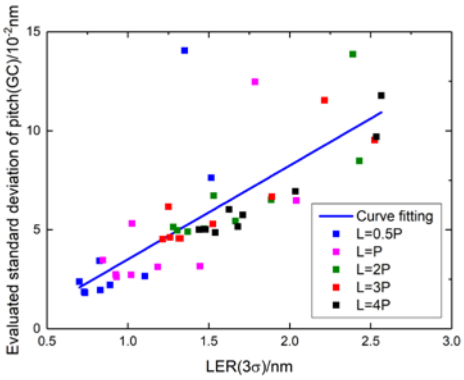
b)

Fig.4. a) Left and Right LER as a function of profile cutting proportion; b) Average LER as a function of profile cutting proportion over different calculation length (0.5P~4P).

Fig.4.b) demonstrates the average LER of left and right edges as a function of profile cutting proportion over different calculation length ranging from 0.5P to 4P. The similar distribution phenomenon shows up over different calculation length in Fig.4.a). As the calculation length increases from 0.5P to 2P, the average LER rises gradually; but after the length exceeds 2P to 4P, the average LER keeps stable without obvious increase. This indicates that a calculation length of 2P (425.6 nm) is long enough to evaluate the maximum LER level of the laser focused Cr atomic nano-gratings.

B. The relationship between line edge roughness and evaluated standard deviation of pitch

Next, we examined the relationship between lined edge roughness and the evaluated standard deviation of pitch. The AFM images we calculated were acquired by a commercial AFM (Bruker, Dimension Edge), which is non-metrological. As we introduced in the context, the Cr atom lithography nano-grating used here is self-traceable, its pitch is expected to be 212.8 nm. Jabez. J. McClelland has even examined the average pitch of Cr nano-gratings by optical diffraction method, which turned out to be 212.7777±0.0069 nm, with a relative uncertainty of a few times 10^{-5} [22]. Therefore, we corrected the calculated average pitch to 212.8 nm and got the evaluated standard deviation of pitch by a correction coefficient.



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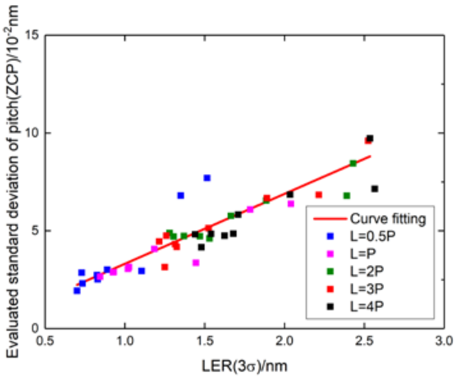

b)

Fig.5. Relationship between LER with evaluated standard deviations of pitch calculated by a) Gravity center method; b) Zero cross points method.

Fig.5. shows the corresponding evaluated standard deviations of pitch under every LER condition over different calculation lengths varying from 0.5P to 4P. Fig.5.a) and Fig.5.b) are the results of the gravity center method and the zero-crossing points method, respectively. From both figures, it is obvious that there is a positive correlation between LER and evaluated standard deviation of pitch, and the relationship tends to be linear. Compared with the ZCP method, the sensitivity scale of evaluated standard deviation of pitch on LER based on the GC method is a little bit higher. The reason for this discrepancy is the difference between GC and ZCP method. In the ZCP method, only the LER information at the reference line are involved in the pitch calculation, while in the GC method all the LER information above the reference line are contained inside. Though some of the lined edge randomness is neutralized because of the nano-gratings' symmetry, the top part of the nano-grating (for example, 10 % of the top profile) has lower symmetry and higher LER as demonstrated in Fig.4.a). The relationship of LER and evaluated standard deviation of pitch determines that LER can be used as an aided pre-evaluated parameter for the pitch evaluation method, which offers a more comprehensive evaluation result for the pitch standards.

C. Pitch evaluation method optimization

The fundamental pitch distance, the pitch uniformity, the quality of the LER and the accuracy of the certified pitch value, and the traceability are the most critical qualities which attribute a pitch standard [18]. From the analysis of self-traceable Cr nano-gratings, there is a strong positive correlation between LER and evaluated standard deviation of pitch. Based on the relevance of these two parameters, it is suggested to introduce LER calculation as an aided pre-evaluation parameter for the pitch calculation method, especially for best profile cutting proportion selection during GC or ZCP method. This not only helps to obtain the accurate pitch value with fewer averaging sample measurements, but also helps to extract more accurate pitch evaluation information with the same experimental data. At the same time, together with evaluated standard deviation of pitch, LER analysis offers a comprehensive evaluation about the critical qualities of a pitch, such as the accuracy and the uniformity characteristics.

4. CONCLUSIONS

In this paper, a LER analysis of self-traceable Cr nano-gratings was conducted to show the relevance between the LER and evaluated standard deviation of pitch in the pitch evaluation method (i.e. gravity center method and zero cross points method). The results demonstrate a positive correlation between LER and the evaluated standard deviation of pitch, which indicates that LER can be used as an aided pre-evaluation parameter for pitch calculation method, especially for effective profile cutting proportion selection for GC or ZCP method. The optimization of the nano-grating pitch evaluation method based on LER would offer convenience to obtain the accurate pitch value with fewer measurements and provide a comprehensive evaluation about the critical qualities of pitch standards.

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