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Measurement and characterization of a nano-scale multiple-step height sample using a stylus profiler

Changsheng Li[a], Shuming Yang[a,*], Yiming Wang[a], Chenying Wang[b], Wei Ren[b], Zhuangde Jiang[a]

[a] State Key Laboratory of Mechanical Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
[b] Electronic Material Research Laboratory, Key Laboratory of the Ministry of Education & International Center for Dielectric Research, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

In this paper, we discussed a method for the measurement and characterization of a three-step height sample using a stylus profiler. The original measurement data were processed by a polynomial fitting based algorithm to reduce low frequency artefacts. A low pass filter with the cutoff frequency of 0.8/μm was used to remove the high frequency noise, and a ten order polynomial was used to effectively remove the low frequency artefacts. The experimental results indicated that the uncertainties of the step heights were between 1 nm and 2.2 nm. Furthermore, the deposition rate of the step films with uncertainty was calculated as an application of the sample measurement. The results indicate that the deposition rate for the step films based on the measurement of the stylus profiler was consistent with that of a spectroscopic ellipsometer.

1. Introduction

For nano-scale measurements, instruments or equipment are normally calibrated by standard samples with nano-scale features. There have been some nano-scale step height standard samples [1–8], but nearly all of them are single step samples. The instruments are necessary to be calibrated before measurements using different height values due to the nonlinearity [9–11]. It is much more convenient to calibrate using a multiple-step height standard because the number of times of positioning the probe or stylus can be reduced and the calibration efficiency can be improved. AFM and stylus profiler are two typical instruments that are widely used to measure nano-scale structures and devices [12,13]. The scanning range of stylus profiler is much larger than AFM and the stylus profiler is not so sensitive to the contaminations of the sample. However, stylus profiler suffers more noise and is more sensitive to environmental conditions. Spectroscopic ellipsometer [14], UV/visible spectrophotometer [15] and spectroscopic reflectometry [16,17] can be used to measure the deposition rate of the nano-films, but are sensitive to the physical properties of material and the fitting model, so the deposition rate of the films does not contain uncertainty. We have reported a three-step height sample at nano-scale for AFM calibration [18]. It focused on the determination of the parameters effectively eliminating or reducing the influence of AFM artefacts such as particles, image bow and high order error on step height.

In this paper, the data processing method and measurement results of stylus profiler were discussed. And the deposition rate of the step films with uncertainty was calculated as an application of the step height measurement.

2. Measurement and characterization

2.1. Stylus profiler measurements

The three-step height samples with nominal values of 8 nm, 18 nm and 26 nm were composed of the calibration structures consisting of lines or grooves and the guiding structures, as shown in Fig. 1, where $h_1 = 18$ nm and $h_2 = 8$ nm. The three-step height sample was measured by stylus profiler (XP-2, AMBIOS, USA). The load force of the stylus was 0.05 mg, and the scanning speed was 0.0435 mm/s. The scanning length of the step height samples was 2 mm to cover all the three steps in the left part to avoid repositioning the sample. Five regions evenly distributed along the calibration

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* Corresponding author.
E-mail addresses: li.changsheng@stu.xjtu.edu.cn (C. Li), shuming.yang@mail.xjtu.edu.cn (S. Yang), wangyiming@stu.xjtu.edu.cn (Y. Wang), wangchenying@mail.xjtu.edu.cn (C. Wang), wren@mail.xjtu.edu.cn (W. Ren), zdjiang@mail.xjtu.edu.c (Z. Jiang).

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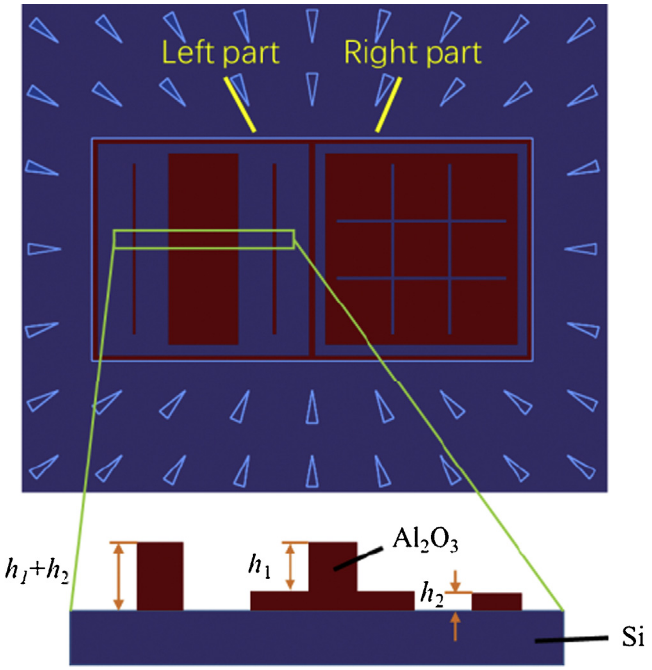

Fig. 1. The structure of the three-step height samples.

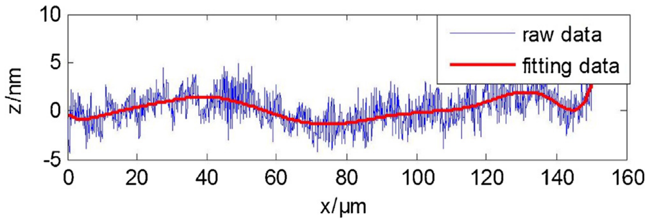

Fig. 2. The scanning profile measured by the stylus profiler.

lines were measured. Before measurements, the stylus profiler was calibrated by three SHS step height standards (AutoloadTM Thin, VLSI Standards, Inc., USA) with the nominal height of 8 nm, 18 nm and 44 nm, and the measurement parameters were identical to that of the three-step height sample to improve the measurement accuracy.

The polynomial fitting based algorithm was used to evaluate the step heights of the sample. Firstly, the particles and pits on the sample surface were removed by the fitting method. Secondly, the right and left edges were detected by the Canny edge detector. The profile was divided into the left, the right and the middle parts. Finally, the low frequency components were removed or reduced by polynomial fitting. The middle part of the profile was shifted up (for the grooves) or down (for the lines) by the optimal shifting distance before fitting, and the optimal shifting distance made the norm of the fitting residue vector minimal. After subtracting the raw profile by the fitted polynomial, the step height can be calculated according to ISO 5436.

The scanning profile of the stylus profiler was shown in Fig. 2. It was clearly that the stylus profiler measurement data suffered from both low frequency artefacts and high frequency noises. The low frequency artefacts can be approximated by a polynomial, and the high frequency noise can be removed by a low pass filter. In order to investigate the frequency of the stylus profiler noise, the power spectrum density (PSD) of the scanning profile of the stylus profiler was calculated and shown in Fig. 3a. Both low frequency components and a lot of high frequency components larger than 0.8/μm existed in the PSD. Because many PSD peaks distributed in the low frequency range, a high order polynomial fitting should be used to effectively remove the low frequency components. The high frequency components larger than 0.8/μm included noise and roughness information. By comparing the PSD of the profile measured by stylus profiler with that of AFM shown in Fig. 3b, we found that all the frequency peaks of stylus profiler larger than 0.8/μm originated from noise. Roughness had weak influence on the evaluation of the step height.

The PSD peak frequencies of the scanning profiles of the stylus profiler in different environment conditions were shown in Fig. 4, to determine the appropriate filter cutoff frequency and investigate the influence of the environmental vibration on the stylus profiler. The peaks at 1.61/μm and 3.22/μm appeared when the vacuum pump of the lithography machine was turned on, and the peak at 1.07/μm appeared in the last profile. The scanning speed of the stylus profiler was 0.0435 mm/s, and the rotate speed of the vacuum pump was 1400 r/min at 23.33 Hz, so the frequency induced by the pump was $23.33/(0.0435 \times 1000) = 0.5364/\mu m$. The frequency peaks of 1.07/μm, 1.61/μm and 3.22/μm were two times, three times and six times of 0.5346/μm respectively, which indicates that these frequency components were induced by the vacuum pump.

The stylus profiler was very sensitive to the environmental vibration whose frequency was tens of Hz, so the stylus profiler need be mounted onto a vibration isolation platform or placed on a quiet place, and a low pass filter need be used to calculate the step height accurately. It was shown in Fig. 4 that almost all the frequency of the noise was larger than 0.8/μm, so the cutoff frequency was set to be 0.8/μm.

2.2. Determination of fitting parameters

The fitting parameters were carefully determined. As shown in Fig. 5, the minimal norm corresponding to the optimal shifting distance decreased with the increase of the polynomial order and finally became stable. After the processing of large volumes of data, we found that the stable polynomial order of the stylus profiler was 4–8, so the polynomial order of stylus profiler was set as 10 to effectively remove the low frequency artefacts. As shown in Fig. 6, the step height became stable if the polynomial order was 10, which indicates that the low frequency artefacts were effectively removed.

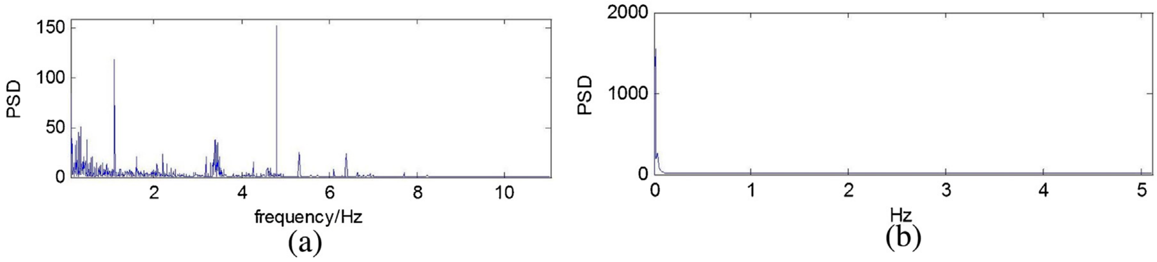

FIG. 3. The PSD of the scanning profile of the stylus profiler (a) and the AFM (b).