Automated Measurement and Analysis of Sidewall Roughness (SWR) Using 3D-AFM

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Abstract

As the semiconductor device architecture develops, from planar field-effect transistor (FET) to FinFET and toward gate all around (GAA), it is more needed to measure 3D structure sidewall precisely. Here, we present a 3D-atomic force microscopy (3D-AFM) by Park Systems Corp., a powerful 3D metrology tool to measure SWR of vertical and undercut structures. First, we measured 3 different dies repeatedly to calculate reproducibility in die level. Reproducible results were derived with relative standard deviation under 2%. Second, we measured 13 different dies, including the center and edge of the wafer, to analyze SWR distribution in wafer level and reliable results were measured. And all analysis was performed using a novel algorithm including auto flattening, sidewall detection, and SWR calculation. In addition, SWR automatic analysis software was implemented to reduce analysis time and to provide standard analysis. The result suggests that our 3D-AFM based on tilted Z scanner enabled an advanced methodology for automated 3D measurement and analysis.

Introduction

1. Necessity of AFM in Semiconductor Indus-try

Since the architecture of the device and the integrated circuit has been developed and a high-performance device is required, it is necessary to measure complex 3D structures such as FinFET devices, 3D NAND flash memory. Compared to other metrologies, atomic force microscopy (AFM) can measure the topography, roughness, angle of the structure by non-destructive measurement with the advantage in high-resolution measure-ment, reproducibility, and reliability [1–6]. AFM is a research tool that can be applied to various fields such as materials science, life science, and metrology, including the semiconductor industry [7]. However, in the semiconductor industry, AFM has a limitation in measurement time. Therefore, AFM industry has been researching on reducing the takt time.

In front end of line (FEOL) EUV photolitho-graphy, the most important technology for the next generation semiconductor chip, SWR optimization and measurement are critical with the line width scales down. Since high SWR reduce the electrical characteristics of the circuit made through the pattern, it is essential to control SWR with precise measurement methodologies [8].

Also, in middle end of line (MEOL) packaging technology, through silicon via (TSV) can cause ineffective charging, yield loss due to rough sidewall (scalloped sidewall) and can lead to long-term device reliability problems. Therefore, the role of 3D-AFM that can measure SWR is crucial in the semiconductor industry [9].

It is reported that SEM is a semiconductor in-line metrology equipment, and it occupies a high proportion as a metrology tool for measuring critical dimension (CD), defect, and particle de-tection in International Roadmap Devices and Systems 2020 Metrology [10]. However, SEM cannot measure CD at the level of 10 nm or less due to its limitation in resolution. And it also has limitations in the destructive sampling process, defects by e-beams, and charging effect. Com-pared to SEM, AFM is a non-destructive metrology tool and has the advantage of measuring CD of 5 nm or less in the isolated line. In addition, surface roughness measurement with AFM, a high-resolution measuring equipment, can accu-rately measure SWR.

1-2. About 3D-AFM

One of the fundamental measurement modes in AFM is “Contact Mode”. The “Contact mode” utilizes the AFM tip to be in contact with the sample and obtains various properties: resis-tance, elasticity, topography, conductivity, and electrostatic. But tip wear and sample damage may occur.
The other mode, "True Non-Contact Mode", obtains a 3D nanostructured surface data through measuring the van der Waals forces between tip and sample. The “True Non-Contact Mode” has the advantage of preventing tip wear so that the tip sharpness can be maintained throughout the measurement. Also, sample damage is minimized so that the high-resolution image of the sample can be obtained uniformly and accurately.
Normal AFMs, whether using “Contact Mode” or “True Non-Contact Mode”, measures samples only perpendicularly and have limitations in measuring 3D information of sidewalls. Unlike normal AFM, 3D-AFM used in this paper utilizes a tiltable Z scanner as Fig. 1. The Z scanner can be tilted to left or right to measure proper 3D information of sidewalls. Through a tiltable Z scanner, our 3D-AFM can measure not only vertical structures but also undercut structures regardless of the shape [11].

As detailed in Fig. 2, the Z scanner can be tilted up to 38° left or right from the perpendicular axis (θ) and can measure the side of the pattern in direction Z’. Note that angle (α) is the angle of the pattern. In normal cases, the sample is vertical, and angle α will be 90°.

Since the AFM tip is attached on the bottom of the Z scanner, we can obtain the desired value X with Z’ and θ. If the Z scanner is tilted to the right by θ, we can measure the displacement of tilted Z scanner, Z’, with AFM system. By multiplying the sin θ with Z’, we can get X = Z’·sin θ.

$$\alpha = 90^\circ$$

$$X = Z' \cdot \sin\theta$$

Experimental

To analyze and compare the repeatability and reproductivity of equipment of 3D-AFM (Park Systems Corp., Republic of Korea), We measured sidewall surface with Z scanner tilting function. As depicted in Fig. 1, Z scanner is tiltable from left 38° to right 38°, totally 76°. Also, 3D-AFM is for industrial, not only full-automation wafer measurement but also customized measurement is possible.

For the SWR measurement, in Fig. 3, we used NCLR (Non-contact / Tapping™ mode - Long Cantilever - Reflex coating type, NanoWorld®, Switzerland) tip. The NCLR tip was customized to reduce hardware interference caused by tilting the Z scanner.

We measured the Metrocal wafer (MetroBoost, USA) with a continuous pattern to reduce the variation caused by non-uniform samples and measured the right side of the repeated pattern.

Since 3D-AFM is for industrial, we loaded the sample onto the sample chuck by equipment front end module (EFEM). The tip was auto-matically positioned at the precise measurement location from wafer step by step. That is con-sisted of approaching, pattern matching and reference scan. Then, we measured sequentially sidewall via the set parameters.

To confirm reproducibility in Non-Contact mode, We repeated roughness measurement 15 times per each 3 wafer dies. Also, we performed 13 wafer dies measurement comparisons to analyze the SWR distribution over the entire wafer area.

We developed algorithm of the SWR automatic analysis program in Fig. 4 which has 4 processes to increase user convenience and reduce the time required for analysis. At first, we selected the image ("Select Image") for analysis. Secondly, we extracted the centerline from the image after Pre-Process, that consists of flatten and filtering. Then, in the extracted line, we defined sidewall depending on the height values. Thirdly, we cropped the “Detect Sidewall Region” area from the entire image. In the end, we achieved the roughness, Rq, after correcting the tilt angle of the AFM Z scanner.

Results And Discussion

The roughness of a sample is an indicator of the roughness or smoothness of the sample surface. Roughness is specified as Rq, in this paper.

Rq: RMS (Root Mean Square) Roughness

$$\mathrm{Rq} = \sqrt{\frac{1}{L}\int_0^L z^2(x)\,dx}$$

q = Quadratic: 2nd Order Polynomial (x^2)

The result of measuring the right sidewall of the pattern is shown as an automatically 3D rendered image in Fig. 5 (a). The 3D rendered image clearly shows the difference in the roughness of each region through the topographic image, dividing the structure into top, sidewall (right sidewall), and bottom. In Fig. 5 (b), line profile measurement was performed after defining each line of region. In the profile of measured line, the Rq of the sidewall line was 1.376 nm, which was rougher than the top line and bottom line. In addition, the Rq of the top line is 0.522 nm and the Rq of the bottom line is 0.218 nm, indicating that the surface is gradually smoothing.

Fig. 5 (c), a 2D image of Fig. 5 (a), was achieved by a post-processing technique that first order flattens the measured 3D image. Then, the 2D image is divided into three regions, top, sidewall, and bottom. Since the image of the sidewall is relatively rough compared to other parts, sidewall can also be distinguished by the difference in image contrast.

As in Fig. 6, to demonstrate the reproducibility of SWR measurements using 3D-AFM, 15 repetitive measurements were performed per identical location on point 1, point 2, and point 3, randomly selected from three locations on the wafer dies.

As a result, in the point 1, mean roughness (Rq) was measured as 2.26 nm, with standard deviation of 0.051 nm, and RMS value with 2.26%. For the point 2, the mean roughness (Rq) was 1.479 nm, with standard deviation of 0.023 nm, and RMS value with 1.56%. For the point 3, the mean roughness (Rq) was measured as 1.124 nm, with standard deviation of 0.016 nm, and RMS value with 1.42%.

From the measurement results, it was found that the RMS value was close to 2% at all measurement positions in the wafer level, and the reproducibility of the measurement was proved based on these results. Accordingly, the Z scanner tilting technique for 3D measurement has high reproducibility, and it has been demonstrated that the measurement method and the structural stability of the equipment are powerful [13].

Above all, even if in the same pattern in single wafer, not only the topography but also the roughness is different depending on the die. The SWR analysis results of measurement points 1, 2 and 3 are distributed as 2.37 nm, 1.67 nm, and 1.23 nm.

After confirming the reproducibility, total of 13 points was measured to compare the overall measurement results of the 300 mm wafer as shown in Fig. 7 (a). Including the center and edge of the wafer, 13 dies were selected, and we measured the same pattern 1 time per each die. As a result, the SWR, Rq, was distributed in 1.124 ~ 2.260 nm. The measured Rq for the entire wafer is distributed as Fig. 7 (b).

Fig. 8 shows the actual analysis result of the developed SWR automatic analysis program. When a raw image is selected, it automatically detects the sidewall with a process developed by the user, and it calculates a roughness value. As shown in Fig. 8 (a), either left or right sidewall of the pattern analysis is possible. Also, even in a repeated trench structure, multi-sides can be detected as shown in Fig. 8 (b).

Furthermore, as in Fig. 8, SWR automatic analysis program defines the maximum value (top of structure) and minimum value (bottom of structure) of the structure height which is used to define the sidewall to be analyzed according to the amount of data desired. After the sidewall is defined, the roughness of the region can be calculated.

The devised algorithm also presents a methodology for analyzing SWR by introducing the basic idea of detecting an inflection point to exclude variations in the measurement sample as shown in Fig. 9. The measurement result shown in Fig. 9 (a) is suitable for use in the existing method of detecting sidewall by obtaining the max and min values of the sample height. In contrast, if the top and bottom of the structure are not flat as shown in Fig. 9 (b), the existing method cannot accurately detect the sidewall. Therefore, the improved algorithm enables accurate sidewall detection even in difficult-to-analyze samples or environments, so an improved algorithm that can obtain the same analysis results in both Fig. 9 (a) and (b).

Conclusions

In the semiconductor industry, the productivity of metrology tools is directly related to measure-ment speed and measurement reliability. Here, we implemented a fully automated 3D-AFM with an SWR automatic analysis program to measure and evaluate the SWR of the vertical patterns.

Compared to previous studies, with 3D-AFM, SWR could be measured at a deeper angle, with high reproducibility of under 2%. Since this 3D-AFM is a fully automated AFM system, this study showed a new possibility of industrial-level 3D-AFM usage. Compared to normal AFMs, 3D-AFM can measure not only SWR but also several 3D structures such as undercut of samples. With the fully automated 3D-AFM, we expect further usage in several challenging measurement appli-cations at the industrial level.

The SWR automatic analysis program enabled SWR calculation without manually defining the sidewall regions. Also, with the feature of auto-flattening, the raw image could be processed automatically. The overall processing time of SWR analysis took under 2 seconds per image. Here, we showed the possibility of implementing an automatic SWR analysis algorithm in many fabrication processes such as TSV, EUV, and GAA. With optimizing the algorithm and additional implementation of GPU, we expect the further reducing analysis time of the SWR automatic analysis program.

Declarations

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Authors' contributions

Su-Been Yoo: Contributions to the investigation, manuscript writing, data acquisition, analysis, and interpretation. Seong-Hun Yun: Contributions to the conception, editing, data acquisition, analysis, and interpretation. Ah-Jin Jo: Contributions to the conception, editing. Jun-Ho Lee, Sang-Joon Cho: Contributions to the review, editing. Haneol Cho: Contribution to the AFM measurement, analysis. Byoung-Woon Ahn: Corresponding author, contributions to the review, editing as project administration. The authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

3D and 2D modeling about the Z scanner tilting motion of 3D-AFM [12].

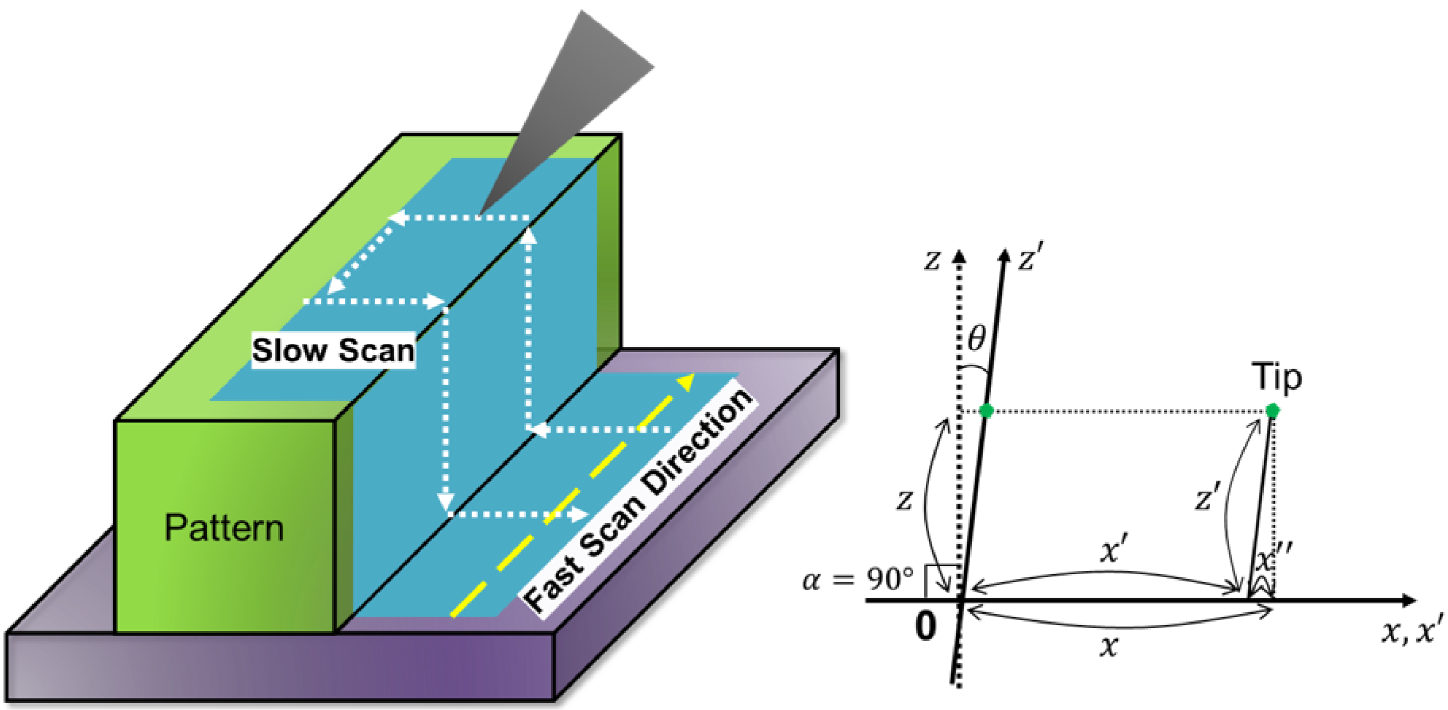

Figure 2

Detail of measurement position and principle of 3D-AFM Z scanner tilting sequence.

(a)

Cantilever Data	Value
Resonance Frequency	190 kHz
Force Constant	48 N/m
Length	225 μm
Mean Width	38 μm
Thickness	7 μm

(b)

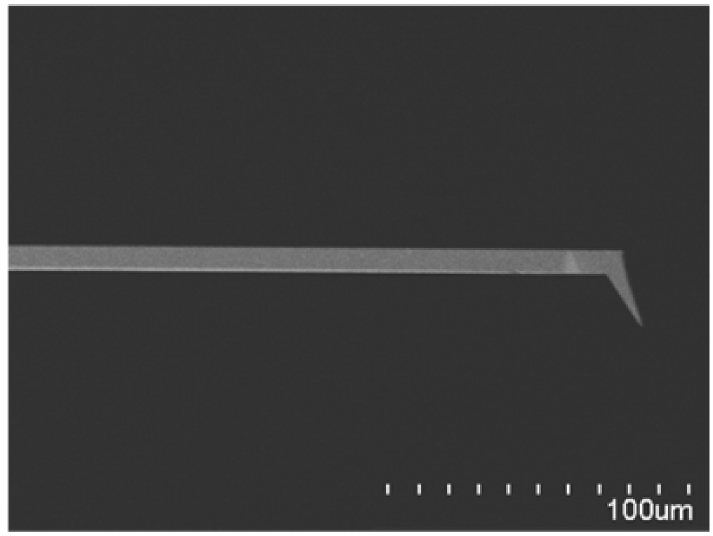

Figure 3

NCLR tip information. (a) Detailed specification [12]. (b) SEM analysis of tip side view.

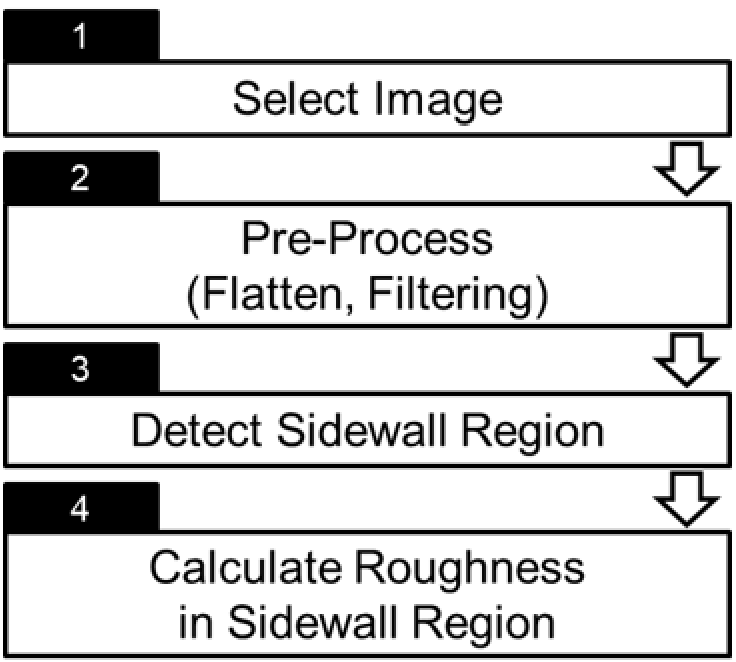

Figure 4

Basic algorithm of the SWR automatic analysis program.

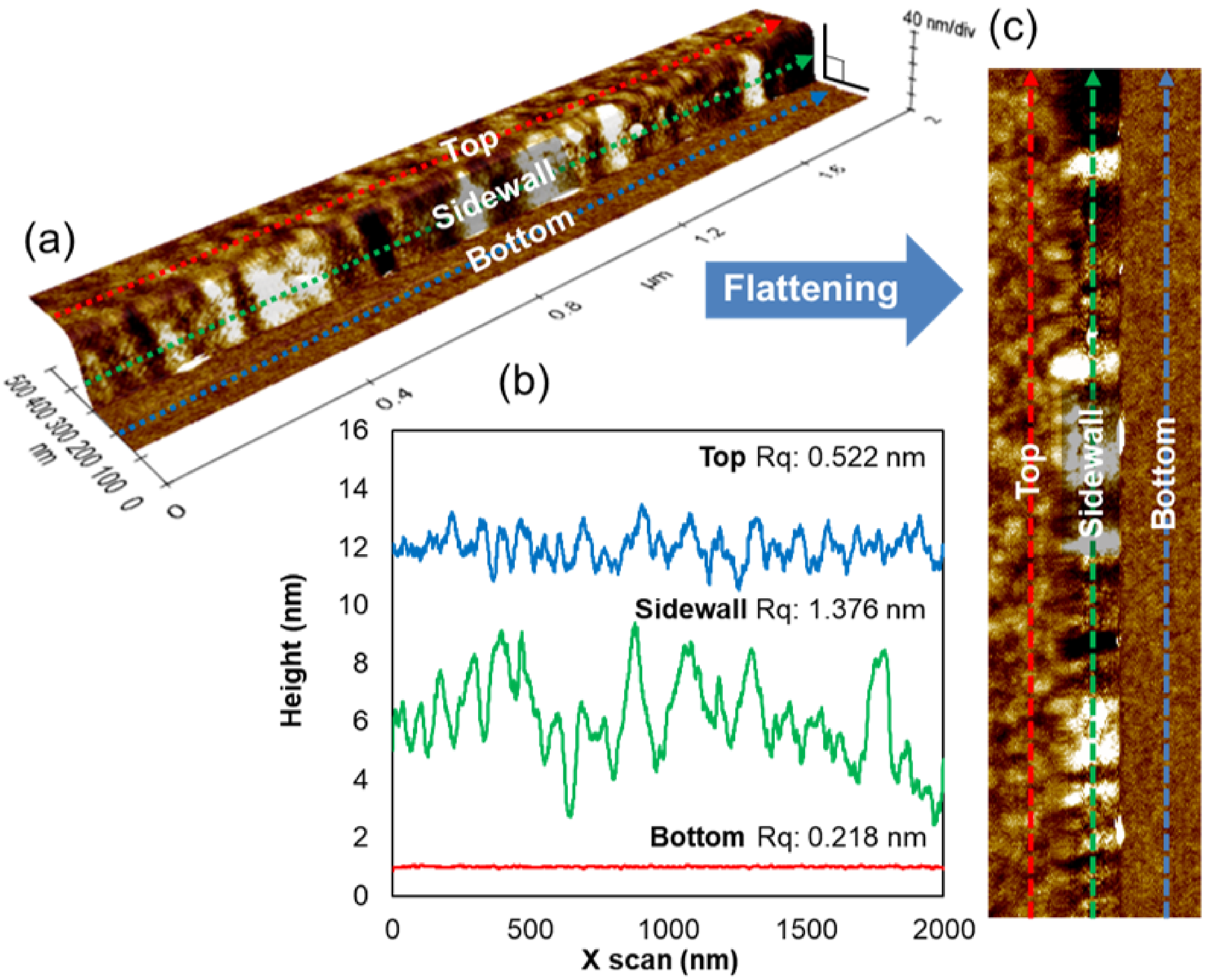

Figure 5

Pattern SWR measurements. (a) 3D image of a line constructed from 128 sequential line scans in the Y direction. (b) Height profiles from selected scan line of each side indicate the variation in surface roughness. (c) 2D plot of surface roughness based on first order flattening of line scan direction.

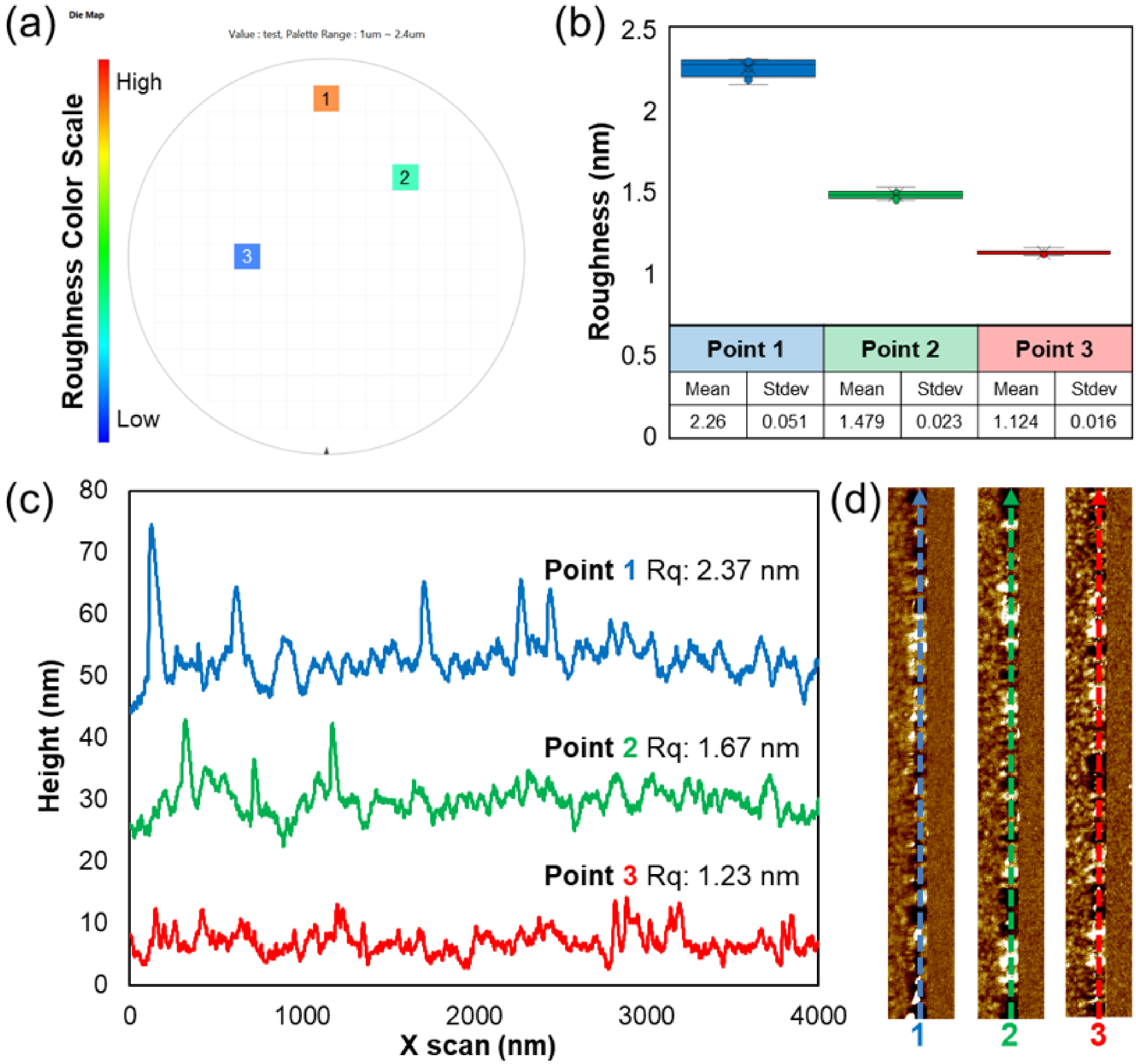

Figure 6

The 15 repetitive measurements of SWR on point 1, 2, and 3, randomly selected from three locations on the wafer dies. (a) The die map of the color scale regarding to the average measurement result. (b) Average and standard deviation results of SWR. (c) Line profile for each measuring point (d) AFM images after first order flattening of line scan direction.

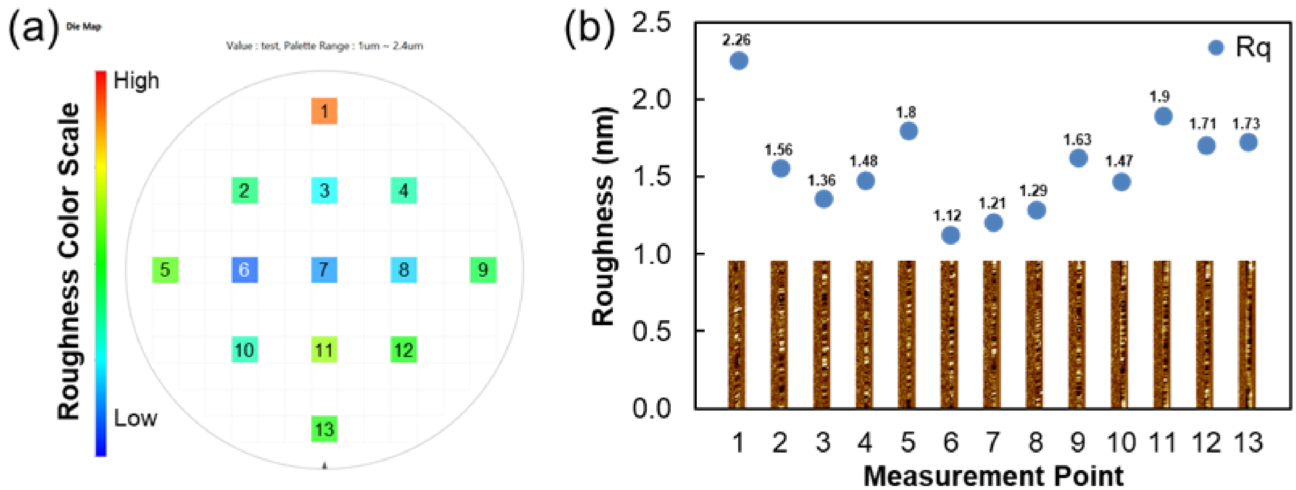

Figure 7

Comparison measurement of 13 points. (a) The die map of the color scale regarding to the average measurement results. (b) Rq results and AFM images after first order flattening of line scans.

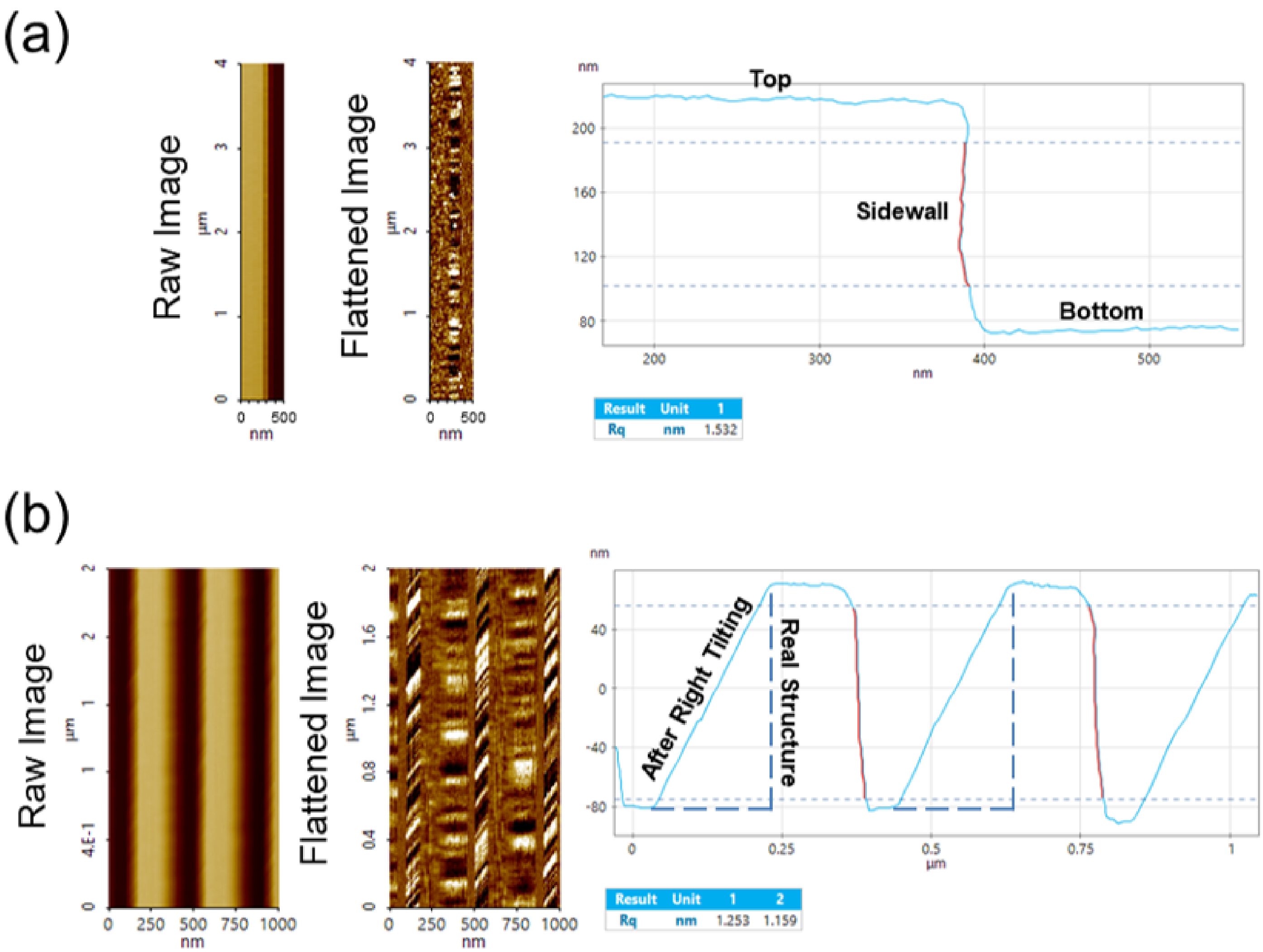

Figure 8

Example of SWR automatic analysis program operation screen including 1. raw image, 2. 2D plot based on first order flattening of line scans, 3. structure topography and 4. Rq results. (a) One side. (b) Multi side.

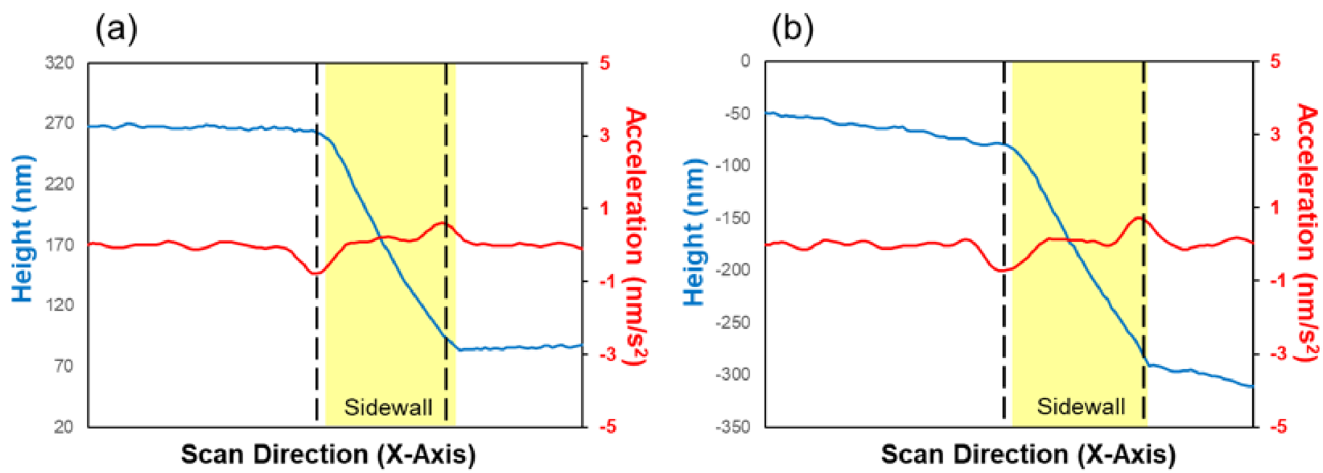

Figure 9

Improvement algorithm applicable to SWR automatic analysis program. (a) When the top and bottom of the structure are flat. (b) When it is not.