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Quantitative Evaluation of Silicon Wafer Backside Morphology and Profilometric Roughness by Optical Imaging During TMAH/IPA-Induced Surface Smoothing

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Abstract

Silicon wafer backside morphology and surface roughness are important parameters that can influence wafer handling, thin-film deposition processes, and optical surface properties during semiconductor manufacturing. Therefore, reliable and rapid monitoring of backside morphological changes is essential for process optimization and quality control. In this study, the effects of TMAH treatment and IPA addition on the morphological evolution, surface roughness, and optical reflectance behavior of silicon wafer back surfaces were investigated. Experiments were conducted at 65 °C with treatment times ranging from 1 to 20 min. Surface characterization was performed using profilometry, optical microscopy, ImageJ-based image analysis, and reflectance measurements at 365 nm. The results showed that surface roughness decreased progressively with increasing treatment time in both pure TMAH and TMAH/IPA systems, accompanied by a corresponding increase in optical reflectance. In the pure TMAH system, the average roughness (R_a) decreased by approximately 39%, while reflectance increased from 19% to 37%. In the solution containing 30 vol.% IPA, surface roughness reached a stable level at an earlier stage, and reflectance exhibited a plateau at approximately 31%. These findings suggest that IPA primarily influences the kinetics of surface evolution rather than the final roughness level. Strong correlations were obtained between the morphological parameters extracted from ImageJ analysis and profilometric roughness values. In particular, the equivalent diameter (Deq) exhibited a strong linear relationship with root-mean-square roughness (R_q) in both systems ($R^2 > 0.90$), demonstrating that image-derived metrics can effectively track surface evolution quantitatively. Overall, the results indicate that TMAH-based etching promotes a surface smoothing mechanism driven by selective dissolution, while IPA addition modifies the progression of this process, resulting in a more controlled morphological evolution. Furthermore, the study demonstrates that optical imaging

combined with image-processing-based analysis can serve as a rapid and cost-effective complementary approach for wafer-scale surface assessment.

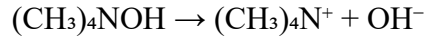
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1. Introduction

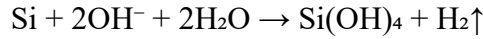
Silicon surface morphology, particularly backside roughness, is a critical parameter influencing both the electrical and optical performance of modern semiconductor devices. As surface roughness increases, light scattering, diffraction, and surface trapping effects become more pronounced, significantly affecting reflectance behavior and the accuracy of optical measurements [1]. Consequently, surface morphology is not merely a geometric characteristic but a multifunctional parameter that governs the optical response of silicon surfaces [2]. This dependency is especially important in applications such as microelectromechanical systems (MEMS), wafer bonding, microfluidic devices, photonics, and optoelectronics, where interface contact quality, adhesion behavior, and device reliability are strongly affected by surface topography [3,4]. In silicon-on-insulator (SOI)-based radio-frequency (RF) integrated circuits, variations in backside roughness have been reported to directly influence interconnect resistance and critical dimension (CD) uniformity [5]. As a result, backside surface control has become an increasingly important process parameter in through-silicon via (TSV) fabrication and wafer-bonding-based three-dimensional (3D) integration technologies. In addition to reducing parasitic resistance and capacitance, backside silicon thinning can also contribute to improved thermal management performance [2].

Both dry and wet etching techniques are widely employed for controlling silicon surface morphology. Among dry etching approaches, deep reactive ion etching (DRIE) is commonly used because of its high anisotropy and dimensional precision. However, the repetitive etching–passivation cycles inherent to the process often generate scalloping structures that limit surface smoothness [6]. Alternative plasma-based treatments have been reported to reduce surface roughness and improve surface quality [7]. Wet chemical etching, on the other hand, offers advantages including lower processing cost, compatibility with complementary metal–oxide–semiconductor (CMOS) technology, and more uniform surface modification. Potassium hydroxide (KOH), ethylenediamine–pyrocatechol (EDP), and tetramethylammonium hydroxide (TMAH) are among the most widely used silicon etchants. In particular, TMAH has attracted considerable interest in MEMS and semiconductor manufacturing because it is free of metallic contaminants and provides controllable anisotropic silicon etching characteristics [8].

The etching mechanism in TMAH-based solutions is governed by hydroxyl ions (OH^-) generated through dissociation of TMAH in water:



The hydroxyl ions interact with the silicon surface, breaking Si–Si bonds and promoting surface hydroxylation. Subsequently, soluble reaction products such as $\text{Si}(\text{OH})_4$ are formed and removed from the surface according to:



Therefore, TMAH etching should be considered not only as a material removal process but also as a dynamic surface evolution process in which the surface topography is continuously reconfigured.

Previous studies have shown that the addition of isopropyl alcohol (IPA) to TMAH solutions can significantly alter etching behavior and surface morphology. IPA reduces the surface tension of the solution, improves wetting characteristics, and modifies the interaction between the etchant and the silicon surface. These effects can promote the formation of smoother etch fronts while suppressing undercutting phenomena [9]. However, increasing IPA concentration generally decreases the silicon etch rate, resulting in a trade-off between surface quality and process throughput [9]. Several studies have further demonstrated that IPA addition reduces surface roughness and improves geometrical control during silicon etching [10,11]. Moreover, additive-assisted etching has been reported to suppress hillock formation and enhance etch uniformity [12].

Despite these advances, previous investigations have generally addressed backside roughness, optical behavior, etching kinetics, and surface morphology independently. Comprehensive studies that simultaneously correlate these parameters within a single experimental framework remain limited. In particular, the combined evolution of profilometric roughness, image-derived morphological descriptors, and optical reflectance during TMAH/IPA treatment has not been systematically investigated.

To address this gap, the present study examines the time-dependent morphological evolution of silicon wafer backside surfaces etched in TMAH and TMAH solutions containing 30 vol.% IPA at 65 °C. Treatment durations ranging from 1 to 20 min were investigated. Surface modifications were evaluated using profilometric measurements of average roughness (R_a) and root-mean-square roughness (R_q), ImageJ-based morphological analysis of optical micrographs, and reflectance measurements at a wavelength of 365 nm. This integrated

approach enables the simultaneous assessment of geometric, morphological, and optical aspects of surface evolution, providing a multi-parameter evaluation of the surface smoothing behavior occurring during TMAH-based silicon etching.

2. 2. Materials and experimental details

2.1. Materials

N-type silicon wafers (Topsil) with a (100) crystal orientation, a diameter of 4 inches, and a thickness of 525 μm were used in this study. To minimize variations in the initial surface condition, all experiments were performed using wafers obtained from the same manufacturing batch.

A 25 wt.% tetramethylammonium hydroxide (TMAH, semiconductor grade) solution was used for backside surface treatment and roughness modification. To investigate the influence of isopropyl alcohol (IPA), a TMAH solution containing 30 vol.% IPA was prepared. All chemicals were of analytical grade, and the same stock solutions were used throughout the study to ensure experimental consistency.

2.2. TMAH and TMAH/IPA surface treatments

Silicon wafer samples were subjected to wet etching in TMAH and TMAH/IPA solutions maintained at a constant temperature of 65 ± 1 °C. Treatment durations of 1, 5, 10, and 20 min were investigated. Independent wafer samples were used for each treatment condition and processing time; no sample was exposed to sequential treatments. This approach was adopted to eliminate potential history effects arising from prior surface modification. After etching, the samples were thoroughly rinsed with deionized (DI) water and dried using nitrogen (N_2) gas.

2.3. Profilometric surface roughness measurements

Surface roughness measurements were performed using a KLA-Tencor P-17 profilometer. Prior to analysis, the instrument was calibrated using a standard reference wafer. For each sample, at least nine independent line-scan measurements were collected from randomly selected locations across the wafer surface. Each scan covered a length of 200 μm , and measurements were distributed along two orthogonal directions to improve spatial representation of the surface morphology.

Surface roughness was quantified using the arithmetic average roughness (Ra) and root-mean-square roughness (Rq) parameters. Representative roughness values for each sample were obtained by averaging all measurements. To facilitate comparison with the untreated reference wafer, normalized relative changes in roughness were calculated according to:

$$\Delta Ra = (Ra_t - Ra_0)/Ra_0$$

$$\Delta Rq = (Rq_t - Rq_0)/Ra_0$$

where Ra_0 and Rq_0 represent the roughness values of the reference wafer, while Ra_t and Rq_t correspond to the values measured after treatment for a given processing time. All results are reported as mean $\pm$ standard deviation ($n = 9$).

2.4. Optical microscopy and image acquisition

Surface morphology was examined using a Leica optical microscope. All images were acquired under identical imaging conditions, including a fixed magnification (500 $\times$), constant illumination, and constant contrast settings, in order to minimize image acquisition variability. For each sample, at least nine different surface regions were imaged, and representative fields were selected for subsequent analysis.

2.5. Image-based morphological analysis

Optical micrographs of the silicon surfaces were quantitatively analyzed using ImageJ software. To ensure consistency, all images were acquired at the same magnification, under identical illumination conditions, and with comparable focal settings. Prior to analysis, the images were converted to grayscale format and contrast-normalized to reduce background variations and improve feature discrimination. Surface structures were segmented using the Otsu automatic thresholding algorithm. Following thresholding, a minimum-area filter was applied to remove small-scale noise and image artifacts, and features below the predefined threshold were excluded from further analysis. The segmented images were then processed using the *Analyze Particles* function to determine the projected area (A , pixel²) and related geometric descriptors of the detected surface features. All images were calibrated using a 50 μ m reference scale, enabling pixel-to-micrometer conversion. A characteristic morphological dimension was defined as the equivalent circular diameter (D_{eq}), which was calculated according to:

$$D_{eq} = 2 \cdot \sqrt{\frac{A}{\pi}}$$

where A represents the average projected area of the detected surface features. It should be noted that D_{eq} does not represent crystallographic grain size; rather, it describes the characteristic lateral scale of morphological features observed within the optical image plane.

To evaluate surface heterogeneity, grayscale intensity histograms were generated for each image, and the standard deviation of the histogram distribution (σ_{hist}) was calculated. Higher σ_{hist} values indicate a broader intensity distribution and, consequently, a more heterogeneous surface morphology.

For each sample, at least nine independent images were analyzed. Mean values of feature area (A), equivalent diameter (D_{eq}), and histogram standard deviation (σ_{hist}) were calculated and reported as mean $\pm$ standard deviation. The reported standard deviations represent the variability observed among independent image regions across the wafer surface.

The ImageJ-derived morphological parameters were subsequently correlated with profilometric roughness measurements (R_a and R_q) and optical reflectance data to provide a multi-parameter assessment of surface evolution during the etching process.

2.6. Optical reflectance measurements

Optical reflectance measurements were performed using a Nanometrics reflectance measurement system. All measurements were conducted at a wavelength of 365 nm under fixed optical geometry conditions. This wavelength was selected because surface scattering effects become more pronounced at shorter wavelengths, making the optical response more sensitive to variations in surface morphology and roughness. Consequently, changes associated with surface smoothing and morphological evolution during TMAH-based etching could be monitored with enhanced sensitivity.

To minimize instrument-related variability, identical optical alignment and measurement configurations were maintained throughout the study. For each sample, at least five independent measurements were collected from the same surface region, and the results are reported as mean $\pm$ standard deviation. The reported reflectance values correspond to the direct percentage

reflectance measured by the instrument and were not subjected to additional normalization beyond the standard instrument calibration procedure.

2.7. Data analysis

All experimental data were analyzed using Microsoft Excel and OriginPro software. Results obtained from profilometric measurements, image-based morphological analysis, and optical reflectance measurements are reported as mean $\pm$ standard deviation.

For each experimental condition, profilometric roughness values were obtained from at least nine independent line scans, while image-based morphological parameters were extracted from at least nine independent optical micrographs acquired from different surface regions. The variability reported for each parameter therefore reflects measurement-to-measurement variations across the wafer surface.

Pearson correlation analysis was performed to evaluate the relationships between profilometric surface roughness parameters (Ra and Rq) and the image-derived morphological descriptors, including feature area (Area), equivalent diameter (D_{eq}), and histogram standard deviation (σ_{hist}). The parameter pairs Area–Ra, Area–Rq, D_{eq}–Ra, D_{eq}–Rq, σ_{hist} –Ra, and σ_{hist} –Rq were analyzed separately. The Pearson correlation coefficient (r) was calculated according to:

$$r = \frac{\sum[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{(\sum[(x_i - \bar{x})^2])(\sum[(y_i - \bar{y})^2])}}$$

where x_i and y_i represent the measured values of the variables being compared, and $\bar{x}$ and $\bar{y}$ denote their corresponding mean values.

The strength of the observed linear relationships was further assessed using the coefficient of determination (R^2). Correlation analyses were performed using the experimental datasets obtained from the independent measurements collected for each treatment condition. The resulting correlation coefficients and R^2 values were used to quantify the degree of association between image-derived morphological descriptors and profilometric roughness parameters. The correlation analysis was employed to determine whether variations in the ImageJ-derived morphological metrics consistently reflected the evolution of surface roughness during TMAH-based surface modification.

3. Results

3.1. Surface morphology evolution, profilometric roughness, and correlation analysis in the TMAH system

The morphological evolution of silicon wafer backside surfaces following treatment in TMAH solution at 65 °C was evaluated using optical microscopy, profilometric measurements, and ImageJ-based image analysis. Time-dependent surface morphologies are presented in Figure 1, profilometric surface profiles are shown in Figure 2, and the profilometric profile of the untreated reference wafer is presented in Figure 3. The quantitative results are summarized in Table 1. The average roughness parameters of the untreated reference surface were 1264 Å (Ra) and 1550 Å (Rq).

A progressive reduction in surface roughness was observed with increasing treatment time. The Ra value decreased from 1230.8 ± 34.4 Å after 1 min of treatment to 998.1 ± 28.3 Å after 5 min, 885.4 ± 22.1 Å after 10 min, and 776.1 ± 18.7 Å after 20 min. A similar trend was observed for Rq, which decreased from 1493.3 ± 41.5 Å to 994.8 ± 24.5 Å over the same treatment period. Relative to the untreated reference wafer, reductions of 38.64% and 35.82% were obtained for Ra and Rq, respectively, after 20 min of etching. The relatively small standard deviations observed at all treatment times indicate good measurement reproducibility and suggest that the observed trends are significantly larger than the experimental variability.

The ImageJ-derived morphological parameters exhibited trends consistent with the profilometric measurements. As the treatment time increased, the average feature area increased from 42.41 ± 4.3 pixel² to 2248.0 ± 152 pixel², while the equivalent diameter (D_{eq}) increased from 7.30 ± 0.82 pixels to 53.51 ± 3.72 pixels. In contrast, the histogram standard deviation (σ_{hist}) decreased from 28.87 ± 0.73 to 21.14 ± 0.38 . These changes indicate substantial modification of the surface morphology during etching and suggest a progressive narrowing of the grayscale intensity distribution. The reduction in histogram width is consistent with a decrease in surface heterogeneity and the development of a more uniform surface appearance.

To evaluate the relationship between the image-derived morphological descriptors and profilometric roughness parameters, Pearson correlation analysis was performed, and the results are summarized in Table 2. Among the investigated parameters, the equivalent diameter (D_{eq}) exhibited the strongest association with surface roughness. Correlation coefficients of

-0.949 and -0.966 were obtained for the D_{eq} – R_a and D_{eq} – R_q relationships, corresponding to R^2 values of 0.901 and 0.934 , respectively. These strong negative correlations indicate that the increase in characteristic surface feature size is closely associated with a progressive reduction in profilometric roughness.

Strong correlations were also observed between the histogram standard deviation (σ_{hist}) and the profilometric roughness parameters. Correlation coefficients of 0.951 and 0.942 were obtained for the σ_{hist} – R_a and σ_{hist} – R_q relationships, corresponding to R^2 values of 0.904 and 0.888 , respectively. In contrast, the correlations involving feature area were weaker, although still substantial, with correlation coefficients of -0.852 for Area– R_a and -0.886 for Area– R_q . These results suggest that D_{eq} and σ_{hist} are more sensitive descriptors of surface evolution than feature area alone and may provide a more reliable representation of changes in surface roughness during TMAH treatment.

The relationship between D_{eq} and R_q is further illustrated in Figure 4. An inverse relationship is evident, with increasing D_{eq} values corresponding to decreasing R_q values. The strong negative correlation indicates that changes in the characteristic dimensions of surface features are closely associated with variations in profilometric roughness.

Overall, the profilometric and image-based analyses reveal highly consistent trends throughout the etching process. The results demonstrate that ImageJ-derived morphological parameters can serve as effective complementary metrics for monitoring surface evolution during TMAH-induced surface smoothing of silicon wafer backside surfaces.

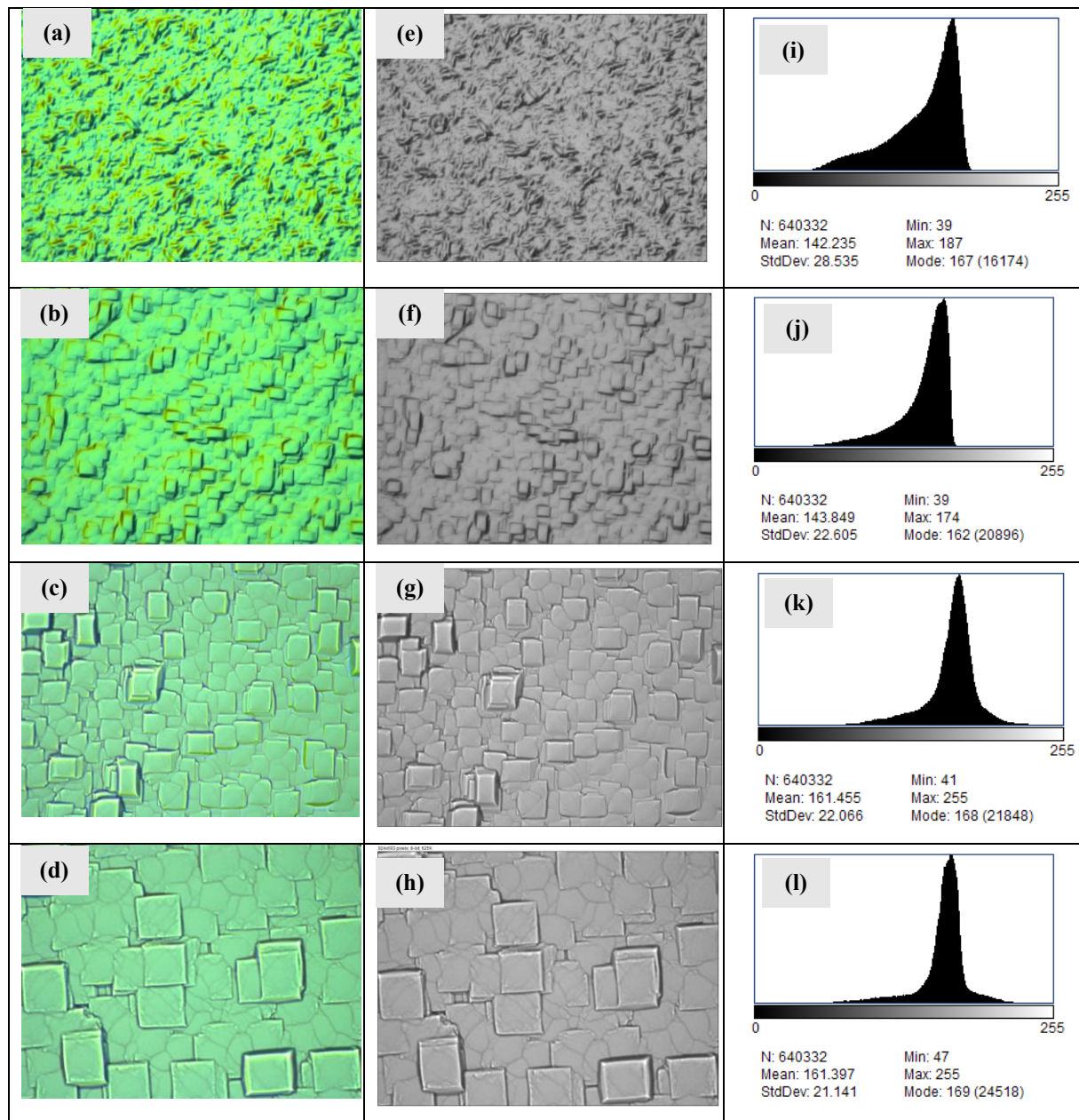


Figure 1. Evolution of silicon wafer backside morphology during TMAH treatment at 65 °C. Optical micrographs (a–d), corresponding binary images obtained by ImageJ processing (e–h), and grayscale intensity histograms (i–l) for treatment times of 1, 5, 10, and 20 min, respectively.

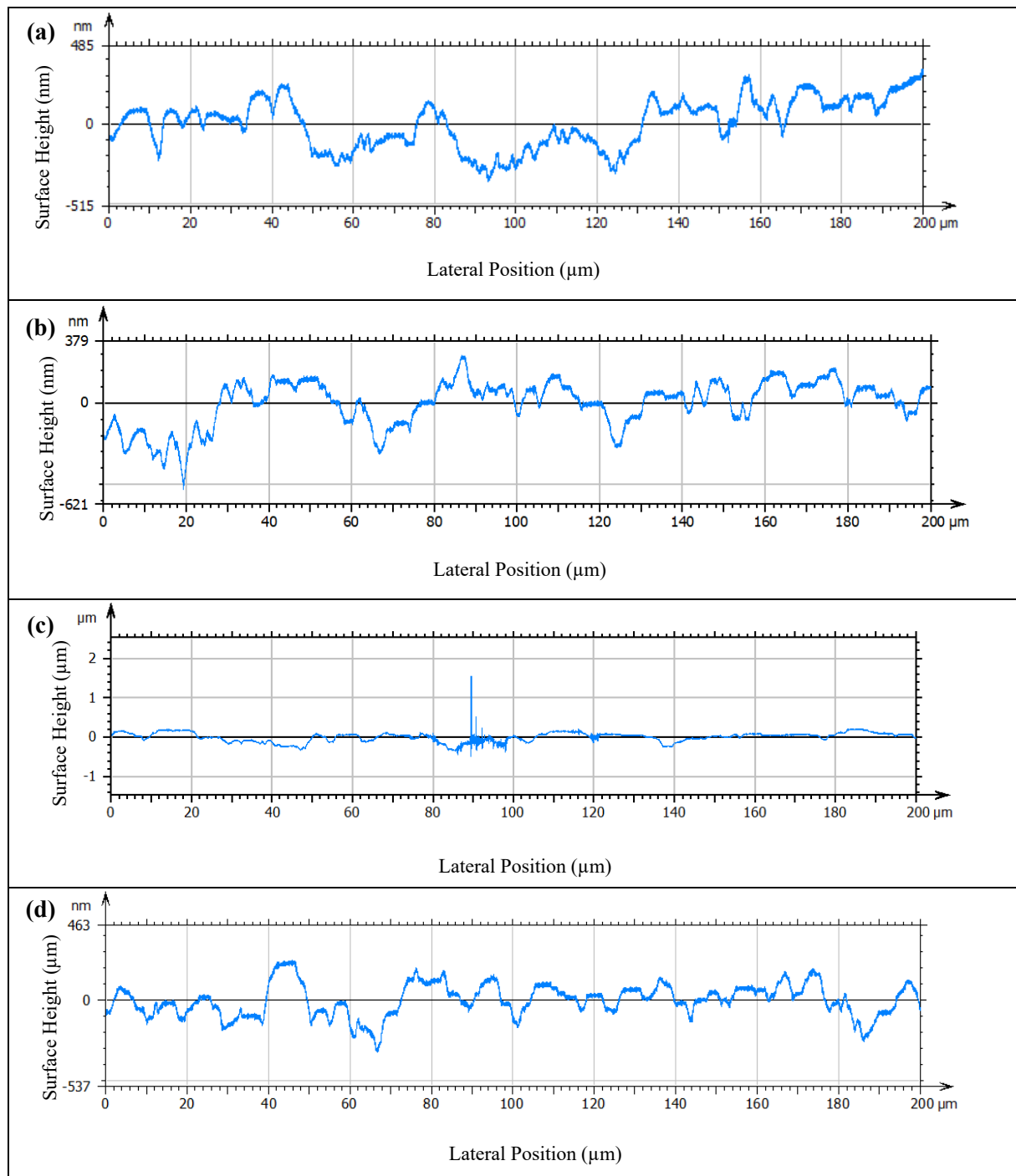


Figure 2. Representative profilometric surface roughness profiles of silicon wafer backside surfaces after TMAH treatment at 65 °C for (a) 1 min, (b) 5 min, (c) 10 min, and (d) 20 min.

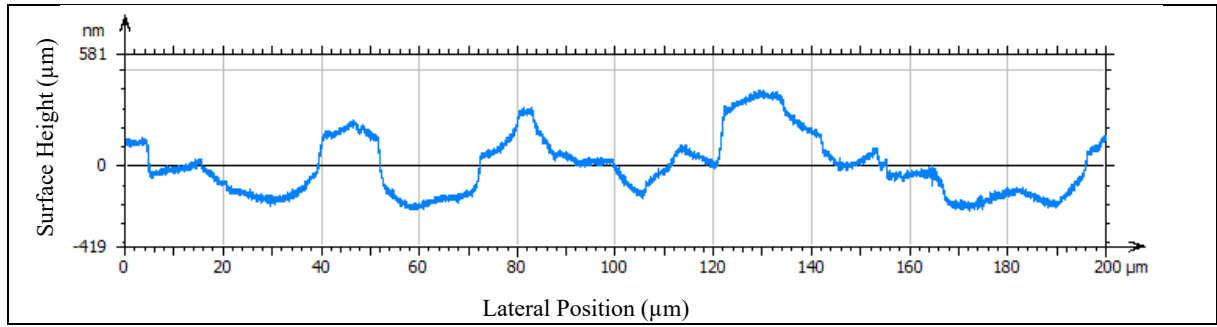


Figure 3. Representative profilometric surface roughness profile of the untreated reference silicon wafer backside surface.

Table 1. ImageJ-derived morphological parameters and profilometric roughness values of silicon wafer backside surfaces after TMAH treatment at 65 °C.

Treatment time (min)	Area (pixel ²)	D _{eq} (pixel)	σ _{hist} (a.u.)	Ra (Å)	ΔRa (%)	Rq (Å)	ΔRq (%)
1	42.41 ± 4.3	7.30 ± 0.82	28.87 ± 0.73	1230.8 ± 34.4	-2.69	1493.3 ± 41.5	-3.66
5	349.57 ± 7.1	21.10 ± 1.41	22.61 ± 0.52	998.1 ± 28.3	-21.09	1237.8 ± 36.3	-20.14
10	741.24 ± 46.8	30.72 ± 1.93	22.06 ± 0.41	885.4 ± 22.1	-30.00	1164.6 ± 29.2	-24.86
20	2248.0 ± 152	53.51 ± 3.72	21.14 ± 0.38	776.1 ± 18.7	-38.64	994.8 ± 24.5	-35.82

Table 2. Pearson correlation coefficients (r) and coefficients of determination (R²) describing the relationships between ImageJ-derived morphological descriptors and profilometric roughness parameters for TMAH-treated silicon wafer backside surfaces.

Parameter pair	r	R ²
Area – Ra	-0.852	0.727
Area – Rq	-0.886	0.785
D _{eq} – Ra	-0.949	0.901
D _{eq} – Rq	-0.966	0.934
σ _{hist} –Ra	0.951	0.904
σ _{hist} –Rq	0.942	0.888

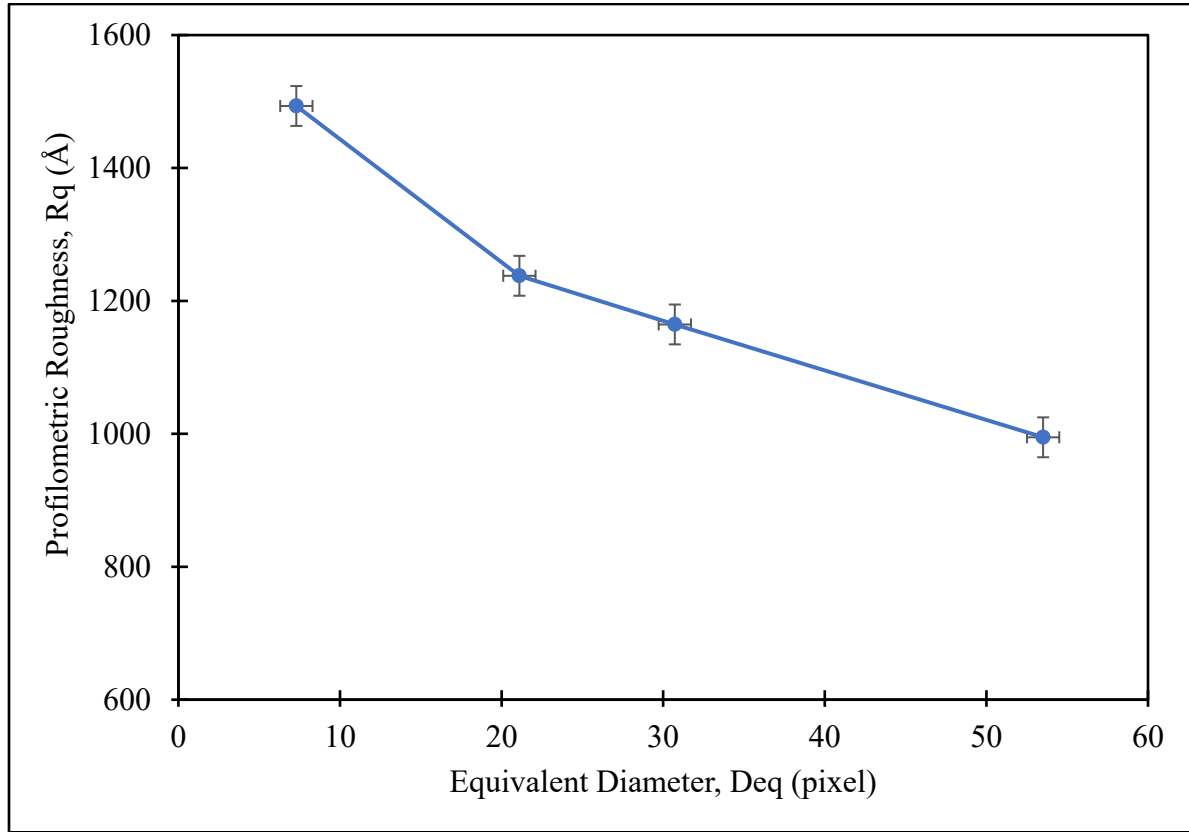


Figure 4. Correlation between equivalent diameter (D_{eq}) obtained from ImageJ analysis and root-mean-square roughness (R_q) measured by profilometry for TMAH-treated silicon wafer backside surfaces.

3.2. Surface morphology evolution, profilometric roughness, and correlation analysis in the TMAH/IPA system

The morphological evolution of silicon wafer backside surfaces treated in TMAH solution containing 30 vol.% IPA at 65 °C was evaluated using optical microscopy, profilometric measurements, and ImageJ-based image analysis. The time-dependent surface morphologies are presented in Figure 5, representative profilometric surface profiles are shown in Figure 6, and the quantitative results are summarized in Table 3.

A pronounced reduction in surface roughness was observed with increasing treatment time. The R_a value decreased from 1171.2 ± 29.5 Å after 1 min of treatment to 909.5 ± 22.3 Å after 5 min and 823.9 ± 18.7 Å after 10 min, remaining nearly unchanged at 823.3 ± 17.6 Å after 20 min. A similar trend was observed for R_q , which decreased from 1491.4 ± 38.3 Å to 1011.1 ± 24.4 Å over the investigated treatment period. Relative to the untreated reference surface, reductions of 34.9% and 34.77% were obtained for R_a and R_q , respectively, after 20 min of treatment.

Notably, the similarity of the roughness values measured after 10 and 20 min suggests that surface evolution in the IPA-containing system approached a quasi-steady-state regime after approximately 10 min. The relatively small standard deviations obtained at all treatment times indicate good measurement reproducibility and confirm the consistency of the observed trends.

The ImageJ-derived morphological parameters exhibited behavior consistent with the profilometric measurements. The average feature area increased from $13.20 \pm 1.3 \text{ pixel}^2$ to $102.0 \pm 7.1 \text{ pixel}^2$, while the equivalent diameter (D_{eq}) increased from $4.10 \pm 0.41 \text{ pixels}$ to $11.39 \pm 0.77 \text{ pixels}$ with increasing treatment time. In contrast, the histogram standard deviation (σ_{hist}) decreased from 36.70 ± 0.83 to 20.93 ± 0.45 . These changes indicate substantial modification of the surface morphology and a progressive narrowing of the grayscale intensity distribution. The decrease in σ_{hist} is consistent with reduced surface heterogeneity and the development of a more uniform surface appearance during treatment.

Pearson correlation analysis was performed to evaluate the relationships between the image-derived morphological descriptors and the profilometric roughness parameters, and the results are summarized in Table 4. Among the investigated metrics, the equivalent diameter (D_{eq}) exhibited the strongest correlation with surface roughness. Correlation coefficients of -0.907 and -0.957 were obtained for the D_{eq} – R_a and D_{eq} – R_q relationships, corresponding to R^2 values of 0.822 and 0.916 , respectively. These strong inverse relationships indicate that the growth of characteristic morphological features is accompanied by a systematic reduction in surface roughness.

Strong correlations were also observed between the histogram standard deviation and the profilometric roughness parameters. The σ_{hist} – R_a and σ_{hist} – R_q relationships yielded correlation coefficients of 0.935 and 0.952 , corresponding to R^2 values of 0.873 and 0.907 , respectively. In comparison, feature area exhibited weaker inverse correlations with roughness, yielding coefficients of -0.860 for $Area$ – R_a and -0.923 for $Area$ – R_q . These findings indicate that D_{eq} and σ_{hist} are more sensitive descriptors of the morphological evolution occurring in the IPA-containing system than the projected feature area alone.

The strong correlations observed between D_{eq} , σ_{hist} , and the profilometric roughness parameters demonstrate that the morphological changes induced by TMAH/IPA treatment can be quantitatively monitored using optical-image-based analysis.

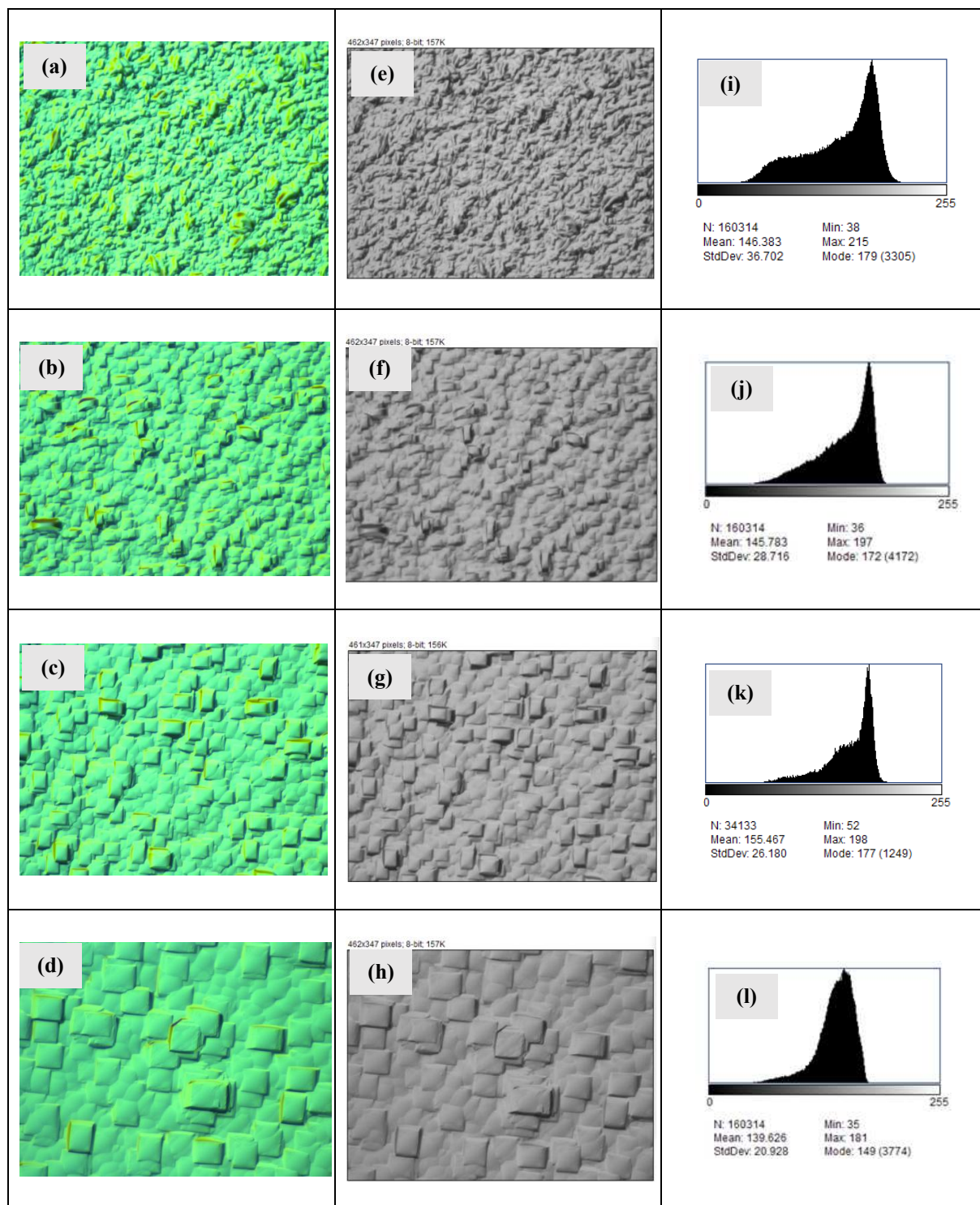


Figure 5. Evolution of silicon wafer backside morphology during treatment in TMAH solution containing 30 vol.% IPA at 65 °C. Optical micrographs (a–d), corresponding binary images obtained by ImageJ processing (e–h), and grayscale intensity histograms (i–l) for treatment times of 1, 5, 10, and 20 min, respectively.

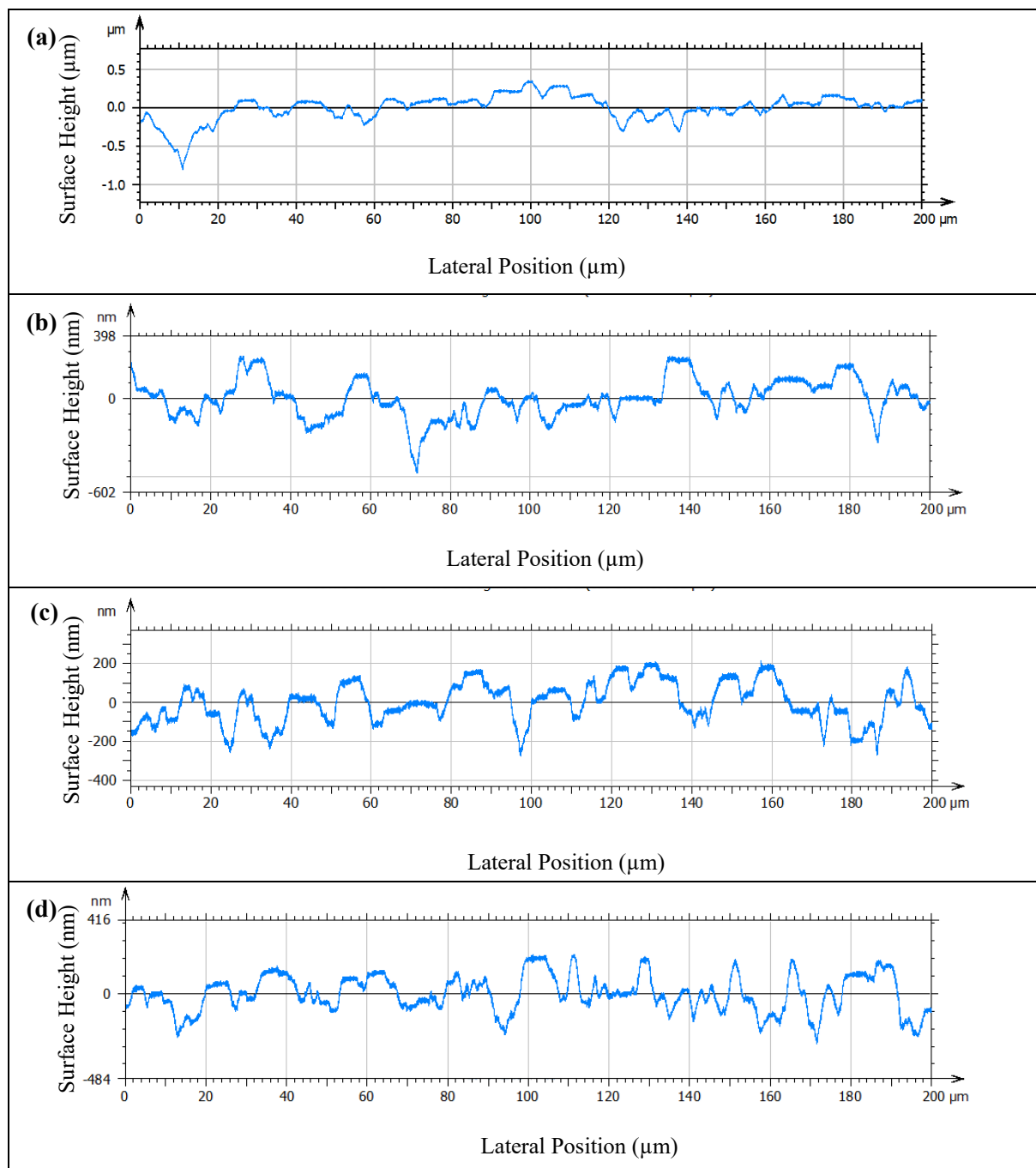


Figure 6. Representative profilometric surface roughness profiles of silicon wafer backside surfaces after treatment in TMAH solution containing 30 vol.% IPA at 65 °C for (a) 1 min, (b) 5 min, (c) 10 min, and (d) 20 min.

Table 3. ImageJ-derived morphological parameters and profilometric roughness values of silicon wafer backside surfaces after treatment in TMAH solution containing 30 vol.% IPA at 65 °C.

Treatment time (min)	Area (pixel ²)	D _{eq} (pixel)	σ _{hist} (a.u.)	Ra (Å)	ΔRa (%)	Rq (Å)	ΔRq (%)
1	13.20 ± 1.3	4.10 ± 0.41	36.70 ± 0.83	1171.2 ± 29.5	-7.4	1491.4 ± 38.3	-3.81
5	32.38 ± 2.8	6.43 ± 0.56	28.72 ± 0.67	909.5 ± 22.3	-28.1	1197.3 ± 31.9	-22.75
10	88.64 ± 6.3	10.62 ± 0.74	26.18 ± 0.53	823.9 ± 18.7	-34.9	1023.5 ± 25.6	-33.97
20	102.0 ± 7.1	11.39 ± 0.77	20.93 ± 0.45	823.3 ± 17.6	-34.9	1011.1 ± 24.4	-34.77

Table 4. Pearson correlation coefficients (r) and coefficients of determination (R²) between ImageJ-derived morphological descriptors and profilometric roughness parameters for silicon wafer backside surfaces treated in TMAH solution containing 30 vol.% IPA.

Parameter Pair	r	R ²
Area – Ra	-0.860	0.740
Area – Rq	-0.923	0.852
D _{eq} – Ra	-0.907	0.822
D _{eq} – Rq	-0.957	0.916
σ _{hist} –Ra	0.935	0.873
σ _{his} –Rq	0.952	0.907

3.3. Comparative evaluation of the TMAH and TMAH/IPA systems

3.3.1. Surface roughness evolution

The effects of pure TMAH and TMAH solution containing 30 vol.% IPA on the evolution of profilometric surface roughness are compared in Figure 7. In both systems, increasing treatment time resulted in a progressive reduction in surface roughness, indicating effective surface smoothing during the etching process. However, the temporal evolution of roughness differed noticeably between the two solutions.

In the pure TMAH system, the Ra value decreased from $1230.8 \pm 34.4 \text{ \AA}$ after 1 min of treatment to $776.1 \pm 18.7 \text{ \AA}$ after 20 min. In contrast, the TMAH/IPA system exhibited a reduction in Ra from $1171.2 \pm 29.5 \text{ \AA}$ to $823.3 \pm 17.6 \text{ \AA}$ over the same treatment period. A similar trend was observed for Rq, which decreased from $1493.3 \pm 41.5 \text{ \AA}$ to $994.8 \pm 24.5 \text{ \AA}$ in the pure TMAH solution and from $1491.4 \pm 38.3 \text{ \AA}$ to $1011.1 \pm 24.4 \text{ \AA}$ in the IPA-containing solution.

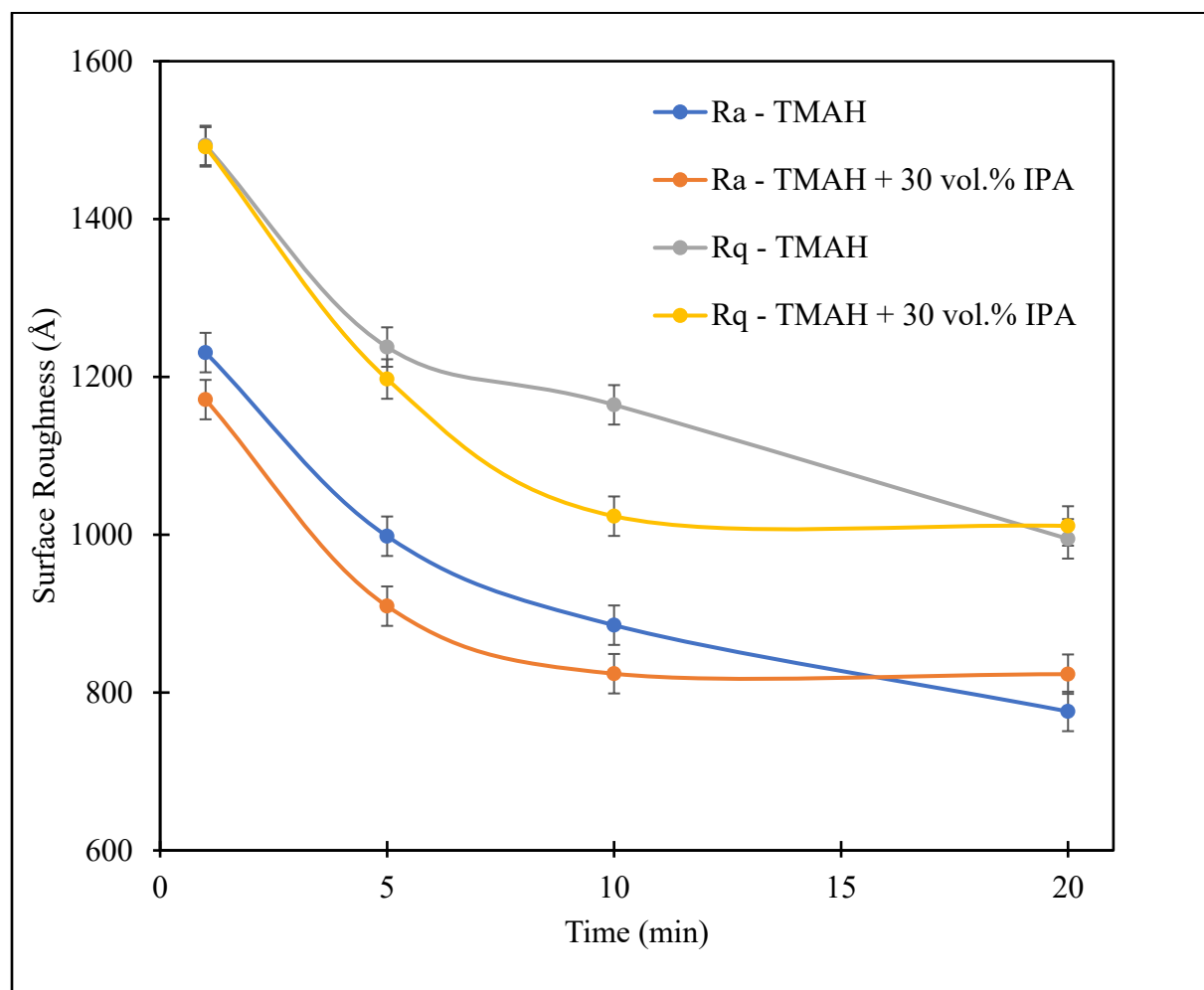


Figure 7. Comparison of the evolution of profilometric roughness parameters (Ra and Rq) for silicon wafer backside surfaces treated in pure TMAH and TMAH solution containing 30 vol.% IPA as a function of treatment time.

Relative to the untreated reference surface, the pure TMAH system produced reductions of 38.64% in Ra and 35.82% in Rq after 20 min of treatment. The corresponding reductions for the TMAH/IPA system were 34.9% and 34.77%, respectively. Although the final roughness values obtained in the two systems were comparable, the evolution pathways differed

significantly. In the TMAH/IPA solution, roughness values approached a plateau after approximately 10 min, whereas surface smoothing continued throughout the entire 20 min treatment period in the pure TMAH system.

This behavior suggests that IPA primarily influences the kinetics of surface evolution rather than the ultimate roughness attainable under the investigated conditions. The early stabilization of both Ra and Rq in the IPA-containing solution indicates that the surface restructuring process reaches a quasi-equilibrium state more rapidly, while the continuous decrease in roughness observed in pure TMAH implies that surface smoothing remains active over a longer treatment period.

3.3.2. Reflectance behavior

The reflectance measurements performed at a wavelength of 365 nm are summarized in Table 5 and Figure 8. In both systems, reflectance increased with increasing treatment time, consistent with the progressive reduction in surface roughness observed by profilometric analysis. In the pure TMAH system, the reflectance increased from 19.00% after 1 min of treatment to 37.33% after 20 min. In comparison, the TMAH/IPA system exhibited an increase from 20.27% to 31.00% over the same treatment period.

Notably, the TMAH/IPA solution produced higher reflectance values during the early stages of treatment. After 1 and 5 min, reflectance values of 20.27% and 26.00% were obtained, respectively, compared with 19.00% and 22.50% for the pure TMAH system. However, this difference gradually diminished with increasing treatment time. After 20 min, the highest reflectance value was observed for the pure TMAH system, reaching 37.33%, whereas the IPA-containing solution exhibited a reflectance of 31.00%.

The observed behavior suggests that IPA accelerates the initial stages of surface reorganization, leading to a more rapid improvement in optical reflectance. As treatment proceeds, however, the reflectance of the IPA-containing system approaches a plateau, consistent with the stabilization of the roughness parameters observed after approximately 10 min. In contrast, the continuous increase in reflectance in the pure TMAH system indicates that surface smoothing remains active throughout the investigated treatment period. These findings further support the conclusion that IPA primarily affects the kinetics of surface evolution rather than the ultimate surface condition achieved under the investigated processing conditions.

Table 5. Mean reflectance values measured at 365 nm for silicon wafer backside surfaces treated in pure TMAH and TMAH solution containing 30 vol.% IPA as a function of treatment time.

Treatment time (min)	TMAH system (%)	TMAH/IPA system (%)
1	19.00	20.27
5	22.50	26.00
10	30.00	30.93
20	37.33	31.00

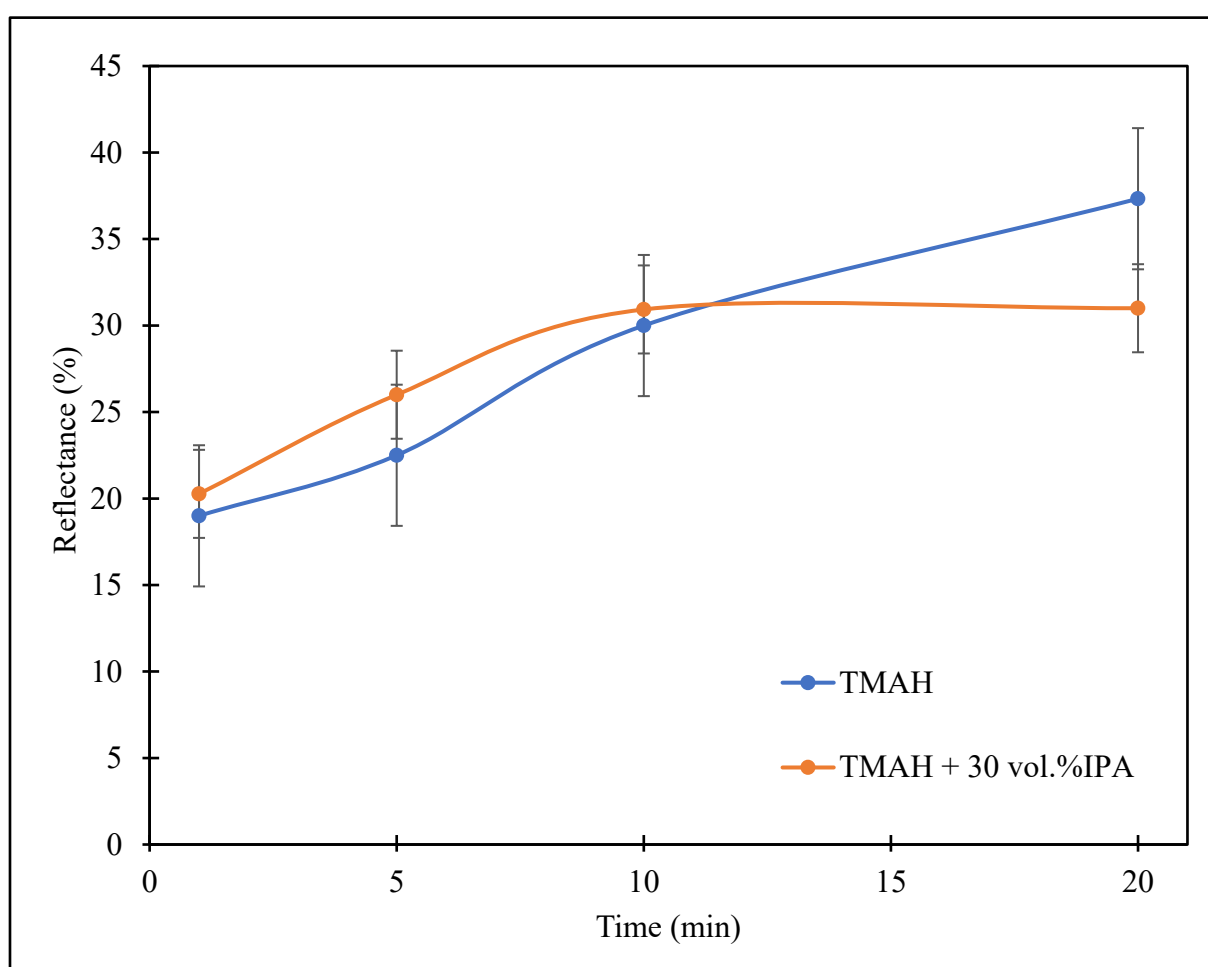


Figure 8. Evolution of reflectance measured at 365 nm for silicon wafer backside surfaces treated in pure TMAH and TMAH solution containing 30 vol.% IPA as a function of treatment time.

3.3.3. Reflectance–roughness relationship

When the reflectance and surface roughness data are considered together, a clear relationship between roughness reduction and reflectance enhancement is observed for both treatment systems (Figure 9). As the R_a values decreased with increasing treatment time, the corresponding reflectance values increased. This behavior is consistent with the reduction of surface scattering losses at the measurement wavelength of 365 nm.

As shown in Figure 9, surfaces exhibiting lower R_a values generally produced higher reflectance values. The pure TMAH system achieved the lowest roughness value, 776.1 ± 18.7 Å, together with the highest reflectance value of 37.33% after 20 min of treatment. In contrast, the TMAH/IPA system reached a relatively stable surface condition at an earlier stage, and the reflectance increase approached a plateau at approximately 31%. These observations indicate that modifications in surface topography have a direct influence on the optical response of the silicon surface.

The observed increase in reflectance can be attributed to the progressive reduction in surface roughness, which promotes more specular reflection and reduces scattering losses. In addition, the decrease in histogram standard deviation (σ_{hist}) and the narrowing of the grayscale intensity distributions obtained from ImageJ analysis are consistent with the development of a more uniform surface morphology and the corresponding improvement in optical reflectance.

Taken together, the profilometric, morphological, and optical measurements reveal highly consistent trends throughout the surface evolution process. While the TMAH/IPA system exhibited earlier morphological stabilization, the pure TMAH system continued to undergo surface smoothing at longer treatment times, ultimately producing the highest reflectance values. These findings demonstrate that image-derived morphological descriptors, profilometric roughness parameters, and optical reflectance measurements provide complementary information for evaluating the evolution of silicon wafer backside surfaces during TMAH-based surface smoothing.

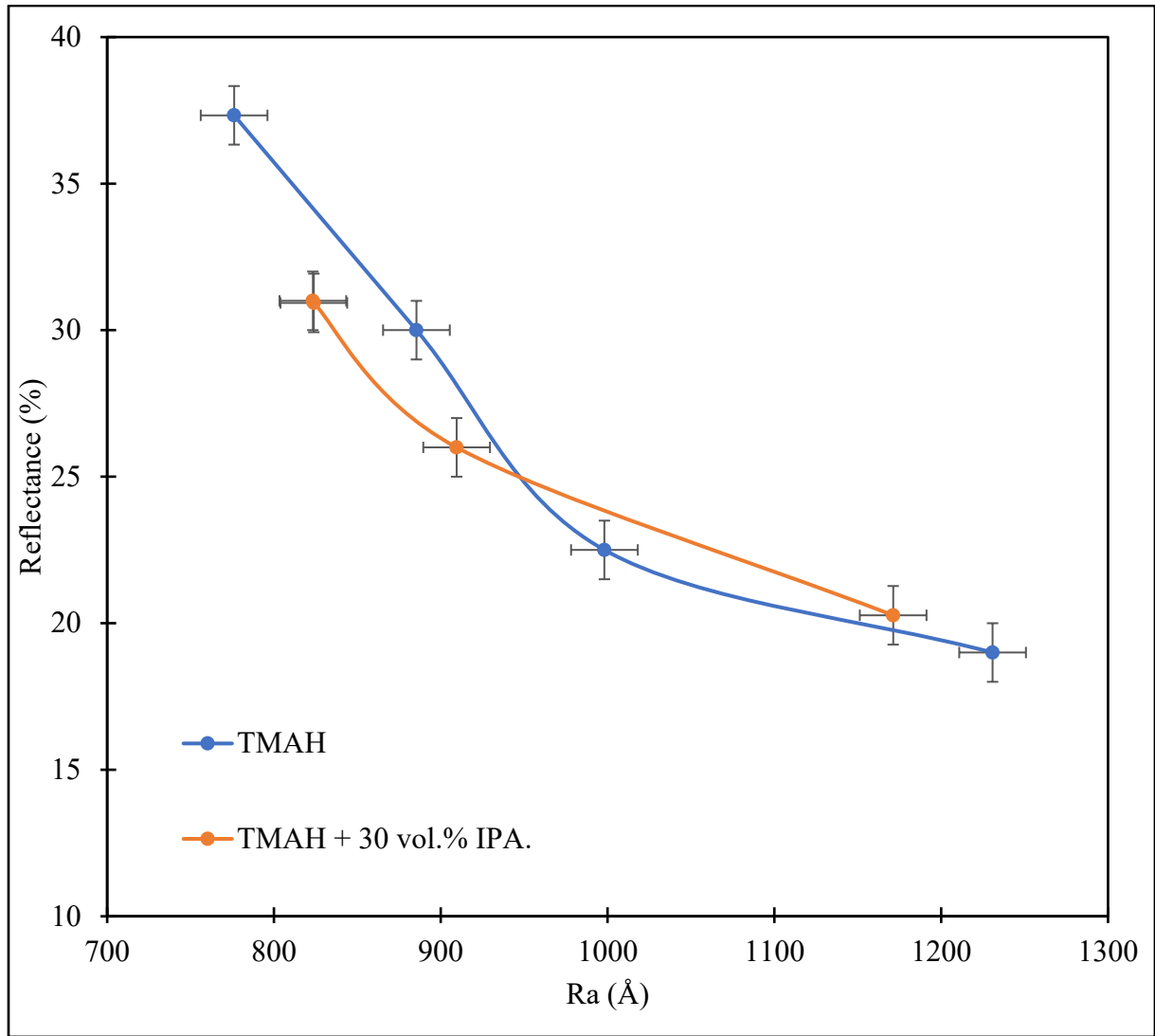


Figure 9. Relationship between optical reflectance measured at 365 nm and average surface roughness (Ra) for silicon wafer backside surfaces treated in pure TMAH and TMAH solution containing 30 vol.% IPA.

4. Discussion

4.1. Surface smoothing and morphological relaxation in TMAH and TMAH/IPA systems

The results obtained in this study indicate that surface smoothing during TMAH-based treatment is governed not only by material removal but also by selective dissolution and surface relaxation processes that continuously modify the surface morphology. In both the pure TMAH and TMAH/IPA systems, the progressive decrease in Ra and Rq values, the narrowing of grayscale intensity distributions, and the increase in optical reflectance with increasing treatment time indicate a gradual evolution of the surface topography toward a more homogeneous state.

In TMAH solutions, hydroxyl ions (OH^-) are the active species responsible for silicon dissolution. According to the widely accepted mechanism reported in the literature, OH^- ions interact with Si–Si bonds at the silicon surface, leading to the formation of Si–OH intermediate species, which subsequently transform into soluble silicate compounds [2,13]. This process does not occur uniformly across the entire surface; regions with higher local curvature and surface asperities exhibit higher reactivity and therefore dissolve more rapidly. As a result, surface irregularities are progressively removed, leading to the development of a smoother morphology over time.

In the TMAH/IPA system, the addition of IPA does not alter the fundamental chemical dissolution mechanism but affects the physicochemical characteristics of the reaction environment. By reducing the surface tension of the solution, improving surface wettability, and facilitating the removal of gas bubbles generated during the reaction, IPA can promote a more homogeneous etching environment [14,15]. A schematic representation of the proposed mechanism is shown in Figure 10.

The experimental results suggest that IPA primarily influences the kinetics of surface evolution rather than the ultimate roughness level achieved. While roughness reduction in the pure TMAH system continued throughout the 20 min treatment period, the TMAH/IPA system exhibited a more stable behavior after approximately 10 min. This observation indicates that IPA contributes to a more uniform progression of the dissolution process across the surface rather than fundamentally modifying the etching mechanism itself. Previous studies have reported that IPA promotes more homogeneous etching behavior and suppresses hillock formation during silicon etching [11,12,14,16]. The reduced morphological variation and earlier stabilization observed in the present study are consistent with these reports.

In addition, the high correlation coefficients obtained for both systems indicate that morphological parameters extracted from optical microscopy images can effectively track changes in profilometric roughness. In particular, the similar trends observed between the equivalent diameter (D_{eq}), histogram standard deviation (σ_{hist}), and the roughness parameters R_a and R_q suggest that image-processing-based analysis can serve as a complementary quantitative approach for evaluating surface evolution.

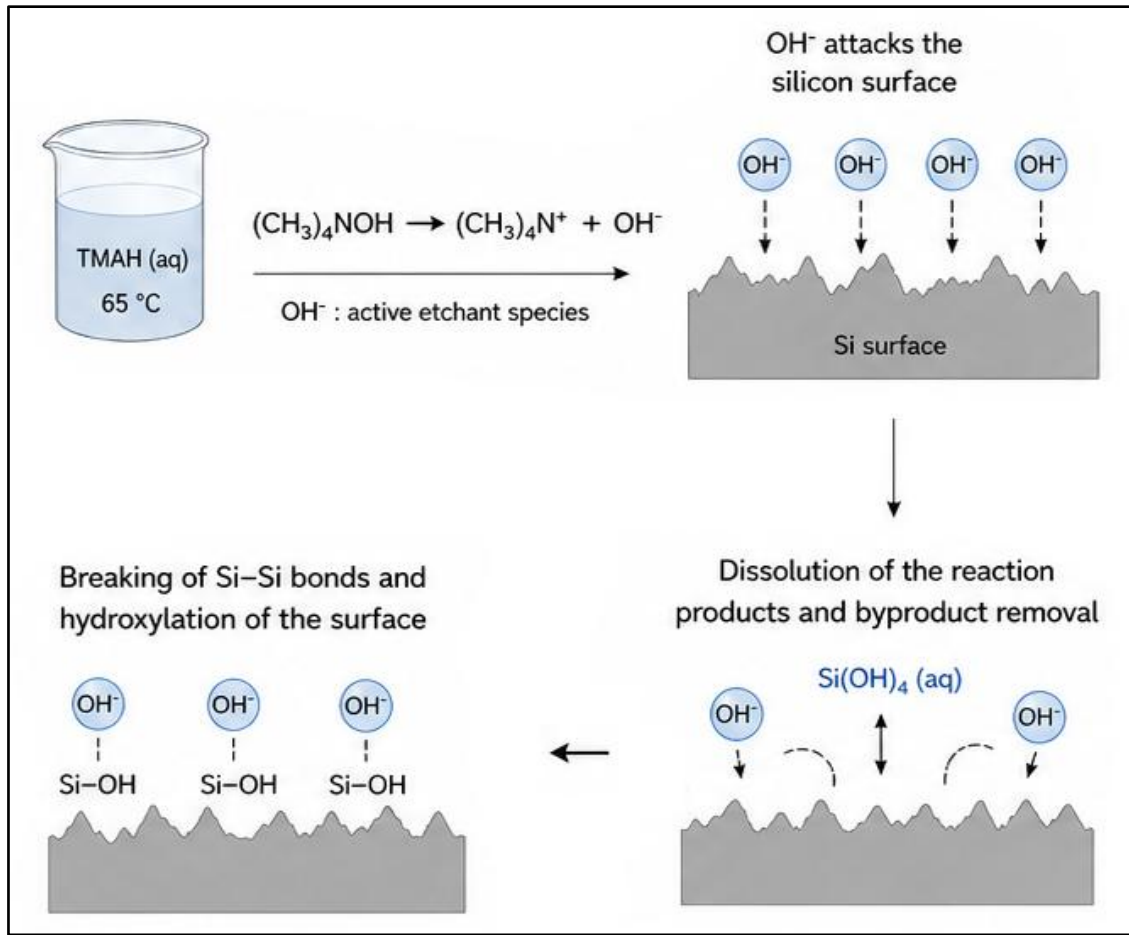


Figure 10. Schematic illustration of selective dissolution, surface relaxation, and morphological homogenization mechanisms occurring on silicon surfaces during treatment in TMAH and TMAH/IPA systems.

4.2. Morphological evolution during TMAH and TMAH/IPA etching

When the profilometric and image-processing results are considered together, a systematic restructuring of the surface morphology becomes evident throughout the treatment process. As the treatment time increases, both the feature area (Area) and equivalent diameter (D_{eq}) increase, whereas the histogram standard deviation (σ_{hist}) decreases. This behavior suggests that small and irregular surface features gradually disappear or merge into larger characteristic morphological units over time.

This interpretation is further supported by the correlation analysis. In particular, the D_{eq} - R_q relationship exhibited correlation coefficients of -0.966 and -0.957 for the TMAH and TMAH/IPA systems, respectively, corresponding to coefficients of determination of 0.934 and 0.916 . These results indicate a strong relationship between characteristic morphological size and surface roughness. Similarly, the strong correlations observed between σ_{hist} and both R_a and R_q indicate that the reduction in surface heterogeneity occurs concurrently with the reduction in surface roughness.

This process is schematically summarized in Figure 11. Initially, the surface is characterized by a high density of small asperities and broad histogram distributions. As the treatment proceeds, larger characteristic morphological regions emerge, surface roughness decreases, and the histogram distributions become narrower. As a result, the surface evolves toward a more homogeneous and lower-energy morphology.

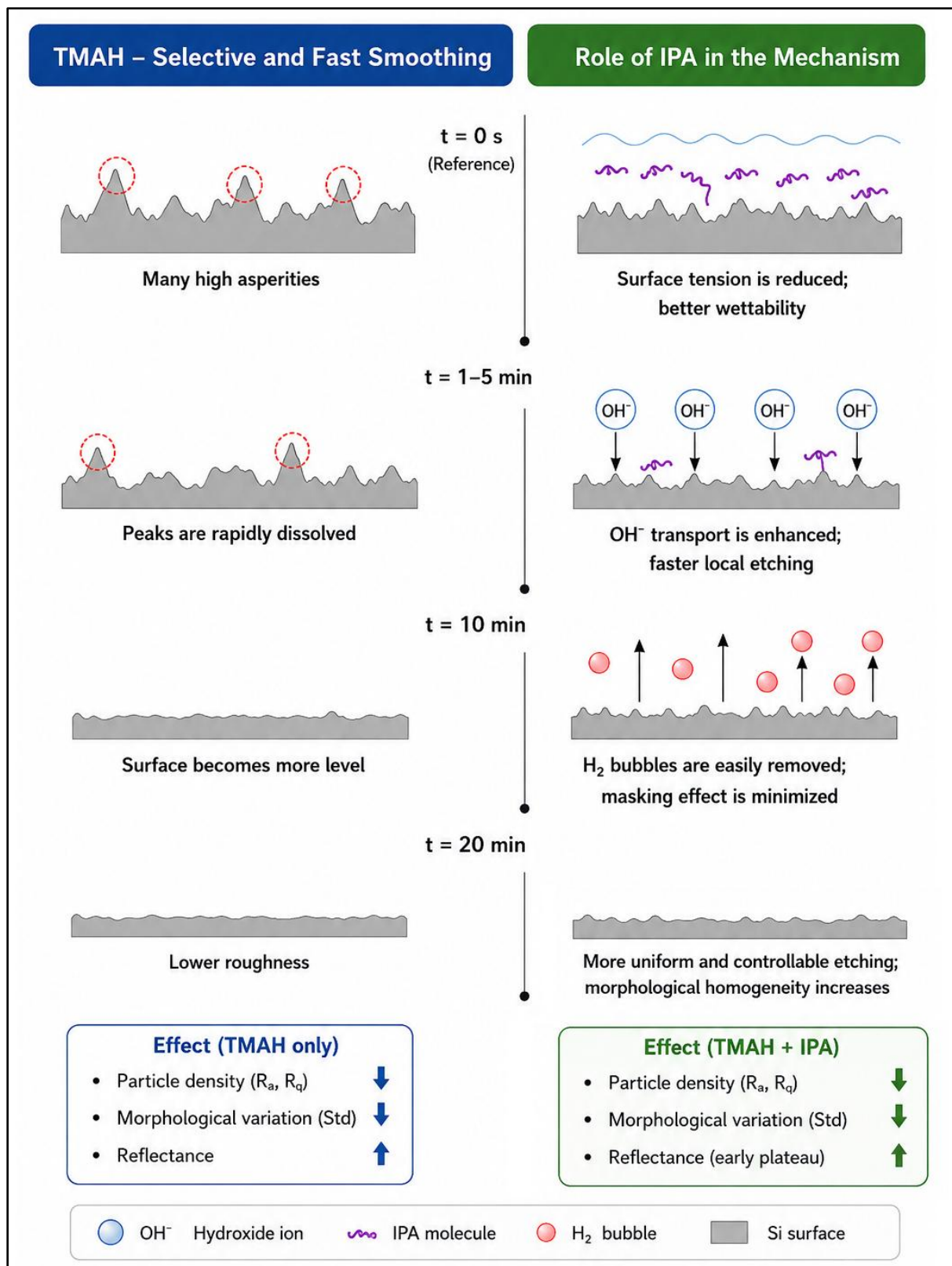


Figure 11. Schematic illustration of the relationship between morphological evolution, characteristic feature size (Deq), histogram standard deviation (σ_{hist}), and surface roughness as a function of treatment time in TMAH and TMAH/IPA systems.

4.3. Correlation between morphology, surface roughness and optical properties

The optical measurements provide additional evidence supporting the morphological and profilometric results. In both systems, increasing treatment time resulted in a reduction in surface roughness accompanied by an increase in reflectance. In the pure TMAH system, reflectance increased from 19.00% to 37.33%, consistent with reduced surface scattering and the development of a smoother surface. In the TMAH/IPA system, the increase in reflectance reached a stable level of approximately 31% at an earlier stage of the treatment process. Examination of the relationship between reflectance and roughness indicates that surfaces with lower Ra values generally exhibit higher reflectance. This observation suggests that changes in surface topography directly influence the optical response of the silicon surface. As surface roughness decreases, light is reflected in a more specular manner and scattering losses are correspondingly reduced. When the morphological parameters, profilometric roughness measurements, and reflectance data are considered together, all parameters appear to represent different manifestations of the same surface evolution process. This relationship is schematically illustrated in Figure 12. The schematic demonstrates the consistent link between morphological homogenization, roughness reduction, and reflectance enhancement as treatment time increases.

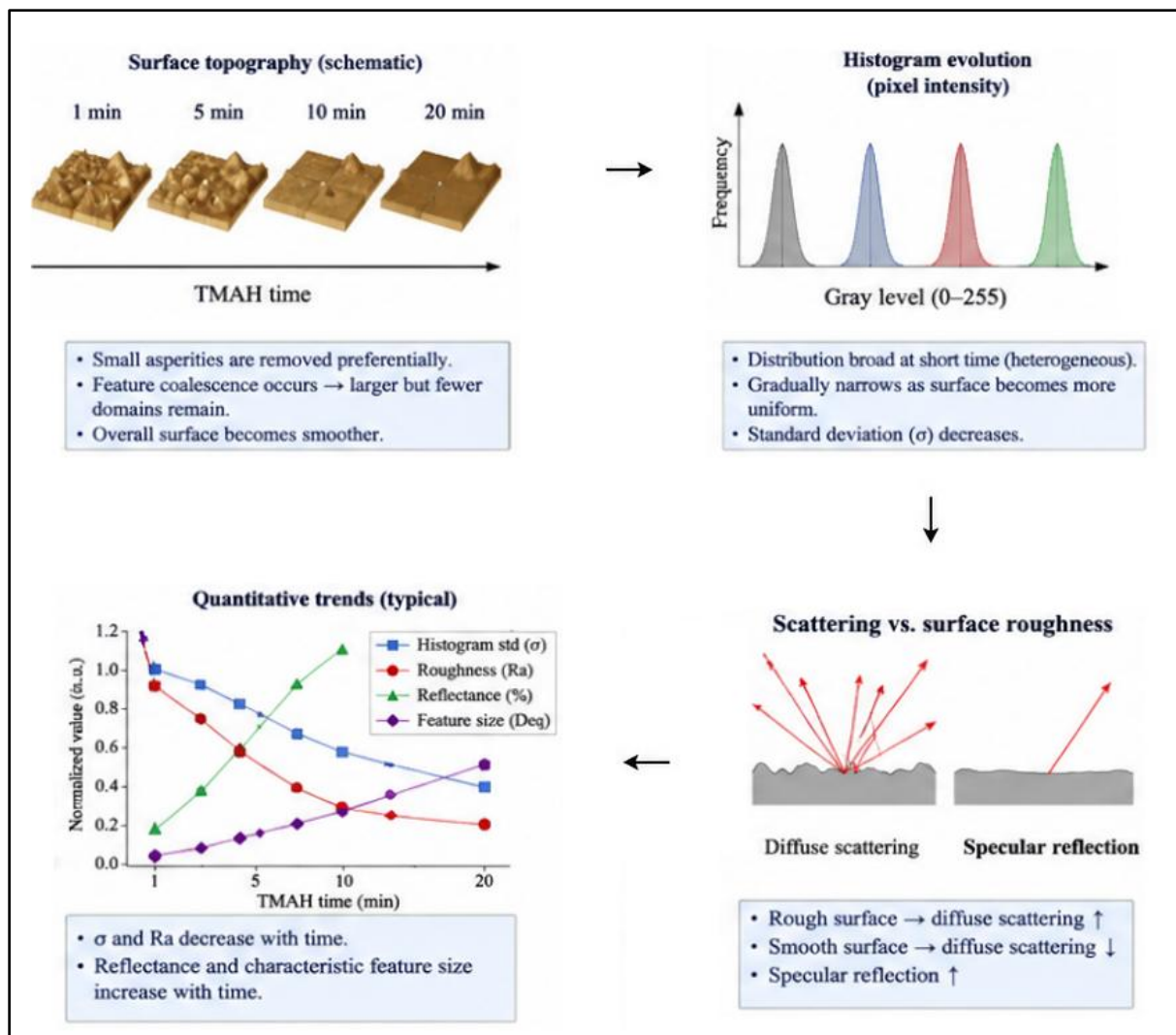


Figure 12. Schematic illustration of the relationship between morphological evolution, surface roughness reduction, and optical reflectance behavior.

5. Conclusion

In this study, the morphological evolution, profilometric surface roughness, and optical reflectance behavior of silicon wafer backside surfaces treated in TMAH and TMAH/IPA systems were systematically evaluated. In both systems, increasing treatment time resulted in a reduction in surface roughness, a narrowing of grayscale intensity distributions, and an increase in optical reflectance. While the pure TMAH system achieved lower final roughness values, the TMAH/IPA system exhibited a more stable morphological behavior at an earlier stage of the treatment process.

Strong correlations were observed between the ImageJ-derived morphological descriptors and the profilometric roughness parameters. In particular, the equivalent diameter (D_{eq}) and histogram standard deviation (σ_{hist}) emerged as effective indicators for quantitatively tracking surface evolution. These findings demonstrate that morphological parameters extracted from optical microscopy images can serve as complementary metrics that support profilometric characterization.

The results further indicate that optical imaging combined with image-processing-based analysis offers a rapid and cost-effective approach for assessing surface condition at the wafer scale. Rather than replacing conventional profilometric characterization, this methodology may be considered a complementary tool for monitoring process trends and rapidly evaluating silicon wafer backside surface conditions in semiconductor manufacturing applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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