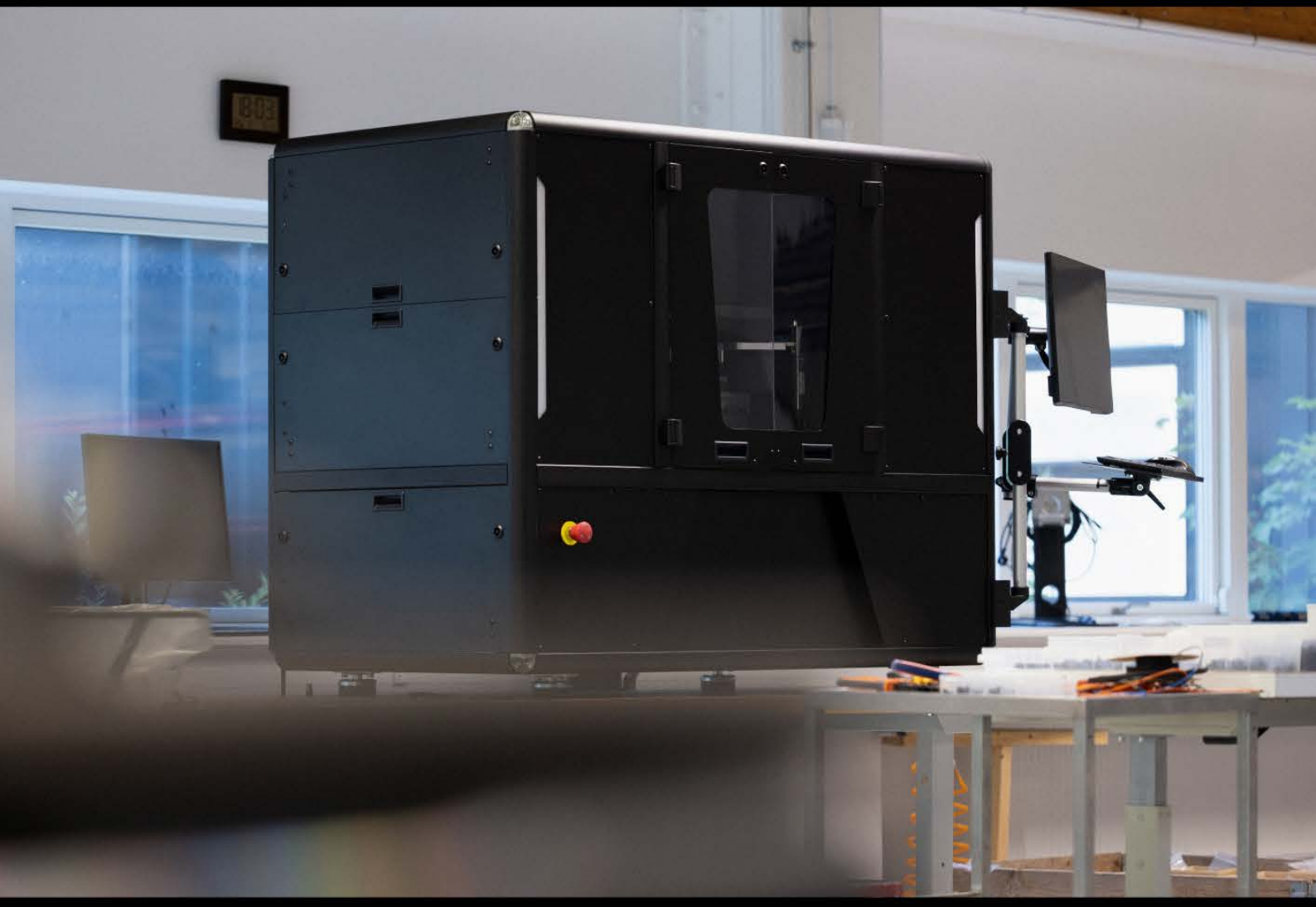
White Paper

NANOFABRICATOR® PROCESS AND SAMPLE REPRODUCIBILITY DATA



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NANOFABRICATOR® PROCESS AND SAMPLE REPRODUCIBILITY DATA

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Executive summary

Reproducibility and process stability are decisive factors in determining whether a thin-film deposition technology can transition from laboratory use to industrial manufacturing. In high-value applications such as microelectronics, MEMS, and photonics, even small variations in film thickness or uniformity can translate into yield loss, performance drift, or long-term reliability concerns. As a result, manufacturers require deposition processes that deliver consistent results during extended tool operation and across large numbers of patterned features.

This white paper evaluates the reproducibility of titanium dioxide (TiO_2) films deposited using ATLANT 3D's Direct Atomic Layer Processing (DALP) during a **single continuous deposition run lasting 48.09 hours**. A total of **300 patterned TiO_2 features** were produced under constant process conditions. Reproducibility was assessed by analyzing thickness and uniformity statistics for the first 100 features, representative of early-run performance, as well as for the full 300-feature dataset, representative of long-duration operation. Film thickness was measured using stylus profilometry with baseline correction to ensure robust and unbiased data extraction.

Within the initial portion of the run, the first 100 features exhibit an average thickness of **88.18 ± 1.80 nm**, corresponding to approximately **2%** variation, which is comparable to the noise floor. Over the full **48.09-hour** operation, the thickness distribution across all 300 features remains **unimodal**. The average thickness shifts slightly from 88.18 nm to 84.97 nm, while the standard deviation increases from **1.80 nm** to **2.38 nm**, a change of only **0.58 nm**. Throughout the entire run, film uniformity remains consistently **below 1%**.

These results demonstrate that DALP maintains stable and predictable deposition behavior during prolonged single operations, with limited drift and no evidence of critical degradation. The combination of atomic-scale growth control, direct patterning capability, and long-term process stability positions DALP as an attractive thin-film deposition system for industrial environments

requiring high tool uptime, reproducible quality, and scalable manufacturing performance.

Introduction

Reproducibility is a crucial parameter for any thin film deposition technique, not only in research and development, but even more so in industrial manufacturing. In manufacturing, the capacity to grow thin films with reproducible microstructural and functional qualities over time, but also after hardware change, is what defines the reliability and scalability of a process. A reproducible process allows for predictable results and stable quality.

ATLANT 3D's Direct Atomic Layer Processing (DALP) is a thin-film deposition technique designed to address precisely the demands of reproducibility and process consistency. DALP combines the precision of atomic-scale deposition and the flexibility of bottom-up patterning. Thanks to DALP, a broad range of materials, including metals, semiconductors and oxides, can be deposited directly where they are needed. The result is a highly controllable technique for building micro- and nanostructures on demand.

Conventional CVD and PVD techniques are highly reliable for growing uniform coatings but offer limited capability for direct patterning. DALP is capable of synthesizing precise nanostructures without the use of masks, vacuum, or post-processing. Thus, DALP combines the reliability and the conformality of ALD with the versatility and the agility of additive manufacturing.

The present white paper evaluates and demonstrates the reproducibility of the growth of TiO_2 using DALP. An array of 300 lines of TiO_2, as well as pads of different pitch values, were grown on SiO_2 wafers to demonstrate the reproducibility and uniformity of ATLANT 3D's DALP deposition. By tracking the deposited feature morphology, we assess the consistency of DALP performance in both time and space. This white paper shows that DALP maintains stable and repeatable performance over extended operation, including 48 hours of continuous deposition. This level of reproducibility confirms the potential of DALP for reliable integration into industrial processes in areas such as microelectronics, MEMS, or photonics, among others.

Technical data

Parameter	Value / Range	Notes
Substrate size	up to 200 mm (8")	Flat/small curvature
Growth rate control	~0.1–2 Å/cycle (material dependent)	Layer-by-layer growth

Min. feature size (if patterned)	~100 µm lateral resolution	Dependent on nozzle/flow design
Temperature range	e.g., 25–400°C	Uniformity ±0.5°C
Within-process repeatability	2%	Calculated on 100 samples
Thickness uniformity	<1%	Stable in time
Throughput	~100 nm in <14 min (TiO_2 @ 150°C)	Includes full-cycle time (0.3 x 3 mm line)
Process drift	+0.58 nm increase in thickness STD after 48 hours	48 hours non-stop deposition

Methodology

Process description

Depositions were conducted using ATLANT 3D's DALP system. A nozzle operates as an independent chemical reactor, delivering the precursor and reactant directly on the wafer surface with controlled temperature and flow conditions. This localized ALD reaction makes the atomic-scale deposition of a pattern possible without the need for vacuum or post-processing.

For this study, titanium dioxide (TiO_2) was deposited. Standardized process conditions (precursor, reactant, substrate, temperature, flow rate) were used to ensure a consistent comparison between the arrays. Arrays of 300 TiO_2 lines were printed, as well as pads with different pitch values. This allows for the study of deposition time, spatial, and temporal reproducibility, and it gives insight into any drift or deviation.

Characterization

Arrays were characterized using a stylus profilometer to obtain their morphological profiles. The profiles consisted of a line scan across the printed features, from which the height and width of each individual feature were extracted. The profilometer scans were acquired with a horizontal resolution of the micrometer, and with a vertical resolution of the nanometer. The noise was estimated after subtraction of a spline baseline modelling the wafer curvature and was ± 1.53 nm.

This baseline was modelled across the full scan range to represent the uncoated substrate and was subtracted to yield the relative height profile corresponding solely to the deposited material. To account for drift, a local baseline correction was applied near each individual feature and was computed using a linear

regression fitting the low quantile of the signal. This procedure allows each feature to be measured relative to its surroundings.

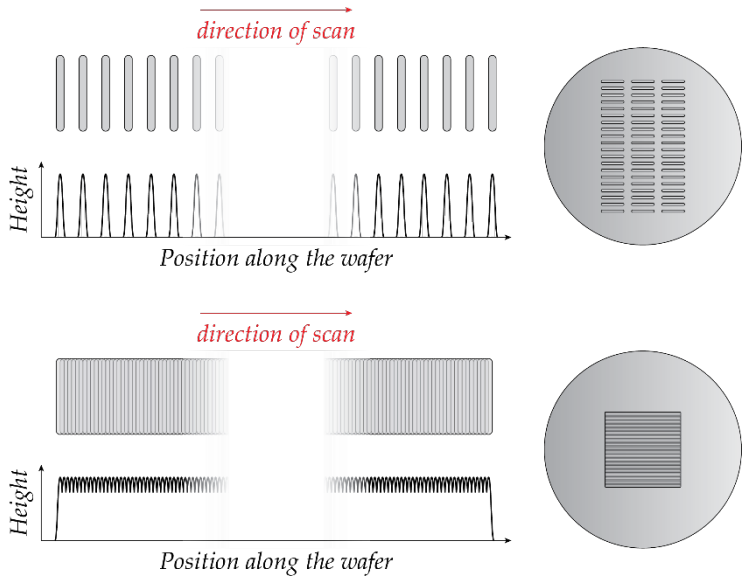


Figure 1: Sketches of the experimental plan of the (a) deposition of 300 features and (b) deposition of a 1 cm² pad

Results and discussion

Within-process reproducibility

Here, we report the reproducibility of samples deposited during the same process. To do this, we scanned **100 TiO_2 samples** (Figure 1) printed across a single wafer in one deposition process.

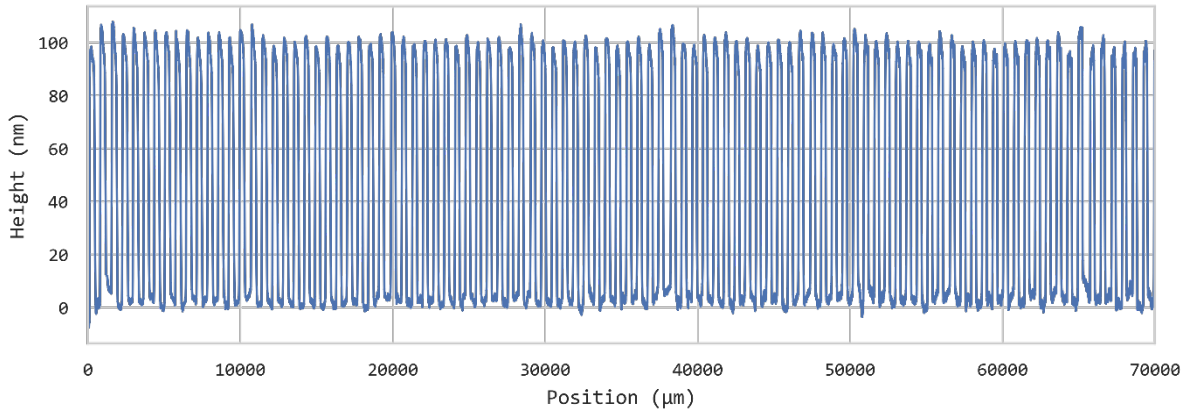


Figure 2: Profilometric scan of 100 features of TiO_2. The average thickness is 88 ± 1.80 nm. In the image, the height appears higher because the baseline is not exactly 0 nm and possible local peaks.

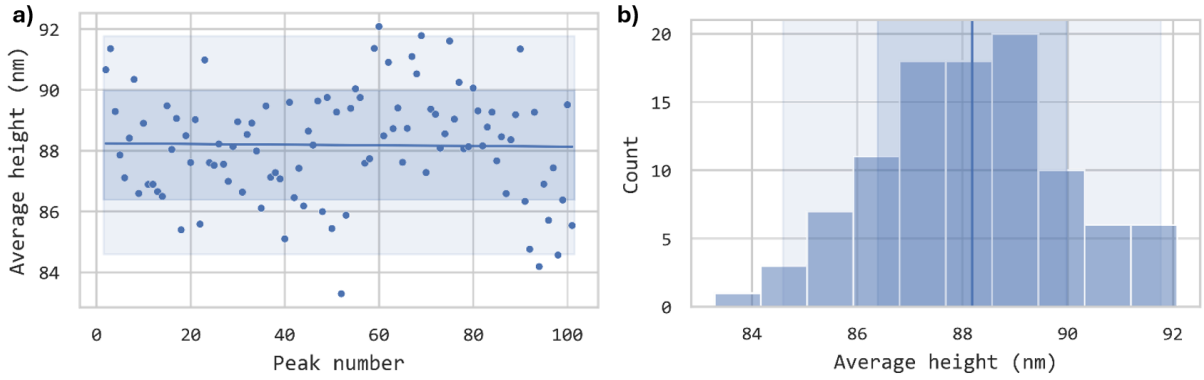


Figure 3: a) Height of 100 lines of TiO2. The line is a linear regression. The shades represent ±σ and ±2σ. b) Histogram of average feature heights. The line is the average height over 100 features. The shades represent ±σ and ±2σ.

Figure 3a shows the profile of each sample as a function of its number (1 to 100). Data scatter narrowly around an average value of **88.18 ± 1.80 nm**, with STD comparable with the experimental error of the profiler (1.53 nm). A linear regression of these data shows a constant trend, indicating that the thickness of the features remains constant with a unimodal distribution (Figure 3b). In other words, the relative standard deviation is **2% over 100 samples deposited** during a **16.7-hour-long deposition run**. This result is to be considered a worst-case interpretation, **because it corresponds with the minimal experimental error of the measurement instrument**.

The thickness of the samples remains constant throughout the process, with a narrow distribution, supporting the reproducibility of the deposition within the same process, with deviations comparable to the background noise. The resulting growth per cycle is 0.44 ± 0.01 Å.

Film quality and surface uniformity

The film uniformity is defined as the relative error in % of thickness across the entire sample surface.

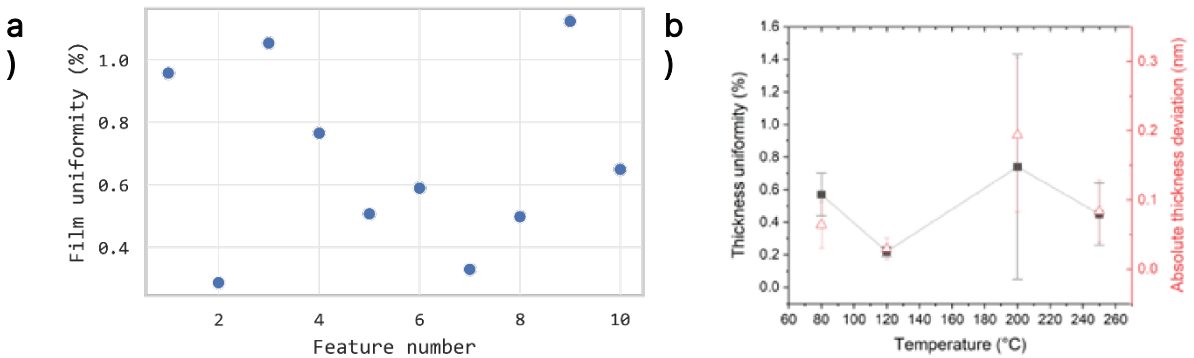


Figure 4: (a) Ratio between the thickness and the average thickness for the 1st 10 features and (b) thickness uniformity for samples grown at different growth temperatures [1].

Figure 4a shows the film uniformity for the 1st 10 features. We also analyzed samples deposited at different temperatures (Figure 4b), showing a uniformity below 1%, with deviations in the range of 0.2 nm on average.

Process drift and nozzle lifetime

Drift in reproducibility

A prolonged process can entail a drift of the deposition characteristics due to nozzle progressive clogging. Even though nozzles are cleanable, it is important to be aware of the drift.

To quantify it, we analyzed the thickness differences of identical TiO2 samples to evaluate the presence of such a drift. Thus, a long **deposition of 48.09 hours** was carried out.

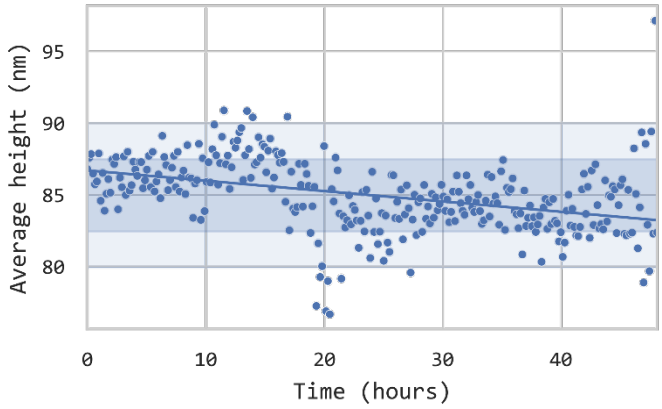


Figure 5: Average height of each feature as a function of deposition time

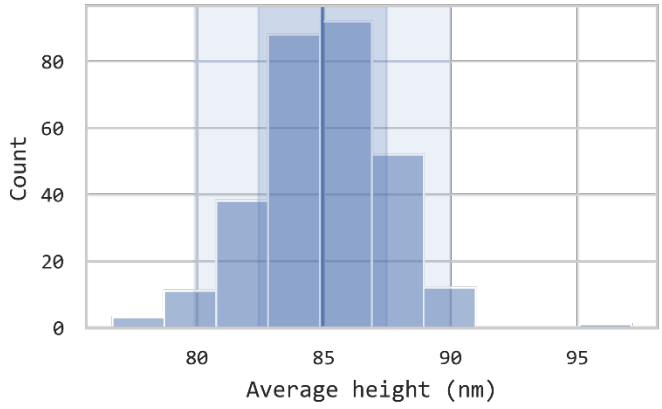


Figure 6: Histogram of average feature heights (300 features). The line is the average height of over 300 features. The shades represent ±σ and ±2σ.

Figure 5 shows the average height of each sample as a function of time of operation. The average thickness over all 300 features is 84.97 nm, compared with 88.18 nm for the first 100 features, indicating a slow downward drift of about 3.6% over 48.09 hours

of operation. Meanwhile, the STD increases from 1.80 nm (first 100 features) to 2.38 nm (300 features). Comparing the beginning of the deposition to the entire deposition, **the drift causes a difference of only 0.58 nm in the STD**. The thickness distribution remains unimodal during the entire process (Fig. 6).

Drift in film uniformity

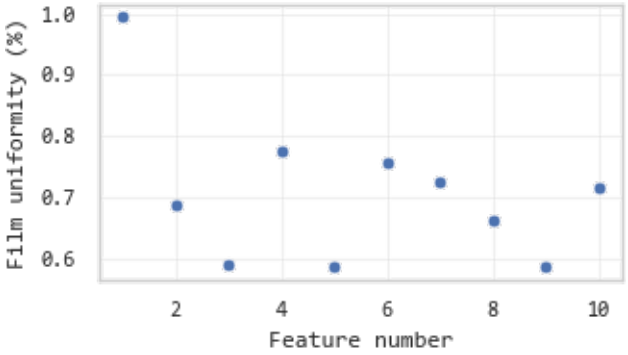


Figure 7: uniformity in % for the last 10 features.

Figure 7 shows the uniformity of the last 10 samples of the two-day process. **The uniformity remained at or below 1% across the sample.**

This highlights the long-term reliability of ATLANT 3D's DALP nozzle, indicating that it can sustain long-term operation. This stability is a prerequisite for industrial reliability and ensures consistent film quality over extended operating times.

The data are reported in the next table:

	Average thickness (nm)	STD (nm)	Film uniformity
First 100 features (16.7 hours)	88.18	1.80	<1%
300 features (48 hours)	84.97	2.38	<1%

Large area uniformity

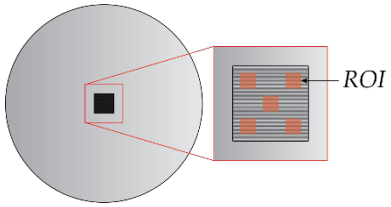


Figure 8: ROIs samples deposited on a 4-inch wafer.

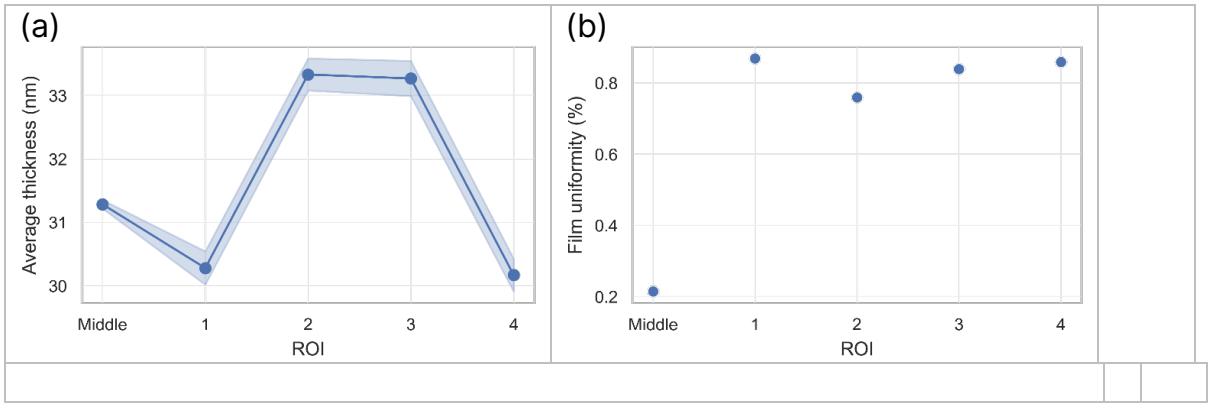


Figure 9: (a) Average thicknesses and (b) film uniformity deviation measured by ellipsometry on 5 different regions of interest (ROIs) of area 500×500 μm² each. The shaded curve in Fig. 9(a) is the standard deviation.

Figure 8 shows a wafer with large-area DALP-deposited TiO_2 depositions across a 4-inch wafer. Here, we report the data of a 1 cm square pad to assess large-area uniformity. Fig. 9 evaluates the average thickness measured in each region of interest (ROI), which are consistent (Fig. 9a). Within each ROI, thickness uniformity is below 1%, in line with the feature-level results. Across the entire 1 × 1 cm pad, the thickness variation between ROIs is 4.27%, with an average thickness of 31.46 ± 1.34 nm. This result demonstrates that DALP not only ensures reproducibility at the feature level, as shown by profilometry, but also maintains good thickness uniformity over larger areas relevant for device-scale integration. Together, these data confirm that DALP can deliver spatially uniform films without compromising local thickness control.

References

[1] Santucci et al. *J. Vac. Sci. Technol. A* 43, 062411 (2025)