Nanoimprint Lithography

Nanoimprint lithography (NIL) is a templating technique for creating micro- and nanostructures on materials. Atomic Force Microscopy (AFM) is a powerful technique for characterizing micro- and nano-scale patterns made by NIL. Common substrates for NIL are thermoplastic and thermosetting polymer materials for applications in nanoelectronics, nano-biology, and nano-optoelectronics. AFM collects high-resolution 3-dimensional images of NIL surfaces, enabling measurement of critical dimensions (CD) as well as surface roughness and defect detection.

Introduction to Nanoimprint Lithography

NIL is fundamentally an advanced embossing process. Typically, NIL entails positioning a resist underneath a rigid master template that has been patterned at the nanoscale. The master template is used as a stamp to imprint the nanoscale pattern on the resist. Some typical NIL techniques that are used include Thermal, UV-cured, and nano-contact imprint lithography. These techniques are shown in Fig. 1.

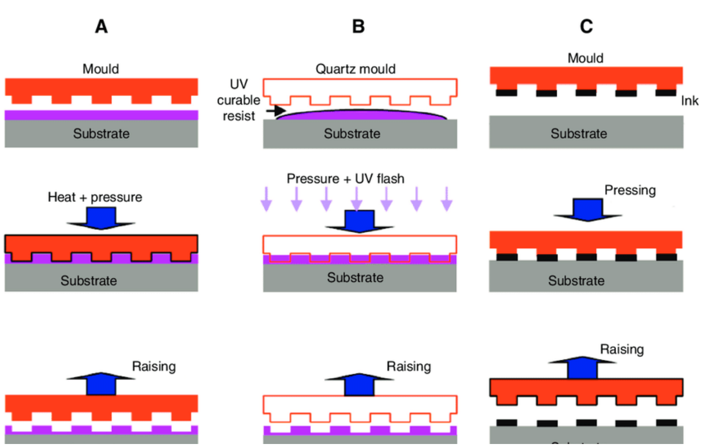


Fig 1. Various approaches for NIL: a) Thermal NIL, b) UV-cured NIL, c) Nano-contact NIL [1]

Reference: [1] Chen YF. Applications of nanoimprint lithography/hot embossing: a review. Appl Phys A-Mater Sci Process 2015;121:451–65.10.1007/s00339-015-9071-x

Quality and Process Control of NIL

In general, NIL process control and quality depends on two major factors: critical dimension (CD) control and local defect control. CD refers to the size (height), pitch and other specifications of the NIL product - the desired shape of the structures. The CD may deviate due to wear and tear of the master template or changes in the process conditions. Local defects on the other hand can include contamination (particles), bubble defects, non-uniformity of the transferred patterns, residual material sticking to the master template after imprinting and scratches or other damage to the master template.

NIL Critical Dimension Characterization

In NIL, process quality is primarily determined by the fidelity of pattern transfer by comparing the CDs of the imprinted pattern to the CDs of the master template. Common techniques for NIL CD characterization include optical microscopy, scanning electron microscopy (SEM), ellipsometry/scatterometry and AFM. Optical microscopy is limited to larger patterns with larger pitches - generally on the micron scale. While SEM provides much higher resolution data than optical microscopy, neither provides quantitative data on the Z-axis. Furthermore, SEM requires complicated sample preparation, especially for non-conductive samples such as polymers and resins which are often used for nanoimprinted samples. Ellipsometry can provide precise data of the Z-axis but does not provide high spatial resolution to study CD non-uniformity across a small area.

AFM is routinely used to collect three-dimensional data of the CDs with sub-nanometer resolution on the Z-axis and with nanometer resolution on the XY axes. The three-dimensional data is helpful when examining NIL samples in comparison to their master to assess pattern transfer quality. In addition to CDs, surface roughness can also be collected among other statistical measurements to help assess process quality.

In the imprinted sample shown in Fig 2, a 3-dimensional scan is produced over a field of view (FOV) of 2 µm x 2 µm. The CDs of the features are: depth of 0.2 µm, diameter of 0.15 µm, and pitch of 0.35 µm.

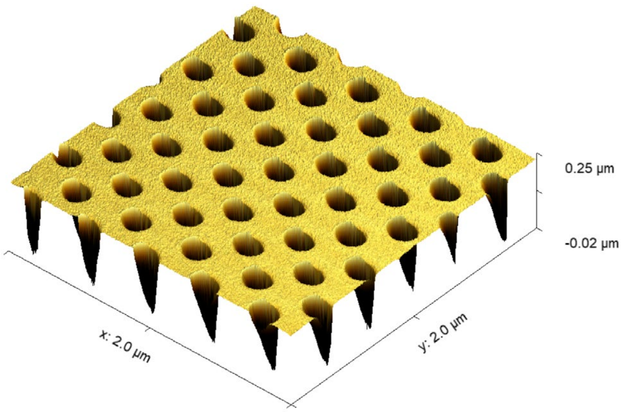
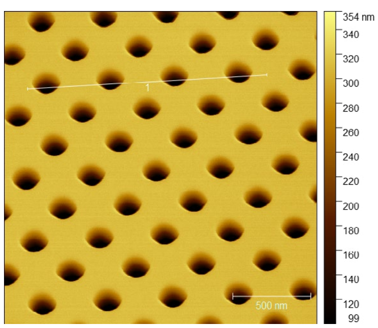
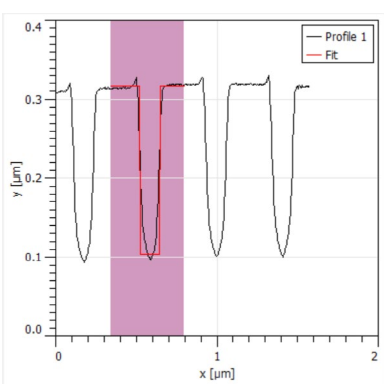


Fig 2. 3D image of a resin imprint sample made using NIL captured using the nGauge AFM. 2 µm x 2 µm topography scan. Lighter colors in an AFM scan typically indicate taller features.





Using the AFM scan and line profile, it can be determined that the imprinted structure fits the desired specification indicating that the master can continue to be used. Over time, the master is susceptible to degradation and contamination which can be assessed by scanning the product using AFM without stopping the manufacturing line. When defects are found through product screening, the master can then be investigated to determine the root cause of the product defects. As a result, issues that impact the master template lifetime such as the presence of a foreign particle can be resolved.

Surface Roughness

It is possible to measure a user-defined area of the sample's surface roughness. For example, the roughness of the masked area in Fig 3 excludes the pores of the sample. The sample's surface roughness is about 2.6 nm (rms). The surface roughness is an indication of the state of the master template and must be monitored to avoid adhesion or problems during release. Systematic characterization and statistical process control (SPC) of the sample surface roughness is an excellent way to prevent catastrophic defects in a NIL manufacturing line without stopping the line.

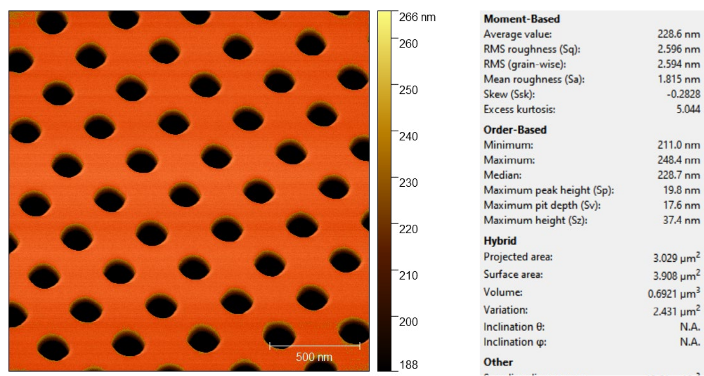


Fig 3 : Statistical analysis of only the masked area (orange area).

Master Template Characterization

In addition to characterizing the surface of NIL imprinted samples, it is important to assess the master template to ensure that defects and inconsistencies do not get imprinted on the resist. This step is extremely important in preventing further complications and avoiding yield loss.

Fig. 4 shows a 3-dimensional representation of a master template of a linear grating. This is an example of a pristine master template where no contamination, defects, or deterioration can be found. Characterizing the master template before using it in the NIL process line is necessary to ensure that the master template meets the intended specs and that irregularities and contaminants are not imprinted on the substrate. Using AFM to characterize the CDs of the master template and comparing them to the CDs of the imprinted samples is useful. Through comparison between master and substrate CDs, the pattern transfer quality can be assessed.

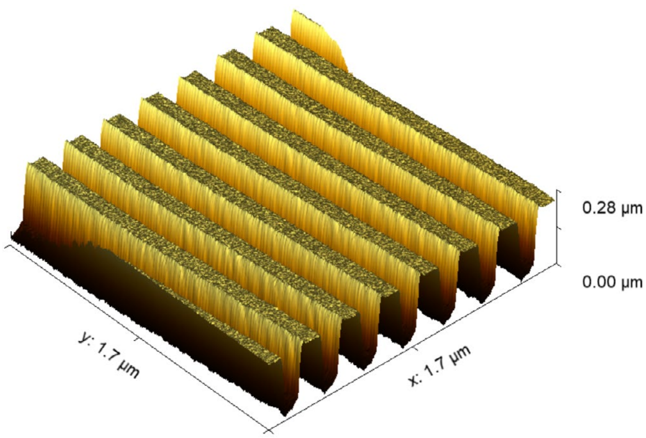


Fig 4. 3D image of a silicon dioxide master template for NIL captured using the nGauge AFM. 1.7 µm x 1.7 µm topography scan.

Local Defect Detection in NIL

NIL relies on direct mechanical deformation of the resist through direct contact with the master template. NIL can achieve resolutions that exceed other conventional lithographic techniques. NIL does however have a high susceptibility to defects due to the contact between the template and the resist to form patterns.

Common defects in NIL processes include bubble defects, non-uniformity of the transferred patterns, and residual material sticking to the master template after imprinting. In addition, particles present between the resist and the master template that are in direct contact risk causing damage to the device and the pattern on the template itself. Other process issues can arise such as incomplete indentation, clogged die, and process condition mismatch (such as speed mismatch in roll-to-roll manufacturing) and must be discovered to prevent further yield loss.

Figure 5 shows an example of an SEM image of structures made using NIL on a polycarbonate film. While the pattern can be seen using SEM and the image can be used to measure CDs, quantitative data and measurements in the Z-axis are not exact and require a cross-section.

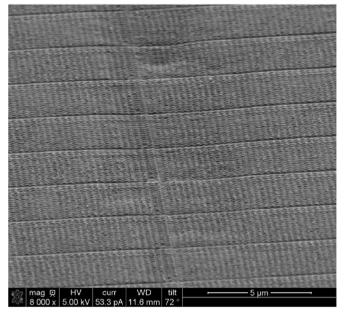


Fig 5. Scanning electron micrograph of NIL patterned polycarbonate film. The scale bar is 5 µm. Courtesy of Smart Materials Solutions, Inc.

Using the nGauge AFM, 3-dimensional data of the polycarbonate film sample is collected and is used to determine CDs along a user-defined line profile. Non-uniformity in the Z-axis of the sample surface can be seen in the scan shown in Fig 6.

AFM can scan non-conductive samples, eliminating the need to sputter metal on the dielectric polycarbonate film surface. AFM also operates under standard atmospheric conditions, meaning unlike SEM, it does not require a vacuum.

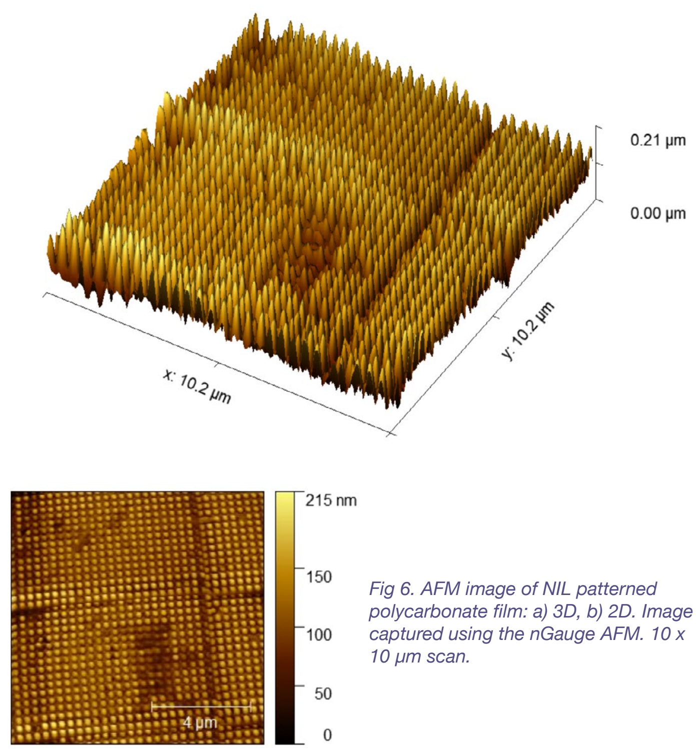


Fig 6. AFM image of NIL patterned polycarbonate film: a) 3D, b) 2D. Image captured using the nGauge AFM. 10 x 10 µm scan.

It is possible to take a user-selected line profile over the projections in the pattern to accurately measure their depth and width. In this case, pillars ranging from 75-100 nm tall and 0.4 µm in diameter are seen. By using AFM, surface defects can be immediately identified. One such issue can be seen in the center lower area of the scan, which may have been caused by a particle landing on the grating surface.

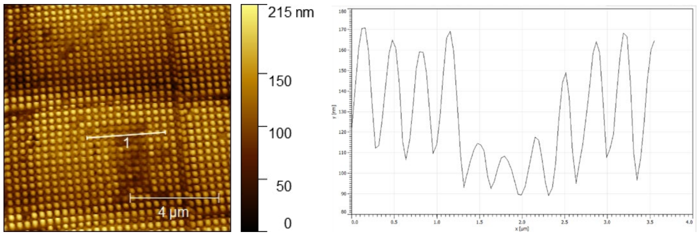


Fig 7. Line profile showing the local defect caused by particle contamination during the NIL embossing process.

The AFM image confirms that there is a local defect where many of the features are shorter. This local defect indicates an issue with the process and a failed part. This AFM data provides valuable localization information about where the defect occurred and assists with an examination of the corresponding location on the master template to prevent the issue from recurring.

In addition, a repeating variation in height across the bottom left of each region is made apparent by the AFM data. From this, it is clear that this defect occurs periodically which provides important information for further investigation of the root cause and subsequent actions that can be made to solve the issue.

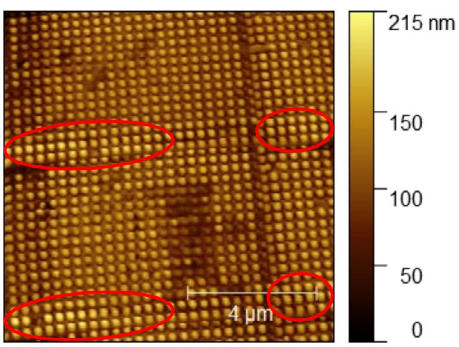


Fig. 8: AFM scan showing raised features in the bottom left corner of each templated region, circled in red.

Comparison Between Techniques

Since NIL defects occur on the nano or microscale, they require high-resolution measurement techniques for adequate characterization. Techniques that are typically used include optical microscopy, SEM, ellipsometry/scatterometry, and AFM. All of these techniques provide CD measurements which play an important role in NIL process control. The table below outlines the advantages and disadvantages of each technique.

Minimum Pitch for CD Measurement: typical measurable minimum pitch of features.

Z Data: technique provides quantitative data in the Z-axis.

Local Defect Characterization: technique is capable of characterizing small local defects.

Wide Field Imaging: technique capable of measuring a large field of view.

Surface Roughness: technique is capable of measuring surface roughness directly.

Limited Sample Preparation: technique does not require sample preparation.

Sample Material Agnostic: the sample material does not impact the data collected by the technique.

Time to data: relative measure of how long it takes to collect data on one sample

	Minimum Pitch for CD Measurement	Z Data	Local Defect Characterization	Wide Field Imaging	Surface Roughness	Limited Sample Preparation	Sample Material Agnostic	Time to Data
Optical microscopy	~500nm	No	Sometimes	Yes	No	Yes	Yes	Fast
SEM	~5nm (only for lateral)	No	Yes	Yes	No	No	Moderate	Slow
Ellipsometry/ Scatterometry	~10nm	Yes	No	Sometimes	No	Yes	No	Fast
AFM	~10nm (depends on feature aspect ratio)	Yes	Yes	No	Yes	Yes	Yes	Fast to slow*

Table 1. Comparison of techniques for measuring NIL substrates.
**Time to data varies between minutes (nGauge AFM) to hours per sample.*

Conclusion

AFM is a powerful and versatile technique for measuring nano-scale patterns imprinted by NIL. AFM provides insight into quality and process control of NIL, quantifying surface roughness, characterizing NIL Critical Dimensions on both master templates and imprinted samples, and is useful in NIL local defect detection. AFM is the ideal candidate for NIL imaging when compared with other available and commonly used techniques due to its minimal time to data (depending on the tool), high XYZ resolution, providing reliable CD measurements and precise data in the Z-range, and providing useful data for local defect characterization. Since AFM requires minimal sample preparation and is compatible with a wide variety of materials, a greater variety of NIL substrates can be characterized without sample preparation or detailed knowledge.