Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

# Development of Joint Manufacturing and In-Line Metrology System for the Patterning of 3D Holographic Structures in Roll-to-Roll Processes

Barbara Groh*, Kwon Sang Lee*, Michael Cullinan*, Chih-Hao Chang*

*Walker Department of Mechanical Engineering, University of Texas at Austin, Austin, TX, 78712

## Abstract

Roll-to-roll (R2R) fabrication at the micro and nano scales promises to increase manufacturing throughput and reduce unit cost while providing avenues for unique product applications. By exploring the potential of creating 3D structures with a single lithography step and being able to confirm success in-situ, existing multilayer patterning error can be mitigated, since 3D features would be created in one step rather than many. This paper demonstrates steps being taken to combine a R2R 3D nanolithography tool and an atomic force microscopy (AFM)-based in-line metrology tool into a functional system for patterning precise 3D structures. An existing manufacturing system will be adapted to pattern complex structures with a flexible PDMS mask currently being proven on stationary substrates. Modifications to the AFM system will include a focus on imaging patterns with varying mechanical properties and tailoring the system to include gathering mechanical information as well as imaging. By mapping surface features, the AFM tool will identify surface imperfections and predict failure modes occurring within the 3D structure.

## Introduction

Current roll-to-roll (R2R) manufacturing uses flexible webs made of thin sheets of metal, glass, polymers, or biomaterials stretched across a series of rolls to enable high-area, high-throughput manufacturing of flexible products. However, flexible substrates have inherent properties that create significant challenge to the production of precise microscale and nanoscale patterns, and further limit the ability to maintain multilayer alignment [1].

The challenges to high precision in R2R manufacturing mainly arise from the instability of the web once it is stretched across the rolls and present themselves in the form of flutter, warping, twisting, slipping and stretching [2], [3]. These instabilities result in a substrate that is difficult to control and monitor at the nanoscale. Fortunately, these challenges have been widely studied and may be accounted for in single-layer patterning applications with precision down to tens of nanometers [4].

Since single-layer patterning can be reliably used in R2R, forms of lithography that create usable products in a single exposure prove to be ideal for this manufacturing process. A commonly used lithography process for this kind of manufacturing is nanoimprinting [4], [5]. Another form of near-field 3D lithography uses near-field interference to leverage optical interference in creating 3D nanostructures within a resist during a single exposure to light [6]. This manufacturing ability will significantly reduce the necessary instances of multilayer alignment and reduce the risk of misalignment ruining a product.

The goal of this research is to design and prototype a R2R tool capable of leveraging this form of interference lithography while simultaneously providing in-line metrology to improve the wholistic control of the manufacturing process and maintain a high-quality final pattern. In-line metrology will help mitigate the risk of failed patterns by monitoring for errors induced by the web instabilities and serve as one of many inputs to the process control algorithm of the system. By building a joint manufacturing and metrology production system, errors will be prevented from propagating across the entire roll and prevent large-scale manufacturing losses.

## Manufacturing Process

The proposed manufacturing tool will be composed of two webs that interact within the lithography module to create the desired pattern. A model of the proposed manufacturing system can be seen in Fig. 1. In the diagram, the green web represents the conformal nanostructured optical mask made of polydimethylsiloxane (PDMS) that acts as an interference lithography mask. This flexible mask will loop to create a continuous mask for the lithography process to occur. The red web in the diagram is the flexible substrate on which the final pattern will be made—and which will proceed beyond this module to development and metrology modules not shown in Fig. 1. This mask will be coated in a layer of photoresist thick enough for the full 3D geometry of the near-field interaction to cure the full 3D structure.

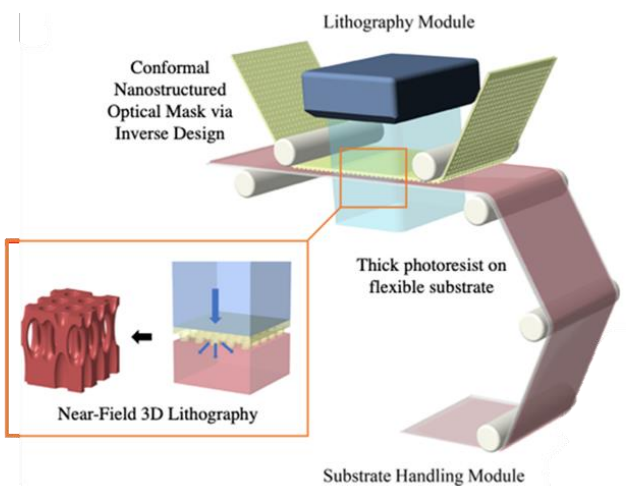

Fig. 1 Diagram of proposed manufacturing system

Currently, the system is creates samples in a batch-to-batch process and does not operate on a continuous R2R system. Instead, every sample is created on a silicon wafer on a sample-by-sample basis. However, the processes necessary to prove the potential success of the R2R setup have been accomplished. The first step of the process is to create a silicon mold of the mask using Lloyd's mirror lithography and RIE processing and is pictured in Fig. 2.

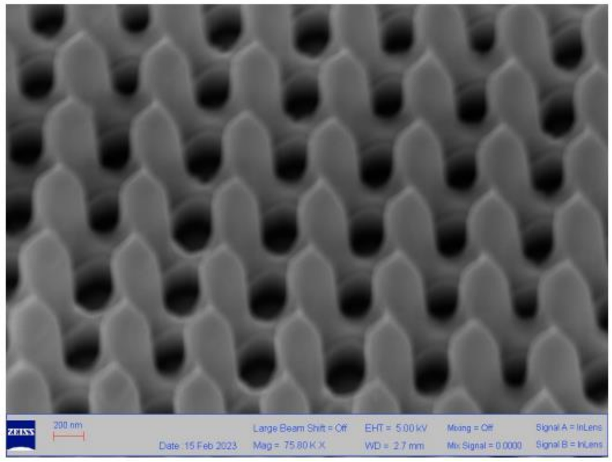


Fig. 2 Silicon nanopattern mold

The silicon mold can then be used to create an inverse PDMS mask by replicating the pattern using soft lithography. The flexible PDMS is at higher risk of damage due to high volume of use and the inherent instability of soft, flexible materials, but the silicon mold allows for nanopattern mask replication at a much faster time-frame than traditional mask manufacturing techniques. This is because the mold can be used repeatedly to form large-area masks rather than using slower processes like laser writing or e-beam writing. An example of the PDMS mask pattern can be seen in Fig. 3.

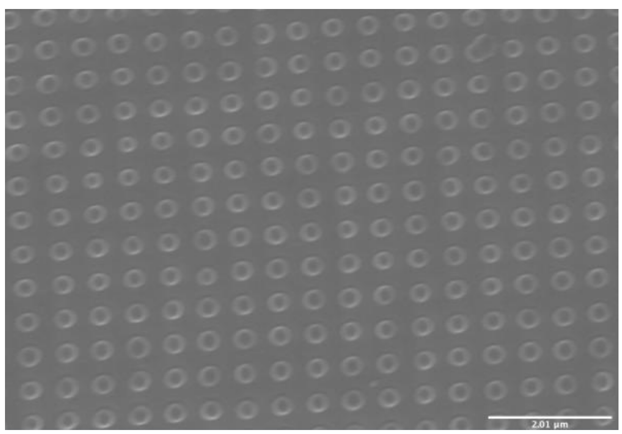


Fig. 3 Conformal nanostructured PDMS optical mask

The final resist structure is made as a result of the PDMS mask, which is the final step of the nanopattern creation process and the ultimate product of the proposed nanolithography module shown in Fig. 1. Currently, the PDMS mask is placed on top of a silicon wafer coated with photoresist and then exposed to an ultraviolet (UV) light source on an optical table, creating the near-field holographic structures within the photoresist. However, this process will eventually be integrated into the R2R-based process as the full lithography module is constructed. A sample result of the 3D pattern can be seen in Fig. 4 as seen from above in a scanning electron microscope (SEM). Defects and inconsistencies in the proof-level testing process, including spin-coating errors and dust particle contamination, have resulted in samples with high variation. However, as the process is improved and optimized for adaptation to R2R fabrication, the resulting patterns will significantly improve in quality.

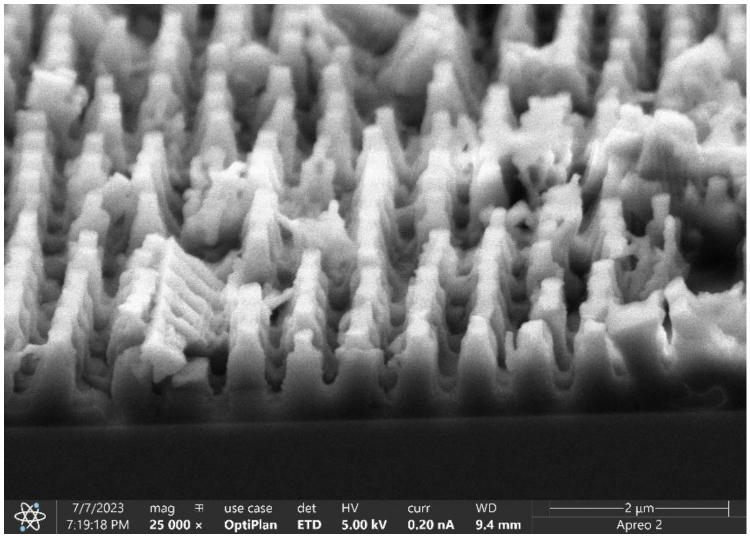


Fig. 4 Final image of 3D holographic lithography pattern

## Metrology

In the interest of working towards a manufacturing tool with self-correcting process control, the development of in-line metrology methods is critical to the success of the research. The assessment of the quality of the patterns takes place in two main branches, atomic force microscopy (AFM) metrology and scatterometry. AFM will target feature-level metrology and take place on a quasi-continuous basis over predetermined sections of the web. Larger-area metrology will be targeted by scatterometry to provide faster results on the quality of the entire web. Scatterometry will provide the added benefit of providing insight on the success of internal structures within the 3D pattern. By working in tandem, the larger-scale metrology can serve to indicate pattern inconsistencies while the feature-scale metrology can determine specific defects that arise from various process failures.

### AFM Metrology:

In-line AFM metrology of a moving web is only achievable when the AFM tip can move in tandem with the web to maintain a constant position relative to the web. This relative stillness is critical for the relatively slow imagining process to have a sufficient amount of time with the same scan area to get a full image. This tool uses a nanopositioning stage consisting of double-parallel flexures driven by voice coil linear actuators to provide XZ motion for AFM tip position control [7]. A picture of the flexure-based motion system is shown in Fig. 5, where the flexure system is further pictured to suspend a gantry system on which a laser distance sensor and the AFM itself are mounted.

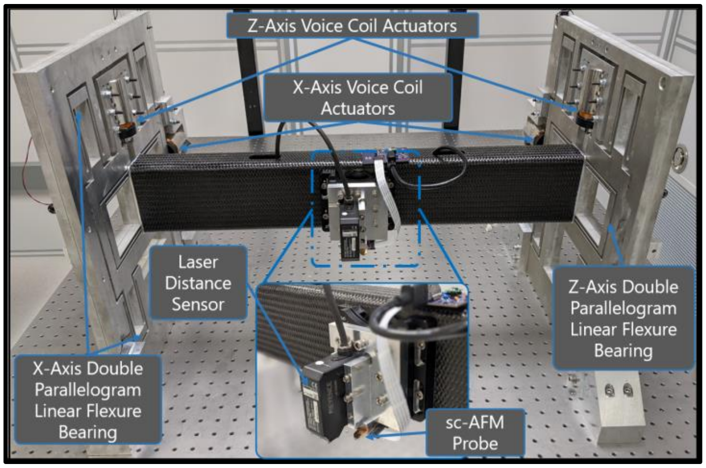


Fig. 5 Double-parallelogram nanopositioning flexure stage

The AFM chip used in this setup is a “single-chip AFM” or sc-AFM (ICSPI Corp.). This chip is a MEMS device with microscale 3D motion driven by thermal actuators and cantilever deflection detected by piezoelectric sensors. An image of the MEMS device is shown in Fig. 6, where the device is mounted on a chip that is mounted to the full-scale machine.

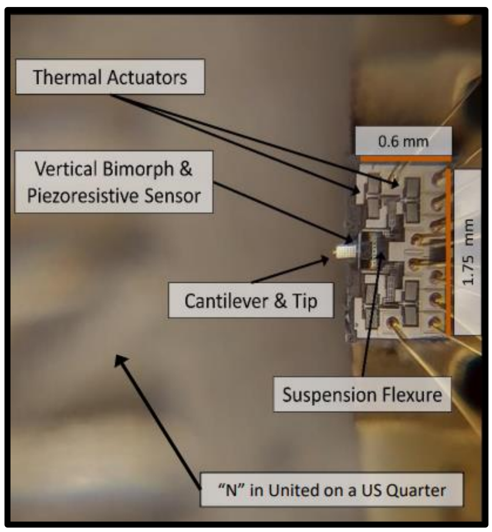


Fig. 6 MEMS sc-AFM [8]

Testing of AFM imaging with moving scans is still underway, but static scans of samples made using the holographic interference lithography process can be seen in Fig. 7. This figure shows an sc-AFM scan of a 60 $mJ/cm^2$ exposed sample with an un-sharpened tip (radius > 100 nm) and demonstrates the device’s ability to detect defects including missing features and pattern collapse.

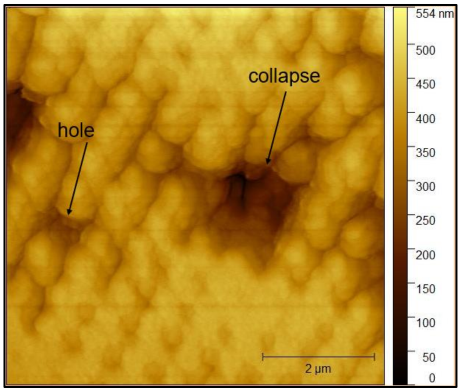


Fig. 7 Static sc-AFM scan of 60 mJ/cm$^2$ exposed sample

AFM scans are limited to areas under 100 um$^2$ every 15-30 seconds and cannot be repositioned relative to the width of the web, and therefore provide only small-area sample to draw process control conclusions. A larger-scale metrology method is necessary to establish the health of the whole pattern, and scans within the visible spectrum of light will work to provide that information.

Scatterometry

Scatterometry will not be able to provide the detailed characterization of a specific area that AFM scans will, but will be able to provide continuous feedback across the entire width of the web. Additionally, comparisons to optical models will allow the system to collect information on the success of the internal structure of the pattern where AFM scans are limited to surface-level detection.

Scatterometry measurements result in reflectance spectra that modulate in period and amplitude that is dependent on both wavelength of light used for detection as well as sample dosage, which can be seen in Fig. 8. By monitoring the modulation phase and amplitude, it will be possible to determine whether the sample was under exposed or over exposed, which would have resulted in internal pattern defects that are reflected in the reflectance spectra.

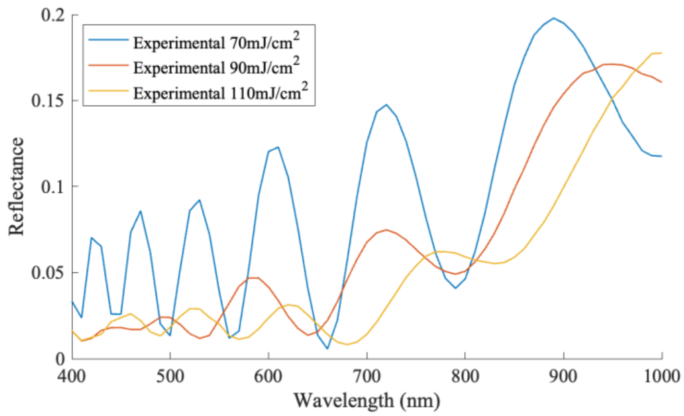


Fig. 8 Reflectance measurements of fabricated samples with 70, 90, and 110 mJ/cm$^2$ exposure dose versus wavelength.

It is important to note that the reflectance spectra demonstrated in Fig. 8 were conducted using a slightly different 3D pattern sample than the samples generated in the manufacturing section. However, the samples were able to serve as proof of the success of the process and the unique reflectance spectra of the PDMS-masked patterns will be taken as the manufacturing process continues to evolve.

## Future Work: Joint Design Proposal

While the manufacturing and metrology processes currently remain separate, plans to adapt these tools to function as a whole-scale system are underway. Fig. 9 outlines a rudimentary system design with all major manufacturing and metrology components. These include the lithography module that uses the manufacturing steps outlined in the manufacturing section, including the continuous PDMS mask and the pre-coated web. This system does not currently include a photoresist application step, as a separate R2R slot-die coating system will coat the substrate roll before it enters the proposed tool.

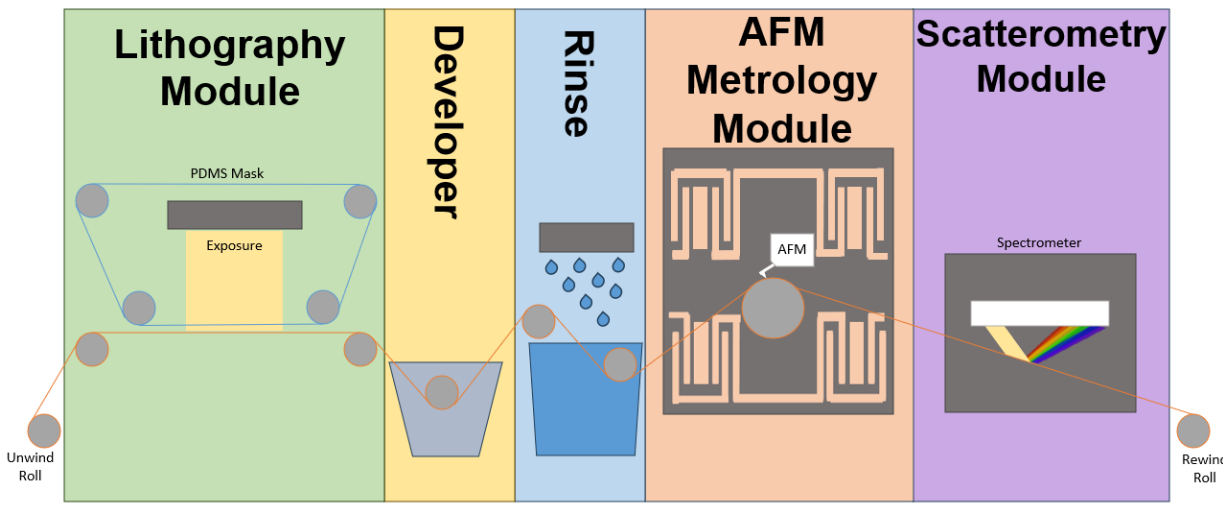


Fig. 9 Diagram of combined manufacturing and metrology system

After exposure, the web must enter a developer step to remove the uncured resist. This is immediately followed by a rinsing step to ensure that excess developer and resist molecules do not interfere with the metrology modules and final pattern. After rinsing, the web will encounter the metrology modules, which consist of the AFM and scatterometry for multiscale metrology.

Not pictured is the process control algorithm that will take the outputs of the metrology modules, as well as countless other sensors system-wide, to determine the success of the pattern and modify any system control inputs to optimize the manufacturing process and improve the quality of the pattern.

This level of process control is only possible with in-line metrology in a system as proposed. Out-of-line metrology would require the patterning of an entire roll before transfer to a separate metrology system, or cutting of the web that may interfere with the roll motion of any subsequent manufacturing. Such delay in metrology could result in significant losses since pattern defects from imperfect process parameters would not be detected until many meters of pattern have been processed. By providing real-time feedback of pattern quality, such losses can be significantly prevented.

## Conclusions

While still in the early stages of development, individual process success demonstrates the feasibility of a 3D holographic lithography tool capable of multiscale metrology for process control optimization. Such a tool would greatly enhance the feasibility flexible-substrate manufacturing in industry by allowing for continuous and reliable 3D structure fabrication.

## References

[1] L. G. Connolly, A. Cheng, J. Garcia, and M. A. Cullinan, "A Roll-to-Roll System for In-line, Tip Based Nanometrology of Patterned Materials and Devices".

[2] J. Deng and L. Liu, "Introducting Rolled-Up Nanotechnology for Advanced Energy Storage Devices," *Advance Energy Materials*, vol. 6, no. 23, Jul. 2016.

[3] Y. B. Chang, S. J. Fox, D. G. Liley, and P. M. Moretti, "Aerodynamics of moving belts, tapes, and webs," *American Society of Mechanical Engineers, Design Engineering Division (Publication) DE*, 1991.

[4] S. H. Ahn and L. J. Guo, "High-Speed Roll-to-Roll Nanoimprint Lithography on Flexible Plastic Substrates," *Adv. Mater.*, vol. 20, no. 11, pp. 2044–2049, Jun. 2008, doi: 10.1002/adma.200702650.

[5] S. V. V. Sreenivasan, "Nanoimprint lithography steppers for volume fabrication of leading-edge semiconductor integrated circuits," *Microsystems & Nanoengineering*, vol. 3, no. April, p. 17075, 2017, doi: 10.1038/micronano.2017.75.

[6] I.-T. Chen, E. Schappell, X. Zhang, and C.-H. Chang, "Continuous roll-to-roll patterning of three-dimensional periodic nanostructures," *Microsyst Nanoeng*, vol. 6, no. 1, p. 22, Apr. 2020, doi: 10.1038/s41378-020-0133-7.

[7] L. G. Connolly, "A tip-based metrology framework for real-time process feedback of roll-to-roll fabricated nanopatterned structures," *Precision Engineering*, 2019.

[8] T.-F. Yao, L. G. Connolly, and M. Cullinan, "Expanded area metrology for tip-based wafer inspection in the nanomanufacturing of electronic devices," *J. Micro/Nanolith. MEMS MOEMS*, vol. 18, no. 03, p. 1, Sep. 2019, doi: 10.1117/1.JMM.18.3.034003.