Manufacturing and Metrology of 3D Holographic Structure Nanopatterns in Roll-to-Roll Fabrication

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ABSTRACT

Eliminating the need for multilayer alignment in nanoscale manufactured devices will streamline the lithography process and open up avenues for flexible substrate roll-to-roll (R2R) manufacturing. A system capable of single-exposure 3D holographic lithography with in-line metrology and real-time feedback will revolutionize micro and nano manufacturing. Work towards such developments are demonstrated to show promise in the field of nanopatterning.

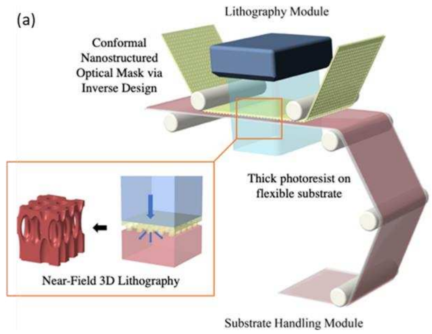

FIGURE1. Diagram of proposed 3D holographic pattern manufacturing system.

INTRODUCTION

Despite its potential to increase manufacturing and reduce production costs, roll-to-roll (R2R) fabrication has yet to compete with solid-substrate manufacturing for nanoscale patterns due to multilayer overlay challenges, on top of other inconsisitencies introduced by flexible substrates.

By pairing precise in-line metrology at the individual feature level with larger scale vision and scatterometry based measurements, the problem of multilayer overlay error can be significantly reduced. Furthermore, exploring the potential of creating 3D structures with a single pattern and being able to confirm the success of those structures in-situ will reduce the number of necessary instances of alignment and increase the production of functional products.

PAPER OUTLINE

This paper will outline steps being taken to combine the functionalities of a R2R 3D nanolithography and an AFM-based in-line metrology tool into a functional system for patterning precise 3D structures. Additionally, this paper will focus on the adaptation of current precision metrology systems to the new application and the metrology outputs that will serve to improve the system process control.

JOINT TOOL FUNCTIONALITY

By using holographic, near-field lithography techniques with subwavelength-patterned phase masks, it will be possible to create multi-material, nanoscale structures in a roll-to-roll (R2R) manner using a single light exposure [1]. The objective of the proposed work is to gain a better understanding of the root causes of low throughput, low precision, and poor yield in nanoscale 3D printing through enhanced, in-line functional metrology and data analytics, along with fundamental modelling of the process and materials physics. The proposed roll-to-roll phase mask 3D Nanolithography (RM3L) process has the potential to break the conventional trade-off between resolution and throughput in nanoscale 3D printing and enable the high-volume, low-cost manufacturing of precise nanoscale structures.

Manufacturing System

The proposed R2R tool for continuous patterning of three-dimensional (3D) structures will use a diffractive optic mask on a flexible polycarbonate (PC) substrate to transfer a 3D pattern to the photoresist film on the

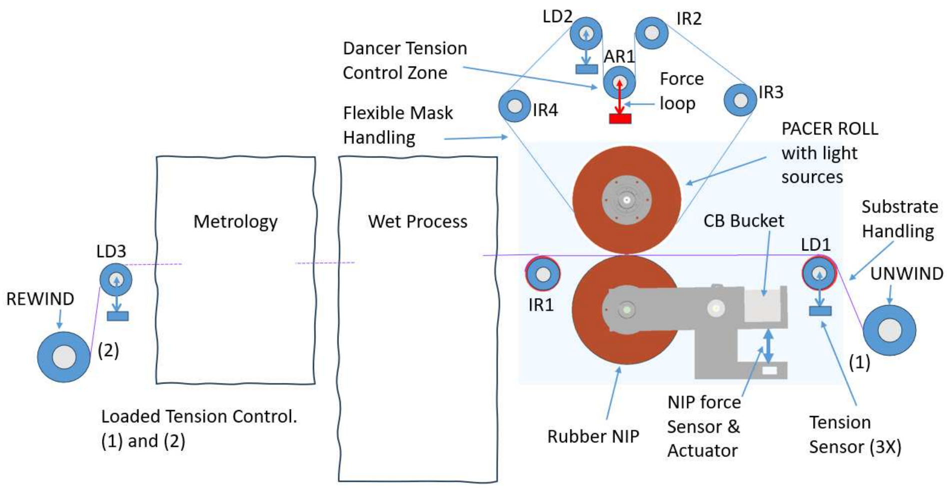

FIGURE 2. Diagram of Planned Manufacturing System.

flexible web using holographic near-field nano-lithography. The tool is an integration of three subsystems, substrate handling, flexible mask handling, and the lithography module. This is followed by a chemical process to develop, rinse, and bake the resist so that the final pattern can be inspected by the in-line metrology systems. To meet our goals, it's crucial to control tension precisely with minimal noise, ensuring high-quality results at the nanometer level, uniform pitch, and preventing films from slipping. Given the challenges of maintaining perfect contact between moving films, the exposure system now utilizes NIP contact rollers. The NIP approach enables high-speed manufacturing by eliminating air entrapment issues and supporting the prevention of natural film oscillations during resist exposure [2]. Maintaining low pressure and uniformity in the NIP (nip in place) is vital to avoid slippage and protect the flexible mask's 3D pattern. The counterbalanced Rubber NIP applies force evenly over the contact zone, controlling pressure. Using NIP for pattern transfer is essential for keeping a precise gap between films and uniform illumination at the same focal point.The line speed is controlled by the PACER, followed by the Rubber NIP below. To eliminate speed fluctuations, the PACER is equipped with a HIDENHAIN high-resolution encoder and both NIP rollers use air bearings for nearly frictionless rotation. The combination of low friction and low-noise tension control ensures zero slippage between films during contact.

Metrology Systems

3D holographic nanopattern manufacturing will require multiscale metrology methods to ensure the success of the material as well as provide real-time in-line feedback for process control. Two main systems contribute to the total metrology module, a spectroscopic scatterometry-based pattern-level feedback system and an AFM-driven feature-level feedback system. Scatterometry is able to give fast, large-scale pattern quality detection of these 3D structures by monitoring reflectance spectra indicators of porosity and exposure dosage [3]. The existing AFM metrology tool is capable of in-line metrology of R2R samples at the feature scale. It consists of a single-chip,

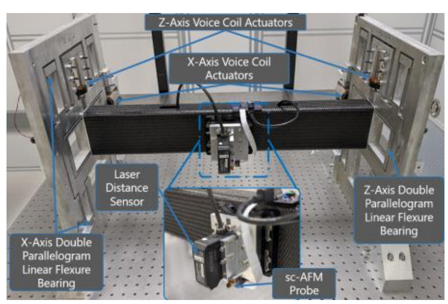

FIGURE 3. Pictured is the nanopositioning AFM metrology system, part of the proposed system's metrology module.

micro-electro-mechanical system (MEMS)-based AFM mounted to a flexure-based gantry system as seen in Fig. 3. The single-chip AFM (sc-AFM) contains full actuation for taking a scan within a 20 µm by 20 µm area and the gantry allows the AFM chip to be suspended above the web and maintains the position of the AFM relative to the moving web [4]. This, in combination with a flexure system stabilizing and actuating the gantry, allows the web to move continuously and the AFM to move with it for the length of the scan [5]. The flexure-mounted AFM system can then lift and reset position to take another moving scan.

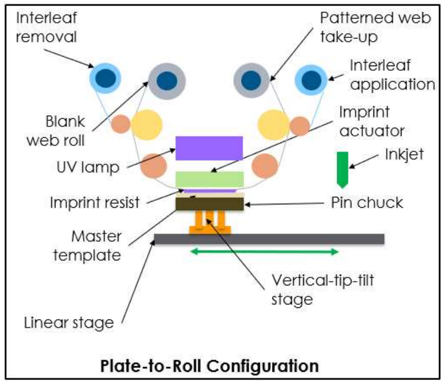

FIGURE 4. Nanoimprint mask-production system [6].

ROLL TO ROLL PATTERNING

The manufacturing line comprises two polycarbonate film loops, as depicted in the Fig. 2. The upper (mask) loop is pre-manufactured with specific features, while the lower substrate handling consists of blank polycarbonate embedded with photoresist sensitive to two wavelengths.

Mask Production

The flexible diffractive optic mask is manufactured in a separate roll-to-roll nanoimprint lithography system. Here, a polycarbonate web coated in a high-index thin film such as Aluminum Oxide is patterned and etched to create the optic necessary to prooduce the 3D holographic strucures in the final product.

A diagram of the nanoimprint system used to create the flexible mask is showin in Fig. 4. The master template is an electron beam etched silicon nanoimprint template that will be mounted onto the linear stage of the plate-to-roll configured system to create a patterned web.

Mask Handling

In the mask loop, the approach involves synchronizing with the lower film through a uniformly applied light pressure using NIP rolls. The same mask is continuously reused to expose the photoresist. The mask loop speed is regulated by a 150 mm diameter motor/encoder situated at the Pacer upper NIP roll. Tension control is achieved using a load cell at LD2 and a dancer employing an air turn AR1 to apply a force to the film without physical contact. Idler rollers IR2-IR4 facilitate directing the loop around the NIP.

Substrate Handling

The lower loop begins with a roll of film featuring the appropriate thickness of photoresist, mounted on the unwind roller. The unwind speed is controlled to maintain tension before the NIP, monitored by load cell 1 roller LD1. The NIP pressure brings the two films together, ensuring the blank film is exposed, following the upper mask film at the same linear speed without slippage or jitter. Post-exposure, the film undergoes the Chemical mill process and inspection. All manufacturing and inspection data is transmitted to our supervisory Artificial Neural Network (ANN) engine, which analyzes the product and implements the necessary adjustments to enhance the manufactured film in line with specifications.

Finally, the lower film is wound back into a roll using the rewind, controlling the speed to achieve the desired tension. For added protection of the nanostructures, an interleaver may be introduced if necessary. In the case of water nanofilters, where only holes are created, the use of an interleaver might be unnecessary. Additionally, simplifying the peeling process may be feasible with a more straightforward machine design. For all turns about the patterned side of the webs, it is necessary to use air turns to prevent damage to the nanoscale structures.

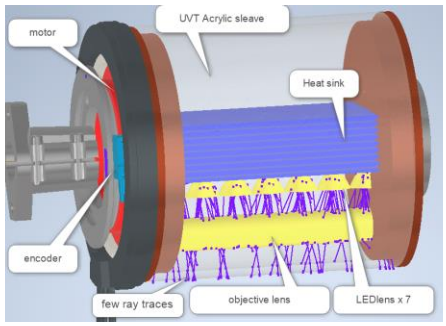

FIGURE 5. Model of acrylic pacer of lithography module with ray traces.

Lithography Module

The lithography module relies on a specialized UVT acrylic pacer to provide the necessary light for exposing patterns. This pacer, depicted in Figure 5, is capable of generating illumination focused on an area approximately 5 mm wide, matching the width of the film resist coating.

This setup is crucial for exposing the resist along the NIP (nip point) between two 152.4 mm rollers. The lower roller's soft rubber layer compresses to establish a 6 mm contact between the films. The system employs 7 LEDs with individual lenses, as illustrated in Figure 5, to provide illumination. The acrylic drum, supported by a stationary shaft, rotates on air bearings and is powered by a torque motor while being monitored by a high-resolution rotary encoder. Additionally, the lower rubber roller also uses air bearings to minimize friction and vibrations, ensuring no slippage between the films held together with low pressure.

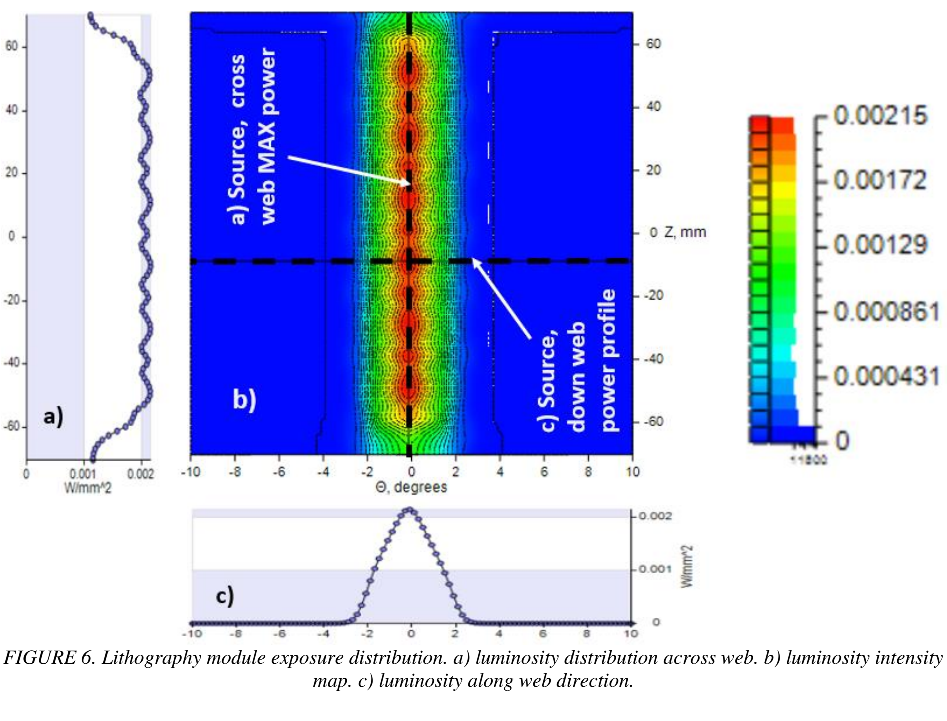

FIGURE 6. Lithography module exposure distribution. a) luminosity distribution across web. b) luminosity intensity map. c) luminosity along web direction.

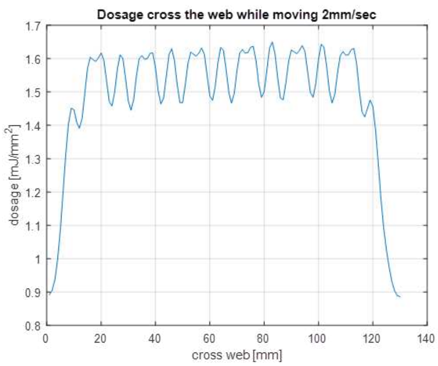

FIGURE 7. Compares the ripple of static exposure versus the MAX irradiance cross web as shown above.

The targeted speed is up to 2 mm/sec, and the dosage is regulated by changing the intensity of the LED UV sources. Slow automated adjustments are made based on feedback received downstreem from the inspection process, thus increasing the intensity for underexposure or decreasing it for overexposure.

Figures 6a and 6c demonstrate the current design's irradiance distribution across the web as it moves through the lithography module, across the web and along the web, respectively. Currently, a peak-to-peak ripple of 6% is possible using independent LED collimator lenses, as shown in Figure 7. However, given that the exposure dosage required to generate the 3D holographic features is 0.5 mJ/mm^2, reducing current to the LEDs will be critical to achieving the exposure goal. Fig. 7 demonstrates that in a given line in the web, the dosage from a 3 second exposure varies similarly to the MAX exposure in Fig 6a and results in curing variations of up to 13%. Minimizing peak-to-peak ripple in exposure while maintaining collimation within 5% is a critical challenge to the success of this lithography module.

Future enhancements involve employing free-form optics to minimize peak-to-peak changes along the cross-web direction. This approach will enable closer LED spacing to accommodate multiple wavelengths in the same line and reduce ripple through illumination overlap. Presently, the irradiance is approximately half of the total focused power due to a 5 mm aperture acting as a spatial filter, limiting rays exceeding 5 degrees and reducing exposure distance to less than 6 mm.

Commented [BG1]: Change left to mJ

In summary, the lithography module under develoment utilizes specialized components and precise adjustments to achieve accurate pattern exposure while minimizing power consumption and maintaining consistent illumination across the web.

MEASUREMENTS AND CONTROL

Metrology of a R2R system requires very many sensor inputs to ensure precise function. Here, we specify only the most critical inputs for controlling the AFM measurement system and how they affect the output of the system.

Web-Handling

The web handling system focuses on the motion of the substrate. A high-precision sin/cos encoder detects the position of the roll to monitor the position of the web. This is mounted to an idler roller underneath the AFM system that stabilizes the web at the point of measurement. In order to maximize the wrap angle about the idler and reduce error from web slip, an air dancer pushes the web down for non-contact web manipulation on the patterned side of the web.

Nanopositioning

The nanopositioning subsystem is actuated in the XZ plane by voice coil linear motors driving a pair of biaxial double parallelogram flexures with a gantry suspending the AFM in between [5]. The x-axis allows for the AFM to move in tandem with the moving web for the duration of the scan while the z-axis motion regulates the approaching and disengaging actions of the probe. A series of laser interferometers monitor the motion of the gantry system in the XZ directions while a laser distance sensor monitors the approach of the AFM to the substrate. The flexure-gantry system is pictured in Fig. 3.

<u>AFM Outputs</u>

In addition to the many sensors used to run the system, the AFM output itself can also be used to inform the control of the system. The shapes of the patterns measured can inform the success of the structures as well as indicate levels of over or under exposure during manufacturing. Additonally, we plan to experiment with the use of force modulation microscopy to monitor various material properties of the pattern in order to further monitor the process control.

FUTURE WORK

Design and prototyping of this system is still underway, but the success of individual subsystems and initial models of the system indicate that the tool will be able to achieve continuous fabrication and characterization of 3D structures.

Headway will be driven by continuous advancement in the individual modules and each of the critical components within those. The final diffractive optics and custom photoresist that will be used to enable this advancement are still in development. The manufacturing system has reached the prototyping stage, and will require webline integration with the existing AFM metrology system. Control of both of these systems is also evolving so as to allow for continuous manufacturing and measurement.

Furthermore, the process control goals of this system require data processing of AFM and scatterometry data that would normally be beyond the scope of feasibility for real-time control, but by developing a machine-learning-driven data processing algorithm based on a thorough library of sample process settings, such feedback control will be possible.

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