DEVELOPING IN-LINE METROLOGY OF 3D HOLOGRAPHIC PATTERNS DURING ROLL-TO-ROLL MANUFACTURING PROCESSES

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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 [1].

Web control challenges can result in substrate instabilities including 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]. The ability to reliably create single-exposure patterns indicates that reducing the number of exposures necessary to create a product will increase its likelihood of success. The use of near-field interference lithography to create 3D holographic nanostructures allows for 3D patterns to be manufactured in a single exposure [5].

The manufacture of 3D structures in one lithoography step does necessitate evaluation of the product in at both a web scale and feature scale. Wholistic evaluation of the manufactured pattern can be executed by pairing precise in-line atomic force microscope (AFM) metrology at the individual feature level with larger scale vision and scatterometry based measurements. Furthermore, in-line metrology can be leveraged as control inputs for real-time process control of the system to optimize the quality of the final product.

MANUFACTURING

The samples currently used for conceptual testing of the proposed manufacturing methods are made in a batch-to-batch process based on the final manufacturing design. A schematic of the manufacturing system can be seen in Figure 1 and features a conformal nanostructured optical mask loop interacting with the photoresist-covered substrate web.

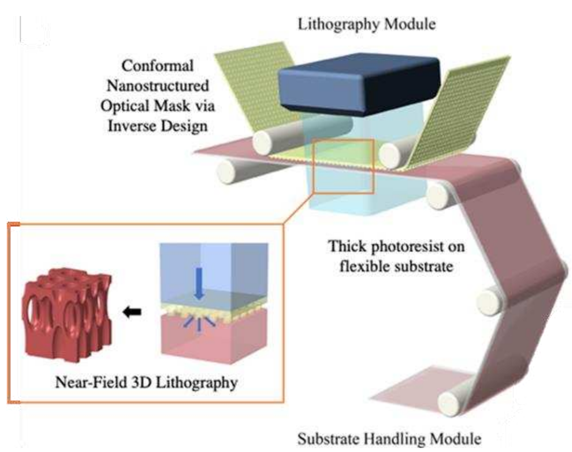

FIGURE 1. Diagram of proposed 3D holographic pattern manufacturing system.

The polydimethylsiloxane (PDMS) mask is aligned with the substrate and exposed to an ultraviolet (UV) light source to create the near-field holographic structures within the thick layer of photoresist. An example of the resulting pattern can be found in Figure 2, although refinement to the process and manufacturing environment is necessary to improve pattern quality.

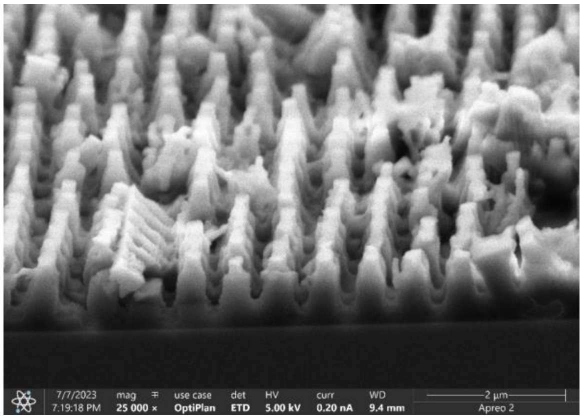

FIGURE 2. SEM image of 3D holographic lithography pattern

METROLOGY

The 3D holographic structures created by the system require metrology at multiple scales to account ensure high quality features across the span of the entire web. Metrology goals include topographical imaging of the pattern at the individual feature level, assessment of the quality of the periodic internal structure of the pattern, and measurement of the material properties of the exposed resist.

AFM System

The existing AFM metrology tool is capable of in-line metrology of R2R samples. It consists of a single-chip, micro-electro-mechanical system (MEMS)-based AFM mounted to a flexure-based gantry system as seen in Figure 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. 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. The flexure-mounted AFM system can then lift and reset position to take another moving scan. This system is known as the nanopositioning subsystem for the remainder of this paper.

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. 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

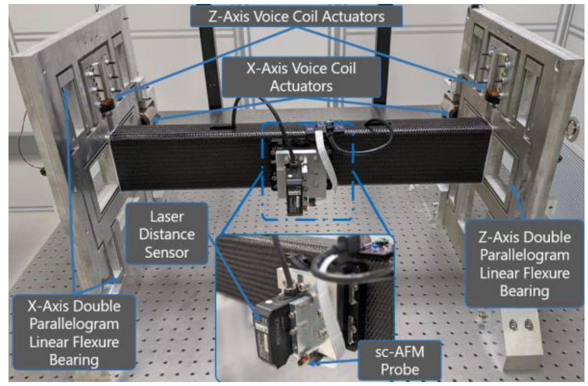

FIGURE 3. Pictured are the web handling components of the rewind roller

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.

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. A laser distance sensor monitors the radius of the roll as material is added or removed, as this will influence the torque applied by the motor to the web as well as how much distance the web moves for each rotation of the motor. Furthermore, an idler roller underneath the AFM system stabilizes the web at the point of measurement. The components of the rewind and unwind rollers are nearly identical, except a higher precision encoder on the rewind roller and an anti-static ionizer on the unwind roll. The rewind half of this system is shown in Figure 4.

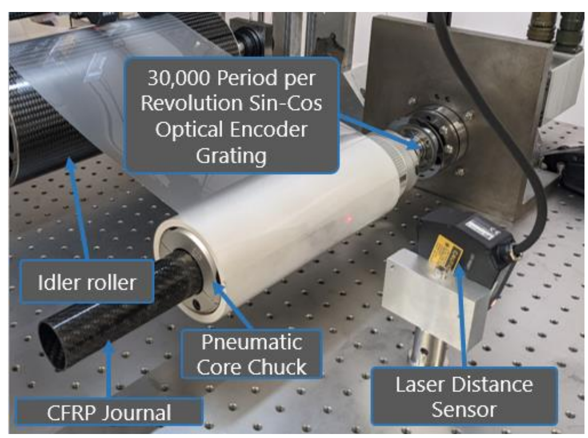

FIGURE 4. Pictured are the web handling components of the rewind roller.

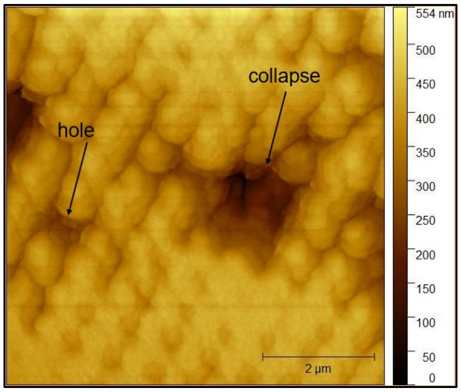

FIGURE 5. Static sc-AFM scan of 60 mJ/cm² exposed sample

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/cm² 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.

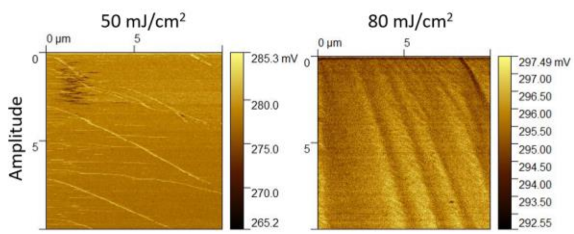

FIGURE 6. FMM data of blank samples exposed at 50 mJ/cm² and 80 mJ/cm²

Other measurements that can be taken on the AFM system include an variant of the traditional scanning method known as force modulation microscopy (FMM). Instead of controlling oscillation frequency like in traditional AFM control, FMM requires periodic force control. By measuring the shift in force amplitude, the FMM is capable of measuring relative change in stiffness. In Figure 6, FMM scans of flood exposed photoresist samples show that the device can indicate a change in mV that scales with exposure dosage. This metrology method will serve to detect changes in exposure and curing completion.

Due to the physical limitations of the flexure nanopositioning system and AFM scan throughput, this metrology method has limited sampling ability. Additionally, the scan location cannot be repositioned relative to the width of the web. Therefore, this metrology technique can only provide topographic and material property data at a relatively low sampling rate, generally under 100 um² every 10-20 seconds. In order to assess the entire web, a larger-scale metrology method is necessary.

Scatterometry

Where AFM will provide periodic sampling of individual feature-scale characterization, scatterometry will provide continuous feedback acrosss the entire web. Additionally, the use of optical modeling of the ideal physical system and comparison to the real-time measurements will create the opportunity to characterise the internal periodic structure.

The periodic nature of the pattern will result in predictable reflectance spectra that modulate in period and amplitude. These characteristics are dependent on both the wavelength of light used for detection as well as the sample exposure dosage. Experimental scatterometry results can be seen in Figure 7, where samples produced more damped reflectance amplitudes and longer periods at higher dosages. By monitoring the modulation phase and amplitude, it is possible to determine over or under exposure, which is further indicative of internal pattern defects that affect the reflectance spectra.

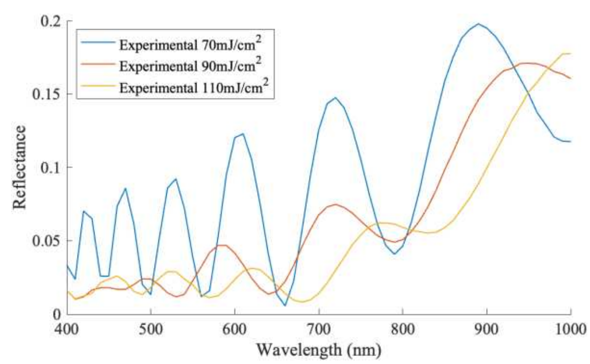

FIGURE 7. Reflectance measuremens of fabricated samples with 70, 90, and 110 mJ/cm² exposure dose versus wavelength.

The experimental data can then be compared to an optical model performed using finite-difference time-domain (FDTD) methods [6]. The 3D holographic interference pattern created by the optical model is then used to create a binary model of the shape created in the photoresist. A transfer-matrix method (TMM) simulation is then performed on the binary resist model to generate a reflectance spectra model [7].

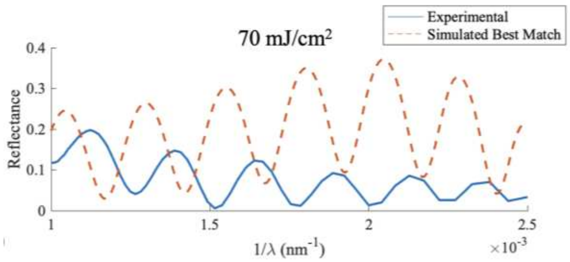

FIGURE 8. Best-match reflectance spectra between experimental results and simulation.

Figure 8 shows an example comparison between the simulated reflectance spectra and the experimental data. In this figure, the internal structure of the pattern most significantly effects the period of the spectral modulation. The models were able to achive period matching within 2% error. The phase shift notable within the figure is due to differences in photoresist thickness, which is not yet accounted for in the model.

Using the model comparison, changes in the period of reflectance modulation can be used to indicate imperfections in the internal structure of the pattern as well as provide exposure dosage information. Reviewing areas of concern indicated by the scatterometry measurements with the AFM metrology system can provide more detailed characterization of manufacturing imperfections to provide robust quality control.

JOINT TOOL FUNCTIONALITY

The adaptation of traditionally off-line metrology techniques for in-line use within a R2R system provides opportunity for revolutionary improvements to real-time process control. Applying multiscale metrology grants process evaluation in both high-throughput, large scale characterization as well as low sampling rate, high detail characterization. With evaluation of pattern success occurring in real-time, optimizing control inputs to the manufacturing process can take place with minimal pattern loss.

Both AFM and scatterometry metrology do require high computational load for pattern evaluation. To minimize processing time, comparisons to a library of fully characterized samples can additionally streamline the computational process and ensure real-time feedback. Metrology analyses that would generally require hours of off-line measurement will be conducted in much shorter time scales to ensure the highest pattern quality.

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