Towards Quasi-real-time, Tip-based Process Control in Roll-to-Roll Nanomanufacturing

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Roll-to-roll (R2R) manufacturing processes are cost-effective, flexible-substrate enabled processes with high throughput compared to traditional nanofabrication solutions. However, the lack of high-throughput, nanometer-scale metrology poses a significant challenge to the adoption of R2R nanomanufacturing. To address this issue, this work presents the design and fabrication of a tip-based measurement tool that uses atomic force microscope (AFM) probes manufactured with a micro-electro-mechanical system (MEMS) approach. The tool is capable of measuring features on the substrate and coordinating with a real-time embedded control system to regulate a flexible web and position the AFM probe.This work presents the development from a proof-of-concept tool to a higher volume prototype to perform tip-based measurements on flexible, nanopatterend substrates in a R2R manner. The goals of this design evolution revolve around improving precision to facilitate quasicontinuous scanning of R2R substrates, or the implementation of atomic force microscope sampling without the need to halt the web as is the case for current step-and-scan measurements.

This work describes the steps taken to improve a prototype design and outlines the main components of the full system, including the nanopositioning system, the web handling system, and the AFM topography system.

I. INTRODUCTION: THE NEED FOR IN-LINE METROLOGY

A Roll-to-roll (R2R) approach as applied to nanomanufacturing aims to bring devices with performance akin to counterparts produced with traditional silicon wafer or glass panel based substrates while possessing unique mechanical properties, and most importantly, significantly lowered cost[1–6]. From optical devices, hydrophobic, anti-fouling, and other coatings to integrated circuits, the promise of lower cost nanofeatured products has driven intense research efforts towards enabling R2R fabrication techniques which can successfully make the jump from academic experimentation to high volume manufacturing (HVM)[7–14]. The barriers in front of profitable R2R HVM centers on yield and throughput[15]. While R2R manufacturing holds a major throughput advantage, it may only become a successful strategy if cost feasible yields may be achieved. The National Institute of Standards and Technology has identified high-throughput alignment, real-time metrology, and closed loop process control as the most critical areas in need of innovation[16,17]. While small-scale fabrication has been demonstrated, there exists a significant hurdle to economically feasible, widespread adoption of these manufacturing techniques — the metrology problem[16,18,19]. Many approaches towards yield enhancement have been studied and demonstrated to be effective at distinct, and often disparate, measures of performance and efficacy. These generally vary by the physical phenomena which they leverage. Despite these approaches originating from years of development for similar tools in the wafer semiconductor fabrication industry, commiserate application to R2R nanomanufacturing remains a challenge.

II. NANOMETROLOGY TOOL DESIGN

An in-line, quasicontinuous metrology tool would need to be able to account for the continuous motion of the measurement substrate so that manufacturing does not need to be halted while measurements are taken. Therefore, several subsystems must work in tandem to achieve a stable sampling environment. The first is the web handling system, which must maintain web stability while also providing the tension necessary to operate. The next is the nanopositioning system that maintains the sc-AFM system positioning relative to the moving web. Finally, there is the sc-AFM itself, which takes the scans of the patterned web.

A. Web Handling System

The particular goals of the web-handling system are to control the velocity and tension of the web while maintaining certainty of the web position and minimizing the noise and vibration from the motion components. Upgrades were made to a prototype tool[20] in order to minimize random errors in linear velocity and tension commands. Low-cost, self-aligning roller bearings were replaced with super precision class cartridge bearings, which were selected for their high stiffness and ease of modification. These are mounted to the precision ground cast iron angle plates in Fig. 1. Precision laser triangulation sensors were added to sense roller diameter change, and inexpensive brushless DC stepper motors were replaced with precision, high-torque slotless, brushless DC motors (see Fig. 1). The rotary actuators and sensors coupled to the spindles were also upgraded to slotless DC motors to minimize noise in velocity control. Finally, a self-sensing static eliminator

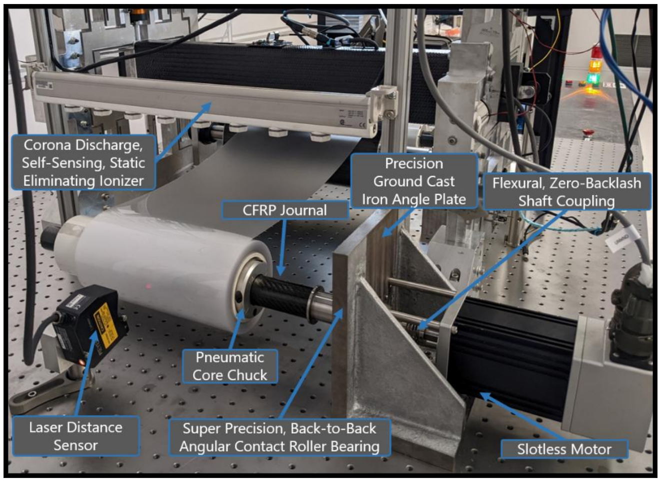

FIG. 1. Unwind stand with major components labeled.

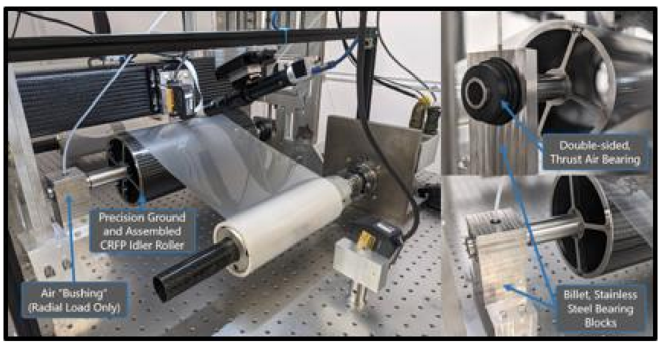

FIG. 2. Air-bearing supported metrology idler roller with major components labeled.

was installed to eliminate surface charging effects (see Fig. 1). These upgrades improve the accuracy and precision of the web motion to minimize error in the alignment between web motion and the nanopositioner motion described in the next subsection.

Another critical web handling component is the idler roller that stabilizes the web at the point on which metrology is conducted. This roller was constructed from a CRFP drum with stainless steel hubs to minimize the angular moment of inertia and reduce slip of the web on the roller that would otherwise induce noise. This roller was attached to a combination radial air bushing and thrust air bearing to minimize rotational friction and vibration. All components can be seen in Fig. 2.

B. Nanopositioning Subsystem

The prototype tool includes a sc-AFM nanopositioning subsystem which regulates the position of the sc-AFM, preventing destructive web-tip crash during startup, high-speed web movement, or when replacing the sc-AFM chip. The subsystem isolates the sc-AFM from external disturbances by using two coupled positioners, one which moves the gantry arm to which the sc-AFM is attached and one which regulates fine

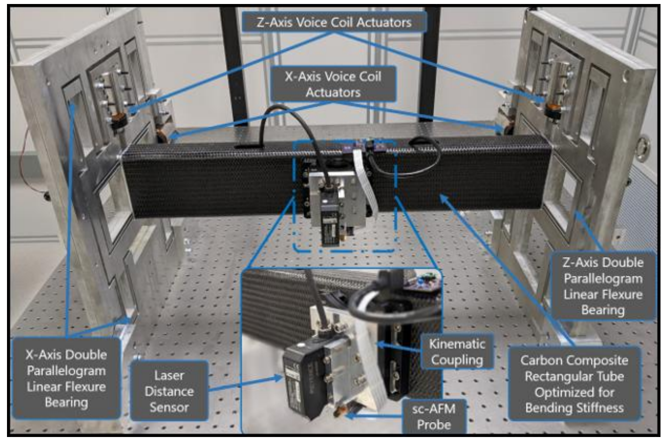

FIG. 3. Nanopositioning module with all major components labeled

sample approach. The flexure geometry is that of a double parallelogram flexure mechanism (DPFMs) and has the z-axis and x-axis directional movement driven by voice coil actuators with interferometric positional feedback. Control of the system is calculated and coordinated by an FPGA-based real-time control system. The DPFMs and the gantry arm on which the sc-AFM probe is mounted is pictured in Fig. 3.

C. Metrology Subsystem

The metrology subsystem is primarily enabled by the single-chip Atomic Force Microscope (sc-AFM) developed by ICSPI. This chip contains a MEMS device with a thermally actuated flexure stage for positioning the AFM in the XY axes and a vertical bimorph stage to position the cantilever in the Z direction. A piezoresistive sensor at the pivot of the cantilever detects the changes in the cantilever vibration amplitude to generate the signal for imaging[21–23].

This sc-AFM is then mounted to the gantry of the nanopositioning subsystem with the module pictured in Fig. 4. The entire metrology subsystem is shown, including the laser distance sensor serving as feedback to the process control, accounting for roller runout, x-axis position above the round idler roller, and web thickness variability. A camera was also added to the system in order to monitor the continued viability of the cantilever. A sample image from the camera is also shown on the right side of the figure, showing the cantilever attached to the MEMS device at the end of the chip.

III. FUTURE WORK

The in-line metrology system as-built would benefit from both mechanical and operational improvements. Mechanical improvements include a more precise final outside diameter grind of the Unwind/Rewind stand journals to reduce runout, and the implementation of an optimized H-Infinity controller to improve dynamic performance. The system would also benefit from a well-designed algorithm for data fusion to cor-

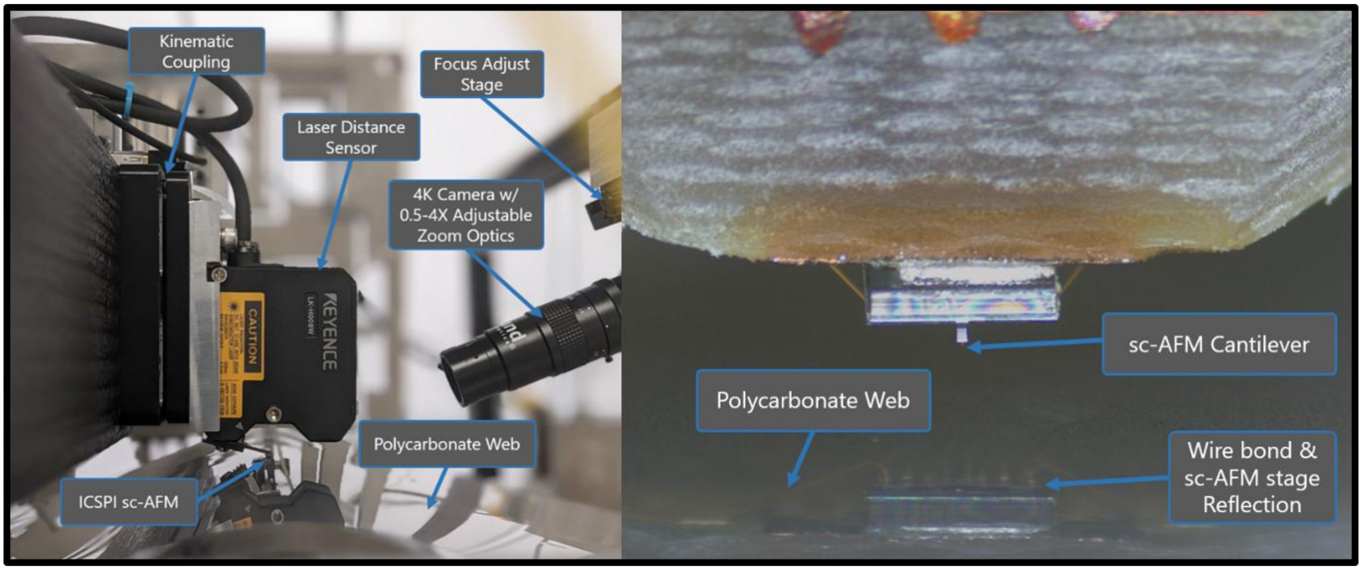

FIG. 4. Left: Metrology subsystem with major components labeled. Right: Camera view of sc-AFM cantilever.

rect for thermal expansion and other sources of measurement uncertainty. Ultimately, the goal is to enable truly in-line measurement of nanoscale topography without negatively impacting the throughput of any new processes or fabrication tools. This would currently only be enabled by the combination of optical metrology at a larger scale and the proposed sc-AFM based in-line process control at the smaller scale.

A. Future Applications

Currently, the tool only conducts metrology on pre-manufactured rolls of patterns. However, this metrology system is already in development to be included into a full lithography manufacturing system with in-line metrology. With measurements enabled by adapting this tool, the manufacturing system will have in-line evaluation of the patterns it produces, allowing for real-time process control adjustment.

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