Process Development for Conformable, Capillary-Driven, Continuous Roll-to-Roll Nanoimprint Lithography

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ABSTRACT

An alternative approach to roll-to-roll nanoimprint lithography is being developed which eliminates the use of an embossing roller. This paper describes a process designed to implement a capillary-driven, conformable, and continuous, roll-to-roll nanoimprint lithography process with a flexible template web and transfer sub-50 nm features on a flexible substrate web with a sub-25 nm residual layer thicknesses (RLT) while maintaining a throughput of up to 5 m/min. The combination of sub-50nm resolution, RLT control and throughput targeted by this equipment technology has not been demonstrated in the literature. Applications in display devices, nanophotonics and flexible electronics can see enhanced performance by reducing feature sizes obtained in roll-to-roll nanoimprint lithography. In a specific example of flexible displays with transparent metal mesh electrodes, reducing RLT to sub-25 nm allows RLT etch which can significantly improve transmission, sheet resistance and haze enhancing its commercial viability. Steps for fabricating a flexible template and replicating patterns on a flexible substrate are described in the following sections along with models for interfacial nanoscale phenomena.

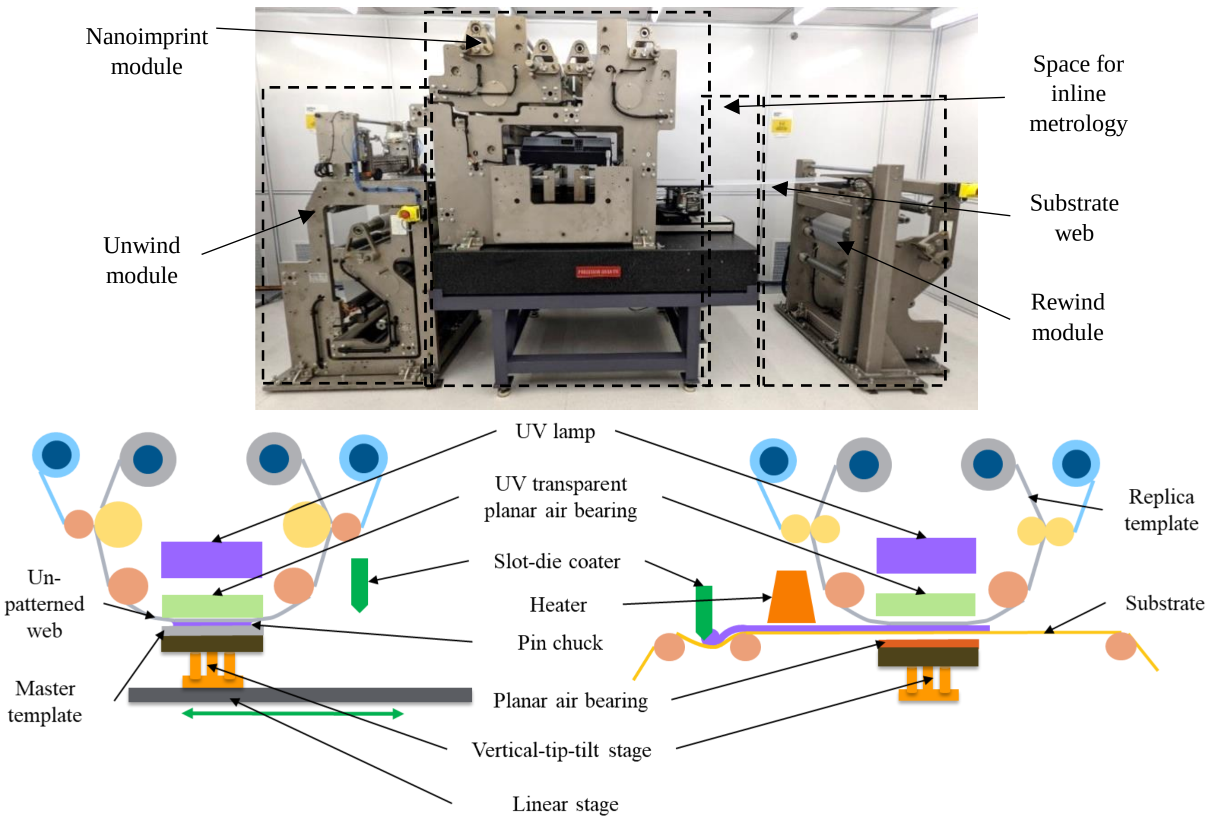

FIGURE 1. Nanoscale roll-to-roll replication tool (top). Schematic of Nanoimprint module used for replica template fabrication (bottom left). Schematic of Unwind, Nanoimprint and Rewind module used for continuous roll-to-roll nanoimprint lithography (bottom right).

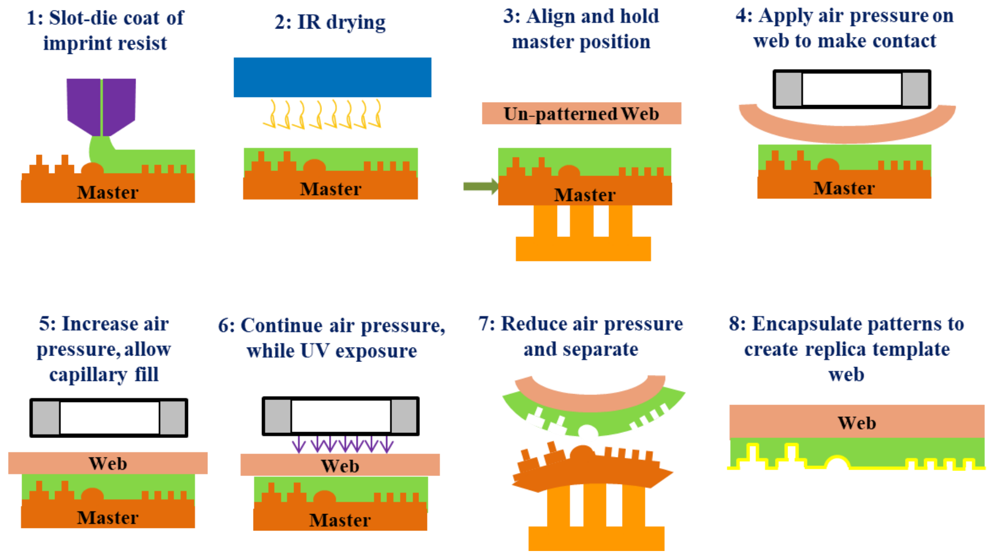

FIGURE 2. Stop-and-start process for flexible replica template fabrication from a rigid master template

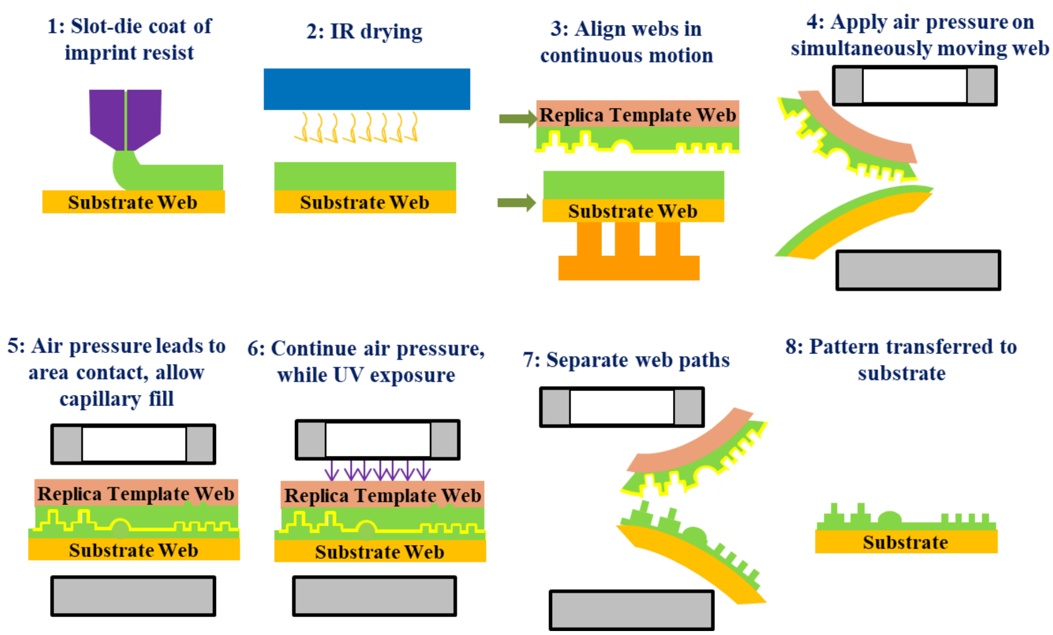

FIGURE 3. Continuous process for pattern replication on a flexible substrate from a flexible replica template

1. SYSTEM DESCRIPTION

Approaches to R2R-NIL typically involve the use of an embossing roller used as a template which is then pressed onto a substrate web using pinch rollers. The embossing roller with nanoscale features is made by manually wrapping sections of a patterned web on an elastomeric roller. Feature sizes of 100 nm, pitch of 250 nm, aspect ratio of 3:1 and RLT of 1 um have been achieved by others in the literature using these approaches [1-7].

The nanoscale roll-to-roll replication (nR3) tool shown in Figure 1 is designed to extend the resolution and pattern transfer capability of R2R-NIL. It consists of an Unwind module, Nanoimprint module and a Rewind module. The Unwind and Rewind modules have been designed and fabricated by Emerson and Renwick Ltd. A flexible substrate is conveyed from the Unwind module supply roller to the Rewind module take-up roller with control over tension, speed and sidelay along with interleaf removal and application. The Unwind module includes a tensioned-web-over-slot die coater which can deposit <1um wet films of UV curable imprint resist solutions. Upon evaporating the solvent from the coated films, <100 nm liquid resist films can be achieved.

The Nanoimprint module can be used as a standalone system to fabricate a flexible replica template from a rigid master template. Along with the Unwind and Rewind modules, the Nanoimprint module can transfer patterns from the flexible replica template to the flexible substrate. The Nanoimprint module consists of the following subsystems: replica template web handling, vertical-tip-tilt stage, horizontal linear stages, substrate and template chucks (or conveyers) and UV exposure. The template web is held in a roll-to-roll configuration between supply and take-up rollers with control over speed, tension, sidelay and interleaf removal and application. The template web motion is synchronized with the substrate *via* electronic gearing. The horizontal free span of the template web is the imprint zone where capillary action enables nanoimprinting over a planar region. The vertical-tip-tilt stage is used to align the substrate and template to each other. The substrate and template conveyers pressurize the webs and act as imprint actuators. This is designed to enable lamination without bubble entrapment and defect-free separation of the template from the substrate following UV-curing.

2. FABRICATION STEPS

As shown in Figure 2, the replica template fabrication process includes a master template mounted on a pin chuck being carried by the vertical-tip-tilt stage and the linear XY stages. An un-patterned web is mounted on the nanoimprint module rollers. A film of resist is deposited on the master template via slot-die coating, spin coating or inkjets or a combination of these material deposition approaches. The master template is aligned with the flat region of the un-patterned web to minimize parallelism errors. The web is chucked in position by turning off the positive air pressure in the porous region of the air bearing. A ramp cavity pressure is applied which initiates a point contact of the un-patterned web with the master template with the resist film in between. As the cavity pressure increases, the point contact expands to an area contact and finally laminates the un-patterned web over the master template. Subsequently, the patterned liquid resist is UV cured which solidifies the patterns. The cavity pressure is then reduced with a ramp function while simultaneously lowering the voice coil stage which separates the master template from the replica template web. The imprint resist is more wetting towards the web material compared to the glass master and therefore, separates cleanly. The transferred patterns on the replica template web are encapsulated with an oxide layer.

As shown in Figure 3, in the process of pattern transfer from the replica template web to the substrate web, the substrate web is mounted on the Unwind-Rewind modules and a slot-die coater deposits an imprint resist solution followed by evaporation of solvent. A planar vacuum preloaded air bearing mounted on the vertical-tip-tilt stage forms a non-contact conveyor of the substrate web. The template web is synchronized with the substrate web and similarly conveyed in a non-contact fashion over the UV transparent air bearing. The horizontal spans of the replica template web and substrate web in the imprint zone are aligned to minimize parallelism errors using the voice coil actuators – this is a calibration step used each time a new roll template is installed. The template web cavity is always pressurized. As the substrate web with the deposited resist enters the planar imprint zone, the replica template web makes a line contact with the substrate web and the liquid resist in between. As both the substrate and template webs move downstream, the line contact develops into an area contact and capillary action fills the nanoscale patterns in the template web with the resist material. A line scan UV lamp is used to cure the resist. The substrate and template web paths downstream of the imprint zone are matched for defect-free separation. An interleaf film is applied on the substrate after it exits the imprint zone.

3. PROCESS MODELLING

The major benefits of using a R2R template web are enabling capillary driven lamination over flat regions, reducing the size of exclusion zones around trapped particles, and allowing imprinting on non-planar substrates. However, unlike flat polished wafers, webs have a topography with micron-scale variations over mm-scale lateral pitches. The effect of web topography in determining RLT uniformity during the lamination process has been modelled based on the effective stiffness of the tensioned web and the capillary forces produced by nm-scale film thicknesses. RLT uniformity also changes as a function of time under lamination and has been studied to identify optimum process parameters. Since continuously moving template and substrate webs have uncertainties in web tension and speeds and laminating pressures, the feasibility of the process under given uncertainty is calculated. This is based on the capillary stiction forces, mechanical rigidity of the cured nanopatterns and flexibility of the webs. These calculations have been used to identify precision requirements of the various subsystems involved in the nR3 tool in order to avoid unacceptable out-of-plane loss of contact of webs and in-plane shear.

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