Nanometer-resolution, wide-field optical measurement of time-varying sub-micron fluid film thicknesses for viscosity determination

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We demonstrate an extremely simple system that uses optical interference to quantify the thickness evolution of nanoimprint lithography resists during deformation, enabling characterization of their nanoscale viscoelastic properties as well as process endpoint detection.

In nanoimprint lithography, faithful pattern transfer relies on achieving complete filling of stamp cavities by a deformable resist under an applied load. The ability to simulate this filling process accurately is imperative for stamp layout design; however, there remains disagreement over whether a linear viscoelastic [1], non-Newtonian shear-thinning [2], or Newtonian [3] model is best suited to describing resist behavior. Nor is there a full understanding of the role of slip and possible non-continuum effects as resist thickness falls below 100 nm. Accurate *in situ* measurement of resist thickness throughout imprinting, as presented here, could provide a complete, quantitative description of resist behavior for the first time.

In our system, an optically transparent, compliant polymeric stamp is pressed into an initially ~200 nm-thick film of resist using a pneumatic pressure that increases linearly with time. The imprinting process is imaged using an optical reflection microscope and a CMOS image sensor (Fig. 1). As the residual layer thickness (RLT) of resist beneath the stamp protrusions reduces, interference between the light reflected from the stamp–resist and resist–substrate interfaces results in a temporally varying reflection spectrum. The stamp surface is sputtered with a semi-transparent ~10 nm gold layer to enhance the amplitude of reflectivity variation with RLT. Illumination is provided by two LEDs with well separated emission spectra that map with negligible crosstalk to the red and blue channels of the image sensor. Consequently, the peaks and troughs of the recorded intensities in each sensor channel can be associated directly with particular RLT values, as computed using Fresnel's equations for reflection and transmission.

Reflection maxima for a particular free-space wavelength λ_0 occur at values of RLT that lie $\lambda_0/2n$ apart, where n is the resist's refractive index. Thus, unambiguous determination of RLT at any time-point relies on matching the overall order of intensity peaks and troughs in both color channels to a simulation of optical reflection versus RLT that is based on Fresnel's equations (Fig. 2). Once the closest correspondence has been found between stationary points in the simulation and in the video data, experimental intensities can be mapped to estimated RLT values using the simulated intensity–RLT curves as interpolants (Fig. 3).

The system's resolution is defined as the change in extracted RLT per bit change in intensity signal at the sensor. Resolution depends on the camera's frame rate, the imprinting speed, and the rate of change of detected intensity with RLT. Our current system operates at 50 frame/s and its resolution is better than 1 nm over 47.6% of the RLT range measured (125–200 nm), and better than 4 nm over 95.2% of the range.

We have used our system to characterize a UV-curable resist, MicroResist uvCur21. This material was imprinted using a stamp patterned with an array of parallel, 50 µm-wide ridges. For RLT values reducing from 200 nm to ~125 nm, a Newtonian model of squeeze-film thinning is found to describe the results with an R^2 correlation coefficient of 0.94–0.99 across five separate measurement locations on a sample. A viscosity of 8.7±2.4 mPa.s is extracted, which is approximately 4 times larger than the datasheet value.

To our knowledge, these are the first reported results that quantify temporally-evolving nanoscale film thicknesses from video data alone. Single-beam interference has previously been used to quantify film thickness [4], but that reported approach is not adaptable to arbitrary stamp geometries, as ours is, and its accuracy was limited to ~100 nm. The simplicity of our scheme makes it appealing for use in nanoimprint lithography systems to detect stamp cavity filling and thus avoid unnecessarily long processing times.

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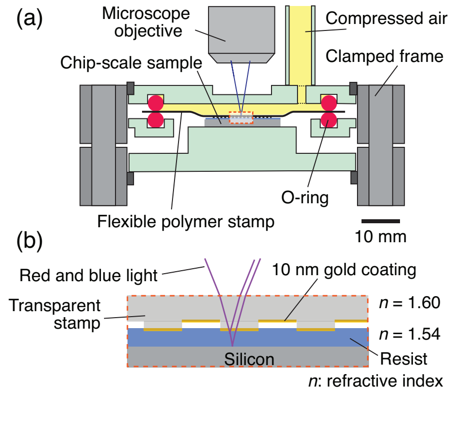

Figure 1. (a) Cross-section of the testbed [5]. A back-pressurized stamp contacts a deformable resist layer, while an objective relays the reflected light field to a CMOS sensor (not shown). (b) Section view of the stamp-resist contact region.

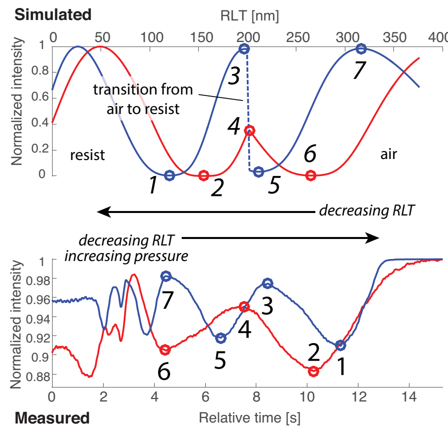

Figure 2. A sequence of peaks and troughs in the measured intensity traces for a particular location is matched to an identical sequence in the simulated intensity data, which includes the effect of the stamp's transition from air contact to resist contact.

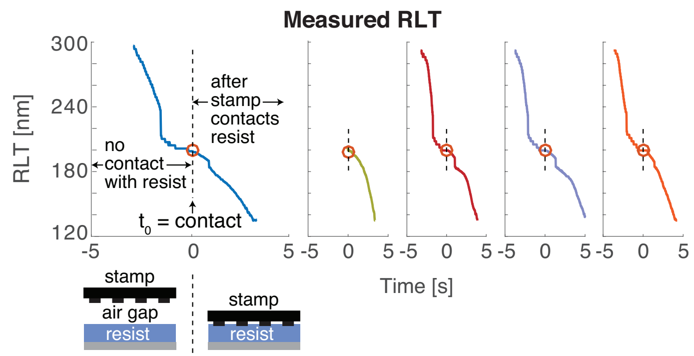

Figure 3. RLT values are assigned to time points in the experiment by matching a point's measured normalized intensity to the simulated intensity. For each time point the color channel offering the higher RLT sensitivity at that point is used. Each trace corresponds to a different resist region in the same video.