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Transient measurement of thin liquid films using a Shack–Hartmann sensor☆

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ABSTRACT

A Shack–Hartmann (SH) wavefront sensor was used to measure the thickness of thin liquid films of n–octane on silicon substrates. A SH device consists of an array of microlenses spaced from an image sensor by their effective focal length. A planar wavefront imposed on a SH device would produce uniformly spaced foci on the sensor for each lenslet. A distorted wavefront would then shift the foci by a calculable amount. Typically used for optical system alignment and calibration, the SH device was coupled with magnifying optics to determine the distortion of a planar wavefront source upon refraction through a film and reflection by a polished substrate. Geometrical optics, in the form of ray transfer matrices, were used to determine the location and orientation of rays emanating from the film surface given their positions and angles recorded by the SH device. The SH foci movements were translated into sample coordinates and film slopes, which were subsequently integrated to produce the film profile.

1. Introduction

Liquid to vapor phase change provides an effective way to absorb a large amount of heat energy. Often, devices are cooled through the evaporation of a liquid in direct contact with a heated solid substrate. Heat flux enhancement can occur when the liquid layer is sufficiently thin such that heat conduction through it allows the liquid–vapor interface to be nearly the same temperature as the substrate, which enhances evaporation. This occurs, for example, when a liquid meniscus decreases in thickness near a substrate. Such situations are found in spray cooling, microchannel devices, and heat pipes [1]. If the liquid layer becomes thin enough (an adsorbed film), intermolecular forces between the liquid and solid molecules can actually suppress evaporation, even at increased temperatures. Between the adsorbed film and the thicker meniscus region, there exists a region of maximal heat flux [2]. For this reason, the characterization of the liquid film in this transition is important.

Previously, we measured the film thickness from the adsorbed film to the meniscus region using a reflectometer [3,4]. The reflectometer measured the reflected spectrum of light from a broad-band source and determined the thickness using its internal model of the complex indices of refraction of the various layers. Spectra were taking at discrete locations along the film using motorized positioning stages. However, this method lacks the acquisition speed required for sub-second transients in the film movement.

The objective of this paper is to present the use of the SH technique and basic optical principles to obtain transient thicknesses of thin liquid films.

2. Methodology

2.1. Measurement technique

This work relies on a commercially available Shack–Hartmann (SH) wavefront sensor to characterize the thin film region. The SH technique has been used previously to determine the topology of thin, transparent solids [5]. It was also coupled with a laser light source to measure the static surface profiles of liquid microlenses, which were then fit to both spherical and conical surface shapes [6]. The sensor consists of three components (Fig. 1). First, there is a microlens array, often called a lenslet array, consisting of 29 × 29 individual but identical lenslets spaced 0.150 mm apart, each with an effective focal length of 5.2 mm. Second, a CCD image sensor is situated a distance from the array equal to the focal length. Finally, software is provided that converts the image data from the sensor into centroid positions of the mean foci locations of each lenslet and ultimately provides a reconstructed wavefront [7]. The advantage of this device over reflectometry is twofold. First, the SH sensor covers a two-dimensional area without needed translation stages to otherwise scan the sample. Second, since it uses conventional imaging sensors, it acquires images much faster than the spectrometer of the reflectometer.

The SH sensor provides the angle of incidence of lights rays that impinge it. To illustrate, we examine a single lenslet (Fig. 2). Given the small aperture of the lenslet, the light rays from a sample in question

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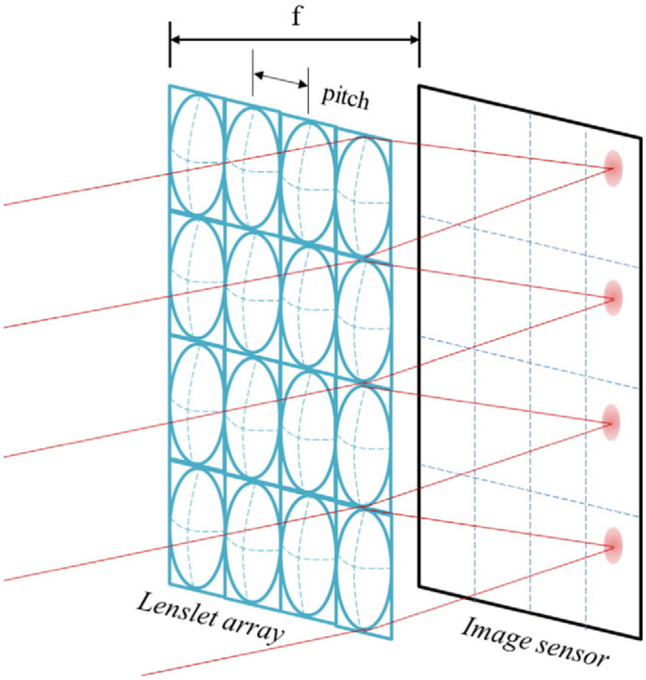

Fig. 1. A Shack–Hartmann wavefront sensor (most foci removed for clarity).

will be nearly parallel and will intersect the lenslet at a given angle. Because the sensor is located at precisely the lenslet focal length, the nearly parallel rays will be focused to a spot at some distance from the calibration spot. The centroid of the focused light is calculated, and the nominal ray angle relative to the SH device is the displacement of the centroid divided by the focal length. This is done in both *x* and *y* components to capture the three-dimensional direction of each ray.

When the sample is non-uniform in the manner in which it reflects or refracts light, each lenslet will receive rays at different angles. By tracing each lenslet ray back to the sample, one can infer its geometry. This requires a light source with a planar wavefront (parallel and normally incident rays).

Fig. 3 shows the optical path of the system. An optical fiber originating from a monochromatic LED (385 nm) enters the system from the top and is collimated by an achromatic triplet. The light passes through a beam splitter down to the sample were it is reflected and refracted. Light from the sample is reflected from the beam splitter toward a pair of relay lens which collect and direct the reflected light to the SH sensor. For this specific implementation, the focal lengths of the relay lenses are $f_1 = 40$ mm and $f_2 = 50$ mm, and the distance L is 70 mm. This provides a magnification of 1.25. Specifically, the lenslet centers cover an area of 4.2 × 4.2 mm; this is mapped to an area on the sample of 3.4 × 3.4 mm. The region of interest could be varied by changing magnification.

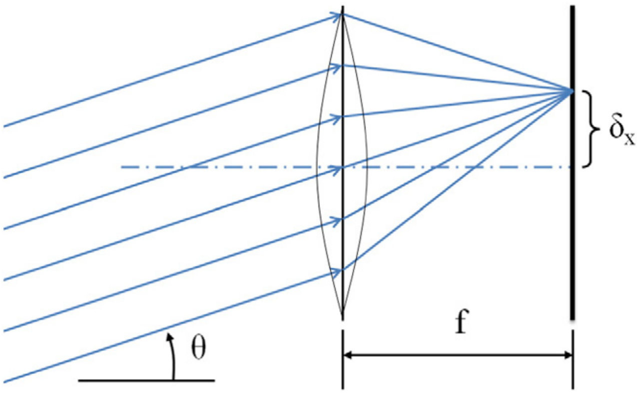

Fig. 2. Geometry of a single lenslet is shown in one dimension, *x*. A similar displacement also occurs in the *y* direction.

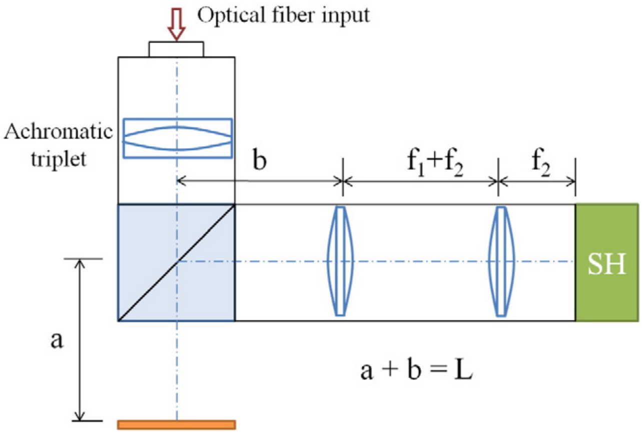

Fig. 3. Diagram of the optical path used to collimate and direct light to the SH sensor.

2.2. Liquid sample

The sample is a meniscus of n–octane residing on a polished silicon wafer. It is produced by micropositioning a 0.01 mm thick plastic shim against the wafer at a shallow angle (Fig. 4). N–octane was introduced using a syringe under the shim and was subsequently wicked to the working side of the shim.

In the absence of liquid, the entire optical system was calibrated to provide a baseline of lenslet focal centroids. By adjusting each component in series, the presence of a planar wavefront at the silicon substrate was confirmed. The centroid locations of the planar (or collimated) illumination were then recorded as the baseline. When the liquid was introduced, the centroids formed by the light traveling through the n–octane were displaced relative to the baseline.

2.3. Interface reconstruction

To determine the geometry of the interface, a known ray was traced back to a point on the interface using the inverse ray transfer matrix of the optical path. A ray transfer matrix, when multiplied by a column-vector consisting of ray displacement and ray angle at the input plane, will provide the ray displacement and angle at the output plane of an optical system. However, the SH gives ray information at the output plane, thus the matrix was inverted. The lenslets lie on a square grid spaced by the array pitch. For each lenslet center, the ray angle was known (from Fig. 2), and the inverse matrix gave the ray location and angle at the sample. This was done for each lenslet center. What resulted was a non-uniform grid of ray origin points and angles at the sample plane.

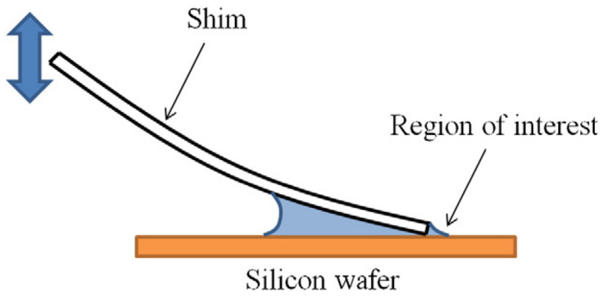

Fig. 4. Method of supplying n–octane to the region of interest.