Laser Surface Profiler

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Abstract

By accurately measuring the angle of reflection of a laser beam incident on a reflective surface with a position sensitive detector, changes in the surface normal direction (slope of the surface) can be determined directly. An instrument has been built that makes repeated measurements over the surface, and uses this data to produce a grayscale image of the slope. The resolution of this system to changes in the surface normal direction is found to be better than 0.01 degrees. By focusing the laser beam to achieve a lateral resolution of 5 μm, the resolvable surface height change due to a variation in slope is estimated to be < 1 nm.
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Methods of measuring surface profiles have been extensively developed over the years because of the numerous commercial applications for the measurement of surface flatness, sphericality, texture, and depth. A surface profiling system can utilize a simple contacting stylus profilometer (e.g. Dektak, TENCOR etc.), a scanning electron microscope, an atomic force microscope (e.g. NanoScope III), a confocal optical microscope, or a white-light interferometer (e.g. WYKO or ZYGO). Each technique has its own advantages and disadvantages and the particular method used is largely dependent upon the type of sample, the measurement requirements, and cost-effectiveness of the method.

In this letter, a non-contacting laser surface profiling system is described that allows the direct mapping of the surface derivative (slope) and the production of surface images that qualitatively illustrate the roughness of the surface being examined. As shown in figure 1, the sample being examined is mounted on a translation stage and a focused laser beam is incident upon the surface at an angle of approximately 45°. The reflected beam is incident upon a position sensitive detector. For a beam of light reflected from a surface, the angle of incidence must equal the angle of reflection. The reflected laser beam is scanned across the sample surface, and changes in the surface normal direction of an angle δ result in a deflection of the reflected beam through an angle of approximately 2δ. This change in direction of the reflected beam is measured by the position sensitive detector. This method of measuring changes in surface profile has been previously reported for large mirror surfaces. The results reported here improve the spatial resolution by orders of magnitude and the measurements are converted to an 8
bit grayscale representation to produce images that qualitatively show variations in surface slope over the surface of the sample.

A practical implementation of the above system is shown in figure 2. A HeNe laser is used as the light source. The spatial noise in the laser beam profile is filtered out by passing the laser beam through a 10X objective and then a 25 μm pinhole (Newport model #900 spatial filter). After the pinhole, the beam is recollimated to ~ 2.5 cm in diameter by a lens (f = 15 cm) in order to match the f/# of the final focusing lens set. A combination of an achromat and an aplanatic meniscus (Melles Griot 01-LAO-126 and 01-LAM-126 with a resulting focal length of 6 cm) is used to focus the laser beam onto the sample. This lens combination, with the expanded incident beam, produces a diffraction limited spot size, which has been measured by the knife-edge method to be ~ 5 μm at the 1/e waist. A long-working-distance microscope is used to visually optimize this spot size on the sample.

The x-y translation stage (Newport-Klinger stepper x-y translation stages and CC-1 controller) on which the sample is mounted has a minimum step size of 1 μm, and a total travel range of 75 mm along each axis. The stage is mounted such that it is perpendicular to the plane formed by the incident and reflected beams and the incident laser beam strikes the sample surface with an incident angle θ as shown in figure 2. The angle θ is not critical but is determined by the need for enough space to mount the detector without blocking the incidenting beam. Since the beam is diverging after being focused on the sample, the detector cannot be located too far away from the sample. At a distance L away from the sample surface, a lateral position-sensing detector (UDT model FIL-C10DG) is employed to monitor the position of the reflected beam. The two-
dimensional position-sensing detector has two outputs for each axis of detection. These axes are oriented in the plane of the incident beam and perpendicular to that plane. The detector is operating in the photovoltaic mode and has an active area of 10 mm by 10 mm. A Macintosh IIci computer with an internal 16 bit A/D converter (National Instruments NB-M10-16XH) and LabVIEW software is used to perform the data acquisition and control the translational stages.

A small change of the surface normal direction by an angle \( \delta \) results in a change of direction of the reflected beam by \( 2\delta_x \) in the plane defined by the propagating laser beam and by \( 2\delta_y \cos(\theta) \) perpendicular to that plane. \( \theta \) is the angle of incidence of the laser beam on the sample and \( \delta_x \) and \( \delta_y \) are the changes in surface normal direction in the plane of the incident laser beam and perpendicular to that plane. The position of the reflected beam on the detector will change by \( \Delta x \) in the plane of incidence, and by \( \Delta y \) perpendicular to that plane, according to the relationship:

\[
\begin{align*}
\Delta x &= 2\delta_x L \\
\Delta y &= 2\delta_y L \cos(\theta)
\end{align*}
\]

(1)

where \( L \) is the distance between the sample and the detector. Measurement of \( \Delta x \) and \( \Delta y \) can be repeated over the surface of the sample to generate an array of data. The in-plane data array has been converted to an 8 bit grayscale representation and is used to produce an image of the in-plane surface profile derivative. Such an image is shown in figure 3a, where the laser beam is incident in a horizontal direction relative to the image. This image, when compared to an optical image in figure 3b, shows the considerable surface roughness of the polished silicon wafer. This roughness is on the tens of nanometers scale, and would not be expected to be visible in the optical image.
The sensitivity of the system to changes in slope of the surface is determined by three factors: (1) the distance $L$ from the sample to the position sensor, (2) the minimum beam position change ($\Delta x$ or $\Delta y$) detectable by the position sensor, and (3) the mechanical and electronic noise of the system. As seen in equation 1 the movement of the laser beam on the detector $\Delta x$ ($\Delta y$) for a given angular deviation $\delta_x$ ($\delta_y$) increases with increasing $L$. However, after being focused onto the sample, the reflected beam will diverge towards the position sensing detector. The expansion of the beam will thus limit how far away the detector can be located without overfilling the detecting area. The other factors, affecting the resolution of the system, can be combined by measuring the noise level in the system. Sources of possible noise include: the laser’s amplitude and directional noise, electronic noise in the detector and amplifier circuits, and mechanical noise associated with the optical mounts and table vibration. Using a 1/20 $\lambda$ optical flat as a sample and monitoring the reflected beam with the detector over several hours, the system noise level was determined. The signal collected over time had a Gaussian distribution with a FWHM $\sim 22.5$ mV. Since the detection sensitivity is 1V/mm and $L=35$ mm, this noise corresponds to a minimum observable deviation in the surface normal of approximately 0.01°. For a laser spot size of 5 $\mu$m, this angular variation corresponds to a minimum detectable height variation of less than one nanometer.

Several practical factors limit the performance of this instrument. The distance of the detector from the sample, the size of the diverging beam spot on the detector, and the size of the position detector determine the maximum observable angular variation of the surface slope. Our detector could accommodate displacements of about $\pm 5$ mm from the center of the detector. For a sample to detector distance of 35 mm this corresponds to
an angular deviation of the surface normal of \( \pm 4^\circ \). This type of instrument is capable of measuring variations of the surface in the normal direction that have a spatial period larger than the spot size on the sample surface. More rapid variations than this are averaged over the laser spot and result only in a spreading of the beam on the detector or the scattering of light out of the beam. The principle of operation of the profiling system also requires that the sample surface be of reflective or semi-reflective type.

In this letter we have described a novel method for surface profiling that is inexpensive, robust and easy to implement. In contrast with more conventional methods where surface height is measured, this technique directly maps the slope of a sample surface. An instrument that can mount samples up to 10 cm in diameter has been built. Changes in the slope of the surfaces from 0.01\(^\circ\) to 4\(^\circ\) can be measured using this system with a spatial resolution on the order of the laser spot size (~ 5 \(\mu\)m). From these values, the vertical resolution of the surface topology is estimated to be less than one nanometer. By converting the surface derivative into a grayscale representation, a surface image can be produced that qualitatively illustrates the roughness of the surface being examined.

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Figure Captions

1. Principle of operation of the surface profiler system.
2. Practical surface profiling instrument.
3. Images of a 2 mm by 2 mm area of mask alignment markers on a polished silicon wafer. The two images shown are produced by (a) the surface profiler and (b) an optical microscope.
References

1 Veeco Instruments Inc., Terminal Drive, Plainview, NY 11803

2 KLA-Tencor, 160 Rio Robles, San Jose, CA 95134


7 see review by J. Schwider, Progress in Opt., 28, 271-359 (1990)

8 ZYGO Co., Laurel Brook Rd, Middlefield, CT 06455


12 Melles Griot Catalog 1995/96, page 1-31 and 7-8
Incident laser beam

surface normal changed by $\delta$

$\theta$

$L$

 reflected beam changed by $2\delta$

$\Delta x$

Translation of the sample

Fig. #1