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Determination of surface waviness using radius of curvature measurement with laser scanning technique

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A method for obtaining the shape of a surface investigated with a laser scanning curvature measurement is presented. Additional simple analysis of raw experimental data allows one to determine waviness of the sample. The accuracy of the method and comparison of the results obtained with the method and commercial profilometer are also described.

Keywords: waviness, curvature, profilometer.

1. Introduction

Laser scanning technique is widely used in many *in-situ* thin film stress measurements during thermal treatment, evaporation or ion implantation. When stress appears a sample becomes strained. The stress corresponds to the radius of curvature and may be calculated with Stoney's formula. A measuring set-up is often based on Flinn's idea [1] which is very simple and easy to realize. The best accuracy of measurement is achieved for spherical surfaces. Surfaces are not perfectly spherical shaped in real experiments, thus measuring errors appear. But the source of the errors brings about additional information about the sample investigated. The analysis of raw measurement data leads to obtaining the shape of the surface (waviness).

This method may be applied for any technique which uses multi-point radius of curvature measurement.

2. Experimental

Schematic of the optical setup is shown in Fig. l**a**. The set-up consists of a laser, a computer positioned mirror, a lens and a detector of laser beam position (CCD). The

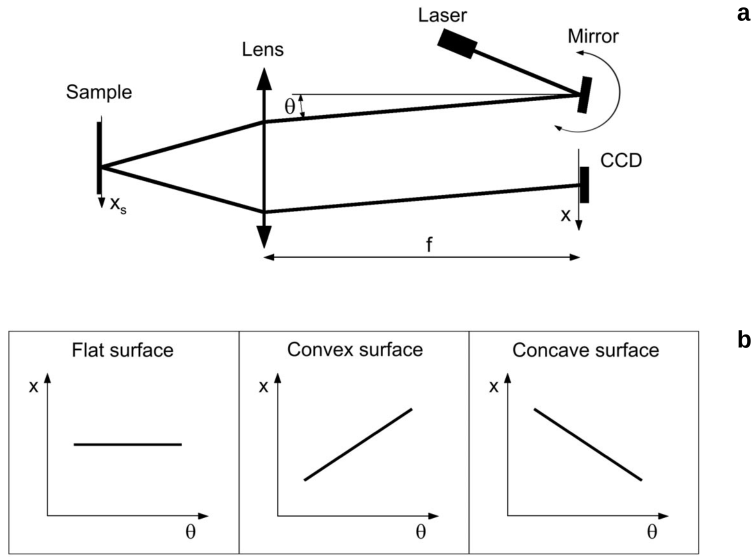

Fig. 1. Schematic of optical set-up (**a**) and typical movements of laser spot on the detector for flat, convex and concave surface (**b**).

detector and the mirror are placed in the same plane. The distance between the mirror and the lens euals focal length *f*. The radius of curvature *R*, the angle θ and the position of a laser spot on the detector *x* are related according to the formula:

$$\frac{dx}{d\theta} = \frac{2f^2}{R}. \tag{1}$$

The measurement (*N*-point scan) provides $x(\theta)$ dependence which for spherical surfaces is linear (Fig. l**b**). Usually, experimental data are not linear but they are fitted with linear function and *R* is calculated from the above formula. The result is the average radius of curvature over the whole scan.

But we can treat the $x(\theta)$ obtained more precisely. When the scan has length *L* and consists of *N* points we can calculate $N - 1$ separate radii of curvature R_n using the formula:

$$R_n = 2f^2 \frac{\theta_{n+1} - \theta_n}{x_{n+1} - x_n}. \tag{2}$$

Each one describes part of the surface $L/(N - 1)$ length. Then, we can connect those $N - 1$ arcs with different R_n. Only one condition is required: a connection point of two arcs has to be smooth (Fig. 2**a**). In addition, each arc is replaced with two straight lines

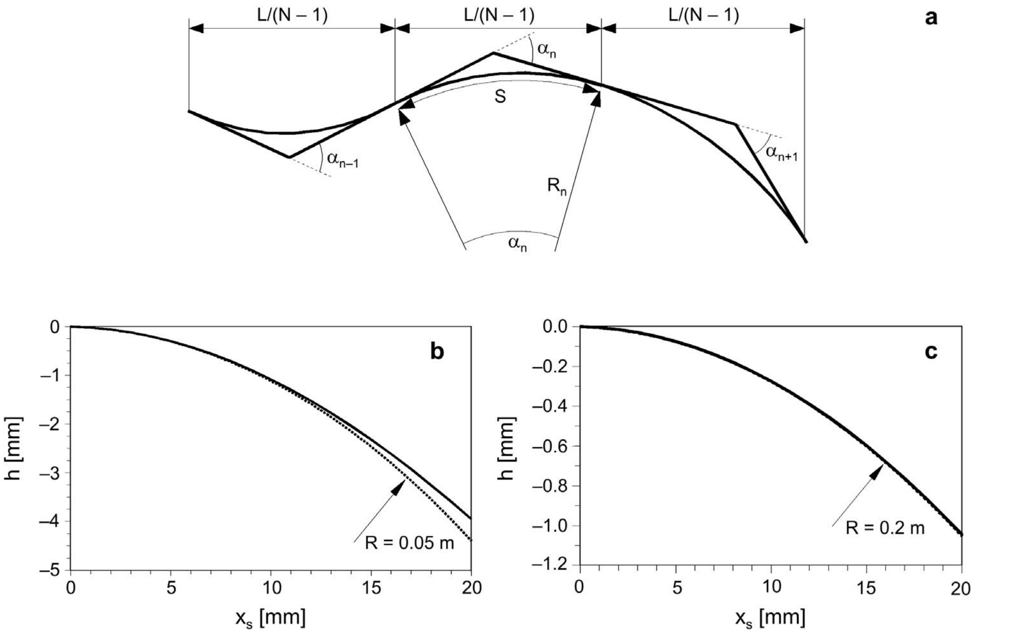

Fig. 2. Illustration of reconstruction of surface shape (**a**). Accuracy of the method for two arcs: R = 0.05 m (**b**) and R = 0.2 m (**c**). Dotted line represents the arcs and solid line – reconstructed shape.

with angle α_n between them. This operation simplifies reconstruction of surface shape. The angle α_n is calculated using the formula:

$$\alpha_n = \frac{S}{R_n} = \frac{L}{(N-1)R_n} \tag{3}$$

where S is the length of an arc. Moreover, we assumed $S = L/(N - 1)$ for large R_n and small α_n. The method described performs well even for relatively small radii. Figure 2**b**, **c** shows results of reconstructing two arcs: R = 0.05 m and R = 0.2 m. The length L of the arcs is about 20 mm and N equals 20. The shape obtained is the result of connecting of $N - 1$ arcs with the same radius $R_n = R$. There is a considerable difference for the first one (Fig. 2**b**) between the reconstructed shape and the arc. The aberration at the end edge of the arc Δh is 0.45 mm. For the second arc the aberration is much smaller at the same point and equals 7.5 μm (Fig. 2**c**). This result confirms good accuracy of the method, because real measurable values of samples are above few meters. An analogous test for an arc with 5 m radius of curvature gives Δh = 25 nm.

Two measurements of the same sample were performed with laser scanning technique and a commercial profilometer (Taylor Hobson Form Talysurf 50i). The sample was 100 μm thick Si wafer with badly polished surface. Three scans in different areas of sample surface were took with both devices. Areas of each scan were marked to obtain the best match of the two measurements. The length L of the scans was 20 mm. The number of points N in laser scanning technique was 40.

3. Results and discussion

The results of the measurements are shown in Fig. 3. Graphs in the first row present position x of laser spot on the detector *vs*. the angle θ of the laser beam. The dependence $x(\theta)$ is not linear for all scans. This means that the surface of the sample is not spherical. Some areas are convex and others are concave. Curvature R_n^{-1} calculated

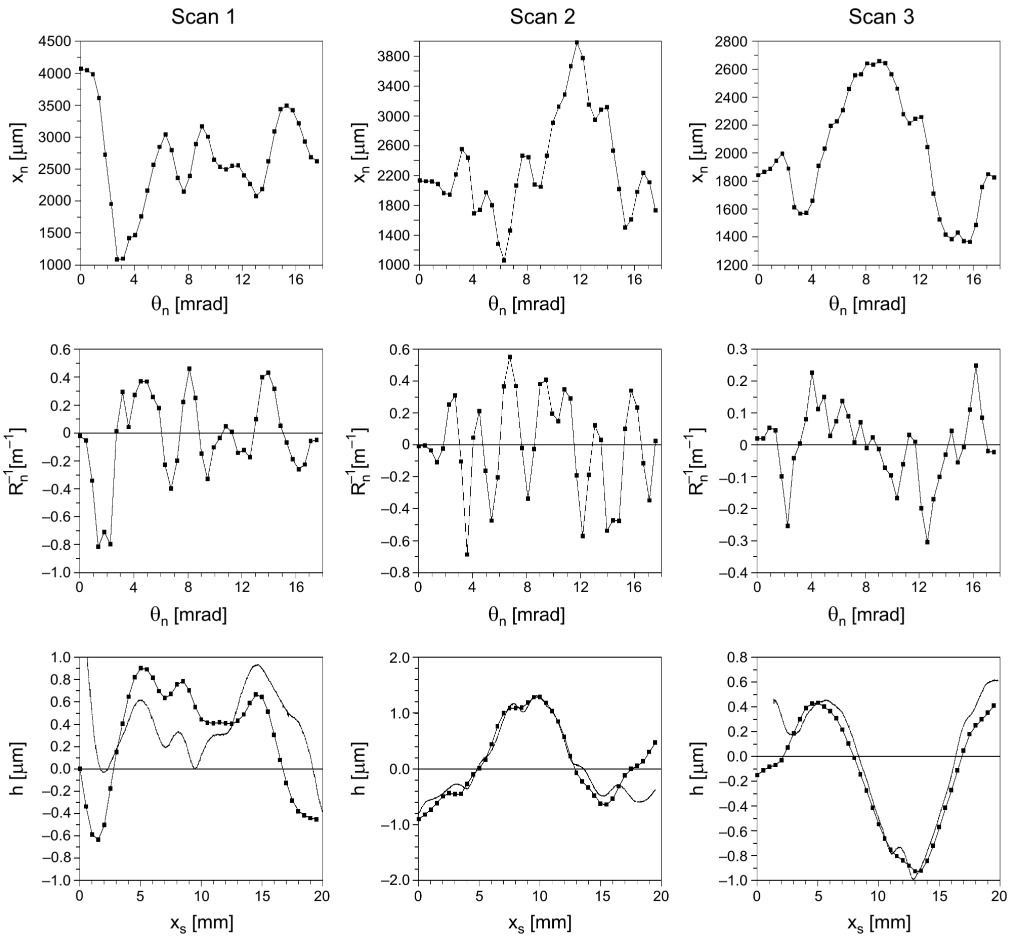

Fig. 3. Results of three scans (in columns), $N = 40$. The dependence $x_n(\theta_n)$ (first row) obtained from optical set-up and corresponding curvature $R_n^{-1}(\theta_n)$ (second row). Reconstructed shape of surface (the curve with symbols) and measured with the profilometer (third row).

with formula (2) is shown in the second row. Maximum convex curvature is 0.56 m^{-1} measured in scan 2. This value corresponds to $R = 1.79$ m. Maximum concave curvature is –0.81 m^{-1} ($R = 1.23$ m) in scan 1. The lowest row of Fig. 3 presents reconstructed shapes of the surface (lines with symbols). There is not a good agreement with the result from profilometer (solid line) for scan 1. Heights h differ in almost every position x_s of the scan. But one can see characteristic peaks shifted up or down. Agreement with profilometer results is much better for the other scans. Some significant aberrations appear only at edges of the scans. The comparison of the results leads to the conclusion that the method of reconstructing surface shape performs very well. The differences obtained are mainly caused by shifts of scans for the two devices (slightly different areas of the sample were investigated). Another source of mismatch is limitation of the method. The resolution in scan direction x_s is determined by the size of the laser spot. In the experiment, the diameter of the spot was about 1 mm. The effect of this limitation is clearly visible for scan 3 (10 mm < x_s < 15 mm). The reconstructed shape is smoothed in this area. The consequence of relatively large spot size is limitation in reconstruction of surface details. Therefore, the method is only applicable for waviness reconstruction. The advantage of this method is the possibility of no-contact measurement.

The method described is one-dimensional, but CCD detector allows us to adapt the optical set-up for two-dimensional measurements. Analogous method of shape reconstruction should yield full waviness topography of a surface.

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