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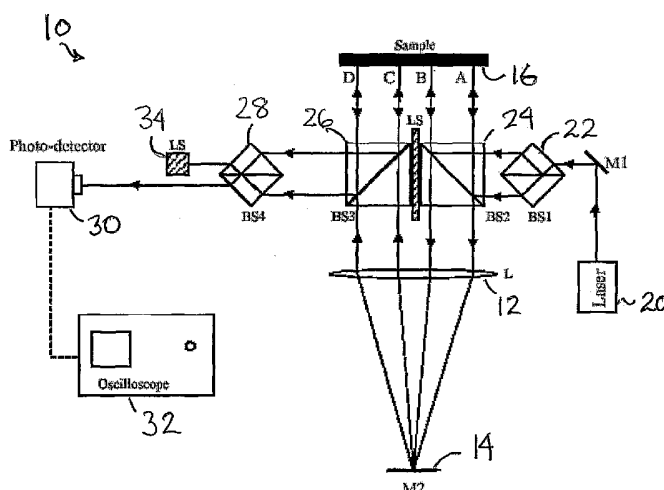
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(54) Title: INTERFEROMETRIC ABSOLUTE AND REAL-TIME SURFACE CURVATURE SENSOR INSENSITIVE TO TILT, TRANSLATION AND VIBRATION



(57) Abstract: An apparatus and a method are disclosed to characterize curvature of a surface (16) of a sample. The apparatus (10) includes a reflector (14), a lens (12) characterized by having two focal planes and an optical source, such as a laser (20), that outputs measurement light that is directed to pass through the lens and to be reflected by the reflector. The reflector and lens are arranged so that when a sample surface of interest is positioned relative to the reflector such that the reflector and the sample surface are each located at one of the two focal planes of the lens, the sample surface becomes the image plane of itself for the lens, and beams b1 and b2 of the measurement light are reflected at least twice from the sample surface and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface. The apparatus further includes a detector (30) for detecting the path length difference.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

**INTERFEROMETRIC ABSOLUTE AND REAL-TIME SURFACE
CURVATURE SENSOR INSENSITIVE TO TILT, TRANSLATION AND
VIBRATION**

TECHNICAL FIELD:

This invention relates generally to optical metrology apparatus and methods and, more specifically, relates to interferometers and to apparatus and methods for measuring surface curvature using an interferometric technique.

BACKGROUND:

It is known in the art to measure curvature of a sample surface by using either a single laser beam to scan the surface or a group of parallel laser beams. However, these prior art techniques generally require complex post-processing of the measurement data to remedy errors due to tilt, translation and vibration of the sample surface. Further, the sensitivity of the multiple parallel laser beam approach is limited by the resolution of the spot-spacing, while the maximum measurable range is limited by the diffraction limit of the laser beams.

The following U.S. Patents are illustrative of prior art surface measurement techniques: U.S. Patent No.: 4,291,990, "Apparatus for Measuring the Distribution of Irregularities on a Surface", issued 09/29/1981 to Takasu; U.S. Patent No.: 4,929,846, "Surface Quality Analyzer and Method", issued on 05/29/1990 to Mansour; U.S. Patent No.: 5,118,955, "Film Stress Measurement System Having First and Second Stage Means", issued on 06/02/1992 to Cheng; and U.S. Patent No.: 5,912,738, "Measurement of the Curvature of a Surface Using Parallel Light Beams", issued on 06/15/1999 to Chason et al.

What is lacking in the prior art is an optically based technique to measure or characterize the curvature of a reflective surface, where the technique is substantially insensitive to tilt, translation and vibration of the surface, and is suitable for both absolute and real-time curvature measurements of any reflective surface with minimal post data processing requirements.

SUMMARY OF THE PREFERRED EMBODIMENTS

The foregoing and other problems are overcome, and other advantages are realized, in accordance with the presently preferred embodiments of these teachings.

In one aspect this invention provides apparatus to characterize curvature of a surface of a sample. The apparatus includes a reflector, a lens characterized by having two focal planes and an optical source, preferably a laser, that outputs measurement light that is directed to pass through the lens and to be reflected by the reflector. The reflector and lens are arranged so that when a sample surface of interest is positioned relative to the reflector such that the reflector and the sample surface are each located at one of the two focal planes of the lens, the sample surface becomes the image plane of itself for the lens, and beams b1 and b2 of the measurement light are reflected at least twice from the sample surface and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface. The apparatus further includes a detector for detecting the path length difference.

In a further aspect thereof this invention provides a method to characterize curvature of a surface of a sample. The method includes providing a reflector, a lens characterized by having two focal planes, and an optical source, such as a laser, that outputs measurement light that is directed to pass through the lens and to be reflected by the reflector. The method further arranges the reflector and the lens so that when a sample surface of interest is positioned relative to the reflector, such that the reflector and the sample surface are each located at one of the two focal planes of the lens, the sample surface becomes the image plane of itself for the lens, and beams b1 and b2 of the measurement light are reflected at least twice from the sample surface and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface. The method further includes detecting the path length difference to determine the curvature, κ , of the sample surface.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other aspects of these teachings are made more evident in the following Detailed Description of the Preferred Embodiments, when read in conjunction with the attached Drawing Figures, wherein:

Fig. 1 is an optical schematic diagram that is useful when explaining the principle of the curvature measurement apparatus in accordance with the invention;

Fig. 2 is a schematic diagram of an embodiment of an interferometric apparatus for high sensitivity curvature measurement;

Fig. 3 shows a setup of a sample etching experiment that uses the interferometric apparatus and method of this invention;

Figs. 4a and 4b, collectively referred to as Fig. 4, show results for a sample loaded to 60 MPa: where Fig. 4a plots detector voltage versus etching time and shows that the raw interferometric signal 2 has a 90 degree phase shift from signal 1; and Fig. 4b illustrates data obtained using the interferometric apparatus of Fig. 3, and more specifically is a plot showing surface residual stress vs. etching thickness; and

Fig. 5 is a table of observations of reversals in the etching data and the associated residual stress and thickness.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention pertains to an interferometer 10, shown in Fig. 2, for absolute and real-time curvature measurements of reflective surfaces by utilizing repeated reflections of two laser beams from the sample surface. The curvature measurement is substantially insensitive to sample tilt, translation and vibration.

The measurement principle can be explained using the schematic diagram shown in Fig. 1. Fig. 1 illustrates a convex lens (L) 12, a reflector or mirror (M) 14, and a reflective sample surface 16 arranged such that the sample surface 16 and the mirror 14 are located on the two focal planes of the lens 12. With this arrangement the sample surface 16 becomes the image plane of itself for the lens 12, i.e., points D and C are images of points A and B. Therefore, a light beam b1 that reflects from point A always reaches point D, while another light beam b2 that reflects from point B always arrives at point C, regardless of their reflection angles. Although for convenience the incident beams b1 and b2 are drawn parallel to each other in Fig. 1, in general the two beams need not be parallel to each other.

In this manner, both beams, b1 and b2, are reflected (at least) twice from the sample surface 16 and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface 16. The curvature is equal to $1/R$, where R is the radius of curvature of the sample surface 16. The relationship between the path length difference and the curvature is derived as follows.

After reflections from points A and B on the sample surface 16, beams b1 and b2 develop a path length difference of $2(y_A - y_B)$, where y_A and y_B are the normal positions of points A and B, with respect to the back focal plane of the lens 12, respectively. Similarly, the reflections from points D and C, result in a path length difference of $2(y_D - y_C)$. Thus, the total path length difference between the two beams is

$$\Delta = 2(y_A - y_B) + 2(y_D - y_C) = 2(y_A + y_D) - 2(y_B + y_C).$$

In this setup, the lateral distance between points A and B is always the same as that between points C and D; the lateral distance is denoted by d . When the distance between the midpoints of the positions (A,B) and (C, D) is represented by c as shown in Fig. 1, the curvature of the sample surface 16, κ , can be expressed in terms of the total path length difference, Δ , and the distances, c and d , as

$$\kappa = \frac{1}{R} \approx \frac{d^2 y}{dx^2} \approx \frac{1}{c} \left(\frac{y_D - y_C}{d} - \frac{y_B - y_A}{d} \right) = \frac{\Delta}{2cd}.$$

The optical path difference, Δ , corresponds to a phase difference of $2\pi\Delta/\lambda$, between the two beams, where λ is the wavelength of an optical source, preferably a laser 20 (shown in Fig. 2). The phase difference can be measured by the interference between the two beams reflected from positions C and D. As a result, the curvature of the sample surface 16 can be determined by measuring the phase difference. In a case where the curvature of the sample surface 16 changes with time, the real time curvature variation, $\kappa(t)$, can be monitored by measuring the variation of the path length difference, $\Delta(t)$.

Alternatively, if the lateral distance between the two beams, d , is changed by a small amount, δd , or, the distance, c , between the midpoints of positions (A, B) and (C, D) is changed by a small amount δc , the curvature κ can be expressed as

$$\kappa = \frac{1}{2c} \frac{\delta \Delta}{\delta d}, \text{ or, } \kappa = \frac{1}{2d} \frac{\delta \Delta}{\delta c},$$

where $\delta \Delta$ is the change of the path difference due to the change in distance d or c . This alternative approach is particularly useful for measuring the absolute curvature of the sample surface 16, since time variations of Δ and d (or c) can be introduced and measured while κ remains constant.

However, it can be appreciated that in all such cases the measured interference signal requires minimal data-processing to determine the absolute curvature, or to determine the real time curvature variation, and can be accomplished by solving the appropriate ones of the relatively simple equations shown above.

It is noted that if no interference fringes are detected, then it is indicated that the curvature of the surface of the sample 12 is a constant, and does not change with time.

Based on the foregoing description it can be appreciated that advantages that are obtained through the use of this invention include, but need not be limited to, the following:

it becomes possible to measure or otherwise characterize both the absolute value and the time variation of sample-surface 16 curvature;
the paths of the two beams can be arranged to be close to each other so that influence of environmental disturbances on the measurement can be minimized, as will be demonstrated below; and
a small tilt, translation or vibration of the sample surface 16 has a minimal influence on the characterization of the curvature.

A non-limiting embodiment of the interferometer 10 that is constructed to implement the teachings of this invention is shown in Fig. 2. The interferometer 10 utilizes a first beam splitter 22, BS1, to produce two parallel laser beams from a single incident beam output from the laser 20, and possibly relayed by a first mirror M2. The two parallel beams are then directed to the sample surface 16 at positions A and B by a second beam splitter 24, BS2. After reflecting back from the sample surface 16, the two beams pass through the lens 12, L, and are focused onto the reflective mirror 14, referred to in Fig. 2 also as M2. The reflected beams from the mirror 14 are sent back through lens 12 to the sample surface 16 at positions C and D. After reflecting back from the sample surface 16, the two beams are steered by a third beam splitter 26, BS3, to a fourth beam splitter 28, BS4, to produce interference fringes at a photodetector 30. Connected to an output of the photodetector 30 is a signal monitoring device shown for convenience, and not by way of limitation, as an oscilloscope 32. In other embodiments the oscilloscope 32 can be replaced by, or supplemented with, a data processor that receives the output of the photodetector 30, digitizes same, and operates on the digital values. A light stop (LS) 34 is also shown for completeness.

In one non-limiting example, contact compression experiments on rough surfaces were carried out to study the residual stress development due to nanoscale contact, and to verify the predictions of a unit process model and to achieve an understanding of mechanisms that cause delamination wear. Polycrystalline aluminum surfaces with a nanoscale roughness were contact loaded using a smooth stainless steel indenter. The residual stress distribution along the thickness direction was then measured using the curvature measuring interferometer 10 in accordance with this invention. A chemical

etching technique was used to gradually release the residual stress and to introduce a time dependent curvature change.

In order to verify the existence of a tensile sub-layer due to contact loading, an experiment was carried out in two steps. In the first step, a polycrystalline aluminum sample with nanoscale surface roughness was loaded using a flat stainless steel indenter to introduce plastic deformation near the contact surface. In the second step, the contact loaded sample was removed from the loading fixture and analyzed with the interferometer 10 of the present invention, that is, with a curvature measuring system to investigate the residual stress developed during the contact loading.

In order to measure the residual stress caused by the contact loading, the present invention curvature interferometer 10 was employed to utilize the interference between two laser beams repeatedly reflected from the sample surface 16.

The physical arrangement of the curvature interferometer 10 for use in the non-limiting embodiment of making a residual stress measurement is shown in Fig. 3, which is based on and is similar to the embodiment shown in Fig. 2, and like configured components are numbered accordingly. The cube beam splitter 22, BS1, was used to produce two parallel beams from a single incident He-Ne ($\lambda = 628 \text{ nm}$) laser beam provided by He-Ne laser 20. The two parallel beams were then directed to the back surface 16A of the sample (unloaded side) by the second beam splitter 24, BS2. After reflecting back from the sample surface 16A the two beams were focused onto the reflective mirror 14, M2, by the focal lens 12. The reflected beams from the mirror 14 are then sent back through the lens 12 to the sample surface 16A. After the second reflection from the sample surface 16A, the two beams were steered by the third beam splitter 26, BS3, to a mixing beam splitter 28, BS4, to generate two sets of interference signals (180° out-of-phase). One set of the interferometric signals was relayed via an optional third mirror, M3, detected by the photodetector 30, and digitized using an Agilent Multi channel Data Logger 34970A connected with a computer (not shown). The other set of signals was directed towards either a screen 34 or a second photodetector (not shown) as a reference.

In order to measure the residual stress at different distances from the contact surface, the loaded surface 16B of the sample was chemically etched in a bath 36 using an aluminum etchant 36A consisting of 16 parts phosphoric acid, 2 parts deionized water, 1 part acetic acid and 1 part nitric acid. The etching rate of this particular etchant 36A was calibrated to be 110 nm/minute. The gradual removal of the material from the loaded surface side of the sample released the residual stress and caused the curvature change of the sample surface 16A. To guarantee uniform removal of the materials and avoid localized reactions, a magnetic stirrer 38 was used to stir the etchant 36A during the measurement.

Once the interferometric signal was obtained by the interferometer 10, simple plate bending theory was used to relate the time dependent curvature variations to the thickness dependent residual stress distribution in the sample. The Stoney equation took a very simple form for this experiment:

$$\sigma(h_e) = \frac{Eh^2}{6(1-\nu)} \frac{dk}{dh_e} = \frac{Eh^2}{12cd(1-\nu)} \frac{d\Delta}{dh_e}.$$

where σ is the thickness-dependent in-plane residual stress, h is the etching thickness which can be obtained from the etching rate and etching time, E and ν are the Young's modulus and Poisson's ratio, respectively, h is the sample thickness, c , d , k , and Δ are the same as defined earlier.

An objective of this experiment was to verify the existence of the sub-surface tensile layer as predicted by previous dislocation models. If such a tensile layer indeed exists, one would expect to observe a reversal in the interferometric signal and, hence, the measured curvature value. In order to unambiguously identify such reversals, a quarter-wave plate was inserted into one of the two interfering laser beams before they reach the mixing beam splitter 26, and two linear polarizers aligned with 90° difference in their orientations were placed in front of the photodetectors. Such an arrangement introduces a 90° phase shift between the two signals. The signals were acquired by two identical photodetectors that comprise the photodetector 30. The etching results of a sample loaded to 60 MPa for an etching time of 70 minutes are shown in Fig. 4.

As expected, the two signals show an exact 90° phase shift indicated by the fact that when signal 2 reached its peak value around 2000 sec, signal 1 was in its fastest changing region. Comparing the magnitudes of the two signals at critical phase angles, such as 0, $\pi/4$, $\pi/2$ and π , indicates that the first peak of signal 1 corresponds to a reversal of phase-difference variation. Since the most reliable part of a sinusoidal curve is the fast changing part instead of the plateau part. The sensitive parts of the two signals were selectively combined to give the final residual stress vs. etching thickness result as shown in Fig. 2b. For an etching period of 70 minutes, a total thickness of $8\text{ }\mu\text{m}$ was removed from the loaded side 16B of the sample. The residual stress showed a tensile value of 175 MPa near the contact surface, while a much lower compressive stress around 50 MPa was observed within a much thicker layer up to $6\text{ }\mu\text{m}$. The tensile sublayer extended to a thickness around 146 nm.

Fig. 5 summarizes the results of 10 samples tested at six loading levels. The results of zero load level show that compressive residual stress exists even in unloaded samples which may be developed during the manufacturing process. Although the magnitudes of the residual stress and the thickness of the tensile layer have a large fluctuation and error bar (typically 10-15%) due to experimental and numerical noise (numerical differentiation), the existence of the reversals in the interferometric signals for samples loaded above 40 MPa is definite. The tensile layer thickness for the 10 samples spreads in a range of 83-222 nm, which is close to the values predicted by the analysis of the unit process dislocation model. As cracks form much more easily in a material under residual tension than under residual compression, the existence of this tensile layer is significant in understanding and modeling the mechanisms associated with delamination wear.

As should be apparent from the foregoing description of the presently preferred embodiments of this invention, this invention provides an optical interferometer that is substantially insensitive to tilt, translation and vibration of the sample surface 16, and is suitable for both absolute and real-time curvature measurements of any reflective or at least partially reflective surface. A phase difference that results from repeated reflections of two laser beams from the sample surface is used to construct an interference signal that

is proportional to the surface curvature. As compared to the prior art techniques, this invention provides a capability to measure both absolute and real-time curvature in a manner that is substantially insensitive to sample tilt, translation and vibration, and with minimal post data processing.

The foregoing description has provided by way of exemplary and non-limiting examples a full and informative description of the best method and apparatus presently contemplated by the inventors for carrying out the invention. However, various modifications and adaptations may become apparent to those skilled in the relevant arts in view of the foregoing description, when read in conjunction with the accompanying drawings and the appended claims. As but some examples, the use of other similar or equivalent lasers, wavelengths, dimensions, detectors and signal processors may be attempted by those skilled in the art. Furthermore, while the utility of the invention was illustrated above in the context of an experiment related to residual stress measurement, it should be realized that the interferometer 10 can be employed in many applications to measure or otherwise characterize the curvature of a surface. For example the surface curvature sensor based on the interferometer 10 can be used as a high sensitivity surface curvature sensor in semiconductor wafer fabrication applications, in thin film deposition process applications, and can be employed in microelectronic and other applications for the inspection of devices during automated quality control. Biological applications of the interferometer 10 include cellular and molecular sensors for making high-resolution force measurements.

Additionally, it can be noted that theoretically the optical source does not need to be embodied as the laser 20, as any light source having a reasonably long coherence length can be used. In a practical sense however, the use of the laser 20 is preferred, as a typical laser can provide coherence lengths in the order of tens of centimeters or meters, while a conventional white or infrared light source can only provide a coherence length of a few microns. In addition, a laser typically exhibits very good collimation.

It can also be noted that the beam splitters 24, 26 (BS2, BS3) may be located instead between the lens 12 and the mirror 14 (M2), and are not limited to being disposed

between the lens 12 and sample 16, as shown in Figs. 2 and 3.

It should also be noted that the optical element 12 is preferably embodied as the convex lens, although a concave mirror can be employed (note that a concave mirror may be basically classified as convex lens). However, the subsequent arrangement would be more complicated than that shown in Figs. 2 and 3.

It is also pointed out that this invention can be used to characterize the curvature of a non-reflective surface if a selective portion or portions of the surface are made reflective, specifically only the portion(s) used to receive the measurement light need be reflective. The reflective surface area is preferably large enough to accommodate the beam size incident on the surface of the sample 16. The surface of the sample 16 that receives the measurement light is preferably sufficiently reflective or specular to provide an adequate signal-to-noise ratio at the output of the photodetector 30, depending on what type or types of signal measurement or signal processing equipment receive the output signal.

However, all such and similar modifications of, and used for, the teachings of this invention will still fall within the scope of this invention.

Furthermore, some of the features of the present invention could be used to advantage without the corresponding use of other features. As such, the foregoing description should be considered as merely illustrative of the principles of the present invention, and not in limitation thereof.

CLAIMS

What is claimed is:

1. Apparatus to characterize curvature of a surface of a sample, comprising:

a reflector;

a lens characterized by having two focal planes;

a source of measurement light that is directed to pass through said lens and to be reflected by said reflector;

where said reflector and lens are arranged so that when a sample surface of interest is positioned relative to said reflector such that said reflector and the sample surface are each located at one of the two focal planes of said lens, the sample surface becomes the image plane of itself for said lens, and beams b1 and b2 of the measurement light are reflected at least twice from the sample surface and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface; and

a detector for detecting the path length difference.

2. Apparatus as in claim 1, where the curvature, κ , of the sample surface is equal to $1/R$, where R is the radius of curvature of the sample surface, and beams b1 and b2 develop a path length difference of $2(y_A - y_B)$, where y_A and y_B are the normal positions of points A and B, with respect to the focal plane of said lens, and where reflections from points D and C result in a path length difference of $2(y_D - y_C)$, and where a total path length difference, Δ , between beams b1 and b2 is

$$\Delta = 2(y_A - y_B) + 2(y_D - y_C) = 2(y_A + y_D) - 2(y_B + y_C).$$

3. Apparatus as in claim 2, where a lateral distance, d , between points A and B is equal to a lateral distance between points C and D; where a distance between midpoints of the positions (A,B) and (C, D) is represented by c , and the curvature of the sample surface, κ , is expressed in terms of the total path length difference, Δ , and the distances, c and d , as

$$\kappa = \frac{1}{R} \approx \frac{d^2 y}{dx^2} \approx \frac{1}{c} \left(\frac{y_D - y_C}{d} - \frac{y_B - y_A}{d} \right) = \frac{\Delta}{2cd}.$$

4. Apparatus as in claim 3, where the optical path difference, Δ , corresponds to a phase difference of $2\pi\Delta/\lambda$ between beams b1 and b2, where λ is the wavelength of the measurement light, and where said detector measures the phase difference from the interference between beams b1 and b2 after reflecting from points C and D, and where the curvature, κ , of the sample surface is determined from the measured phase difference.

5. Apparatus as in claim 1, where the curvature, κ , of the sample surface changes with time, and where a real time curvature variation, $\kappa(t)$, is monitored by measuring a variation of the path length difference, $\Delta(t)$.

6. Apparatus as in claim 3, where one of the lateral distance, d , between beams b1 and b2 changes by an amount, δd , and the distance, c , between the midpoints of positions (A, B) and (C, D) changes by an amount, δc , then the absolute curvature, κ , of the sample surface is expressed as

$$\kappa = \frac{1}{2c} \frac{\delta \Delta}{\delta d}, \text{ or, } \kappa = \frac{1}{2d} \frac{\delta \Delta}{\delta c},$$

where $\delta \Delta$. is the change of the path difference due to the change in distance d or c .

7. Apparatus as in claim 1, further comprising a first beam splitter disposed relative to said lens, said reflector and the sample surface for splitting said measurement light and directing the split measurement light as beams b1 and b2 towards the sample surface and towards said reflector.

8. Apparatus as in claim 7, further comprising a second beam splitter disposed relative to said lens, said reflector and the sample surface for directing at least twice reflected beams b1 and b2 towards said detector.

9. Apparatus as in claim 1, where said lens comprises a convex lens, and where said optical source is comprised of a laser.

10. Apparatus as in claim 1, where said detector is responsive to receiving twice reflected beams b1 and b2 for determining interference fringes between the at least twice reflected beams b1 and b2.

11. A method to characterize curvature of a surface of a sample, comprising:

providing a reflector, a lens characterized by having two focal planes, and an optical source outputting measurement light that is directed to pass through said lens and to be reflected by said reflector;

arranging said reflector and said lens so that when a sample surface of interest is positioned relative to said reflector, such that said reflector and the sample surface are each located at one of the two focal planes of said lens, the sample surface becomes the image plane of itself for said lens, and beams b1 and b2 of the measurement light are reflected at least twice from the sample surface and accumulate a path length difference, Δ , that is proportional to the curvature, κ , of the sample surface; and

detecting the path length difference to determine the curvature, κ , of the sample surface.

12. A method as in claim 11, where the curvature, κ , of the sample surface is equal to $1/R$, where R is the radius of curvature of the sample surface, and beams b1 and b2 develop a path length difference of $2(y_A - y_B)$, where y_A and y_B are the normal positions of points A and B, with respect to the focal plane of said lens, and where reflections from points D and C result in a path length difference of $2(y_D - y_C)$, and where a total path length difference, Δ , between beams b1 and b2 is

$$\Delta = 2(y_A - y_B) + 2(y_D - y_C) = 2(y_A + y_D) - 2(y_B + y_C).$$

13. A method as in claim 12, where a lateral distance, d , between points A and B is equal to a lateral distance between points C and D; where a distance between midpoints of the positions (A,B) and (C, D) is represented by c , and the curvature of the sample surface, κ , is expressed in terms of the total path length difference, Δ , and the distances, c and d , as

$$\kappa = \frac{1}{R} \approx \frac{d^2 y}{dx^2} \approx \frac{1}{c} \left(\frac{y_D - y_C}{d} - \frac{y_B - y_A}{d} \right) = \frac{\Delta}{2cd}.$$

14. A method as in claim 13, where the optical path difference, Δ , corresponds to a phase difference of $2\pi\Delta/\lambda$ between beams b1 and b2, where λ is the wavelength of the measurement light, and where said detector measures the phase difference from the interference between b1 and b2 after reflecting from points C and D, and where the curvature, κ , of the sample surface is determined from the measured phase difference.

15. A method as in claim 11, where the curvature, κ , of the sample surface changes with time, and where a real time curvature variation, $\kappa(t)$, is monitored by measuring a variation of the path length difference, $\Delta(t)$.

16. A method as in claim 13, where one of the lateral distance, d , between beams b1 and b2 changes by an amount, δd , and the distance, c , between the midpoints of positions (A, B) and (C, D) changes by an amount, δc , then the absolute curvature, κ , of the sample surface is expressed as

$$\kappa = \frac{1}{2c} \frac{\delta \Delta}{\delta d}, \text{ or, } \kappa = \frac{1}{2d} \frac{\delta \Delta}{\delta c},$$

where $\delta \Delta$ is the change of the path difference due to the change in distance d or c .

17. A method as in claim 11, further comprising splitting said measurement light and directing the split measurement light as beams b1 and b2 towards the sample surface and

towards said reflector.

18. A method as in claim 11, further comprising directing the at least twice reflected beams b1 and b2 towards a detector via a combining beam splitter.

19. A method as in claim 11, where providing said lens provides a convex lens, and where providing said optical source provides a laser.

20. A method as in claim 11, where detecting comprises receiving the at least twice reflected beams b1 and b2 for determining interference fringes between said at least twice reflected beams b1 and b2.

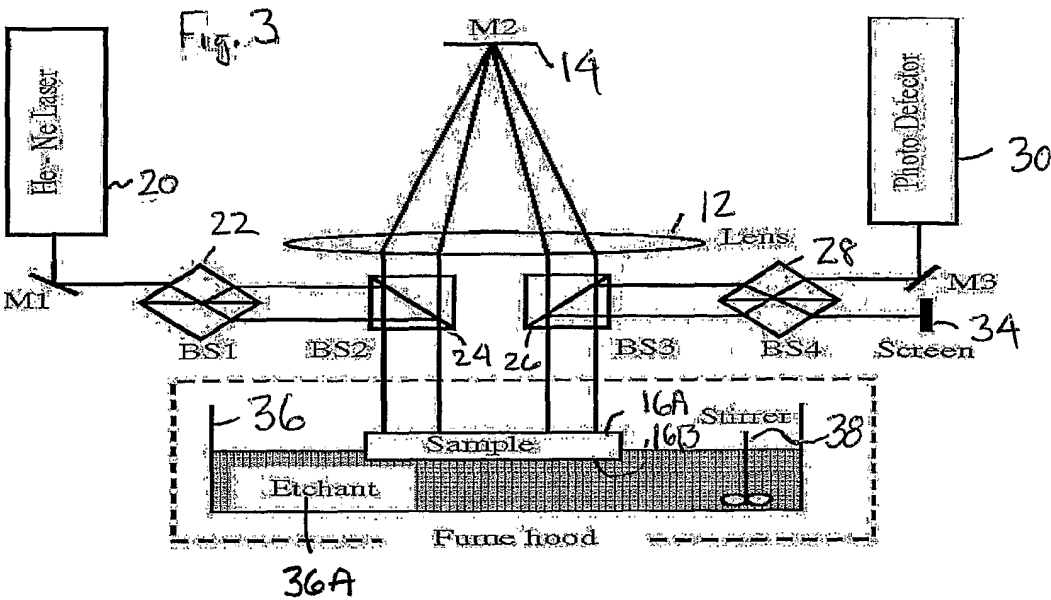
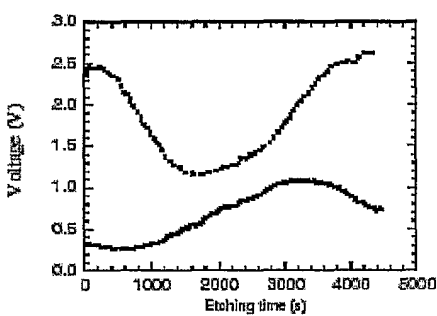
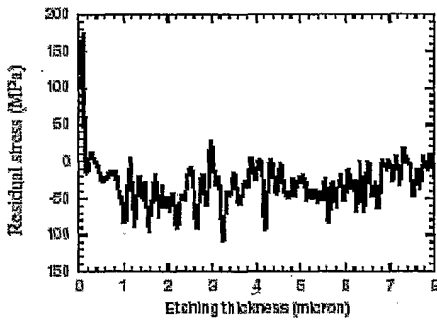


Fig. 4a



(a)

Fig. 4b



(b)

Fig. 5

Loading level	Whether or not exists reversal	Thickness at reversal (nm)	stress level (MPa)
0	No.		-60
0	No		-93
20	No		-100
40	No.		-163
40	Yes	128	132
50	Yes	169	55
60	Yes	146	175
60	Yes	83	154
80	Yes	222	254
80	Yes	117	60