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A preliminary study of spatial resolution enhancement of confocal and triangulation displacement meters using contact mode scanning probes

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This paper presents a method for the spatial resolution enhancement of confocal and triangulation meters using cantilever probes. Integration of a cantilever with existing commercially available meters is substantially eased by the absence of feedback control of the cantilever position. Confocal and triangulation meters are used for a number of applications in research and industrial settings including thickness measurements, topography measurements, step height measurements, flatness measurements, and profile measurements. These instruments provide a vertical (out-of-plane) resolution of a few nanometers. However, they are limited in their spatial resolution to the laser beam diameter, which is typically larger than 2 μm and often about 20 μm. Using a cantilever probe to make contact with the sample, the lateral resolution of standard commercial instruments can be improved to less than 1 μm.
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I. INTRODUCTION

The primary object of the present paper is to describe a method for improving the spatial resolution of laser confocal and triangulation meters by using a cantilever probe to detect topographical variations, without feedback control of the cantilever position.[1] Topographical variations are measured by directly determining the change in disposition of the cantilever to provide a three dimensional topographical reconstruction. Triangulation mathematical principles, or alternatively, confocal microscopy principles are used to measure the vertical (out-of-plane) movement of the cantilever from the light reflected off the cantilever, and correlate it to the horizontal movement of the cantilever on the sample.

Confocal and triangulation techniques for measuring topographic variations have matured enough to allow nanometer resolution in the vertical (out-of-plane) direction. Examples of algorithms and commercially available systems that use triangulation mathematical principles include Refs. 2–9. Laser confocal displacement meters have been described in literature and are commercially available.[10–15] Both types of instruments find applications in a number of areas including thickness measurements, alignment, topography measurements, step height measurements, flatness measurements, profile measurements, etc. However, these techniques provide inadequate spatial resolution for many applications due to the laser beam diameter, which is typically larger than 2 μm and often about 20 μm.

Scanning probe methods developed within the past two decades offer high-resolution images of sample properties. Scanning probe microscopes (SPM) measure properties at localized spots, such as topography, thermal conductance, temperature, capacitance, optical absorption, or magnetism. They all use a cantilever probe at a very close proximity or in contact with the sample. This close proximity allows for very high resolution. The image is formed by scanning a cantilever probe over the sample while measuring the desired property. Unlike light based microscopes such as laser confocal and laser triangulation meters, scanning probe microscopes are not wavelength limited; hence their resolution is limited only by the size of the probe tip at the edge of a cantilever and not by the diffraction effects of light. The atomic force microscope (AFM) is one of many types of SPM. AFMs employ a cantilever probe, a light source, an electronic feedback circuit controlling the vertical position of the probe, an *XYZ* piezoelectric transducer, and a photodetector. As the cantilever moves horizontally relative to the sample, topographical variations of the sample change the light reflected off the cantilever. A closed loop piezoelectric feedback control controls the vertical position of the cantilever. The cantilevers or the samples are moved to maintain the cantilever and the light reflected from it at a constant angle. In almost all SPMs, cantilever positioning is achieved with piezoelectric transducers such as cylindrical piezotubes. Applying a voltage between electrodes of the piezotube causes the length of the tube to change with a limited maximum motion along the tube axis depending on the tube length.

A combination of confocal or triangulation techniques with a cantilever probe can operate without the need for closed loop piezoelectric feedback control. This type of arrangement would allow for improved spatial resolution of confocal or triangulation meters without the additional complexity of an AFM. The cantilever can be easily added and separated from the displacement meter. In this effort, confocal and triangulation meters have been used with a cantilever to produce topographical surface maps. This paper presents an initial exploration of a scanning probe confocal and triangulation techniques. In the following text, Sec. II describes the operating principles of the cantilever probe based trian-

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gulation and confocal methods; Sec. III presents experimental results; and Sec. IV offers a discussion of the results and concluding remarks.

II. SYSTEM CONCEPT

A. Triangulation

Triangulation systems have been widely used.[2–9] Their use has also been reported in the semiconductor industry for a number of applications including inspection, quality control, and defect detection of integrated circuits during various manufacturing stages,[16] measuring the change in thickness of a wafer and other planarizing parameters in processes such as chemical-mechanical polishing[17] and inspection of chip packages.[6]

Triangulation meters measure the position of an object by tracking the light reflected from the target surface. A light beam, typically laser, is projected on an object. The reflected beam is focused through a lens on a light-receiving element (photodetector) such as a position sensitive device or charge coupled device (CCD). As the scan of the sample progresses, variations in the sample topography lead to variations in the position of the reflected signal as measured by the photodetector. A number of mathematical algorithms can be used to calculate the topography from the change in the signal on the photodetector and from the geometry of the setup. Examples of algorithms include Refs. 2–7

The proposed modification, a triangulation meter with a cantilever probe, operates in a similar way to a scanning probe microscope, but with one key difference: there is no need for vertical actuation or vertical feedback and so the cantilever can be disconnected from the original measurement apparatus. Topography is produced using triangulation principles that correlate the reflected signal on the photodetector to the vertical movement of the cantilever. In this setup, the sample is moved in the *XY* plane while the cantilever and the detection system are kept fixed in the *XY* plane. The cantilever is brought in contact with the sample. As the sample is moved, the light beam is focused on the cantilever and reflected from the cantilever to strike the photodetector. Any topographical changes in the vertical direction cause the cantilever to move in the vertical direction. Changes in the vertical position of the cantilever cause the light beam to strike the photodetector at different locations (Fig. 1). The use of a cantilever allows for the detection of features smaller than the laser beam's diameter. In this case, spatial resolution is a function of the cantilever's tip radius.

B. Confocal

Confocal meters have been used for a number of applications, including surface characterization,[10] measuring the position of micro objects,[11] highly reflective surface measurements,[12] microelectromechanical system devices evaluation,[13] characterization of biological structures,[18,19] and measurement of solder, gold, and stud bumps.[20]

In a typical laser confocal displacement meter, a lens attached to a tuning fork focuses a laser beam on the surface of the sample.[15] The tuning fork oscillates a lens rapidly in the vertical (out-of-plane) direction, focusing and defocusing the laser on the sample. The beam returned from sample is reflected by a half mirror and focused on a pinhole. A peak signal is formed on a receiving element when the focal plane coincides with the sample. A detector transforms the light signal to an electrical signal. Changes in surface reflectance do not affect the focal position and, therefore, the topography measurement.

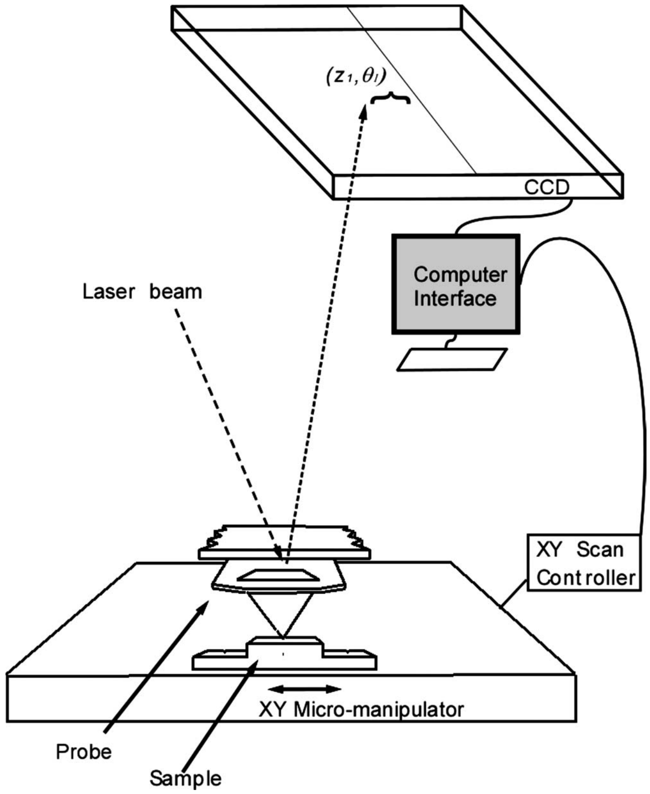

FIG. 1. This figure shows how triangulation mathematical principles are employed to detect the vertical deflection of a cantilever. In this setup, the sample is moved in the *XY* plane while the cantilever and the detection system are kept fixed. The cantilever is brought in contact with the sample. As the sample is moved, the light beam is focused on the cantilever. The light is then reflected from the cantilever and strikes the photodetector. Any topography changes in the vertical direction cause the cantilever to move in the *Z* direction. Changes in the cantilever cause the light beam to strike the photodetector at different locations.

In the proposed modification, a laser confocal displacement meter is used to measure the displacement of a cantilever. In this case, the laser beam is focused on the cantilever with a sharp probe tip in contact with the sample (Fig. 2). The beam returned from cantilever is reflected by a half mirror and focused on a pinhole and the change in the cantilever's displacement is determined in a similar way as described above. In this system, a cantilever is kept fixed in the *XY* plane while the sample is being scanned. Any surface variations can be measured by focusing the laser beam of the confocal displacement meter on the cantilever and by measuring the cantilever's deflection which corresponds to the changes in topographical changes. This arrangement enables the detection of sample characteristics with smaller features than the laser beam's diameter.

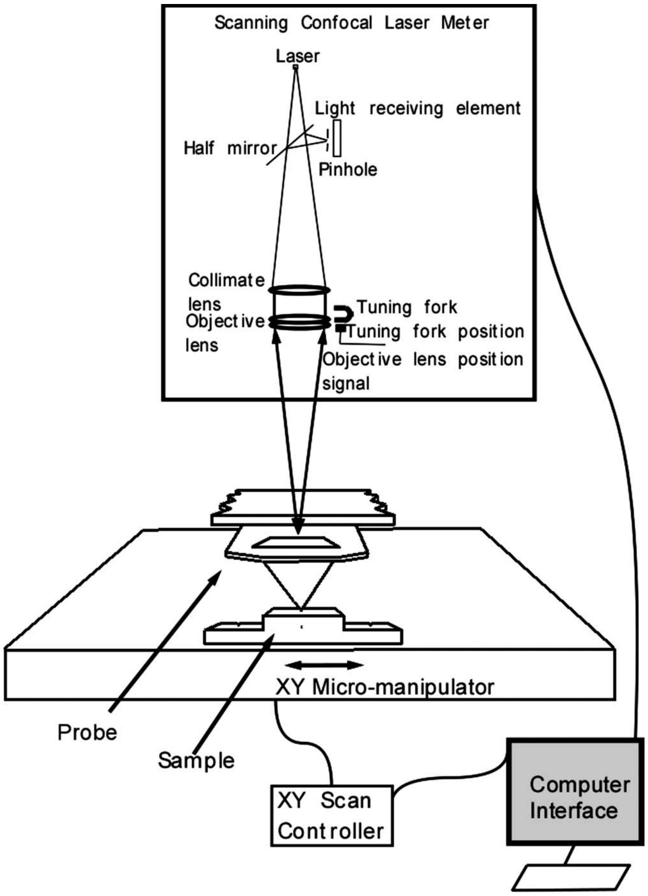

FIG. 2. The laser beam is focused on the cantilever that is in contact with the sample. The beam returned from cantilever is reflected by a half mirror and focused on a pinhole. The tuning fork is used to modulate the focal position of the optical system. A peak signal is formed on a receiving element when the focal plane coincides with the sample. While the tuning fork is oscillating, the focusing point moves accordingly. The variation of the position of the focusing point will be determined by the displacement of the lens.

III. EXPERIMENTAL RESULTS

A. Triangulation

To demonstrate the cantilever enhanced spatial resolution in a commercial triangulation system, the LK-G10 CCD laser displacement sensor by Keyence[7] was used. This system offers a 10 nm resolution in the vertical (out-of-plane) axis and has a laser spot diameter of 20 μm. A piezonanopositioning scanning stage by Physik Instrumente (model P-517.3CL and E-710 controller) was used. The stage has a travel range of $100 \times 100 \times 20\ \mu\text{m}^3$ and a closed loop resolution of 1 nm. A commercially available Si_xN_y triangular cantilever was mounted on a specially designed board that rested on a micromanipulator. The displacement meter and the stage were controlled using LABVIEW. A LABVIEW data acquisition (DAQ) card was used to obtain the voltage signal from the displacement meter.

The sample was placed on the stage. An optical microscope was used to view and control the relative position of the cantilever, the sample, and the displacement sensor's laser beam, that was also used to align the cantilever to the point of measurement. LABVIEW interface software was developed and used to control the movement of stage and capture the readout of the instrument at each position.

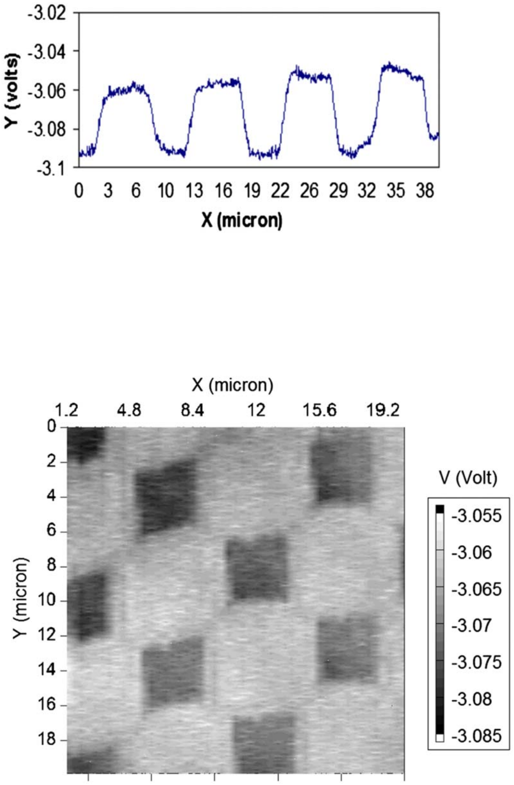

FIG. 3. (Color online) Typical scans of $5 \times 5\ \mu\text{m}^2$ squares using triangulation principles to detect the vertical deflection of a cantilever. Using a cantilever features smaller than the laser spot size ($\sim$20 μm) were clearly detectable. (a) A line scan of a 10 μm pitch grating is shown. (b) A $20 \times 20\ \mu\text{m}^2$ area scan with minimum feature resolution $<1\ \mu$m was obtained.

A number of successful line scans were obtained using the setup described above. To obtain the scan of Fig. 3(a), a commercially available grating was used. It included a 10 μm pitch with $\sim$5 μm wide $\times$5 μm long $\times$0.9 μm high features. Figure 3(a) shows a 40 μm line, 1000 data points were acquired in the X direction at 10 μm/s speed. In Fig. 3(a) the four 5 μm squares separated by 5 μm gaps are clearly visible. A number of successful three dimensional scans were obtained using the same grating sample. Figure 3(b) shows a scan of a $20 \times 20\ \mu\text{m}^2$ area of the same grating where the $5 \times 5\ \mu\text{m}^2$ squares are clearly visible. Measurements were made every 100 nm in the X direction and every 400 nm in the Y direction; the scanning stage moved at a speed of 10 μm/s. In these scans, the laser beam diameter is 20 μm and thus the features shown would not have been visible if the displacement meter was used to directly scan the sample.

B. Confocal

A commercial confocal system, the LT-9010 confocal displacement meter from Keyence was used.[15] This meter provides a minimum of 10 nm resolution in the vertical (out-of-plane) direction, with a laser spot diameter of 2 μm. To demonstrate large area scanning, two inexpensive Zaber KT-LS80-M T-LS motorized linear stages were used, offer-

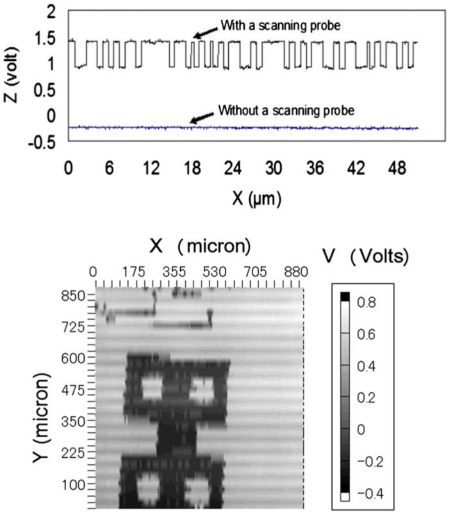

FIG. 4. (Color online) Typical images obtained using a confocal meter with a cantilever probe. (a) 2 μm lines are visible in this 50 μm line scan, which contains a number of 2 μm wide lines with 2 μm spacing. The scanning rate was 10 μm/s. This result demonstrates <2 μm resolution. When similar area was scanned without a cantilever, the lines were not visible. (b) A large area scan is shown. The sample was a glass wafer with 100 nm thick gold features. The area scanned was 900×900 μm^2. 180 data points were obtained in the X direction, while the sample was moved at 25 μm steps in the Y direction.

ing an 80 mm travel range each. The stages had compromises in accuracy (12 μm), repeatability (0.4 μm), and backlash (12 μm). As with the previous setup, a National Instruments DAQ card and LABVIEW were used to interface the confocal meter and to control the stages with a laptop. A commercially available Si_xN_y triangular cantilever was used. The cantilevers were mounted on a specially designed board that rested on a micromanipulator.

The sample was placed on the first stage, which rested on top of the second stage. The LT-9010 offers an embedded camera, facilitating viewing, controlling, and aligning the cantilever, the sample, and the laser beam. The laser beam appeared as a red spot on the sample. Initially, the cantilever was brought into contact with the surface. The cantilever was closely monitored using the camera to avoid damaging the probe. Then, the laser beam was focused on the cantilever, by moving the cantilever until the laser beam appeared to be on the cantilever. LABVIEW interface software was developed and used to control the stages' movement and capture the values of the confocal sensor at each position.

A number of scans were successfully obtained demonstrating resolution smaller than 2 μm and large area scanning [Figs. 4(a) and 4(b)]. In Fig. 4(a), the sample used was a grating. It included 2 μm wide, 200 nm thick lines separated by 2 μm gaps. The 2 μm wide line lines were visible using a cantilever [top line of Fig. 4(a)]. When the confocal laser was scanned directly on the sample, without a cantilever, the 2 μm lines were not observed [see, for example, the bottom line of Fig. 4(a)]. In Fig. 4(b), a large area scan is shown. The sample contained a number of features on a glass wafer made from a thin 100 nm layer of gold. The area scanned was 900×900 μm^2. 180 data points were obtained in the X direction, while the sample was moved at 25 μm steps in the Y direction. The scanning speed was 100 μm/s.

IV. DISCUSSION AND CONCLUSIONS

The results presented in this paper demonstrate that scanning cantilever probes can be used to improve the spatial resolution of confocal and triangulation systems. Integration of a cantilever with existing commercially available meters is substantially eased by the absence of feedback control of the cantilever position. In both cases, the minimum detectable feature size (<2 μm) was smaller than the laser beam diameter (2 μm for the confocal system and 20 μm for the triangulation system). In addition, the scanning probe confocal and triangulation systems have no inherent limitations in the XY-plane scanning range. Any limitations in the scanning range are due to the scanning stage, in contrast with SPMs which are limited by the piezoelectric tube (a conventional SPM can usually scan an 80×80 μm^2 area).

Confocal and triangulation techniques do not provide information about the sample physical properties unlike scanning probe techniques. Embedded sensing elements in a cantilever would permit simultaneous piezoresistive, thermal, mechanical, electrical, or magnetic property measurement, providing additional information about the sample. The hybrid systems presented in this paper enable the use of such cantilever probes allowing for additional characterization. These techniques also allow for angular measurement in order to determine the twist of the cantilever. Angular changes are related to the lateral moment of the cantilever and therefore represent a map of the lateral forces on the cantilever due to surface roughness or friction. Lateral measurements are enabled using a confocal meter by directing the laser beam at two locations of the cantilever and measuring the angular twist of the cantilever. Using triangulation methods, the angle can be calculated by deconvoluting the photodetector's image into the vertical response and the lateral response.

The AFM has been a very successful research tool, but emphasis has not been put on high throughput. Scan speeds of current SPMs are limited to about 180–250 μm/s. Furthermore, piezoelectric transducers are designed to control a single probe. A combination of confocal or triangulation techniques with a cantilever probe (or an array of cantilever probes) does not require closed loop piezoelectric feedback control (it is also possible to operate conventional scanning probe microscopes without feedback by turning down the gain) allowing for higher throughput and large area scanning, enabling the simultaneous use of multiple cantilevers. Diffraction gratings can be used to form a plurality of light beams, each with a selectable shape and intensity, from a single light source and directed on each cantilever of an array. The reflected light from each single cantilever may be detected by a photodetector. Alternatively, a scanning laser may be employed, in which case, one light source scans each cantilever in an array of cantilevers. Higher throughput is very important in many applications from biological applications to semiconductor failure analysis and production applications, where entire wafers or large areas need to be examined in relatively short time with submicron resolution.

The results in this paper suggest that the two detection systems presented can be used for high-resolution large area high throughput topographical imaging. Further study of these systems is needed to better define resolution and performance compromises.

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