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(54) **MEASURING ELASTIC MODULUS OF DIELECTRIC THIN FILMS USING AN OPTICAL METROLOGY SYSTEM**

MESSUNG DES ELASTIZITÄTSMODULS DIELEKTRISCHER DÜNNFILME UNTER VERWENDUNG EINES OPTISCHEN METROLOGIESYSTEMS

MESURE DU MODULE D'ELASTICITE DE FILMS MINCES DIELECTRIQUES PAR SYSTEME METROLOGIQUE OPTIQUE

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Description**TECHNICAL FIELD:**

- 5 **[0001]** This invention relates generally to optical metrology methods and apparatus and, more specifically, relates to measuring elastic moduli of dielectric thin films.

BACKGROUND:

- 10 **[0002]** The increasing sophistication of semiconductor technology has resulted in a significant shift away from aluminum as the dominant metal in multi-level metallization processes. As semiconductor chip manufacturing has moved from AlCu/SiO₂ based interconnect technology to Cu/Low k ILD (low dielectric constant interlayer dielectrics) technology, several integration issues such as delamination, peeling, and cracking have become apparent. Accordingly, these issues have evidenced a need for accurate measurement and control of the mechanical strength of the dielectric layers.

- 15 **[0003]** Nano-indentation and bending tests have been the commonly used methods to determine the elastic moduli of both opaque and transparent materials. With nano-indentation, a load is applied to an indenter to force it into a material. As the indenter is forced into the material, the amount that the indenter is displaced into the material is measured. Concurrently with the measurement of the indenter displacement, the load applied to the indenter is measured. However, when forcing an indenter into a thin film, not only will the thin film deform, but the substrate will deform as well. Bending tests apply strain to measure failure characteristics of a material.

- 20 **[0004]** When applied to thin films, these methods fail to accurately describe behavior as the scale of thin films is reduced to micron and sub-micron dimensions. Because both nano-indentation and bending tests are destructive, are contact based in nature, and have large errors and very low throughput, they are not suitable for semiconductor process control. Another disadvantage of these methods is that they require larger test areas than the area that the typical process design rules allow.

- 25 **[0005]** As can be appreciated, a non-destructive, non-contact, small spot, high throughput and high accuracy method is needed that is compatible with semiconductor production throughput requirements, and for accurate measurement and control of the elastic moduli of the dielectric films used in the semiconductor industry.

- 30 **[0006]** US6208418 discloses characterizing a sample comprising the steps of depositing the sample on a substrate, measuring a first change in optical response of the sample, changing the lateral strain of the sample, measuring a second change in optical response of the sample, comparing the second change in optical response of with the first change in optical response and associating a difference between the second change and the first change in optical response with a property of interest in the sample. The measurement of the first change in optical response is made with the sample having an initial lateral strain. The measurement of the second change in optical response is made after the lateral strain in the sample is changed from the initial lateral strain to a different lateral strain. The second change in optical response is compared to the first change in optical response to find the difference between the second change and the first change.

- 35 **[0007]** US2001028460 discloses a system for the characterization of thin films and interfaces between thin films through measurements of their mechanical and thermal properties. In the system light is absorbed in a thin film or in a structure made up of several thin films, and the change in optical transmission or reflection is measured and analyzed. The change in reflection or transmission is used to give information about the ultrasonic waves that are produced in the structure.

- 40 **[0008]** US6694284 discloses monitoring semiconductor fabrication processes by a system that may include a stage configured to support a specimen and coupled to a measurement device. The measurement device may include an illumination system and a detection system. The illumination system and the detection system may be configured such that the system may be configured to determine multiple properties of the specimen. For example, the system may be configured to determine multiple properties of a specimen including, but not limited to, at least four properties of a specimen such as critical dimension, overlay, a presence of macro defects, and thin film characteristics. In this manner, a measurement device may perform multiple optical and/or non-optical metrology and/or inspection techniques.

- 50 **SUMMARY OF THE PREFERRED EMBODIMENTS:**

[0009] The foregoing and other problems are overcome, and other advantages are realized, in accordance with the presently preferred embodiments of these teachings.

- 55 **[0010]** A method is provided which uses an optical metrology system to determine the elastic moduli of optically transparent dielectric films such as silicon dioxide, Black Diamond(TM), Coral(TM), other carbon doped oxides over metal or semiconductor substrates. A light pulse (pump) focused onto the wafer surface generates a sound wave traveling through the dielectric film. In one aspect, a second light pulse (probe) from the same or a different laser focused onto the same spot measures the changes in the optical reflectivity of the wafer. The reflected probe beam includes two

components, one from the dielectric/substrate interface and one from the propagating sound wave in the dielectric film. The period of the interference of these two components of the reflected probe beam is used to determine the elastic moduli of the dielectric layer. In another aspect, the same result is obtained by directing the second light pulse onto a different spot along the surface, where there the optical reflectance at the first and second spots differ, such as where

there is a different dielectric film at the two spots in a reference sample.

[0011] The data analysis method enables the determination of the period from the measured signal with, for example, +/-0.5% accuracy. The invention further provides hardware calibration and adjustments to the optical metrology system in order to minimize the variation of the results from tool to tool down to about 0.5% or below.

BRIEF DESCRIPTION OF THE DRAWINGS:

[0012] 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:

Figure 1 is a block diagram of an optical metrology system;

Figure 2 is a block diagram of a photoacoustic film thickness measurement system wherein the optical paths are illustrated;

Figure 3 illustrates a pump pulse as it passes through the transparent interlayer dielectric according to the present invention; and

Figure 4 is a flow chart that illustrates the method of calibrating the metrology system according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS:

[0013] This invention provides a method to measure the elastic moduli of optically transparent dielectric films on opaque substrates using an optical metrology system. One suitable and non-limiting type of optical metrology system is known as the MetaPULSE™ system, which is available from the assignee of this patent application. Reference can also be made to, as example, U.S. Patent No. 6,621,582, "Optical metrology system and method employing laser-server supplying laser energy to distributed slave metrology heads," and U.S. Patent No. 5,748,318, "Optical stress generator and detector."

[0014] By way of introduction, and referring to Figure 1, there is shown a metrology system 50 that includes measurement stage 60, robotics and wafer handling system 65, measurement system 75, cassette station 70, computer controller 55, and communication lines 80. Computer controller (controller) 55 may be a commonly available personal computer system and is electrically connected to measurement system 75, measurement stage 60, robotics and wafer handling system 65, and cassette station 70 via communication lines 80. Controller 55 further includes software embodied in a computer-readable medium (not shown) capable of carrying out the steps of the present invention.

[0015] In operation, controller 55 sends an instruction to the robotics and wafer handling system 65 to extract a wafer from cassette station 70, and to position the wafer on the measurement stage 60. The controller 55 then issues commands to the measurement stage 60 to position the wafer relative to the measurement system so that measurements can be made at a predetermined location. The controller 55 then issues commands to the measurement system 75 to make a measurement and display the results of the measurement. Once the measurement is complete, the controller 55 issues instructions to the robotics and wafer handling system 65 to return the wafer to the cassette station 70.

[0016] The measurement stage 60 includes a test surface upon which the wafer is placed for measurements, and translation stages to provide wafer manipulation in three degrees of freedom.

[0017] Figure 2 is a schematic diagram of a photoacoustic measurement system 75 that includes, as arranged in Figure 2, a pulsed light source 100, a sample stage 220, a stage/ vacuum chuck 230, a first probe steering mirror 180, a pump beam steering mirror 150, a first steering mirror 110, a pump-probe beamsplitter 120, a polarizer 135, and an electro-optic modulator (EOM) 130. Additionally, photoacoustic system 75 includes a probe retroreflector 160, a delay scanning stage 170, a dither EOM 205, a beam dump 242, and a detector 250. Furthermore, photoacoustic measurement system 75 includes a linear pump-discriminating polarizer 245, a harmonic generator wavelength selector (wavelength selector) 102, a projecting lens 210, a collimating lens 240, a pump retroreflector 140, and a second probe steering mirror 190.

[0018] Pulsed light source 100 may be a titanium-sapphire laser operating at 80 MHz and emitting light at 800 nm. The laser can also be alternatively configured with a frequency doubling birefringent crystal to emit laser beam 105 at 400 nm. Other types of lasers operating with different wavelengths and different frequencies can be used as well.

[0019] In operation, pulsed light source 100 emits laser beam 105 that is redirected by first steering mirror 110. Pump probe beamsplitter 120 splits incident laser beam pulse (preferably of picosecond or shorter duration) into pump beam 125A and probe beam 125B. Electro-optic modulator (EOM) 130 rotates pump beam 125A polarization between horizontal and vertical at a frequency of, for example, 10 kHz to 10 MHz. Polarizer 135 converts pump beam 125A polarization rotation into an amplitude-modulated pump beam 200. Pump retroreflector 140 and pump beam steering mirror 150 deflect modulated pump beam 200 onto dither EOM 205.

[0020] A probe beam 125B is transmitted to probe retroreflector 160 where delay scanning stage 170 is used to modify the length of the beam path of probe beam 125B relative to the length of modulated pump beam 200, thus forming time delayed probe beam 195. Delayed probe beam 195 and modulated pump beam 200 propagate through dither EOM 205 and then through projecting lens 210 and finally onto sample 220. Stage/ vacuum chuck 230 acts as a positioning unit for the sample wafer and is preferably a multiple-degree of freedom stage that is adjustable in height (z-axis), position (x and y-axes), and tilt (T), and allows motor controlled positioning of a portion of the sample relative to the modulated pump beam 200 and delayed probe beam 195. Alternatively or additionally, the stage may have rotational freedom of movement. The z-axis is used to translate the sample vertically into the focus region of the pump and probe beams, the x and y-axes translate the sample parallel to the focal plane, and the tilt axes adjust the orientation of the sample 220 to establish a desired angle of incidence for the probe beam.

[0021] Modulated pump beam 200 and delayed probe beam 195 propagate through collimating lens 240 where the modulated pump beam 200 is gathered by beam dump 242. Pump-discriminating polarizer 245 isolates reflected probe beam 225 from the modulated pump beam 200. Detector 250 converts reflected probe beam 225 into a signal versus delay stage 170 position. This signal is demodulated and sent to controller 55 (shown in Figure 1) for analysis (e.g. to determine film thickness).

[0022] Presently preferred techniques for performing the analysis to determine film thickness, as well as to determine other film characteristics, can be found in the following U.S. Patent Nos.: 4,710,030, "Optical Generator and Detector of Stress Pulses"; 5,706,094, "Ultrafast Optical Technique for the Characterization of Altered Materials"; 5,748,318, "Optical Stress Generator and Detector"; 5,844,684, "Optical Method for Determining the Mechanical Properties of a Material"; 5,864,393, "Optical Method for the Determination of Stress in Thin Films"; 6,008,906, "Optical Method for the Characterization of the Electrical Properties of Semiconductors and Insulating Films"; 6,025,918, "Apparatus and Method for Measurement of the Mechanical Properties and Electromigration of Thin Films" and 6,038,026, "Apparatus and Method for the Determination of Grain Size in Thin Films", all of which are incorporated by reference herein in their entireties.

[0023] Referring now to Figure 3A and 3B collectively referred to as Figure 3, the optical metrology system 50 is configured to measure the elastic moduli of the optically transparent dielectric films on opaque substrates. A light pulse (pump) passing through a dielectric film 310 and focused onto a $5 \times 7 \mu\text{m}^2$ spot on the substrate surface generates a sound wave 320, illustrated as a dashed line, traveling through the dielectric film 310. A second light pulse (probe) 325 from the same or a different laser focused onto the same spot, measures the optical reflectivity of the dielectric film 310 modified by the sound wave 320. The reflected probe beam 325A has two components, one from the dielectric/substrate interface and one from the sound wave 320 as it travels in the dielectric layer 310. As the sound travels in the dielectric layer 310, it causes small local changes in the optical properties which reflect the probe beam 325. These two components of the probe beam interfere at a detector 330 resulting in a signal oscillating with a fixed period. The period of the oscillations depends on the wavelength of the probe beam 325, the incident angle of the probe beam 325, the sound velocity in the dielectric film 310, and the index of refraction of the dielectric film 310. Figure 3A shows the case where the reflected probe beam 325 destructively interferes with itself, and Figure 3B shows the case where the reflected probe beam 325A constructively interferes.

[0024] The period of the oscillations can be used to determine the sound velocity v , in the dielectric layer 310 using

$$v = \lambda / 2n\tau \cos\theta \quad (\text{Eq. 1})$$

where n is the index of refraction of the dielectric layer 310; τ is the period of the interference oscillations; λ is the wavelength of the probe beam 325; and θ is the angle of refraction.

[0025] The elastic stiffness of the dielectric film 310 is described by $c_{1111} = \rho v^2$. Young's modulus (Y) of the dielectric film can then be calculated by:

$$Y = 1/s_{1111} = \rho v^2 (1-2\nu)/(1-\nu). \quad (\text{Eq. 2})$$

[0026] Similarly the Bulk Modulus of the dielectric film 310 can be calculated using:

$$B = \rho v^2(1+\nu)/3(1-\nu), \quad (\text{Eq. 3})$$

where ρ and ν are the density and Poisson's ratio of the dielectric film 310.

[0027] Additionally, in order to determine the elastic moduli with the accuracy and repeatability required for semiconductor process monitoring, while minimizing the variation of the results from tool to tool, a method, as illustrated in Figure 4, is provided with several hardware adjustments for determining the value of each parameter in Eq.1.

[0028] The index of refraction, if not known a priori, may be measured by an ellipsometer, and the wavelength of the laser beam may be measured using a laser spectrometer 420 that is integrated inside the metrology system. Wavelength measurement accuracy of better than 0.1% is attainable with commercially available compact spectrometers (e.g. Ocean Optics model S2000), and it can be seen by Eq. 1 that this accuracy is sufficient to achieve 0.5% accuracy in the modulus measurement. The angle of refraction is determined by the following method.

[0029] A SiO₂ pattern wafer or a reference chip (cut from a SiO₂ pattern wafer) with areas of two different films with contrasting optical reflectance, for example native and 1000 Angstrom SiO₂, can be also be used for the measurement. The probe beam scans across the edges in both the x and y direction of a measurement area with the 1000 Angstrom SiO₂ residing in an area with native oxide (or vice versa). Since the reflectivity of the laser is different between these two films, two curves are generated from the scans, one for the scan in the x direction and one for the scan in the y direction. By fitting each curve to a complementary error function (based on the assumption that the intensity of the laser beam has a Gaussian distribution), the spot location and size in both the x and y directions can be obtained. The spot locations (x, y) are detected by this method at different positions in the z direction. The angle of incidence (AOI) at block 445 is calculated by:

$$\text{AOI} = \text{ArcTan}([(x_2-x_1)^2 + (y_2-y_1)^2]^{1/2} / (z_2-z_1)).$$

[0030] To increase the accuracy in the AOI measurements, one can measure the laser beam location (x, y) for successive six or seven positions in the z direction, and use linear data modeling to reduce noise. With one time setup, these measurements of angle and wavelength can be performed automatically without any user intervention.

[0031] In a presently preferred embodiment a near normal incidence angle may be used. The presently preferred optical metrology system shown at block 50 operates at a probe angle of incidence of about 40 degrees with respect to normal. As the probe incidence angle becomes smaller (more normal to the film), the angle-dependent term in Eq. 1 becomes less sensitive to uncertainty in the angle, and measurement matching between systems improves.

[0032] A discrete Fourier transform (DFT) 460 preferably is used to analyze the frequency content of the signal to obtain the period. The DFT 460 is well suited to find the frequency of sine waves in high frequency noise. However the DFT 460 is circular in nature and if the beginning and ends do not match, an artifact called 'spectral leakage' (smearing of the spectrum) will occur. Another artifact is known as scalloping or 'picket fence' effect. This results when the actual frequency of the wave does not correspond with the frequency resolution of the DFT 460. The frequency resolution of a DFT 460 is the ratio of the sampling frequency f_s to the number of digitized samples N . Because the signal from the interlayer dielectric is not stationary (i.e. it changes with time), due to sound reflections at interfaces and acoustic damping, it is difficult to arbitrarily increase N by taking longer measurements. However, *sinc* or frequency preserving interpolation in the frequency domain can be accomplished in the frequency domain by simply zero-padding in the time domain.

[0033] To combat the artifacts associated with the DFT 460, the following algorithm is preferred for use. Recorded data is windowed 465 using a rectangular or 'boxcar' function to ensure an integral number of wavelengths present. The DFT 460 is performed. An ideal filter is applied that has a center frequency equal to the frequency at which the maximum amplitude occurs and narrow bandwidth that is a function of the center frequency. Sinc-interpolation in the frequency domain is performed on the resulting spectrum and a peak refinement algorithm is used to find a high precision value of the frequency of oscillation.

[0034] In addition to the oscillatory component coming from the interference of the reflected probe beam components that carry information about the sound velocity, the signal, measured by the optical metrology system contains "background" contribution due to the dissipation of the heat energy delivered by the pump pulse. This component is slowly decaying with time. This component additionally contributes to the signal being non-stationary, and decreases the accuracy obtained using the DFT 460 method. In addition, this background component depends on the fine details of the optical alignment and contributes to the tool-to-tool variability. Thermal background can be subtracted by fitting an exponential or a polynomial function to the signal, and subtracting it.

[0035] To obtain fine frequency resolution and sensitivity of the measurement, the *sinc*-interpolation is done on the padded dataset, which may contain several times more data points. The *sinc*-interpolation may become time-consuming due to the increased dataset.

[0036] A faster algorithm comprising the following can be used. The thermal background is subtracted by fitting a low order polynomial function to the raw data. The resulting signal is de-noised by using Ideal frequency filtering. Ideal frequency filtering involves applying the DFT transform 460, finding the maximal intensity frequency within the pre-specified range, removing any component outside the narrow band surrounding the maximal intensity component, and calculating the inverse DFT to obtain the de-noised data in the time domain.

[0037] As this signal consists of a single frequency oscillation, the signals' period can be determined by locating the times of its maxima and minima using a peak refinement algorithm. These times can be obtained with improved resolution over the resolution obtained by time sampling of the signal.

[0038] Separations between the peaks can be averaged over the pairs of peaks, separated by at least k_{min} counts, to obtain the oscillation period T by using the following formula for a set of M extrema times $\{e_i\}$, sorted by the peak time

in ascending order: $T = \frac{1}{N_p} \sum_{k=k_{min}}^{k=k_{max}} \sum_{i=1, M-k} \frac{e_{i+k} - e_i}{k}$. It is important to exclude the close peaks as much as possible, as they contribute more variability to the answer.

[0039] Alternatively, by linear fitting peak times vs. peak number, the slope and the intercept may be obtained. The slope equals one half of the oscillation period.

[0040] In the situation where the ILD film is thinner, and only a few, or no oscillation periods can be observed before the first sound reflection from the bottom of the film, the above methodology may not be adequate. In this situation MUSIC or DMUSIC algorithms can be used, or alternatively some non-linear fitting of the signal with the single frequency sinusoid, optimizing its amplitude, phase and frequency to obtain the best fit to the data. The goal function of such optimization can be either the usual Fit Error defined as a sum of the squares of the differences between the measured and fitted signal, or the cross-correlation of the fitted and measured signals.

[0041] Density can be determined 470 by measuring the amplitude change between the oscillations incident and reflected at the dielectric/Si interface by the following:

$$R = B/A = (Z_{\text{substrate}} - Z_{\text{dielectric}}) / (Z_{\text{substrate}} + Z_{\text{dielectric}}) \quad (\text{Eq. 4})$$

$$\rho = Z/v, \quad (\text{Eq. 5})$$

where R is the reflection coefficient, A is the incident wave amplitude, B is the reflected wave amplitude, and Z is the characteristic acoustic impedance. It is assumed that the characteristic acoustic impedance is known for the Si substrate. For the Young's modulus or the Bulk modulus calculations, the published value of the Poisson's ratio can be used.

[0042] It is noted that another technique to address the problem solved by the teachings of this invention includes a narrow-bandwidth / long pulse system. The 100 fsec laser pulses generated by titanium sapphire lasers typically have bandwidths on the order of 10nm at 800nm and doubled pulses have bandwidths around 3 nm. Longer pulse widths, around 1 psec, may be used to practice this technique and these pulses have significantly smaller bandwidths (< 1 nm). The smaller bandwidth improves the accuracy of the technique via Eq. 1 by limiting the range of wavelengths.

[0043] Another alternative includes the use of a derivative mode modulus measurement system, as the oscillatory nature of the measurement signals lends these measurements to a derivative type of measurement (see, for example, U.S. Patent 5,748,318). The result is an improved signal to noise ratio, leading to improved repeatability and shorter measurement time (higher throughput).

[0044] A further alternative includes the use of tilt correction. The wafer tilt relative to the optics head contributes to uncertainty in the angle as calculated in Eq. 1. Such tilts can be different depending on measurement location across the sample due to sample, chuck, or stage non-uniformities. A tilt measurement may be performed at each site to correct for these effects, for example using a standard laser diode and position sensitive detector.

[0045] Additionally, one or more optimized "check samples" (for example SiO_2/Si , bare Si, and SiN/Si) with known acoustic and optical properties maybe used to calibrate and/or monitor multiple optical metrology systems for improved repeatability and/or matching between systems. Such samples may be periodically loaded into the tool or included inside the tool and periodically monitored.

[0046] Another alternative includes the use of a multiple angle probe beam system. Measuring the sample at multiple known probe angles allows for an independent calculation of refractive index n in Eq. 1. This allows the system to uniquely discriminate between process variations that may impact sound velocity from those that may impact refractive index.

[0047] A further alternative includes matched spot size and pump/probe beam intensities. Previous work suggests that most film measurement results have a small empirical dependence on pump and probe spot sizes and powers. Likewise, some degree of control of these system parameters may be preferred for modulus measurement matching.

Additionally, reducing uncertainty in the incident probe angle with an extremely flat chuck (< 0.01 deg) leads to improved tool matching through Eqs. 1 and 2.

[0048] Film temperature compensation is another alternative. According to the experimental literature on temperature dependence of sound velocity, many films have temperature coefficients on the order of 10^{-4} 1/C. Therefore, to the extent that the film temperature is not similar between tools a difference in the measured sound velocity is expected. Temperature differences may be due to ambient temperature or temperature rise in the film as a result of the absorption of the laser pulses. A calibration table may be created to match tools for each material based upon the film's velocity and refractive index temperature coefficients, an accurate measurement of ambient temperature, and a calculation of film temperature rise on the basis of the measured quantities: pump and probe laser powers, spot sizes, and film reflectance.

[0049] Further, although described in terms of preferred embodiments, it should be realized that a number of modifications of the teachings of this invention may occur to one skilled in the art and will still fall within the scope of this invention as claimed. By example, the method is not limited to dielectric blanket films; it can also be applied to measure an effective value for the elastic moduli of metal/dielectric pattern structures such as in Cu/ILD damascene interconnects.

Claims

1. A method of optical metrology, comprising:

directing a first light pulse to a surface of a sample;
determining (430) a first set of x_1, y_1, z_1 coordinates using a reflected portion of the first light pulse;
moving (435) the sample in the z direction;
directing a second light pulse onto the surface of the sample;
determining (440) a second set of x_2, y_2, z_2 coordinates using a reflected portion of the second light pulse;
calculating (445) an angle of incidence from the first and second sets of coordinates;
calculating (450) an angle of refraction using the calculated angle of incidence;
using the calculated angle of refraction to determine a sound velocity v in at least a portion of the sample surface;
and
using the determined sound velocity v , to determine a modulus of elasticity of the portion of the sample surface.

2. A method as in claim 1, wherein the angle of refraction is calculated from the angle of incidence using Snell's law.

3. A method as in claim 1, wherein the angle of incidence is calculated using $AOI = \text{ArcTan}([(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} / (z_2 - z_1))$.

4. A method as in claim 1, wherein the sample surface comprises at least two different films.

5. A method as in claim 4, wherein the optical reflectivity is different between the at least two different films.

6. A method as in claim 4, wherein the light pulse scans across edges of the at least two different films in the x direction and the y direction generating an x direction curve and a y direction curve at different positions in the z direction to determine the angle of incidence.

7. A method as in claim 1, wherein the sample comprises a semiconductor wafer having at least one dielectric film disposed on the surface.

8. A method as in claim 7, wherein the dielectric film comprises SiO_2 .

9. A method as in claim 7, wherein the dielectric film comprises polymer.

10. A method as in claim 7, wherein the dielectric film comprises carbon doped oxide.

11. A method as in claim 1 further comprising:

determining an index of refraction of a sample;
determining a wavelength of a laser beam;
determining an angle of refraction of the sample by marking a surface of a first portion of the sample with a first

light pulse, said first portion having a first reflectivity;

marking a surface of a second portion of the sample with a second light pulse, said second portion having a second reflectivity.

12. A method as in claim 11, wherein a plurality of marks are obtained and averaged to increase the accuracy of the angle of incidence measurement.

13. A method as in claim 11, wherein an oscillating signal is used to determine a sound velocity v , in a film layer using $v = \lambda / 2n\tau \cos\theta$, where n is the index of refraction of the film layer, τ is a period of an interference oscillation, λ is the wavelength of the laser beam, and θ is the angle of refraction.

14. A method as in claim 11, wherein a discrete Fourier transform algorithm is used to analyze a frequency content of a signal to obtain a period, the algorithm comprising windowing recorded data using a rectangular function to ensure an integral number of wavelengths present, performing the discrete Fourier transform, applying an ideal filter with a center frequency equal to a frequency at which the maximum amplitude occurs, sinc interpolation in the frequency domain performed on the resulting spectrum and a peak refinement algorithm to find a precision value of a frequency of oscillation.

15. A method as in claim 12, wherein a density is determined by measuring an amplitude variation between the oscillation incident and reflected at a dielectric interface using $R = B/A = (Z_{\text{substrate}} - Z_{\text{dielectric}}) / (Z_{\text{substrate}} + Z_{\text{dielectric}})$ and $\rho = Z/v$ where R is a reflection coefficient, A is a incident wave amplitude, B is a reflected wave amplitude, and Z is a characteristic acoustic impedance.

16. A method as in claim 11, wherein an algorithm is used to refine a frequency resolution, the algorithm comprising subtracting a thermal background by fitting a low order polynomial function to a raw dataset, removing a noise from a resulting signal by using Ideal frequency filtering, locating the signals maxima and minima times using a peak refinement algorithm to obtain an oscillation period T of the signal, the oscillation period T obtained by using

$$T = \frac{1}{N_p} \sum_{k=k_{\min}}^{k=k_{\max}} \sum_{i=1, M-k} \frac{e_{i+k} - e_i}{k}.$$

17. A method as in claim 1, further comprising measuring an index of refraction using an ellipsometer.

18. A method as in claim 1, further comprising measuring a wavelength of a laser using a spectrometer.

19. A method as in claim 1, further comprising using a check sample with known acoustic and optical properties to calibrate one or more optical metrology systems.

20. A method as in claim 1, further comprising using a multiple angle probe beam system to measure the sample.

21. A method as in claim 1, further comprising using matched spot sizes and intensities for a pump and probe.

22. A method as in claim 1, wherein the steps determining the first and second sets of coordinates involve laterally scanning the reference sample.

23. An optical metrology system (501), comprising:

an optical source subsystem for laterally scanning a beam over a reference sample along x and y axes to induce a reflection off of the reference sample and for moving the reference sample relative to the beam along a z axis; a detector for locating a first set of reflected x_1 , y_1 coordinates and a second set of reflected x_2 , y_2 coordinates corresponding to a first z axis location and a second z axis location, respectively; and a processor operating under control of a stored program, configured to:

calculate an angle of incidence of the beam from the first and second set of coordinates;
determine an angle of refraction associated with the reference sample using the calculated angle of incidence;
determine a sound velocity v in at least a portion of the reference sample using the determined angle of

refraction; and

determine the modulus of elasticity in at least the portion of the reference sample using the determined sound velocity v .

24. A system as in claim 23, where said reference sample comprises a patterned reference sample.

25. The system of claim 23, further comprising:

a sample stage having multiple degrees of freedom.

26. A system as in claim 23, wherein the processor uses $\text{AOI} = \text{ArcTan}([(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} / (z_2 - z_1))$ to calculate the angle of incidence.

27. A system as in claim 23, where the optical subsystem includes an ellipsometer.

28. A system as in claim 23, wherein the optical subsystem includes a spectrometer.

29. An optical metrology system as in claim 23, wherein the optical subsystem includes a light pulse source used to obtain a plurality of marks which are averaged to increase the accuracy of the angle of incidence measurement.

Patentansprüche

1. Optisches Messverfahren, das Folgendes umfasst:

Richten eines ersten Lichtimpulses auf eine Oberfläche einer Probe;

Bestimmen (430) eines ersten Satzes von x_1 -, y_1 -, z_1 -Koordinaten unter Verwendung eines reflektierten Abschnitts des ersten Lichtimpulses;

Verschieben (435) der Probe in der z -Richtung;

Richten eines zweiten Lichtimpulses auf die Oberfläche der Probe;

Bestimmen (440) eines zweiten Satzes von x_2 -, y_2 -, z_2 -Koordinaten unter Verwendung eines reflektierten Abschnitts des zweiten Lichtimpulses;

Berechnen (445) eines Einfallswinkels aus dem ersten und dem zweiten Satz von Koordinaten;

Berechnen (450) eines Brechungswinkels unter Verwendung des berechneten Einfallswinkels;

Verwenden des berechneten Brechungswinkels, um eine Schallgeschwindigkeit v in mindestens einem Abschnitt der Probenoberfläche zu bestimmen; und

Verwenden der bestimmten Schallgeschwindigkeit v , um einen Elastizitätsmodul des Abschnitts der Probenoberfläche zu bestimmen.

2. Verfahren nach Anspruch 1, wobei der Brechungswinkel unter Verwendung des Snell'schen Gesetzes aus dem Einfallswinkel berechnet wird.

3. Verfahren nach Anspruch 1, wobei der Einfallswinkel unter Verwendung von $\text{EW} = \text{ArcTan}([(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} / (z_2 - z_1))$ berechnet wird.

4. Verfahren nach Anspruch 1, wobei die Probenoberfläche mindestens zwei unterschiedliche Filme umfasst.

5. Verfahren nach Anspruch 4, wobei der optische Reflexionsgrad zwischen den mindestens zwei unterschiedlichen Filmen unterschiedlich ist.

6. Verfahren nach Anspruch 4, wobei der Lichtimpuls in der x -Richtung und der y -Richtung über Ränder der mindestens zwei unterschiedlichen Filme streicht und eine x -Richtungskurve und eine y -Richtungskurve an unterschiedlichen Positionen in der z -Richtung erzeugt, um den Einfallswinkel zu bestimmen.

7. Verfahren nach Anspruch 1, wobei die Probe einen Halbleiterwafer mit mindestens einem auf der Oberfläche angeordneten dielektrischen Film umfasst.

8. Verfahren nach Anspruch 7, wobei der dielektrische Film SiO_2 umfasst.

9. Verfahren nach Anspruch 7, wobei der dielektrische Film Polymer umfasst.

10. Verfahren nach Anspruch 7, wobei der dielektrische Film mit Kohlenstoff dotiertes Oxid umfasst.

11. Verfahren nach Anspruch 1, das weiter Folgendes umfasst:

Bestimmen eines Brechungsindex einer Probe;

Bestimmen einer Wellenlänge eines Laserstrahls;

Bestimmen eines Brechungswinkels der Probe durch Markieren einer Oberfläche eines ersten Abschnitts der Probe mit einem ersten Lichtimpuls, wobei der erste Abschnitt einen ersten Reflexionsgrad aufweist;

Markieren einer Oberfläche eines zweiten Abschnitts der Probe mit einem zweiten Lichtimpuls, wobei der zweite Abschnitt einen zweiten Reflexionsgrad aufweist.

12. Verfahren nach Anspruch 11, wobei eine Vielzahl von Markierungen erhalten und gemittelt werden, um die Genauigkeit der Einfallswinkelmessung zu erhöhen.

13. Verfahren nach Anspruch 11, wobei ein schwingendes Signal verwendet wird, um eine Schallgeschwindigkeit v in einer Filmschicht unter Verwendung von $v = \lambda / 2n\tau \cos\theta$ zu bestimmen, wobei n der Brechungsindex der Filmschicht ist, τ eine Periode einer Interferenzschwingung ist, λ die Wellenlänge des Laserstrahls ist und θ der Brechungswinkel ist.

14. Verfahren nach Anspruch 11, wobei ein diskreter Fouriertransformationsalgorithmus verwendet wird, um einen Frequenzinhalt eines Signals zu analysieren, um einen Periode zu erhalten, wobei der Algorithmus Folgendes umfasst: Fensterung aufgezeichneter Daten unter Verwendung einer Rechteckfunktion, um eine ganzzahlige Anzahl vorhandener Wellenlängen sicherzustellen, Ausführen der diskreten Fouriertransformation, Anwenden eines idealen Filters mit einer Mittenfrequenz, die gleich einer Frequenz ist, bei der die maximale Amplitude auftritt, Sinusinterpolation im Frequenzbereich, ausgeführt an dem resultierenden Spektrum und eines Spitzenverfeinerungsalgorithmus, um einen Präzisionswert einer Schwingungsfrequenz zu finden.

15. Verfahren nach Anspruch 12, wobei eine Dichte bestimmt wird, indem eine Amplitudenabweichung zwischen der an einer dielektrischen Grenzfläche einfallenden und reflektierten Schwingung unter Verwendung von $R = B/A - (Z_{\text{Substrat}} - Z_{\text{Dielektrikum}}) / (Z_{\text{Substrat}} + Z_{\text{Dielektrikum}})$ Und $\rho = Z/v$ gemessen wird, wobei R ein Reflexionskoeffizient ist, A eine Einfallswellenamplitude ist, B eine Reflexionswellenamplitude ist und Z eine charakteristische akustische Impedanz ist.

16. Verfahren nach Anspruch 11, wobei ein Algorithmus verwendet wird, um eine Frequenzauflösung zu verfeinern, wobei der Algorithmus Folgendes umfasst: Abziehen eines thermischen Hintergrunds durch Anpassen einer Polynomfunktion niedriger Ordnung an einen Rohdatensatz, Entfernen eines Rauschens von einem resultierenden Signal durch Verwenden von idealer Frequenzfilterung, Orten der Maximums- und Minimumszeiten des Signals unter Verwendung eines Spitzenverfeinerungsalgorithmus, um eine Schwingungsperiode T des Signals zu erhalten,

wobei die Schwingungsperiode T durch Verwenden von
$$T = \frac{1}{N_P} \sum_{k=k_{\min}}^{k=k_{\max}} \sum_{i=l, M-k} \frac{e_{i+k} - e_i}{k}$$
 erhalten wird.

17. Verfahren nach Anspruch 1, weiter umfassend das Messen eines Brechungsindex unter Verwendung eines Ellipsometers.

18. Verfahren nach Anspruch 1, weiter umfassend das Messen einer Wellenlänge eines Lasers unter Verwendung eines Spektrometers.

19. Verfahren nach Anspruch 1, weiter umfassend das Verwenden einer Kontrollprobe mit bekannten akustischen und optischen Eigenschaften, um ein oder mehrere optische Messsysteme zu kalibrieren.

20. Verfahren nach Anspruch 1, weiter umfassend das Verwenden eines Mehrwinkel-Sondenstrahlensystems zum Messen der Probe.

21. Verfahren nach Anspruch 1, weiter umfassend das Verwenden aneinander angepasster Fleckgrößen und Intensi-

täten für einen Pump-and-Probe.

22. Verfahren nach Anspruch 1, wobei die Schritte zum Bestimmen des ersten und des zweiten Satzes von Koordinaten das Überstreichen in Querrichtung der Bezugsprobe beinhalten.

23. Optisches Messsystem (501), das Folgendes umfasst:

ein Teilsystem mit einer optischen Quelle zum Streichen eines Strahls in Querrichtung über eine Bezugsprobe entlang der x- und y-Achse, um eine Reflexion von der Bezugsprobe hervorzurufen und zum Verschieben der Bezugsprobe relativ zu dem Strahl entlang einer z-Achse;
einen Detektor zum Orten eines ersten Satzes reflektierter x_1 -, y_1 -Koordinaten und eines zweiten Satzes reflektierter x_2 -, y_2 -Koordinaten, die einem ersten z-Achsenort bzw. einem zweiten z-Achsenort entsprechen; und einen Prozessor, der unter der Steuerung eines gespeicherten Programms arbeitet und dazu konfiguriert ist:

einen Einfallswinkel des Strahls aus dem ersten und dem zweiten Satz von Koordinaten zu berechnen;
einen mit der Bezugsprobe assoziierten Brechungswinkel unter Verwendung des berechneten Einfallswinkels zu bestimmen;
eine Schallgeschwindigkeit v in mindestens einem Abschnitt der Bezugsprobe unter Verwendung des bestimmten Brechungswinkels zu bestimmen; und
den Elastizitätsmodul in mindestens dem Abschnitt der Bezugsprobe unter Verwendung der bestimmten Schallgeschwindigkeit v zu bestimmen.

24. System nach Anspruch 23, wobei die Bezugsprobe eine strukturierte Bezugsprobe umfasst.

25. System nach Anspruch 23, das weiter Folgendes umfasst:

einen Probenstisch mit mehreren Freiheitsgraden.

26. System nach Anspruch 23, wobei der Prozessor $EW = \text{ArcTan} \left(\left[(x_2 - x_1)^2 + (y_2 - y_1)^2 \right]^{1/2} / (z_2 - z_1) \right)$ verwendet, um den Einfallswinkel zu berechnen.

27. System nach Anspruch 23, wobei das optische Teilsystem ein Ellipsometer umfasst.

28. System nach Anspruch 23, wobei das optische Teilsystem ein Spektrometer umfasst.

29. Optisches Messsystem nach Anspruch 23, wobei das optische Teilsystem eine Lichtimpulsquelle umfasst, die verwendet wird, um eine Vielzahl von Markierungen zu erhalten, die gemittelt werden, um die Genauigkeit der Einfallswinkelmessung zu erhöhen.

Revendications

1. Procédé de métrologie optique, comportant :

l'étape consistant à diriger une première impulsion lumineuse sur une surface d'un échantillon ;
l'étape consistant à déterminer (430) un premier ensemble de coordonnées x_1 , y_1 , z_1 en utilisant une partie réfléchie de la première impulsion lumineuse ;
l'étape consistant à déplacer (435) l'échantillon dans la direction z ;
l'étape consistant à diriger une deuxième impulsion lumineuse sur la surface de l'échantillon ;
l'étape consistant à déterminer (440) un deuxième ensemble de coordonnées x_2 , y_2 , z_2 en utilisant une partie réfléchie de la deuxième impulsion lumineuse ;
l'étape consistant à calculer (445) un angle d'incidence à partir des premier et deuxième ensembles de coordonnées ;
l'étape consistant à calculer (450) un angle de réfraction en utilisant l'angle d'incidence calculé ;
l'étape consistant à utiliser l'angle de réfraction calculé pour déterminer une vitesse du son v dans au moins une partie de la surface de l'échantillon ; et
l'étape consistant à utiliser la vitesse du son déterminée v , pour déterminer un module d'élasticité de la partie de la surface de l'échantillon.

2. Procédé selon la revendication 1, dans lequel l'angle de réfraction est calculé à partir de l'angle d'incidence en utilisant la loi de Snell.
3. Procédé selon la revendication 1, dans lequel l'angle d'incidence est calculé en utilisant $AOI = \text{ArcTan}([(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} / (z_2 - z_1))$.
4. Procédé selon la revendication 1, dans lequel la surface de l'échantillon comporte au moins deux films différents.
5. Procédé selon la revendication 4, dans lequel la réflexion optique est différente entre lesdits au moins deux films différents.
6. Procédé selon la revendication 4, dans lequel l'impulsion lumineuse balaye en travers des bords desdits au moins deux films différents dans la direction x et la direction y pour générer une courbe dans la direction x et une courbe dans la direction y en différentes positions dans la direction z pour déterminer l'angle d'incidence.
7. Procédé selon la revendication 1, dans lequel l'échantillon comporte une plaquette de semi-conducteur ayant au moins un film diélectrique disposé sur la surface.
8. Procédé selon la revendication 7, dans lequel le film diélectrique comporte de la SiO_2 .
9. Procédé selon la revendication 7, dans lequel le film diélectrique comporte du polymère.
10. Procédé selon la revendication 7, dans lequel le film diélectrique comporte de l'oxyde dopé au carbone.
11. Procédé selon la revendication 1, comportant par ailleurs :
 - l'étape consistant à déterminer un indice de réfraction d'un échantillon ;
 - l'étape consistant à déterminer une longueur d'onde d'un faisceau laser ;
 - l'étape consistant à déterminer un angle de réfraction de l'échantillon en marquant une surface d'une première partie de l'échantillon au moyen d'une première impulsion lumineuse, ladite première partie ayant une première réflexion ;
 - l'étape consistant à marquer une surface d'une deuxième partie de l'échantillon au moyen d'une deuxième impulsion lumineuse, ladite deuxième partie ayant une deuxième réflexion.
12. Procédé selon la revendication 11, dans lequel une pluralité de marques sont obtenues, et leur moyenne est calculée, pour accroître la précision de la mesure de l'angle d'incidence.
13. Procédé selon la revendication 11, dans lequel un signal d'oscillation est utilisé pour déterminer une vitesse du son v, dans une couche de film en utilisant $v = \lambda / 2n\tau \cos\theta$, où n est l'indice de réfraction de la couche de film, τ est une période d'une oscillation d'interférence, λ est la longueur d'onde du faisceau laser, et θ est l'angle de réfraction.
14. Procédé selon la revendication 11, dans lequel un algorithme de transformée de Fourier discrète est utilisé pour analyser un contenu en fréquences d'un signal pour obtenir une période, l'algorithme comportant un fenêtrage de données enregistrées au moyen d'une fonction rectangulaire pour assurer un nombre entier des longueurs d'onde présentes, une exécution de la transformée de Fourier discrète, l'application d'un filtre idéal avec une fréquence centrale égale à une fréquence à laquelle l'amplitude maximale se produit, une interpolation de type sinc dans le domaine fréquentiel effectuée sur le spectre résultant et un algorithme d'affinage de pic pour trouver une valeur de précision d'une fréquence d'oscillation.
15. Procédé selon la revendication 12, dans lequel une densité est déterminée en mesurant une variation d'amplitude entre l'oscillation incidente et réfléchie au niveau d'une interface diélectrique en utilisant $R = B/A = (Z_{\text{substrate}} - Z_{\text{dielectric}}) / (Z_{\text{substrate}} + Z_{\text{dielectric}})$ et $\rho = Z/v$ où R est un coefficient de réflexion, A est une amplitude de l'onde incidente, B est une amplitude de l'onde réfléchie, et Z est une impédance acoustique caractéristique.
16. Procédé selon la revendication 11, dans lequel un algorithme est utilisé pour affiner une résolution en fréquence, l'algorithme comportant la soustraction d'un fond thermique en plaçant une fonction polynomiale d'ordre faible au niveau d'un ensemble de données brutes, le retrait d'un bruit en provenance d'un signal résultant en utilisant le filtrage fréquentiel idéal, la localisation des temps maximum et minimum de signaux en utilisant un algorithme

d'affinage de pic pour obtenir une période d'oscillation T du signal, la période d'oscillation T étant obtenue en utilisant

$$T = \frac{1}{N_P} \sum_{k=k_{\min}}^{k=k_{\max}} \sum_{i=1, M-k} \frac{e_{i+k} - e_i}{k}.$$

17. Procédé selon la revendication 1, comportant par ailleurs l'étape consistant à mesurer un indice de réfraction en utilisant un ellipsomètre.

18. Procédé selon la revendication 1, comportant par ailleurs l'étape consistant à mesurer une longueur d'onde d'un laser en utilisant un spectromètre.

19. Procédé selon la revendication 1, comportant par ailleurs l'étape consistant à utiliser un échantillon témoin ayant des propriétés acoustiques et optiques connues pour calibrer un ou plusieurs systèmes de métrologie optique.

20. Procédé selon la revendication 1, comportant par ailleurs l'étape consistant à utiliser un système à faisceau sonde à angle multiple pour mesurer l'échantillon.

21. Procédé selon la revendication 1, comportant par ailleurs l'étape consistant à utiliser des tailles et des intensités de points assorties pour une pompe et sonde.

22. Procédé selon la revendication 1, dans lequel les étapes consistant à déterminer les premier et deuxième ensembles de coordonnées impliquent l'étape consistant à balayer dans le sens latéral l'échantillon de référence.

23. Système de métrologie optique (501), comportant :

un sous-système de source optique servant à balayer dans le sens latéral un faisceau sur un échantillon de référence le long des axes x et y pour induire une réflexion en provenance de l'échantillon de référence et servant à déplacer l'échantillon de référence par rapport au faisceau le long d'un axe z ;
un détecteur servant à localiser un premier ensemble de coordonnées x_1, y_1 réfléchies et un deuxième ensemble de coordonnées x_2, y_2 réfléchies correspondant à un premier emplacement le long de l'axe z et un deuxième emplacement le long de l'axe z , respectivement ; et
un processeur fonctionnant sous le contrôle d'un programme enregistré, configuré pour :

calculer un angle d'incidence du faisceau à partir des premier et deuxième ensembles de coordonnées ;
déterminer un angle de réfraction associé à l'échantillon de référence en utilisant l'angle d'incidence calculé ;
déterminer une vitesse du son v dans au moins une partie de l'échantillon de référence en utilisant l'angle de réfraction déterminé ; et
déterminer le module d'élasticité dans au moins la partie de l'échantillon de référence en utilisant la vitesse du son déterminée v .

24. Système selon la revendication 23, dans lequel ledit échantillon de référence comporte un échantillon de référence géométrique.

25. Système selon la revendication 23, comportant par ailleurs :

un porte-échantillon ayant de multiples degrés de liberté.

26. Système selon la revendication 23, dans lequel le processeur utilise $AOI = \text{ArcTan}([(x_2 - x_1)^2 + (y_2 - y_1)^2]^{1/2} / (z_2 - z_1))$ pour calculer l'angle d'incidence.

27. Système selon la revendication 23, dans lequel le sous-système optique comprend un ellipsomètre.

28. Système selon la revendication 23, dans lequel le sous-système optique comprend un spectromètre.

29. Système de métrologie optique selon la revendication 23, dans lequel le sous-système optique comprend une source d'impulsions lumineuses utilisée pour obtenir une pluralité de marques dont la moyenne est effectuée pour

accroître la précision de la mesure de l'angle d'incidence.

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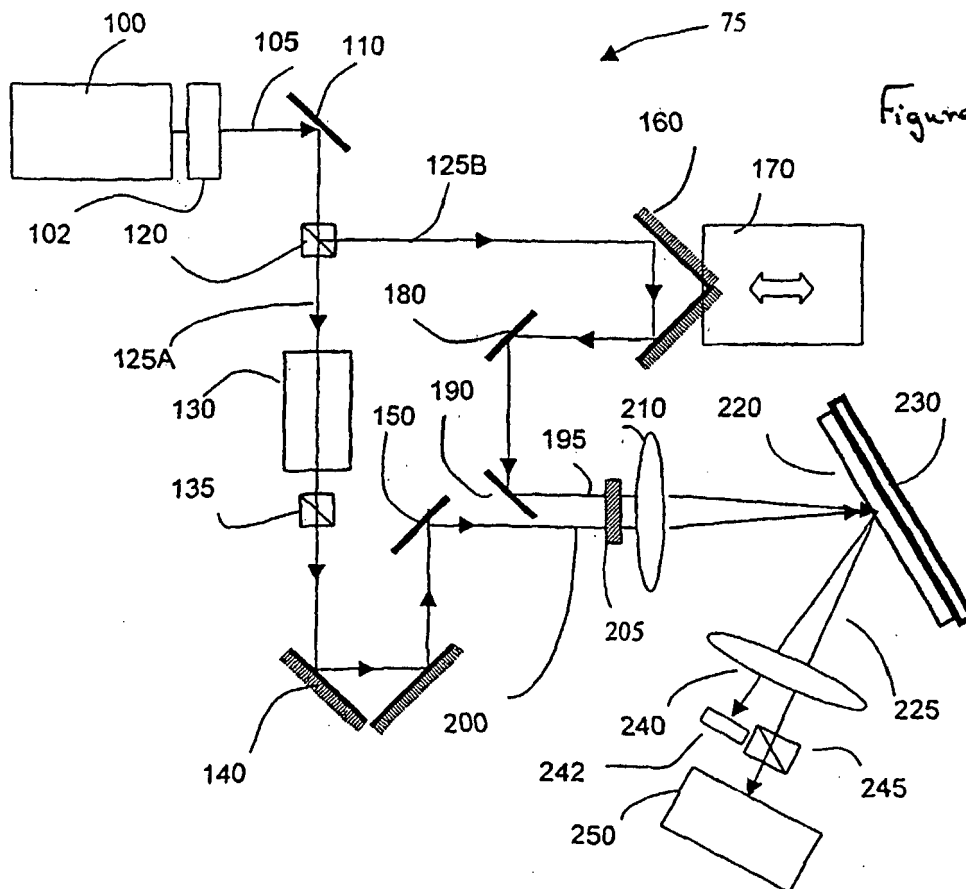
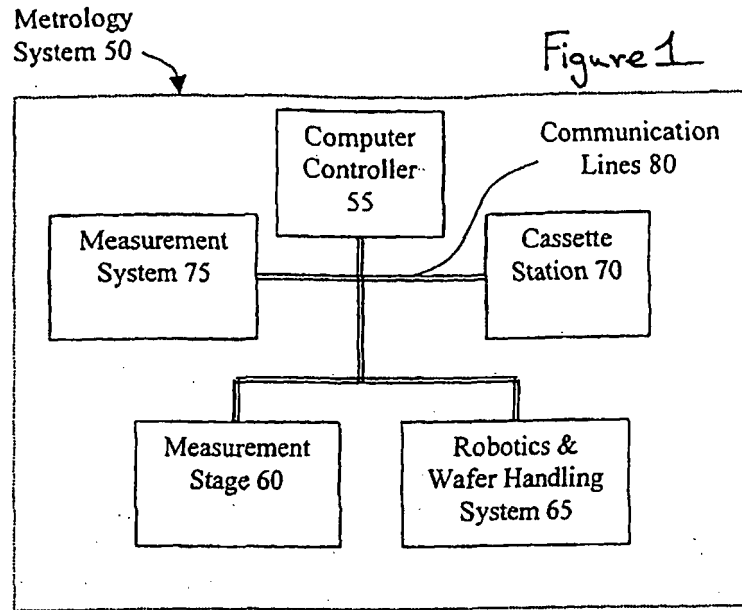


Figure 3

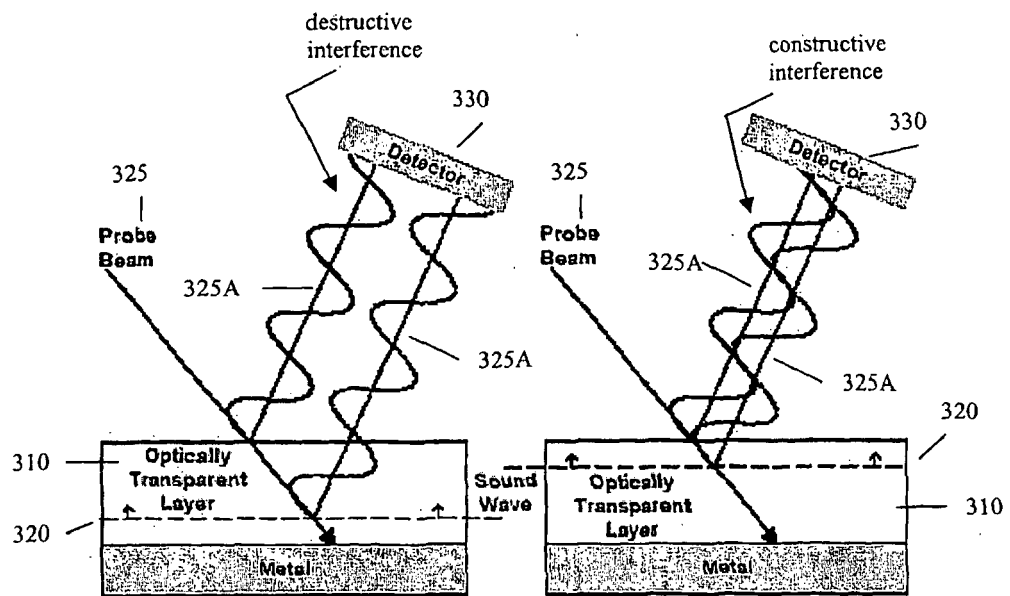
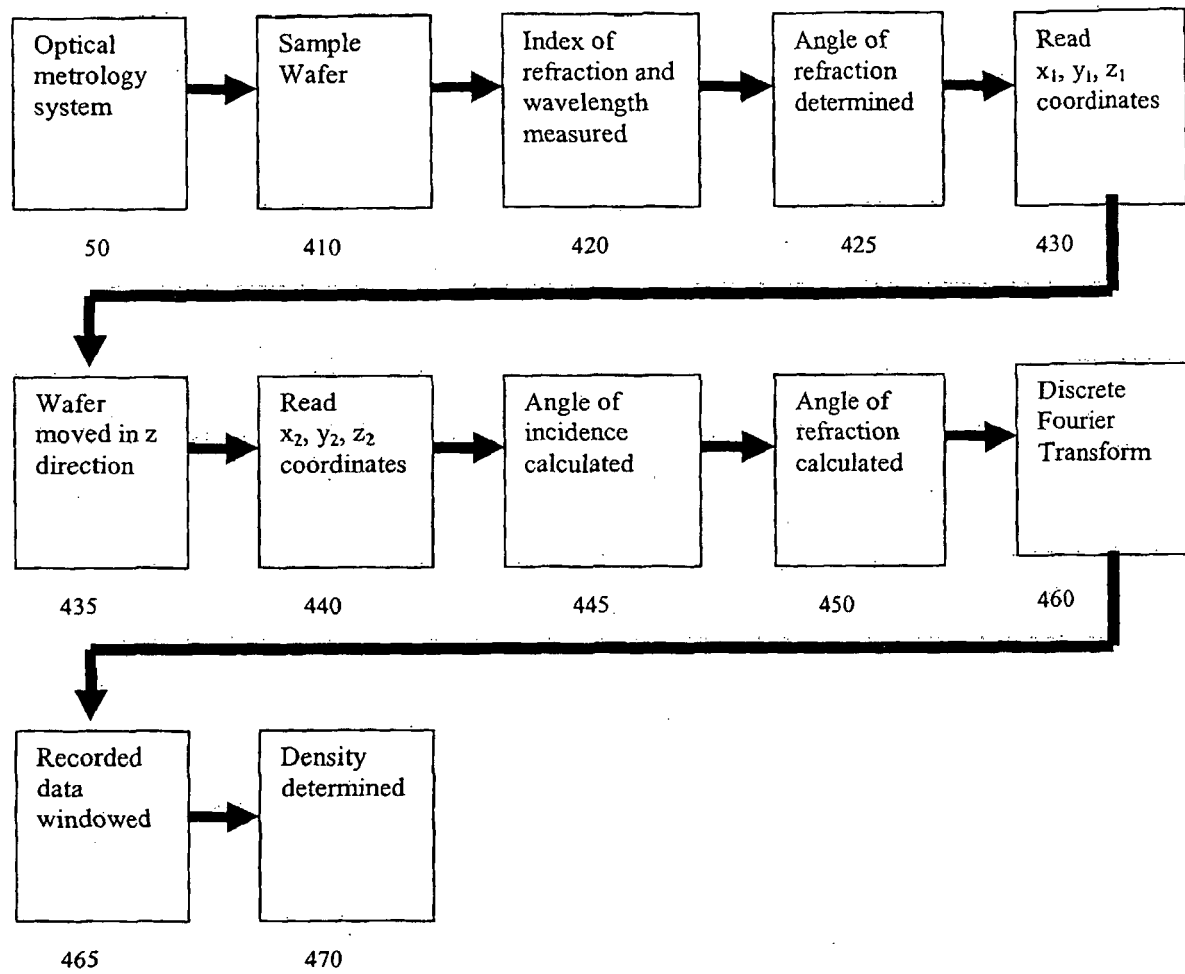


Fig. 3A

Fig. 3B

Figure 4



REFERENCES CITED IN THE DESCRIPTION

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