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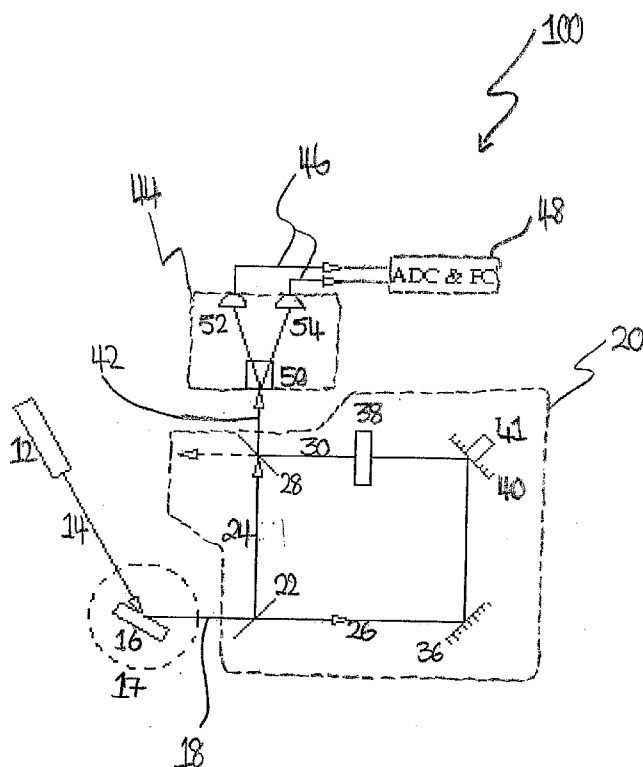


FIGURE 1

(57) Abstract: An interferometric ellipsometer (100) for measuring ellipsometric parameters of a sample. The ellipsometer comprises a light source (12) that is arranged to direct a light beam (14) onto the sample (16) for reflection. An interferometer (20) is arranged to receive and split the reflected light beam (18) from the sample (16) into two beams, one split beam (26) being modified by an optical system to generate a reference beam (30) that has p- and s-polarisations with a common phase and with a fixed relative amplitude and which is recombined with the remaining split beam (24) to generate an output beam (42) having temporal p- and s-fringes. An output detector (44) is arranged to detect the output beam (42) and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample (16) can be determined.



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AN INTERFEROMETRIC ELLIPSOMETER

FIELD OF THE INVENTION

- 5 The present invention relates to an ellipsometer for performing optical measurements on a sample, such as ellipticity measurements.

BACKGROUND TO THE INVENTION

- 10 Ellipsometers are very widely used in industry and research to, amongst other things, measure and control the deposition of thin coatings on semi-conductor wafers and optical components. They do this by measuring the ellipticity of polarized light after reflection from a sample. Commercial ellipsometers are mostly based on one of three methods: polarisation modulation, a rotating component or nulling.

- 15 Typically, the ellipsometers are arranged to measure the ellipsometric angles ψ and Δ , defined as:

$$\tan \psi = \left| \frac{r_p}{r_s} \right| \text{ and } \Delta = \arg \left(\frac{r_p}{r_s} \right)$$

- where r_p and r_s are the amplitude Fresnel reflection coefficients of a sample for p- and s-polarized light, respectively. A number of techniques can be used within commercial
20 ellipsometers to measure these angles, including: nulling, rotating element (usually a polariser or a waveplate) or polarisation modulation[1].

- Interferometric based ellipsometers have also been proposed. For example, Hazebroek and Holscher proposed an interferometric ellipsometer [2] that is based on a modified Michelson interferometer and requires a double reflection of the light by the sample in the
25 measurement arm. At the interferometer output, a Wollaston prism separates the beam into its p- and s-polarized components before detection by a pair of photodetectors. Temporal fringes are generated at the photodetectors by driving a corner cube reflector in the reference arm at a constant speed via an electromechanical driver. This design has two disadvantages: the rate at which data may be acquired is severely limited by the

electromechanical driver and the double reflection from the sample causes the fringe amplitude to be proportional to $|r_p|^2$ and $|r_s|^2$. For weakly reflecting samples, this results in small amplitude fringes with consequent difficulty of detection and decreased signal-to-noise ratio. Improvements [3] have been proposed to this design, including modifications
5 to the signal processing and the addition of optical components to allow reflectometry, but the basic instrument retains the modified Michelson interferometer, mechanical scanning and the double reflection from the sample.

Other designs based on the basic modified Michelson interferometer approach have also been proposed. For example, Wind and Hemmes [4,5] proposed a design called the “Le
10 Poole configuration” in which a Zeeman-split two frequency laser is utilised. This configuration obviates the need for mechanical scanning and allows much faster data acquisition since the two frequencies of the laser can differ by a few MHz. Alternatively, it has been recognised that one can apply a small modulation current to a semiconductor laser diode which causes the laser wavelength to vary slightly [6] and this, together with an
15 interferometer with unbalanced arms, can be used to create a heterodyne interferometric ellipsometer [7, 8, 9, 10]. Both approaches create instruments that have the advantages of rapid data acquisition, no moving parts and inexpensive, compact optical sources. As an alternative to directly modulating the laser diode, or using a two frequency laser, it has been recognised that one can generate the necessary frequencies via acousto-optic modulators
20 [11] in a design similar to the “Le Poole” configuration. These alternative approaches that exploit the basic modified Michelson interferometer design all still require a double reflection of the measurement beam by the sample.

The ellipsometric parameters of transparent or semi-transparent films can be determined in a modified Mach-Zehnder interferometer in which one reflection from, and one
25 transmission through, the film are used to generate signals from which the film parameters may be inferred [12, 13, 14, 15]. The difficulty with this approach is that the substrate must obviously be transparent as well, which greatly restricts the applicability of the design. In addition, since the sample itself is used as one of the beam splitters in the interferometer (at 45° angle of incidence), it is inconvenient to rotate the sample to access different angles of
30 incidence.

A two beam interferometer based on a Köster prism beam splitter has been proposed in [16]. It operates at normal incidence and is capable of measuring the thickness of opaque films and the thickness and refractive index of transparent films. It does not measure the ellipsometric angles, but rather relies on measuring phase shifts associated with transmission through the substrate alone and the film plus substrate to determine the film parameters. As such, it does not constitute a true ellipsometer. A variety of other schemes have been proposed that allow the measurement of thin films at arbitrary angles of incidence [17] with the Köster prism beam splitter. However, all of the proposed instruments require a double reflection from the sample in the measurement of Δ and, in addition, require the substrate to be partially covered in order to provide a reference surface. Furthermore, the proposed methods do not measure ψ , but rather rely on a modest rearrangement that enables the intensity reflection (or transmission) coefficients to be measured directly.

In this specification where reference has been made to patent specifications, other external documents, or other sources of information, this is generally for the purpose of providing a context for discussing the features of the invention. Unless specifically stated otherwise, reference to such external documents is not to be construed as an admission that such documents, or such sources of information, in any jurisdiction, are prior art, or form part of the common general knowledge in the art.

It is an object of the present invention to provide an improved interferometric ellipsometer that can be utilised for measuring ellipsometric parameters of a sample, or to at least provide the public with a useful choice.

SUMMARY OF THE INVENTION

In a first aspect, the present invention broadly consists in an interferometric ellipsometer for measuring ellipsometric parameters of a sample, comprising: a light source that is arranged to direct a light beam onto the sample for reflection; an interferometer that is arranged to receive and split the reflected light beam from the sample into two beams, one split beam being modified by an optical system to generate a reference beam that has p- and s-polarisations with a common phase and with a fixed relative amplitude and which is recombined with the remaining split beam to generate an output beam having temporal p-

and s-fringes; and an output detector that is arranged to detect the output beam and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.

5 In one form, the interferometer may comprise: an input beam splitter that is arranged to split the reflected light beam from the sample into two beams; a measurement arm following the input beam splitter down which one split beam travels; a reference arm following the input beam splitter down which the other split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a reference
10 beam that has p- and s-polarisations with common phase and fixed relative amplitude; and an output beam splitter that is arranged to combine the split beam from the measurement arm and the reference beam from the reference arm to generate an output beam having temporal p- and s-fringes.

15 Preferably, the optical system of the reference arm of the interferometer may comprise a first polariser having its transmission axis at approximately 45° with respect to the plane of incidence.

Additionally, the optical system of the reference arm of the interferometer may further
20 comprises a second polariser prior to the first polariser in the reference arm, the second polariser having its transmission axis at approximately 90° or 0° . Preferably, the optical system of the reference arm may comprise a wave plate between the first and second polarisers in the reference arm that is arranged to rotate the polarization of the split beam in the reference arm to provide enhanced fringe visibility in the output beam of the
25 interferometer. More preferably, the wave plate is a half- or quarter-wave plate.

Preferably, the reference arm of the interferometer may comprise one or more reflecting surfaces that guide the split beam of the reference arm from input beam splitter, through the optical system of the reference arm, to the output beam splitter. By way of example, the
30 reflecting surfaces may be mirrors or the like.

Preferably, the measurement arm of the interferometer comprises one or more reflecting surfaces that guide the split beam of the measurement arm from the input beam splitter to

the output beam splitter. By way of example, the reflecting surfaces may be mirrors or the like.

5 In an alternative form, the interferometer may comprise: a beam splitter that is arranged to split the reflected light beam from the sample into two beams; and a reference arm following the beam splitter down which one split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a reference beam that has p- and s-polarisations with common phase and fixed relative amplitude, the reference arm also being arranged to direct the reference beam back into the beam splitter for recombining
10 with the other split beam to generate an output beam having temporal p- and s-fringes.

Preferably, the optical system of the reference arm of the interferometer may comprise a polariser having its transmission axis at approximately 45° with respect to the plane of incidence.

15 Preferably, the reference arm of the interferometer may comprise an arrangement of reflecting surfaces that guide the split beam of the reference arm from beam splitter, through the optical system of the reference arm, and back to the beam splitter. By way of example, the reflecting surfaces may be mirrors.

20 Alternatively, the reference arm of the interferometer may comprise an arrangement of reflecting components that guide the split beam of the reference arm from beam splitter, through the optical system of the reference arm, and back to the beam splitter. By way of example, the reflecting components may be selected from any one or more of the
25 following: mirrors, corner cube reflectors, and prisms.

In one form, the interferometric ellipsometer may further comprise a time-varying component that is arranged to create a time-varying difference between the split beams of the measurement and reference arms to thereby generate an output beam having temporal
30 fringes at the output of the interferometer. The time-varying component may be provided at the light source. For example, the time-varying component may be a modulation component in the light source that is arranged to modulate the wavelength of the light beam directed at the sample to thereby create the time-varying difference. Alternatively,

the time-varying component may be provided in either arm of the interferometer. For example, the time-varying component may be a mechanical scanning device that is mounted to a reflecting surface in either of the measurement or reference arms of the interferometer, the mechanical scanning device being arranged to translate in a linear fashion at a constant speed to thereby create the time-varying difference in the split beam travelling in that that arm.

In another form, the interferometric ellipsometer may further comprise a frequency-shifting component that is arranged to create a frequency-difference between the split beams of the measurement and reference arms to thereby generate an output beam heterodyne signal having temporal fringes at the output of the interferometer. For example, the frequency-shifting component may be an acousto-optical or electro-optic modulator provided in either of the reference or measurement arms of the interferometer, the acousto-optical modulator being arranged to shift the source frequency of the split beam in that arm thereby generating a frequency difference for creating an output beam heterodyne signal with temporal fringes at the output of the interferometer.

In one form, the light source may be arranged to generate a light beam that has a wavelength falling within any of the following bands: ultraviolet, visible, near infrared, or infrared. In another form, the light source may be arranged to generate a broadband light beam to enable spectroscopic measurements of the ellipsometric parameters.

Preferably, the output detector comprises: a Wollaston prism or a polarising beam splitter cube for separating the output beam from the interferometer into its p- and s-component beams; and first and second optical detectors that are arranged to sense the respective p- and s-component beams and generate output signals representing the amplitude and phase of the p- and s-components of the output beam. More preferably, the optical detectors are photodetectors.

Preferably, the interferometric ellipsometer further comprises a control system that is arranged to receive and process the p- and s-component signals from the output detector to thereby generate ellipsometric parameters from which physical properties of the sample specimen can then be determined.

In a second aspect, the present invention broadly consists in a method for measuring the ellipsometric parameters of a sample comprising the steps of: directing a light beam onto the sample for reflection; splitting the reflected light beam from the sample into two beams; modifying one of the split beams with an optical system to generate a reference beam having p- and s-polarisations with common phase and fixed relative amplitude; recombining the reference beam with the remaining split beam to generate an output beam having temporal p- and s-fringes; detecting the p- and s-components of the output beam; and generating signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.

In one form, the step of directing a light beam onto the sample for reflection may comprise directing light that has a wavelength falling within any of the following bands: ultraviolet, visible, near infrared, or infrared. In another form, this step may comprise directing broadband light to enable spectroscopic measurements of the ellipsometric parameters.

Preferably, the step of splitting the reflected light beam from the sample into two beams may comprise providing an input beam splitter in the path of the reflected light beam. More preferably, the step further comprises providing a measurement arm down which one split beam (the measurement beam) travels and a reference arm down which the other split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a reference beam that has p- and s-polarisations with common phase and fixed relative amplitude.

Preferably, the step of modifying one of the split beams into a reference beam may comprise providing an optical system in the path of the split beam that comprises any one or more of the features defined in respect of the first aspect of the invention.

Preferably, the step of recombining the reference beam with the remaining split beam to generate an output beam having temporal p- and s-fringes may comprise providing an output beam splitter in the path of the beams.

Preferably, the method further comprises the step of either generating a time-varying difference between the split beams of the measurement and reference arms such that the output beam has temporal fringes when the beams are recombined, or alternatively generating a frequency-difference in the beams of either the reference or measurement arms such that the output beam heterodyne signal has temporal fringes when the beams are recombined. In one form, the time-varying difference may be generated by operating a mechanical scanning or translation device to time-vary either of the beams in either of the arms. In an alternative form, the time-varying difference may be generated by modulating the wavelength of the light beam that is directed onto the sample for reflection. In one form, the frequency-difference may be generated by operating an acousto-optic modulator in either of the measurement or reference arms to shift the source frequency of the split beam of that arm to generate the frequency-difference.

Preferably, the steps of detecting the p- and s-components of the output beam and generating signals representing the p- and s-components may comprise providing an output detector having any one or more of the features defined in respect of the first aspect of the invention.

Preferably, the method may further comprise the step of processing the p- and s-component signals to generate ellipsometric parameters, for example the ellipsometric angles ψ and Δ , from which physical properties of the sample specimen can then be determined.

In a third aspect, the present invention broadly consists in an interferometric ellipsometer for measuring ellipsometric parameters of a sample, comprising: a light source that is arranged to direct a light beam onto the sample for reflection from the sample once; an interferometer that is arranged to receive and modify the single reflected light beam from the sample into an output beam having temporal p- and s-fringes; and an output detector that is arranged to detect the output beam and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.

The third aspect of the invention may comprise any one or more of the features mentioned above in respect of the first aspect of the invention.

5 In a fourth aspect, the present invention broadly consists in a method for measuring the ellipsometric parameters of a sample comprising the steps of: directing a light beam onto the sample for reflection from the sample once; providing an interferometer that is arranged to receive and modify the single reflected light beam from the sample into an output beam having temporal p- and s-fringes; detecting the p- and s-components of the output beam; and generating signals representing the p- and s-components of the output
10 beam from which the ellipsometric parameters of the sample can be determined.

The fourth aspect of the invention may comprise any one or more of the features mentioned above in respect of the second aspect of the invention.

15 In a fifth aspect, the present invention broadly consists in an interferometer for use in a system for measuring ellipsometric parameters of a sample, the interferometer being arranged to: receive a light beam that has been reflected from the sample once; modify the received light beam into an output beam having temporal p- and s-fringes; and output the output beam.

20 Preferably, the interferometer may be arranged to receive and split the reflected light beam from the sample into two beams, one split beam being modified by an optical system to generate a reference beam that has p- and s-polarisations with a common phase and with a fixed relative amplitude and which is recombined with the remaining split beam to generate
25 the output beam having temporal p- and s-fringes.

The interferometer may comprise any one or more of the features described in respect of the interferometer of the interferometric ellipsometer of the first and/or third aspects of the invention. Further, the interferometer may further comprise or be coupled to one or
30 more of the other parts or components of the interferometric ellipsometer of the first and/or third aspects of the invention. By way of example only, the interferometer may further comprise or be coupled to: a light source that is arranged to direct a light beam onto the sample for reflection; and/or an output detector that is arranged to detect the

output beam and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined. It will be appreciated that the light source and/or output detector may have any one or more of the features described in respect of the first and/or third aspects of the invention. Even
5 further, the interferometer may be a part or component of a system for measuring ellipsometric parameters of a sample that has one or more of the features described in respect of the interferometric ellipsometer of the first and/or third aspects of the invention.

10 In a sixth aspect, the present invention broadly consists in an interference method for performing on a light beam reflected from a sample once in a system for measuring ellipsometric parameters of that sample, the method comprising the steps of: receiving the reflected light beam from the sample; modifying the received light beam into an output beam having temporal p- and s-fringes; and outputting the output beam.

15 Preferably, the step of modifying the received light beam may comprise: splitting the light beam into two beams; modifying one of the split beams with an optical system to generate a reference beam having p- and s-polarisations with common phase and fixed relative amplitude; and recombining the reference beam with the remaining split beam to generate
20 the output beam having temporal p- and s-fringes.

The interference method may comprise any one or more of the features described in respect of the interference steps of the method for measuring ellipsometric parameters of the second and/or fourth aspects of the invention. Further, the interference method may
25 further comprise one or more of the other steps of the method for measuring ellipsometric parameters of the second and/or fourth aspects of the invention. By way of example only, the interference method may further comprise the step(s) of: directing a light beam onto the sample for reflection; and/or detecting the p- and s-components of the output beam; and/or generating signals representing the p- and s-components of the output beam from
30 which the ellipsometric parameters of the sample can be determined. It will be appreciated that these further steps may have any one or more of the features described in respect of the second and/or fourth aspects of the invention. Even further, the interference method may form an aspect of a system for measuring ellipsometric parameters of a sample that

has one or more of the features described in respect of the method for measuring ellipsometric parameters of the second and/or fourth aspects of the invention.

5 The phrase "plane of incidence" as used in this specification and claims, unless the context specifies otherwise, is intended to mean the plane that is spanned by the incident and reflected beams of the sample and which contains the normal to the surface of the sample.

10 The term "arm" as used in this specification and claims, unless the context specifies otherwise, is intended to mean optical path or pathway along which a light beam travels.

The term "comprising" as used in this specification and claims means "consisting at least in part of". When interpreting each statement in this specification and claims that includes the term "comprising", features other than that or those prefaced by the term may also be present. Related terms such as "comprise" and "comprises" are to be interpreted in the
15 same manner.

The invention consists in the foregoing and also envisages constructions of which the following gives examples only.

20 BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will be described by way of example only and with reference to the drawings, in which:

25 **Figure 1** is a schematic diagram of a first preferred form of the interferometric ellipsometer of the present invention;

Figure 2 is a schematic diagram of a second preferred form of the interferometric ellipsometer of the present invention;

30 **Figure 3** is a schematic diagram of a third preferred form of the interferometric ellipsometer of the present invention;

Figure 4 is a schematic diagram of a fourth preferred form of the interferometric ellipsometer of the present invention;

Figure 5 is a schematic diagram of a fifth preferred form of the interferometric ellipsometer of the present invention;

Figure 6 is a graph showing a comparison of expected ellipsometric angles and measured ellipsometric angles obtained with an interferometric ellipsometer of the present invention

5 for a sample of silicon dioxide film on a silicon substrate;

Figure 7 is a graph showing a comparison of expected ellipsometric angles and measured ellipsometric angles obtained with an interferometric ellipsometer of the present invention for a sample of BK7 glass sample; and;

10 Figure 8 is a graph showing the observed noise for a straight-through measurement of ellipsometric angles obtained with an interferometric ellipsometer of the present invention for air with no sample present.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

15 The present invention is an interferometric ellipsometer for measuring ellipsometric parameters of samples such as, for example but not limited to, semiconductor wafers and optical components. It will be appreciated that other suitable specimens could also be measured with the ellipsometer instrument. The ellipsometer only requires a single reflection from the sample and this characteristic makes it suitable for interrogating
20 samples having relatively low reflectivity in addition to those having higher reflectivity.

At a broad level, the ellipsometer comprises a light source that is arranged to direct a light beam at the surface of the sample, an interferometer that receives and modifies the reflected light beam, and an output detector that is arranged to detect and generate signals
25 representing the p- and s-components of the polarised output beam from the temporal fringes produced by the interferometer. The p- and s-component signals can then be processed to extract ellipsometric parameters, such as the angles ψ and Δ , of the sample. In one preferred form, the interferometer is arranged to split the reflected light beam into two beams or signals for its measurement and reference arms. The split beam of the
30 reference arm passes through an optical system to generate a reference beam which is then recombined with the remaining split beam of the measurement arm at the output of the interferometer to produce a beam with temporal fringes. The fringes can give directly the state of polarisation of the reflected light from the sample via interrogation of the p- and s-

components of the output beam. The ellipsometer creates the temporal fringes at the output of the interferometer either by creating a time-varying difference between the beams of the measurement and reference arms or by creating a heterodyne signal via a frequency shifting component. The time-varying difference may be generated by a time-varying component at the light source or in the interferometer. For example, the light source may be modulated in wavelength or a mechanical scanning or translation device may be provided in the interferometer to time-vary either beam of the measurement or reference arms. The frequency difference may be created by an acousto-optic or electro-optic modulator in either arm of the interferometer.

First preferred form interferometric ellipsometer

Referring to Figure 1, a first preferred form of the interferometric ellipsometer 100 will be described. The ellipsometer 100 includes a light source 12 that is arranged to direct an incident light beam 14 onto the surface of a sample 16 that is being measured. The light source 12 may be, for example, a laser or any other optical source for generating a light beam. The light source 12 can be arranged to direct light at any desired wavelength or wavelengths in the electromagnetic spectrum, including ultraviolet, visible, near infrared, and infrared. The light beam 14 from the light source 12 incident on the sample 16 is reflected once from the sample and the reflected light beam 18 is arranged to enter an interferometer 20. The angle of incidence of the light beam 14 is determined by, for example, a goniometer 17 or other angle measurement device associated with the sample 16.

In the first preferred form, the interferometer 20 is provided with a beam splitter 22 at the input that is arranged to split the reflected light beam 18 into two beams 24 and 26. Preferably, the beam splitter 22 is a neutral beam splitter that is non-polarising and is arranged to split the reflected light beam 18 into two beams 24, 26 having equal amplitude components. Upon exiting the input beam splitter 22, split beam 24, known as the measurement beam, is arranged to travel down the measurement arm of the interferometer 20 directly to an output beam splitter 28, which is also preferably a neutral beam splitter that is non-polarising. The other split beam 26 is arranged to travel down a reference arm of the interferometer 20. The reference arm of the interferometer 20 comprises an optical

system having one or more optical components that modify split beam 26 into a suitable reference beam 30 for recombining with the measurement beam 24 at the output beam splitter 28 so as to produce an output beam 42 having polarization fringes representative of the reflected beam 18 from the sample.

5

The optical system of the reference arm of the interferometer 20 will now be described in more detail. The optical component or components of the optical system are arranged to generate a reference beam 30 having p- and s-components or polarisations that have a common phase and a fixed relative amplitude. The reference beam 30 has p- and s-
10 polarisations with a common phase and fixed relative amplitude so as to allow these common factors to cancel out when calculating the ellipsometric angles from the ratio of the p- and s-components of the output beam 42 after interference at output beam splitter 28. The optical system in the reference arm is arranged such that a suitable reference beam having p- and s-polarisations with common phase and fixed relative amplitude can be
15 generated from split beam 26 from input beam splitter 22 irrespective of the sample 16. In other words, the reference arm is arranged to generate a suitable reference beam having p- and s-polarisations with common phase and fixed relative amplitude from the split beam 26, regardless of the polarisation of the reflected beam 18 from the sample.

20 By way of example, in the optical system of the reference arm of interferometer 20, the split beam 26 first encounters a first reflecting surface or component 36 that is arranged to reflect or guide the beam toward a second reflecting surface or component 40. The reflecting surfaces 36,40 may be mirrors or the like, and the mirrors may be planar for example. The split beam 26 is then reflected from the second mirror 40 through a
25 polariser 38 and toward the output beam splitter 28. The polariser 38 is preferably oriented with its transmission axis at approximately 45° with respect to the plane of incidence (the reference plane), although this does not necessarily have to be accurately set and may be varied to other angles if desired. It will be appreciated that the plane of incidence is the plane spanned by the incident 14 and reflected 18 beams and contains the normal to the
30 surface of the sample 16.

In the first preferred form, the second mirror 40 is mounted or fixed to a translation or scanning device, such as a piezoelectric transducer 41 or the like, that is arranged to

translate in a linear fashion at a constant speed to generate a time-varying difference between the beams 24,30 of the measurement and reference arms. This creates the necessary heterodyne signal having temporal fringes in the output beam 42. It will be appreciated that the first mirror 36 may alternatively be mechanically scanned by the piezoelectric transducer if desired. Further, it will be appreciated that the split beam 24 in the measurement arm may alternatively be time-varied in a similar fashion in other arrangements. In other alternative forms, it will be appreciated that time-varying difference between the beams or signals of measurement and reference arms may be provided by modulating the laser wavelength of the light source 12. In other alternative forms, it will be appreciated that a suitable heterodyne signal may also be produced by placing an acousto-optic or electro-optic modulator in one of the arms of the interferometer 20 to create a frequency-difference via frequency-shifting. It will be appreciated that any other form of heterodyne signal generating component or means could alternatively be used in the ellipsometer to create temporal fringes in the output beam.

As mentioned, the optical system in the reference arm of the interferometer 20 is arranged to modify the split beam 26 into a suitable reference beam 30 for recombining with the measurement beam 24 to produce an output beam with fringes. As will be demonstrated in the theory section of this specification below, the effect of the optical system in the reference arm, when the polariser 38 is set at 45°, is to provide a polarised reference beam of the form:

$$\alpha \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

where α is a complex term that is common to both the p- and s-polarisations of the reference beam 30. In other words, the amplitude and phase of the p- and s-polarisations of the reference beam 30 are common. The effect of the optical system in the reference arm, when polariser 38 is set at some arbitrary azimuthal angle P, is to provide a polarised reference beam of the form:

$$\alpha \begin{bmatrix} \cos P \\ \sin P \end{bmatrix}$$

In other words, the p- and s-polarisations of the reference beam 30 have a common phase and fixed relative amplitude as previously mentioned.

As mentioned, a neutral beam splitter 28 is provided at the output of the interferometer 20.

5 The output beam splitter 28 is arranged to combine split beam 24 (measurement beam) from the measurement arm and the reference beam 30 from the reference arm into an output beam 42 having temporal p- and s-fringes. The ellipsometer 100 comprises an output detector 44 that is arranged to detect the output beam 42 from the interferometer 20 and output signals 46 representing the p- and s-components of the output beam. These
10 can then be converted into digital signals for processing by, for example, a control system such as a computer 48 or other programmable device or microprocessor, which may form part of the control system of the ellipsometer. By way of example, the p- and s-component signals, which represent the p- and s-fringes, may be processed to extract ellipsometric parameters such as, for example, the ellipsometric angles ψ and Δ from which physical
15 properties of the sample specimen 16 can be determined in a manner known to a skilled person in the art.

In the preferred form, the output detector 44 may comprise a Wollaston prism 50 for separating the polarised output beam 42 into its p- and s-components. It will be
20 appreciated that a polarising beam splitter cube or other optical component capable of separating the output beam into its p- and s-components could alternatively be used instead of the Wollaston prism 50. The p- and s-components of the light emanating from the Wollaston prism 50 are then sensed by respective optical detectors, such as photodetectors 52,54 or the like, that are arranged to convert the p- and s-component light
25 beams into electrical output signals for processing. In the preferred form, the output signals are converted by an analogue-to-digital converter into digital signals for processing by a computer or other processor to generate the measured ellipsometric parameters of the sample.

30 Other alternative forms of the interferometric ellipsometer will now be described. Like components are referenced by like numerals. The alternative forms utilise modified interferometer designs relative to the first preferred form ellipsometer 100 but the light source and output detector remain substantially the same. The alternative components

mentioned in respect of the first preferred form may also be employed in the alternative forms of the ellipsometer.

Second preferred form interferometric ellipsometer

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The first preferred form of the ellipsometer 100 does not particularly lend itself to spectroscopic measurements with low coherence sources in view of the unbalanced nature of the measurement and reference arms of the interferometer 20. However, the components of the interferometer may be rearranged to balance the measurement and reference arms as shown in the second preferred form of the ellipsometer 200 of Figure 2 to produce an instrument that is better suited to spectroscopic work.

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The second preferred form of ellipsometer 200 may employ a broadband light source 120 such as a light bulb or any other appropriate broadband light source that is capable of generating a broadband light beam 140 for directing at the sample 16. The interferometer 220 of the ellipsometer 200 is rearranged such that split beam 24 is guided via the first reflecting surface 36 to the output beam splitter 28 in the measurement arm. Further, the reference arm is modified such that split beam 26 is reflected from the second reflecting surface 40 toward and through the polariser 38 to the output beam splitter 28. As before, the split beam 26 is converted into the reference beam 30 after it passes through the polariser 38. The reference beam 30 is then recombined with split beam 24 (measurement beam) at the output beam splitter 28. As shown, the second reflecting surface 40, such as a mirror or the like, is coupled to a piezo-electric transducer 41 to create the time-varying difference between the beams of the reference and measurement beams. It will be appreciated that the piezo-electric transducer may alternatively be coupled to the first reflecting surface 36 in the measurement arm or that any other alternative means of generating the necessary heterodyne signal mentioned in respect of the first preferred form may be used. With this interferometer 220 configuration, the reference and measurement arm are balanced with similar or substantially equal optical path lengths and therefore the ellipsometer 200 is more suited to spectroscopic work.

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Third preferred form interferometric ellipsometer

Referring to Figure 3, the third preferred form of the ellipsometer 300 comprises a modified interferometer 320 having fewer components than the first 100 and second 200 forms but with the same measurement functionality and principle of operation.

- 5 The interferometer 320 in the third preferred form comprises a single neutral input/output beam splitter 280 that is arranged to divide the light beam 18 reflected by the sample 16 into two equal split beams 24,26. The first split beam 24 (measurement beam) is reflected directly toward the Wollaston prism 50 of the output detector 44. The second split beam 26 is guided through the polariser 38 and converted into the reference beam 30. As before, the polariser is preferably oriented at 45° with respect to the place of incidence. The reference beam 30 is then redirected back toward the input/output beam splitter 24 by an arrangement of reflecting surfaces or components.

- 15 In the preferred form, the reference beam 30 may first encounter an arrangement of two separate reflecting surfaces 36a,36b, such as mirrors or the like, that are arranged to reflect the incoming reference beam 30 back toward the input/output beam splitter 24 in a path parallel to the incoming reference beam. For example, the two reflecting surfaces may be oriented at right angles with respect to each other. In alternative forms, the reflecting surfaces 36a,36b may be replaced by a corner cube reflector, prism, or any other suitable reflecting arrangements or components. Once reflected from the reflecting surfaces 36a,36b, the reference beam 30 travels toward a second reflecting surface 40. The second reflecting surface 40 is arranged to reflect the reference beam 30 into the input/output beam splitter 24 for recombining with the measurement beam 24 to generate the output beam 42 having temporal fringes for detection by the output detector 44. In the preferred form, the first reflecting surfaces 36a,36b are fixed or mounted to the piezoelectric transducer 41 to generate a time-varying difference between the measurement and reference beams 24,30 as before. However, it will be appreciated that the piezoelectric transducer could be provided on the second reflecting surface 40 or that any of the other alternative forms mentioned for generating the necessary heterodyne signal having temporal fringes in the output beam 42 could be used.

Fourth preferred form interferometric ellipsometer

Referring to Figure 4, the fourth preferred form of the ellipsometer 400 is similar to the first preferred form shown in Figure 1. The difference is that the interferometer 420 is provided with additional optical components in the reference arm. In particular, the interferometer 420 comprises a second polariser 32 after the input beam splitter 22 in addition to the first polariser 38. The second polariser 32 is preferably set or oriented with its transmission axis at an angle of approximately 90° with respect to the reference plane or alternatively it may be set at an angle of approximately 0° . An optional half- or quarter-wave plate 34 is also provided after the first reflecting surface 36. The half- or quarter-wave plate 34 is arranged to rotate the polarisation caused by the additional polariser 32 in order to provide better fringe visibility, although the half- or quarter-wave plate 34 is not essential to the optical system.

Fifth preferred form interferometric ellipsometer

Referring to Figure 5, the fifth preferred form of the ellipsometer 500 is similar to the second preferred form shown in Figure 2. The difference is that the interferometer 520 is provided with additional optical components in the reference arm as described with respect to the fourth preferred form. In particular, the interferometer 520 comprises a second polariser 32 after the input beam splitter 22 in addition to the first polariser 38. Again, the polariser 32 is preferably set at an angle of approximately 90° with respect to the reference plane or alternatively it may be set at an angle of approximately 0° . Also, an optional half- or quarter-wave plate 34 is provided after the second reflecting surface 40 before polariser 38. The purpose of the additional polariser 32 and half- or quarter-wave plate 34 is the same as that described above.

Theory

The theory behind the design and operation of the first preferred form ellipsometer 100 will now be described, although this theory applies generally to all forms of the ellipsometer. For complete generality, it is assumed that the input light is elliptically polarized, with azimuthal angle θ and ellipticity ε . For convenience, it will be assumed that the ellipsometer instrument employs a time-varying component to create the temporal

fringes and in which polariser 38 is set to 45° . Consider first the case when there is no sample, that is, the light enters the interferometer directly. This step will serve as the calibration step. Using Jones' matrix algebra, the input state may be written as:

$$\begin{aligned}
 E_{in} &= \begin{bmatrix} \cos\theta\cos\varepsilon - i\sin\theta\sin\varepsilon \\ \sin\theta\cos\varepsilon + i\cos\theta\sin\varepsilon \end{bmatrix} \\
 &= \begin{bmatrix} u\exp(i\xi) \\ v\exp(i\eta) \end{bmatrix}
 \end{aligned} \tag{1}$$

where u , v , ξ and η represent the polar components of the input state as this form will be more convenient. The first beam splitter 22 creates two equal amplitude beams; the measurement beam E_m and the beam which will become the reference beam, E_r . Using the appropriate Jones' matrix algebra for each of the components in the two paths we have, for E_m :

$$\begin{aligned}
 E_m &= \frac{1}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} E_{in} \exp(i\phi_1) \\
 &= \frac{1}{2} \begin{bmatrix} u\exp(i\xi) \\ v\exp(i\eta) \end{bmatrix} \exp(i\phi_1)
 \end{aligned} \tag{2}$$

where ϕ_1 is the phase acquired by this beam in travelling to the second beam splitter 28.

As an intermediate step, the Jones' matrix for a polariser at 45° is given by:

$$P_{45} = R\left(-\frac{\pi}{4}\right) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R\left(\frac{\pi}{4}\right) = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \tag{3}$$

where $R(\varphi)$ is the rotation matrix for angle φ . For E_r , we have:

$$\begin{aligned}
E_r &= \frac{1}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} r_p^M & 0 \\ 0 & r_s^M \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} E_m \exp(i\phi_2) \\
&= \frac{1}{4} (r_p^M u \exp(i\xi) + r_s^M v \exp(i\eta)) \begin{bmatrix} 1 \\ 1 \end{bmatrix} \exp(i\phi_2) \\
&= \frac{1}{2} \frac{w}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \exp(i\phi_2)
\end{aligned} \tag{4}$$

where ϕ_2 is the time-varying phase, for example produced by the linear motion of the second mirror 40, acquired by E_r in travelling to the second beam splitter 28. For the first preferred form ellipsometer 100, r_p^M and r_s^M represent the combined effect of the reflections from the first 36 and second 40 mirrors. For the second preferred form ellipsometer 200, the effect of the mirrors 36,40 is clearly split between the measurement and reference arms, but this does not affect the principle of operation in any way. $w = r_p^M u \exp(i\xi) + r_s^M v \exp(i\eta)$ is a complex number whose magnitude and phase are common to both p- and s-polarisations.

At the output of the interferometer 20, the Wollaston prism 50 of the output detector 44 separates the output beam 42 into its p- and s-polarised components. Interference causes temporal fringes at the heterodyne frequency for each of these components at their respective photodetectors 52,54. The photocurrents for the p- and s-polarised components are given by:

$$I_p \propto u^2 + \frac{|w|^2}{4} + u|w| \cos(\omega_0 t + \xi) \tag{5}$$

$$I_s \propto v^2 + \frac{|w|^2}{4} + v|w| \cos(\omega_0 t + \eta) \tag{6}$$

where $\omega_0 t = \phi_2(t) - \phi_1$ is the temporal fringe frequency.

The ratio of the ac components of these two signals yields the calibration quantities:

$$V_r^c = \left(\frac{v_p}{v_s} \right)^{ac} = \frac{k_p u}{k_s v} \tag{7}$$

$$\Delta\phi^c = \arg(v_p)^{ac} - \arg(v_s)^{ac} = \xi - \eta \quad \dots(8)$$

where k_p, k_s are constants that encapsulate the losses at the mirrors and beam splitters,
 5 the electric field amplitude, and the optical-to-voltage conversion process.

When the light is reflected from a sample 16, E_{in} becomes:

$$E_{in} \rightarrow \begin{bmatrix} r_p u \exp(i[\xi + \delta_p]) \\ r_s v \exp(i[\eta + \delta_s]) \end{bmatrix} \quad (9)$$

The beam in the reference arm now becomes:

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$$\begin{aligned} E_r &\rightarrow \frac{1}{4} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} r_p^M |r_p| u \exp(i[\xi + \delta_p]) \\ r_s^M |r_s| v \exp(i[\eta + \delta_s]) \end{bmatrix} \\ &= \frac{1}{4} \left(r_p^M |r_p| u \exp(i[\xi + \delta_p]) + r_s^M |r_s| v \exp(i[\eta + \delta_s]) \right) \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (10) \\ &= \frac{1}{2} \frac{z}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \end{aligned}$$

where $z = (r_p^M |r_p| u \exp(i[\xi + \delta_p]) + r_s^M |r_s| v \exp(i[\eta + \delta_s]))$ is a complex number whose
 magnitude and phase are common to both p- and s-polarisations. The photocurrents are

15 now:

$$I_p \propto u^2 |r_p|^2 + \frac{|z|^2}{4} + u |r_p| |z| \cos(\omega_0 t + \xi + \delta_p) \quad (11)$$

$$I_s \propto v^2 |r_s|^2 + \frac{|z|^2}{4} + v |r_s| |z| \cos(\omega_0 t + \eta + \delta_s) \quad (12)$$

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The ratio of the ac components will be:

$$V_r^m = \frac{k_p}{k_s} \frac{u|r_p|}{v|r_s|} = \tan \psi V_r^c \quad (13)$$

and the relative phase

$$\Delta\phi^m = \xi + \delta_p - \eta - \delta_s = \Delta\phi^c - \Delta \quad (14)$$

Equations (13) and (14) allow ellipsometric angles ψ and Δ to be readily determined from the calibration and measurements ratios and phases according to:

$$\tan \psi = \frac{|r_p|}{|r_s|} = \frac{V_r^m}{V_r^c} \quad (15)$$

$$\Delta = \delta_{rp} - \delta_{rs} = \Delta\phi^c - \Delta\phi^m \quad (16)$$

Experimental Results

A prototype of the ellipsometer instrument of Figure 1 has been built and results of some experimental trials with the prototype are described below. These experimental results are to demonstrate the capability of the ellipsometer instrument by way of example only and it will be appreciated that the capability of the ellipsometer instrument is not necessarily limited to these experimental results.

Measurements were made in 5° steps from 45° to 85° angle of incidence (AOI) on two representative samples: a silicon dioxide film on a silicon substrate (Figure 6) and a BK7 glass surface (Figure 7). A He-Ne laser ($\lambda = 632.8\text{nm}$) was used as the light source. The photodetector outputs were sampled by a 16 bit A-to-D card and a direct, least squares algorithm was used to fit the ellipse formed when V_s is plotted against V_p [18]. The algorithm returns the geometric parameters of the ellipse that were subsequently used to calculate the voltage ratio and phase difference. The fringe frequency was arbitrarily set to approximately 320Hz and each pair of $(\tan \psi, \Delta)$ values obtained by averaging 50 consecutive fringes.

Referring to Figure 6, a reference wafer was used to establish the accuracy of the interferometric ellipsometer. The accompanying calibration certificate gives the oxide thickness, as measured by a Plasmos ellipsometer, as 102.73nm. The solid curves in Figure 6 show the calculated values for $\tan\psi$ and Δ as a function of angle of incidence for an oxide layer of this thickness. The open symbols, which are the experimentally measured values, are seen to be in good agreement with their expected values. The oxide thickness that best fits the experimental data was found by numerically minimizing the error function [1]:

$$\varepsilon = \sum_{AOI} \left[(\rho^m - \rho^c)^2 + (\Delta^m - \Delta^c)^2 \right] \quad (17)$$

Where $\rho = \tan\psi$ and superscripts m and c represent the measured and calculated quantities, respectively. The best fit value for the oxide thickness was accordingly found to be 102.25nm, which was in good agreement with the certificate value.

Referring to Figure 7, a polished BK7 glass surface was measured as this is representative of substrates that are difficult to measure with known interferometric ellipsometers that employ a double reflection from the sample, especially near the Brewster angle. In particular, BK7 glass has a low reflectivity. Figure 7 shows experimental values for $\tan\psi$ and Δ as a function of angle of incidence. The solid curves were obtained by assuming the surface was covered with a thin film of water and by using the error function (17) above to find the optimal film thickness, which was 2.2nm. Note that even close to the Brewster angle of 56.57°, $\tan\psi$ and Δ are readily measured with the ellipsometer instrument.

Referring to Figure 8, repeated measurements were made with the ellipsometer instrument with no sample at a fixed AOI of 90° to establish the precision of the instrument. In particular, the instrument was also placed in its straight-through configuration with no sample, and $\tan\psi$ and Δ were measured repeatedly every 2s for 1 minute. The resulting series is plotted in Figure 8. The estimated uncertainties are $\sigma_{\tan\psi} = 5.4 \times 10^{-4}$ and $\sigma_{\Delta} = 0.024^\circ$. If it is assumed that noise in Δ is due to variations in the optical path length difference of the interferometer arms, then precision for the “air” samples is ~41pm.

Summary of benefits and advantages

By way of example only, the ellipsometer instrument of the present invention may, in some embodiments, offer one or more of the following characteristics:

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1. The ellipsometer may have an inherent reference condition. A measurement in the straight through position allows one to determine V_r^c and $\Delta\phi^c$.

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2. Alignment of the light beam from the light source can be performed with interferometric precision. The amplitude of the temporal fringes provides immediate feedback about the beam alignment which can be done with very high precision.

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3. Data acquisition is fast and is limited only by the rate at which the beam can be modulated. If this is done electronically, rates of a few MHz can be easily achieved; if it is done mechanically, for example via the piezoelectric transducer mounted to one of the mirrors, it may be limited to a few kHz.

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4. The ellipsometer requires only a single reflection from the sample. This is advantageous when measuring samples having low reflectivity.

5. The sample may be mounted at (almost) any angle of incidence. There is typically no inherent restriction, apart from mechanical ones, that limit the range of incidence angles.

6. The ellipsometer can be broadband. The beam splitters and polarisers can all be broadband optical components. The design does not necessarily require any waveplates and is thus inherently broadband. It can therefore be adapted to suit spectroscopic work.

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7. The light source does not need to be modulated if mechanical scanning of one of the mirrors is used.

8. None of the optical components needs to be actively rotated.

The foregoing description of the invention includes preferred forms thereof. Modifications may be made thereto without departing from the scope of the invention as defined by the accompanying claims.

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CLAIMS

1. An interferometric ellipsometer for measuring ellipsometric parameters of a sample, comprising:
 - 5 a light source that is arranged to direct a light beam onto the sample for reflection;
 - an interferometer that is arranged to receive and split the reflected light beam from the sample into two beams, one split beam being modified by an optical system to generate a reference beam that has p- and s-polarisations with a common phase and with a fixed relative amplitude and which is recombined with the remaining split beam to generate an
 - 10 output beam having temporal p- and s-fringes; and
 - an output detector that is arranged to detect the output beam and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.
- 15 2. An interferometric ellipsometer according to claim 1 wherein the interferometer comprises:
 - an input beam splitter that is arranged to split the reflected light beam from the sample into two beams;
 - a measurement arm following the input beam splitter down which one split beam
 - 20 travels;
 - a reference arm following the input beam splitter down which the other split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a reference beam that has p- and s-polarisations with common phase and fixed relative amplitude; and
 - 25 an output beam splitter that is arranged to combine the split beam from the measurement arm and the reference beam from the reference arm to generate an output beam having temporal p- and s-fringes.
- 30 3. An interferometric ellipsometer according to claim 2 wherein the optical system of the reference arm of the interferometer comprises a first polariser having its transmission axis at approximately 45° with respect to the plane of incidence.

4. An interferometric ellipsometer according to claim 3 wherein the optical system of the reference arm of the interferometer comprises a second polariser prior to the first polariser in the reference arm, the second polariser having its transmission axis at approximately 90° .

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5. An interferometric ellipsometer according to claim 4 wherein the optical system of the reference arm comprises a wave plate between the first and second polarisers in the reference arm that is arranged to rotate the polarization of the split beam in the reference arm to provide enhanced fringe visibility in the output beam of the interferometer.

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6. An interferometric ellipsometer according to claim 5 wherein the wave plate is a half-wave plate.

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7. An interferometric ellipsometer according to claim 3 wherein the optical system of the reference arm of the interferometer comprises a second polariser prior to the first polariser in the reference arm, the second polariser having its transmission axis at approximately 0° .

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8. An interferometric ellipsometer according to claim 7 wherein the optical system of the reference arm comprises a wave plate between the first and second polarisers in the reference arm that is arranged to rotate the polarization of the split beam in the reference arm to provide enhanced fringe visibility in the output beam of the interferometer.

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9. An interferometric ellipsometer according to claim 8 wherein the wave plate is a quarter wave-plate.

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10. An interferometric ellipsometer according to any one of claims 2-9 wherein the reference arm of the interferometer comprises one or more reflecting surfaces that guide the split beam of the reference arm from input beam splitter, through the optical system of the reference arm, to the output beam splitter.

11. An interferometric ellipsometer according to any one of claims 2-10 wherein the measurement arm of the interferometer comprises one or more reflecting surfaces that guide the split beam of the measurement arm from the input beam splitter to the output beam splitter.
- 5
12. An interferometric ellipsometer according to claim 10 or claim 11 wherein the reflecting surfaces are mirrors.
13. An interferometric ellipsometer according to claim 1 wherein the interferometer
- 10 comprises:
- a beam splitter that is arranged to split the reflected light beam from the sample into two beams; and
- a reference arm following the beam splitter down which one split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a
- 15 reference beam that has p- and s-polarisations with common phase and fixed relative amplitude, the reference arm also being arranged to direct the reference beam back into the beam splitter for recombining with the other split beam to generate an output beam having temporal p- and s-fringes.
- 20
14. An interferometric ellipsometer according to claim 13 wherein the optical system of the reference arm of the interferometer comprises a polariser having its transmission axis at approximately 45° with respect to the plane of incidence.
15. An interferometric ellipsometer according to claim 13 or claim 14 wherein the
- 25 reference arm of the interferometer comprises an arrangement of reflecting surfaces that guide the split beam of the reference arm from beam splitter, through the optical system of the reference arm, and back to the beam splitter.
16. An interferometric ellipsometer according to claim 15 wherein the reflecting surfaces
- 30 are mirrors
17. An interferometric ellipsometer according to claim 13 or claim 14 wherein the reference arm of the interferometer comprises an arrangement of reflecting

components that guide the split beam of the reference arm from beam splitter, through the optical system of the reference arm, and back to the beam splitter.

- 5 18. An interferometric ellipsometer according to claim 17 wherein the reflecting components are selected from any one or more of the following: mirrors, corner cube reflectors, and prisms.
- 10 19. An interferometric ellipsometer according to any one of the preceding claims further comprising a time-varying component that is arranged to create a time-varying difference between the split beams of the measurement and reference arms to thereby generate an output beam having temporal fringes at the output of the interferometer.
- 15 20. An interferometric ellipsometer according to claim 19 wherein the time-varying component is provided at the light source.
- 20 21. An interferometric ellipsometer according to claim 20 wherein the time-varying component is a modulation component in the light source that is arranged to modulate the wavelength of the light beam directed at the sample to thereby create the time-varying difference.
- 25 22. An interferometric ellipsometer according to claim 19 wherein the time-varying component is provided in either arm of the interferometer.
- 30 23. An interferometric ellipsometer according to claim 22 wherein the time-varying component is a mechanical scanning device that is mounted to a reflecting surface in either of the measurement or reference arms of the interferometer, the mechanical scanning device being arranged to translate in a linear fashion at a constant speed to thereby create the time-varying difference in the split beam travelling in that that arm.
24. An interferometric ellipsometer according to any one of claims 1-18 further comprising a frequency-shifting component that is arranged to create a frequency-difference between the split beams of the measurement and reference arms to thereby

generate an output beam heterodyne signal having temporal fringes at the output of the interferometer.

25. An interferometric ellipsometer according to claim 24 wherein the frequency-shifting component is an acousto-optical modulator provided in either of the reference or measurement arms of the interferometer, the acousto-optical modulator being arranged to shift the source frequency of the split beam in that arm thereby generating a frequency difference for creating an output beam heterodyne signal with temporal fringes at the output of the interferometer.

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26. An interferometric ellipsometer according to claim 24 wherein the frequency-shifting component is an electro-optical modulator provided in either of the reference or measurement arms of the interferometer, the acousto-optical modulator being arranged to shift the source frequency of the split beam in that arm thereby generating a frequency difference for creating an output beam heterodyne signal with temporal fringes at the output of the interferometer.

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27. An interferometric ellipsometer according to any one of the preceding claims wherein the light source is arranged to generate a light beam that has a wavelength falling within any of the following bands: ultraviolet, visible, near infrared, or infrared.

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28. An interferometric ellipsometer according to any one of claims 1- 26 wherein the light source is arranged to generate a broadband light beam to enable spectroscopic measurements of the ellipsometric parameters.

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29. An ellipsometer according to any one of the preceding claims wherein the output detector comprises: a Wollaston prism for separating the output beam from the interferometer into its p- and s-component beams; and first and second optical detectors that are arranged to sense the respective p- and s-component beams and generate output signals representing the amplitude and phase of the p- and s-components of the output beam.

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30. An ellipsometer according to any one claims 1-28 wherein the output detector comprises: a polarising beam splitter cube for separating the output beam from the interferometer into its p- and s-component beams; and first and second optical detectors that are arranged to sense the respective p- and s-component beams and generate output signals representing the amplitude and phase of the p- and s-components of the output beam.
31. An ellipsometer according to claim 29 or claims 30 wherein the optical detectors are photodetectors.
32. An ellipsometer according to any one of the preceding claims further comprising a control system that is arranged to receive and process the p- and s-component signals from the output detector to thereby generate ellipsometric parameters from which physical properties of the sample specimen can then be determined.
33. A method for measuring the ellipsometric parameters of a sample comprising the steps of:
- directing a light beam onto the sample for reflection;
 - splitting the reflected light beam from the sample into two beams;
 - modifying one of the split beams with an optical system to generate a reference beam having p- and s-polarisations with common phase and fixed relative amplitude;
 - recombining the reference beam with the remaining split beam to generate an output beam having temporal p- and s-fringes;
 - detecting the p- and s-components of the output beam; and
 - generating signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.
34. A method according to claim 33 wherein the step of splitting the reflected light beam from the sample into two beams comprises providing a beam splitter in the path of the reflected light beam.
35. A method according to claim 33 or claim 34 wherein the step of splitting the reflected beam from the sample further comprises providing a measurement arm down which

one split beam travels and a reference arm down which the other split beam travels, the reference arm having an optical system that is arranged to modify the split beam into a reference beam that has p- and s-polarisations with common phase and fixed relative amplitude.

5

36. A method according to any one of claims 33-35 wherein the step of modifying one of the split beams into a reference beam comprises providing an optical system in the path of the split beam that comprises a polariser having its transmission axis at approximately 45° with respect to the plane of incidence.

10

37. A method according to any one of claims 33-36 wherein the step of recombining the reference beam with the remaining split beam to generate an output beam having temporal p- and s-fringes comprises providing a beam splitter in the path of the beams.

15

38. A method according to any one of claims 33-37 wherein the step of directing a light beam onto the sample for reflection comprises directing light that has a wavelength falling within any of the following bands: ultraviolet, visible, near infrared, or infrared.

20

39. A method according to any one of claims 33-37 wherein the step of directing a light beam onto the sample for reflection comprises directing broadband light to enable spectroscopic measurements of the ellipsometric parameters.

25

40. A method according to any one of claims 33-39 further comprising the step of generating a time-varying difference between the split beams such that the output beam has temporal fringes when the beams are recombined.

30

41. A method according to any one of claims 33-39 further comprising the step of generating a frequency-difference between the split beams such that the output beam heterodyne signal has temporal fringes when the beams are recombined.

42. An interferometric ellipsometer for measuring ellipsometric parameters of a sample, comprising:

a light source that is arranged to direct a light beam onto the sample for reflection from the sample once;

an interferometer that is arranged to receive and modify the single reflected light beam from the sample into an output beam having temporal p- and s-fringes; and

5 an output detector that is arranged to detect the output beam and output signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.

10 43. A method for measuring the ellipsometric parameters of a sample comprising the steps of:

directing a light beam onto the sample for reflection from the sample once;

providing an interferometer that is arranged to receive and modify the single reflected light beam from the sample into an output beam having temporal p- and s-fringes;

detecting the p- and s-components of the output beam; and

15 generating signals representing the p- and s-components of the output beam from which the ellipsometric parameters of the sample can be determined.

44. An interferometer for use in a system for measuring ellipsometric parameters of a sample, the interferometer being arranged to:

20 receive a light beam that has been reflected from the sample once;

modify the received light beam into an output beam having temporal p- and s-fringes; and

output the output beam.

25 45. An interferometer according to claim 44 that is arranged to receive and split the reflected light beam from the sample into two beams, one split beam being modified by an optical system to generate a reference beam that has p- and s-polarisations with a common phase and with a fixed relative amplitude and which is recombined with the remaining split beam to generate the output beam having temporal p- and s-

30 fringes.

46. An interference method for performing on a light beam reflected from a sample once in a system for measuring ellipsometric parameters of that sample, the method comprising the steps of:
- receiving the reflected light beam from the sample;
- 5 modifying the received light beam into an output beam having temporal p- and s-fringes; and
- outputting the output beam.
47. An interference method according to claim 46 wherein the step of modifying the
- 10 received light beam comprises:
- splitting the light beam into two beams;
- modifying one of the split beams with an optical system to generate a reference beam having p- and s-polarisations with common phase and fixed relative amplitude; and
- recombining the reference beam with the remaining split beam to generate the output
- 15 beam having temporal p- and s-fringes.

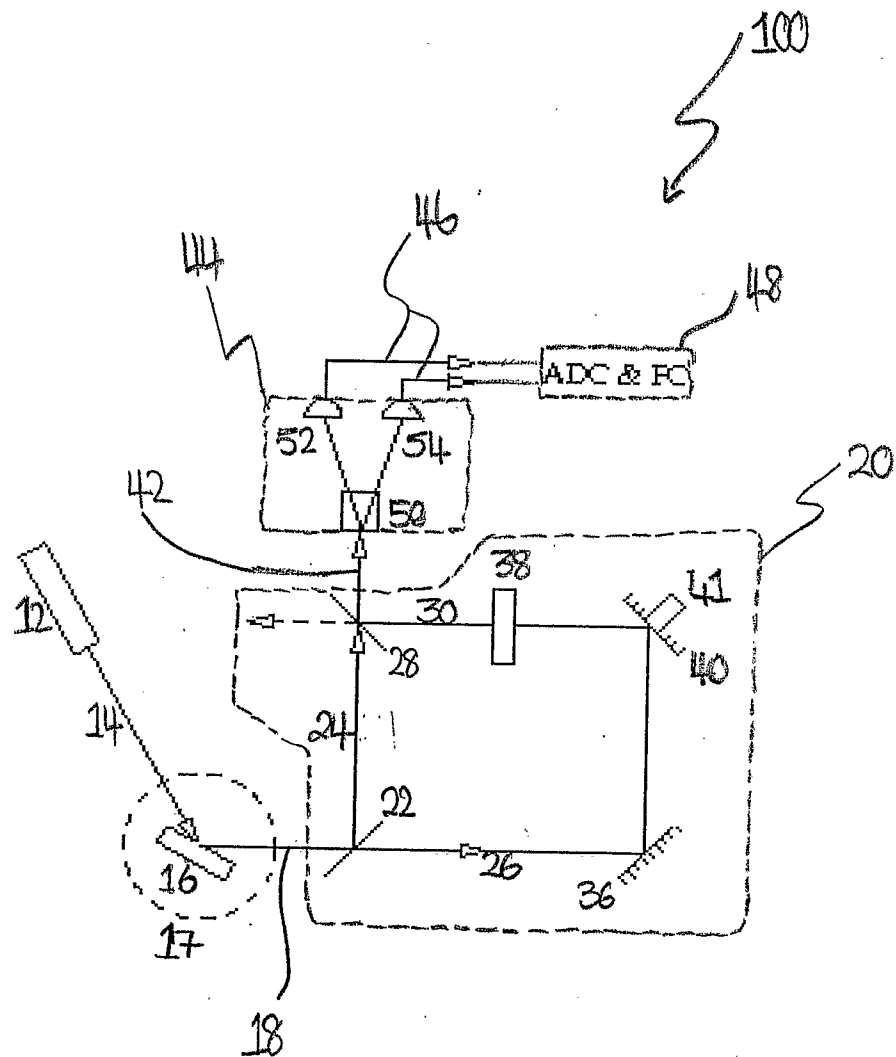


FIGURE 1

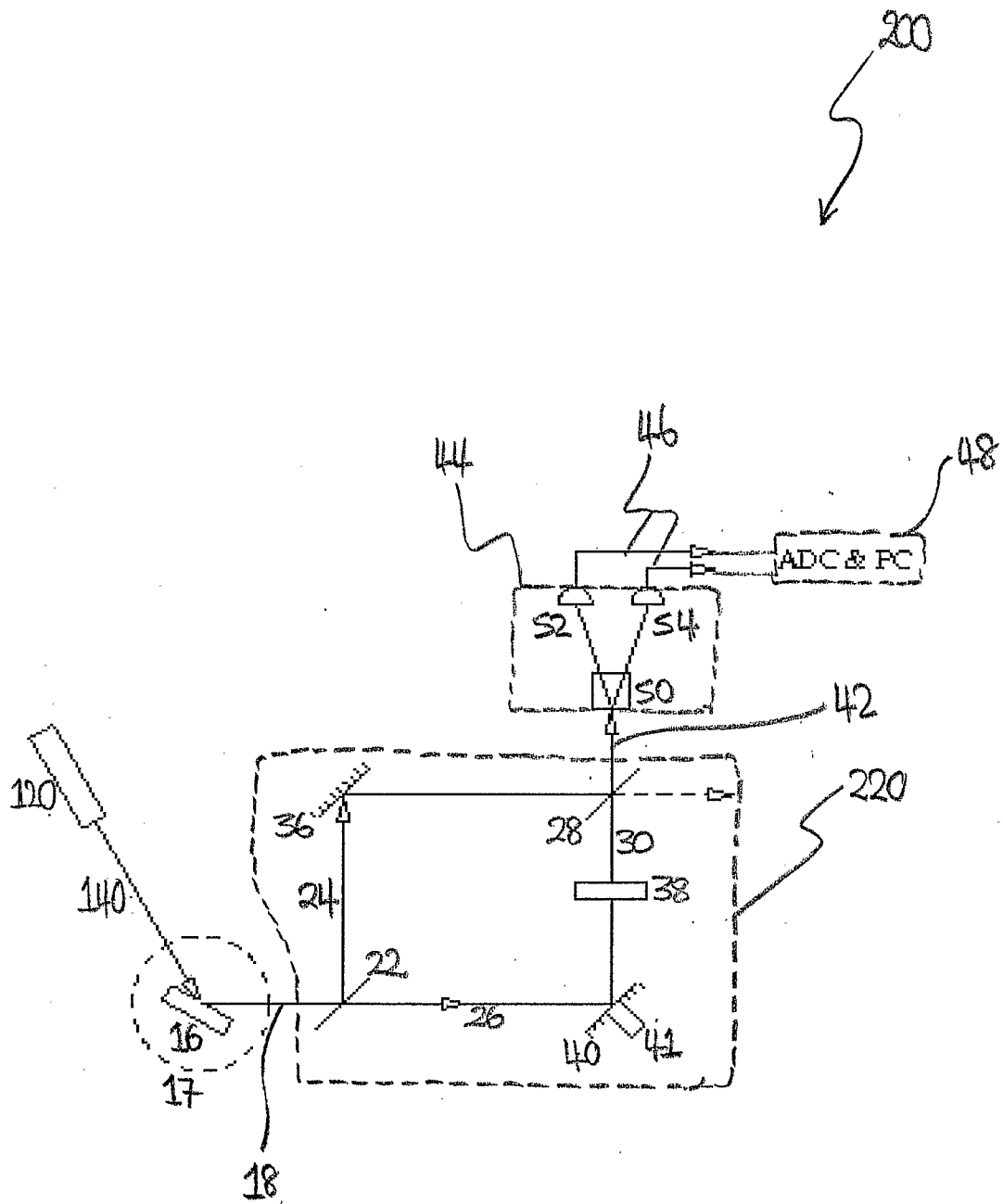


FIGURE 2

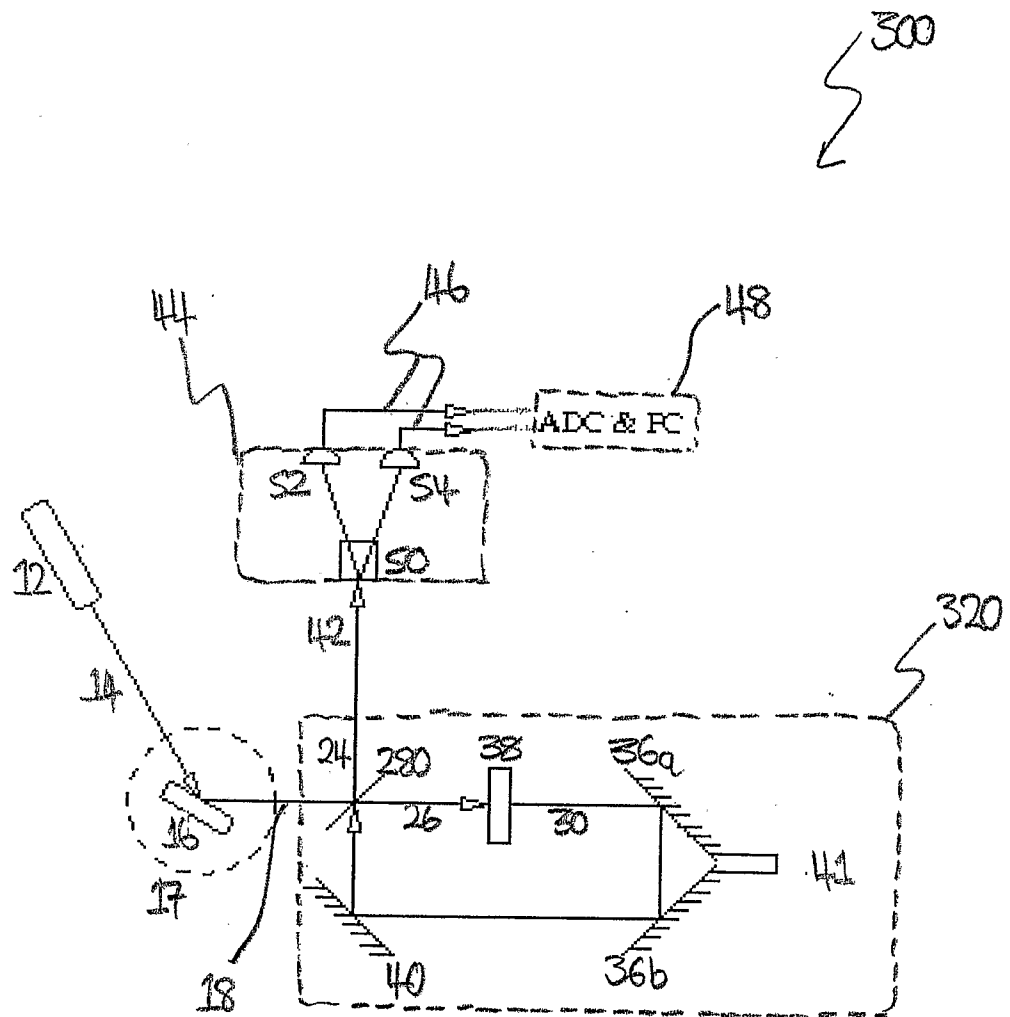


FIGURE 3

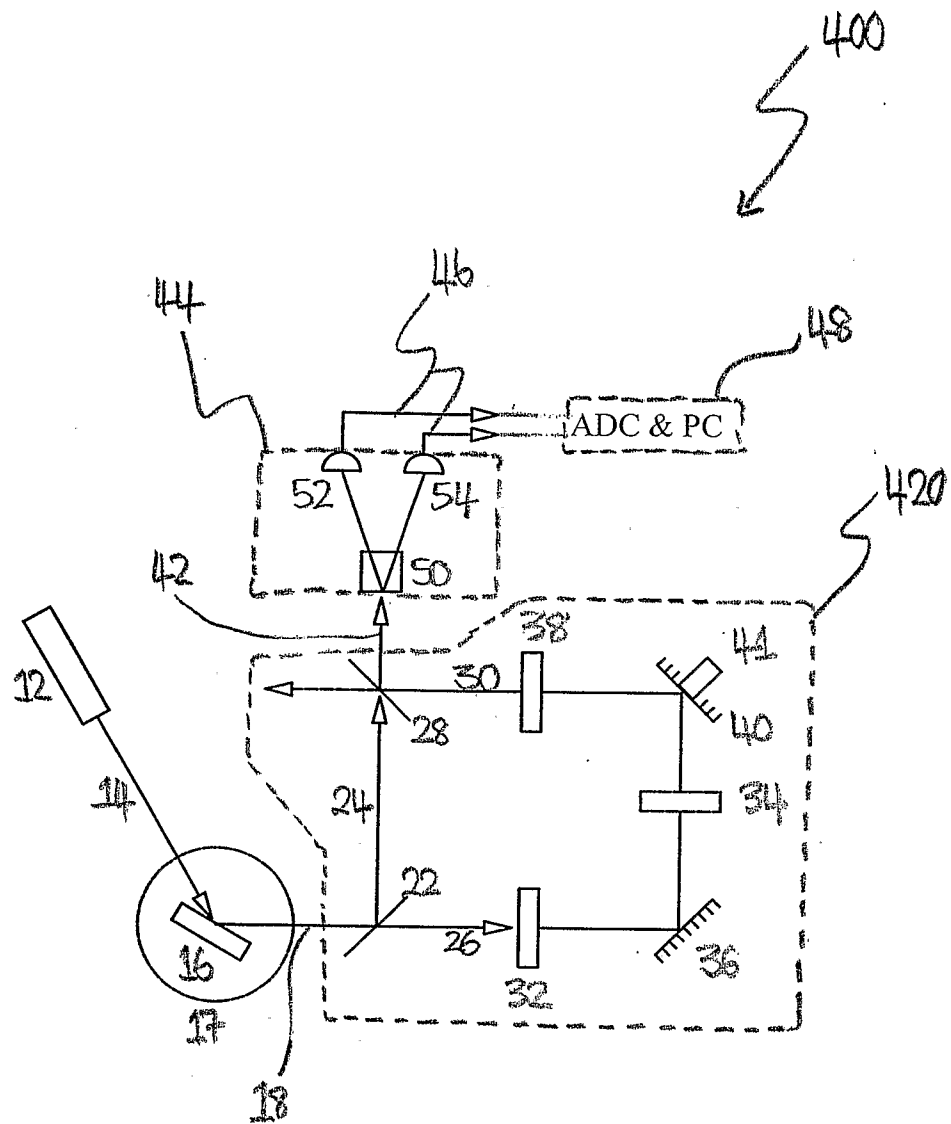


FIGURE 4

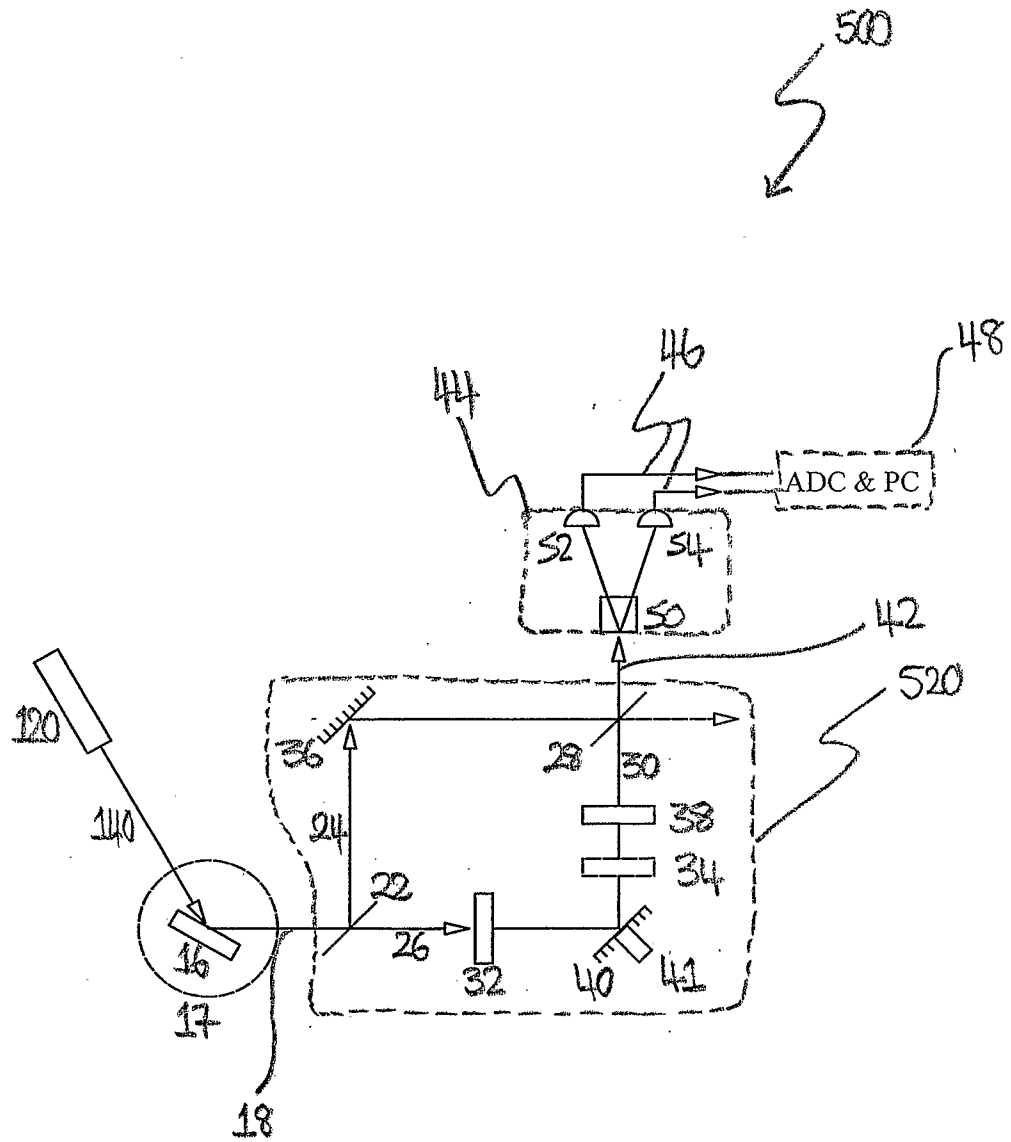


FIGURE 5

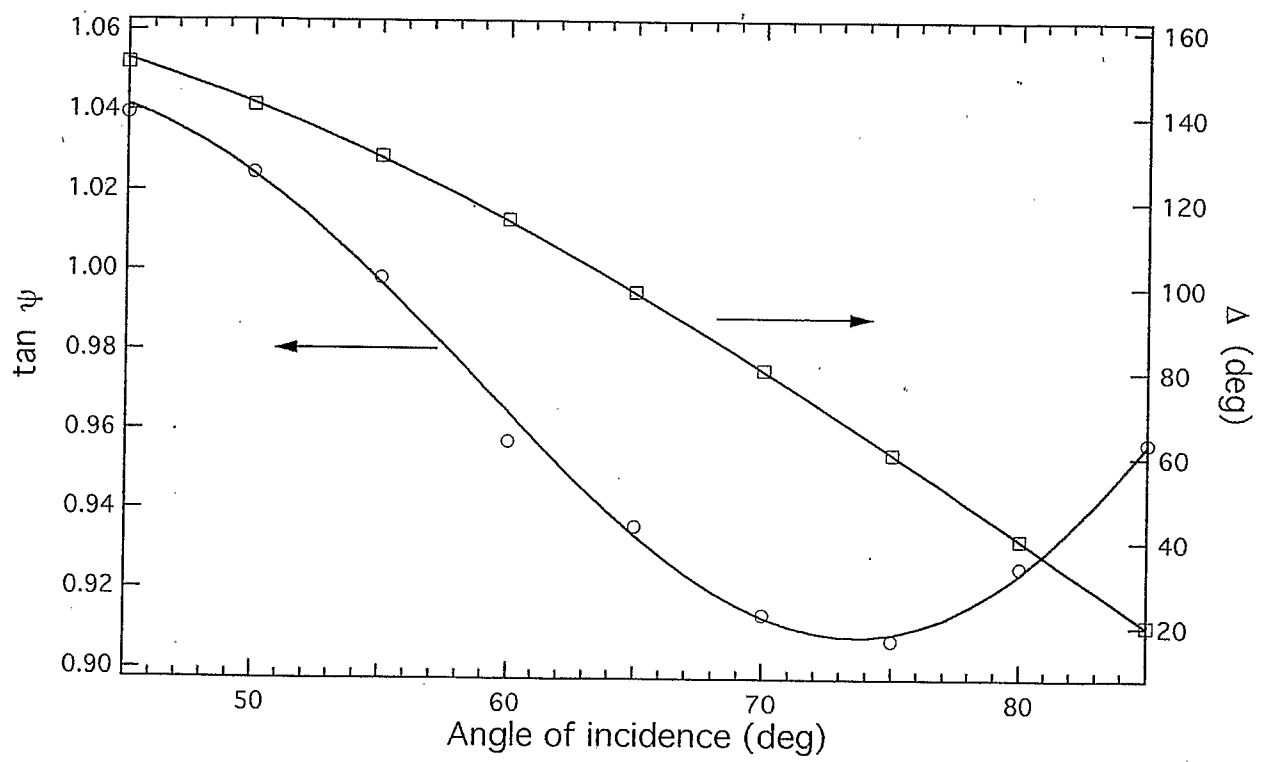


FIGURE 6

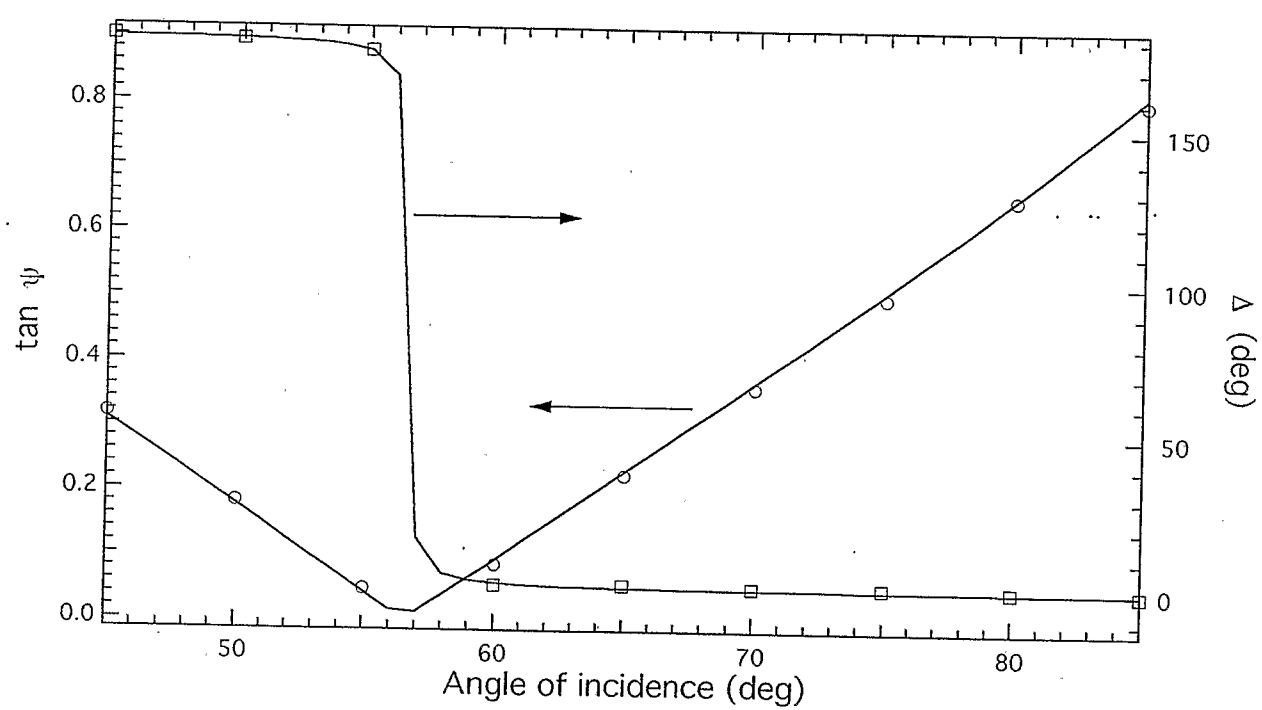


FIGURE 7

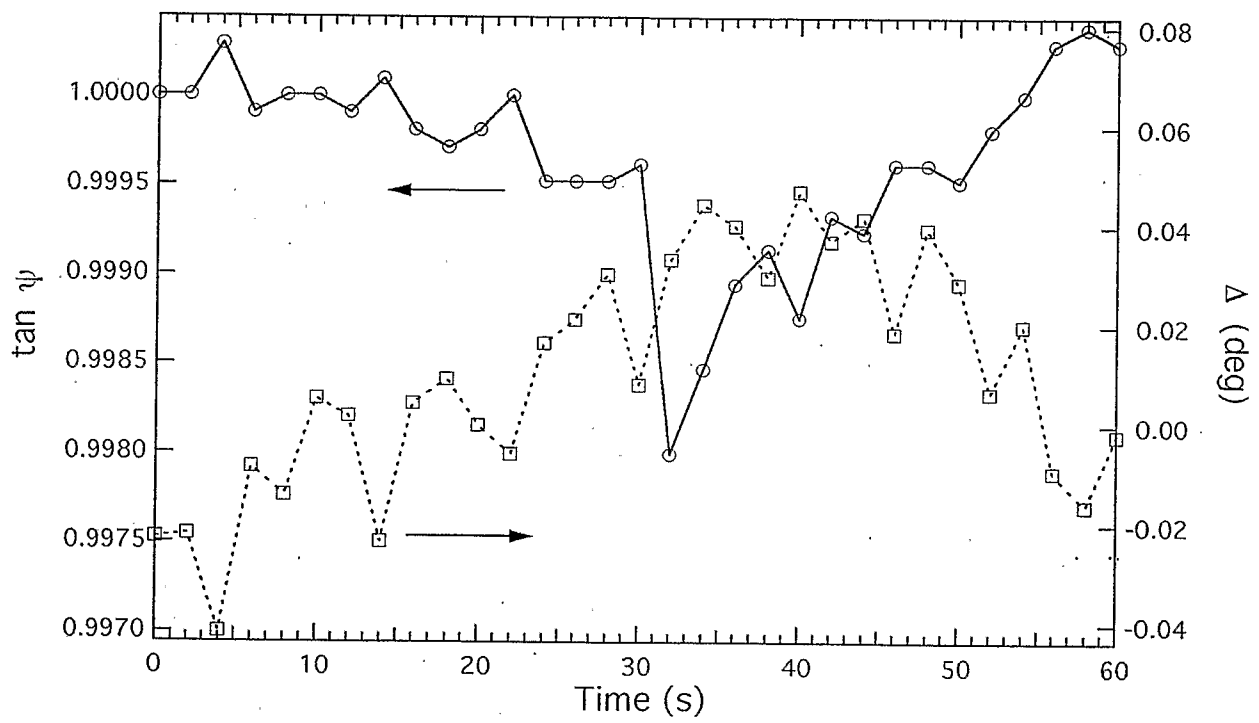


FIGURE 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/NZ2008/000122

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G01N 21/00 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI, EPODOC, Internet; Keywords: ellipsometer, interferometer, heterodyne and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	WATKINS, LR. 'Interferometric ellipsometer', <i>Applied Optics</i> , 22 May 2008, Vol. 47, No. 16, pages 2998-3001, Optical Society of America. See whole document.	1-47
T	TSAI, CC, <i>et al.</i> 'High speed interferometric ellipsometer', <i>Optics Express</i> , 14 May 2008, Vol. 16, No. 11, pages 7778-7788, OpticsInfoBase [online], Optical Society of America. Retrieved on 19 September 2008 from http://www.opticsinfobase.org/DirectPDFAccess/7998E25C-BDB9-137E-C81EA55D7BBBB126_160067.pdf?da=1&id=160067&seq=0&CFID=14030377&CFTOKEN=51140689 See whole document.	1-47



Further documents are listed in the continuation of Box C



See patent family annex

* Special categories of cited documents:	
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"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

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