

METHOD OF PRODUCING REFERENCE SPECTRAL LIBRARY FOR USE IN FILM-THICKNESS ESTIMATION FOR WORKPIECE

BACKGROUND OF THE INVENTION

5 Field of the Invention:

[0001] The present invention relates to a method for creating a reference spectral library for use in estimating a film thickness of a workpiece, such as a wafer or a substrate, and particularly relates to a method for creating a reference spectral library including a plurality of reference spectra to be compared with a measurement spectrum of reflected light from the
10 workpiece.

Description of the Related Art:

[0002] An optical film-thickness measuring apparatus is configured to generate a measurement spectrum of reflected light from a wafer, determine a reference spectrum having a shape closest to a shape of the measurement spectrum from a reference spectral
15 library, and determine a film thickness associated in advance with the determined reference spectrum.

[0003] FIG. 12 is a diagram explaining a process of determining a film thickness from a comparison between a measurement spectrum and a plurality of reference spectra. The optical film-thickness measuring apparatus compares a measurement spectrum generated during polishing of a wafer with a plurality of reference spectra prepared in advance,
20 determines a reference spectrum having a shape closest to a shape of the measurement spectrum, and determines a film thickness associated in advance with this determined reference spectrum. The reference spectrum having the shape closest to the shape of the measurement spectrum is a spectrum having the smallest difference in shape between the
25 reference spectrum and the measurement spectrum.

[0004] The plurality of reference spectra are obtained by polishing a reference wafer having the same surface structure as a wafer to be polished in advance. Each reference spectrum is associated with a film thickness at a point in time when the reference spectrum was obtained. Specifically, the plurality of reference spectra were obtained when the film

thicknesses of the reference wafer were different, and the plurality of reference spectra correspond to a plurality of different film thicknesses. Therefore, by identifying the reference spectrum having the shape closest to the shape of the measurement spectrum, a current film thickness of the wafer can be estimated.

5 [0005] An example of a process of obtaining the plurality of reference spectra and the corresponding film thicknesses will be described. First, a reference wafer having the same surface structure as the wafer to be polished is prepared. The reference wafer is transported to a film-thickness measuring device, and an initial film thickness of the reference wafer is measured by the film-thickness measuring device. Next, the reference wafer is transported
10 to a polishing apparatus, and the reference wafer is polished by the polishing apparatus. During polishing of the reference wafer, a surface of the reference wafer is irradiated with light, and a spectrum of reflected light from the reference wafer (i.e., a reference spectrum) is generated. The reference spectra are generated periodically during polishing of the reference wafer. Therefore, during polishing of the reference wafer, the plurality of
15 reference spectra are obtained as the film thickness decreases. After the polishing of the reference wafer is terminated, the reference wafer is transported to the film-thickness measuring device again, and a film thickness of the polished reference wafer (i.e., a final film thickness) is measured.

[0006] FIG. 13 is a graph showing a relationship between the film thickness and a polishing
20 time of the reference wafer. Under a condition where a polishing rate (which may be referred to as a removal rate) of the reference wafer is constant, as shown in FIG. 13, the film thickness linearly decreases from an initial film thickness T_0 to a final film thickness T_f together with the polishing time. In other words, the film thickness can be represented by a linear function including the polishing time as a variable. The polishing rate can be
25 calculated by dividing a difference between the initial film thickness T_0 and the final film thickness T_f by a difference between a polishing time t_{fin} at the final film thickness T_f and a polishing time t_{ini} at the initial film thickness T_0 .

$$\text{Polishing rate} = [T_0 - T_f] / [t_{fin} - t_{ini}]$$

[0007] Times $t_1, t_2, \dots, t_n$ at which the plurality of reference spectra were generated are

within a range from the polishing time t_{ini} to the polishing time t_{fin} . From the initial film thickness T_0 , the final film thickness T_f , and the times t_1 to t_n at which the reference spectra were generated, film thicknesses corresponding to the reference spectra can be calculated. For example, a film thickness corresponding to a reference spectrum generated at a time t_2 can be calculated from the following formula.

$$T_0 - [(T_0 - T_f) / (t_{fin} - t_{ini})] \cdot [t_2 - t_{ini}]$$

[0008] In this manner, the plurality of reference spectra corresponding to different film thicknesses are obtained. Each reference spectrum is associated (or linked) with a corresponding film thickness. The optical film-thickness measuring apparatus can estimate a current film thickness of the wafer from the film thickness associated with the reference spectrum by identifying the reference spectrum having the shape closest to the shape of the measurement spectrum during polishing of the wafer.

Citation List

Patent Literature

[0009] Patent document 1: Japanese laid-open patent publication No. 2022-10553

Patent document 2: Japanese laid-open patent publication No. 2016-510953

[0010] As can be seen from FIG. 13, the reference spectra are generated while the film thickness of the reference wafer decreases from the initial film thickness T_0 to the final film thickness T_f . Therefore, a reference spectrum corresponding to a film thickness larger than the initial film thickness T_0 and a reference spectrum corresponding to a film thickness smaller than the final film thickness T_f are not obtained. When the current film thickness of the wafer is larger than the initial film thickness T_0 or smaller than the final film thickness T_f , the current film thickness of the wafer cannot be estimated, because there is no corresponding reference spectrum.

SUMMARY OF THE INVENTION

[0011] Therefore, the present invention provides a technique for widening a range of a plurality of reference spectra for use in estimating a film thickness of a workpiece, such as a wafer, to expand a range of film thicknesses that can be estimated.

[0012] In an embodiment, there is provided a method for producing a reference spectral library for use in estimating a film thickness of a workpiece, comprising: measuring an initial film thickness of a reference workpiece before polishing of the reference workpiece; polishing the reference workpiece by a polishing apparatus; generating a plurality of actual reference spectra of reflected light from the reference workpiece at a plurality of actual polishing times in polishing of the reference workpiece; measuring a final film thickness of the reference workpiece after polishing of the reference workpiece; calculating a polishing rate by dividing a difference between the initial film thickness and the final film thickness by a time from start of polishing to end of polishing of the reference workpiece; generating, by extrapolation, a pre-polishing reference spectrum corresponding to a pre-polishing time which is a time before the start of polishing of the reference workpiece and a post-polishing reference spectrum corresponding to a post-polishing time which is a time after the end of polishing of the reference workpiece; calculating a plurality of reference film thicknesses corresponding to the pre-polishing reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum, respectively, based on the polishing rate; and creating a reference spectral library by associating the plurality of reference film thicknesses with the pre-polishing reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum, respectively.

[0013] In an embodiment, the pre-polishing reference spectrum and the post-polishing reference spectrum are generated by an extrapolation model.

In an embodiment, the pre-polishing reference spectrum is outputted from the extrapolation model by inputting the pre-polishing time into the extrapolation model, and the post-polishing reference spectrum is outputted from the extrapolation model by inputting the post-polishing time into the extrapolation model.

In an embodiment, the extrapolation model is a trained model constructed by machine learning using training data including the plurality of actual reference spectra and the plurality of actual polishing times.

In an embodiment, the machine learning is Long Short-Term Memory (LSTM).

In an embodiment, the extrapolation model is a statistical model that analyzes the

plurality of actual reference spectra and the plurality of actual polishing times according to a statistical algorithm and generates the pre-polishing reference spectrum and the post-polishing reference spectrum based on an analysis result.

[0014] The reference spectral library includes, in addition to the plurality of actual reference spectra obtained during polishing of the reference workpiece, the pre-polishing reference spectrum and the post-polishing reference spectrum generated by the extrapolation. The pre-polishing reference spectrum is a virtual reference spectrum corresponding to a film thickness larger than the initial film thickness of the reference workpiece, and the post-polishing reference spectrum is a virtual reference spectrum corresponding to a film thickness smaller than the final film thickness of the reference workpiece. Therefore, a range of reference spectra included in the reference spectral library is widened, and a range of film thicknesses that can be estimated during polishing of the workpiece is expanded.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a schematic diagram showing an embodiment of a polishing apparatus;

FIG. 2 is a cross-sectional view showing a detailed configuration of an optical film-thickness measuring apparatus;

FIG. 3 is a schematic diagram showing an example of a measurement spectrum generated from light-intensity measurement data;

FIG. 4 is a schematic diagram showing an embodiment of a workpiece processing system including the polishing apparatus and a film-thickness measuring device used in a method for producing a reference spectral library;

FIG. 5 is a diagram showing an example of a plurality of actual reference spectra generated at different polishing times during polishing of a reference workpiece.

FIG. 6 is a graph showing an example of a decrease in film thickness of the reference workpiece with a polishing time of the reference workpiece;

FIG. 7 is a graph showing an example of a pre-polishing reference spectrum corresponding to a pre-polishing time and a plurality of actual reference spectra generated during polishing of the reference workpiece;

FIG. 8 is a graph showing an example of a post-polishing reference spectrum corresponding to a post-polishing time and a plurality of actual reference spectra generated during polishing of the reference workpiece;

5 FIG. 9 is a graph showing an example of a plurality of reference spectra including the pre-polishing reference spectrum and the post-polishing reference spectrum shown in FIGS. 7 and 8 and the plurality of actual reference spectra generated during polishing of the reference workpiece;

FIG. 10 is a graph showing an example of a plurality of reference film thicknesses at a plurality of times corresponding to the plurality of reference spectra shown in FIG. 9;

10 FIG. 11 is a flowchart explaining an embodiment of a method of producing a reference spectral library;

FIG. 12 is a diagram explaining a process of determining a film thickness from a comparison between a measurement spectrum and a plurality of reference spectra; and

15 FIG. 13 is a graph showing a relationship between a film thickness of a reference wafer and a polishing time.

DESCRIPTION OF EMBODIMENTS

[0016] Hereinafter, embodiments of the present invention will be described with reference to the drawings.

20 FIG. 1 is a schematic diagram showing an embodiment of a polishing apparatus. As shown in FIG. 1, a polishing apparatus 100 includes a polishing table 3 configured to support a polishing pad 2, a polishing head 1 configured to press a workpiece W against the polishing pad 2, a table motor 6 configured to rotate the polishing table 3, a polishing-liquid supply nozzle 5 configured to supply a polishing liquid, such as slurry, onto the polishing
25 pad 2, and an operation controller 9 configured to control operations of the polishing apparatus 100. An upper surface of the polishing pad 2 constitutes a polishing surface 2a for polishing the workpiece W.

[0017] The workpiece W has a film constituting an interconnect structure on a surface of the workpiece W. Examples of the workpiece W include a wafer, a substrate, an

interconnect substrate, a quadrilateral substrate, etc. for use in manufacturing of semiconductor devices. In one example, the workpiece W is a product wafer on which multilayered films are formed.

[0018] The polishing head 1 is coupled to a head shaft 10, and the head shaft 10 is coupled to a polishing-head rotating device 15. The polishing-head rotating device 15 is configured to rotate the polishing head 1 together with the head shaft 10 in a direction indicated by an arrow. Although a configuration of the polishing-head rotating device 15 is not particularly limited, in one example, the polishing-head rotating device 15 includes an electric motor, a belt, a pulley, etc. The polishing table 3 is coupled to the table motor 6, and the table motor 6 is configured to rotate the polishing table 3 and the polishing pad 2 in a direction indicated by an arrow. The polishing head 1, the polishing-head rotating device 15, and the table motor 6 are coupled to the operation controller 9.

[0019] The workpiece W is polished as follows. While the table motor 6 and the polishing-head rotating device 15 rotate the polishing table 3 and the polishing head 1 in the directions indicated by the arrows in FIG. 1, the polishing liquid is supplied from the polishing-liquid supply nozzle 5 onto the polishing surface 2a of the polishing pad 2 on the polishing table 3. While the workpiece W is rotated by the polishing head 1, the workpiece W is pressed against the polishing surface 2a of the polishing pad 2 by the polishing head 1 in the presence of the polishing liquid on the polishing pad 2. The surface of the workpiece W is polished by a chemical action of the polishing liquid and a mechanical action of abrasive grains contained in the polishing liquid and/or the polishing pad 2.

[0020] The operation controller 9 includes a memory 9a storing a program, and an arithmetic device 9b configured to execute an arithmetic operation according to instructions included in the program. The operation controller 9 is composed of at least one computer. The memory 9a includes a main memory, such as a random access memory (RAM) and an auxiliary memory, such as a hard disk drive (HDD) or a solid state drive (SSD). Examples of the arithmetic device 9b include a CPU (Central Processing Unit) and a GPU (Graphic Processing Unit). However, a specific configuration of the operation controller 9 is not limited to these examples.

[0021] The polishing apparatus 100 includes an optical film-thickness measuring apparatus 20 configured to measure a film thickness of the workpiece W. The optical film-thickness measuring apparatus 20 includes a light source 22 configured to emit light, an optical sensor head 25 configured to irradiate the workpiece W with the light of the light source 22 and receive reflected light from the workpiece W, a spectrometer 27 coupled to the optical sensor head 25, and a processing system 30 configured to determine the film thickness of the workpiece W based on a spectrum of the reflected light from the workpiece W. The optical sensor head 25 is disposed in the polishing table 3 and rotates together with the polishing table 3.

[0022] The processing system 30 includes a memory 30a storing a program, and an arithmetic device 30b configured to execute an arithmetic operation according to instructions included in the program. The processing system 30 is composed of at least one computer. The memory 30a includes a main memory, such as a random access memory (RAM) and an auxiliary memory, such as a hard disk drive (HDD) or a solid state drive (SSD). Examples of the arithmetic device 30b include a CPU (Central Processing Unit) and a GPU (Graphic Processing Unit). However, a specific configuration of the processing system 30 is not limited to these examples.

[0023] Each of the operation controller 9 and the processing system 30 may be composed of a plurality of computers. For example, each of the operation controller 9 and the processing system 30 may be composed of a combination of an edge server and a cloud server. In one embodiment, the operation controller 9 and the processing system 30 may be composed of one computer.

[0024] FIG. 2 is a cross-sectional view showing a detailed configuration of the optical film-thickness measuring apparatus 20. The optical film-thickness measuring apparatus 20 includes a light-emitting optical fiber cable 31 coupled to the light source 22, and a light-receiving optical fiber cable 32 coupled to the spectrometer 27. A distal end 31a of the light-emitting optical fiber cable 31 and a distal end 32a of the light-receiving optical fiber cable 32 constitute the optical sensor head 25. Specifically, the light-emitting optical fiber cable 31 casts the light, emitted by the light source 22, onto the workpiece W on the polishing

pad 2, and the light-receiving optical fiber cable 32 receives the reflected light from the workpiece W and transmits the reflected light to the spectrometer 27.

[0025] The spectrometer 27 is coupled to the processing system 30. The light-emitting optical fiber cable 31, the light-receiving optical fiber cable 32, the light source 22, and the spectrometer 27 are attached to the polishing table 3, and rotate integrally together with the polishing table 3 and the polishing pad 2. The optical sensor head 25, which is composed of the distal end 31a of the light-emitting optical fiber cable 31 and the distal end 32a of the light-receiving optical fiber cable 32, is disposed so as to face the surface of the workpiece W on the polishing pad 2.

[0026] A position of the optical sensor head 25 is such that the optical sensor head 25 moves across the surface of the workpiece W on the polishing pad 2 each time the polishing table 3 and the polishing pad 2 make one rotation. The polishing pad 2 has a through-hole 2b located above the optical sensor head 25. The optical sensor head 25 irradiates the workpiece W with the light through the through-hole 2b and receives the reflected light from the workpiece W through the through-hole 2b each time the polishing table 3 makes one rotation.

[0027] In one embodiment, a flow of pure water may be formed in the through-hole 2b of the polishing pad 2 in order to prevent the polishing liquid and polishing debris from contacting the optical sensor head 25. The light is emitted from the optical sensor head 25 through the pure water to the workpiece W, and the reflected light from the workpiece W travels through the pure water and is received by the optical sensor head 25. In another embodiment, a transparent window (not shown) may be fitted in the through-hole 2b of the polishing pad 2. The transparent window is made of a material permitting transmission of light (e.g., a transparent resin). In this case, the light is emitted from the optical sensor head 25 through the transparent window to the workpiece W, and the reflected light from the workpiece W travels through the transparent window and is received by the optical sensor head 25.

[0028] The light source 22 may be a flash light source configured to repeatedly emit light at short time intervals. Examples of the light source 22 include a xenon flash lamp. The

light source 22 is electrically coupled to the operation controller 9, and emits the light upon receiving a trigger signal sent from the operation controller 9. More specifically, while the optical sensor head 25 sweeps across the surface of the workpiece W on the polishing pad 2, the light source 22 receives a plurality of trigger signals and emits the light a plurality of times. Therefore, each time the polishing table 3 makes one rotation, the light is directed to a plurality of film thickness measurement points including a center point on the workpiece W.

[0029] The light emitted by the light source 22 is transmitted to the optical sensor head 25. Specifically, the light is transmitted through the light-emitting optical fiber cable 31 to the optical sensor head 25, and is emitted from the optical sensor head 25. The light passes through the through-hole 2b of the polishing pad 2 and is incident on the workpiece W on the polishing pad 2. The light reflected from the workpiece W passes through the through-hole 2b of the polishing pad 2 again, and is received by the optical sensor head 25. The reflected light from the workpiece W is transmitted through the light-receiving optical fiber cable 32 to the spectrometer 27.

[0030] The spectrometer 27 is configured to decompose the reflected light according to wavelength and measure an intensity of the reflected light at each wavelength over a predetermined wavelength range. Specifically, the spectrometer 27 decomposes the reflected light from the workpiece W according to wavelength, measures the intensity of the reflected light at each wavelength over the predetermined wavelength range to generate light-intensity measurement data. The intensity of the reflected light at each wavelength can be expressed as a relative value, such as reflectance or relative reflectance. The light-intensity measurement data is sent to the processing system 30.

[0031] The processing system 30 generates a spectrum of the reflected light as shown in FIG. 3 from the light-intensity measurement data. In the following description, the spectrum of the reflected light from the workpiece W is referred to as a measurement spectrum. The measurement spectrum of the reflected light from the workpiece W includes information on the film thickness of the workpiece W. In other words, the measurement spectrum of the reflected light changes depending on the film thickness of the workpiece W.

The processing system 30 is configured to determine (or estimate) the film thickness of the workpiece W based on the measurement spectrum of the reflected light. More specifically, the processing system 30 determines, from among a reference spectral library 38 (see FIG. 1), a reference spectrum having a shape closest to a shape of the measurement spectrum of the reflected light, and determines a film thickness associated in advance with this determined reference spectrum. The reference spectral library 38 is created in advance before polishing of the workpiece W, and is stored in the memory 30a of the processing system 30.

[0032] Hereinafter, an embodiment of a method of producing the reference spectral library 38 will be described. FIG. 4 is a schematic diagram showing an embodiment of a workpiece processing system including the polishing apparatus 100 and a film-thickness measuring device 101 used in the method of producing the reference spectral library 38.

[0033] First, a reference workpiece RW having the same surface structure as the workpiece W is prepared. More specifically, the reference workpiece RW has an exposed surface composed of the same material(s) as the workpiece W, and has the same multilayer structure. Next, the reference workpiece RW is transported to the film-thickness measuring device 101 by a transporter 103, and an initial film thickness, which is a film thickness of the reference workpiece RW before polishing, is measured by the film-thickness measuring device 101.

[0034] The film-thickness measuring device 101 irradiates the stationary reference workpiece RW with light, generates a spectrum of reflected light from the reference workpiece, and determines the film thickness of the reference workpiece RW by analyzing the spectrum. Although a basic configuration of this film-thickness measuring device 101 is the same as that of the optical film-thickness measuring apparatus 20, the film-thickness measuring device 101 differs from the optical film-thickness measuring apparatus 20 in that the film-thickness measuring device 101 is configured to measure the film thickness of the reference workpiece RW in a stationary state. A measured value of the initial film thickness of the reference workpiece RW is transmitted from the film-thickness measuring device 101 to the processing system 30.

[0035] After the measurement of the initial film thickness, the reference workpiece RW is

transported to the polishing apparatus 100 by the transporter 103, and is polished by the polishing apparatus 100. Polishing of the reference workpiece RW is performed in the same manner as polishing of the workpiece W. Specifically, while the table motor 6 and the polishing-head rotating device 15 rotate the polishing table 3 and the polishing head 1 in the directions indicated by the arrows in FIG. 1, the polishing liquid is supplied from the polishing-liquid supply nozzle 5 onto the polishing surface 2a of the polishing pad 2 on the polishing table 3. While the reference workpiece RW is rotated by the polishing head 1, the reference workpiece RW is pressed against the polishing surface 2a of the polishing pad 2 by the polishing head 1 in the presence of the polishing liquid on the polishing pad 2, whereby the surface of the reference workpiece RW is polished.

[0036] During polishing of the reference workpiece RW, the light is emitted from the optical sensor head 25 onto the reference workpiece RW, and a spectrum of reflected light from the reference workpiece RW is generated, as well as the polishing of the workpiece W. In the following description, the spectrum of the reflected light from the reference workpiece RW obtained during polishing of the reference workpiece RW is referred to as an actual reference spectrum. Each time the polishing table 3 makes one rotation, the optical sensor head 25 emits the light onto a plurality of film thickness measurement points including a center point on the reference workpiece RW. The processing system 30 generates an actual reference spectrum from the light-intensity measurement data generated by the spectrometer each time the polishing table 3 makes one rotation.

[0037] FIG. 5 is a diagram showing an example of a plurality of actual reference spectra generated at different polishing times during polishing of the reference workpiece RW. In FIG. 5, a vertical axis represents intensity of the reflected light from the reference workpiece RW, and a horizontal axis represents wavelength of the reflected light. As shown in FIG. 5, since the actual reference spectrum is generated from the reflected light from the reference workpiece RW being polished, the actual reference spectrum changes gradually with a decrease in the film thickness of the reference workpiece RW (i.e., with the polishing time). Therefore, shapes of the plurality of actual reference spectra generated from the reflected light at different polishing times during polishing of the reference workpiece RW are slightly

different.

[0038] In this manner, during polishing of the reference workpiece RW, a plurality of actual reference spectra corresponding to a plurality of polishing times are generated with the decrease in the film thickness of the reference workpiece RW. In the following description, the plurality of polishing times at which the plurality of actual reference spectra are generated may be referred to as a plurality of actual polishing times. After the polishing of the reference workpiece RW, the reference workpiece RW is transported to the film-thickness measuring device 101 by the transporter 103, and a final film thickness, which is a film thickness of the reference workpiece RW after polishing, is measured by the film-thickness measuring device 101. A measured value of the final film thickness is transmitted from the film-thickness measuring device 101 to the processing system 30. The processing system 30 calculates a polishing rate of the reference workpiece RW by dividing a difference between the initial film thickness and the final film thickness by a time from start of polishing to end of polishing of the reference workpiece RW.

[0039] FIG. 6 is a graph showing an example of the decrease in film thickness of the reference workpiece RW with the polishing time of the reference workpiece RW. The film thickness linearly decreases from an initial film thickness T_{ini} to a final film thickness T_{fin} with the polishing time. In other words, the film thickness can be represented by a linear function including the polishing time as a variable. The polishing rate is calculated by dividing a difference between the initial film thickness T_{ini} and the final film thickness T_{fin} by the time from the start of polishing to the end of polishing of the reference workpiece RW. The time from the start of polishing to the end of polishing of the reference workpiece RW corresponds to a difference between a polishing time t_n at the final film thickness T_{fin} and a polishing time t_m at the initial film thickness T_{ini} . The polishing rate is expressed by the following formula.

$$\text{Polishing rate} = [T_{ini} - T_{fin}] / [t_n - t_m]$$

[0040] The processing system 30 is configured to generate, by extrapolation, a pre-polishing reference spectrum corresponding to a pre-polishing time (e.g., t_{m-1} , t_{m-2} , etc.) which is a time before the start of polishing of the reference workpiece RW, and a post-

polishing reference spectrum corresponding to a post-polishing time (e.g., t_{n+1} , t_{n+2} , etc.) which is a time after the end of polishing of the reference workpiece RW. As shown in FIG. 1, the processing system 30 has an extrapolation model 40 stored in advance in the memory 30a, and generates the pre-polishing reference spectrum and the post-polishing reference spectrum using the extrapolation model 40. Since the polishing time is proportional to the number of rotations of the polishing table 3, the pre-polishing time, the post-polishing time, and the plurality of actual polishing times (t_m to t_n) during polishing of the reference workpiece RW may be represented by the number of rotations of the polishing table 3.

[0041] In one embodiment, the extrapolation model 40 is a trained model constructed by machine learning using training data. The training data includes the plurality of actual reference spectra obtained from the polishing of the reference workpiece RW (see FIG. 5) and the plurality of actual polishing times (t_m to t_n) corresponding to the plurality of actual reference spectra. The plurality of actual reference spectra included in the training data are associated with the plurality of corresponding actual polishing times, respectively. The processing system 30 constructs the extrapolation model 40 by executing machine learning according to instructions included in the program stored in the memory 30a. The machine learning is supervised machine learning using the training data.

[0042] As described with reference to FIG. 5, each actual reference spectrum represents a plurality of intensities of reflected light corresponding to a plurality of wavelengths. The plurality of intensities of reflected light corresponding to the plurality of wavelengths can be treated as numerical data representing a feature of the actual reference spectrum. The extrapolation model 40 learns features of the plurality of actual reference spectra included in the training data, and generates the pre-polishing reference spectrum and the post-polishing reference spectrum, which are unknown spectra, according to the learned features. Since each actual reference spectrum included in the training data is associated with a corresponding actual polishing time, the extrapolation model 40 learns a correlation between the actual reference spectrum and the actual polishing time. Therefore, the extrapolation model 40 as a trained model can generate a reference spectrum corresponding to a polishing

time outside a range of the actual polishing times t_m to t_n of the reference workpiece RW.

[0043] In the present embodiment, the extrapolation model 40 is constructed by the machine learning. Examples of machine learning applicable to the present embodiment include Long Short-Term Memory (LSTM), Convolutional Neural Network (CNN), and Recurrent Neural Network (RNN). In the present embodiment, Long Short-Term Memory (LSTM) is used as the machine learning.

[0044] In another embodiment, the extrapolation model 40 may be a statistical model constructed according to a statistical algorithm. The statistical model is configured to analyze the plurality of actual reference spectra and the plurality of actual polishing times according to a statistical algorithm, and generate the pre-polishing reference spectrum and the post-polishing reference spectrum based on an analysis result. Examples of the statistical algorithm used for constructing the statistical model include autoregression, moving average, autoregressive moving average, and state space.

[0045] However, a specific configuration of the extrapolation model 40 is not particularly limited as long as the extrapolation model 40 can generate the pre-polishing reference spectrum corresponding to the pre-polishing time and the post-polishing reference spectrum corresponding to the post-polishing time.

[0046] In the example shown in FIG. 6, the processing system 30 outputs the pre-polishing reference spectrum corresponding to a pre-polishing time t_{m-1} from the extrapolation model 40 by inputting the pre-polishing time t_{m-1} , which is a time before the start of polishing of the reference workpiece RW, into the extrapolation model 40. Further, the processing system 30 outputs the post-polishing reference spectrum corresponding to a post-polishing time t_{n+1} from the extrapolation model 40 by inputting the post-polishing time t_{n+1} , which is a time after the end of polishing of the reference workpiece RW, into the extrapolation model 40. In the same manner, the processing system 30 can generate reference spectra corresponding to polishing times outside the range of the actual polishing times t_m to t_n , such as the pre-polishing time t_{m-2} and the post-polishing time t_{n+2} .

[0047] The reference spectra generated by the extrapolation model 40 are virtual spectra. The number of pre-polishing reference spectra and the number of post-polishing reference

spectra to be generated by the extrapolation model 40 are not particularly limited. Three or more pre-polishing reference spectra and three or more post-polishing reference spectra may be generated, or one pre-polishing reference spectrum and one post-polishing reference spectrum may be generated.

5 [0048] FIG. 7 is a graph showing an example of pre-polishing reference spectra corresponding to pre-polishing times t_{m-1} , t_{m-2} and a plurality of actual reference spectra generated during polishing of the reference workpiece RW, FIG. 8 is a graph showing an example of post-polishing reference spectra corresponding to post-polishing times t_{n+1} , t_{n+2} and the plurality of actual reference spectra generated during polishing of the reference
10 workpiece RW, and FIG. 9 is a graph showing an example of a plurality of reference spectra including the pre-polishing reference spectra and the post-polishing reference spectra shown in FIGS. 7 and 8 and the plurality of actual reference spectra generated during polishing of the reference workpiece RW.

[0049] The pre-polishing reference spectrum is a virtual reference spectrum corresponding
15 to a film thickness larger than the initial film thickness of the reference workpiece RW, and the post-polishing reference spectrum is a virtual reference spectrum corresponding to a film thickness smaller than the final film thickness of the reference workpiece RW. The processing system 30 obtains a plurality of reference spectra including the pre-polishing reference spectra, the post-polishing reference spectra, and the plurality of actual reference
20 spectra as shown in FIG. 9 by adding the pre-polishing reference spectra and the post-polishing reference spectra shown in FIGS. 7 and 8 to the plurality of actual reference spectra generated during polishing of the reference workpiece RW.

[0050] Next, the processing system 30 calculates a plurality of reference film thicknesses at a plurality of times t_{m-2} to t_{n+2} corresponding to the plurality of reference spectra
25 (including the pre-polishing reference spectra, the post-polishing reference spectra, and the plurality of actual reference spectra) shown in FIG. 9. FIG. 10 is a graph showing an example of a plurality of reference film thicknesses at a plurality of times corresponding to the plurality of reference spectra shown in FIG. 9. The processing system 30 calculates reference film thicknesses at the plurality of times t_{m-2} to t_{n+2} from the polishing rate and

the plurality of times t_{m-2} to t_{n+2} corresponding to the plurality of reference spectra. The polishing rate corresponds to a slope of the graph in FIG. 10. The times t_{m-2} to t_{n+2} used for calculating the reference film thicknesses include the pre-polishing times t_{m-1} , t_{m-2} , the post-polishing times t_{n+1} , t_{n+2} , and the actual polishing times t_m to t_n .

5 [0051] For example, a reference film thickness at a time t_{m+1} can be calculated from the following formula.

$$T_{ini}-[[T_{ini}-T_{fin}]/[t_n-t_m]]\cdot[t_{m+1}-t_m]$$

10 In the same manner, the processing system 30 can calculate reference film thicknesses $T-1$, $T-2$, $T+1$, $T+2$ corresponding to the pre-polishing times t_{m-1} , t_{m-2} and the post-polishing times t_{n+1} , t_{n+2} . Since the time is proportional to the number of rotations of the polishing table 3, the time shown on the horizontal axis of FIG. 10 may be represented by the number of rotations of the polishing table 3.

[0052] The processing system 30 creates the reference spectral library 38 by associating the plurality of reference film thicknesses shown in FIG. 10 with the plurality of reference spectra (including the pre-polishing reference spectra, the plurality of actual reference spectra, and the post-polishing reference spectra) shown in FIG. 9, respectively. The plurality of reference film thicknesses uniquely correspond to the plurality of reference spectra. The reference spectral library 38 is stored in the memory 30a of the processing system 30.

20 [0053] During polishing of the workpiece W shown in FIG. 1, the film thickness of the workpiece W is estimated using the reference spectral library 38. Specifically, the optical sensor head 25 irradiates the workpiece W with the light and receives the reflected light from the workpiece W. The spectrometer 27 decomposes the reflected light from the workpiece W according to wavelength, measures an intensity of the reflected light at each wavelength over a predetermined wavelength range, and generates light-intensity measurement data. The processing system 30 generates a measurement spectrum of the reflected light from the workpiece W from the light-intensity measurement data. The processing system 30 determines, from among the reference spectral library 38, a reference spectrum having a shape closest to a shape of the measurement spectrum of the reflected

light, and determines a reference film thickness associated with this determined reference spectrum. This reference film thickness is an estimated film thickness of the workpiece W.

[0054] The reference spectral library 38 includes the pre-polishing reference spectrum and the post-polishing reference spectrum, which are virtual spectra generated by the extrapolation, in addition to the plurality of actual reference spectra obtained during polishing of the reference workpiece RW. Therefore, the range of the reference spectra included in the reference spectral library 38 is widened, and the range of film thicknesses that can be estimated during polishing of the workpiece W is widened.

[0055] FIG. 11 is a flowchart explaining an embodiment of the method of producing the reference spectral library 38.

In step S101, the reference workpiece RW having the same surface structure as the workpiece W is prepared. The reference workpiece RW has an exposed surface composed of the same material(s) as the workpiece W, and has the same multilayer structure.

In step S102, an initial film thickness, which is a film thickness of the reference workpiece RW before polishing, is measured by the film-thickness measuring device 101 (see FIG. 4).

[0056] In step S103, the reference workpiece RW is chemically mechanically polished by the polishing apparatus 100 shown in FIG. 1.

In step S104, the reference workpiece RW is irradiated with the light at different actual polishing times during polishing of the reference workpiece RW. The processing system 30 generates actual reference spectra of the reflected light from the reference workpiece RW.

In step S105, after the polishing of the reference workpiece RW, a final film thickness, which is a film thickness of the polished reference workpiece RW, is measured by the film-thickness measuring device 101 (see FIG. 4).

In step S106, the processing system 30 calculates a polishing rate of the reference workpiece RW by dividing a difference between the initial film thickness and the final film thickness by a time from start of polishing to end of polishing of the reference workpiece RW. The polishing rate of the reference workpiece RW corresponds to a slope of the graph

shown in FIG. 6.

[0057] In step S107, the processing system 30 generates, by the extrapolation, a pre-polishing reference spectrum corresponding to a pre-polishing time which is a time before the start of polishing of the reference workpiece RW and a post-polishing reference spectrum
5 corresponding to a post-polishing time which is a time after the end of polishing of the reference workpiece RW (see FIGS. 7 and 8). In one embodiment, the processing system 30 inputs the pre-polishing time into the extrapolation model 40 and outputs the pre-polishing reference spectrum corresponding to the pre-polishing time from the extrapolation model 40. Further, the processing system 30 inputs the post-polishing time into the
10 extrapolation model 40 and outputs the post-polishing reference spectrum corresponding to the post-polishing time from the extrapolation model 40.

The order of step S106 and step S107 may be reversed, or step S106 and step S107 may be executed simultaneously.

[0058] In step S108, the processing system 30 adds the pre-polishing reference spectrum
15 and the post-polishing reference spectrum to the actual reference spectra to create a plurality of reference spectra constituting the reference spectral library 38 (see FIG. 9).

In step S109, the processing system 30 calculates reference film thicknesses corresponding to a plurality of times, respectively, from the polishing rate and the plurality of times corresponding to the plurality of reference spectra (including the pre-polishing
20 reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum) (see FIG. 10). The plurality of times include the pre-polishing time corresponding to the pre-polishing reference spectrum, the plurality of actual polishing times corresponding to the plurality of actual reference spectra, and the post-polishing time corresponding to the post-polishing reference spectrum.

25 In step S110, the processing system 30 creates the reference spectral library 38 by associating the plurality of reference film thicknesses with the plurality of reference spectra (including the pre-polishing reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum), respectively.

[0059] The previous description of embodiments is provided to enable a person skilled in the art to make and use the present invention. Moreover, various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles and specific examples defined herein may be applied to other embodiments. Therefore, the present invention is not intended to be limited to the embodiments described herein but is to be accorded the widest scope as defined by limitation of the claims.

What is claimed is:

1. A method for producing a reference spectral library for use in estimating a film thickness of a workpiece, comprising:

5 measuring an initial film thickness of a reference workpiece before polishing of the reference workpiece;

polishing the reference workpiece by a polishing apparatus;

generating a plurality of actual reference spectra of reflected light from the reference workpiece at a plurality of actual polishing times in polishing of the reference workpiece;

10 measuring a final film thickness of the reference workpiece after polishing of the reference workpiece;

calculating a polishing rate by dividing a difference between the initial film thickness and the final film thickness by a time from start of polishing to end of polishing of the reference workpiece;

15 generating, by extrapolation, a pre-polishing reference spectrum corresponding to a pre-polishing time which is a time before the start of polishing of the reference workpiece and a post-polishing reference spectrum corresponding to a post-polishing time which is a time after the end of polishing of the reference workpiece;

20 calculating a plurality of reference film thicknesses corresponding to the pre-polishing reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum, respectively, based on the polishing rate; and

creating a reference spectral library by associating the plurality of reference film thicknesses with the pre-polishing reference spectrum, the plurality of actual reference spectra, and the post-polishing reference spectrum, respectively.

25 2. The method of producing the reference spectral library according to claim 1, wherein the pre-polishing reference spectrum and the post-polishing reference spectrum are generated by an extrapolation model.

3. The method of producing the reference spectral library according to claim 2, wherein the pre-polishing reference spectrum is outputted from the extrapolation model by inputting the pre-polishing time into the extrapolation model, and

the post-polishing reference spectrum is outputted from the extrapolation model by
5 inputting the post-polishing time into the extrapolation model.

4. The method of producing the reference spectral library according to claim 2, wherein the extrapolation model is a trained model constructed by machine learning using training data including the plurality of actual reference spectra and the plurality of actual
10 polishing times.

5. The method of producing the reference spectral library according to claim 4, wherein the machine learning is Long Short-Term Memory (LSTM).

15 6. The method of producing the reference spectral library according to claim 2, wherein the extrapolation model is a statistical model that analyzes the plurality of actual reference spectra and the plurality of actual polishing times according to a statistical algorithm and generates the pre-polishing reference spectrum and the post-polishing reference spectrum based on an analysis result.

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