

Various optical metrology systems, e.g., spectrographic or ellipsometric, can be used to measure the thickness of the substrate layer pre-polishing and post-polishing, e.g., at an in-line or stand-alone metrology station. In addition, various in-situ monitoring techniques, such as optical or eddy current monitoring, can be used to detect a polishing endpoint.

SUMMARY

In one aspect, a polishing system includes a polishing station including a platen to support a polishing pad, a support to hold a substrate, an in-line metrology station to measure the substrate before or after polishing of a surface of the substrate in the polishing station, and a controller. The in-line metrology station includes a color line-scan camera having detector elements arranged along a first axis that is parallel to the surface of the substrate during scanning of the substrate, an elongated white light source having a longitudinal axis parallel to the first axis and configured to direct light toward the substrate at a non-zero incidence angle during scanning of the substrate, a frame supporting the light source and the camera, and a motor to cause relative motion between the frame and the support along a second axis perpendicular to the first axis to cause the light source and the camera to scan across the substrate. The controller is configured to receive a color data from the camera, to generate a 2-dimensional color image from the color data, and to control polishing at the polishing station based on the color image.

Implementations may include one or more of the following features. A diffuser may be positioned in a path of light between the light source and the substrate. The non-zero angle is between 5° and 85° . A circular polarizer may be positioned in a light path between the substrate and the camera.

The motor may be coupled to the frame and controller may be configured to cause the substrate to be held stationary while the motor moves the frame with the light source to cause the line-scan camera to scan across the substrate. The frame may be fixed, the motor may be coupled to the support, and the controller may be configured to cause the motor to move the support while the light source and the camera remain stationary to scan across the substrate. The support may include a carrier head to hold the substrate against the polishing pad and the in-line metrology station may be positioned between the

FIG. 8 illustrates a graphical-user interface to permit a user to select regions in a hue-saturation space.

Like reference symbols in the various drawings indicate like elements.

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DETAILED DESCRIPTION

The thickness of a layer on a substrate can be optically measured before or after polishing, e.g., at an in-line or stand-alone metrology station. However, some optical techniques such as spectrometry require expensive spectrographs and computationally heavy manipulation of spectra data. Even apart from computational load, in some
10 situations the algorithm results do not meet the ever increasing accuracy requirements of the user. However, another metrology technique is to take a color image of the substrate, and analyze the image in a color space to determine regions with acceptable thickness.

Referring to FIG. 1, a polishing apparatus 100 includes an in-line (also referred to as in-sequence) optical metrology system 160, e.g., a color imaging system.

15 The polishing apparatus 100 includes one or more carrier heads 126, each of which is configured to carry a substrate 10, one or more polishing stations 106, and a transfer station to load substrate to and unload substrates from a carrier head. Each polishing station 106 includes a polishing pad 130 supported on a platen 120. The polishing pad 130 can be a two-layer polishing pad with an outer polishing layer and a
20 softer backing layer.

The carrier heads 126 can be suspended from a support 128, and movable between the polishing stations. In some implementations, the support 128 is an overhead track and the carrier heads 126 are coupled to a carriage 108 that is mounted to the track. The overhead track 128 allows each carriage 108 to be selectively positioned over the
25 polishing stations 106 and the transfer station. Alternatively, in some implementations the support 128 is a rotatable carousel, and rotation of the carousel moves the carrier heads 126 simultaneously along a circular path.

Each polishing station 106 of the polishing apparatus 100 can include a port, e.g., at the end of an arm 134, to dispense polishing liquid 136, such as abrasive slurry, onto
30 the polishing pad 130. Each polishing station 106 of the polishing apparatus 100 can also

include pad conditioning apparatus to abrade the polishing pad 130 to maintain the polishing pad 130 in a consistent abrasive state.

Each carrier head 126 is operable to hold a substrate 10 against the polishing pad 130. Each carrier head 126 can have independent control of the polishing parameters, for example pressure, associated with each respective substrate. In particular, each carrier head 126 can include a retaining ring 142 to retain the substrate 10 below a flexible membrane 144. Each carrier head 126 also includes a plurality of independently controllable pressurizable chambers defined by the membrane, e.g., three chambers 146a-146c, which can apply independently controllable pressurizes to associated zones on the flexible membrane 144 and thus on the substrate 10. Although only three chambers are illustrated in FIG. 1 for ease of illustration, there could be one or two chambers, or four or more chambers, e.g., five chambers.

Each carrier head 126 is suspended from the support 128, and is connected by a drive shaft 154 to a carrier head rotation motor 156 so that the carrier head can rotate about an axis 127. Optionally each carrier head 126 can oscillate laterally, e.g., by driving the carriage 108 on the track 128, or by rotational oscillation of the carousel itself. In operation, the platen is rotated about its central axis 121, and each carrier head is rotated about its central axis 127 and translated laterally across the top surface of the polishing pad. The lateral sweep is in a direction parallel to the polishing surface 212. The lateral sweep can be a linear or arcuate motion.

A controller 190, such as a programmable computer, is connected to each motor to independently control the rotation rate of the platen 120 and the carrier heads 126. For example, each motor can include an encoder that measures the angular position or rotation rate of the associated drive shaft. Similarly, the controller 190 is connected to an actuator in each carriage 108 and/or the rotational motor for the carousel to independently control the lateral motion of each carrier head 126. For example, each actuator can include a linear encoder that measures the position of the carriage 108 along the track 128.

The controller 190 can include a central processing unit (CPU) 192, a memory 194, and support circuits 196, e.g., input/output circuitry, power supplies, clock circuits, cache, and the like. The memory is connected to the CPU 192. The memory is a non-

beam expander, to spread the light from the light source into an elongated region. Alternatively or in addition, the light source 162 can include a linear array of light sources. The light source 162 itself, and the region illuminated on the substrate, can be elongated and have a longitudinal axis parallel to the surface of the substrate.

5 A diffuser 170 can be placed in the path of the light 168, or the light source 162 can include a diffuser, to diffuse the light before it reaches the substrate 10.

 The detector 164 is a color camera that is sensitive to light from the light source 162. The camera includes an array of detector elements. For example, the camera can include a CCD array. In some implementations, the array is a single row of detector
10 elements. For example, the camera can be a linescan camera. The row of detector elements can extend parallel to the longitudinal axis of the elongated region illuminated by the light source 162. Where the light source 162 includes a row of light emitting elements, the row of detector elements can extend along a first axis parallel to the longitudinal axis of the light source 162. A row of detector elements can include 1024 or
15 more elements.

 The camera 164 is configured with appropriate focusing optics 172 to project a field of view of the substrate onto the array of detector elements 178. The field of view can be long enough to view the entire width of the substrate 10, e.g., 150 to 300mm long. The camera 164, including associated optics 172, can be configured such that individual
20 pixels correspond to a region having a length equal to or less than about 0.5 mm. For example, assuming that the field of view is about 200 mm long and the detector 164 includes 1024 elements, then an image generated by the linescan camera can have pixels with a length of about 0.5 mm. To determine the length resolution of the image, the length of the field of view (FOV) can be divided by the number of pixels onto which the
25 FOV is imaged to arrive at a length resolution.

 The camera 164 can be also be configured such that the pixel width is comparable to the pixel length. For example, an advantage of a linescan camera is its very fast frame rate. The frame rate can be at least 5 kHz. The frame rate can be set at a frequency such that as the imaged area scans across the substrate 10, the pixel width is comparable to the
30 pixel length, e.g., equal to or less than about 0.3 mm.

The light source 162 and the light detector 164 can be supported on a stage 180. Where the light detector 164 is a line-scan camera, the light source 162 and camera 164 are movable relative to the substrate 10 such that the imaged area can scan across the length of the substrate. In particular, the relative motion can be in a direction parallel to the surface of the substrate 10 and perpendicular to the row of detector elements of the linescan camera 164.

In some implementations, the stage 180 is stationary, and the carrier head 126 moves, e.g., either by motion of the carriage 108 or by rotational oscillation of the carousel. In some implementations, the stage 180 is movable while the carrier head remains stationary for the image acquisition. For example, the stage 180 can be movable along a rail 184 by a linear actuator 182. In either case, this permits the light source 162 and camera 164 to stay in a fixed position relative to each other as the area being scanned moves across the substrate 10.

A possible advantage of having a line-scan camera and light source that move together across the substrate is that, e.g., as compared to a conventional 2D camera, the relative angle between the light source and the camera remains constant for different positions across the wafer. Consequently, artefacts caused by variation in the viewing angle can be reduced or eliminated. In addition, a line scan camera can eliminate perspective distortion, whereas a conventional 2D camera exhibits inherent perspective distortion, which then needs to be corrected by an image transformation.

The sensor assembly 161 can include a mechanism to adjust vertical distance between the substrate 10 and the light source 162 and detector 164. For example, the sensor assembly 161 can have an actuator to adjust the vertical position of the stage 180.

Optionally a polarizing filter 174 can be positioned in the path of the light, e.g., between the substrate 10 and the detector 164. The polarizing filter 184 can be a circular polarizer (CPL). A typical CPL is a combination of a linear polarizer and quarter wave plate. Proper orientation of the polarizing axis of the polarizing filter 184 can reduce haze in the image and sharpen or enhance desirable visual features.

Assuming that the outermost layer on the substrate is a semitransparent layer, e.g., a dielectric layer, the color of light detected at detector 164 depends on, e.g., the composition of the substrate surface, substrate surface smoothness, and/or the amount of

channel for both the unsmoothed image, shown by line 252, and the filtered image, shown by line 254.

In some implementations, the smoothing is performed only along the first axis. For example, the luminance values of the pixels along the direction of travel 186 can be averaged together to provide an average luminance value that is a function of just the position along the first axis. Then each row of image pixels can be divided by the corresponding portion of the average luminance value that is a function of the position along the first axis.

The controller can use image processing techniques to analyze the image to locate a wafer orientation feature 16, e.g., a wafer notch or wafer flat, on the substrate 10 (see FIG. 6) (step 240). Image processing techniques can also be used to locate a center 18 of the substrate 10 (see FIG. 6).

Based on this data, the image is transformed, e.g., scaled and/or rotated and/or translated, into a standard image coordinate frame (step 250). For example, the image can be translated so that the wafer center is at the center point of the image and/or the image can be scaled so that the edge of the substrate is at the edge of the image, and/or the image can be rotated so that there is a 0° angle between the x-axis of the image and the radial segment connecting the wafer center and the wafer orientation feature.

Optionally, an image mask can be applied to screen out portions of the image data (step 260). For example, referring to FIG. 6, a typical substrate 10 includes multiple dies 12. Scribe lines 14 can separate the dies 12. For some applications, it may be useful to process only image data corresponding to the dies. In this case, referring to FIG. 7, an image mask can be stored by the controller, with unmasked region 22 corresponding in spatial position to the dies 12 and masked region 24 corresponding to the scribe lines 14. Image data corresponding to the masked region 24 is not processed or not used during the thresholding step. Alternatively, the masked region 24 could correspond to the dies so that the unmasked region corresponds to the scribe lines, or the unmasked region could be only a portion of each die with a remainder of each die being masked.

The hue and saturation data at this stage can be used in feed-forward or feed-back algorithm use to control polishing parameters, providing improved thickness uniformity. For example, the hue and saturation for each pixel can be compared to a target hue and

saturation to generate an error signal image, and this error signal image can be used for feed-forward or feed-back control.

Next, the image is subjected to a thresholding process (step 270). In particular, a thresholding process can be performed for both the hue and saturation color channels. In some implementations, thresholding is not performed for the luminance channel.

For example, the controller 190 can store an upper hue limit UHL and a lower hue limit LHL for the hue channel, and an upper saturation limit USL and a lower saturation limit LSL for the saturation channel. For each pixel, the hue value H of the pixel is compared to the upper hue limit UHL and the lower hue limit LHL, and the saturation value S of the pixel is compared to the upper saturation limit USL and the lower saturation limit LSL. If the hue value and saturation value both fall within the limits, then the pixel is marked as “passing” the threshold, e.g., assigned a value of 1. In contrast, if either the hue value or the saturation value both fall outside the limits, then the pixel is marked as “failing” the threshold, e.g., assigned a value of 0. In short, the threshold image T(x,y) can be calculated as

if $LHL \leq H(x,y) \leq UHL$ AND $LSL \leq S(x,y) \leq USL$ then $T(x,y) = 1$ else $T(x,y) = 0$

In some implementations, the luminance value of the pixel is not compared to a threshold to determine the threshold image.

An advantage of performing thresholding in the hue-saturation color space is that spatial variations in the hue-saturation color space are generally due to variation in stack properties of the substrate, e.g., variations in thickness in one or more layers in the stack, rather than variations in the light source or other environmental factors. Consequently, thresholding in this space, rather than using luminance or an RGB color space, can provide increased reliability for detecting the substrate meets thickness specifications.

A user interface for setting thresholds in the hue-saturation space is illustrated in FIG. 8. The user interface 300 displays a histogram 302 of a test substrate in the hue-saturation color space. For example, the system 100 can be used to generate a color image of a test substrate that is determined with a conventional metrology system, e.g., a profilometer, to meet required thickness specifications. The number of pixels in the image having a given combination of hue and saturation are counted to generate a histogram of the hue-saturation color space. When displayed, each coordinate in the

histogram 302 can an intensity that scales with the counted number of pixels. As a result, the histogram 302 can have regions of different intensity, e.g., a regions 306 having a greater intensity than a region 304 indicates that more pixels in the image have a particular combination of hue and saturation in region 306 than a given combination of hue and saturation in region 304.

The user interface 300 can also display a cursor 310 overlaid on the histogram 302. The position of the cursor 310 can be adjusted using an input device, e.g., a mouse or touch-sensitive screen. By clicking and dragging from a first position 312 to a second position 314 in the histogram 302 (as shown by arrow 316), a selection box 320 can be defined. The boundaries of the selection box 320 thus define the upper and lower limits for the thresholds.

For example, for the histogram of FIG. 8 in which hue is shown on the y-axis and saturation on the x-axis. the upper hue limit UHL is the larger y-value of the first and second positions, the lower hue limit LHL is the smaller y-value of the first and second positions, the upper saturation limit USL is the larger x-value of the first and second positions, and the lower saturation limit LSL is the smaller x-value of the first and second positions. Of course, x and y values would be reversed if hue was shown on the x-axis and saturation on the y-axis.

Next, a uniformity analysis can be performed for each region of the substrate, e.g., each die, or for the entire image (step 280). For example, for each die, the total number of “failing” pixels within the die can be calculated. This total can be compared to a threshold to determine whether the die is acceptable, e.g., if the total is less than the threshold then the die is marked as acceptable. This gives a pass/fail indication for each die.

As another example, the total number of “failing” pixels within the unmasked region of the substrate can be calculated. This total can be compared to a threshold to determine whether the substrate is acceptable, e.g., if the total is less than the threshold then the substrate is marked as acceptable. The threshold can be set by a user. This gives a pass/fail indication for the substrate.

Where a die or a wafer is determined to “fail”, the controller 190 can generate an alert or cause the polishing system 100 to take corrective action. For example, an audible

processing apparatus, e.g., a programmable processor, a computer, or multiple processors or computers.

Terms of relative positioning are used to denote positioning of components of the system relative to each other, not necessarily with respect to gravity; it should be
5 understood that the polishing surface and substrate can be held in a vertical orientation or some other orientations.

A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made. For example

- Rather than a line scan camera, a camera that images the entire substrate
10 could be used. In this case, motion of the camera relative to the substrate is not needed.
- The camera could cover less than the entire width of the substrate. In this case, the camera would need to undergo motion in two perpendicular directions, e.g., be supported on an X-Y stage, in order to scan the entire substrate.
- The light source could illuminate the entire substrate. In this case, the
15 light source need not move relative to the substrate.
- The light detector can be a spectrometer rather than a color camera; the spectra data can then be reduced to the HSL color space.
- The sensor assembly need not an in-line system positioned between polishing stations or between a polishing station and a transfer station. For example, the
20 sensor assembly could be positioned within the transfer station, positioned in a cassette interface unit, or be a stand-alone system.
- The uniformity analysis step is optional. For example, the image generated by applying the threshold transformation can be fed into a feed-forward process to adjust a later processing step for the substrate, or into a feed-back process to
25 adjust the processing step for a subsequent substrate.

Accordingly, other implementations are within the scope of the claims.