

APPARATUS AND METHOD FOR THREE DIMENSIONAL INSPECTION OF WAFER SAW MARKS

5 CROSS REFERENCE TO RELATED APPLICATIONS

[001] This patent application claims priority of US provisional patent application No. 61/368,543 filed July 30, 2010, the application is incorporated herein by reference.

FIELD OF THE INVENTION

10 [002] The present invention relates to an apparatus for the three dimensional inspection of saw marks on at least one surface of a wafer.

[003] The invention relates as well to a method for determining saw marks on at least one surface of a wafer.

BACKGROUND OF THE INVENTION

15 [004] Silicon wafers are used to manufacture photovoltaic cells. Each silicon wafer is cut from an ingot with a specialized saw. The surface of the wafers needs to be inspected for various defects. One type of defect is caused by the process of sawing-off the wafer from the silicon ingot. Saw grooves or saw marks are local, elongated, 3-dimensional departures from the normally flat surface of the wafer. Each saw mark is extended and formed in the sliding direction of the saw and parallel to said solar cell wafer in the surface
20 of said solar cell wafer. In case of a cylindrical shaped ingot the saw marks run in the same direction as the saw is operated. In case of a cubical ingot the saw marks are almost parallel to one edge of the wafer. The length of the saw marks may vary between a few centimeters and the entire width of the wafer. Additionally, also the width and depth of the saw marks may vary. The form and status of a saw mark in a solar cell wafer influences the quality of
25 the solar cell wafer.

[005] Japanese patent application JP 2010-181328 A discloses a test equipment for a solar cell wafer surface which inspects a formation state of a saw mark in the surface of the solar cell wafer. The solar cell wafer being subject of examination is conveyed by a conveyor in a direction parallel to the longitudinal direction of a saw mark formed in the surface. The test equipment is provided with a floodlight, a camera and a computer. The floodlight is arranged at an oblique direction to the surface and is adapted for lighting a sub-division to the surface of said solar cell wafer. The lightning direction perpendicularly intersects the longitudinal direction of the saw mark. The floodlight is a halogen lamp, a fluorescent lamp, etc., for example. A diffusion plate is used to diffuse the light for irradiating said solar cell wafer. The camera generates data of the picture of the surface of said solar cell wafer. The imaging direction (optical axis direction) of said camera may be an oblique direction to the surface of said solar cell wafer.

[006] Japanese patent application JP 2008-134196 A discloses a technology wherein the picture of the surface of the solar cell wafer has dispersion in the light and darkness according to the grain boundary which exists in the solar cell wafer. In the picture of the surface of a solar cell wafer, the brightness of the image of said saw mark is relatively low. Therefore, the image of said saw mark cannot be exactly identified as a candidate of a defect.

[007] Japanese patent application JP 2005-345290 A discloses a technology, whereby a pixel of a predetermined number with high brightness is extracted from a division picture. In many cases, the problem is that an image of a saw mark cannot be exactly extracted from a picture of the surface of a solar cell wafer as a candidate for a defect. Therefore, it is difficult to set up a predetermined region centering on said pixel which distinguishes one image of said saw mark at a time.

[008] The Japanese patent application JP 2000-046743 A applies inspection light to a wafer where recesses and projections in a specific direction are formed in parallel from a specific direction. A plurality of LEDs is arranged in semi-circular shape, a lighting direction is controlled by a lighting-controlling device. The lighting-controlling device sets a lighting direction in the initial state of a wafer on a turntable and successively adjusts the

lighting direction for an angle based on a rotary angle signal from the encoder of the turntable. Cameras pick up the image of the edge part of the wafer every time when the turntable stops at a specific angle. An image-processing device picks up an image from the cameras and detects a defect by image processing.

5 [009] The German patent application DE 10 2009 010 837 A1 discloses a method for inspecting existence of sawing grooves on wafers utilized for manufacturing solar cells. The method involves projecting a light line on a wafer by a laser light source, and transporting the wafer on a transport device. The wafer is inspected during continuous transport of the wafer, where the wafer is arranged on the transport device such that sawing
10 grooves are aligned at a right-angle to a transportation direction. A partial region of the wafer is examined such that images of the partial region are recorded using a surface camera.

[0010] The prior art methods show drawbacks. The manual methods are slow and do not inspect all solar cell wafers. As a result there is an insufficient detection of the defect (saw
15 mark). Furthermore, many prior art methods are less accurate and less repeatable.

[0011] Some of the prior art methods only inspect part of the solar cell wafer, whereas saw grooves or saw marks can be present anywhere on the wafer. Particularly, also the deepest part of the saw groove can be anywhere on the wafer, too. As a consequence, the prior art methods may miss a groove completely or underestimate its depth. This also
20 results in an insufficient detection of the defect.

[0012] There are some prior art methods which inspect the solar cell wafers in one direction only. However, the wafers are on a moving belt, and consequently, grooves perpendicular to the direction of transport of the belt can be detected and measured. In order to provide a sufficient detection these methods require operators knowing the
25 direction in which the previous sawing process occurred. All wafers need to be placed in the same orientation onto the moving belt. As a consequence, the inspection process is slower, more error-prone, and less flexible.

- projecting a first pattern of lines of a first orientation onto the at least one surface of the wafer;
- capturing a first set of first images of the surface of the wafer, wherein for each image of the first pattern of lines the lines are shifted a definite distance perpendicular to the orientation of the first pattern of lines;
- projecting a second pattern of lines of a second orientation onto the surface of the wafer;
- capturing a second set of second images of the surface of the wafer, wherein for each image of the second pattern of lines the lines are shifted a definite distance perpendicular to the second orientation of the second pattern of lines;
- generating a combined first image from the set of first images and generating a combined second image from the set of second images, and thereby computing an improved set of first images from the combined first image and an improved set of second images from the combined second image;
- detecting grooves in at least one of the improved set of first images and in at least one of the improved set of second images;
- measuring a depth of a detected groove in at least one image of the improved set of first images or improved set of second images;
- averaging the depth of the grooves across the images of the improved set of first images and the images of the improved set of second images; and
- documenting the depth and the location and the orientation of the detected grooves on the surface of the wafer.

[0017] In case a second pattern of lines is projected in a second orientation onto the surface of the wafer. A second set of second images of the surface of the wafer is captured, wherein for each image of the second pattern of lines the lines are shifted a definite distance perpendicular to the second orientation of the second pattern of lines. The first pattern of lines may be identical to second pattern of lines. The only difference is that the first pattern of lines is not parallel to the second pattern of lines.

light bundle between the first and second line projectors respectively and the surface of the wafer. This arrangement of the first and second line projectors is advantageous if there is no information available about the orientation of the saw grooves or saw marks on the surface of the wafer.

5 [0020] A further embodiment of the invention enables to simultaneously capture the front side and the back side of the wafer. The inventive apparatus comprises two cameras. Each camera defines a field of view and being arranged perpendicular to a plane of the front side of the wafer and the back side of the wafer. The field of view of the two cameras is designed such that the entire front side and the entire back side respectively of the wafer is captured. At least one first line projector providing a light bundle which is centered
10 about a central beam axis, wherein the first line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane and the front side respectively of the wafer. At least one second line projector providing a light bundle which is centered about a central beam axis, wherein the second line projector is arranged such
15 that the central beam axis is arranged at an acute angle with regard to the plane and the back side of the wafer respectively. A line shifter is positioned in the light bundle between each line projector and the surface of the wafer.

[0021] Moving means may be provided for enabling a relative rotation between the wafer and the at least one line projector. The relative rotation is such that the acute angle of the at
20 least line projector with regard to the plane of the wafer is maintained. With the moving means it is possible to project a second pattern of a plurality of lines in a second orientation onto the surface of the wafer. Preferably, the lines of the first pattern of lines are perpendicular to the lines of the second pattern of lines. According to one embodiment, the moving means rotates the wafer so that the first pattern of lines and the second pattern of
25 lines can be projected one after the other onto the surface of the wafer. Another possibility is that the line projector is pivoted with respect to the surface of the wafer. In a first orientation the line projector projects a first pattern of lines and in a second orientation the line projector projects a second pattern of lines onto the surface of the wafer. The frame grabber and the image processor synchronize the image capture of the first pattern of lines
30 and the second pattern of lines projected onto the surfaces of the wafer, the position of the

line projectors enclose an angle of 90° with respect to the X- and Y-directions of a Cartesian coordinate system. The respective central beam axis of each line projector encloses an angle of 18° with the plane of the wafer (horizontal plane). The camera is looking down vertically and three images are captured by the camera. The first set of
5 images is captured whilst the first line projector is illuminated. A motor tilts a 2mm thick glass plate in front of each line projector. The tilt angles are -4.44° , 0° and 4.44° relative to the respective perpendicular central beam axis of the respective line shifter. For each tilt angle an image is captured. The captured images are combined in order to remove unwanted artifacts. Image processing methods look for and measure saw marks or saw
10 grooves in each set of the three images.

[0029] According to a preferred embodiment of a method of the present invention the orientation of the saw marks is known a priori, for example from a preceding inspection step. At least one camera and at least two line projectors are needed in order to detect saw marks/grooves on a wafer. Each line projector can project a pattern of a plurality of lines
15 onto a front side or a back side of the wafer and thereby covering at least a portion of the surface of the front side or the back side of the wafer. The patterns of lines of the line projectors are under an angle with respect to each other, that means the patterns of lines of the line projectors are not parallel but of different orientations. In a preferred embodiment consisting of two line projectors the two patterns of lines of the line projectors are
20 approximately perpendicular to each other. Additionally at least one of the patterns of lines is oriented at an angle with respect to the saw marks. In a preferred embodiment the lines of one projector are oriented approximately perpendicular to the saw marks. The a priori information about the orientation of the saw marks is used to select the line projector that projects the line pattern that is closest to perpendicular to the saw marks. This line project
25 is used during image capture to project line patterns. A first set of first images of the surface of the wafer is captured, wherein for each image of the first pattern of lines the lines is shifted a definite distance perpendicular to the orientation of the first pattern of lines. A combined first image from the set of first images is generated, and thereby computing an improved set of first images from the combined first image. Grooves are
30 detected in at least one of the improved set of first images. Finally an averaging and

documenting step is carried out. (The advantage of this embodiment is that throughput can be higher because image capture time is minimized).

[0030] Finally, the apparatus reports the position and depth of the deepest saw marks detected. The saw grooves or saw marks are measured in pixels by estimating the position of each line on either side of the saw groove by means of curve fitting. The differences between the two sides are computed by averaging over a certain distance along the groove. A calibration model is used to translate depth measured in pixel to depth expressed in actual distance units. The calibration model takes into account the perspective and other distortion caused by the line projectors and the camera.

10 BRIEF DESCRIPTION OF THE DRAWINGS

[0031] The nature and mode of operation of the present invention will now be more fully described in the following detailed description of the invention taken with the accompanying drawing figures, in which

[0032] Figure 1 shows a part of a saw groove which has a step-like shape and the image is taken with a confocal microscope;

[0033] Figure 2 shows a schematic side view of an embodiment of an apparatus for three dimensional inspection of wafer saw marks, wherein at least one line projector is used;

[0034] Figure 3 shows a schematic side view of another embodiment of the apparatus for the three dimensional inspection of wafer saw marks, wherein means for carrying out a relative rotational motion between the wafer and the single line projector are provided so that the wafer surface can be illuminated in two different orientations;

[0035] Figure 4 shows a schematic side view of the apparatus for the three dimensional inspection of wafer saw marks, wherein according to this embodiment the front side and the back side of the wafer are inspected simultaneously by at least two line projectors;

projector according to Fig. 7B, and the glass plate in the second illumination light bundle, the glass plate being tilted in the counter clockwise direction; and

[0044] Figure 10 shows a schematic flow chart of the inventive method to detect saw marks oriented in both directions on the surface of a wafer.

5 DETAILED DESCRIPTION OF THE INVENTION

[0045] Same reference numerals refer to same elements throughout the various figures. Furthermore, only reference numerals necessary for the description of the respective figure are shown in the figures. The shown embodiments represent only examples of how the apparatus and method according to the invention can be designed. This should not be
10 regarded as limiting the invention.

[0046] **Fig. 1** shows a partial view of a saw groove 2 on the front side 3F of a wafer 4 (see **Fig. 2**), wherein the saw groove 2 has a step-like shape. Silicon wafers used to manufacture photovoltaic cells need to be inspected for various defects. One type of defect is caused by the process of sawing-off the wafer from a silicon ingot (not shown). The form
15 of the silicon ingot can be a cuboid or a cylinder. Consequently, wafer 4 is round or rectangular, respectively. Saw grooves 2 or saw marks are local, elongated and 3-dimensional departures from the normally flat front side 3F or back side 3b of wafer 4. In case wafer 4 is rectangular the saw grooves 2 run almost parallel to the edge of wafer 4, in the same direction as the saw, and their length can vary between a few centimeters and the
20 entire width of wafer 4. The width of saw grooves 2 and their depth can also vary.

[0047] **Fig. 2** shows a schematic side view of an embodiment of the inventive apparatus 1 for the three dimensional inspection of saw marks 2 on at least one surface 3 of wafer 4. The surface 3 of wafer 4 is the front side 3F or the back side 3B of wafer 4. Surface 3 of wafer 4 is imaged by a camera 6 defining a field of view 7 and being arranged
25 perpendicular to a plane P of wafer 4. The optical system 15 of camera 6 is designed such that next to defining the field of view 7 also the entire surface 3 of wafer 4 is captured by a sensor (not shown) of camera 6. The sensor can be an area sensor or can work according to

[0058] The embodiments of the apparatus 1 disclosed in **Figs. 2 to 4** are exemplary embodiments and should not be considered as a limitation of the invention. A skilled person in the art would consider as well an apparatus 1 with a first line projector 8₁, a second line projector 8₂, a third line projector 8₃ (not shown) and a fourth line projector 8₄ (not shown). In this embodiment the first line projector 8₁ and the third line projector 8₃ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the front side 3F of wafer 4. The second line projector 8₂ and the fourth line projector 8₄ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the back side 3B of wafer 4. In order to speed up image capture it is possible to use different wavebands for each line projector 8₁, 8₂, 8₃ or 8₄. At least one color sensitive camera or a camera with filters is required to capture the images.

[0059] In a further embodiment (not shown) a first line projector 8₁ and a second line projector 8₂ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the front side 3F of wafer 4.

[0060] The wafers 4 to be inspected rest on a belt (not shown) which transports the wafers 4 into the inspection position, i. e., into the field of view 7 of the camera 6. It is possible to inspect the front side 3F of the wafer 4. As disclosed in **Fig. 4** the front side 3F and the back side 3B of the wafer 4 can be inspected simultaneously while the wafer 4 is held by a vacuum pick-up gear (not shown) or any equivalent.

[0061] **Fig. 5** shows a schematic top view of a wafer 4 used for solar cells, wherein wafer 4 has the shape of a rectangle. As mentioned above, wafer 4 is sawed-off from a silicon ingot. Since the form of the silicon ingot is a cuboid, the wafer 4 is rectangular. The saw marks 2 on the front side 3F of wafer 4 are oriented along a direction 35 of the saw.

[0062] **Fig. 6** shows a schematic view of an image 40 of the wafer 4 according to **Fig. 5**. Wafer 4 is registered by pixels 60_{n,m} of an image sensor of camera 6, wherein the field of view 7 of camera 6 captures the entire surface, here the front side 3F, of wafer 4. The image sensor of camera 6 with the plurality of pixels 60_{n,m} is oriented with wafer 4 so that

skilled person in the art that the amount of images 40 taken per set is not limited to three images 40.

[0067] **Fig. 10** shows a schematic flow chart of the inventive method to detect saw marks 2 on the surface 3 of a wafer 4. As shown in **Figs. 7A, 7B, 8A, 8B, 9A, and 9B** a first line projector 8₁ and a second line projector 8₂ are arranged to illuminate the front side 3F of wafer 4. The first line projector 8₁ and the second line projector 8₂ are positioned such that their respective central beam axes 9 are perpendicular to each other. Initially, first line projector 8₁ projects a first pattern 20 of lines 22 of a first orientation (parallel to the X-direction) onto the at least one surface 3 of wafer 4. A first raw image 51, a second raw image 52 and a third raw image 53 are captured, wherein for each raw image 51₁, 52₁, 53₁ of the first pattern 20 of lines 22 the lines 22 are shifted a definite distance perpendicular to the orientation of the first pattern 20 of lines 22. The same is done with a second set of raw images 51₂, 52₂, 53₂ of a second pattern 20 of lines 22, wherein the lines 22 are oriented parallel to the Y-direction.

[0068] After the raw images 51₁, 52₁, 53₁ and 51₂, 52₂, 53₂ of each set are captured, the multiple raw images 51₁, 52₁, 53₁ and 51₂, 52₂, 53₂ in each orientation are combined to improve the quality of each image and to remove unwanted artifacts. A reference image 54₁, 54₂ is computed, wherein the pixel values of the first reference image 54₁ are maximum pixel values of the first set of raw images 51₁, 52₁, 53₁. Analogously, a second reference image 54₂ is computed, wherein the pixel values of the second reference image 54₂ are maximum pixel values of the second set of raw images 51₂, 52₂, 53₂. In the next step each image of the first set of raw images 51₁, 52₁, 53₁ and each image of the second set of raw images 51₂, 52₂, 53₂ is divided by the first reference image 54₁ and the second reference image 54₂ respectively. The first set of raw images 51₁, 52₁, 53₁ and the second set of raw images 51₂, 52₂, 53₂ are numerically rescaled which is done by multiplying them with a constant value in order to obtain the same range of values (for example 0 – 255) as the original images have.

[0069] In the next process step, candidate grooves (saw grooves 2) are detected in all improved images. Assuming, without any loss generality, that the projected lines are

approximately horizontal in the image, the groove detection is achieved by a variety of steps. Firstly, a detection of a location of the projected lines 22 is carried out in each column of pixels $60_{n,m}$. Secondly, each line 22 is tracked horizontally and local deviations from a straight line are computed. Thirdly, a Hough transformation is carried out with
5 positions of a straight line where the local deviation is above a threshold. Fourthly, peaks are searched in the Hough transformation, which correspond to the position and orientation of detected grooves 2.

[0070] According to a further embodiment of the invention the raw images #1, #2 and #3 are combined into one single image of improved quality. That is done by a process known
10 as "phase shift extraction" that compares the intensity of the three images 51_1 , 52_1 , 53_1 at each pixel location. The combined image is known as a "phase image". The grooves are detected and measured in the phase image. The nature of the phase image is such that phase jumps (from $-\pi$ to $+\pi$ or from $+\pi$ to $-\pi$) must be taken into account ("unwrapped") when line fits and deviations are computed.

15 [0071] In next step, the depths of the detected grooves 2 in all improved images are measured. For each candidate groove 2 detected, a high and low point of a groove profile is computed along each direction of a detected groove 2. The computation starts from the tracked line positions. The high points and low points are tracked across adjacent directions or lines. A local depth of detected grooves 2 is estimated by means of curve fittings
20 through line positions near the high and low points. An average depth of the grooves is estimated in pixels over a certain length along the groove 2 by means of a moving average. Finally, the depth of the groove 2 is translated from pixels to microns by means of pre-computed calibration parameters.

[0072] In a next step, the depth of the grooves 2 is averaged, which is achieved by an
25 averaged depth profile computed in three dimensions over the improved set of first images 51_1 , 52_1 , 53_1 and set of second images 51_2 , 52_2 , 53_2 . At the end, the location and depth of the grooves 2 are reported. A file is written, from which file the location and the depth of the grooves 2 can be retrieved by a line engineer. The location and the depth of the deepest saw groove 2 on the surface 3 of wafer 4 is retrievable from the file as well.

REFERENCE NUMERALS:

	1	apparatus
	2	saw mark; saw groove
	3	surface
5	3B	back side of wafer
	3F	front side of wafer
	4	wafer
	5	light bundle
	6, 6 ₁ , 6 ₂	camera
10	7	field of view
	8	line projector
	8 ₁	first line projector
	8 ₂	second line projector
	8 ₃	third line projector
15	8 ₄	forth line projector
	9	central beam axis
	10	light source
	11	motor
	12	line shifter
20	12G	glass plate
	14	frame grabber
	15	optical system
	16	image processor
	18	patterned glass plates
25	19	propagation direction
	20	pattern
	22	lines
	24	exit lens
	26	condenser lense; condenser system
30	27	first glass plate
	28	second glass plate

WHAT IS CLAIMED IS:

1. Apparatus for three dimensional inspection of saw marks on at least one surface of a wafer comprising:
 - 5 • at least one camera defining a field of view and being arranged to image a plane of the wafer, wherein the field of view is designed such that at least a portion of a surface of the wafer is captured;
 - 10 • at least one line projector providing a light bundle centered about a central beam axis, wherein the at least one line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane of the wafer, and wherein the at least one line projector is provided with light from at least one light source and is adapted to project a pattern of a plurality of lines onto a front side and/or a back side of the wafer and thereby covering at least a portion of the surface of the front side or the back side of the wafer;
 - 15 • at least one line shifter being positioned in the light bundle between the line projector and the surface of the wafer; and
 - a frame grabber and an image processor, wherein image capture of the front side or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the front side and/or the back side of the wafer.
- 20 2. Apparatus of claim 1, wherein the at least one line projector and the surface of the wafer are placeable with respect to each other such that the at least one line projector projects a first and a second pattern of lines onto the surface of the wafer, wherein the first pattern of lines is oriented at an angle with respect to the second pattern of lines.
- 25 3. Apparatus of claim 2, wherein the lines of the first pattern of lines are perpendicular to the lines of the second pattern of lines.

4. Apparatus of claim 1, wherein the at least one line shifter is a glass plate and connected to a motor for rotating the glass plate so that the first or second pattern of lines is shifted on the surface of the wafer.
5. Apparatus of claim 1, wherein the at least one line shifter has a plurality of glass plates, each glass plate being arranged at a different angle in a positioner, the positioner being drivable by a motor in order to bring a glass plate of a different tilt angle into the light bundle so that the first or second pattern of lines is shifted on the surface of the wafer.
- 10 6. Apparatus of claim 1, wherein each of the at least one line projectors has two patterned glass plates with a pattern of lines arranged between an exit lens and a condenser system, wherein a first glass plate has a variable-pitch Ronchi ruling in order to compensate for a perspective effect and to project the uniform pattern of lines onto the surface of the wafer and the second glass plate has a variable transmittance pattern to compensate for a perspective effect and to project the pattern of lines of uniform brightness onto the surface of the wafer.
- 15 7. Apparatus of claim 1, wherein the at least one light source is directly attached to the at least one line projector.
8. Apparatus of claim 7, wherein the at least one light source comprises LEDs.
9. Apparatus of claim 1, wherein the at least one light source is connected to the at least one line projector via a light guide.
- 20 10. Apparatus of claim 9, wherein the at least one light source comprises LEDs.
11. Apparatus of claim 1, wherein the at least one camera is communicatively connected to the frame grabber and the image processor so that a motion of the at least one line shifter, a switching of the at least one light source and a capture of an image of the surface of the wafer at different positions of the pattern of lines on the surface of the wafer are synchronized by the frame grabber.
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12. Method for determining saw marks on at least one surface of a wafer, comprising the steps of:

- projecting a first pattern of lines of a first orientation onto the at least one surface of the wafer wherein an orientation of the saw marks is unknown;
- 5 • capturing a first set of first images of the surface of the wafer, wherein for each image of the first pattern of lines the lines are shifted a definite distance perpendicular to the orientation of the first pattern of lines;
- projecting a second pattern of lines of a second orientation onto the surface of the wafer
- 10 • capturing a second set of second images of the surface of the wafer, wherein for each image of the second pattern of lines the lines are shifted a definite distance perpendicular to the second orientation of the second pattern of lines;
- generating a combined first image from the set of first images and generating a combined second image from the set of second images, and thereby computing
- 15 an improved set of first images from the combined first image and an improved set of second images from the combined second image;
- detecting grooves in at least one of the improved set of first images and in at least one of the improved set of second images;
- measuring a depth of a detected groove in each image of the improved set of
- 20 first images and in each image of the improved set of second images;
- averaging the depth of each groove across the images of the improved set of first images or the images of the improved set of second images; and
- documenting the depth and the location and the orientation of the detected grooves on the surface of the wafer.

25 13. Method according to claim 12, wherein the combined first image and the combined second image is achieved by:

- computing a first reference image, wherein the pixel values of the first reference image are maximum pixel values of the first set of images and computing a
- 30 second reference image, wherein the pixel values of the second reference image are maximum pixel values of the second set of images;

- dividing each image of the first set of images and each image of the second set of images by the respective reference image; and
 - numerically rescaling the first set of images and the second set of images.
14. Method according to claim 12, wherein the detection of the grooves in at least one image of the improved set of first images and the improved set of second images is achieved by:
- detecting a location of the projected lines in each column of pixels;
 - tracking the detected lines along a specific direction;
 - computing local deviations from a straight line along the specific direction;
 - carrying out a Hough transformation with positions of a straight line where the local deviation is above a threshold; and
 - finding peaks in the Hough transformation, which correspond to position and orientation of detected grooves.
15. Method as defined in claim 12, wherein the measuring of depth of a detected groove is achieved by:
- computing for each detected groove a high and low point of a groove profile along each direction of a detected groove;
 - tracking high points and low points across adjacent directions;
 - estimating a local depth of detected grooves by means of curve fittings along line positions near the high and low points;
 - estimating in pixels an average depth of the grooves over a certain length along the groove by means of a moving average; and
 - translating the depth of the groove from pixels to microns by means of pre-computed parameters.
16. Method as defined in claim 12, wherein the averaging of the depth of the grooves is achieved by averaging a depth profile computed in three dimensions over the improved first set of images or second set of images.

17. Apparatus for three dimensional inspection of saw marks on a surface of a wafer comprising:
- a camera, defining a field of view and being arranged perpendicular to a plane of the wafer, wherein the field of view is designed such that an entire surface of the wafer is captured;
 - a first line projector providing a light bundle, centered about a central beam axis, wherein the first line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane of the wafer, wherein the first line projector is provided with light from a light source and is adapted to project a pattern of a plurality of lines in a first orientation onto a front side or a back side of the wafer and thereby covering the complete surface of the front side or the back side of the wafer;
 - a second line projector providing a light bundle, centered about a central beam axis, wherein the second line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane of the wafer, wherein the second line projector is provided with light from a light source and is adapted to project a pattern of a plurality of lines in a second orientation onto the front side or the back side of the wafer and thereby covering the complete surface of the front side or the back side of the wafer;
 - a line shifter is positioned in each light bundle between the first and second line projector respectively and the surface of the wafer; and
 - a frame grabber and an image processor, wherein image capture of the front side or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the front side or the back side of the wafer.
18. Apparatus of claim 17, wherein the first pattern of plurality of lines is perpendicular to the second pattern of plurality of lines.
19. Apparatus of claim 17, wherein the line shifter is a glass plate and connected to a motor for rotating the glass plate so that the first or second pattern of a plurality of lines is shifted on the surface of the wafer.

20. Apparatus of claim 17, wherein the line shifter has a plurality of glass plates and each glass plate is arranged at a different angle in a positioner which is drivable by a motor in order to bring a glass plate of a different tilt angle into the light bundle of the first and second line projector respectively, so that the first and the second the pattern of lines is shifted on the surface of the wafer in an X-direction and in a Y-direction respectively.
21. Apparatus of claim 17, wherein the first and the second line projector has two patterned glass plates each with a pattern of lines arranged between an exit lens and a condenser system, wherein a first glass plate has a variable-pitch Ronchi ruling in order to compensate for a perspective effect and to project the uniform pattern of lines onto the surface of a wafer and the second glass plate has a variable transmittance pattern to compensate for a perspective effect and to project a pattern of lines of uniform brightness onto the surface of a wafer.
22. Apparatus of claim 17, wherein the camera is communicatively connected to the frame grabber and the image processor so that a motion of the line shifter, a switching of the at least one light source and a capture of an image of the pattern on the surface of the wafer produced by the first line projector and the second line projector are synchronized and coordinated by the frame grabber.
23. Apparatus for three dimensional inspection of saw marks on a surface of a wafer comprising:
- a camera, defining a field of view and being arranged perpendicular to a plane of the wafer, wherein the field of view is designed such that an entire surface of the wafer is captured;
 - one line projector providing a light bundle, centered about a central beam axis, wherein the line projector such that the central beam axis is arranged at an acute angle with regard to the plane of the wafer, wherein the line projector is provided with light from a light source and is adapted to project a first pattern of a plurality of lines in a first orientation onto surface of the wafer and thereby covering the complete surface of the wafer;

- at least one line shifter 12 is positioned in the light bundle between the line projector and the surface of the wafer;
- moving means for providing a relative rotation between the wafer and the line projector and thereby maintaining the acute angle of the line projector with regard to the plane of the wafer in order to project a second pattern of a plurality of lines in a second orientation onto the surface of the wafer; and
- a frame grabber and an image processor, wherein image capture of the first pattern of lines and the second pattern of lines projected onto the surface of the wafer is synchronized by the frame grabber in coordination with the position of the line shifter in the light bundle and the relative rotational position of the wafer and the line projector.

24. Apparatus for three dimensional inspection of saw marks on a surface of a wafer comprising:

- two cameras, each defining a field of view and each being arranged perpendicular to a plane of the front side of the wafer and the back side of the wafer, wherein the field of view of the two cameras is designed such that an entire front side and the entire back side respectively of the wafer is captured;
- at least one first line projector providing a light bundle, centered about a central beam axis, wherein the first line projector is arranged such that the central beam axis is at an acute angle with regard to the plane and the front side of the wafer respectively, at least one second line projector providing a light bundle, centered about a central beam axis, wherein the second line projector is arranged such that the central beam axis is at an acute angle with regard to the plane and the back side of the wafer respectively, wherein the at least first and second line projector are provided with light from at least one light source and are adapted to project a pattern of a plurality of lines onto a front side and/or the back side of the wafer and thereby covering the complete surface of the front side or the back side of the wafer;
- at least one line shifter is positioned in the light bundle between the line projector and the surface of the wafer; and

- a frame grabber and an image processor, wherein image capture of the front side or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the front side and/or the back side of the wafer.

5 25. Apparatus of claim 24, wherein moving means enable a relative rotation between the wafer and the line projectors and thereby maintaining the acute angle of the line projectors with regard to the plane of the wafer in order to project a second pattern of a plurality of lines in a second orientation onto the surface of the wafer, and the frame grabber and the image processor synchronize the image capture of the first
10 pattern of lines and the second pattern of lines projected onto the surfaces of the wafer, the position of the line shifter in the light bundle and the relative rotational position of the wafer and the line projector with respect to each other.

26. Apparatus for three dimensional inspection of saw marks on at least one surface of a wafer comprising:

- 15
- at least one camera defining a field of view and being arranged to image a plane of the wafer, wherein the field of view is designed such that at least a portion of a surface of the wafer is captured;
 - means for loading the wafer so that the saw marks are in a defined orientation in the field of view of the camera;

20

 - at least one line projector providing a light bundle centered about a central beam axis, wherein the at least one line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane of the wafer, and wherein the at least one line projector is provided with light from at least one light source and is adapted to project a pattern of a plurality of lines onto a
25 front side and/or a back side of the wafer and thereby covering at least a portion of the surface of the front side or the back side of the wafer;
 - at least one line shifter being positioned in the light bundle between the line projector and the surface of the wafer; and
 - a frame grabber and an image processor, wherein image capture of the front side or the back side of the wafer is synchronized by the frame grabber in
30

coordination with the position of the pattern of lines on the front side and/or the back side of the wafer.

27. Method for determining saw marks on at least one surface of a wafer, comprising the steps of:

- 5 • determining an orientation of the saw marks on the wafer;
- providing at least one line projector;
- projecting a first pattern of lines of a first orientation onto the at least one surface of the wafer, wherein the first pattern of lines is oriented at an angle with respect to the saw marks;
- 10 • capturing a first set of first images of the surface of the wafer, wherein for each image of the first pattern of lines the lines is shifted a definite distance perpendicular to the orientation of the first pattern of lines;
- generating a combined first image from the set of first images, and thereby computing an improved set of first images from the combined first image;
- 15 • detecting grooves in at least one of the improved set of first images;
- measuring a depth of a detected groove in each image of the improved set of first images;
- averaging the depth of each groove across the images of the improved set of first images; and
- 20 • documenting the depth and the location and the orientation of the detected grooves on the surface of the wafer.

28. Method of claim 27, wherein moving means are provided for enabling a relative rotation between the wafer and the at least one line projector so that the orientation of the saw marks on the wafer is not parallel with the first pattern of lines projected onto the surface of the wafer.

APPARATUS AND METHOD FOR THREE DIMENSIONAL INSPECTION OF WAFER SAW MARKS

5 CROSS REFERENCE TO RELATED APPLICATIONS

[001] This patent application claims priority of US provisional patent application No. 61/369,543 filed July 30, 2010, the application is incorporated herein by reference.

FIELD OF THE INVENTION

10 [002] The present invention relates to an apparatus for the three dimensional inspection of saw marks on at least one surface of a wafer.

[003] The invention relates as well to a method for determining saw marks on at least one surface of a wafer.

BACKGROUND OF THE INVENTION

15 [004] Silicon wafers are used to manufacture photovoltaic cells. Each silicon wafer is cut from an ingot with a specialized saw. The surface of the wafers needs to be inspected for various defects. One type of defect is caused by the process of sawing-off the wafer from the silicon ingot. Saw grooves or saw marks are local, elongated, 3-dimensional departures from the normally flat surface of the wafer. Each saw mark is extended and formed in the sliding direction of the saw and parallel to said solar cell wafer in the surface
20 of said solar cell wafer. In case of a cylindrical shaped ingot the saw marks run in the same direction as the saw is operated. In case of a cubical ingot the saw marks are almost parallel to one edge of the wafer. The length of the saw marks may vary between a few centimeters and the entire width of the wafer. Additionally, also the width and depth of the saw marks may vary. The form and status of a saw mark in a solar cell wafer influences the quality of
25 the solar cell wafer.

[005] Japanese patent application JP 2010-181328 A discloses a test equipment for a solar cell wafer surface which inspects a formation state of a saw mark in the surface of the solar cell wafer. The solar cell wafer being the subject of examination is conveyed by a conveyor in a direction parallel to the longitudinal direction of a saw mark formed in the surface. The test equipment is provided with a floodlight, a camera and a computer. The floodlight is arranged at an oblique direction to the surface and is adapted for lighting a sub-division to the surface of said solar cell wafer. The lighting direction perpendicularly intersects the longitudinal direction of the saw mark. The floodlight is a halogen lamp, a fluorescent lamp, etc., for example. A diffusion plate is used to diffuse the light for irradiating said solar cell wafer. The camera generates data of the picture of the surface of said solar cell wafer. The imaging direction (optical axis direction) of said camera may be an oblique direction to the surface of said solar cell wafer.

[006] Japanese patent application JP 2008-134196 A discloses a technology wherein the picture of the surface of the solar cell wafer has dispersion in the light and darkness according to the grain boundary which exists in the solar cell wafer. In the picture of the surface of a solar cell wafer, the brightness of the image of said saw mark is relatively low. Therefore, the image of said saw mark cannot be exactly identified as a candidate of a defect.

[007] Japanese patent application JP 2005-345290 A discloses a technology, whereby a pixel of a predetermined number with high brightness is extracted from a division picture. In many cases, the problem is that an image of a saw mark cannot be exactly extracted from a picture of the surface of a solar cell wafer as a candidate for a defect. Therefore, it is difficult to set up a predetermined region centering on said pixel which distinguishes one image of said saw mark at a time.

[008] The Japanese patent application JP 2000-046743 A applies inspection light to a wafer where recesses and projections in a specific direction are formed in parallel from a specific direction. A plurality of LEDs is arranged in a semi-circular shape, and a lighting direction is controlled by a lighting-controlling device. The lighting-controlling device sets a lighting direction in the initial state of a wafer on a turntable and successively adjusts the

lighting direction for an angle based on a rotary angle signal from the encoder of the turntable. Cameras pick up the image of the edge part of the wafer every time the turntable stops at a specific angle. An image-processing device picks up an image from the cameras and detects a defect by image processing.

5 [009] The German patent application DE 10 2009 010 837 A1 discloses a method for inspecting for the existence of sawing grooves on wafers utilized for manufacturing solar cells. The method involves projecting a light line on a wafer by a laser light source, and transporting the wafer on a transport device. The wafer is inspected during continuous transport of the wafer, where the wafer is arranged on the transport device such that sawing
10 grooves are aligned at a right-angle to a transportation direction. A partial region of the wafer is examined such that images of the partial region are recorded using a surface camera.

[0010] The prior art methods show drawbacks. The manual methods are slow and do not inspect all solar cell wafers. As a result there is an insufficient detection of the defect (saw
15 mark). Furthermore, many prior art methods are less accurate and less repeatable.

[0011] Some of the prior art methods only inspect part of the solar cell wafer, whereas saw grooves or saw marks can be present anywhere on the wafer. Particularly, also the deepest part of the saw groove can be anywhere on the wafer, too. As a consequence, the prior art methods may miss a groove completely or underestimate its depth. This also
20 results in an insufficient detection of the defect.

[0012] There are some prior art methods which inspect the solar cell wafers in one direction only. However, the wafers are on a moving belt, and consequently, grooves perpendicular to the direction of transport of the belt can be detected and measured. In order to provide a sufficient detection these methods require operators knowing the
25 direction in which the previous sawing process occurred. All wafers need to be placed in the same orientation onto the moving belt. As a consequence, the inspection process is slower, more error-prone, and less flexible.

- projecting a first pattern of lines of a first orientation onto the at least one surface of the wafer;
- capturing a first set of first images of the surface of the wafer, wherein for each image of the first pattern of lines the lines are shifted a definite distance perpendicular to the orientation of the first pattern of lines;
- 5 • projecting a second pattern of lines of a second orientation onto the surface of the wafer;
- capturing a second set of second images of the surface of the wafer, wherein for each image of the second pattern of lines the lines are shifted a definite distance
- 10 perpendicular to the second orientation of the second pattern of lines;
- generating a combined first image from the set of first images and generating a combined second image from the set of second images, and thereby computing an improved set of first images from the combined first image and an improved set of second images from the combined second image;
- 15 • detecting grooves in at least one of the improved set of first images and in at least one of the improved set of second images;
- measuring a depth of a detected groove in at least one image of the improved set of first images or improved set of second images;
- averaging the depth of the grooves across the images of the improved set of first images and the images of the improved set of second images; and
- 20 • documenting the depth and the location and the orientation of the detected grooves on the surface of the wafer.

[0017] In case a second pattern of lines is projected in a second orientation onto the surface of the wafer, a second set of second images of the surface of the wafer is captured

25 wherein for each image of the second pattern of lines the lines are shifted a definite distance perpendicular to the second orientation of the second pattern of lines. The first pattern of lines may be identical to second pattern of lines. The only difference is that the first pattern of lines is not parallel to the second pattern of lines.

light bundle between the first and second line projectors respectively and the surface of the wafer. This arrangement of the first and second line projectors is advantageous if there is no information available about the orientation of the saw grooves or saw marks on the surface of the wafer.

5 [0020] A further embodiment of the invention enables to simultaneously capture the front side and the back side of the wafer. The inventive apparatus comprises two cameras. Each camera defines a field of view and is arranged perpendicular to a plane of the front side of the wafer and the back side of the wafer. The field of view of the two cameras is designed such that the entire front side and the entire back side respectively of the wafer is
10 captured. At least one first line projector provides a light bundle which is centered about a central beam axis, wherein the first line projector is arranged such that the central beam axis is arranged at an acute angle with regard to the plane and the front side respectively of the wafer. At least one second line projector provides a light bundle which is centered about a central beam axis, wherein the second line projector is arranged such that the
15 central beam axis is arranged at an acute angle with regard to the plane and the back side of the wafer respectively. A line shifter is positioned in the light bundle between each line projector and the surface of the wafer.

[0021] Moving means may be provided for enabling a relative rotation between the wafer and the at least one line projector. The relative rotation is such that the acute angle of the at
20 least one line projector with regard to the plane of the wafer is maintained. With the moving means it is possible to project a second pattern of a plurality of lines in a second orientation onto the surface of the wafer. Preferably, the lines of the first pattern of lines are perpendicular to the lines of the second pattern of lines. According to one embodiment, the moving means rotates the wafer so that the first pattern of lines and the second pattern of
25 lines can be projected one after the other onto the surface of the wafer. Another possibility is that the line projector is pivoted with respect to the surface of the wafer. In a first orientation the line projector projects a first pattern of lines and in a second orientation the line projector projects a second pattern of lines onto the surface of the wafer. The frame grabber and the image processor synchronize the image capture of the first pattern of lines
30 and the second pattern of lines projected onto the surfaces of the wafer, the position of the

line projectors enclose an angle of 90° with respect to the X- and Y-directions of a Cartesian coordinate system. The respective central beam axis of each line projector encloses an angle of 18° with the plane of the wafer (horizontal plane). The camera is looking down vertically and three images are captured by the camera. The first set of
5 images is captured whilst the first line projector is illuminated. A motor tilts a 2mm thick glass plate in front of each line projector. The tilt angles are -4.44° , 0° and 4.44° relative to the respective perpendicular central beam axis of the respective line shifter. For each tilt angle an image is captured. The captured images are combined in order to remove unwanted artifacts. Image processing methods look for and measure saw marks or saw
10 grooves in each set of the three images.

[0029] According to a preferred embodiment of a method of the present invention the orientation of the saw marks is known a priori, for example from a preceding inspection step. At least one camera and at least two line projectors are needed in order to detect saw marks/grooves on a wafer. Each line projector can project a pattern of a plurality of lines
15 onto a front side or a back side of the wafer and thereby covering at least a portion of the surface of the front side or the back side of the wafer. The patterns of lines of the line projectors are under an angle with respect to each other, meaning the patterns of lines of the line projectors are not parallel but of different orientations. In a preferred embodiment consisting of two line projectors the two patterns of lines of the line projectors are
20 approximately perpendicular to each other. Additionally at least one of the patterns of lines is oriented at an angle with respect to the saw marks. In a preferred embodiment the lines of one projector are oriented approximately perpendicular to the saw marks. The a priori information about the orientation of the saw marks is used to select the line projector that projects the line pattern that is closest to perpendicular to the saw marks. This line project
25 is used during image capture to project line patterns. A first set of first images of the surface of the wafer is captured, wherein for each image of the first pattern of lines the lines are shifted a definite distance perpendicular to the orientation of the first pattern of lines. A combined first image from the set of first images is generated, and thereby computing an improved set of first images from the combined first image. Grooves are
30 detected in at least one of the improved set of first images. Finally an averaging and

documenting step is carried out. (The advantage of this embodiment is that throughput can be higher because image capture time is minimized).

[0030] Finally, the apparatus reports the position and depth of the deepest saw marks detected. The saw grooves or saw marks are measured in pixels by estimating the position of each line on either side of the saw groove by means of curve fitting. The differences between the two sides are computed by averaging over a certain distance along the groove. A calibration model is used to translate depth measured in pixel to depth expressed in actual distance units. The calibration model takes into account the perspective and other distortion caused by the line projectors and the camera.

10 BRIEF DESCRIPTION OF THE DRAWINGS

[0031] The nature and mode of operation of the present invention will now be more fully described in the following detailed description of the invention taken with the accompanying drawing figures, in which

15 [0032] Figure 1 shows a part of a saw groove which has a step-like shape in an image taken with a confocal microscope;

[0033] Figure 2 shows a schematic side view of an embodiment of an apparatus for three dimensional inspection of wafer saw marks, wherein at least one line projector is used;

20 [0034] Figure 3 shows a schematic side view of another embodiment of the apparatus for the three dimensional inspection of wafer saw marks, wherein means for carrying out a relative rotational motion between the wafer and the single line projector are provided so that the wafer surface can be illuminated in two different orientations;

25 [0035] Figure 4 shows a schematic side view of the apparatus for the three dimensional inspection of wafer saw marks, wherein according to this embodiment the front side and the back side of the wafer are inspected simultaneously by at least two line projectors;

projector according to Fig. 7B, and the glass plate in the second illumination light bundle, the glass plate being tilted in the counter clockwise direction; and

[0044] Figure 10 shows a schematic flow chart of the inventive method to detect saw marks oriented in both directions on the surface of a wafer.

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DETAILED DESCRIPTION OF THE INVENTION

[0045] Same reference numerals refer to same elements throughout the various figures. Furthermore, only reference numerals necessary for the description of the respective figure are shown in the figures. The shown embodiments represent only examples of how the apparatus and method according to the invention can be designed. This should not be
10 regarded as limiting the invention.

[0046] **Fig. 1** shows a partial view of a saw groove 2 on the front side 3F of a wafer 4 (see **Fig. 2**), wherein the saw groove 2 has a step-like shape. Silicon wafers used to manufacture photovoltaic cells need to be inspected for various defects. One type of defect is caused by the process of sawing-off the wafer from a silicon ingot (not shown). The form
15 of the silicon ingot can be a cuboid or a cylinder. Consequently, wafer 4 is round or rectangular, respectively. Saw grooves 2 or saw marks are local, elongated and 3-dimensional departures from the normally flat front side 3F or back side 3B of wafer 4. In case wafer 4 is rectangular the saw grooves 2 run almost parallel to the edge of wafer 4, in the same direction as the saw, and their length can vary between a few centimeters and the
20 entire width of wafer 4. The width of saw grooves 2 and their depth can also vary.

[0047] **Fig. 2** shows a schematic side view of an embodiment of the inventive apparatus 1 for the three dimensional inspection of saw marks 2 on at least one surface 3 of wafer 4. The surface 3 of wafer 4 is the front side 3F or the back side 3B of wafer 4. Surface 3 of wafer 4 is imaged by a camera 6 defining a field of view 7 and being arranged
25 perpendicular to a plane P of wafer 4. The optical system 15 of camera 6 is designed such that next to defining the field of view 7 also the entire surface 3 of wafer 4 is captured by a sensor (not shown) of camera 6. The sensor can be an area sensor or can work according to

[0058] The embodiments of the apparatus 1 disclosed in **Figs. 2 to 4** are exemplary embodiments and should not be considered as a limitation of the invention. A skilled person in the art would consider as well an apparatus 1 with a first line projector 8₁, a second line projector 8₂, a third line projector 8₃ (not shown) and a fourth line projector 8₄ (not shown). In this embodiment the first line projector 8₁ and the third line projector 8₃ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the front side 3F of wafer 4. The second line projector 8₂ and the fourth line projector 8₄ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the back side 3B of wafer 4. In order to speed up image capture it is possible to use different wavebands for each line projector 8₁, 8₂, 8₃ or 8₄. At least one color sensitive camera or a camera with filters is required to capture the images.

[0059] In a further embodiment (not shown) a first line projector 8₁ and a second line projector 8₂ are arranged such that they project the respective pattern 20 of lines 22 at 0° and 90° degrees respectively onto the front side 3F of wafer 4.

[0060] The wafers 4 to be inspected rest on a belt (not shown) which transports the wafers 4 into the inspection position, i. e., into the field of view 7 of the camera 6. It is possible to inspect the front side 3F of the wafer 4. As disclosed in **Fig. 4** the front side 3F and the back side 3B of the wafer 4 can be inspected simultaneously while the wafer 4 is held by a vacuum pick-up gear (not shown) or any equivalent.

[0061] **Fig. 5** shows a schematic top view of a wafer 4 used for solar cells, wherein wafer 4 has the shape of a rectangle. As mentioned above, wafer 4 is sawed-off from a silicon ingot. Since the form of the silicon ingot is a cuboid, the wafer 4 is rectangular. The saw marks 2 on the front side 3F of wafer 4 are oriented along a direction 35 of the saw.

[0062] **Fig. 6** shows a schematic view of an image 40 of the wafer 4 according to **Fig. 5**. Wafer 4 is registered by pixels 60_{n,m} of an image sensor of camera 6, wherein the field of view 7 of camera 6 captures the entire surface, here the front side 3F, of wafer 4. The image sensor of camera 6 with the plurality of pixels 60_{n,m} is oriented with wafer 4 so that

skilled person in the art that the amount of images 40 taken per set is not limited to three images 40.

[0067] **Fig. 10** shows a schematic flow chart of the inventive method to detect saw marks 2 on the surface 3 of a wafer 4. As shown in **Figs. 7A, 7B, 8A, 8B, 9A, and 9B** a first line projector 8₁ and a second line projector 8₂ are arranged to illuminate the front side 3F of wafer 4. The first line projector 8₁ and the second line projector 8₂ are positioned such that their respective central beam axes 9 are perpendicular to each other. Initially, first line projector 8₁ projects a first pattern 20 of lines 22 of a first orientation (parallel to the X-direction) onto the at least one surface 3 of wafer 4. A first raw image 51, a second raw image 52 and a third raw image 53 are captured, wherein for each raw image 51₁, 52₁, 53₁ of the first pattern 20 of lines 22 the lines 22 are shifted a definite distance perpendicular to the orientation of the first pattern 20 of lines 22. The same is done with a second set of raw images 51₂, 52₂, 53₂ of a second pattern 20 of lines 22, wherein the lines 22 are oriented parallel to the Y-direction.

[0068] After the raw images 51₁, 52₁, 53₁ and 51₂, 52₂, 53₂ of each set are captured, the multiple raw images 51₁, 52₁, 53₁ and 51₂, 52₂, 53₂ in each orientation are combined to improve the quality of each image and to remove unwanted artifacts. A reference image 54₁, 54₂ is computed, wherein the pixel values of the first reference image 54₁ are maximum pixel values of the first set of raw images 51₁, 52₁, 53₁. Analogously, a second reference image 54₂ is computed, wherein the pixel values of the second reference image 54₂ are maximum pixel values of the second set of raw images 51₂, 52₂, 53₂. In the next step each image of the first set of raw images 51₁, 52₁, 53₁ and each image of the second set of raw images 51₂, 52₂, 53₂ is divided by the first reference image 54₁ and the second reference image 54₂ respectively. The first set of raw images 51₁, 52₁, 53₁ and the second set of raw images 51₂, 52₂, 53₂ are numerically rescaled which is done by multiplying them with a constant value in order to obtain the same range of values (for example 0 – 255) as the original images have.

[0069] In the next process step, candidate grooves (saw grooves 2) are detected in all improved images. Assuming, without any loss of generality, that the projected lines are

approximately horizontal in the image, the groove detection is achieved by a variety of steps. Firstly, a detection of a location of the projected lines 22 is carried out in each column of pixels $60_{n,m}$. Secondly, each line 22 is tracked horizontally and local deviations from a straight line are computed. Thirdly, a Hough transformation is carried out with positions of a straight line where the local deviation is above a threshold. Fourthly, peaks are searched for in the Hough transformation, which correspond to the position and orientation of detected grooves 2.

[0070] According to a further embodiment of the invention the raw images #1, #2 and #3 are combined into one single image of improved quality. That is done by a process known as “phase shift extraction” that compares the intensity of the three images 51_1 , 52_1 , 53_1 at each pixel location. The combined image is known as a “phase image”. The grooves are detected and measured in the phase image. The nature of the phase image is such that phase jumps (from $-\pi$ to $+\pi$ or from $+\pi$ to $-\pi$) must be taken into account (“unwrapped”) when line fits and deviations are computed.

[0071] In next step, the depths of the detected grooves 2 in all improved images are measured. For each candidate groove 2 detected, a high and low point of a groove profile are computed along each direction of a detected groove 2. The computation starts from the tracked line positions. The high points and low points are tracked across adjacent directions or lines. A local depth of detected grooves 2 is estimated by means of curve fittings through line positions near the high and low points. An average depth of the grooves is estimated in pixels over a certain length along the groove 2 by means of a moving average. Finally, the depth of the groove 2 is translated from pixels to microns by means of pre-computed calibration parameters.

[0072] In a next step, the depth of the grooves 2 is averaged, which is achieved by an averaged depth profile computed in three dimensions over the improved set of first images 51_1 , 52_1 , 53_1 and set of second images 51_2 , 52_2 , 53_2 . At the end, the location and depth of the grooves 2 are reported. A file is written, from which file the location and the depth of the grooves 2 can be retrieved by a line engineer. The location and the depth of the deepest saw groove 2 on the surface 3 of wafer 4 is retrievable from the file as well.

REFERENCE NUMERALS:

	1	apparatus
	2	saw mark; saw groove
	3	surface
5	3B	back side of wafer
	3F	front side of wafer
	4	wafer
	5	light bundle
	6, 6 ₁ , 6 ₂	camera
10	7	field of view
	8	line projector
	8 ₁	first line projector
	8 ₂	second line projector
	8 ₃	third line projector
15	8 ₄	fourth line projector
	9	central beam axis
	10	light source
	11	motor
	12	line shifter
20	12G	glass plate
	14	frame grabber
	15	optical system
	16	image processor
	18	patterned glass plates
25	19	propagation direction
	20	pattern
	22	lines
	24	exit lens
	26	condenser lenses; condenser system
30	27	first glass plate
	28	second glass plate

CLAIMS

1. An apparatus for inspection comprising:
 - at least one camera defining a field of view, wherein the field of view is configured such that at least a portion of a surface of the wafer is captured;
 - at least one light source;
 - at least one line projector configured to provide a light bundle centered about a central beam axis, wherein the at least one line projector is arranged such that the central beam axis is oriented at an acute angle with respect to a plane of the wafer, wherein the at least one light source is configured to provide light to the at least one line projector, wherein the at least one line projector is configured to project a pattern of a plurality of lines onto at least one of a front side or a back side of the wafer;
 - at least one line shifter positioned in the light bundle between the at least one line projector and the surface of the wafer;
 - a frame grabber; and
 - an image processor, wherein image capture of the at least one of the front side or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the at least one of the front side of the wafer or the back side of the wafer, wherein the image processor is configured to perform a three-dimensional inspection of one or more saw marks of the wafer.
2. The apparatus of claim 1, wherein the at least one line projector and the surface of the wafer are positionable with respect to each other such that the at least one line projector projects a first and a second pattern of lines onto the surface of the wafer, wherein the first pattern of lines is oriented at an angle with respect to the second pattern of lines.
3. The apparatus of claim 2, wherein the lines of the first pattern of lines are perpendicular to the lines of the second pattern of lines.

4. The apparatus of claim 1, wherein the at least one line shifter includes a glass plate connected to a motor for rotating the glass plate such that at least one of the first pattern of lines or the second pattern of lines is shifted on the surface of the wafer.
5. The apparatus of claim 1, wherein the at least one line shifter includes a plurality of glass plates, at least some of the glass plates being arranged at different angles in a positioner, the positioner being drivable by a motor in order to position a glass plate of a different tilt angle into the light bundle such that at least one of the first pattern of lines or the second pattern of lines is shifted on the surface of the wafer.
6. The apparatus of claim 1, wherein the at least one line projector includes at least two patterned glass plates with a pattern of lines arranged between an exit lens and a condenser system, wherein a first glass plate has a variable-pitch Ronchi ruling in order to compensate for a perspective effect and to project a uniform pattern of lines onto the surface of the wafer, wherein a second glass plate includes a variable transmittance pattern to compensate for a perspective effect and to project the uniform pattern of lines onto the surface of the wafer.
7. The apparatus of claim 1, wherein the at least one light source is directly optically coupled to the at least one line projector.
8. The apparatus of claim 7, wherein the at least one light source comprises one or more LEDs.
9. The apparatus of claim 1, wherein the at least one light source is optically coupled to the at least one line projector via a light guide.
10. The apparatus of claim 9, wherein the at least one light source comprises one or more LEDs.

11. The apparatus of claim 1, wherein the least one camera is communicatively coupled to the frame grabber and the image processor such that a motion of the at least one line shifter, a switching of the at least one light source and a capture of an image of the surface of the wafer at different positions of the pattern of lines on the surface of the wafer are synchronized by the frame grabber.

12. A method of inspection comprising:

- projecting a first pattern of lines of a first orientation onto at least one surface of a wafer;

- capturing a first set of first images of the at least one surface of the wafer, wherein lines of the first pattern of lines of at least some images of the first pattern of lines are shifted a definite distance perpendicular to the orientation of the first pattern of lines;

- projecting a second pattern of lines of a second orientation onto the at least one surface of the wafer;

- capturing a second set of second images of the at least one surface of the wafer, wherein lines of the second pattern of lines of at least some images of the second pattern of lines are shifted a definite distance perpendicular to the second orientation of the second pattern of lines;

- generating a combined first image from the set of first images;

- generating a combined second image from the set of second images;

- computing an improved set of first images from the combined first image and an improved set of second images from the combined second image;

- detecting grooves in at least one of the improved set of first images and/or in at least one of the improved set of second images;

- measuring a depth of a detected groove in at least some of the improved set of first images;

- measuring a depth of a detected groove in at least some of the improved set of second images;

- averaging the depth of at least some grooves across the at least some of the improved set of first images or the at least some of the improved set of second images;
- and

recording the depth, location and the orientation of the detected grooves on the surface of the wafer to perform a three-dimensional inspection of one or more saw marks of the wafer.

13. The method of claim 12, wherein the combined first image and the combined second image comprises:

- computing a first reference image, wherein pixel values of the first reference image are maximum pixel values of the first set of images;

- computing a second reference image, wherein pixel values of the second reference image are maximum pixel values of the second set of images;

- dividing at least some of the first set of images by the first reference image;

- dividing at least some of the second set of images by the second reference image; and

- numerically rescaling the first set of images and the second set of images.

14. The method of claim 12, wherein detecting grooves in at least one of the improved set of first images and/or in at least one of the improved set of second images comprises:

- detecting a location of the projected lines in each column of pixels in at least one of the improved set of first images and/or in at least one of the improved set of second images;

- tracking the location of the projected lines along a specific direction;

- computing one or more local deviations from a straight line along the specific direction;

- carrying out a transformation with positions of a straight line, wherein the one or more local deviations are above a threshold; and

- finding peaks in the transformation corresponding to at least one of position or orientation of detected grooves.

15. The method of claim 12, wherein at least one of the measuring a depth of a detected groove in at least some of the improved set of first images or the measuring a

depth of a detected groove in at least some of the improved set of second images comprises:

- computing for each detected groove a high and low point of a groove profile along each direction of a detected groove;
- tracking high points and low points across adjacent directions;
- estimating a local depth of detected grooves utilizing one or more curve fittings along line positions proximate to the high and low points; and
- estimating an average depth of the grooves over a length along the groove utilizing a moving average.

16. The method of claim 12, wherein the averaging the depth of at least some grooves across the at least some of the improved set of first images or the at least some of the improved set of second images comprises:

- averaging a depth profile computed in three dimensions over at least one of the improved set of images or the improved set of second images.

17. An apparatus for inspection comprising:

- at least one camera defining a field of view, the at least one camera arranged substantially perpendicular to a plane of a wafer, wherein the field of view is configured such that an entire surface of the wafer is captured;

- at least one light source;

- a first line projector configured to provide a first light bundle centered about a central beam axis, wherein the first line projector is arranged such that the central beam axis is oriented at an acute angle with respect to the plane of the wafer, wherein the at least one light source is configured to provide light to the first line projector, wherein the first line projector is configured to project a first pattern of a plurality of lines having a first orientation onto at least one of a front side of the wafer or a back side of the wafer;

- a second line projector configured to provide a second light bundle centered about a central beam axis, wherein the second line projector is arranged such that the central beam axis is oriented at an acute angle with respect to the plane of the wafer, wherein the at least one light source is configured to provide light to the second line

projector, wherein the second line projector is configured to project a second pattern of a plurality of lines having a second orientation onto at least one of the front side of the wafer or the back side of the wafer;

a first line shifter positioned in the first light bundle between the first line projector and the first surface of the wafer;

a second line shifter positioned in the second light bundle between the second line projection and the second surface of the wafer;

a frame grabber; and

an image processor, wherein image capture of at least one of the front side of the wafer or the back side of the wafer is synchronized by the frame grabber in coordination with the position of at least one of the first pattern of a plurality of lines or the second pattern of a plurality of lines on at least one of the front side of the wafer or the back side of the wafer, wherein the image processor is configured to perform a three-dimensional inspection of one or more saw marks of the wafer.

18. The apparatus of claim 17, wherein the first pattern of plurality of lines is perpendicular to the second pattern of plurality of lines.

19. The apparatus of claim 17, wherein at least one of the first line shifter or the second line shifter includes a glass plate connected to a motor for rotating the glass plate such that the at least one of the first pattern of a plurality of lines or the second pattern of a plurality of lines is shifted on at least one of the first surface of the wafer or the second surface of the wafer.

20. The apparatus of claim 17, wherein at least one of the first line shifter or the second line shifter includes a plurality of glass plates, where at least some glass plates are arranged at different angles in a positioner, the positioner being drivable by a motor in order to position a glass plate of a different tilt angle into at least one of the first light bundle of the first line projector or the second light bundle of the second line projector such that at least one of the first pattern of a plurality of lines of the second pattern of a

plurality of lines is shifted on at least one of the first surface of the wafer or the second surface of the wafer in at least one of an X-direction or a Y-direction.

21. The apparatus of claim 17, wherein at least one of the first line projector or the second line projector includes two patterned glass plates, each of the two patterned glass plates having a pattern of lines arranged between an exit lens and a condenser system, wherein a first glass plate has a variable-pitch Ronchi ruling in order to compensate for a perspective effect and to project uniform pattern of lines onto at least one of the first surface of the wafer or at least one of the second surface of the wafer, wherein the second glass plate has a variable transmittance pattern to compensate for a perspective effect and to project uniform pattern lines onto at least one of the first surface of the wafer or at least one of the second surface of the wafer.

22. The apparatus of claim 17, wherein the at least one camera is communicatively coupled to the frame grabber and the image processor such that a motion of at least one of the first line shifter or the second line shifter, a switching of the at least one light source and a capture of an image of the surface of the wafer produced by the first line projector and the second line projector are synchronized by the frame grabber.

23. An apparatus for inspection comprising:

- at least one camera defining a field of view, wherein the at least one camera is arranged perpendicular to a plane of the wafer, wherein the field of view is configured such that an entire surface of the wafer is captured;

- at least one light source;

- at least one line projector configured to provide a light bundle centered about a central beam axis, wherein the at least one line projector is arranged such that the central beam axis is oriented at an acute angle with respect to the plane of the wafer, wherein the at least one line projector is configured to project a first pattern of a plurality of lines with a first orientation onto the surface of the wafer;

at least one line shifter positioned in the light bundle between the at least one line projector and the surface of the wafer;

moving means for providing a relative rotation between the wafer and the at least one line projector to maintain the acute angle of the line projector with regard to the plane of the wafer in order to project a second pattern of a plurality of lines with a second orientation onto the surface of the wafer;

a frame grabber; and

an image processor, wherein image capture of at least one of the first pattern of lines or the second pattern of lines projected onto the surface of the wafer is synchronized by the frame grabber in coordination with the position of the at least one line shifter in the light bundle and the relative rotational position of the wafer and the at least one line projector, wherein the image processor is configured to perform a three-dimensional inspection of one or more saw marks of the wafer.

24. An apparatus for inspection comprising:

at least two cameras, each camera defining a field of view, each camera arranged perpendicular to a plane of at least one of a front side of the wafer or a back side of the wafer, wherein the field of view of the at least two cameras is configured such that at least one of an entire front side of the wafer or an entire back side of the wafer is captured;

at least one light source;

a first line projector configured to provide a light bundle centered about a central beam axis, wherein the first line projector is arranged such that the central beam axis is at an acute angle with respect to the plane and the front side of the wafer;

a second line projector configured to provide a second light bundle centered about a central beam axis, wherein the second line projector is arranged such that the central beam axis is at an acute angle with respect to the plane and the back side of the wafer, wherein the at least one light source is configured to provide light to at least one of the first line projector or the second line projector, wherein at least one of the first line projector or the second line project are configured to project a pattern of a plurality of lines onto at least one of a front side or a back side of the wafer;

at least one line shifter positioned in at least one of the first light bundle or the second light bundle between the at least one of the first line projector or the second line projector and the surface of the wafer;

a frame grabber; and

an image processor, wherein image capture of at least one of the front side of the wafer or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the at least one of a front side or a back side of the wafer, wherein the image processor is configured to perform a three-dimensional inspection of one or more saw marks of the wafer.

25. The apparatus of claim 24, wherein the moving means provides a relative rotation between the wafer and the at least one line projector to maintain the acute angle of the at least one line projector with respect to the plane of the wafer in order to project a second pattern of a plurality of lines with a second orientation onto the surface of the wafer, wherein the frame grabber and the image processor synchronize the image capture of the first pattern of lines and the second pattern of lines projected onto the at least one of a front side of the wafer or a back side of the wafer, the position of the at least one line shifter in the light bundle and the relative rotational position of the wafer and the first line projector and second line projector with respect to each other.

26. An apparatus for inspection wafer comprising:

at least one camera defining a field of view, wherein the field of view is configured such that at least a portion of a surface of a wafer is captured, wherein the wafer and camera are arranged such that one or more saw marks of the wafer have a defined orientation in the field of view of the camera;

at least one light source;

at least one line projector configured to provide a light bundle centered about a central beam axis, wherein the at least one line projector is arranged such that the central beam axis is oriented at an acute angle with respect to a plane of the wafer, wherein the at least one light source is configured to provide light to the at least one line projector, wherein the at least one line projector is configured to project a pattern of a plurality of lines onto at least one of a front side of the wafer or a back side of the wafer;

at least one line shifter positioned in the light bundle between the at least one line projector and the surface of the wafer;

a frame grabber; and

an image processor, wherein image capture of the at least one of the front side of the wafer or the back side of the wafer is synchronized by the frame grabber in coordination with the position of the pattern of lines on the at least one of the front side of the wafer or the back side of the wafer, wherein the image processor is configured to perform a three-dimensional inspection of the one or more saw marks of the wafer.

27. A method of inspection comprising:

determining an orientation of one or more saw marks on a wafer;

providing at least one line projector;

projecting a first pattern of lines of a first orientation onto at least one surface of the wafer, wherein the first pattern of lines is oriented at an angle with respect to the one or more saw marks;

capturing a set of first images of the at least one surface of the wafer, wherein one or more lines of the first pattern of lines of at least some images are shifted a definite distance perpendicular to the orientation of the first pattern of lines;

generating a combined first image from the set of first images;

computing an improved set of first images from the combined first image;

detecting grooves in at least one of the improved set of first images;

measuring a depth of a detected groove in at least some of the improved set of first images;

averaging the depth of at least some grooves across the at least some of the improved set of first images; and

recording at least one of the depth, location or the orientation of the detected grooves on the at least one surface of the wafer to perform a three-dimensional inspection of one or more saw marks of the wafer.

28. The method of claim 27, further comprising:

performing a rotation between the wafer and the at least one line projector such that the orientation of the one or more saw marks on the wafer is non-parallel with the first pattern of lines.