

## METHODS AND APPARATUS FOR CLASSIFICATION OF DEFECTS USING SURFACE HEIGHT ATTRIBUTES

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### BACKGROUND OF THE INVENTION

#### *Field of the Invention*

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The present invention relates to inspection and review of substrates using electron beam imaging.

#### *Description of the Background Art*

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In a conventional electron beam inspection instrument, a manufactured substrate (such as a silicon wafer or a reticle) is scanned with a focused beam of electrons which results in the emission of electrons, including secondary and/or backscattered electrons, from the substrate surface. The emitted electrons are detected, and the detection data is typically converted into an image of the surface of the specimen. The image is typically from a "normal" view (i.e. a view from a perspective perpendicular to the surface). These images are then analyzed numerically to detect abnormalities (referred to as defects) in the manufactured substrate.

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Furthermore, the detected defects may be reviewed by further imaging and classified, either manually or automatically, into different classes or categories. The classification of a defect may be used to determine its cause such that appropriate adjustments may be made in the manufacturing process so as to improve its yield.

It is highly desirable to improve methods and apparatus for electron beam inspection. More particularly, it is highly desirable to improve the classification of defects imaged by electron beam instrumentation.

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## SUMMARY

One embodiment relates to a method of classifying a defect on a substrate surface. The method includes scanning a primary electron beam over a target region of the substrate surface causing secondary electrons to be emitted  
10 therefrom, wherein the target region includes the defect. The secondary electrons are detected from the target region using a plurality of at least two off-axis sensors so as to obtain a plurality of image frames of the target region, each image frame of the target region including data from a different off-axis sensor. The plurality of image data frames are processed to generate a surface height map of the target  
15 region. Surface height attributes are determined for the defect. The surface height attributes for the defect are input into a defect classifier.

The method may be applied to a bare substrate, such as a bare semiconductor wafer, or a patterned substrate, such as an integrated circuit being manufactured or a reticle for lithography. In the latter case, a plurality of  
20 corresponding image frames may be obtained of a reference site which corresponds to the target region, a surface height map of the reference site is generated, and the determination of surface height attributes for the defect may also use the surface height map of the reference site.

Another embodiment relates to an apparatus including a source for  
25 generating a primary electron beam, scan deflectors configured to controllably deflect the primary electron beam, a control system configured to control the scan deflectors such that the primary electron beam is scanned over areas on a substrate surface, and a detection system configured for the detection of secondary electrons using a plurality of at least two off-axis sensors so as to generate a plurality of image  
30 frames of each of the areas. The areas scanned may include a target region which

includes a defect to be classified, and, in certain cases, a reference site corresponding to the target region. An image data processing system may be configured to process the plurality of image frames to generate a surface height map of the target region and the reference site, if applicable. The image data processing  
5 system may determine surface height attributes for the defect using the surface height map(s), and input the surface height attributes for the defect into a defect classifier.

Other embodiments, aspects and features are also disclosed.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a flow chart of a method for classifying defects using surface height attributes in accordance with a first embodiment of the invention.

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FIG. 1B is a flow chart of a method for classifying defects using surface height attributes in accordance with a second embodiment of the invention.

FIG. 2 is a schematic diagram of an electron beam apparatus in accordance with an embodiment of the invention.

FIG. 3 is a schematic diagram of a detector segmentation in  
20 accordance with an embodiment of the invention.

FIGS. 4A, 4B and 4C show three secondary electron image frames collected at different view angles for an example target region in accordance with an embodiment of the invention.

FIGS. 5A, 5B, and 5C show three corresponding secondary electron  
25 image frames collected at different view angles for a reference site corresponding to the example target region in accordance with an embodiment of the invention.

FIG. 6 shows a defect mask generated for the example target region in accordance with an embodiment of the invention.

FIGS. 7A and 7B show surface height maps for the example target  
30 region and corresponding reference site, respectively, in accordance with an embodiment of the invention.

FIG. 8 shows the effectiveness of surface height attributes in distinguishing between certain types of defects in accordance with an embodiment of the invention.

FIGS. 9A and 9B show example secondary electron image frames of a  
5 fall-on particle (i.e. a bump) and a gouge, respectively.

FIGS. 10A and 10B show example surface height maps for the particle and the gouge, respectively.

FIGS. 11A and 11B show example defect masks corresponding to the particle and gouge, respectively.

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#### DETAILED DESCRIPTION

Methods and apparatus for the generation of surface height attributes and the use of these attributes are disclosed herein. These methods and apparatus  
15 may be employed to substantially improve the accuracy of automated defect classification using electron-beam instrumentation.

FIG. 1A is a flow chart of a method **100** for the automated generation of surface height attributes for a previously-detected defect so as to classify the defect in accordance with a first embodiment of the invention. The method **100** of  
20 FIG. 1A may be particularly suitable for use with a bare substrate, such as a bare silicon wafer.

As shown, the method **100** may be performed under the control of several software modules of the defect review system. These modules may include a defect review scan module **101**, a surface height map generation module **105**, a  
25 review images generation module **107**, a defect mask generation module **109**, a surface height attribute generation module **111**, and an automatic defect classification module **121**. Each module may include computer-readable program code which may be stored in data storage (such as a hard disk drive or memory circuits) and executed by one or more microprocessors of a computer system, such

as a computer system used for instrument control and image processing for a defect review system, for example.

As shown, the defect review scan module **101** may translate **102** a stage holding a substrate such that a target region of the substrate surface is positioned in the field of view (FOV) of the imaging system. Thereafter, while the target region is scanned by the incident beam, image data is collected **104** from two or more view angles. The collection **104** of the image data from two or more view angles may be done simultaneously.

After the secondary electron image data is collected **104** of the target region, the surface height map generation module **105** may receive the image data and generate **106** a surface height map of the target region. In accordance with one embodiment, the procedure to generate **106** the surface height map may include the generation of a three-dimensional model or representation of the surface of the target region. Such a three-dimensional representation may be constructed based on a Lambertian model, or, alternatively, based on stereo vision. The surface height map may be generated **106** from the three-dimensional model. Other techniques may be employed to generate **106** the surface height map in other embodiments.

A review images generation module **107** may also receive the image data from the defect review scan module **101**. The review images generation module **107** may generate review images **108** and provide them to a defect mask generation module **109**. The defect mask generation module **109** generates **110** a defect mask corresponding to at least one of the review images. The defect mask differentiates pixels associated with the previously-detected defect from other pixels in the image frame.

Based on the surface height map of the target region and the defect mask, a set of surface height attributes may be determined **112** by a surface height attribute generation module **111**. In accordance with an embodiment of the invention, the surface height attributes may include a height difference **114** between the defect area and the background area surrounding the defect area, a measure of

the height variation **116** within the defect area, and a measure of the height variation **118** within the background area surrounding the defect area.

The background area surrounding the defect may be selected in an automated or manual manner. For example, the background area may be selected  
5 as those pixels within a certain range from the defect area, but not within the defect area. The height difference **114** between the defect area and the background area surrounding the defect area may be determined by calculating an average height of the defect area, calculating the average height of the background area, and calculating a difference between the two average heights. The measure of the  
10 height variation **116** within the defect area and the measure of the height variation **118** within the background area may be statistical measures. An example of a statistical measure of height variation is the standard deviation of the height.

In other embodiments, alternative surface height attributes may be used. For example, a useful surface height attribute that reflects topographic  
15 information may be generated by calculating the disparity distance or phase/orientation between the defect blobs (defect areas) detected in the secondary electron images of different perspectives of the same defect.

The surface height attributes for the previously-detected defect may then be fed (input) into an automatic defect classification module (defect classifier)  
20 **121**. The automatic defect classification module **121** may advantageously utilize the surface height attributes in classifying **122** the previously-detected defect. The classifier. The automatic defect classification module **121** may be a statistical classifier that may be operated in either a classifier training mode or a classification mode. The classifier training mode may receive the surface height attributes and  
25 other attributes of known types of defects so as to train the defect classifier used by the automatic defect classification module **121**. The classification mode uses the trained defect classifier to classify a defect based on the surface height attributes and other attributes. Alternatively, the automatic defect classification module **121** may utilize a rule-based classifier.

FIG. 1B is a flow chart of a method **150** for the automated generation of surface height attributes for a previously-detected defect so as to classify the defect in accordance with a second embodiment of the invention. The method **150** of FIG. 1B may be particularly suitable for use with a patterned substrate, such as an integrated circuit in the process of being formed on a silicon substrate, or a reticle for use in photolithography.

Compared to the method **100** of FIG. 1A, additional steps in the method **150** of FIG. 1B include steps which obtain and use image data from a reference site that corresponds to the target region. The reference site includes a non-defective area which corresponds to the defect area in the target region. In addition, the method **150** of FIG. 1B includes an additional surface height attribute that is generated by the surface height attribute generation module **111**. This additional attribute is the height difference **158** between the defect area in the target region and the corresponding area in the reference site.

As shown in FIG. 1B, the defect review scan module **101** may obtain the image data from the reference site by translating **152** a stage holding the substrate such that the reference site is positioned in the field of view of the imaging system. The reference site may then be scanned by the incident beam and image data may be collected **154** from two or more view angles. The collection **154** of the image data from two or more view angles may be done simultaneously. After the secondary electron image data is collected **154** of the reference site, the surface height map generation module **105** may receive the image data, align **155** the image data of the reference site with the image data of the target region, and generate **156** a surface height map of the reference site. The surface height generation module **111** receives the surface height maps for the target region and the reference site and also receives the defect mask.

In accordance with this embodiment, the attributes generated by the surface height generation module **111** include may include the height difference **114** between the defect area and the background area surrounding the defect area, the measure of the height variation **116** within the defect area, the measure of the height

variation **118** within the background area surrounding the defect area, and the height difference **158** between the defect area and the corresponding area of the reference site. The latter height difference **158** may be determined by measuring each of the two heights relative to a height of surrounding background area in its image frame.

5 In other words, the height of the defect area relative to its background area is computed, the height of the corresponding non-defective area at the reference site relative to its background area is computed, and then the difference **158** is found between those two heights.

As described above, the method **150** of FIG. 1B may obtain two or  
10 more secondary electron image frames at different view angles for both the target region (which includes the previously-detected defect) and a corresponding reference site (which does not have the defect). An example of three secondary electron image frames collected **104** at different view angles for a target region including a defect is shown in FIGS. 4A, 4B, and 4C. A corresponding example of  
15 three secondary electron image frames collected **154** at different view angles for reference site which does not have the defect is shown in FIGS. 5A, 5B, and 5C. An example of a defect mask generated **110** for the target region is shown in FIG. 6. For the particular mask **601** shown in FIG. 6, the non-defective pixels **602** are shown as white pixels, the pixels associated with two defects **604** and **606** are shown as  
20 dark pixels. Further in this example, FIG. 7A shows a surface height map generated **106** for the target region, and FIG. 7B shows a surface height map generated **156** for the reference site. In surface height maps of FIGS. 7A and 7B, higher surface heights are represented by lighter grey-scale pixels and lower surface heights are represented by darker grey-scale pixels.

25 In accordance with an embodiment of the invention, defect classification using the surface height attributes is highly advantageous in the classification of certain types of defects. For example, FIG. 8 shows that various conventional attributes have great difficulty distinguishing between defects which are "gouges" and defects which are "bumps".

Conventional attributes for defect classification include a maximum dimension (eDR Max Dim) **802** of the defect, an area (eDR Area) **804** of the defect, an energy density (eDR Energy Density) **806** of the defect area, and a brightness (eDR Defect Brightness) **808** of the defect area. As seen, defects which are bumps  
5 not well separated from defects which are gouges using these conventional attributes. In contrast, the height difference **114** of the defect area relative to the background area (SH Relative to Background) **810** is shown to be highly effective in separating defects which are bumps and defects which are gouges. In the example of FIG. 8, the height difference **114** is negative fifty units or less for the vast majority  
10 of the gouges and is positive fifty units or more for the vast majority of bumps.

Example secondary electron image frames of a fall-on particle and a gouge are shown in FIGS. 9A and 9B, respectively. Note that from these images alone, the particle and gouge are similar in appearance. Example surface height maps for the particle and the gouge are shown in FIGS. 10A and 10B, respectively.  
15 In these maps, lighter pixels represent higher surface heights, while darker pixels represent lower surface heights. As seen, the defect is lighter (higher) than the background in FIG. 10A, while the defect is darker (lower) than the background in FIG. 10B. Example defect masks corresponding to the particle and gouge are shown in FIGS. 11A and 11B, respectively. The dark areas in the masks represent  
20 the defect areas.

More generally, the surface height attributes generated in accordance with embodiments of the invention may be used advantageously to assist in the more robust and detailed classification of defects when used in conjunction with other attributes. Even defects which are flat in relation to the background area may  
25 be more readily classified using the surface height attributes disclosed herein. This is because the surface height attributes may be used to distinguish such a flat defect from a bump or gouge.

An exemplary embodiment of an apparatus configured to simultaneously collect the image data from multiple view angles is described below  
30 in relation to FIGS. 2 and 3. FIG. 2 provides a cross-sectional diagram of the

electron beam column, and FIG. 3 provides a planar view of a segmented detector that may be used with the column.

As shown in FIG. 2, a source **201** generates a primary beam (i.e. an incident beam) **202** of electrons. The primary beam **202** passes through a Wien filter **204**. The Wien filter **204** is an optical element configured to generate electrical and magnetic fields which cross each other. Scanning deflectors **206** and focusing electron lenses **207** are utilized. The scanning deflectors **206** are utilized to scan the electron beam across the surface of the wafer or other substrate sample **210**. The focusing electron lenses **207** are utilized to focus the primary beam **202** into a beam spot on the surface of the wafer or other substrate sample **210**. In accordance with one embodiment, the focusing lenses **207** may operate by generating electric and/or magnetic fields.

As a result of the scanning of the primary beam **202**, secondary electrons are emitted or scattered from the surface of the substrate **210** (which may be, for example, a semiconductor wafer or a reticle). The substrate **210** may be held by a movable stage **211**. The secondary electrons are then extracted from the substrate **210** by exposure to the electromagnetic field of the objective (final) lens **208**. The electromagnetic field acts to confine the emitted electrons to within a relatively small distance from the primary beam optic axis and to accelerate these electrons up into the column. In this way, a secondary electron beam **212** is formed from the secondary electrons.

The Wien filter **204** deflects the scattered electron beam **212** from the optic axis of the primary beam **202** to a detection axis (the optic axis for the detection system **214** of the apparatus). This serves to separate the scattered electron beam **212** from the primary beam **202**. In accordance with one embodiment of the invention, the detection system **214** may include, for example, a segmented detector **300**, which is shown in further detail in FIG. 3.

An instrument control and image processing (control/processing) system **250** may include one or more processors (i.e. microprocessors or microcontrollers) **252**, data storage (including, for example, hard disk drive storage

and memory chips) **254**, a user interface **256** and a display system **258**. The data storage **254** may be configured to store or hold computer-readable program code (instructions) **255** and data, and the processor **252** may be configured to execute the program code **255** and process the data. The user interface **256** may be configured to receive user inputs. The display system **258** may be configured to display views of the substrate surface to a user.

The control/processing system **250** may be connected to, and may be used to control, various components of the electron beam column so as to implement procedures disclosed herein. For example, the movement of the stage **211**, and the scanning by the deflectors **206** may be controlled by computer-readable program code **255** executed by the control/processing system **250**.

In addition, the control/processing system **250** may be configured to receive and process the electron image data from the detection system **214**. In particular, the computer-readable program code **255** in the control/processing system **250** may be used to implement procedures relating to the automated classification of defects using surface height attributes which are described in the present disclosure.

As shown in FIG. 3, the segmented detector **300** may include five sensors or detector segments **302**, **304-1**, **304-2**, **304-3**, and **304-4**. The center (on-axis) segment **302** may be configured to detect image data from a center of the scattered electron beam **212**. The center segment **302** is on-axis in that it lies on the detection axis. The image data from the center segment **302** may correspond to image data from a normal view (i.e. a view angle which is normal to the sample surface at a polar angle of zero degrees). The four outer (off-axis) segments (**304-1**, **304-2**, **304-3**, and **304-4**) may correspond to image data from angular views (i.e. view angles which are non-normal to the sample surface at a non-zero polar angle and at different azimuthal angles). In other words, each of the four outer segments (**304-1**, **304-2**, **304-3**, and **304-4**) detect scattered electrons emitted from the substrate surface at a different azimuthal angle (for example, spaced approximately 90 degrees apart), but at the same, or approximately the same, polar angle. The

outer segments (304-1, 304-2, 304-3, and 304-4) are off-axis in that they lie off the detection axis. In alternative implementations, different segmentations may be implemented.

In the above description, numerous specific details are given to provide  
5 a thorough understanding of embodiments of the invention. However, the above  
description of illustrated embodiments of the invention is not intended to be  
exhaustive or to limit the invention to the precise forms disclosed. One skilled in the  
relevant art will recognize that the invention can be practiced without one or more of  
the specific details, or with other methods, components, etc. In other instances,  
10 well-known structures or operations are not shown or described in detail to avoid  
obscuring aspects of the invention. While specific embodiments of, and examples  
for, the invention are described herein for illustrative purposes, various equivalent  
modifications are possible within the scope of the invention, as those skilled in the  
relevant art will recognize.

15 These modifications can be made to the invention in light of the above  
detailed description. The terms used in the following claims should not be construed  
to limit the invention to the specific embodiments disclosed in the specification and  
the claims. Rather, the scope of the invention is to be determined by the following  
claims, which are to be construed in accordance with established doctrines of claim  
20 interpretation.

## CLAIMS

What is claimed is:

1. A method of classifying a defect on a substrate surface, the method  
5 comprising:
  - scanning a primary electron beam over a target region of the substrate surface causing secondary electrons to be emitted therefrom, wherein the target region includes the defect;
  - 10 detection of the secondary electrons from the target region using a plurality of at least two off-axis sensors so as to generate a plurality of image frames of the target region, each image frame of the target region including data from a different off-axis sensor;
  - processing the plurality of image data frames to generate a surface height map of the target region;
  - 15 determining surface height attributes for the defect based on the surface height map of the target region; and
  - feeding the surface height attributes for the defect into a defect classifier.
2. The method of claim 1, wherein the surface height attributes include a  
20 difference in height between a defect area and a background area surrounding the defect area.
3. The method of claim 2, wherein the surface height attributes further include a  
measure of height variation within the defect area.
- 25 4. The method of claim 3, wherein the surface height attributes further include a measure of height variation within the background area surrounding the defect area.
5. The method of claim 4, wherein the substrate surface comprises a bare  
30 semiconductor surface.

6. The method of claim 4, wherein the substrate surface comprises a patterned surface.
- 5 7. The method of claim 6, further comprising:  
detection of the secondary electrons from a reference site using the plurality of at least two off-axis sensors so as to generate a plurality of image frames of the reference site, each image frame of the reference site including data from a different off-axis sensor; and  
10 aligning the image frames of the target region with the image frames of the reference site.
8. The method of claim 7, further comprising:  
processing the plurality of image frames of the reference site to generate a  
15 surface height map of the reference site.
9. The method of claim 8, wherein determining the surface height attributes for the defect is also based on the surface height map of the reference site.
- 20 10. The method of claim 9, wherein the surface height attributes further includes a difference in height between the defect area and a corresponding non-defective area in the reference site.
11. An apparatus comprising:  
25 a source for generating a primary electron beam;  
scan deflectors configured to controllably deflect the primary electron beam;  
a control system configured to control the scan deflectors such that the primary electron beam is scanned over a target region such that secondary electrons are emitted therefrom, wherein the target region includes a defect;

a detection system configured for the detection of the secondary electrons using a plurality of at least two off-axis sensors so as to generate a plurality of image frames of the target region, each image frame including data from a different off-axis sensor; and

5        an image data processing system configured to process the plurality of image frames to generate a surface height map of the target region, determine surface height attributes for the defect using the surface height map of the target region, and input the surface height attributes for the defect into a defect classifier.

10    12.    The apparatus of claim 11, wherein the surface height attributes include a difference in height between a defect area and a background area surrounding the defect area.

13.    The apparatus of claim 12, wherein the surface height attributes further  
15    include a measure of height variation within the defect area.

14.    The apparatus of claim 13, wherein the surface height attributes further include a measure of height variation within the background area surrounding the defect area.

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15.    The apparatus of claim 11, wherein the off-axis sensors comprise off-axis detector segments.

16.    The apparatus of claim 11, wherein the control system is further configured to  
25    control the scan deflectors such that the primary electron beam is scanned over a reference site so that a plurality of image frames of the reference site is generated by the detection system.

17. The apparatus of claim 16, wherein the image data processing system is further configured to align the image frames of the target region with the image frames of the reference site.

5 18. The apparatus of claim 17, wherein the image data processing system is further configured to process the plurality of image frames of the reference site so as to generate a surface height map of the reference site.

19. The apparatus of claim 18, wherein the image processing system is further  
10 configured to also use the surface height map of the reference site in determining the surface height attributes of the defect.

20. The apparatus of claim 19, wherein the surface height attributes comprise:  
a difference in height between a defect area and a background area  
15 surrounding the defect area;  
a measure of height variation within the defect area;  
a measure of height variation within the background area surrounding the  
defect area; and  
a difference in height between the defect area and a corresponding non-  
20 defective area in the reference site.

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