DESCRIPTION

TITLE: METHOD FOR MEASURING THE THICKNESS OF A SURFACE LAYER OF AN SOI SUBSTRATE

FIELD OF THE INVENTION

The present invention relates to the field of semiconductors and in particular of SOI (silicon-on-insulator) substrates. The invention relates to a thickness-measuring method applicable to a surface layer of an SOI substrate, in particular when the surface layer has a mean thickness less than 50 nm: the method drastically improves the reliability of the thickness parameters (mean, minimum, maximum, etc.) that are obtained, reliability being understood here by the fact that these parameters are representative of the surface layer over its entire surface.

TECHNOLOGICAL BACKGROUND OF THE INVENTION

More and more applications based on SOI substrates require the thickness of the silicon surface layer to have very high uniformity. For example, in digital applications, the active layer of FDSOI (fully depleted SOI) substrates must exhibit very low variations in thickness because these affect the threshold voltage of transistors produced in and/or on the active layer.

The specifications in terms of thickness and uniformity therefore become very aggressive: for a layer with a thickness typically less than 50 nm, or even less than 25 nm, uniformity (corresponding to the difference between the maximum thickness and the minimum thickness of the layer) of less than 1 nm is expected.

In a manufacturing line, the thickness parameters (mean thickness, uniformity, etc.) of an FDSOI substrate surface layer are extracted from a limited number of measuring points (for example 41 points), for understandable reasons of production rate. Although the position of the measuring points on the surface of the surface layer is predefined in an attempt to capture the thickness information most representative of all of said surface, it is not guaranteed that the thickness minima and maxima will be found, the location of these being liable to vary from one substrate to another.

SUBJECT MATTER OF THE INVENTION

The present invention aims to improve the reliability of the thickness parameters (mean, minimum, maximum, uniformity, etc.) that are obtained, reliability being understood here by the fact that these parameters are representative of the surface layer over its entire surface. It relates to a thickness-measuring method applicable to a surface layer of an SOI substrate, in particular when the surface layer has a mean thickness less than 50 nm; the method implements a standard thickness-measuring tool at a finite number of points, and uses information derived from a map to identify signatures of potential variations in thickness, and where applicable carry out additional thickness measurements in the localized regions corresponding to these signatures.

BRIEF DESCRIPTION OF THE INVENTION

The invention relates to a method for measuring at least one thickness parameter of a surface layer of an SOI substrate, the surface layer having a surface extending in a main plane, the method comprising the following steps:

a) carrying out a thickness measurement at a predefined number of first points that are spatially distributed over the surface, resulting in a first series of values comprising a first maximum and a first minimum; the thickness measurement being carried out using a first technique and the first points not covering the entire surface;

b) producing a complete map of the surface of the surface layer using a second technique, different from the first technique, the map reflecting a physical characteristic of the surface layer correlated with thickness;

c) analysing the map so as to identify whether there is a signature liable to reflect a variation in thickness, greater than or equal to the difference between the first maximum and the first minimum, in a localized region of the surface layer;

d) if a signature is identified, carrying out a thickness measurement at a second point or a plurality of second points positioned in the localized region, resulting in a second series of values comprising a second maximum and/or a second minimum; the thickness measurement being carried out using the first technique;

e) calculating at least one thickness parameter, based on the first series of values and, potentially, on the second series of values.

According to other advantageous and non-limiting features of the invention, taken individually or in any technically feasible combination:

- the surface layer has a mean thickness less than or equal to 50 nm, less than or equal to 25 nm, less than or equal to 20 nm, or else less than or equal to 15 nm;
- the second technique is reflectometry and the physical characteristic is thickness;
- the second technique is based on laser scattering surface inspection in which a laser beam scans the surface of the surface layer, and the physical characteristic is haze;
- a signature corresponds to an abnormal variation in the intensity of the haze signal, and may be in the form of a point pattern, a periodic wave, or other patterns;
- the signature is identified on the map via an image recognition algorithm or by carrying out thresholding of the intensity of the haze signal;
- at the end of step c), coordinates are assigned to the signature, in the main plane, by an equipment – referred to as second equipment – implementing the second technique, and said coordinates are communicated, prior to step d), to a first equipment implementing the first technique;
- the second points are positioned in the main plane in accordance with distribution schemes established on the basis of the shape of the signature;
- the - at least one - thickness parameter calculated in step e) is uniformity;
- multiple thickness parameters are calculated in step e), including a mean, and/or a median, and/or a standard deviation;
- the first technique is spectral ellipsometry;
- the predefined number of first points is 12, 41, or 625;
- there are 2, 9, 16 or 25 second points.

BRIEF DESCRIPTION OF THE FIGURES

Further features and advantages of the invention will become apparent from the following detailed description of the invention, which is provided with reference to the appended figures, in which:

[Fig. 1] Figure 1 shows the steps of a measuring method according to the present invention;

[Fig. 2]

[Fig. 3] Figures 2 and 3 illustrate two examples of maps obtained in step b) of the measuring method according to the invention (Figure 2: using reflectometry, first embodiment; Figure 3: using laser scattering inspection, second embodiment);

[Fig. 4a]
[Fig. 4b]
[Fig. 4c]
[Fig. 4d] Figures 4a, 4b, 4c, 4d illustrate four examples of maps obtained according to the second embodiment of step b), having particular signatures; they also illustrate four associated examples of the arrangement of the second measuring points in step d), in a measuring method according to the invention;

[Fig. 5a]
[Fig. 5b]
[Fig. 5c]
[Fig. 5d] Figures 5a, 5b, 5c, 5d illustrate one example of results obtained respectively in steps a), b), c), d) when implementing a method according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a method for measuring one or more thickness parameters of a silicon surface layer of an SOI (silicon-on-insulator) substrate.
Thickness parameters are understood to mean thickness uniformity, mean (mean thickness), median, standard deviation, etc. These parameters are usually calculated based on the thickness values of the surface layer as obtained at multiple measuring points. In particular, thickness uniformity may be determined as the difference between the measured maximum and minimum thickness.

An SOI substrate is usually in the form of a circular wafer, with a diameter that may range from 150 mm to 450 mm, for example conventionally 300 mm for FDSOI substrates. The silicon surface layer is arranged on a dielectric layer, which is itself arranged on a carrier substrate. The surface of the surface layer extends in a main plane (x,y).

Advantageously, this method is applicable to an SOI substrate having a very thin surface layer, typically with a mean thickness less than or equal to 50 nm, less than or equal to 25 nm, less than or equal to 20 nm, or even less than or equal to 15 nm. For such substrates, the buried dielectric layer of the SOI substrate is generally between 10 nm and 100 nm.

The physical characteristics that need to comply with specifications at the end of a manufacturing line of course include the thickness parameters of the surface layer of an SOI substrate. As mentioned in the introduction, it is not easy to guarantee that these thickness parameters are representative of the entire surface layer, because very often a limited number of measuring points are implemented in metrology processes, in order to comply with production rates, grading and shipping.

To overcome this problem, the measuring method according to the invention comprises a succession of steps (Figure 1), which will now be described.

Step a) corresponds to measuring the thickness of the surface layer of the SOI substrate, at a predefined number of points (referred to as first points) that are spatially distributed over the surface of said layer. The spatial distribution of the first points in the main plane (x,y) may adopt various shapes that are more or less conventional, for example a cross, a spiral, a star, etc. The most peripheral points preferably extend up to 3 mm from an edge (contour) of the SOI substrate, knowing that the surface layer generally extends up to at least 0.5 mm from said edge.

This thickness measurement is carried out using a first technique, chosen so as to be precise and reliable on an SOI substrate. Preferably, the first technique is spectral ellipsometry. The F5X industrial equipment from KLA may be mentioned in particular. The wavelength range is typically 240 nm – 750 nm and the measurement accuracy is 0.03 nm for an SOI substrate having a surface layer with a mean thickness less than or equal to 50 nm.

The predefined number of first points may for example be 12, 41 or 625. A relatively small number of points is preferred in order to limit the loss of time in this metrology step a): the first points thus might not cover the entire surface of the layer.

Step a) results in a first series of thickness values comprising a maximum (referred to as first maximum) and a minimum (referred to as first minimum). At this stage, an intermediate thickness uniformity may be calculated from the first maximum and minimum.

Step b) of the method corresponds to producing a complete map of the surface of the surface layer, said map reflecting a physical characteristic of the surface layer that is more or less correlated with or representative of thickness. In other words, the physical characteristic is correlated with the specular reflectivity of the SOI substrate, which reflectivity is itself a function of the thickness of the multilayer according to Fresnel formalism.

A complete map is understood to mean that the physical characteristic is measured over the entire surface of the surface layer, with a measuring mesh (spacing between two consecutive measuring points) less than or equal to 5 mm, 1 mm, or even less than or equal to 500 μm (for example 200 μm, corresponding to the size of one pixel).

Step b) implements a second technique, different from the first technique. This second technique is advantageously chosen from among techniques that allow a high measurement rate.

According to a first embodiment, the second technique is reflectometry and the physical characteristic is thickness. An ACUMAP equipment from ADE may be used, for example. This allows a thickness measurement in grids the pitch of which may be as low as 1 mm, that is to say more than 70000 points, thereby providing a thickness map of the entire surface of the surface layer. Figure 2 illustrates one example of a thickness map obtained by reflectometry.

Although a reflectometry measurement is less accurate than an ellipsometry measurement (as used in step a)), the measurement rate makes it possible to quickly obtain a map that, in the next step, may be analysed so as possibly to identify signatures of large variations in thickness, potentially outside the areas measured in step a).

According to a second embodiment, the second technique corresponds to laser scattering surface inspection, in which a UV laser beam scans the surface of the surface layer.

It is common to inspect an SOI substrate by way of dark field microscopy using an incident light beam projected onto an inspection point scanning the exposed surface of the substrate, so as to qualify the defectiveness level thereof. A light-collecting device and a detector make it possible to measure the light scattered at the inspection point. Such an inspection may be carried out in particular using a Surfscan™ SP1, SP2, SP3 or SP5 inspection equipment from KLA. When the inspected surface comprises a surface irregularity or a particle, present at the inspection point, this leads to the scattered light signal being increased. The measurement of this radiation constitutes a signature that carries information concerning the presence, the position and/or the nature of a surface defect or particle at the inspection point. Scanning the entire surface layer by way of the laser beam makes it possible to obtain a complete defectiveness map, which is also essential for grading an SOI substrate. The wavelength of the laser beam is between 200 nm and 500 nm, depending on the equipment. It is preferably situated in the ultraviolet (UV), or even deep ultraviolet (DUV, deep UV), typically between 200 nm and 280 nm. By way of example, the SP5 equipment offers a 266 nm laser.

After scanning the surface of the surface layer by way of the laser beam, in addition to a defectiveness map, this type of equipment may also compile a map based on the haze signal. Haze corresponds to the diffuse reflectance of the measured substrate. One example of a haze map is illustrated in Figure 3, for an SOI substrate with a diameter of 300 mm, with a surface layer with a mean thickness of 12 nm and a buried dielectric layer (SiO2) with a mean thickness of 25 nm.

The haze signal is known to be representative of the surface roughness of the surface layer. In the case of a surface layer with a low thickness (typically less than or equal to 50 nm), in particular when the surface roughness is low and uniform (for example less than 0.5 nm RMS on an AFM scan of 30x30 μm^2, with a uniformity less than 0.3 nm), the haze may be correlated with the thickness of the surface layer (Brun et al, “Defect inspection challenges and solutions for ultra-thin SOI" – 2012 SEMI Advanced Semiconductor Manufacturing Conference).
Indeed, diffuse reflectance is then affected by surface roughness to a very small extent, and is correlated with specular reflectance, in the particular case where the surface layer is sufficiently transparent to the wavelength of the laser beam, so as to probe the entire thickness of the layer.

Thus, in the second embodiment, the physical characteristic imaged by the map in step b) is haze. This embodiment is particularly advantageous in that, with laser scattering surface inspection being required

to verify the defectiveness level of an SOI substrate, producing the haze map does not add any metrology time to the process of producing the SOI substrate.

Returning to the general description of the method according to the invention, following **step c)** corresponds to analysing the map obtained in step b) in order to identify whether there is a signature liable to reflect a variation in thickness greater than or equal to the difference between the first maximum and the first minimum in a localized region of the surface layer.

Taking the map of Figure 2 (first embodiment of step b)) as an example, it is possible to observe a wave pattern S1 that extends globally over the entire surface of the surface layer. This signature S1 is visible on the map (marked pattern in relation to the surrounding areas), and is also characterized by a large variation in thickness.

Taking the map of Figure 3 (second embodiment of step b)) as an example, it is also possible to observe at least one signature S2 corresponding to an abnormal variation in intensity of the haze signal, in the form of a periodic wave. Other signatures may be in the form of a point pattern, an aperiodic wave, or other patterns.

Advantageously, the signature is identified on the map via an image recognition algorithm or by carrying out thresholding of the intensity of the haze signal.
An image recognition algorithm may be fed with and trained on various types of signatures liable to be present on a haze map; it is thus able to learn to recognize each of these signatures and to classify them into predefined categories, taking into account criteria with regard to size, shape, contrast, etc.
As an alternative, the signatures may be identified by applying a certain threshold (or multiple thresholds) to the intensity of the haze signal, on parameters such as the standard deviation, relative median or relative mean of the signal: a detected intensity above (or below) the threshold on the map then reflects a signature liable to correspond to a significant variation in thickness, in a localized region of the surface layer.

Figures 4a, 4b, 4c and 4d show four examples of haze maps on which various signatures are found (surrounded by a white square). In Figure 4a, the signature S3 corresponds to a point pattern, reflecting a localized excess thickness of the surface layer. In Figure 4b, the signature S4 corresponds to a scratch

starting from the edge of the wafer and extending towards the inside of the layer, and may cause a large variation in thickness of the surface layer. In Figure 4c, the signature S5 corresponds to an extended dark area, reflecting an excess thickness of the surface layer. Finally, in Figure 5d, the signature S6 corresponds to a wave pattern characterized by variations in thickness of the surface layer.

By way of example, when thresholds are applied in order to detect signatures:

- a point pattern signature S3 is identified when the relative median of the haze signal collected in the narrow channel (haze narrow) is greater than 0.025;
- a signature S4 that is a scratch or other fine variations is identified when the standard deviation of the haze signal collected in the narrow channel (haze narrow) is greater than 0.04;
- a signature S5 that is an extended area of excess thickness is identified when the relative median of the haze signal collected in the narrow channel (haze narrow) is less than 0.95;
- a wave signature S6 is identified when the relative mean of the haze signal collected in the wide channel (haze wide) is less than -0.006.

It will be recalled that, in an SPx equipment, scattered light coming from the substrate is collected either by an elliptical mirror, for incident rays far from the normal (z) to the main plane (x,y) of the layer (collector called wide or wide channel), or by a lens, for incident rays close to the normal (z) (collector called narrow or narrow channel).

Step b) and step c) may be carried out on just a single equipment, which implements the second technique and comprises an analysis module for finding potential signatures on the map.
As an alternative, step c) may be carried out by another equipment comprising the analysis module. The latter receives the haze map files produced in step b), applies signature detection to them (via an image recognition algorithm or by carrying out thresholding) and, if signatures of interest are present, generates a file containing the location of the signatures in question.

If no signature is found on the map from step b), the one or more thickness parameters (including for example uniformity) may be calculated based on the first series of values obtained in step a). The absence of a signature reinforces the fact that these thickness values are representative of the entire surface layer.

If at least one signature of interest is found on the map, the method according to the invention provides a **step d)** of carrying out a thickness measurement at a second point or at a plurality of second points positioned in the localized region (attached to the signature on the map). This thickness-measuring step results in a second value (in the case of a single second measuring point) or in a second series of values, comprising a second maximum and/or a second minimum. The measurement is carried out using the first technique (for example spectral ellipsometry).

Preferably, at the end of step c), coordinates are assigned to the signature, in the main plane, by the second equipment (the one implementing the second technique). These coordinates are communicated automatically, prior to step d), to the first equipment implementing the first technique, via the generation of a file containing the location of the signature.

In the first equipment, the second points are positioned in the main plane in accordance with distribution schemes that are established as a function of the shape and type of signature. In the examples illustrated in Figures 4a, 4b, 4c, 4d, it may be seen that the distribution schemes of the second points may be in the shape of a cross, centred on the coordinates of the centre of the signature. The cross is larger in size than the signature so that at least the extreme points of said cross fall outside the signature: this makes it possible to ensure that the entire signature has indeed been evaluated. In the figures, the size of the square surrounding all or part of the distribution scheme of the second points is indicated above said square.

In the example of Figure 4d, a star-shaped or concentric distribution is preferred in order to capture possible variations in thickness in all directions; a high density of second points in the centre favours the detection of the thickness extremum, and the outer points, which are further away (typically 10 mm away), capture the other thickness extremum of the wave pattern.
Preferably, there are 10, 16 or 25 second points, in order to avoid taking too much measurement time. Of course, any other number of second points may be envisaged, depending on the size, shape and type of signature.

Of course, if multiple signatures are identified on the map, each of the localized regions of the surface layer corresponding to these signatures will be evaluated in step d), by way of a local thickness measurement.

The measuring method according to the invention finally comprises a **step e)** corresponding to the calculation of at least one thickness parameter of the surface layer, based on the first series of values and, potentially, on the second series of values, if step d) has taken place.
In the particular case where the - at least one - thickness parameter is uniformity, the first minimum and maximum are compared with the second minimum and maximum: the lowest of the minima and the highest of the maxima is then taken into consideration to determine the thickness uniformity of the layer.

Step e) may also comprise calculating other thickness parameters of interest, that is to say mean, median, standard deviation, etc. These may be established based on the first series of values, possibly supplemented by the second series of values.

Example:

- SOI: mean thickness of the silicon surface layer 12 nm; thickness of the buried oxide layer (SiO2) 25 nm;
- Step a): carrying out a measurement on 41 first points (Figure 5a) using spectral ellipsometry (first equipment, first technique); obtaining a first series of thickness values: maximum 12.29 nm, minimum 11.66 nm;
- Step b): producing a haze map (second equipment, second technique) (Figure 5b);
- Step c): analysing the map (analysis module), identifying a point pattern signature (Figure 5c) and transferring the coordinates of the signature to the first equipment;
- Step d): carrying out a measurement on 9 second points, in a cross-shaped distribution, centred on the signature, using spectral ellipsometry (first equipment, first technique); obtaining a second series of thickness values: maximum 14.47 nm, minimum 13.15 nm;
- Step e): calculating the thickness parameters so as to obtain in particular a uniformity, based on the first and second series of values, of 2.81 nm; the uniformity based on the first series of values was 0.64 nm. For a thickness uniformity specification of 1 nm, the measurement in step d) made it possible to identify that the surface layer of this SOI did not meet the specification, whereas the first series of values (step a)) alone would not have been sufficient to find this.

The measuring method according to the present invention drastically improves the reliability of the thickness parameters (mean, minimum, maximum, uniformity) taken into account for grading an SOI

substrate. These parameters are representative of the surface layer over its entire surface, and the expected specifications are thus complied with perfectly.

Of course, the invention is not limited to the embodiments and examples described, and alternative embodiments may be applied thereto without departing from the scope of the invention as defined by the claims.

CLAIMS

1. **Method for measuring at least one thickness parameter of a surface layer of an SOI substrate**, the surface layer having a surface extending in a main plane (x,y), the method comprising the following steps:

a) carrying out a thickness measurement at a predefined number of first points that are spatially distributed over the surface, resulting in a first series of values comprising a first maximum and a first minimum; the thickness measurement being carried out using a first technique and the first points not covering the entire surface;

b) producing a complete map of the surface of the surface layer using a second technique, different from the first technique, the map reflecting a physical characteristic of the surface layer correlated with thickness;

c) analysing the map so as to identify whether there is a signature liable to reflect a variation in thickness, greater than or equal to the difference between the first maximum and the first minimum, in a localized region of the surface layer;

d) if a signature is identified, carrying out a thickness measurement at a second point or a plurality of second points positioned in the localized region, resulting in a second series of values comprising a second maximum and/or a second minimum; the thickness measurement being carried out using the first technique;

e) calculating the - at least one - thickness parameter, based on the first series of values and, potentially, on the second series of values.

2. Measuring method according to the preceding claim, wherein the surface layer has a mean thickness less than or equal to 50 nm, less than or equal to 25 nm, less than or equal to 20 nm, or even less than or equal to 15 nm.

3. Measuring method according to either of the preceding claims, wherein the second technique is reflectometry and the physical characteristic is thickness.

4. Measuring method according to Claim 2, wherein the second technique is based on laser scattering surface inspection in which a laser beam scans the surface of the surface layer, and the physical characteristic is haze.

5. Measuring method according to the preceding claim, wherein a signature corresponds to an abnormal variation in the intensity of the haze signal, and may be in the form of a point pattern, a periodic wave, or other patterns.

6. Measuring method according to either of the two preceding claims, wherein the signature is identified on the map via an image recognition algorithm or by carrying out thresholding of the intensity of the haze signal.

7. Measuring method according to one of the preceding claims, wherein:

- at the end of step c), coordinates are assigned to the signature, in the main plane, by an equipment - referred to as second equipment - implementing the second technique, and
- said coordinates are communicated, prior to step d), to a first equipment implementing the first technique.

8. Measuring method according to the preceding claim, wherein the second points are positioned in the main plane in accordance with distribution schemes established on the basis of the shape of the signature.

9. Measuring method according to one of the preceding claims, wherein the - at least one - thickness parameter calculated in step e) is uniformity.

10. Measuring method according to one of the preceding claims, wherein multiple thickness parameters are calculated in step e), including a mean, and/or a median, and/or a standard deviation.

11. Measuring method according to one of the preceding claims, wherein the first technique is spectral ellipsometry.

12. Measuring method according to one of the preceding claims, wherein the predefined number of first points is 12, 41 or 625.

13. Measuring method according to one of the preceding claims, wherein there are 2, 9, 16 or 25 second points.