

Method for Measuring the Depth of a Trench
in the Surface of Semiconductor Wafer ✓

Field of the Invention

5 This invention relates generally to the manufacture of semiconductor wafers. More specifically it relates to a method for using optical apparatus to measure the depth of a trench formed in the surface of a wafer.

Introduction

10 In a familiar step in manufacturing a semiconductor wafer, a component such as a transistor is electrically isolated from neighboring components. For components with very small dimensions, an isolation technique called shallow trench isolation (STI) can be used: a trench is formed in the surface of the chip between a component and neighboring components. The
15 trench is later filled with a suitable nonconductor. The trench dimensions are selected to suitably isolate a component, and the dimension are from fractions of a micron to a few microns (micro meters).

20 It is a general object in this art to measure the depth of a trench with respect to the surface of the wafer. At this stage of the manufacturing process, the wafer comprises a silicon substrate and a structure of overlying layers. For example, the wafer that will be described later has a layer of silicon dioxide formed on the substrate and a layer of silicon nitride formed
25 over the silicon dioxide. The silicon nitride forms the wafer surface. The layers are generally planar and the method of this invention uses the surface of the wafer as a reference plane.

Measuring the trench depth is important in order to monitor the manufacturing process and also to adjust the following steps.

For example the actual measured depth of the trench can be used to adjust or control the step of filling the trench with an insulator.

The Prior Art

5 As a simple example of measuring trench depth, the wafer can be sectioned across a trench and the section can be viewed with a scanning electron microscope. This test is destructive, whereas it is a general object in this art to measure trench depth non-destructively.

10 One known measurement technique, called CD-AFM, has high spacial resolution and simultaneously measures the trench depth, the profile and the CD. But the CD-AFM technique is very slow, the machines are expensive, their maintenance is difficult, and an engineer is required for their routine operation on a
15 manufacturing line.

Another trench depth measuring apparatus, called a long scan profiler, has higher speed than CD-AFM but it has low spatial resolution and the space being measured must be more than 2 microns. This is also a destructive measurement; a wafer can no
20 longer be released back to the manufacturing line once a trench has been measured by the long scan profiler.

Summary of the Invention

A general object of our invention is to provide a new, absolute, and non-destructive method for measuring the depth of a
25 trench in the surface of a wafer. A related object is to provide a high accuracy and absolute trench depth measurement and to measure the smallest dimensions that can be achieved with lithography.

Another object of our invention is to measure trench depth
30 faster than before, with just few seconds required for each

sample point on the wafer surface. Another object is to provide a trench measuring method that is economical and easy to use.

5 We direct a light of a predetermined wavelength onto a trench and detect the reflected light. The trench is narrow enough that the light reflected from the bottom of the trench and light reflected from the surface at the top of the trench are coherent. The intensity of the reflected beam is compared with the intensity of the incident beam. The equations that describe the depth of the trench in relation to the intensity of these
10 beams will be explained and tests that have verified the calculations will be described.

Other objects and features of the invention will appear in the description of the preferred embodiment of the invention.

The Drawing

15 Fig. 1 is a simplified section view of a wafer showing the substrate and the overlying layers in the region of a trench.

Fig. 2 is a diagram of the apparatus used in our new method.

Fig. 3 is a diagram, similar to Fig. 1, showing light reflected from different layers of the wafer.

20 Fig. 4 is a plot of the reflection spectra with different trench depths in a test wafer.

Fig. 5 is a plot of a spectrum shift that is associated with a change in trench depth in a test wafer.

Fig. 6 is a plot of trench depth as a function of etch time.

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The preferred Embodiment

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Overview of the Invention - Figs. 1 and 2

Fig. 1 shows a wafer 11 at a stage in its manufacture where it has a silicon substrate 12, a silicon dioxide pad 13 with a thickness of about 50Å to 400Å, formed on the silicon substrate, and layer 14 of silicon nitride with a thickness of about 1000Å to 3000Å that is deposited on the silicon dioxide pad.

The section view of Fig. 1 is in the neighborhood of trenches 15 which are formed by plasma etching from the upper surface 16 of the silicon nitride 14 into the silicon substrate 12. The depth from the silicon nitride surface 16 to the trench bottom 17 is called the total trench depth. The depth from the interface 18 between the silicon substrate 12 and the silicon dioxide pad to the trench bottom 17 is called the silicon trench depth.

In Fig. 1, the depth and width of a trench 15 are approximately to the same scale. The thickness of the wafer (in the vertical dimension of the drawing) is of course many times the dimensions of a trench and the thickness of the layers 13, 14 overlying the substrate 12.

Fig. 1 shows two trenches. When several trenches of equal width are equally spaced apart, they form an optical grating structure. The surfaces 16 are called SEM bars. When our analysis later of a single trench and the adjacent SEM bars is

understood, it will be seen that multiple bars and trenches provide additional light to the detector and make the signal easier to interpret.

Fig. 2 is schematic diagram showing the optical system of a reflective spectrometer of the Opti-Probe 2600 (a product of Thermal-wave Inc.). White light 19 from a source 20 is split into two parts, 21 and 22 by a beam splitter 23. Part 21 goes through the beam splitter to an incident light detector 23 for monitoring the intensity of incident light. The other part 22 is reflected downward in the drawing and irradiates a wafer 24. The wafer reflects the light, and the reflected beam 25 goes through the beam splitter 23 and reaches a spectrometer 26. The spectrometer 26 detects a spectrum of reflected beam.

The components of the apparatus used in our method are well known in various optical devices and further details of the Opti-Probe apparatus is not needed for understanding and practicing our invention.

The Trench Depth Measuring Step - Fig. 3

With the apparatus of Fig. 2, we shine a beam of light on a trench 15 formed in the surface of the wafer illustrated in Fig. 1. The structure of Fig. 3 will be familiar from the corresponding components of Fig. 1. The light will be reflected by both the trench top surface 16 and the trench bottom surface 17, as shown in Fig. 3 in which the arrows represent light.

The top surface consists of three interfaces, which are the air and silicon nitride interface 16, the silicon nitride and silicon dioxide interface 28, and the silicon dioxide and silicon substrate interface 18. A superposition of lights from the three interfaces is identified in Fig. 3. by the legend "reflection from top surface." The lights from the top surface 16 and bottom surface 17 are coherent or partially coherent.

From the information in the interference spectrum of this reflected light, we are able to find the trench depth. The way the light spectrum carries this information will be described next.

5 Operation Theory

10 It will be helpful to review some equations that describe the way light is reflected from a wafer trench. Since the symbols are conventional, it will be easy to relate this summary to a more complete explanation in any standard text. Vectors are printed in bold type, as is customary.

15 Light can also be described as photons. When a photon comes out from a small pin hole we can not predict in which direction the photon will go. This is a famous uncertainty principle, $\Delta x \cdot \Delta p \sim h/2\pi$, (where h is Plank's constant) the basis for light diffraction. In our new method, a photon from relatively far away illuminates a wafer in the region of one or more trenches. If the trench width is small enough, we are unable to tell whether this photon will be bounced back from the trench bottom or from top surface adjoining the trench. Thus, the light from 20 the trench bottom and the light from top surface are coherent or partially coherent, dependent on trench width and coherency of light source. The interference occurring between the reflected lights provides important information about trench depth. Based on this principle, we have developed an in-line optical method 25 for trench depth measurement.

30 A light wave can be described by the equation $E_0 \cdot \exp(i\omega t - i\mathbf{k} \cdot \mathbf{r})$, where $\omega = 2\pi c/\lambda$ and $k = 2\pi/\lambda$; λ and c represent the wavelength and speed of light in a vacuum, respectively; and E_0 the amplitude of the electric field. The Poynting vector is defined as $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ with the units of $J/(m \cdot m \cdot \text{sec})$ (where $m \cdot m$ is area in meters). The average Poynting

vector is related to the intensity of light, $\langle S \rangle = (n/2\mu c) \mathbf{E}_0 \cdot \mathbf{E}_0$ $k/k \propto \mathbf{E}_0 \cdot \mathbf{E}_0$. The light beams reflected back from trench bottom and top can be described by $\mathbf{E}_t = \mathbf{E}_{t0} \exp(i\omega t - i\mathbf{k} \cdot \mathbf{r})$ and $\mathbf{E}_b = \mathbf{E}_{b0} \exp(i\omega t - i\mathbf{k} \cdot \mathbf{r} - i\delta)$, respectively. There might exist a certain extent of coherency between micro-spatial splitted lights $\mathbf{E}_b$ and $\mathbf{E}_t$. The interference between the two light beams results in

$$I \propto \mathbf{E} \cdot \mathbf{E}^* = (\mathbf{E}_t + \mathbf{E}_b) \cdot (\mathbf{E}_t + \mathbf{E}_b)^* = [\mathbf{E}_{t0} \exp(i\omega t - i\mathbf{k} \cdot \mathbf{r}) + \mathbf{E}_{b0} \exp(i\omega t - i\mathbf{k} \cdot \mathbf{r} - i\delta)] \cdot [\mathbf{E}_{t0}^* \exp(-i\omega t + i\mathbf{k} \cdot \mathbf{r}) + \mathbf{E}_{b0}^* \exp(-i\omega t + i\mathbf{k} \cdot \mathbf{r} + i\delta)]$$

Since the top surface may consist of a multilayer structure, $\mathbf{E}_t$ is a sum of electric field from the multilayer. The phase shift between two beams can be obtained in the following:

$$\delta = 2\pi n h [1/\cos \alpha + 1/\cos \beta - (\tan \alpha - \tan \beta) \sin \alpha] / \lambda$$

where α ($0^\circ \sim 90^\circ$) is the incidence angle; β ($90^\circ \sim -90^\circ$) is the outgoing angle of light; and h is a stack depth from top to trench bottom. See Fig. 3. The constant n is the refractive index of air.

In a special case of $\alpha = \beta = 0^\circ$, the solutions to the equations are much simplified. The phase shift ($\delta = 4\pi n h / \lambda$) is a function of light wavelength λ and trench depth h . The total intensity of light is $\langle S \rangle = (n/2\mu c) \mathbf{E} \cdot \mathbf{E} k/k \propto \mathbf{E}_0 \cdot \mathbf{E}_0$, also a function of λ and h . We assume that the top reflective coefficient is a constant R_t and bottom reflective coefficient is a constant R_b , where R_t and R_b are complex. The electric field strengths are $\mathbf{E}_t = t \cdot R_t \cdot \mathbf{E}_0$ and $\mathbf{E}_b = b \cdot R_b \cdot \mathbf{E}_0$, in which t and b are related to the spatial splitting of light. Therefore, total light intensity given by the interference of $\mathbf{E}_t$ and $\mathbf{E}_b$ is $I = b^2 I_b + t^2 \cdot I_t + 2 \cdot b \cdot t \cdot (R_{tr} \cdot R_{br} + R_{ti} \cdot R_{bi})$.

It is seen that there are three terms contributing to the

intensity of interfered light. The first and second stand for the reflection spectra from the bottom and top layers, respectively. The effect of light interference is included in the last term. In the case of silicon trench depth measurement, the bottom layer is only silicon wafer. For the convenience of data analysis, the total intensity can be normalized as

$$f = I/I_b = k_b + k_t \cdot I_t/I_b + k_c \cdot (R_{tr} \cdot R_{br} + R_{ti} \cdot R_{bi})/I_b,$$
where $I_b = R_b \cdot R_b^*$.

$I_t = R_t \cdot R_t^*$, R_{br} and R_{bi} , the real and image parts of R_b is related to the trench depth. R_{br} and R_{bi} on the other hand, are functions of wavelength and incident angle. In the equation, k_b and k_t contain the information about the light spatial split ratio and light scattering, depending on wafer pattern. k_c is a factor of light coherency, determined by the wavelength as well as wafer pattern. Trench depth information can be obtained in the third term. If k_c is equal to 0, it is obvious that the measurement will not provide trench depth. Therefore, it is necessary for us to select a suitable light source and correct wafer pattern in order to make k_c as big as possible. By varying the wavelength or incident angle of light, the correlation between reflective intensity vs λ or α can be readily measured. Using k_b , k_t , k_c and trench depth h as parameters, fitting the experimental curves will provide the information on trench depth. In this work, only the wavelength is achieved using Opti-probe 2600DUV. The trench is filled with air only and the refractive index of air is taken to be 1. The consideration of dispersion model of air is not necessary for fitting experiment data. It is also clear that the trench depth obtained in our measurement is the absolute value, since no other depth standard is involved. A computer program can process the data from the Opti-probe 2600DUV. The program is straight forward from our description and does not require explanation.

Experimental Results and Discussion

We have prepared a few wafer samples with different trench depths. 100Å thermal silicon oxide is on a silicon wafer, and 1500Å CVD (chemical vapor deposition) silicon nitride is deposited on the thermal silicon oxide, as shown in Fig. 1 and described earlier. Photoresist mask was used for silicon nitride etch, stopping on silicon. The silicon nitride works as a hardmask during trench etching. Our trench depth measuring method is useful with trenches etched by any suitable method for etching the silicon wafer, but we use Lam TCP9400SE to etch into silicon wafers. The trench profile is shown in Fig. 1. Trench depth can be controlled by adjusting trench etch time (as discussed later in relation to Fig. 6). Opti-probe 2600DUV from Therma-Wave Inc was used to characterize trench depth at SEM bar areas or cell areas. Opti-probe 2600DUV is three-in-one thin film measurement system. Reflection spectrophotometry, beam profile reflectometry and ellipsometry are compiled in Opti-probe 2600DUV. Reflection spectrophotometry and beam profile reflectometry change incident angle of light. Here we demonstrated trench depth measurement only by reflection spectrophotometry, because the problem is simple when incident angle is equal to 0°.

At the beginning of our test, we have three wafers with different trench depths. For each wafer, we made two point measurements, one point is on the center of the wafer and another is on the bottom edge. Based on our physical model all of our experimental data are fitted to the calculated data very well. Fig. 4 shows measurement data and fitted curves from three different wafers. (GOF is a goodness of fit parameter.)

The horizontal axis is the wavelength in Angstroms of the reflected light and the vertical axis is the reflectivity in a relative scale of 0 to 1. In each of the three plots, the

heavier line is the plot from a test wafer and the thinner line is the calculated value. The two plots substantially overlap for each wafer but the two lines can be seen toward the longer wavelength side of Fig. 4.

5 The value of reflectivity is based on the residual and can range from 0 to 1. GOF equal to 0 means no fit at all. The fitting is perfect and complete confidence if the GOF is equal to 1. The relation between GOF and residual is $GOF = 1.00 - 10 \cdot \text{Residual}$. All GOFs of our fittings are larger than 0.9; see
10 Table 1. This means our fittings are good in high confidence. Trench depths are also shown in Table 1. Total trench depth is the depth from the top of silicon nitride to the bottom of
15 1. During our fitting we keep pad oxide thickness $100\text{\AA}$ unchanged.

 The reflection spectrum is quite sensitive to trench depth. With $78.6\text{\AA}$ trench depth change we have about $157.2\text{\AA}$ spectrum shift. This is shown in Fig. 5. In order to know the precision
20 we must study repeatability and reproducibility (R&R). Ten-point measurements are carried out on a selected production wafer. We measure different wafers three times a day, and do it for three days. The average trench depth was $3699.76\text{\AA}$.

 The repeatability and reproducibility are $28.1\text{\AA}$ and $6.5\text{\AA}$,
25 i.e. 0.76% and 0.17% respectively. So R&R is $28.9\text{\AA}$ (0.78%). This means our measurement precision is $29\text{\AA}$ at $3700\text{\AA}$ trench depth. In order to calculate gauge repeatability and reproducibility (GR&R), we assume our process requires $\pm 10\%$ control, our measurement GR&R is 3.9%. If process control is
30 $\pm 5\%$, our GR&R will be 7.8%. This means our trench depth measurement as a gauge can meet our process control requirement

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excellently, no matter whether the process control is $\pm 10\%$ or $\pm 5\%$.

We compared the results from the Opti-probe 2600DUV and P-2h Long Scan Profiler. P-2h long scan profiler is made by Tencor Inc. It performs a contact step depth measurement, a small tip moving on the wafer surface. For non-production wafers, trench depth can be measured by P-2h. The 9-point measurement is carried out. Trench depths from trench bottom to wafer top are worked out by P-2h and Opti-probe, listed in Table 2. Average difference between data from two machines is $3.57\text{\AA}$. Three standard deviations of the difference (σ is the symbol for one standard deviation) is $63\text{\AA}$, 1.8% in percentage. So we are able to tell with 99.73% confidence that if we did another measurement, the difference would fall in the range from $-60\text{\AA}$ to $67\text{\AA}$.

We have tested the optical trench depth measurement in our fabrication line. Data are shown in Table 3. We get one wafer from each lot. After optical trench depth measurement, wafer was cut for cross section SEM to get off-line trench depth data. We prepared two samples for each wafer, one is on wafer center, another is on wafer edge. Fourteen samples from seven wafers have been studied. The data are shown in Table 3. X-SEM trench depth measurement is based on a SEM image. The largest magnification used is $80,000\times$. It is very hard to judge the position of the top edge and the bottom edge. It is also dependent on a person who is making the test. The X-SEM measurement repeatability is about $\pm 150\text{\AA}$ from time to time, from person to person. After 14 measurements, the average trench depths are very close to each other. 3-Sigma of depth difference is $147\text{\AA}$, which is comparable with measurement error. So we can not tell any difference between two measurements.

Trench depth will change with trench etch time. The longer the etch time, the deeper the trench. Opti-probe is able to measure all of the trench depths we prepared from 500Å to 7100Å. The relation between etch time and trench depth is linear, shown in Fig. 6. Based on the linear fitting, we get the following relation: Silicon trench depth (in Angstroms) = 69.022 Å/sec * Trench etch time (in seconds) + 439.93Å.

Thus, the trench etch rate is 69.022Å per second, which is a by-product of our research. The constant term (439.93Å) means that silicon gouging before the trench etch is 439.93Å. This gouging comes from the previous silicon nitride etch.

Summary and Conclusions

Our novel trench depth measurement principle has been illustrated based on the first theory. The coherency between micro spatial splits of light is the core of the principle. A physical model has been worked out. In this model, reflection spectra contains three parts: $f = k_b \cdot I_b + k_t \cdot I_t + k_c \cdot (R_{tr} \cdot R_{br} \cdot R_{ti} \cdot R_{bi})$.

Trench depth information is included in only the third term. k_c is dependent on coherency of light source and wafer pattern. If k_c is equal to 0, no trench depth can be calculated. We have to increase coherency of light source and adjust wafer pattern to make k_c as big as possible. k_c and k_c will also change with wafer pattern. Our measurement is an absolute measurement because there is no parameter that can be tuned to meet other depth standard except wavelength calibration.

We have developed a trench depth calculation software to fit experimental data from the Opti-probe 2600DUV. All our fittings are good, with GOF greater than 0.9, regardless of the trench depth variation from 500Å to 7100Å. Measurement repeatability and reproducibility have also been studied. We have compared our

performance with that of a Tencor P-2h long scan profiler and X-SEM. Results are quite consistent with each other.

Those skilled in the art will recognize variations in our method within the skill of the art and the scope of the claims.



The Claims

1 1. A method for measuring the depth of a trench formed in the
2 surface of a semiconductor wafer at a stage of wafer manufacture
3 where the wafer has a substrate and a layer structure overlying
4 the substrate, the layer structure having a planar upper surface,
5 and at least one trench formed in the upper surface, the trench
6 having a predetermined length and width along the surface and
7 having a bottom surface, the measuring method comprising the
8 following steps

9 using the plane of the planar upper surface as a first
10 reference and the length direction of the trench as a second
11 reference, illuminating the trench with a light of predetermined
12 intensity and wavelength at first and second predetermined angles
13 with respect to said first reference and said second reference,

14 detecting the intensity of light reflected from the top and
15 bottom of the trench at third and fourth predetermined angles
16 with respect to said first reference and said second reference,

17 and ascertaining the trench depth from the intensity of the
18 reflected light at the predetermined angles.

1 2. The testing method of claim 1 wherein the width of the trench
2 is small enough that light from the top and bottom of the trench
3 is coherent.

1 3. The testing method of claim 2 wherein the step of finding the
2 depth from the intensity of the reflected light comprises the
3 steps of comparing the intensity of the light with the intensity
4 of light reflected from a trench of known depth in a test wafer.

1 4. The testing method of claim 2 wherein the predetermined angle
2 of illuminating the trench is 90° with respect to the length
3 direction of the trench (said second reference).



1 5. The testing method of claim 4 wherein the predetermined angle
2 of detecting the intensity of light from the trench is 0° with
3 respect to the first reference.

1 6. The testing method of claim 5 wherein the steps of
2 illuminating the trench, detecting the reflected light, and
3 finding the trench depth are performed separately at a plurality
4 of locations along the length of the trench.

1 7. The testing method of claim 6 wherein the light of
2 predetermined intensity and wavelength is incoherent.

1 8. The testing method of claim 7 wherein the layer structure
2 comprises a layer of silicon dioxide overlying the wafer and a
3 layer of silicon nitride overlying the silicon dioxide, the outer
4 surface of the silicon nitride forming the reference surface.

1 9. The method of claim 2 wherein the substrate has a plurality
2 of locations for components and said one trench is arranged for
3 conductively separating neighboring components.

1 10. A method for measuring the depth of a trench formed in the
2 surface of a semiconductor wafer, the wafer having
3 a substrate,
4 and a layer structure overlying the substrate, the layer
5 structure having a planar upper surface, and
6 at least one trench formed in the upper surface, the trench
7 having a predetermined length and width along the surface
8 and having a bottom surface,
9 the measuring method comprising the following steps
10 forming a plurality of spaced apart trenches in the process
11 for forming said one trench, whereby said plurality of trenches
12 have the depth of said one trench,



13 using the plane of the planar upper surface as a first
14 reference and the length direction of one of said plurality of
15 trenches as a second reference, illuminating said plurality of
16 trenches with a light of predetermined intensity and wavelength
17 at first and second predetermined angles with respect to said
18 first reference and said second reference,
19 detecting the intensity of light reflected from the tops and
20 bottoms of the illuminated trenches at third and fourth
21 predetermined angles with respect to said first reference and
22 said second reference,
23 and ascertaining the trench depth from the intensity of the
24 reflected light at the predetermined angles.

1 11. The testing method of claim 10 wherein the width of the
2 illuminated trenches is small enough that light from the top and
3 bottom of a trench is coherent.

1 12. The method of claim 11 wherein said trenches of said
2 plurality of trenches are equally spaced apart and parallel in
3 their length directions to form a grating structure.

1 13. The method of claim 12 wherein the trenches of said grating
2 structure are equal in length.

1 14. The method of claim 13 wherein the trenches forming the
2 grating structure are equally spaced apart.



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1 15. A method for manufacturing and testing a silicon wafer,
2 comprising the following steps

3 selecting a wafer at a point in a manufacturing process at
4 which a plurality of trenches isolating components of the wafer
5 have been formed and at least one grating structure with a
6 plurality of trenches has been formed in the surface of the wafer
7 substrate and through overlying structural layers by a process
8 that produces equal depths in the isolating trenches and in the
9 trench of the grating structure,

10 using the plane of the surface of the wafer as a first
11 reference and the long direction of the trenches of the grating
12 structure as a second reference, directing a light beam at the
13 grating structure at predetermined angles with respect to said
14 first reference and said second reference,

15 detecting the intensity of light reflected at predetermined
16 angles with respect to said first reference and said second
17 reference, and

18 comparing the reflected light intensity with previously
19 collected data relating the light intensity to trench depth at
20 the predetermined angles,

21 and returning the wafer to the manufacturing process.