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Invited

Depth Measurement Techniques for Silicon Trenches

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Nondestructive trench-depth measurement has been carried out using two novel methods: higher-order optical interferometry and electron-beam generated X-ray absorption (EXAD). The interferometry method reveals the average depth of the trenches inside the light-probe spot. When dielectric films exist on the wafer, depth data shifts smaller in proportion to increasing film thickness and refractive index. EXAD, on the other hand, provides a sharp probe of 10nm diameter, which enables individual trench measurement. With highly packed trenches, adjacent trenches lying in the way of detecting X-rays must be taken into account to correct obtained data.

1. INTRODUCTION

The effective fabrication of higher packing density VLSI's depends not only on processing techniques but also on precise measurement techniques.

Recently, various types of trench devices such as corrugated capacitor $\operatorname{cell}^{1)}$ and groove isolation²⁾ have been proposed for reducing the device size. However, many difficulties arise in the measurement of these trench structures. In many cases, the depth of the trenches are several times their width, e.g., 5µm-deep and sub-µm-wide. Such high-aspect-ratio structures make it difficult to measure the depth or observe the bottom of trenches.

Although cross-sectional views with SEM TEM are capable of very high resolution or (tens or several Å), they are not applicable to in-line measurement. Nondestructive and preferably individual trench depth measurement techniques are required in particular. In this paper, we present examples of depth measurements using an interferometry for a wide area and an X-ray absorption method for individual included is a review on trenches. Also nondestructive depth measurement techniques from the standpoint of resolution. Several

inspection techniques for trench capacitors, though destructive, are presented as well.

2. DEPTH MEASUREMENT TECHNIQUES

(1) **PROFILOMETER**

Stylus profilometers are widely used for general step-height measurement. The stepheight resolution is as high as 1nm; however, this mechanical method has two drawbacks. Measuring the trench, we should consider the relative size of the trench and the stylus as a probe. Although the stylus tip radius has been reduced to as small as 0.5µm, the tip is not sharp enough. Therefore, the stylus cannot reveal the bottom of a narrow trench. Further, the stylus scratches the surface which may cause contamination.

Optical profilometers using a focused light as an optical stylus and a focus detection technique can eliminate such scratching³⁾. However, as with the mechanical stylus, the optical stylus must be reduced to measure sub- μ m trenches. In these methods, as well as other advanced methods such as STM⁴⁾, the stylus size is a crucial point for applicability, as summarized in Table 1.

Table I Depth measurement methods		
Method	Probe	Typical Probe Size
Mechanical Profilometer	Stylus	1 µ m
Optical Profilometer	Focused Light	1.6µm
Interfero- metry	Light	
Stereo SEM	Electron Beam	
X-ray Absorption		
Replica/SEM		

m 11 1

(2) INTERFEROMETRY

Interference of rays reflected from two different planes can be correlated to the separation of the two planes. Thus the relation between the trench depth d and the wavelength λ where constructive interference occurs is given by

> (1)

where m is an integer and the incident light is perpendicular to the plane. By observing the change in reflected intensity at a fixed wavelength, the trench depth can be monitored during etching. On the other hand, the trench depth can be measured after etching using a spectrophotometer and given by

 $d = i \lambda_0 \lambda_i / 2(\lambda_0 - \lambda_i), - - (2)$ where λ_i is the wavelength at a successive maxima of reflected light and i the number of complete intensity-cycles from λ_0 to λ_i .

Figure 1 shows the depth measurement for detecting both 0-th order and system higher-order diffracted light. By taking the higher-order diffracted light as a signal, the noise of reflected light can be eliminated⁵⁾. Since the diffraction angle changes according to the wavelength, a rotating mirror is adopted to detect constructive diffraction. In this manner

a high signal-to-noise spectrum was obtained as shown. and the depth was calculated by Eq.(2). Here, the spot radius of an incident light is 1mm; thus, the calculated depth represents an average depth of the trenches within the spot The spot radius should be selected from area. the signal-to-noise viewpoint, and it may be reduced to 0.1mm or less with a high-power light source or microscope optics.

The error in this measurement was found to be 0.2µm for a 1µm-wide, 5µm-deep trench array where the total trench area was about 10% of the spot area. Furthermore, an additional error should be taken into account when dielectric films are formed on the surface. In a trench capacitor process, isolation oxide may be formed prior to trench etching and CVD SiO, is used as an etching mask. Such SiO, layers cause phase-shift of reflected light given by 2(n-1)t, where n is the refractive index of the layer and t is its thickness. For example, if a 1.0µm-thick SiO, (n=1.45) layer exists on trench depth is errorneously the surface, estimated to be 0.45µm smaller than the actual depth. In order to correct this error, our system of Fig.1 is equipped with a photometer for 0-th order diffracted light to measure the film thickness.

Interferometry using a spectrophotometer like this one or a Michelson interferometer is useful to quickly obtain an average depth^{6,7}. An application limit may exist where a trench width is smaller than the wavelength of the light probe.



Fig.1 Diagram of a higher-order interferometer for trench depth measurement.

(3) ELECTRON BEAM METHOD

An electron beam presents a very sharp probe, which has led to increased popularity of electron microscopy. SEM. is most useful for in-line inspection of sub-µm pattern widths. Step-heights or three-dimensional structures can also be observed by tilted images. Although a larger tilt angle is favorable to measure a steep step, high-precision stereo SEM can still be applied to individual trench measurement⁸⁾.

As another application of an electron beam we have proposed the X-ray absorption method $(EXAD)^{9}$. The equipment is similar to an X-ray microprobe analyzer. By irradiating a silicon surface with an electron beam, X-rays are generated as shown in Fig.2; the X-rays consist of characteristic emission peaks and background. We measured the Si¹⁴K α peak intensity by a Si(Li) crystal detector, and compared the intensity from the surface (I₀) with one from the trench bottom (I_d). These intensities follow Beer's law and are related by

 $I_d = I_0 \exp(-\mu d \operatorname{cosec} \theta), --$ (3) where μ is the absorption coefficient (about $10^3 \mathrm{cm}^{-1}$), d the trench depth, and θ the X-ray detection angle relative to the wafer surface.

Figure 3 shows an example of EXAD measurement. At a detection angle of 25°, three kinds of intensity-ratios were obtained. is caused by the difference between This trench-sites in a trench array. If the X-ray generated at the trench bottom passes through other trenches, I_d is affected and shifted In Fig.3, the minimum value obtained larger. from the trench at the array edge could reveal the trench depth. Although the larger values from the other sites contain an error due to adjacent trench width, they could also reveal the depth after a correction of I_d shifts. To avoid such shifts the X-ray detection angle and direction should be chosen so that the X-ray beam does not cross the adjacent trenches. One point to remember is that even though the electron-beam-spot size is as small as 10nm,

the X-ray beam may be 1μ m in diameter at an electron beam energy of 10keV.

Because of some other error factors such as reflected electrons (about 20% of incident electrons) which cause I_d to increase, the intensity does not exactly follow Eq.(3). Therefore, we used a calibration by SEM. so that the resulting error was within 5%.

Since the probe of EXAD is very sharp and the probe incident angle is perpendicular to the wafer surface, it can cope with a narrow trench comparable to electron beam diameter.



Fig.2 Diagram of EXAD (Electron-beam X-ray Absorption method for Depth measurement).



Fig.3 An example of EXAD measurement for 1µm-wide trenches.

3. INSPECTION TECHNIQUES

Replicas have been used for preparation of TEM samples¹⁰⁾, and recently they were applied to trench measurement¹¹⁾. We reconfirmed the applicability of a replica to narrow trench measurement as follows. By using acetylcellulose and aceton solvent, 0.2μ m-wide and 2μ m-deep

trench profiles could be transferred to a onestep replica as shown in Fig.4. Some imperfect transfers such as bending and dropping-out were observed on the replica, so that the replication limit is around an aspect ratio of 10.

A one-step replica which shows a reversed profile makes it easy to observe the trench bottom by SEM. For example, etch pits formed by Secco-etching at crystallographic dislocation sites on the trench bottom can be observed as shown in Fig.5.

Another way to observe the trench bottom is given by an etch-off technique. The silicon substrate of trench capacitors was etched off from the back-side of the wafer. Using highly selective etching with hydrazine, the insulator the trench capacitor remained as shown in of Fig.6. In this way the reversed profile of the trench similar to the one-step replica was obtained. Because of the real image obtained unlike the replica, we could observe the fine structures of trench capacitors.



Fig.4 0.2µm-wide trench and its replica.



Fig.5 Scanning electron micrograph of the replica showing etch-pits at the trench bottom.

Fig.6 Scanning electron micrograph of trench poles after etching-off the silicon substrate.

4. SUMMARY

This paper has reviewed and evaluated a variety of trench-depth measurement techniqes. Nondestructive trench-depth measurement has been carried out using a new interferometry procedures and a newly developed X-ray absorption method (EXAD).

The interferometry of higher-order diffraction is useful for an average depth measurement of a trench array. If dielectric films exist on the surface, it is necessary to correct the obtained data according to the thickness and the refractive index of the film.

Individual trench depth can be obtained by EXAD having a sharp electron-beam probe of 10nm diameter, where an adjacent trench lying in the way of detecting X-rays must be taken into account.

replica A one-step and a substrate etch-off method are also useful to observe the inside structure of trench devices.

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