Precision Depth Measurement of Shallow SIMS Craters Using a Stylus Profilometer

Profiler Series

KLA-Tencor
Metrology Group

Introduction

Design of complex electrical circuits is highly dependent upon the ability to fabricate well characterized and controlled locally doped regions of the substrate material. It is therefore common to require techniques to measure diffused impurities concentration to within parts per billion. Secondary ion mass spectroscopy (SIMS) has been the most popular technique to meet this requirement.

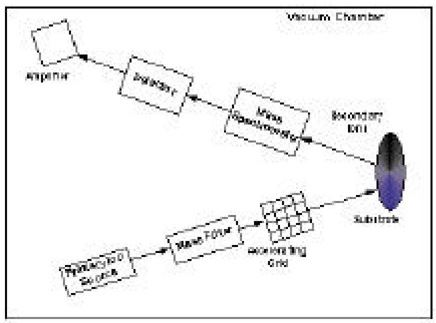

Fig. 1. A typical SIMS arrangement.

In a typical SIMS arrangement, shown in Figure 1, the surface of a sample is exposed to a beam of high-energy (several Kev) ions in an ultrahigh vacuum. The energetic ions strike the surface of the sample, destroying the crystal lattice and ejecting atoms from the top few monolayers of the sample as shown in Figure 2. A fraction of the ejected or sputtered atoms are ionized that are then collected and accelerated toward a mass spectrometer. The mass analysis of the sputtered atoms determines the chemical composition of the sample. In order to control the diffusion or implantation of impurities, however, it is desirable to know their concentration as a function of depth into the substrate material.

Typical SIMS analyses result in impurities concentration as a function of time using Eqns. (1) and (2).

$$\frac{\mathbf{I_s}}{\mathbf{C_s}} = \mathbf{RSF_i}\,\frac{\mathbf{I_i}}{\mathbf{C_i}} \qquad (1)$$

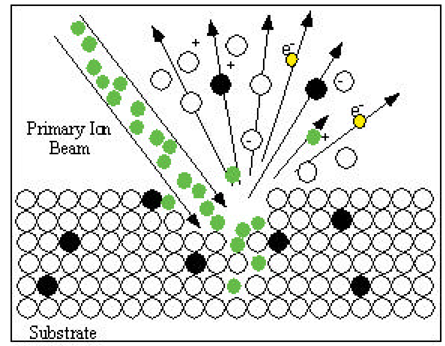

Fig. 2. Bombardment of a sample surface with energetic primary ions. The sputtered impurity and substrate ions are represented by black and white colors respectively.

$\mathbf{I_s}$	Secondary ion current of the substrate material
$\mathbf{I_i}$	Secondary ion current of the implanted element
$\mathbf{C_s}$	Concentration of the substrate material
$\mathbf{C_i}$	Concentration of the implanted element
$\mathbf{RSF_i}$	Relative sensitivity factor of the implanted element

$$\mathbf{C_i} = \mathbf{RSF_i}\,\mathbf{C_s}\,\frac{\mathbf{I_i}}{\mathbf{I_s}} \qquad (2)$$

Assuming that the concentration of the substrate material ($\mathbf{C_s}$) remains constant, a new constant, **RSF**, is defined as follows:

$$\mathbf{RSF} = \mathbf{RSF_i}\,\mathbf{C_s} \qquad (3)$$

Substituting Eqn. (3) into Eqn. (2) results in

$$\mathbf{C_i} = \mathbf{RSF}\frac{\mathbf{I_i}}{\mathbf{I_s}} \qquad (4)$$

RSF values are tabulated, $\mathbf{I_s}$ is a constant and $\mathbf{I_i}$ is given as a function of time. Thus, $\mathbf{C_i}$ can be calculated as a function of time. To determine $\mathbf{C_i}$ as a function of depth into the substrate material, the final SIMS crater depth (**D**) must be measured. Since the total sputter time (**T**) is already known, the average sputter rate is obtained from Eqn. (5).

$$\overline{\mathbf{S}} = \frac{\mathbf{D}}{\mathbf{T}} \qquad (5)$$

Once the average sputter rate is determined, $\mathbf{C_i(x)}$ is simply obtained from Eqn. (6).

$$\mathbf{C_i(x)} = \overline{\mathbf{S}}\,\mathbf{C_i(t)} \qquad (6)$$

The analysis above indicates that the final SIMS crater depth is a key parameter in obtaining dopant profiles as a function of depth into the substrate and thus must be measured with the highest degree of precision. It is often necessary to require less than 2% deviation from a mean depth. Meeting this requirement has been particularly challenging when the SIMS craters are shallow (i.e. less than 1000 Å in depth). The objective of this note is to devise a technique to measure shallow SIMS craters depth with less than 1% deviation from a mean depth using a stylus profilometer.

Measurement Procedure

The focus of this application note is precision depth measurement of shallow SIMS caters using a KLA-Tencor P-11 surface profiler. SIMS craters that are deeper than 0.1 µm can be routinely measured using the P-11 with less than 1% repeatability, represented here by one standard deviation from a mean depth obtained from ten separate measurements. Percentage reparability is obtained from multiplying 100 by the ratio of standard deviation to mean depth.

Achieving less than 1% repeatability when measuring SIMS craters that are less than 0.1 µm deep poses a challenge since the order of magnitude of mechanical and acoustic noise as well as surface roughness is closer to the depth of the SIMS crater. Figure 3 shows a comparison between a scan trace in a region on the substrate that is outside of the SIMS crater, representing the cumulative effects of both surface roughness and environmental noise, and a trace across a shallow SIMS crater. The SIMS crater represented in Figure 3 is only about 300 Å deep while the TIR value, the difference between the maximum and minimum values, of the roughness and noise trace is over 100 Å.

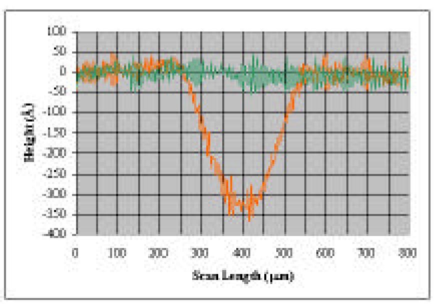

Fig. 3. Comparison of noise to a SIMS crater depth measurement.

One of the most important factors in achieving high precision in measuring step heights using any of the KLA-Tencor surface profilers is ensuring that the same location on the sample is measured every time the measurement is repeated. This implies that the location of successive scans should be as close to each other as possible and that the measurement cursors are placed at the same location on each scan trace. Scanning the same location repeatedly can be easily achieved using the profiler screen's cross hairs. Measuring the same location in a trace, however, requires enabling the edge detection feature of the profiler software. The success of edge detection depends upon certain considerations that will be discussed below. The following sections are intended to serve as a general guide to successful edge detection when measuring SIMS craters using any of the KLA-Tencor surface profilers operating under the KLA-Tencor profiler software version 4.x.

Mechanical Leveling

Despite the high degree of flatness of the KLA-Tencor surface profilers' sample stage, a substrate placed upon the stage often may not be entirely parallel to the stage. Consequently, a scan trace across any region on the substrate will have a slope relative to the horizontal as shown in Figure 4. The slope of the scan trace is eliminated by the leveling feature of the profile software during post scan analysis. For edge detection to be successful when measuring shallow SIMS craters, however, it is important that any slope is eliminated before scanning; that is making sure that the substrate is seated on the sample stage as flatly as possible. The mechanical leveling feature of the profile software accomplishes this task by physically moving the sample stage until it is leveled relative to the substrate. The operation of mechanical leveling is similar to trace leveling during post scan analysis.

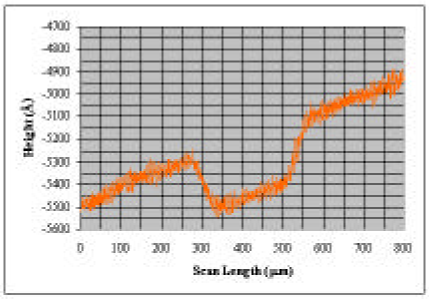

Fig. 4. An unleveled trace, indicating that the substrate is not flatly seated on the profiler stage.

Mechanical leveling is recommended only when an initial test scan across a SIMS crater of interest shows the trace to have risen by at least half the depth of the crater by the time the first edge of the crater is reached. For example, if the scan trace appears to have risen by about 250 Å by the time the first edge of the crater, that is about 500 Å deep, appears in the scan trace, then mechanical leveling should be performed. Detecting a change in the slope of the crater edge without mechanical leveling would be very difficult when the slope of the overall trace changes much more rapidly compared to that of the crater edge.

Stylus

SIMS craters tend to have rough surfaces, which introduce inaccuracies and adversely effect precision measurements of crater depth. Surface roughness may be minimized if a large stylus such as the KLA-Tencor 12.5-µm tip radius L-stylus is used. However, to be sure that the accuracy of the SIMS craters depth measurement is not compromised, it is recommended that a 5.0-µm tip radius stylus be used.

Scan Recipe

The scan recipe for SIMS crater depth measurements should be designed such that the effect of environmental noise is minimized. Higher scan speeds and larger stylus forces tend to make the stylus less susceptible to noise. Higher scan speeds require relatively higher scan lengths and higher sampling rates so that an appropriate amount of the data can be collected. The following scan parameters are recommended as a guide when measuring SIMS craters depth.

Scan length: 3 – 4 times the length of the crater

Scan speed: 100 µm/s

Sampling rate: 200 Hz

Stylus force: 2 mg

Edge Detection

The KLA-Tencor profilers' feature detection software makes it possible to automatically detect a rising or a falling edge of a feature and place leveling and measurement cursor relative to that edge. This ensures that the same location is measured automatically each time the scan is repeated. Applying edge detection to step height measurement of features that are over 0.1 µm in height or depth and have well-defined edges is a simple matter. SIMS craters, however, tend to have very rough surfaces, which combined with background noise, makes it difficult to distinguish the edge of a crater that is only about 300 Å deep. It is, therefore, necessary to filter noise and surface roughness before the edge detection feature of the profiler software is applied. The profiler software release 4.x allows such filtering.

The Gaussian noise filter of the feature detection software can be used to filter noise ranging from 0.25 µm to 800 µm in wavelength. The scan data is filtered in this part of the profiler software version 4.x solely for the purpose of edge detection. Once the edge of a feature is detected and the cursors are placed appropriately by the software, the user is presented with the original raw scan data. Filtering of the raw scan data can be accomplished similarly by the filtering part of the KLA-Tencor profiler software, which will not be discussed here.

In order to select the proper noise filter when measuring SIMS craters depth, a region on the substrate outside of the crater is scanned to determine the minimum wavelength of the noise trace to filter. SIMS craters do not have well-defined edges and thus lower slope threshold values would work better. Then following feature detection parameters are recommended as a guide.

Feature: Down Edge

Feature number: 1

Slope threshold: 2

Plateau Threshold: 2

Min. Plateau Width: 2

If the software is unable to detect the desired edge of the crater using the recommended parameters, then the noise wavelength to filter should be increased. For detecting the edge of the SIMS crater shown in Figure 3, wavelengths below 14 µm were filtered.

Conclusion

Secondary ion mass spectroscopy (SIMS) is the most accurate method of measuring impurities concentration as a function of time. To determine impurities concentration as function of depth into the substrate material, a profilometer is required to measure the final depth of the crater, created by the primary ions. In order to maintain accuracy in measuring dopant profiles, it is imperative that the SIMS crater depth be measured with the highest degree of precision. The KLA-Tencor P-11 stylus profilometer, operating under the KLA-Tencor profiler software release 4.x, meets this challenge by measuring the depth of a 250 Å SIMS crater with a 2 Å (0.7%) repeatability.

Precision measurement of shallow SIMS craters mostly depends upon minimizing noise and successful edge detection. Noise is minimized by using a large stylus (5.0 µm), high scan speeds and sampling rates and long scan lengths. Crater edges can be detected successfully by mechanically leveling the profiler stage, if necessary and setting the appropriate noise filters prior to edge detection. Filtering scan data to facilitate edge detection is a unique feature of the KLA-Tencor profiler software release 4.x. Although a P-11 surface profiler was used for the purpose of this application note, techniques devised here will be applicable to measurement of SIMS craters depth using any of the of KLA-Tencor surface profilers such as the P-22, P-30 and the HRP (High Resolution Profiler).

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Printed in USA 5/98 M-SM-AN1