SEMI 3D5-0314 (Reapproved 1218)
GUIDE FOR METROLOGY TECHNIQUES TO BE USED IN MEASUREMENT OF GEOMETRICAL PARAMETERS OF THROUGH-SILICON VIAS (TSVs) IN 3DS-IC STRUCTURES

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1 Purpose

1.1 This Guide will assist the user in selection and use of tools for performing measurements of geometrical parameters of an individual through-silicon via (TSV), or of an array of TSVs. TSVs are expected to be a critical element in future three-dimensional stacked integrated circuit (3DS-IC) packaging. Advanced TSV designs with higher aspect ratios and smaller diameters may challenge TSV metrology techniques. This Guide will address the various metrology techniques that are currently available that enable TSV dimensional measurements. This Guide can also assist producers and users of TSV metrology to develop products and conduct meaningful evaluations.

2 Scope

2.1 This Guide focuses on the geometrical parameters of the openings (i.e., holes) in thin silicon slices, within which the conductive vias will be constructed. Additional layers on the surface of the silicon wafer, such as a hard mask, may be present; such layers may affect the performance of the metrology tools described below.

2.2 A complete TSV will typically require additional components, for example, a conductive material and insulating layers. The measurement tools described in this Guide represent the present state of the art for measurements of the TSV opening. Some of them may be applicable to other TSV features that become present at a later stage of manufacture, while others may not.

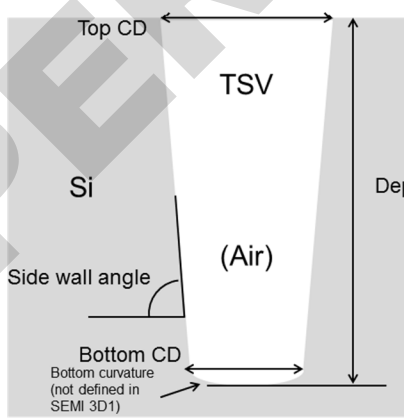

Figure 1
Sketch of a TSV Showing Some Geometrical Properties of Interest for TSV Metrology

2.3 This Guide will assist the user in selection and use of TSV metrology tools, as well as a protocol for performing TSV measurements of geometrical parameters of an individual TSV, or of an array of TSVs, such as pitch, top CD, top diameter, top area, depth, taper (or sidewall angle), bottom area, bottom CD, bottom diameter, and possibly others (e.g., scalloping and overall tilt). Figure 1 shows some of these.

2.4 This Guide will provide examples of measurements of TSVs at different sizes and aspect ratios, TSV measurement using a variety of metrology tools, the relative levels of substrate interaction, and recommendations by application. It

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targets the particular set of geometrical parameters defined in SEMI 3D1. It focuses on the various measurement principles available, rather than on particular instruments.

2.5 The examples given have been provided by qualified industry colleagues, and are believed to be representative of instrument performance that can be routinely achieved. Substantial efforts have been made to obtain performance data that are representative of the marketplace in 2012. However, this Guide is not an exhaustive survey of the state of the art of TSV geometrical metrology.

2.6 The TSV measurements described in this Guide extend over TSV diameters from a few micrometers up to tens and even hundreds of micrometers, and TSV depths in the range of 10 to 200 µm.

2.7 Company names, brand names, and trademarks of individual instruments are not included in this Guide.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 The content of this Guide is limited to examples of TSV measurement methods gathered from the published technical literature and contributed by the participating organizations. No independent verification of the performance of the metrology approaches or tools described here has been conducted.

3.2 While this Guide provides guidance on the capability and conditions of use for available techniques, it does not provide the level of detail typically available in test methods.

3.3 This Guide does not contain guidance as to whether any particular technique should be applied in any particular case or any particular stage of process development or production. The strategy for applying TSV metrology must be selected by each individual investigator or company, based on their particular manufacturing process sequence and the purpose of the measurements made.

3.4 The examples of TSV measurements presented in this Guide should not be construed as indications of the limits of applicability of the corresponding measurement techniques or instruments. The examples were made available by contributors from data that were available at a particular moment in time, mid-2012. These measurement techniques, and the commercial products at which they are targeted, are evolving rapidly.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI 3D1 — Terminology for Through Silicon via Metrology

SEMI M59 — Terminology for Silicon Technology

SEMI MF1530 — Test Method for Measuring Flatness, Thickness, and Total Thickness Variation on Silicon Wafers by Automated Noncontact Scanning

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 General terms, acronyms, abbreviations and symbols associated with silicon technology and used in this Standard are listed and defined in SEMI M59.

5.2 The important geometrical parameters of TSV's are defined in SEMI 3D1.

5.3 *Other Abbreviations and Acronyms*

5.3.1 *IR* — infrared

5.3.2 *SEM* — scanning electron microscopy

5.3.3 *TSOM* — through-focus scanning optical microscopy

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5.4 *Other Definitions*

5.4.1 *destructive* — operations that prevent a wafer from being processed through the subsequent bonding, thinning, edge-bevel trimming, and thermal processes in 3D integration. Some methods and instruments for measuring the geometrical parameters of TSVs require destructive specimen preparation techniques.

5.4.2 *etch* — any process used to remove silicon in a controlled fashion to create the TSV opening.

5.4.3 *image-based* — as applied to TSVs, a metrology technique in which TSV dimensions are extracted from an image of the TSV. The image is obtained by some type of microscopy or tomography, and the dimensions are then measured from point to point in the image.

5.4.4 *nondestructive* — operations that allow a wafer to be processed through the subsequent bonding, thinning, edge-bevel trimming, and thermal processes in 3D integration.

5.4.5 *specimen preparation* — operations needed to prepare a wafer for examination by use of a metrology tool, or to extract a portion of a wafer and prepare it for examination.

6 Considerations in Making Dimensional Measurements on TSVs

6.1 *Image-Based Dimensional Measurements* — A typical route to performing image-based dimensional measurements of TSVs consists of two steps: (a) Acquire a digital image of the TSV; and (b) Analyze the image. The capability of acquiring images is offered by multiple vendors. Basic interactive tools for the analysis of digital images are widely available, in some cases free, for example *ImageJ*.[1] Several images of TSVs have been published in the open technical literature; scanning electron microscopy (SEM) images are particularly popular.[2,3] Examples are shown below in ¶ 8.2.

6.2 *Challenges to Accurate and Consistent Extraction of Dimensional Parameters* — The metrology issues in SEM imaging and image analysis have been discussed at length in a technical article[4] on SEM as a technique for dimensional metrology. These usually come down to identifying the exact pixel or fraction of a pixel that corresponds to the edge of a feature to be measured. Best practices in image analysis are beyond the scope of this Guide.

6.3 *Substrate Interactions* — Additional layers on the surface of the silicon wafer, such as a hard mask, may be present on a wafer that contains TSVs to be measured; such layers may affect the performance of the metrology tools described in this Guide. These layers are typically visible and distinguishable from silicon in SEM, optical, and x-ray microscopy techniques. Therefore, they can be accounted for in the analysis of the image and the extraction of the TSV dimensions. However, the transmittance and reflectance of these layers may be different from that of silicon, and therefore may affect spectral reflectometry measurements, which are discussed below. The models used to extract TSV dimensions from spectral reflectometry data may need to account for layers of material present on top of the silicon. This may require more effort in the modeling, and more care in the measurements to be sure that the surface layers are properly accounted for.

7 Measurement Techniques

7.1 *Scanning Electron Microscopy* — Cross-section SEM is an image-based metrology technique that has been used to measure TSV dimensions from their beginning.[5] The submicrometer resolution (<10 nm) of a cross-sectional SEM micrograph is typically much better than that required for relatively large features like 1 to 5 micrometer diameter TSVs. Dimensional metrology in the SEM down to the nanometer level is available.[4, 6] This level of precision is easily sufficient to meet the needs of present-day TSV metrology. Specimen preparation is required to allow cross-sectional

[1] Rasband, W.S. ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://imagej.nih.gov/ij/, 1997–2012.

[2] Kamto, A., Liu, Y., Schaper, L., and Burkett, S.L. "Reliability study of through-silicon via (TSV) copper filled interconnects." *Thin Solid Films 518* (2009): pp.1614–1619.

[3] Ham, Y.H., Kim, D.P., Park, K.S., Jeong, Y.S., Yun, H. J., Baek, K. H., Kwon, K. H., Lee, K. and Do, L. M. "Dual etch processes of via and metal paste filling for through silicon via process." *Thin Solid Films 519* (2011): pp. 6727–6731.

[4] Postek, M. T. "Critical Issues in Scanning Electron-Microscope Metrology." *Journal of Research of the National Institute of Standards and Technology 99* (1994): pp. 641–671.

[5] Swinnen, B., Ruythooren, W., De Moor, P., Bogaerts, L., Carbonell, L., De Munck, K., Eyckens, B., Stoukatch, S., Tezcan, D.S., Tokei, Z., Vaes, J., Van Aelst, J., and Beyne, E. "3D integration by Cu-Cu thermo-compression bonding of extremely thinned bulk-Si die containing 10 µm pitch through-Si vias." in *Electron Devices Meeting, IEDM '06* (2006): pp. 1–4.

[6] Larrabee, R.D. and Postek, M.T. "Precision, Accuracy, Uncertainty and Traceability and their Application to Submicrometer Dimensional Metrology." *Solid-State Electronics 36* (1993): pp. 673–684.

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geometrical measurements on TSVs. Examples of two different procedures are described below: cleavage, and focused-ion-beam (FIB) milling. Both of these techniques are destructive, although FIB milling can be done in such a manner as to affect only a very small portion of the wafer surface at the TSV of interest. An issue that may arise is the selection, creation, and verification of a suitable cross-section plane. The exact location of the surface plane of the cross-section influences the dimensions measured on the imaged surface. Despite these limitations, cross-section SEM is the technique usually used in verification of other, less direct methods of obtaining TSV dimensions.

7.2 *Optical Microscopy* — The precision of dimensional measurements by optical microscopy in the focal plane is in the range of tenths of a micrometer. Similar levels of precision for selected features can be obtained in the out-of-plane direction (*z*-direction) by use of instruments with a calibrated focus distance. An elaboration of optical microscopy that is being researched is through-focus scanning optical microscopy (TSOM). TSOM utilizes a set of images acquired at different focus settings, that is, at different settings of the distance between the specimen and the objective lens.[7] By analyzing this series of images, the TSOM procedure provides improved lateral and vertical measurement resolution, relative to conventional optical microscopy, enabling measurement of in-plane dimensions and line widths as well as out-of-plane dimensions such as via depths with measurement resolution into the nanoscale. TSOM operates by comparing a TSOM image set either against a library of images, to find a best match, or against another TSOM image set. The library can consist of simulated or actual images. TSOM does not produce enhanced-resolution images; it applies comparative analysis to extract hidden information from conventional optical images.

7.3 *Infrared (IR) Microscopy and Reflectometry* — Because silicon is partially transparent to infrared light, IR microscopy can be used as an image-based technique in a nondestructive procedure. The longer wavelength of infrared light, compared to the visible, and other issues associated with imaging through the partially transparent silicon, cause the resolution of this method to be typically below that of a conventional optical microscope. However, the ability to image through silicon may be a decisive advantage, and technical advances have been proposed.[8] Measurement of reflectometry over a wide band of wavelengths of light, combined with detailed interpretation of the collected signal as a function of wavelength by various techniques, forms the basis for several commercially-available tools aimed at non-destructive, rapid inspection of wafers in the production setting.

7.4 *Interferometry* — Some of the measurement techniques to be introduced below utilize interferometry. Interferometry refers to measurements that rely on the interference of light; optical interference occurs for light of all wavelengths, including, in the present context, visible and IR. A beam of light has several properties that can affect an interferometric measurement; here we give a simplified description that considers only the wavelength, and assume that other properties, such as spectral purity, polarization, coherence length, and velocity of light in the transmission medium present, are controlled as needed. In interferometry, the optical beam from a light source is caused to impinge on a material or structure that splits the beam, reflecting or refracting part of the beam, but not all of it. The two parts of the original optical beam are then redirected along separate paths toward a single detector, which may be an optical intensity measuring device or a camera. The basis of the measurement operation is that the effective length of the optical path traveled by the reflected or refracted part of the beam is different from the length of the path traveled by the undisturbed part. Because of the wavelike nature of light, the physical recombination of the two parts of the beam at the detector can be additive or subtractive, depending on the difference in the two effective path lengths relative to the wavelength of the light. If the paths differ by a full wavelength, or a multiple thereof, the interference is constructive, while if the path difference has a value different from an even multiple of a wavelength, interference occurs. For well-conditioned signals, this interference can be completely destructive, resulting in a null signal. The sensitivity of interferometric measurements results from the change from constructive to destructive interference produced by an effective path length change of only one half of the wavelength of light. The strategy for designing an interferometric measurement is to define the relationship between the quantity to be measured and an accessible effective optical path length. Interferometry is useful in a variety of applications because a variety of physical effects can cause changes in the effective optical path length, which includes the physical length, the velocity of light along the path, and the effect of any reflective or refractive elements that are present in the path.

NOTE 1: X-ray microscopy may be added to future versions of this Document. To date, the published technical literature contains some examples of the use of X-ray microscopy to detect voids in the copper fill of TSVs, but no examples of measurements of the TSV properties listed in ¶ 2.3. The X-ray microscope works by detecting transmitted X-rays after they pass through a material. The x-ray microscopy technique as practically applied to date is image-based and destructive, because of the specimen preparation as

[7] Attota, R. "TSOM Method for Nanoelectronics Dimensional Metrology." in *Frontiers of Characterization and Metrology for Nanoelectronics:2011 1395*, D. G. Seiler, A. C. Diebold, R. McDonald, A. Chabli and E. M. Secula, Eds., (Amer Inst Physics, 2011).

[8] Delacretaz, Y. and Depeursinge, C. "Digital holographic microscopy for silicon microsystems metrology." in *Silicon Photonics and Photonic Integrated Circuits 7719*, G. C. Righini, Ed., SPIE-Int Soc Optical Engineering, Bellingham, 2010, art. 77191M.

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explained below. Most commercially available lab-based X-ray microscopes are founded on the principle of point projection, wherein the incident X-ray source is transmitted through the sample and onto a detector. The achievable resolution depends on the X-ray source spot size, the detector resolution, and the geometrical arrangement. As the distance between the source and object becomes shorter, the magnification of the image increases, but with image blur in the detector plane. Therefore, a high-resolution detector is required. Generally, resolution as high as ~100 nm can be achieved. For better resolution (50 nm), an improved X-ray optical system is implemented using diffraction instead of refraction to focus the X-rays. However, the improved optical system will limit the rotating area (required for tomography), requiring sample preparation to fit, and high precision measurements may require long imaging times.

8 Examples of Dimensional Metrology of TSVs by Use of SEM

8.1 *Specimen Preparation for Measurements on TSVs by Use of SEM* — This section describes two methods of specimen preparation for examination and measurement of TSVs by SEM: cleavage, and FIB milling.

8.1.1 *Cleavage* — Wafers of certain crystallographic orientations, particularly (100), can be fractured, or cleaved, to obtain a cross-section of the wafer. If the cleavage plane intersects a TSV, the exposed TSV cross-section can be observed by SEM. Cleavage is a destructive technique. An offset array of TSVs can be used to facilitate obtaining a cleave at the TSV center for SEM metrology (SEM bar). These features can be built into the die and located by naked eye for cleaving, resulting in some usable TSVs being visible. Depth and profile measurements are easily obtained on unfilled TSVs. By use of a commercially-available micro-cleaver, the cleave line can be more accurately placed (reported placement accuracy to within 300 nm of a feature of interest in the product literature). The micro-cleaver used in this example was equipped with a high magnification camera to precisely locate and position the cleaving mechanism. An individual TSV could then become the targeted feature of interest, and the cleave could be positioned close to the center of that particular TSV. A micro-cleaver is also useful when die layouts do not have sufficient area to include an offset array of TSVs for SEM metrology (SEM bar).

8.1.2 *FIB-Milling* — Subsurface SEM imaging is possible on whole 300 mm wafers, without cleaving, when an in-line dual beam FIB-SEM is utilized.[9] The cross-sectioning is done by a gallium beam ion-mill (liquid metal ion source) to excavate wells on the wafer surface, in order to expose a cross-section of one or more TSVs. Although the wafer does not need to be cleaved before FIB milling, the wells used to reveal the TSV are considered destructive and prevent the wafer from being processed through the subsequent bonding, thinning, edge-bevel trimming, and thermal processes in three-dimensional (3D) integration. Furthermore, the milled wells may weaken the wafer and create cracks or breaks when the wafer is subjected to the forces associated with subsequent processing. The FIB method does not allow an exactly vertical (90°) observation of the TSV cross section. Dimensional metrology under nonvertical examination conditions may require trigonometric calculations to extract the desired quantities. An example of a SEM image of a TSV with metallization, from a cross section prepared by FIB milling, is shown in Figure 2.

[9] Krause, M., Altmann, F., Schmidt, C., Petzold, M., Malta, D., and Temple, D. "Characterization and Failure Analysis of TSV Interconnects: From Non-destructive Defect Localization to Material Analysis with Nanometer Resolution." in *Electronic Components and Technology Conference (ECTC)* (2011): pp: 1452–1458.

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