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# Metallization defect detection in 3D integrated components using scanning acoustic microscopy and acoustic simulations

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ABSTRACT

In the context of More than Moore 3D integration concepts, the µm to nm sized failure detection and analysis represents a highly demanding task. In this work, micron sized artificially induced metallization defects in open TSVs are detected by scanning acoustic microscopy (SAM). Micro X-ray computed tomography (µXCT) and scanning electron microscopy (SEM) are used to validate the SAM results. Notably, the SAM results show that the failures for certain TSVs are located at a different position as illustrated by µXCT and SEM. In order to interpret these controversial results, 2D elastodynamic finite integration technique (EFIT) simulations are performed. We discuss the results by taking the excitation of surface acoustic waves (SAWs) or Rayleigh waves into account which are leading to characteristic interference patterns within the TSV. The simulation and understanding of such interference effects can be highly beneficial for the use of SAM with respect to modern failure detection and analyses.

## 1. Introduction

In the current trends of miniaturization and increased functionality of devices, 3D integration displays an important key-technology [1]. The electrical connection between various layers through the silicon substrate can be achieved by etching holes into the silicon which are then filled or coated with conducting materials, e.g. copper or tungsten. These metallized vertical electrical interconnections are referred to as through silicon vias (TSVs) [1]. Due to the size of defects in TSVs, which are often in the micron or even nanometer range, the defect detection is highly demanding [2]. Unfilled or "open" TSVs [2–4] in comparison to filled ones [5,6] show metalized side walls instead of a full e.g. copper filling. Open TSVs show beneficial properties regarding stress relaxation [3]. They are for instance frequently used in sensor applications [4] with respect to More than Moore applications. The detection of failures in open (i.e. unfilled) TSVs, represents a demanding problem. State of the art failure analysis [7–9] comprise e.g. automated optical inspection (AOI), scanning electron microscopy (SEM), electrical measurements (EM), radioscopic measurements (RM) and micro X-ray computed tomography measurements (µXCT), EMMI (emission microscopy)/EBAC (electron beam absorbed current)/OBIRCH (optical beam induced resistance change), and scanning acoustic microscopy (SAM). AOI is a very time-efficient method, but can be mainly used for the inspection of the bottom of the TSV [8]. SEM demands special sample stages and preparation of the sample, is time consuming and costly due to the necessary step by step inspection of single TSVs [9]. EM is fast and applicable for TSV arrays, but is only sensitive to defects triggering a short circuit to the substrate, cannot help to localize the failure in the TSV and is only applicable for special test structures. For RM the possible resolution is strongly limited and the interpretation of the failures is difficult. µXCT provides a 3D reconstruction of the sample and higher resolution, however needs small sample sizes, is time consuming and costly. EMMI/EBAC provides a method with high resolution capability, but it needs electrical active test structures and is time consuming and expensive [10]. SAM represents in general a fast, cost-efficient, non-destructive analysis tool of microelectronic relevant components [11–15] and shows high potential for automatization, see e.g. [11,12]. The use of SAM for the characterization of open TSVs, including the detection of bottom defects with an extension of approximately 50 µm, was demonstrated recently in [2].

In this work, we discuss the detection of artificially induced failures in open cylindrical shaped TSVs with an extension between 10 and 25 µm by using SAM with a frequency of about 100 MHz. In order to achieve this we excite Rayleigh or surface acoustic waves (SAWs). To

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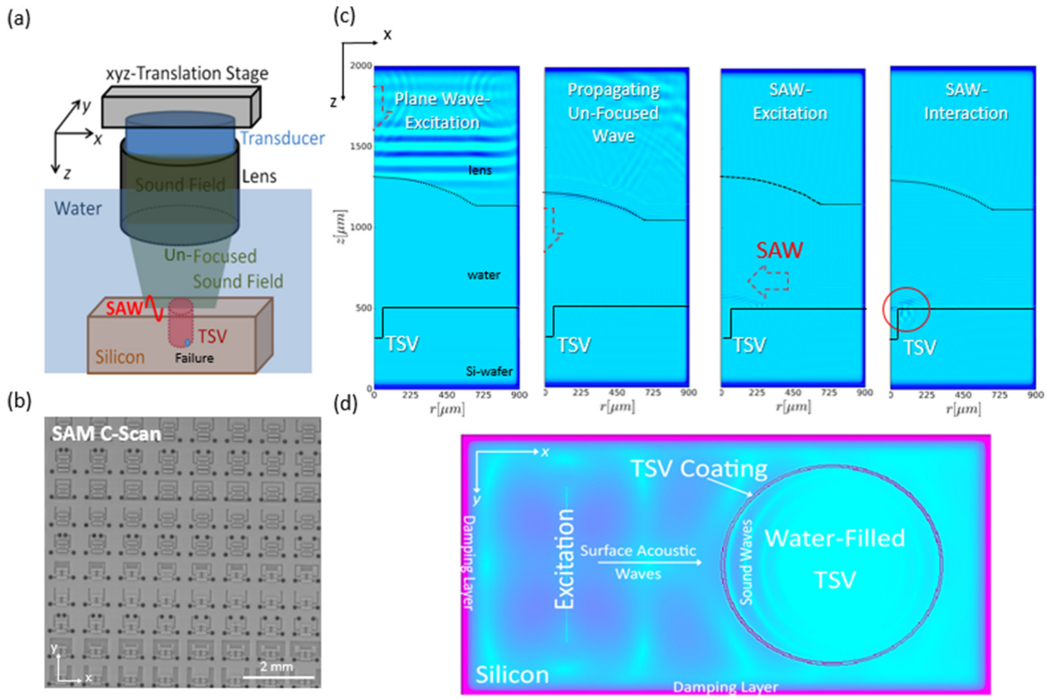


**Fig. 1.** (a) Schematic of the experimental SAM set-up with an un-focused sound field. The excited Rayleigh waves or surface acoustic waves (SAWs) in the x-y plane are highlighted in red. Transducer is immersed in water to couple the excited plane waves to the sample. The cylindrical TSV with a metallized side-wall is embedded in a Si-matrix. (b) Experimentally obtained SAM C-Scan of the used TSV test array. (c) EFIT simulation of different time steps in the x-z plane showing, the excitation of the plane wave, the propagation of the un-focused wave, the excitation of the SAW and the interaction of the SAW with the TSV. Arrow highlights the propagation direction of the acoustic waves. (d) EFIT simulation of the TSV in the x-y plane. SAWs are excited at the excitation line. The propagation of the waves within the TSV is investigated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

validate the results we use micro X-ray computed tomography (µXCT) and scanning electron microscopy (SEM).

Notably, the µXCT and the SEM analysis detect the failure in the metallization for certain TSVs, in comparison to the SAM C-scan analysis, at a different position. In order to interpret these controversial results, acoustic simulations are performed and the generation of characteristic interference patterns within the TSVs is taken into account.

## 2. Experimental procedure

### 2.1. Scanning acoustic microscopy

In scanning acoustic microscopy (SAM), a transducer generates and sends ultrasonic waves through a lens towards the sample of interest, see Fig. 1(a). At the sample, a part of the acoustic field is reflected and travels back to the transducer where it is detected (see e.g. [16]). In particular, we analyse the reflected acoustic field, by scanning the transducer in the x-y plane, keeping the z-position constant over the TSV-test sample (Fig. 1(b)). The TSV diameter is about 100 µm and the metallization at the side wall is about 1 µm thick. If the z — distance from lens to the sample is shorter than the focal length (de-focused) and the opening angle of the transducer is exceeding the critical Rayleigh angle, surface acoustic waves (SAWs) can be excited on the sample surface and leak energy back to the lens and subsequently to the transducer, (Fig. 1(c)). At the transducer, the wave fields from the longitudinal and Rayleigh wave interfere. The SAW or Rayleigh waves can excite additional wave modes and may cause interference patterns. It has been shown in the past [16] that such interference patterns enable the detection of surface failures even below the lateral resolution. The latter is given by the frequency of the transducer.

In our analysis, the customized scanning acoustic microscope “SAM 400” was utilized to detect failures below the surface within the TSV. The “SAM 400” was operated in reflection mode, where the same transducer was used as a sender and a receiver. The sample is fully immersed in water to couple the ultrasound waves efficiently to the samples. We use a 7 GHz ADC function card providing a sufficient time resolution of about 142 ps. For the presented SAM measurement we use a 100 MHz transducer equipped with an “acoustic objective (AO) lens”. Such a lens has an opening angle of about 60°. The reflected signal was analysed via the “WinSAM5” software. Amplitude (A)-scans as well as 2D cross-sections in the x-y-plane or SAM C-scans can be obtained. The scanning time for an area of about 50 mm$^2$ is 7 to 8 min.

### 2.2. X-ray computed tomography

The “nanotom m” lab system was used for complementary analysis providing micro X-ray computed tomography (µXTC) [2]. The “nanotom m” system is equipped with a nano-focus X-ray tube™ with a minimum focal spot size of about 800 nm. During the µXTC measurement the sample is placed between the X-ray tube and detector and is rotated by 360° to obtain the 3D reconstructed data. Due to the cone beam configuration, the sample needs to be placed very close to the X-ray tube to gain maximal magnification. This restricts the size of the sample. Thus, the achievable resolution depends on the sample size and in addition on the analysed material.

The achieved voxel size is about 2 µm, the scanning time for a volume with an area of about 50 mm$^2$ in the x-y-plane and a thickness of about 750 µm is approximately 2 h.

### 2.3. Scanning electron microscopy

The scanning electron microscope (SEM) was used as the second complementary analysis tool. Here, we use a SEM Auriga 40 setup from Zeiss. The samples were adequately cut and prepared by using a gold film of a few nm before the SEM measurements. In addition we use a 360° rotation- and a 70° tilting-stage. This set-up allows the imaging of an entire single TSV including the metallized side-wall and the bottom without destructive sample preparation. The SEM images were acquired by the use of secondary electrons and the voltage was set between 2 and 5 kV during the SEM measurements.

## 3. Ultrasonic simulation

For the simulation of the propagating acoustic waves, 2D EFIT [17] simulations are performed. EFIT makes use of a staggered grid formalism and a leap frog time evolution scheme. In this matter, the equations concerning the kinematics, kinetics and material laws are