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# Machine learning assisted characterization of sub-micron-sized failures in 3D interconnect technologies utilizing scanning acoustic microscopy

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## 1. Introduction

Moore´s law and More than Moore [1)] technologies drive the trend in the semiconductor industry and are leading to miniaturized devices with higher complexity. The ongoing trend strongly triggers challenges in context to material development and failure analysis. Especially three-dimensional (3d) integration displays an important technology in context to conventional microelectronics, power semiconductors but also for modern quantum information processing devices. 3d integration enables the fabrication of highly integrated heterogeneous devices with a drastically reduced form factor by using vertically stacked different functional components. Electrical conductivity through such stacked architectures can be achieved by so-called through silicon vias (TSVs) [2)]. TSVs can be either filled with an electrically conducting metal like copper or coated with a conductive metal. Challenging for the design of TSVs and their reliability are the emerging thermo-mechanical stresses resulting from the mismatch of the thermal expansion (CTE) as well as the formed residual stresses arising after the deposition process, especially by using thin film technologies. The latter

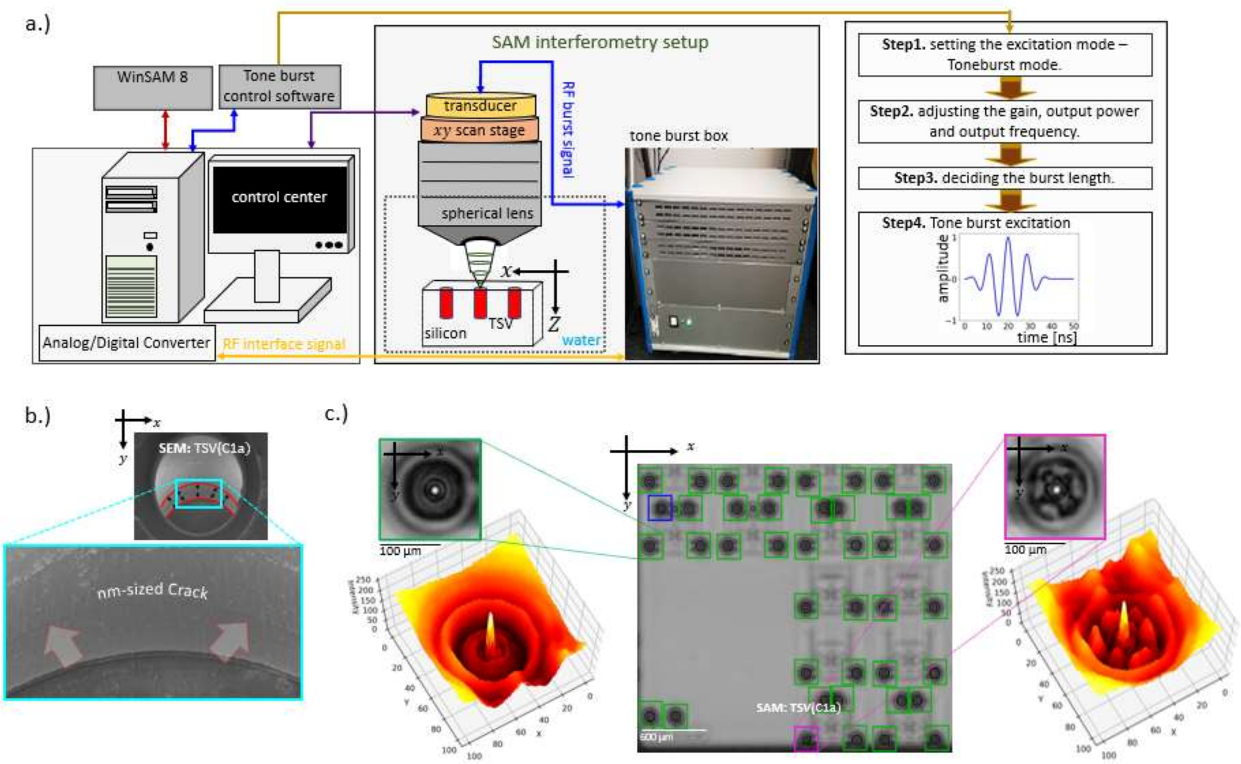


Fig. 1 a.) Modified SAM interferometry setup with incorporated transducer, signal processing and control for efficient failure analysis of TSVs. Four working steps are indicated on the right to perform the acoustic interferometry. b.) SEM images illustrating a TSV and indicating a crack, with an opening of about 200 nm, within the metallized TSV wall. c.) Automated classification and localization of the TSVs using the developed E2E-CNN algorithm. Exemplary, the generated interferometry C-scan image of a TSV without failure (green box) and a TSV with a nm-sized crack in the TSV wall (purple box) is illustrated, see also [3,4)].

may cause critical damage within the TSV such as cracks and delaminations. Here, time- and cost-efficient non-destructive failure characterization on µm-level and below is crucial to allow a reliable production of 3d integrated devices. Various advancements have been made in the last decades in the field of failure analysis of microelectronic components. Such techniques include automatic optical inspection (AOI), scanning electron microscopy (SEM), emission microscopy (EMMI), X-ray tomography techniques, scanning acoustic microscopy etc. [3,4]. However, not all of them meet the above-mentioned requirements in particular the combination of high resolution and high throughput inspection as well as the ability to produce statistically relevant data for subsequent sophisticated data analysis and rapid learning routines. Yet, scanning acoustic microscopy (SAM) represents a most completed state of the art method for the inspection of microelectronic parts close to the production line. It is fast, cost-efficient and shows non-destructive damage analysis capabilities. A drawback concerns the achievable image resolution and contrast which is strongly determined by the wavelength of the excited acoustic waves, that is the frequency and transducer. High-frequency transducers are possible nevertheless are limited due the weak penetration depth to defect detection close to the surface. Another possibility for failure analysis represents the utilization of interferometry-based approaches like optical interferometric techniques. Constructive and destructive interference may occur between elastic waves and surface acoustic waves (SAWs). The utilization of such acoustic interference effects could be applied for more advanced failure analysis and my enhance possibilities with respect to detectability.

## 2. Results

In this paper, we review our recent work [4,5] in context to machine learning (ML) assisted characterization of sub-micron-sized failures in 3D interconnect technologies utilizing scanning acoustic microscopy. In detail, we apply the concept of acoustic interferometry utilizing a modified scanning acoustic microscope setup, to detect nm-sized cracks, see **Fig.1 a.)** and **b.)** respectively. The utilized customized transducer with a center frequency of 100 MHz and a lens opening angle exceeding the Rayleigh angle enables the excitation of surface acoustic waves. A narrow band, tone burst driven setup is used to enhance the acoustic wave detection capabilities as well as enables the systematic excitation of SAWs. The approach balances the penetration depth and resolution capabilities. The interferometry approach allows us to be not solely dependent on the frequency of the transducer. The excitation of SAWs renders the detection of defects smaller than the frequency-determined resolution limit as well as gain sufficient penetration depth for the characterization of the bottom of the TSV, which is 250 µm deep. The TSVs show a diameter and a pitch size of 100 µm 350 µm, respectively.

SAM represents an imaging technique therefore, the automatic analysis of the generated image data is essential for the industry. In particular, the analysis of TSVs on wafer level demands the time-efficient characterization of up to thousands of TSVs. Usually, various defect types need to be detected within the entire TSV geometry incorporating the TSV side wall as well as bottom of the TSV. Here, machine learning-based algorithm provide novel possibilities for a statistically relevant analysis. Mainly semi-automated approaches have been utilized recently. However, those approaches lack specifically in their application. A generalized analysis, due to a specific feature definition is usually not feasible with such approaches. On the other hand, convolutional neural networks (CNNs) display well-known deep learning ML-based architectures suitable to extract multi-level features from images. Here, complex preprocessing or prior specific feature definition becomes obsolete and shows potential for enhanced failure analysis. **Figure 1 c.)** illustrates exemplarily the localization and classification of the TSVs on wafer level based on a developed End-to-End convolutional neural network (E2E-CNN). We conclude, that the presented SAM-interferometry-based approach incorporating ML, advances failure analysis drastically.

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**References**

1) W. Arden et al. More-than-Moore white paper. Version 2, 14 (2010).
2) Khorramdel et al. Microsyst. Nanoeng. 3, 1 (2017)
3) C. Cui et al. npj Mater Degrad 8, 40 (2024).
4) P. Paulachan et al. Sci Rep 13, 9376 (2023).
5) P. Paulachan et al. Commun Eng 3, 100 (2024).