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Enhanced failure analysis on open TSV interconnects

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Abstract

In this paper different methods and novel tools for failure localisation and high resolution material analysis for open TSV interconnects will be discussed. The paper shows the application of enhanced methods for the localisation of sidewall shorts in open TSV structures by adapted Photoemission Microscopy (PEM), Lock-in Thermography (LIT) and Electron Beam Absorbed Imaging (EBAC). In addition, a new highly efficient target preparation technique is presented, which allows the combination of Laser and FIB milling, in order to access TSV sidewall defects. Finally the use of this technique is demonstrated in a failure analysis case study.

Introduction

In recent years, technological solutions for 3D integration of semiconductor devices have increasingly attracted attention. For that reason the ams AG has developed new technologies based on open TSV interconnects. Deep reactive ion etching of Silicon and other standard Silicon processing steps are used to form TSV sidewall isolations and metallisation with Ti/TiN, W and Al. Finally, the TSVs are capped by a SiO_2 film and SiN layers. A schematic cross section of the final TSV structure is depicted in Fig. 1.
Available failure analysis methods have to be adapted, in order to overcome specific challenges for physical failure analysis at three-dimensional TSV structures. Therefore a crucial requirement is the precise localisation of electrical shorts on TSV sidewalls to enable a target preparation via TSV cross sectioning for high resolution material analysis. Within this paper, new approaches for Emission Microscopy (PEM), Lock-in Thermography (LIT) and Electron Beam Absorbed Current (EBAC) imaging are shown. High-rate Laser and Focused Ion Beam (FIB) milling is applied to provide precise and efficient TSV cross sections and defect preparation. Finally, case studies are presented to show the successful application of the described novel failure analysis strategies.

Open TSV Technology

The TSVs in the technological approach of the ams AG connect a bottom and a top wafer electrically as depicted in Fig. 1. Thus e.g. a sensor application on the bottom wafer can send signals on the shortest possible way through the top wafer substrate to a processing circuitry on the top wafer. The large diameter enables deep TSVs with a moderate aspect ratio of 2.5. The thick top wafer is of advantage for handling issues. Though the TSV has a depth of 250µm a contact resistance of only 0.35 Ω is achieved.
The bottom and top wafer are bonded by Si/SiO_2 direct bonding. Both wafers are fabricated with a modified 0.35 µm CMOS process flow. The TSVs are processed after finishing the CMOS devices. A deep reactive ion etch process is used for etching the TSVs into the substrate (Bosch process). A spacer module provides the isolation towards the substrate and opens the TSV bottom down to the landing pad (metal on bottom wafer). The metallisation is done with a conformal CVD deposition of W inside the TSV and a sputtered AlCu layer, which covers mainly the top wafer surface. A large overlap of W and AlCu ensures a good electrical contact from the TSV to the top metal layer. Finally the passivation consisting of a combined Si Oxide and Si Nitride layer is deposited.

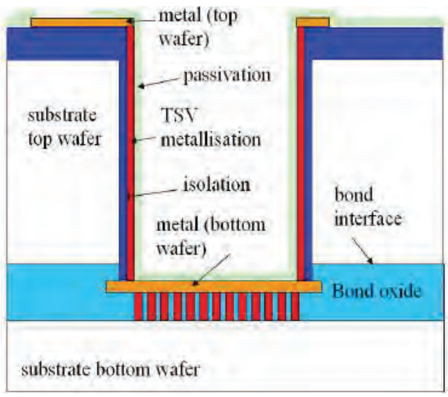

Figure 1: Schematic build-up of a TSV

Failure localisation using optical, thermal and SEM based techniques

For test specimen containing TSV chains, electrical shorts between the TSV metallisation and the silicon substrate were investigated. Optical and thermal imaging techniques can be used to localise the origin of such shorts due to their light emission and local resistive heating. Photoemission Microscopy (PEM) has been proven to be a useful method to determine the defect position in a lateral projection [2]. Defocussing series [3] produced by Lock-in Thermography enables a three-dimensional localisation of the sidewall short within the open TSV. A precise and high sensitive localisation is provided by a new approach based on Electron Beam Absorbed Current (EBAC) imaging within a SEM

3D-Localisation by side-fed Emission Microscopy

A standard PEM setup was modified to investigate tilted specimens to get additional information about the defect depth within the open TSV (see Fig. 2).

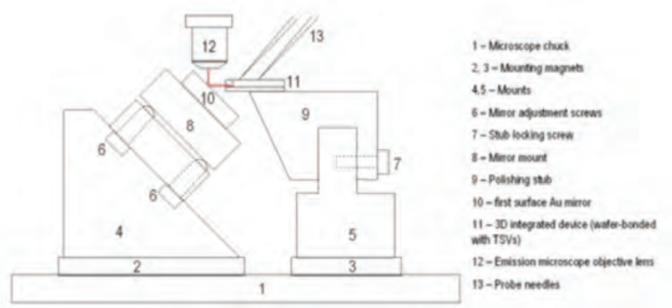

Figure 2: Schematic of Emission microscopy on specimen at tilted conditions

Using electrical probing and a tilted device setup, the defective TSV was stimulated and analysed from the side. While imaging through silicon, lateral emission detection is enabled (see Fig. 3 left). An example of a localised emission spot at the bottom area of the TSV is depicted in Fig. 3 right.

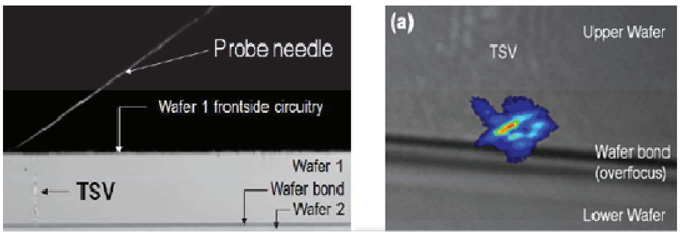

Figure 3: Build-up of TSV specimen for side-fed-Emission Microscopy (left); localised photoemission spot indicating defect position (right)

3D-Localisation by LIT Defocussing

In addition to the previously described method, the localisation of the short position inside open TSV structures can be determined by a new defocusing method based on the Lock-in Thermography (LIT) technique. Here, the shorted circuitry is operated by a periodically pulsed supply voltage with adjustable frequencies and the device is imaged from the surface side by a high sensitive IR camera system. Two channel images processing in correlation to the electrical stimulation is applied to improve the signal-to-noise-ratio significantly. As a result, LIT provides a high spatial resolution down to 1 µm and a high sensitivity in µW range. In consequence, the detection and investigation of thermal emissions and the distribution to the surrounding area is feasible. In terms of open TSV structures, LIT can be used to investigate defect-related heat distributions in relation to the axial focus position. By shifting the focus position with µm accuracy, thermal imaging can be focused down into the TSV structure, which is demonstrated in Fig. 4.

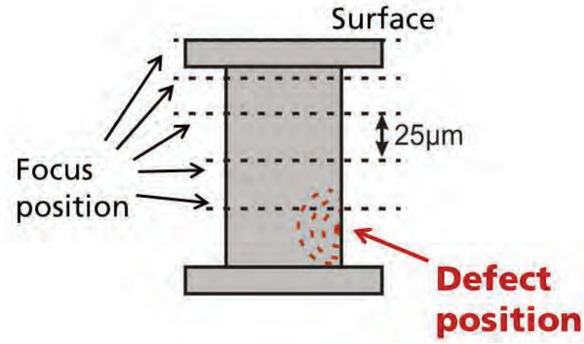

Figure 4: Schematic built-up of the LIT defocussing on a TSV

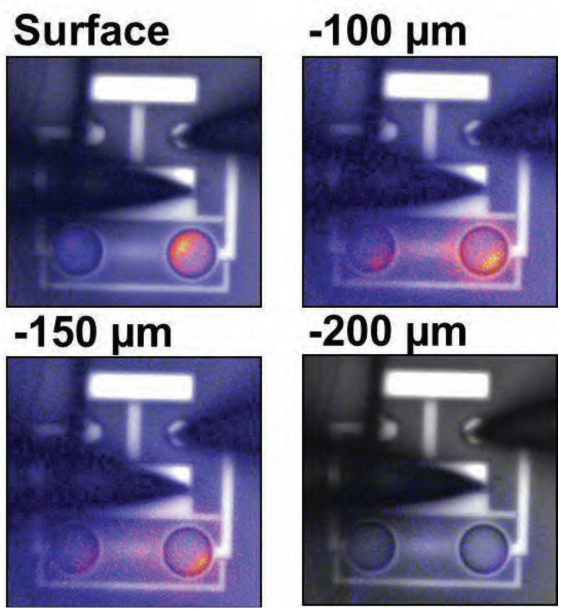

Figure 5: Local electrical probing of the investigated TSV structure and imaging of the resulting thermal emission at various focus positions

Therefore, precise 3D-defect localisation is provided. Figure 5 depicts the application of this method on a defective TSV structure. By using local electrical probing, the device is stimulated and the resulting heat propagation at the surface is imaged by the LIT system. The focus position is shifted towards the bottom in 25 µm steps. With further defocusing, a decrease of the spot size can be observed. A minimum spot size is reached for a focus distance of 200 µm to the surface. An analysis of the relationship between thermal amplitude and lateral position for different focus positions is shown in Fig. 6. With an increasing focus depth relative to the surface a decrease of the absolute amplitude as well as a decrease of the lateral extension is visible.

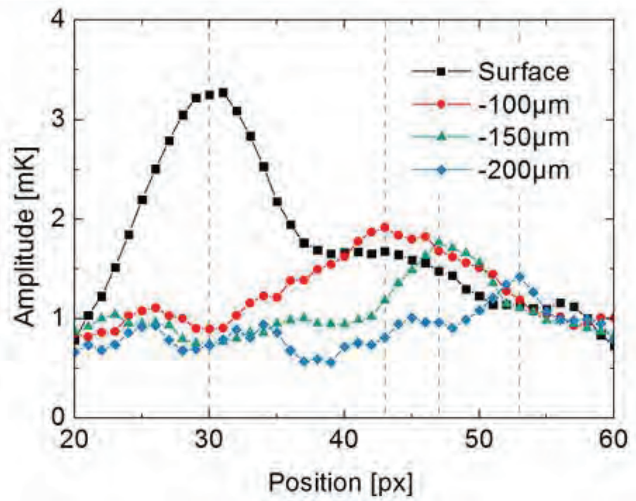

Figure 6: Comparison of the lateral temperature distribution in relation to the focus position

In order to correlate the measured thermal emissions to a spot size, Gaussian fitting functions in combination with the pixel size and optical magnification factor were applied. The results are shown in Fig. 7.

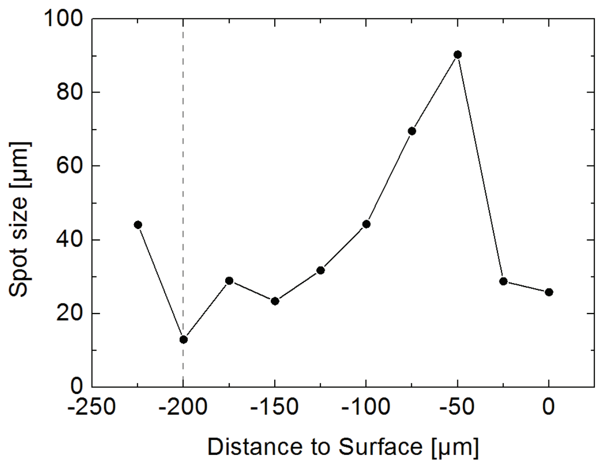

Figure 7: Determined spot size in relation to the focus position

Starting from the investigations on the TSV surface, a strong increase of the spot size is observed for the -25 µm and -50 µm defocus. Due to reflections of the generated heat radiation on the TSV side walls, the detected temperature distribution is shifting with increasing defocus position. With closer distance to the real defect position these influences are more and more negligible. For focus positions deeper than the defect position, an increase of the spot size can be observed.

Precise Short Localisation by EBAC

The PEM and LIT methods are limited in their sensitivity with regards to high ohmic leakage failures. Additionally the original defect could be altered by the electrical stimulation during PEM or LIT. Therefore the EBAC technique was evaluated for electrical short localisation, which is using Secondary Electron Microscopy (SEM). The SEM beam is used to create a local current in the TSV sidewall metallisation layer. The absorbed current is measured by local probing. The measured current is processed into a current intensity image. At the electrical short a current divider is active and modifies the EBAC signal, thus allowing a precise localisation with a sub-micron lateral resolution. EBAC enables the localisation of electrical shorts with a dissipation power in the nW range for further physical root cause analysis.

An example of the application of EBAC on open TSV structures revealing a sidewall-related defect is depicted in Fig. 8. The EBAC analysis was applied after connecting the TSV metallisation and the Si substrate to detect the defect position of the relevant leaking path to the Si substrate. To evaluate the feasibility of the method different EBAC setups were tested. The final analysis was performed with a SEM accelerating voltage of 15 kV and an absorbed current of 175 nA was measured at the spot position. A biasing voltage of -0.4 V was applied to gain an improved S/N ratio. The absorbed current signal was observed and the EBAC spots indicate the location of the defect (see Fig. 8).

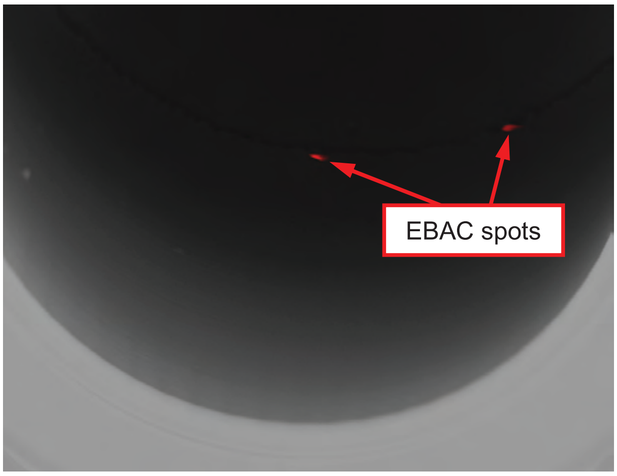

Figure 8: Overlay of SE- and EBAC-signal - EBAC analysis on a complete TSV structure to localise relevant electrical shorts to the Si substrate (red spots)

Enhanced Target Preparation Techniques

Typically FIB techniques are used to provide a high precision site specific cross sectioning. The access for FIB preparation and SEM observation of sidewall shorts in open TSVs is very limited and only defects near the surface can be analysed in this standard procedure.
In order to get access to deeper located defects for FIB/SEM analyses and also TEM preparation, high volume cross sectioning is required. In a first step precise site specific mechanical grinding was used for a cross section through the middle of the TSV structure (see Fig. 9).

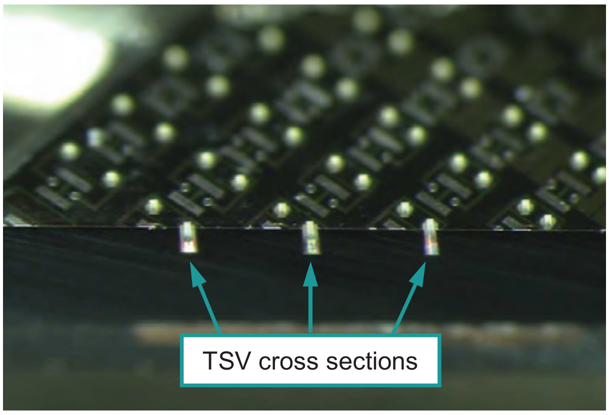

Figure 9: Light-optical image - tilted view of cross sectioned TSV specimens directly after target preparation by mechanical grinding

Further approaches based on fast and precise laser ablation have been considered for a reliable and repeatable preparation. An ultra-short pulse Laser system was evaluated for accurate micromachining. Crucial parameters for a fast, secure and reliable preparation of open TSV structures are the wavelength, the average pulse power and the repetition rate. In this study, a fibre-based picosecond Laser working at 532 nm wavelength was used for specimen preparation. During the ablation process an averaged pulse power between 0,15 µJ and 0,25 µJ at 200kHz repetition rate was used.

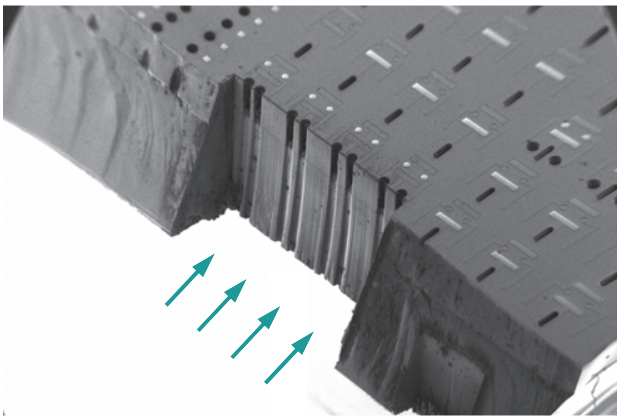

Figure 10: SEM image of open TSVs prepared by optimised laser processing

By developing smart laser milling strategies even wafer bonded substrates with a thickness of ~1mm could be cross sectioned with a sufficient quality, which enables further specimen preparation by FIB or a direct access for localisation techniques (see Fig. 10).

Failure Analysis Case Study

The newly adapted techniques for precise and three dimensional defect localisation and site specific defect preparation were applied at an electrically shorted TSV chain to demonstrate a full and effective failure analysis flow for determining the physical root cause of the shorts.
The case study was performed at high-ohmic shorted TSVs respectively with a leakage current of µA range @10 V. As a first method Lock-in Thermography was used to localise several defective TSVs within the chain. Then local probing of a single defective TSV was performed to measure the IV characteristic of the short. It was revealed that the electrical behaviour was like a Schottky diode (see Fig. 11).

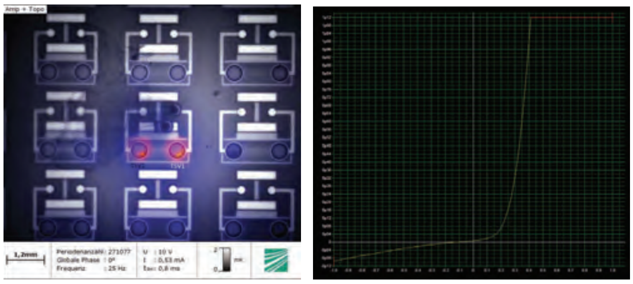

Figure 11: LIT image with two thermally active TSVs (left); curve tracing of a single TSV shows characteristic of a Schottky diode (right)

By further LIT investigations, using the explained defocussing procedure, the defect could be localised at the TSV sidewall near the bottom of the TSV at about 200 µm depth (see Fig. 12).

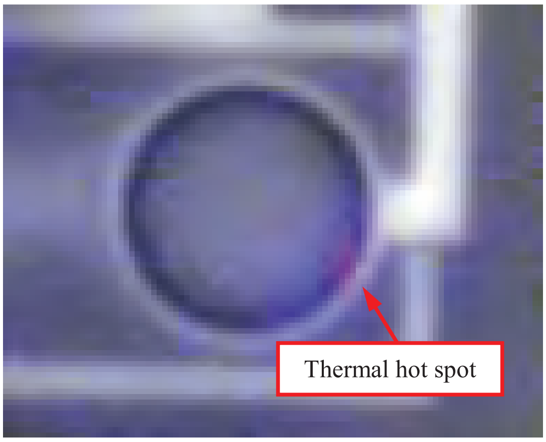

Figure 12: Result of Lock-in Thermography defocussing series localising the high-ohmic short at TSV sidewall

The localisation and characterisation of the defect by using electrical (see Fig. 11) and LIT investigations was confirmed by an additional EBAC analysis.
For that purpose the specimen was tilted and rotated to get full access to the TSV failing position. The increased sensitivity of EBAC permits highly precise defect localisation for target preparation by SEM/FIB. Even though no external voltage is biased during the EBAC investigation, the charging by electron beam may alter the defect and need to be minimised. Several EBAC spots were detected at the sidewall near the bottom of the TSV (see Fig. 13).

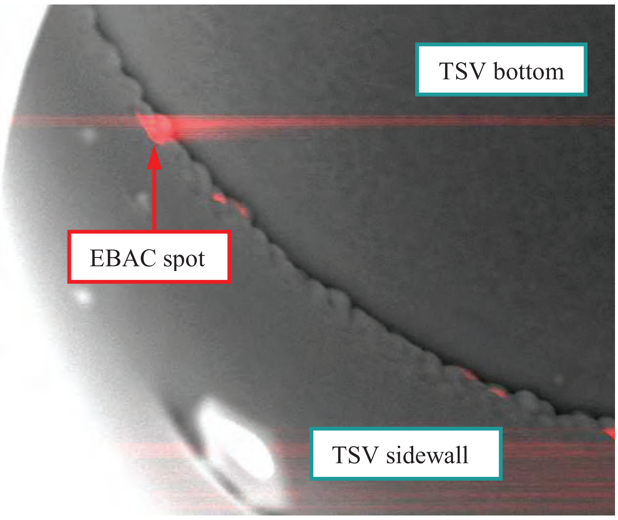

Figure 13: Overlay of SE- and EBAC-signal - EBAC analysis on a complete TSV structure to localise relevant defect positions (red spots) as leaking path

After the localisation the specimen was cross sectioned through the middle of the TSV by precise mechanical grinding and polishing steps. Thus the localised defect was preserved and so FIB/SEM cross sectioning had been performable at the remaining TSV structure. The specimen was tilted in two directions to get access for the FIB milling and SEM observation at the defect site using a pre-tilted specimen holder (see Fig. 14).

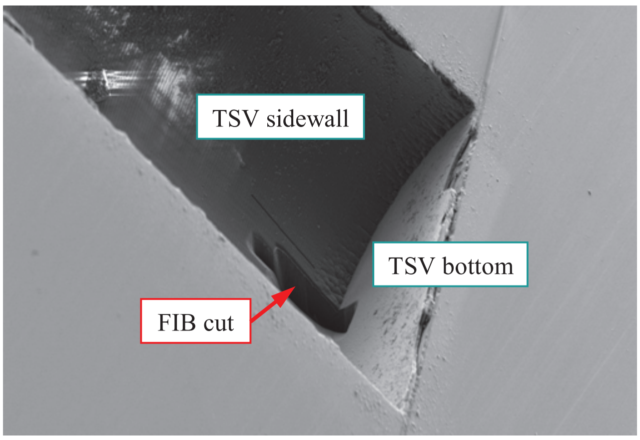

Figure 14: SEM image of 45° tilted specimen with cross section at the localised defect position

Afterwards FIB milling and simultaneous SEM observation were performed to screen the defect area. A rough inhomogeneous sidewall can be seen at the TSV bottom with abnormal thickness deviations of the isolation oxide layer between the substrate and the sidewall metallisation. Additional embedded voids were observed at the interface with three dimensional Si artefacts. Such defects are caused by an insufficient Si etch process at TSV bottom.

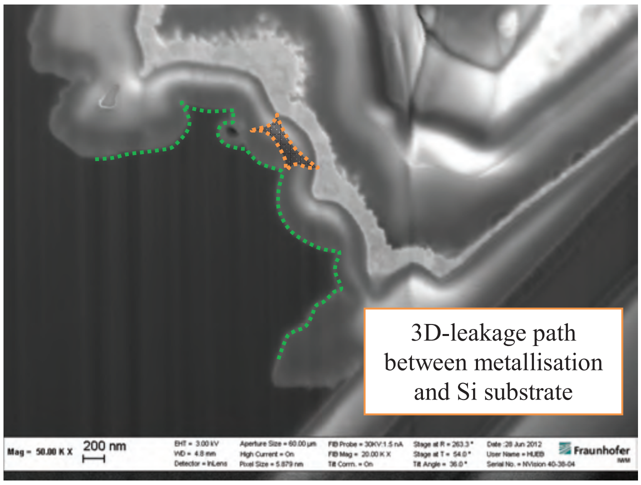

Figure 15: SEM cross section image at middle of EBAC spot position after FIB polishing (overlay of two cross section images)

A three dimensional formed Si residue was detected within the EBAC active area (see Fig. 15). It shorts the substrate with the TSV metallisation at the bottom sidewall and thus generates a high-ohmic leakage path. Due to the three-dimensional shape the complete leakage path was only observable by reviewing several cross sections. This kind of failure can occur when the last Si etch steps were processed insufficiently and thus significant layer thickness variations were caused. The described case study shows the feasibility of the explained localisation and preparation methods to characterise complex three-dimensional defects at interconnect structures.

Summary and Conclusions

LIT and EBAC imaging techniques have been adapted for three dimensional and precise short localisation within open TSV structures. The defect sites can be easily navigated within the FIB/SEM system for further cross sectional analysis. In order to get access to the defect sites for destructive physical analysis full cross sectioning of the devices exactly through the defective TSV structure is necessary. In addition to precise mechanically grinding also ps-laser milling was demonstrated to speed up the preparation process. As an outlook combined laser milling and FIB cross sectioning within one device could be a very effective way for specimen preparation at TSV interconnects. The feasibility of these techniques was demonstrated on a device with shorted open TSVs.

Acknowledgments

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