

Microstructural based reliability investigation of water- and suspension free prepared integrated electronic packages

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Abstract—In micro- and power electronics reliability limiting mechanical and (electro-) chemical processes are increasingly caused by the complex structure of the systems, the material compositions and often heterogeneous mixtures of metals, polymers, and ceramics. Additionally, this causes challenging requirements for microstructural analyses and reliability characterization of materials, interfaces, components, and systems. Standardized metallographic routines are not suitable for high resolution analyses of corrosion products and mechanically sensitive systems. Focused ion beam preparation is limited in terms of dimension of the cross sectioned area. Therefore, we developed new preparation concepts by complete water- and suspension free preparation methods using laser and broad ion beam techniques. Two case studies for analyses of power electronic systems potted by inorganic materials and embedded SiC dies show the great potential of these methods for following microstructural analyses.

Keywords—high resolution analyses, microstructure, laser preparation, ion beam preparation, reliability assessment, electronic packaging

I. INTRODUCTION

In microelectronics and power electronics, reliability-reducing mechanical and (electro-)chemical processes are increasingly occurring due to the complex structure of the systems, material compositions, and often heterogeneous mixtures of metals, polymers, and ceramics. In most cases, non-destructive analysis is not sufficient to understand the detailed causes of failures and subsequently decide on effective countermeasures. To enable the application of high-resolution microstructure techniques such as scanning electron microscopy (SEM) and X-ray spectroscopy (EDS), destructive target preparation methods must be used to gain direct access to the site of the failure. Furthermore, this poses demanding requirements for microstructural analysis and reliability characterization of materials, interfaces, components, and systems. Standardized metallographic routines are not suitable for high-resolution analysis of corrosion products and mechanically sensitive systems. The selection of the preparation method depends on the materials and samples under investigation, as well as the required precision and level of artifact risks. Especially in industrial applications, the analysis throughput and efficiency are mostly determined by the efficiency of the preparation. For the analysis of quality or reliability-critical interfaces of electronic components, precise cross-section preparation is required. The

standard method is defined by metallographic techniques based on cutting, grinding, and polishing. For material boundaries between very hard and soft materials, such as the chip contact between a semiconductor chip, soft solder material or silver, used for sintering application, and a hard DCB ceramic substrate, metallographic cross-sectioning is not an easy task. Problems such as crack damage and the risk of smearing effects at the material interfaces must be avoided. Today, precise ion and laser-based preparation techniques are established, which can avoid mechanically induced preparation artifacts and improve both the quality and precision of preparation. For example, by ion beam cross-section polishing, where a broad ion beam is used to create relatively large cross-sections. Based on these methods, we have developed new preparation concepts that employ completely water- and suspension-free methods using laser and broad ion beam techniques. Two case studies on the analysis of power electronic systems using inorganic materials and embedded SiC chips demonstrate the great potential of these methods for subsequent microstructural analysis.

II. EXPERIMENTAL

A. Typical process flow for advanced material diagnostic

New routines have been developed for advanced material diagnostics to investigate the reliability of complex electronic systems. Especially in the investigation of corrosion and migration effects, new failure modes occur that can be strongly influenced by liquid-based preparation methods. Therefore, dry preparation methods are needed to minimize the influence of preparation artifacts to the origin failure mode. Pico- or femto-based laser techniques are a good alternative to water-/suspension cooled wire sawing methods for fast and efficient pre-preparation. Followed by high broad ion beam techniques a fast and efficient final preparation can be assured. Now, high-resolution analyses of interfaces and material interaction are possible to perform material-based reliability studies and failure analyses. Figure 1 shows a chart for a typical process workflow for advanced material diagnostics as described before.

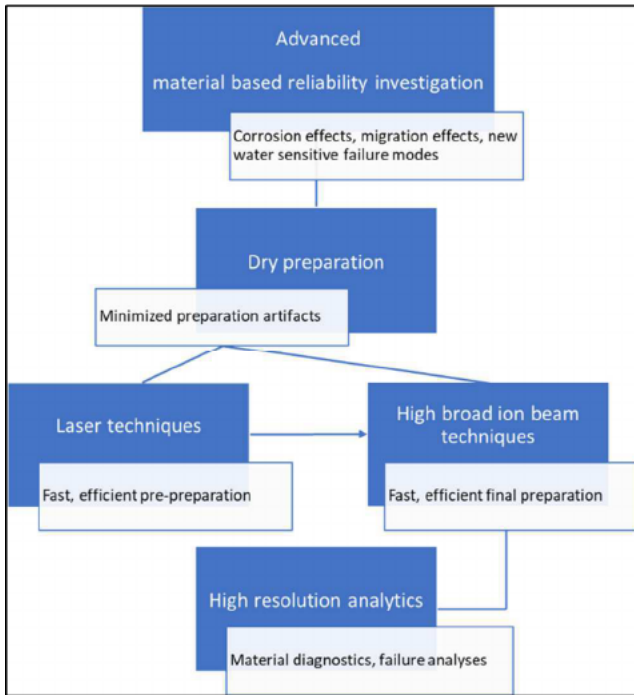


Fig. 1: Workflow for advanced material-based reliability investigation.

B. Laser Preparation

Laser have been commercially available for many decades and are used in various areas such as industrial manufacturing (welding, drilling, scribing, etc.), science (e.g., material characterization, measuring), and medical applications (invasive surgery techniques, LASIK). Laser radiation can ablate all kinds of materials when provided with sufficiently high power or fluence. By using ultrashort pulses and/or very high pulse energies, ablation is achieved through multiphoton absorption, allowing for the machining of transparent materials at the laser's wavelength. Lasers can be precisely delivered and focused using standard optical elements like galvanometer scanners. Laser micromachining is very clean in terms of contamination since laser radiation consists of photons, unlike corpuscular radiations like ion beams that may cause unwanted implantation effects. The ablation rate in laser micromachining is approximately six orders of magnitude higher than that of Ga⁺-FIB and roughly three orders of magnitude higher than the milling rate of Xe⁺-Plasma-FIB. These mentioned advantages make laser micromachining a highly interesting option for preparation applications related to analysis issues in electronics, such as connection technology and packaging. The continuous trend of miniaturization enables an increasing level of integration, including 3D systems in packages (3D-SiP). Consequently, the structure of electronic packages is becoming more complex, with material compositions often consisting of heterogeneous mixtures of metals, polymers, and ceramics. This poses challenging requirements for investigating and characterizing the reliability of materials, interfaces, components, and systems. The target positions are often buried or covered, and the cover and housing materials are designed to be resistant against chemical attack for harsh environment applications. These developments make the preparation for tasks such as local access for electrical measurements or artifact-free cross-sectioning increasingly complex. Focused ion beam preparation is limited in terms of ablation volume, chemical de-capping lacks selectivity and faces difficulties due to the resistivity of mold compounds or

alternative packaging materials like ceramics or inorganic potting against chemicals, and metallographic cross-sectioning may compromise the system's functionality or introduce artifacts that limit further investigations. Therefore, there is a growing demand for preparation techniques for microstructure diagnostics that are fast, reliable, cost-effective, artifact-free, and targeted at the micron scale or below. The MicroPrep Pro™ tool used, is a laser micromachining tool developed by 3D-Micromac AG (Chemnitz, Germany) with the intention of providing a fast, clean, and efficient development platform for laser preparation. By utilizing an ultrashort pulse laser, samples can be effectively and cost-efficiently prepared. This approach enables the creation of complex samples or 3D geometries. The flexibility of the laser process allows for comprehensive analysis of deep-lying structures, such as exposing contacts (e.g., through-silicon vias - TSVs) or targeted removal and exposure of traces in semiconductor structures (e.g., systems-in-packages - SiP). Furthermore, larger samples can be processed directly with micrometer-level accuracy. The integrated overview camera simplifies navigation on larger samples, and the high-resolution process camera ensures precise positioning. By using a picosecond laser, structural damage is significantly reduced, and material contamination is avoided. With the MicroPrep Pro™, much higher removal rates can be achieved compared to ion beam-based methods only [1]. Typical sample dimensions processable with this tool range from several hundred microns to several centimetres in size, with thicknesses up to several millimetres.



Fig 2.: MicroPrep Pro™, that can be used for efficient laser preparation.

C. Broad beam ion polishing

While Focused Ion Beams (FIB) have been successfully used for sample preparation in advanced CMOS device analysis, their relatively low milling rates (around 5-10 $\mu\text{m}^3/\text{s}$ for Silicon) do not make these systems well-suited for cross-sectioning package level interconnects, making large volume removal impractical. Some years ago, a new FIB technology has been developed that offers much higher material removal

rates by utilizing an Inductively Coupled Plasma (ICP) Xenon ion source. This source can deliver beam currents 20-50 times higher than the traditional Ga Liquid Metal Ion source (LMIS). The Plasma FIB system, therefore, becomes an attractive tool for analysing interconnect structures by scanning electron microscopy (SEM) with relatively large cross sections. The Xenon ion beam can be used to deposit protective layers, mill cross sections with dimensions up to millimetres, and image the region of interest. This system achieves removal rates of approximately 20000 $\mu\text{m}^3/\text{min}$ for Silicon, allowing the removal of a volume of, for example, 200x200x100 μm^3 in about 3 hours. The removal rate can be further improved by chemically induced FIB etching. We used a FEI Vion™ Plasma single-beam FIB system to evaluate its capability for high-quality, large-area cross-section preparation of selected interconnects in microelectronic devices as an alternative to traditional mechanical grinding, polishing steps, and ion beam bevel etch techniques for different packaging materials [2]. Furthermore, the Plasma FIB system incorporates charge neutralization based on low-energy electron flooding of the sample. The electron gun enables milling of non-conductive materials such as mold compounds or ceramic substrates, effectively preventing sample charging even at high ion beam currents. Thus, we have now developed ion-based preparation routines to investigate the reliability of new material compositions and their interaction with different contact materials (solder, wire bonds) and to assess the reliability of embedded SiC semiconductors in ceramic materials.

III. CASE STUDY 1: EMBEDDED SiC SEMICONDUCTOR

Silicon carbide (SiC) semiconductor devices offer significant economic potential for power electronic applications. To support the develop of a new packaging and

integration technology of SiC devices into a monolithic ceramic package for high-power applications our work focuses on artifact minimized preparation and reliability investigation. This approach allows us to assess the inherent advantages of ceramics, such as high temperature stability, high insulation resistance, and high reliability, which are beneficial for SiC packaging concepts [3, 4]. The main challenge for this technology trend is a functional integration of non-shrinking SiC devices into a structured ceramic multilayer laminate, which undergoes shrinkage during the sintering process. This requires establishing mechanical, hermetic, and electrical connections between the SiC device and the ceramic prepackage during the sintering process. Cracks and delamination must be assessed after processing and reliability testing without the influence of mechanical artifacts. To perform sufficient failure analysis on such integrated power devices, laser-assisted target preparation was used in combination with ion beam polishing. The use of laser-assisted target preparation in conjunction with ion beam polishing enables the creation of an artifact-free surface for microscopic analysis. In comparison to conventional metallographic techniques for preparing SiC chips and ceramic structures, this approach allows the desired target plane to be reached much faster and without mechanical influences. The polished surfaces created without mechanical intervention allow a more targeted assessment of cracks and delamination at interfaces. This is demonstrated in Figure 3, which depicts a cross-section of a SiC chip prepared using laser-assisted preparation and ion beam polishing showing fine cracks in the ceramic near the buried silver via. Details of the crack are shown in Figure 4.

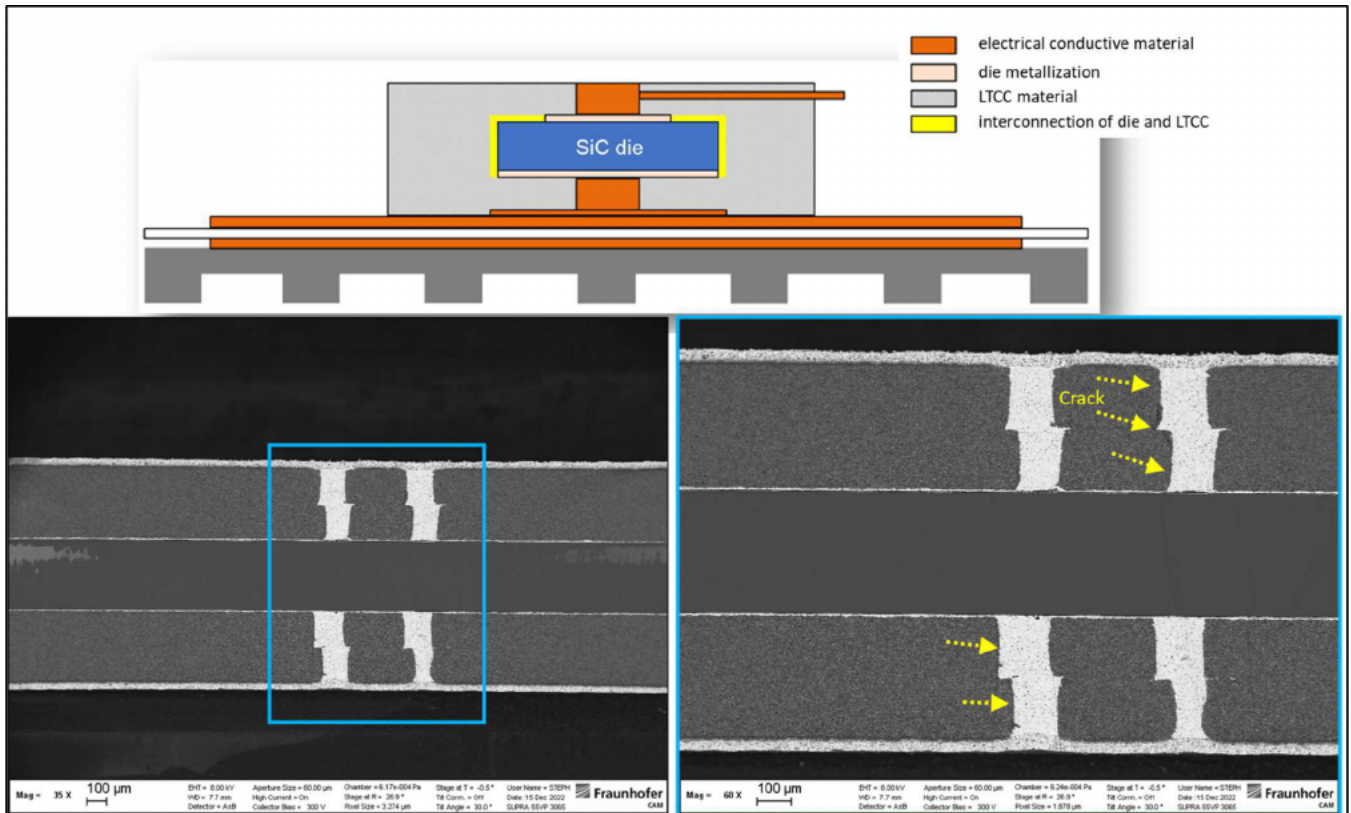


Fig 3.: Concept for an integrated SiC component and cross section prepared without mechanical influences.

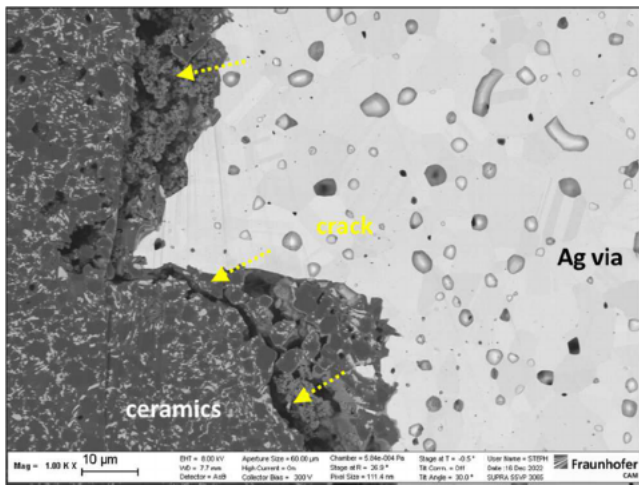


Fig 4.: Detail of cracked interface between buried silver via and sintered ceramic, cracks are marked by yellow arrows.

CASE STUDY 2: INTERFACE FAILURE MODES OF CEMENT ENCAPSULATION AND ADJACENT MATERIALS

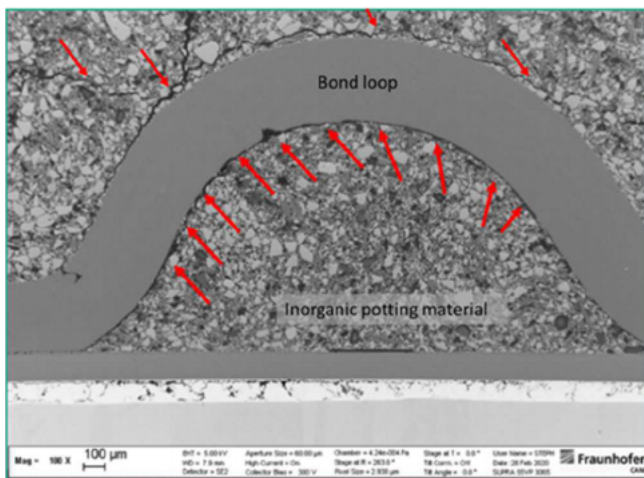


Fig. 5.: Aluminum bond wire with inorganic potting material shows interface delamination and cracking marked by red arrows [5]

In [5] we showed potential failure modes for electronic components potted by inorganic cement-based materials. As these materials become more and more popular, it is very important to develop preparation routines that can prevent smearing effects. Here, the combination of laser preparation and high-rate ion polishing is also suitable to ensure a proper interface preparation. For example, small cement cracks at the interface to the wire bonded contacts can lead to initial

weakening for delamination failure, see Figure 5. **Error! Reference source not found..** If this interface is not prepared without smearing effects, misinterpretation is possible.

Figure 6 shows a direct comparison between a metallographic preparation and high broad ion beam polishing of a wire bond contact with mold encapsulation material. After broad beam ion polishing the wire bond shows a corroded area on top that appears porous with a void line below. As this layer has a thickness of about 1 µm EDS analyses can be performed and the material composition can be analysed. In direct comparison, the metallographically prepared contact shows no clear layer of corrosion products. Only a brittle decomposed area is detectable on top of the stitch bond with a small gap to the mold compound. It is assumed that the corroded layer was dissolved in the liquids used for the metallographic preparation.

DISCUSSION & SUMMARY

In [6] we already showed the potential for combined laser preparation and broad ion beam polishing for 3D-integrated systems. It offers solutions to a wide range of problems and challenges, including the removal of potting compounds like mold compounds and gel, as well as the creation of large-scale cross-sections for ion beam-based target preparations. Laser pretreatment enables water-free or chemical-free preparation routines, or significantly reduces their usage, allowing for subsequent elemental analysis. Additionally, laser pre-preparation minimizes or eliminates the need for mechanical processing of sensitive samples, thereby avoiding or greatly limiting associated effects. This ensures artifact-free access that may not be possible with classical metallography, for example. Extensive investigations have been conducted to understand the impact of laser beam ablation on samples, such as the heat-affected zone, debris, and surface impairment, to ensure that subsequent analyses are not affected by the preparation process.

In this paper, additional case studies have demonstrated the versatility of the laser preparation method tool also for power electronics application. It has proven itself effective in processing large volume encapsulants and creating cross-sections of potted materials or integrated dies. Failure modes and material reactions can only be accurately determined and analysed if the preparation artifacts are minimised as far as possible. Therefore, it is crucial to adapt the preparation and analysis methods to the material and technological advancements.

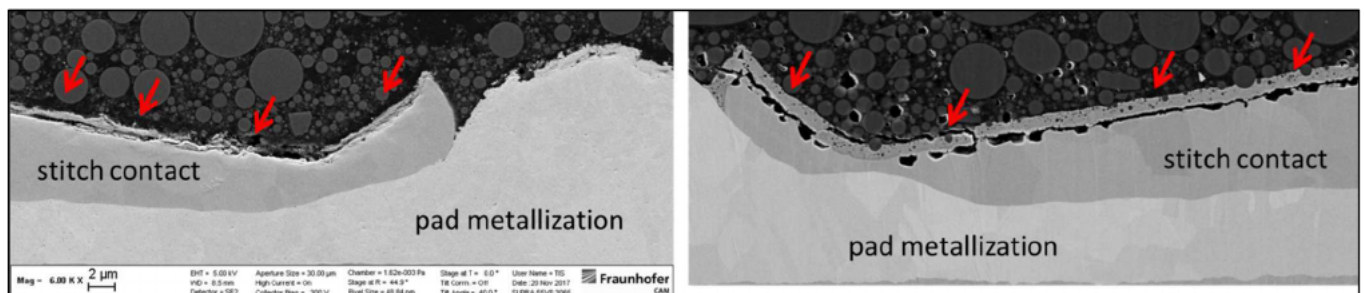


Fig. 6: Direct comparison between a metallographic preparation (left) and high broad ion beam polishing (right) of an encapsulated wire bond contact with encapsulation material showing corrosion products for the high-end prepared contact and a decomposed area for the metallographic prepared contact only.

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