Metal-Dielectric Stack Damage Evaluation Utilizing Acoustic Emission Signal Analysis

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Abstract. The mechanical reliability is of major importance for the development, qualification, and implementation of semiconductor devices. This is especially the case for demanding application cases like e.g. automotive, aerospace, and industrial. Mechanically critical aspects like the stability of metal-dielectric stacks, the so called "back end of line" (BEoL), have to be evaluated thoroughly before implementation. This evaluation is mainly conducted by inflicting (thermo-)mechanical damage to the respective samples and a consequent damage analysis. A new approach presented in this work contains the utilization of acoustic emission measurements during the damage infliction process to identify damage occurrence and obtain more information on the damage mode. This enables the identification of the most damage prone areas in the BEoL stack. The sample analyzed in this work is an unpackaged microchip bumped with Copper pillars (Cu-Pillars) as electrical connectors. These pillars are attached to the subjacent BEoL stack which provides the power supply and distribution of electrical signals of the chip. The application of shear force to the Cu-pillars utilizing a customized indenter tip enables the controlled infliction of damage into the BEoL stack. A sample holder was specifically designed for the experiments which facilitates the placement of an acoustic emission (AE) sensor below the sample. This enables the immediate identification and measurement of AE events during the damage infliction process. Previous works have already exhibited the potential of AE measurements for damage indication in semiconductor structures [1,2]. Acoustic data analysis techniques like cluster analysis can be utilized for damage evaluation, e.g. in composite materials, as well [3]. In this work, the possibility of utilizing this approach for the analysis of damages like delamination or cracking occurring in BEoL stacks is evaluated. This is done by correlating the occurring lateral forces and damage modes with the characteristics of the AE signals. The developed setup as well as first results regarding damage mode evaluation and categorization are provided in this work.
Keywords: Acoustic emission (AE), Cluster analysis, Copper pillar shear-off, Mechanical BEoL reliability, Chip package interaction (CPI)

1. Introduction and Motivation

Reliability challenges are a demanding aspect of the development and implementation of semiconductor applications. Especially in fields with harsh environmental conditions like automotive, aerospace, and industrial, coping with these challenges requires thorough electrical and mechanical testing as well as strict qualification and quality control procedures to prevent failure in the field. Testing in this area is time and resource demanding, therefore the development of accelerated approaches or such that generate additional relevant data is desired. One strategy to accelerate mechanical reliability testing is the direct application of micromechanical load to the respective region of interest (ROI) utilizing e.g. a tribo indenter system. A customized approach to apply shear load to the electrical connectors of a microchip with a tribo indenter to stress and damage the subjacent material stack is presented in this work. To obtain further information on the damage processes triggered by the mechanical loading, the applicability of acoustic emission (AE) measurement was taken into consideration. AE testing is commonly utilized for structural health monitoring (SHM) in fields like e.g. aerospace, civil engineering, gas tanks, pipelines etc. to monitor structural integrity and identify occurring damages. Therefore, it is an excellent tool for damage indication. It has been shown in other works that this concept is indeed transferable to semiconductor samples [1,2]. However, the analysis of AE signals can provide much more information than the only the qualitative identification of a damage event. Examples include for instance studies on type and location of damaging events in fiber-reinforced and other composite materials [7, 8]. This indicates that the application of AE measurements bears major potential to compliment mechanical semiconductor reliability testing procedures and optimize the damage evaluation method. This work explores this potential and represents a first step in the development of an evaluation methodology combining micromechanical loading and AE testing for semiconductor applications.

2. Terminology and State of the Art

In the following, the investigated structures in general and the current state of the art regarding micromechanical reliability testing of semiconductor samples as well as the application of AE testing and data analysis approaches are laid out.

2.1 Microchip Structures and Mechanical Reliability Testing

Microchips are complex devices which contain various materials with different electrical and mechanical properties and structure dimensions in the range of several 100 µm down to the nanometer regime. This work focuses on the mechanical reliability of the back end of line (BEoL) stack, which is a heterogenous material stack, mainly consisting of Copper and brittle organosilicate glasses (OSG). Its function is to provide the distribution of electrical power and signals for the microchip. A BEoL stack bumped with Cu-pillars is schematically depicted in figure 1.

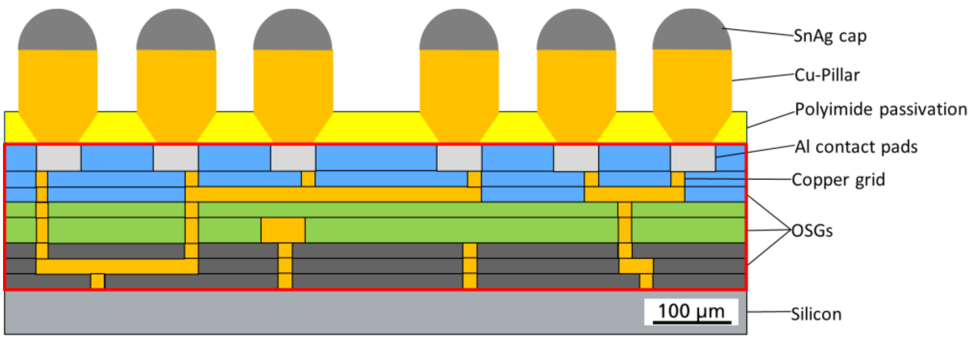

Fig. 1. Schematic microchip cross section with BEoL magnified twentyfold (red)

Due to the size of single elements and the interfaces between them, they cannot be investigated separately but the stability of the stack must be evaluated as a whole. The applied testing procedures can be extremely time and resource demanding. A typical approach is to mimic the stresses that the device is exposed to during its expected lifetime and accelerate the degradation process. This can be achieved for example by temperature cycling (TC), a method for which different procedures with adequate acceleration models exist. This approach harnesses the difference of the coefficients of thermal expansion (CTE) of the materials in the BEoL stack. When heating up, some materials expand more than others which induces mechanical stress that eventually leads to failures. However, even this technique is very time and resource consuming which led to a constant demand for further accelerated testing procedures. This can for instance be achieved by pure micromechanical approaches.

For established technologies like solder bumps, standards are already available [4]. For Cu-pillar bumps, no standardized testing procedure has been developed yet, only experimental approaches like Cu-pillar shear experiments or the bump assisted BEoL stability indentation (BABSI) [6]. However, open questions regarding the damage initiation and propagation in the BEoL stack still remain. Therefore, the development of approaches which accelerate mechanical reliability testing further or extend the range of information on the damage mechanisms is crucial.

A very promising method in this regard is acoustic emission (AE) testing. It has been shown in previous works that AE can be utilized for damage indication in semiconductor samples [1, 2]. With this approach it should be possible to obtain additional information on the extremely fast damage processes without influencing the measurement of the mechanical properties. Based on the respective processing and evaluation method applied to AE data, this technique can provide highly relevant insights to occurring damage modes. Therefore, the application of AE testing during the damage infliction process is explored.

2.2 Acoustic Emission Testing and Data Analysis

Mechanical stress within structures can lead to plastic deformations under the release of energy, leading to acoustic waves that can be detected. Especially within composite structures, starting with Bohse [4], these effects were studied to detect position and type of the occurring changes. For this, a detected signal must be filtered out from the surrounding noise and can then be analyzed regarding its different properties within the time and frequency domain. Especially notable was the discovery, that it is possible to identify different damage mechanism using cluster analysis within a plot of the Partial Power over the Weighted Peak Frequency (WPF) [5]. This can be described as

$$f_{WPF} = \sqrt{f_{peak} f_{cent}} \quad \text{with} \quad f_{cent} = \frac{\int f \tilde{U}(f) df}{\int \tilde{U}(f) df} \qquad [1]$$

and

$$P_n = \frac{\int_{f_1}^{f_2} \tilde{U}^2(f) df}{\int_{f_{begin}}^{f_{end}} \tilde{U}^2(f) df} \qquad [2]$$

where the Weighted Peak Frequency f_{WPF} is determined from the Peak Frequency f_{peak} and the Centroid Frequency f_{cent}, which in return is calculated from the Amplitude within the frequency domain $\tilde{U}$. While the Partial Power P of range n is the proportion of an integral within a frequency range $[f_1, f_2]$ to one calculated over the full frequency range.

The specific objective of this work is to explore the applicability of this approach by triggering and distinguishing between two different damage modes and implement a damage mode categorization based on the AE signal.

3. Experimental Implementation

In the following, the specific samples investigated in this research, the customized experimental setup as well as the experimental parametrization and the resulting damage modes are introduced.

3.1 Sample and Experimental Approach

The sample which was investigated is an unpackaged high-end microchip bumped with round Cu-pillars with a diameter of 95 µm and a height of 65 µm. They are capped with 35 µm of SnAg solder. The BEoL thickness is approximately 10 µm and the thickness of the Silicon substrate measures 700 µm. A sample overview is given in figure 2.

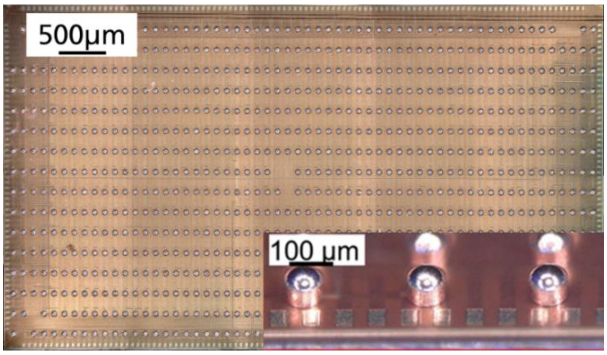

Fig. 2. Test chip overview

The sample overview in figure 1 displays the geometrical size of the sample as well as the Cu-pillar distribution. For the experiments, only the Cu-pillars in the center of the chip were considered. This is due to the fact that the BEoL structures are different close to the edges of the chip which might result in different mechanical and acoustic signals. The experimental setup with the customized sample-sensor holder is schematically depicted in figure 3.

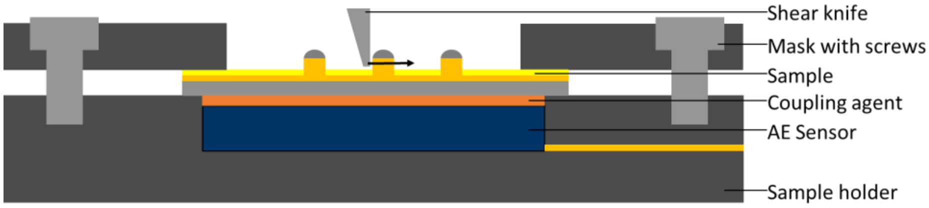

Fig. 3. Schematic experimental setup (side view)

The application of mechanical load was provided utilizing a Hysitron/Bruker TI 950 tribo indenter system with a customized shear indenter tip. The geometrical characteristics of this shear tool had to be adapted to the small features of the sample. It has a base of 50 µm x 50 µm and a 90° edge to enable pure lateral loading. An incline would induce an additional perpendicular force component. During the experiment, the sample was immobilized with a clamping mask. To connect the sample acoustically to the AE sensor, Dow Corning high vacuum grease was used as a coupling agent. The AE events occurring during the Cu-pillar shear-off were measured with a Mistras PICO sensor. This broadband sensor enables measurements from ~200 kHz up to more than 1 MHz and has a peak frequency of 434.57 kHz. To augment the signal, a Mistras 2/4/6 preamplifier was interposed between the sensor and the measurement system, an HBM transient recorder.

3.2 Experimental Parametrization and Conduct

The shear load was induced to the Cu-pillars by a displacement-controlled shear experiment. This means that a specific shear distance and time were set and the occurring force was measured. It could be shown in a previous work that different shear parametrizations can trigger different failure modes [2]. Two failure modes, the cratering mode and the surface shear-off mode were selected for this work. In case of the cratering, the occurring damage progresses through the BEoL stack and several layers delaminate. To trigger this damage, the Cu-pillar is sheared at its base with a velocity of 10 µm/s. In case of the surface shear-off mode only the Cu-pillar and the subjacent Aluminum contact pad delaminate. To trigger this damage, a Cu-pillar is sheared at a height of 20 µm with a velocity of 1 µm/s. The resulting damages are depicted in figure 4 together with the corresponding shear parametrization.

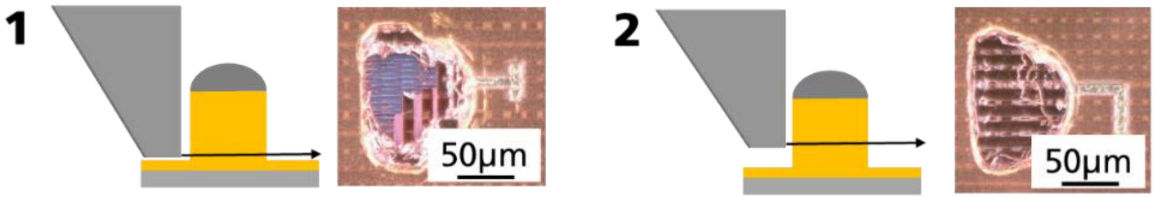

Fig. 4. Visualization of two shear heights resulting in different damages, Cratering mode on the left side(1) and surface shear mode on the right side (2)

In addition to the two damage modes shown in figure 4, mixed modes occurred in some cases. These were taken into account as well for the acoustic analysis. The AE signal, which was amplified with 40 dB was constantly measured during the shear experiments with a sample rate of 100 MS/s and saved to a memory loop with a signal length of 1 s. It was recorded as soon as a threshold of 50 mV was exceeded. With this approach, the signal part right before reaching the threshold could be made available for analysis as well.

4. Experimental Results and Data Analysis

The experimental results and the analyses of the mechanical and acoustic data are presented in the following. Firstly, the mechanical loading scenarios and the resulting damages are introduced and then an AE data analysis approach is provided to enable a categorization concept for BEoL damage modes.

4.1 Mechanical Results and Damage Imaging

During the displacement-controlled shear experiments, the respective lateral force was measured by a sensor in the transducer of the tribo indenter system. The force was then plotted over the measurement time. The force progression curves for 11 experiments respectively triggering the cratering and the surface shear-off mode are depicted in figure 5.

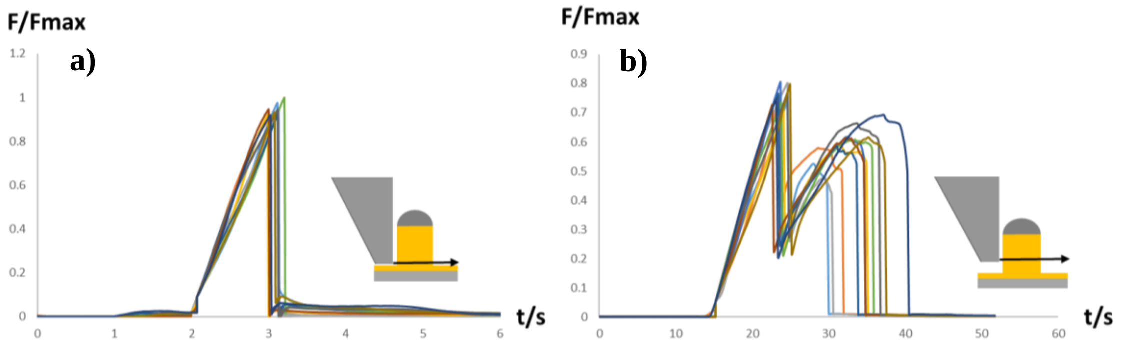

Fig. 5. Force progression curves over time of the cratering (a) and the surface shear-off mode (b)

The graphs in figure 5 show that the shear experiments are well reproducible. The standard deviation is 2.9 % of the average shear force for the cratering mode and 3.7 % for the surface shear-off mode. It is also evident that the cratering mode only consists of one damage event while the surface shear-off mode contains of two separate ones. The average maximum shear force of the cratering mode is approximately 25 % higher than the one of the surface shear-off mode. Both damage events of the latter trigger an AE signal, the second one being considerably smaller than the first one. One example for both damage modes is presented in figure 6.

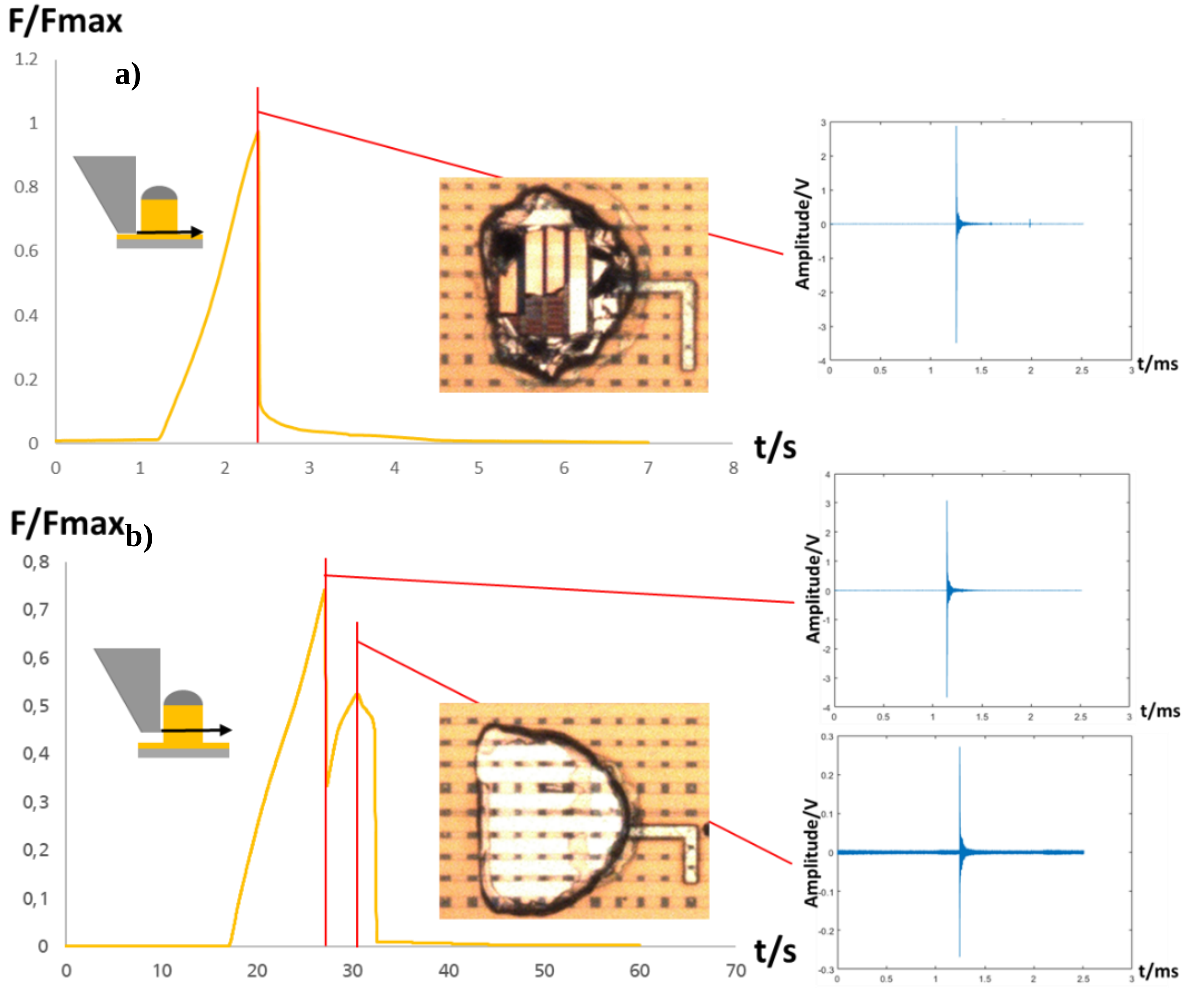

Fig. 6. Force progression curves over time and the respective AE signals of the cratering (a) and the surface shear-off mode (b)

The graphs in figure 6 show the damage progression curves for the two failure modes as well as the respective AE signals and their moment of occurrence. More information can be derived from the AE data by applying acoustic analysis methods to the signals.

4.2 Cluster Analysis, Weighted Peak Frequency, and new Averaging Approach

The experimental data was first cropped into parts of equal length and sorted into the respective damage by manual selection. Four Damage categories were chosen: Two of which show a pure catering or surface shear-off mode and two which do not show a clear mode but a tendency towards one of the pure modes.

For a first analysis, Partial Power ranges were chosen as proposed within [5]. If a damage hit has more then one detectable event, every event is counted separately. Results are shown in figure 8 While some events are separated, most of the events are clustered together.

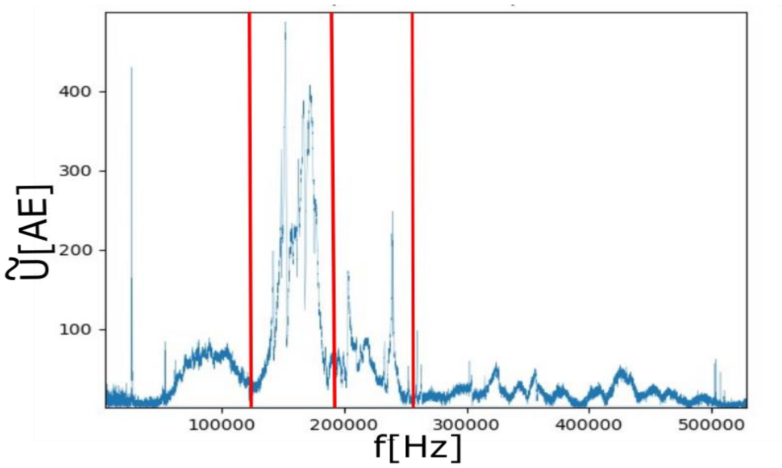

Fig. 7. Example of frequency distribution with Partial Power ranges

Each signal was selected using an AIC-Filter and analysed to extract the different signal parameters. Using the frequency domain, ranges for the Partial Powers were chosen.

As shown in an example in figure 7, some distinct areas can be seen, therefore without loss of generality, the ranges were chosen as displayed in table 1.

Table 1: Ranges of the Partial Powers

Partial Power 1	0 - 125000 Hz
Partial Power 2	125000 - 188000 Hz
Partial Power 3	188000 - 270000 Hz
Partial Power 4	> 270000 Hz

For some damage processes more than one signal was detected. For these ones, the parameters were assumed to be the mean value. The analyzed data is presented in figure 9. Using customized Partial Power ranges in addition to mean values distinguishes the two overall damage modes from each other.

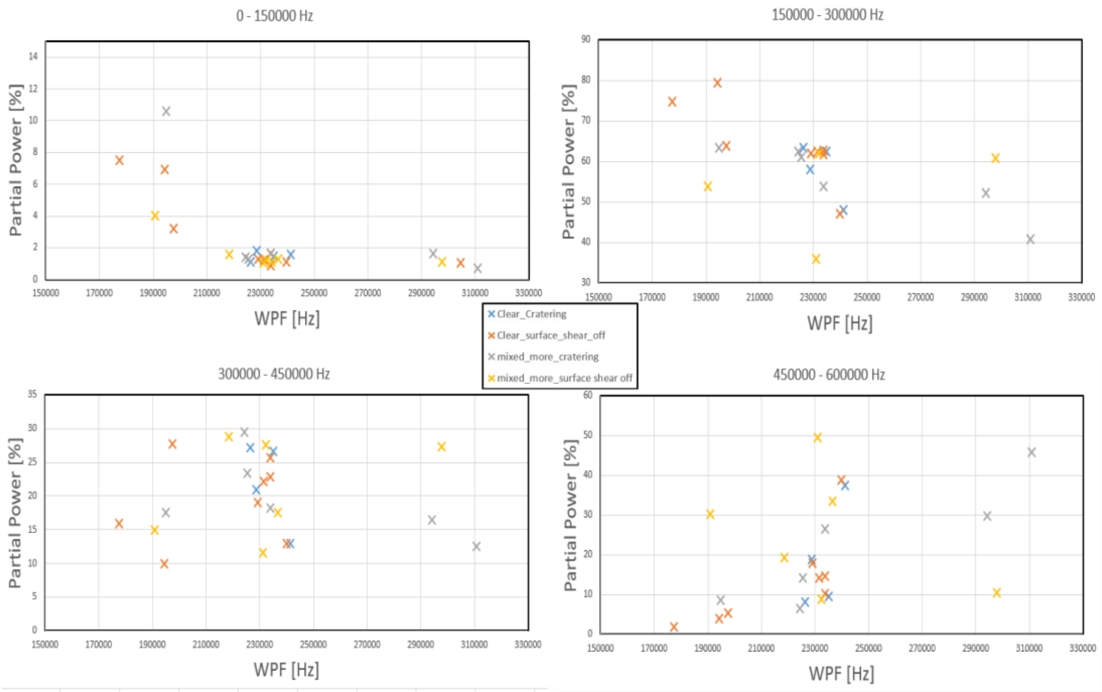

Fig. 8. Diagrams over 4 ranges of partial power, displayed over their dependencies on the WPF

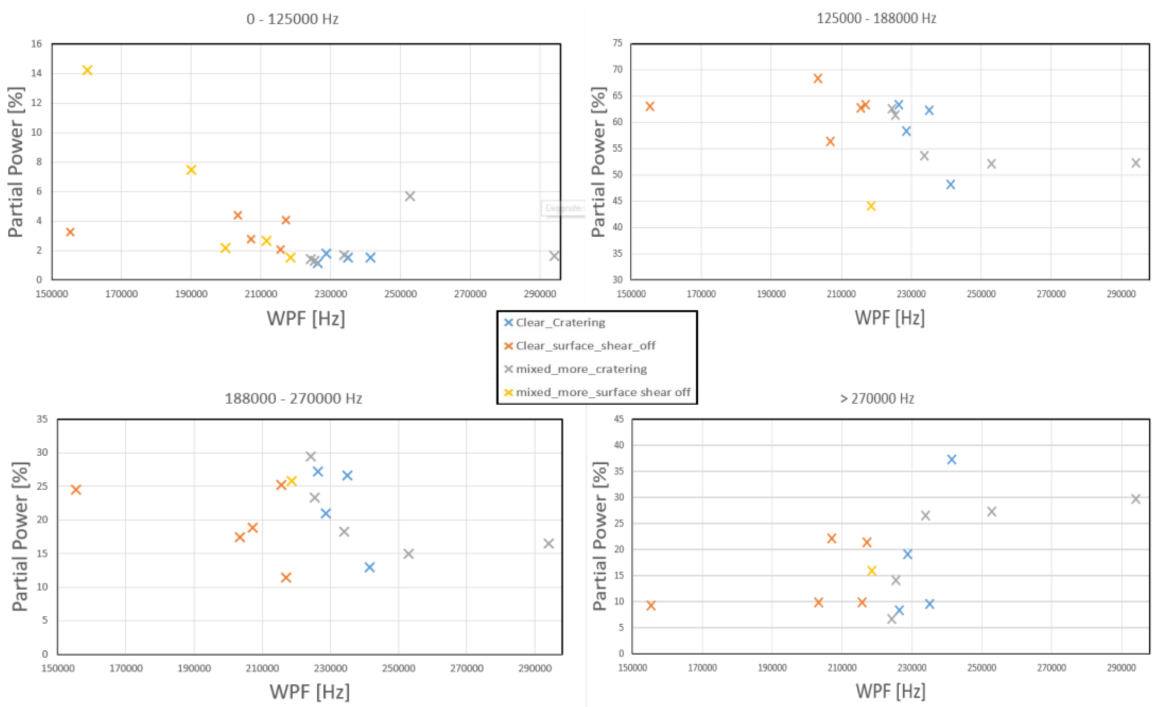

Figure 9. Diagrams of the different partial powers in dependence on the WPF of a set of data within 4 custom chosen frequency ranges

5. **Conclusion and Outlook**

This work presents a proof-of-concept approach to evaluate BEoL damages with AE data analysis. Two different damage modes and two mixed modes with tendencies to the main ones were investigated. The mechanical damage was triggered by Cu-pillar shear-off utilizing a tribo indenter system and a customized experimental setup. The parameters of the resulting acoustic data were analyzed using processes already established in the field of AE-analysis. With this approach it was indeed possible to allocate the occurring damages to the respective categories “cratering” and “surface shear-off” only by evaluating the acoustic dataset. It could especially be shown that the Weighted Peak Frequency is a promising parameter to differentiate between the selected damage types and can therefore be a good complementary tool for the damage analysis procedure of BEoL stacks.

However, distinguishing between the clear modes and the mixed modes only based on the AE signal analysis is not possible yet. Therefore, some refinements and improvements are proposed future research approaches:

- The experiment should be improved by identifying and controlling the parameters which might have an influence on the AE signals like clamping of the sample with a defined pressure or the specific design of the sample/sensor holder.
- The approach should be extended to other samples and other damage modes to evaluate a more holistic applicability for damage analysis in BEoL stacks.
- Further acoustic parameters could be taken into account to add further dimensions to the analysis approach and enable a clearer distinction between the different damage modes.
- Image analysis algorithms are developed to replace the manual damage categorization. This should result in the automatic of damage parameters, which could provide further insight.
- With automatically generated damage parameters, further automatization, and statistical approaches and eventually even the application of neural networks should be enabled.

The approach presented in this work represents a promising first step regarding damage categorization in BEoL stacks based on AE data analysis. The refinement of the presented approach should lead to the development of a methodology which could be a helpful tool for the damage evaluation procedure in BEoL stacks under mechanical load.

Acknowlegment

The authors like to thank Bruno Mendes Oliveira (Universidade Nova de Lisboa) for the support regarding the conduct of Cu-pillar shear experiments. The manufacturing of the customized indenter tip by Synton-MDP is acknowleged as well.

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