Micro-tube insertion into aluminum pads: Simulation and experimental validations

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Abstract

Following the trend towards more densely integrated electronic devices; new flip-chip technologies are developed to address very fine pitch interconnection. Among them, it was demonstrated that the hybridization technique based on insertion of gold coated micro-tubes into aluminum pads (Al-0.5Cu) has the capability for a 10µm bonding pitch and the advantage of a room temperature assembly process.

In this study, we propose to thoroughly study the electro-mechanical behavior of the micro-tube inserted into an aluminum pad.

A finite element model has been used to simulate the micro-tube insertion into an aluminum pad. This numerical model deals with critical issues such as contacts, large deformations and remeshing. It was used to predict the main process parameter: the minimum load required for the micro-tube insertion into the pad. On one hand, the load should be high enough to fracture the native alumina layer on the pad during insertion and to achieve an appropriate electrical contact. On the other hand it must be low enough to prevent over-stress and deterioration of the tube and the underneath technology.

These results are generalized to assemble an array of over 100 000 micro-tubes into an array of pads using a pick and place equipment. The D2W bonding process has been optimized in order to reach a 100% yield of interconnection and a high mechanical strength. Electrical measurements show that these assemblies exhibit an electrical resistance lower than 300mΩ at 10µm pitch.

1. Introduction

New requirements for 3D integration stimulate research and development of new interconnection technologies. Most efforts are currently focused on five bonding technologies: reflow soldering, thermo-compression, Direct Bond Interconnect (DBI), Solid Liquid Inter Diffusion (SLID) and insertion. The room temperature micro tube insertion technology is a candidate to address this challenge [1]. Keys attribute of this technology are ultra-fine pitch capability, high pick & place throughput, low temperature process, high tolerance to non-planarity and roughness defects. Moreover, no flux or reducing atmosphere is needed to achieve a reliable electrical contact.

The reliable electromechanical contact is established by inserting hard golden micro tubes into a ductile aluminum pad. The process is schematically described in figure 1.

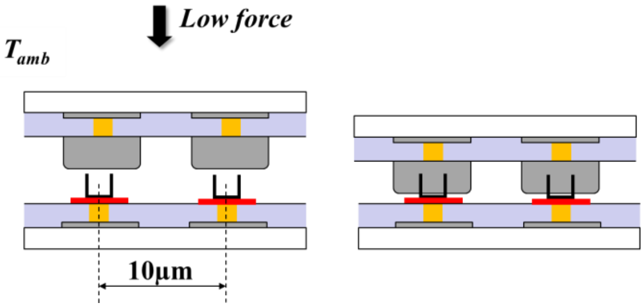

Fig. 1: Schematic drawing of the insertion flip-chip technique

2. Materials and methods

In this study, we worked with 2.8µm high micro tubes coated with a 110nm thick gold layer inserted in 7x7µm square pads. SEM image of the experimental vehicles is given in Figure 2.

As presented in figure 2, cross-sections of the micro-tube have been prepared using Focused Ion Beam (FIB) in order to study the initial micro tube structure. The hard frame of the micro tube is made of titanium and tungsten alloys. These images are used as geometrical input for the Finite Element Model (FEM) construction.

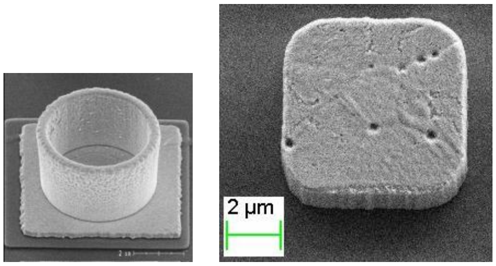

Fig. 2: 4µm diameter micro tube (left) and ductile pad (right)

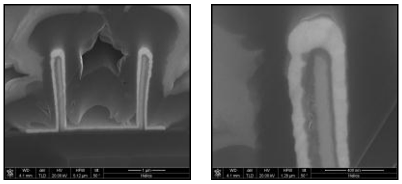

Fig. 3: SEM view of a micro tube cross section

The micro tube and pad are modeled as a 2D-axisymmetric problem using ANSYS software. The pad is therefore modeled as a cylinder with a 7µm diameter. Figure 4 illustrates the boundary conditions of the model: displacements are set to zero on revolution axis and at the bottom of the underneath substrate (red arrows). The model is driven by an applied displacement at the top end silicon substrate (black arrow).

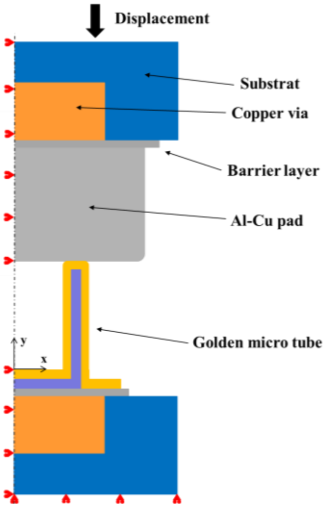

Fig. 4: Schematic axisymmetric model of the single micro tube insertion into an Al-Cu pad

The gold coating of the tube and the aluminum (Al-0.5Cu) ductile pad are modeled as elasto-plastic materials and described using multi linear laws. The mechanical properties such as the Young modulus (E), the yield strength (σ_y), the ultimate strength (σ_u), the ultimate strain (ε_u) and the Poisson ratio (υ) are given in table 1. Other materials are considered as purely elastic.

In order to take the friction into account, contact elements are used over the tube shape. They are responsible for transferring the mechanical load from one piece to the other. The friction coefficient of gold varies from 0.17 to 1.05 depending on the nature and surface roughness of the opposite material [2]. For this study (couple Gold/aluminum) a coefficient of 0.25 was used.

	E (GPa)	σ_y (MPa)	σ_u (MPa)	ε_u	υ
Au	90	300	825	0.08	0.45
Al-0.5Cu	64	110	350	0.6	0.35
Al2O3	150	Brittle material	1500		

Table 1: Mechanical properties of key materials [3-5]

The insertion of a 4µm (diameter) tube into a 7µm (diameter) pad is simulated. Figure 5 shows the element view of the model. The meshing is refined in the different regions of interest.

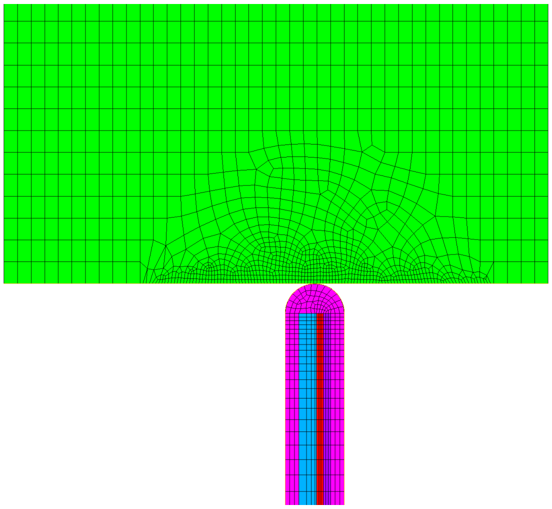

Fig. 5: Zoom at the interface tube/pad before insertion. Mesh view.

During the insertion phase, the mesh is constantly checked and rebuild if necessary in order to avoid high distortion of the element and to ensure calculation convergence. Figure 7 shows the mesh after an insertion of 0.6 µm. The comparison of Figure 5 and 6 helps understanding the mesh adaptation through the calculation process.

3. Aluminum native oxide breakage

A small layer of aluminum oxide appears naturally on top of the pad after fabrication. This Al2O3 brittle layer is 3 to 5 nm thin, non-conductive and may impede a good electrical contact. As shown in Table 1, its ultimate tensile strength approaches 1.5 GPa. If the layer undergoes a stress beyond this value, the oxide will break and the electrical contact may be formed.

Using the ultimate tensile strength (1.5 GPa) and Young's modulus (150 GPa) of the Al2O3 layer, one can deduce its ultimate strain (1%). If the layer undergoes a deformation greater than 1% it will break.

Let's assume that the very thin oxide layer undergoes the same deformation as the aluminum pad surface. In other terms, the deformation of the layer will be driven by the ductile aluminum material underneath.

The oxide layer is not modeled in the FE model but the strain at the surface of the aluminum pad may be easily observed. Figure 6 shows the strain in the pad after a 0.1µm insertion. The oxide starts breaking at the top cap of the gold coated tube. It helps to conclude that an insertion of 0.1µm is enough to break the oxide and may initiate the electrical contact.

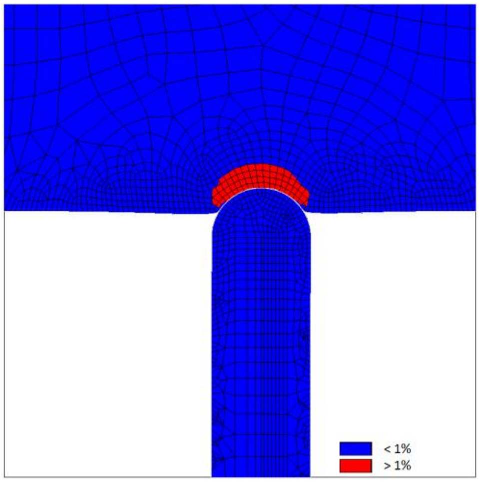

Fig. 6: View of the strain in the pad after a 0.1µm insertion

3. FEM simulation of a single micro-tube insertion

The model allows a full understanding of the mechanical behavior during insertion. Figure 7 gives a view of the stress mapping and material deformation at the interface after a 0.6µm insertion.

We observe a large deformation of the pad which justifies the use of remeshing cycles during the solving process. The highest stresses are found in the hard frame of the tube made of titanium and tungsten alloys which have a high Young's modulus and high ultimate strength. This hard frame can be seen as the mechanical structure of the tube, while the gold coating ensures a good electrical contact.

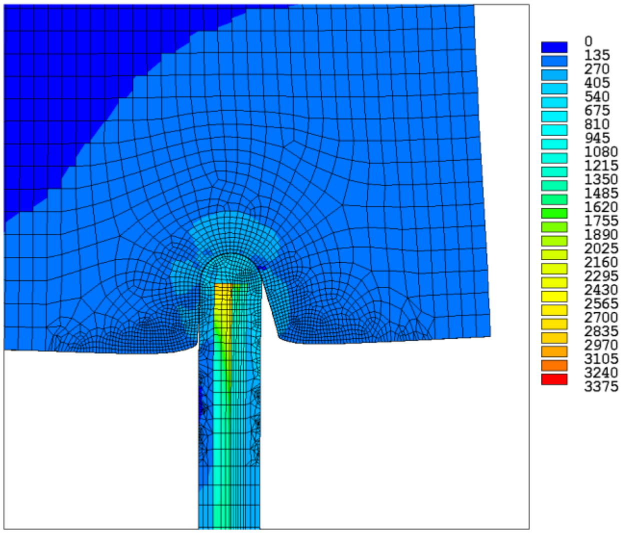

Fig. 7: View of the mesh and of the Von Mises stress map (in MPa) after an insertion of 0.6 µm

Figure 8 shows the relationship between insertion force and insertion depth. The stress of the bottom substrate has also been recorded. Using these results, it is possible to optimize the process parameter for the desired application: a high insertion force leads to a more reliable mechanical bond but induce a higher stress at the bottom substrate.

On the pad-side, the stress is released at the pad level by the deformation of the aluminum. It allows the substrate to be nearly stress-free and works as a stress buffer. At the actual state of the art, for the bonding of substrates with delicate technology, the pad should be fabricated on the fragile substrate; the tube will be built on the other substrate.

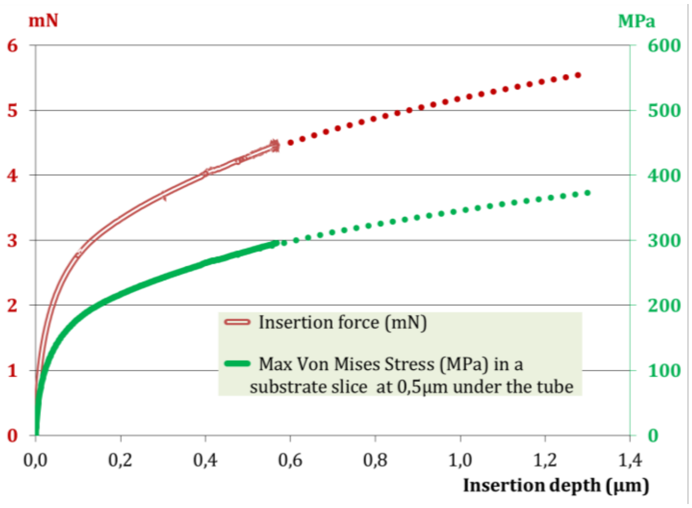

Fig. 8: FEM mechanical result for a single micro tube insertion. Dashed line is extrapolated.

4. Generalization for a full micro-tube array

The simulated results were used to conduct an experimental campaign. The process parameters needed for the D2W integration with chip having more than 100 000 interconnections were extrapolated from this single micro-tube study.

Figure 9 gives a view of a 200mm fully populated wafer with the FC300 flip-chip bonder from Smart Equipment Technology (SET SAS). The experimental setup, conditions and materials are described elsewhere [6].

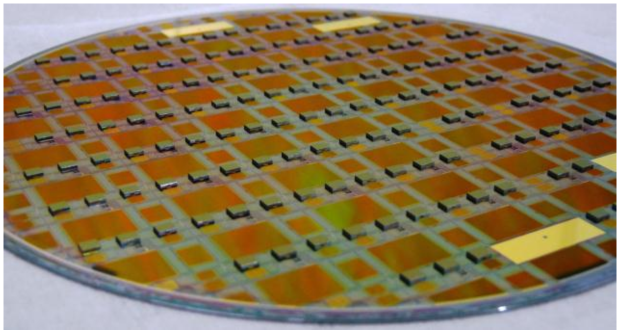

Fig. 9: 200mm fully populated wafer

The experiment output consists in electrical measurements as well as cross sections and SEM analysis.

Electrical measurement is run on automatic probing station for each stacked die. On each die, 9724 representative interconnections are tested out of the 100 000 connections. Collected data are analyzed to extract global yield and mean resistance value for each chip. The yield gives an image of well-connected interconnection. Yield greater than 99% indicates that electrical contact between tube and pad is formed in almost every case, which confirms that the native aluminum oxide of the pad is broken during the insertion process.

By adjusting the process parameters, it was possible to achieve a repeatable global yield of 100% coupled with an electrical resistance as low as 293mΩ. This value includes the resistance access. In other terms, a kelvin measurement of the resistance is expected to give lower values.

Qualitative assessment of the stacked dies is done using a non-focus ion beam cutter (Leica TIC-3X) followed by SEM inspection. Figure 10 shows a 50µm observation window with 4 interconnects. The homogeneity of the inserted shape from one interconnect to the other should be pointed out.

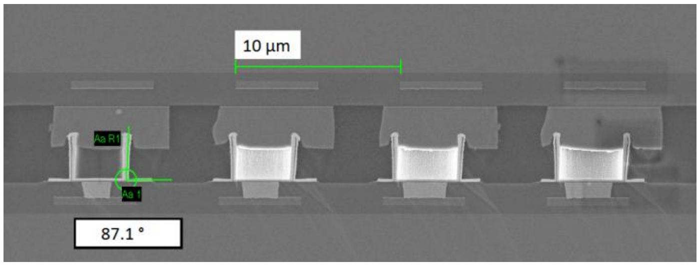

Fig. 10: SEM view of an interconnection row

Figure 11 shows a detailed view of an interface tube/pad. The chip has been assembled on the substrate with an insertion force of *5.4 mN/tube*. The observed insertion depth (almost 1µm) is a bit lower than the predicted insertion depth (1.2µm) of Figure 8 for this force. The difference may be explained by the geometry: the tube is not perfectly vertical as assumed in our model. A variation of almost 3° with the vertical line can be observed in Figure 10. The final shape of the pad is fairly similar to the one simulated on Figure 7.

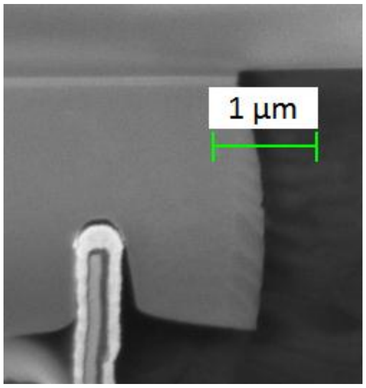

Fig. 11: Detailed SEM view of a tube inserted in a pad with a force of 5.4 mN/tube

Conclusions and outlook

Finite element simulation was conducted on a single micro-tube. It gave valuable insight on aluminum oxide breakage and insertion force. These results were generalized in a D2W setup to assemble chips with over 100 000 simultaneous electrical connections. The electrical measurement shows a yield of 100% and an electrical resistance as low as 293mΩ.

The simulation showed a high stress level in the substrate under the tube. Geometrical modification of the pad and tube shape may be investigated in order to lead to a lower substrate stress.

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