Power Module Ceramic Substrates: mechanical characterization and modeling

(support of TF2 in IPCEI)

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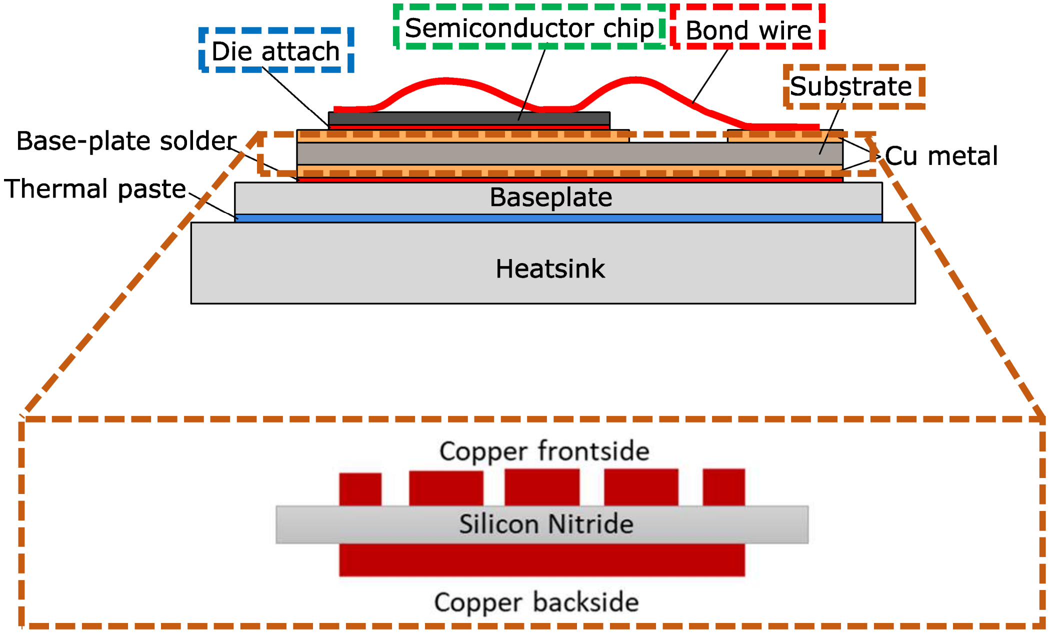
Introduction



Schematic of AMB substrate. Due to different topology between front and bottom copper layers, the temperature variation induces cyclic warpage in AMB

Developments in packaging and assembly technologies for power electronic systems are driven by:

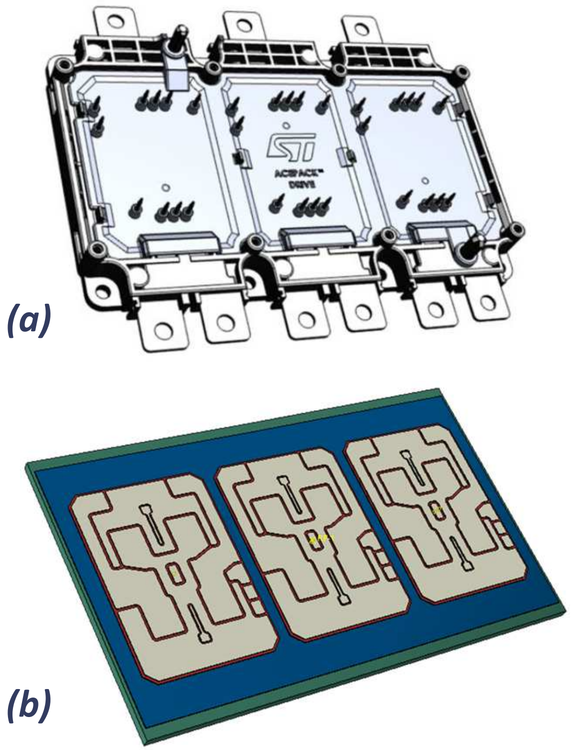
- The need for higher power densities
- Increased chip temperatures
- Longer life cycles.

The choice of insulating substrate and carrier material has also become one of the focus for the power module designers.

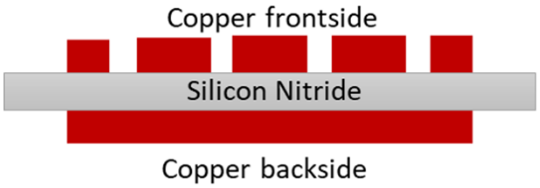
In the presented work

- a mixed experimental/numerical approach has been proposed to model and optimize the out of plane warpage of an AMB substrate.
- Cu and Ceramic Layers have been experimental characterized by means of tensile tests and nanoindentation techniques
- Finite Element Analysis has benchmarked the raw AMB and final assembly out of plane warpage experimental measurements done with interferometric technique by means of Moiré fringes.

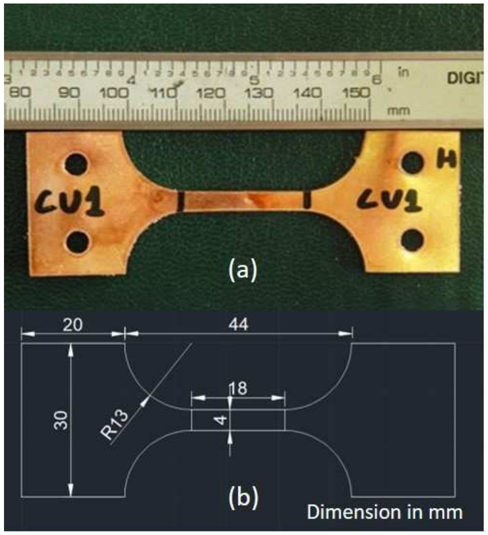
Sample Description



Acepack Drive module (a) and its baseplate with AMB substrates (b)



Active metal brazed substrate

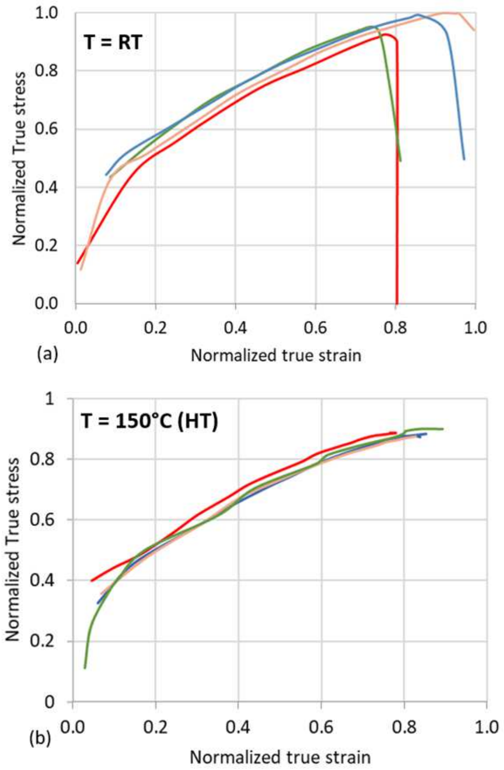


Copper dogbone sample for tensile test

- The AMB substrate is constituted by two Copper foils, brazed at high temperature (over 500 °C) together with a Si_3N_4 ceramic layer.
- The elastoplastic characterization of the copper layer has been performed on a copper flat dogbone samples.
- Cu sample thickness is 0.8 mm
- In addition to the single layer characterization, nanoindentation and warpage measurements have been performed on the assembled AMB.

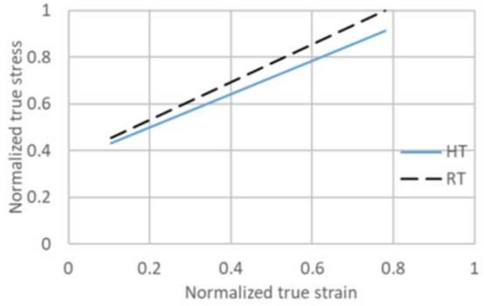
Mechanical Characterization: Tensile Tests

Tensile Test Equipment with climatic chamber



For each thermal condition, four identical samples have been tested in order to have a statistically relevance of the test itself.

- Tests done at different temperatures: reported data for room temperature (RT) and HT (150 ˚C).
- Stress and strain data from 10 kN uniaxial force equipment in displacement control, at a strain rate of 3E-3 1/s.



Copper plastic thermal softening

- Loads and length are then transformed in engineering and true strain/stress values by equations below:

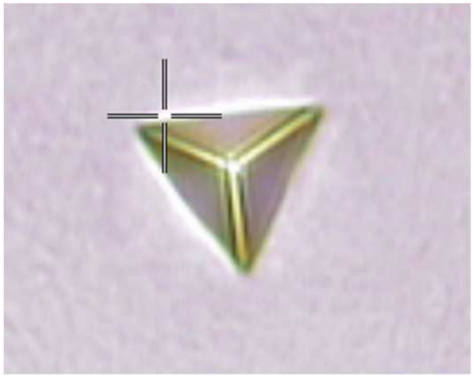
$$\varepsilon_{eng} = \frac{l(t) - l_0}{l_0}, \quad \varepsilon_{true} = log(1 + \varepsilon_{eng})$$

$$\sigma_{eng} = \frac{F(t)}{A_0}, \quad \sigma_{true} = \sigma_{eng}\,(1 + \varepsilon_{eng})$$

- Moderate thermal softening between RT and HT conditions occurs, in which the stress-strain curves at high temperature are slightly lower than those at room temp.

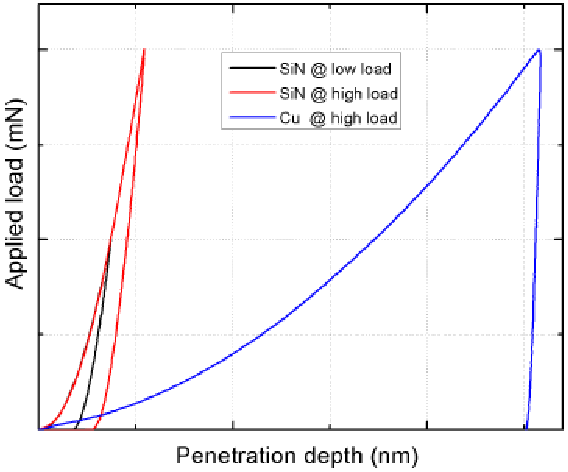
Mechanical Characterization: Nanoindentation

Nanoindenter equipment



Nanoindention imprint

- Nanoindentation has characterized the linear elastic properties, in terms of bi-axial Young modulus, of Si_3N_4 and Cu layers.
- Contact stiffness and elastic modulus have been evaluated according to Oliver and Pharr formulation.
- Silicon Nitride bi-axial modulus is much higher than Copper one (315 vs 153 GPa)
- Copper shows a large plastic permanent deformation, while the permanent strain is almost negligible for the silicon nitride layer.

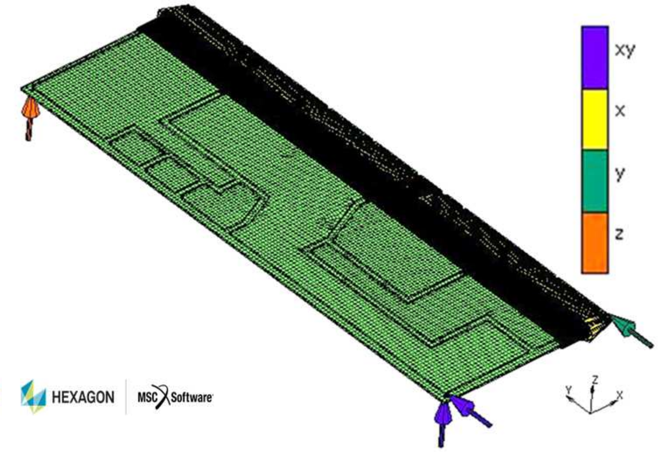


Indentation curves for copper and Si_3N_4 layers

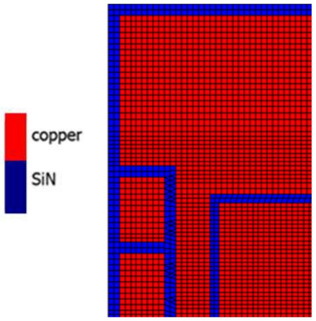
E_{IT} →

Si_3N_4 = 315 GPa
Cu = 153 GPa

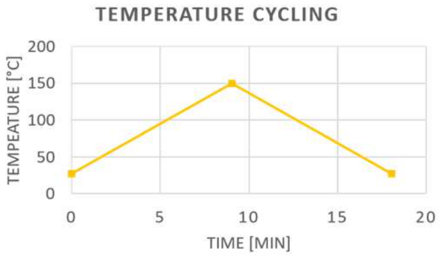
Finite Element Modeling



Boundary conditions for FE model and details on material and mesh



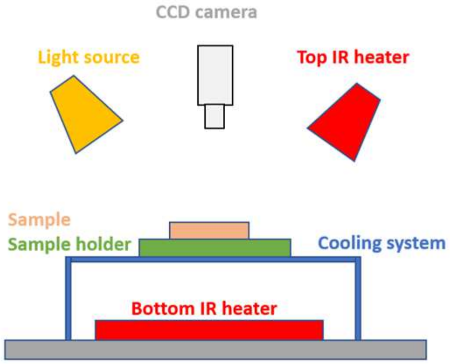
- A Finite Element Model has been developed to calculate AMB deformation due to thermal loads.
  - The experimentally characterized material properties have been accounted.
- Stress-free conditions reproducing the AMB Brazing Process and further stress release Cu etching is considered by merging parts of the model at 70 °C.
- AMB has been "virtually" cooled from stress-free temperature to room temperature to calculate the "as-received" substrate deformation.
- AMB warpage variation has been modelled according to the operating thermal cycle shown below. At the end, the soldering reflow process to the baseplate has been simulated to predict the overall system warpage.



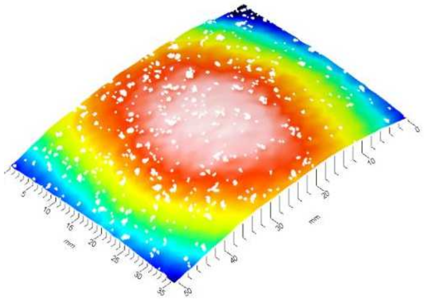
Operative temperature cycle considered in the model

Optical Measurement of Out of Plane

Equipment ("TDM Compact") used for warpage measurements

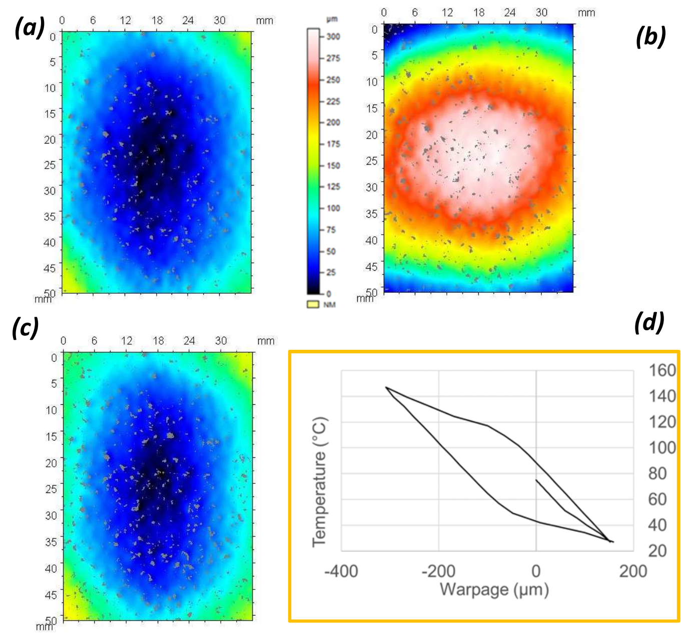


TDM schematic and example of 3D reconstruction

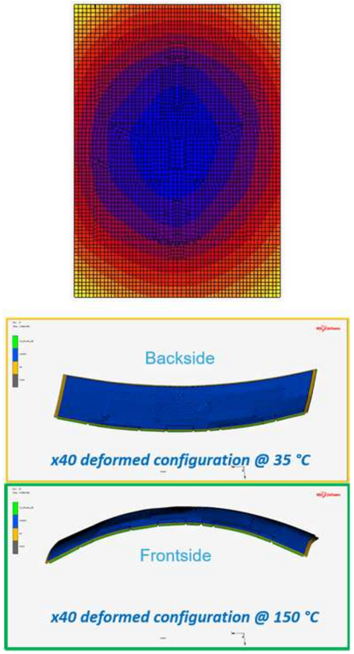


- The AMB substrate warpage has been measured at different temperature.
  - An equipment based on Moiré Phase Shift Method has been used.
- The method correlates the stripe pattern deformation with the sample surface structure, estimating the sample warpage.
- Equipment regulates temperature by the infrared heater and air cooler. Dedicated thermocouple continuously check the temperature.
- Temperature profile (maximum temperature 150 °C, heating and cooling rate 0.24 °C/s) are typically of the regulations for product assessment and qualification.

Benchmarking FE with experiments



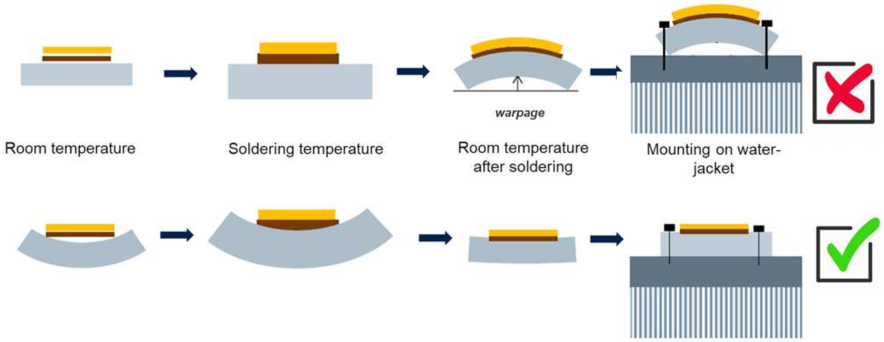
Measured warpage as different time of thermal cycle: (a) at RT, (b) at the maximum temperature of 150 °C and (c) at the end of cycle, again at RT. Calculated FE warpage at different temperature has been plotted in (d)



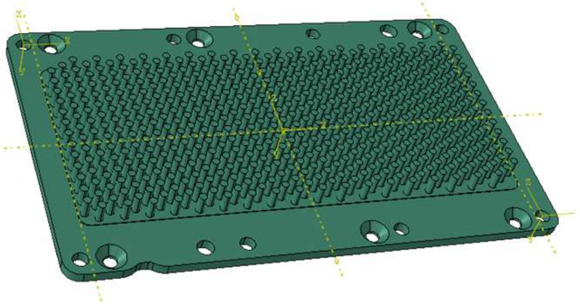
FE result: warpage map and deformation

- A benchmark between experiments and simulation has been performed on “as received” raw AMB, before to perform any temperature cycling.
- This analysis predicts the substrate warpage just by AMB layout design.
- A second benchmark has been performed considering warpage variation vs temperature on raw AMB.
- Due to the imposed stress free conditions, warpage increases at cooling down phase and changing curvature when heated over the initial stress free temperature.
- A residual substrate deformation is generated by the initial assembly process (brazing plus Cu etching).

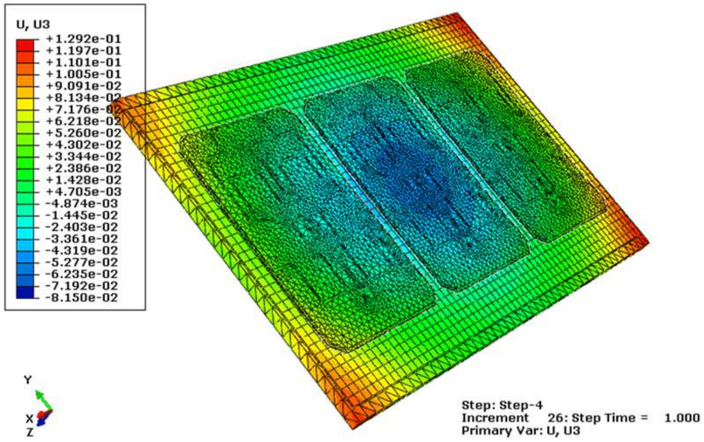
Impact of further process steps



Typical mismatch deformation between AMB substrate and baseplate after solder reflow, considering a flat baseplate (above) and pre-bowed one (below)



3D CAD of baseplate



FE results for baseplate/AMB after solder reflow

The optimization of baseplate/AMB system at reflow process is important to:

- Better hydraulic sealing capability
- To reduce solder thickness and spread
- Better thermal dissipation (R_{th})
- To improve reliability

This last simulation has helped to optimize solder reflow.

Conclusion

- ✓ Simulation method for evaluating the warpage of AMB substrate has been developed.
- ✓ An assessment has been done considering the raw AMB and AMB assembled by soldering reflow on baseplate.
- ✓ AMB materials have been characterized: Cu by means of tensile tests and ceramic layer by nanoindentation technique.
- ✓ Finite Element Model of the AMB has been validated by comparing the simulated results with experimental warpage measurements done by interferometric Moiré fringes shift technique. Good agreement between model and experiments has been found.
- ✓ According both to the numerical simulation and to experiments, in the considered AMB design, strain is mainly generated by the manufacturing process.
- ✓ The developed numerical model, which predicts the substrate warpage at time zero and during temperature cycling and it is capable to reproduce the assembly process itself of the AMB brazing on the baseplate, helps to improve the whole package reliability since design level.

“Acknowledgement”

This is one of **STMicroelectronics** initiatives to share our technology and innovations with various communities and foster microelectronics-related activities in the frame of the **Important Project of Common European Interest** (IPCEI)

IPCEI on Microelectronics