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Evaluation and thermal ageing of power semiconductor die attachment based on porous film electrodeposition

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Abstract

Driven by applications in the field of electric mobility, power electronics face the challenge of being able to operate at higher power densities. 3D packaged power modules appear as a promising solution, but are difficult to manufacture. Electrodeposited copper allows for flexibility in the module's design. This paper evaluates a die attachment method based on the thermocompression of electrodeposited porous copper films. A characterization study of this solution, including its behaviour after thermal ageing, is carried out.

1. Introduction

The trend in power electronics, and in the transportation field particularly, is the increase of power density. In this context, 3D power modules, where semiconductor dies are sandwiched between two substrates [1], appear as a promising technology. However, this technology faces several technological issues as the electric field management around the top faces of chips, and the quality of die attaches to increase the lifetime of power modules. Hence, technologies for connecting electrically and mechanically dies to substrates are still widely under development [2].

Concerning die attach materials, one efficient technology is silver sintering, as it provides a relatively low temperature process (200 - 250°C) and melts at a much higher temperature (961°C). This process shows excellent thermal, mechanical and electrical properties [3]. However, it presents several drawbacks as the cost of silver powders, the criticality of the material [4], and electromigration problems during operation [5]. For all these reasons, new die attachment methods based on the use of copper are becoming increasingly popular today, even if the oxidation of this metal during process and operation is a limitation to their development. The sintering of copper pastes is therefore under the focus of intense researches. Compared to sintered silver, sintered copper presents higher yield strength, lower plastic

strain, coefficient of thermal expansion closer to substrate's one, leading to a better thermal cycles reliability [6]. One important issue with paste sintering in double-side modules is that it requires very precise deposition to fit the different thicknesses between dies, interposers, and substrates [7]. To overcome that issue, another solution under development is the use of electrodeposited copper nanowires [8]. This bonding technique is very promising, but requires the use of a sacrificial membrane.

This paper proposes a preliminary evaluation of a novel attachment technique based on the thermocompression of porous electrodeposited copper. Fig. 1 shows an example of what could be achieved using an electro-chemical process: massive copper would firstly be deposited on a substrate. Then, by controlling the current density and the acidity of the chemical bath, a 100 µm thick layer of porous copper could be deposited on it by a method described later in the letter. This easily deformable porous deposit should allow for better manufacturability of double-side power modules, without the need of a sacrificial membrane.

The next section describes briefly the methodology. Then, various thermocompression parameters are tested and evaluated. Finally, thermal characterizations after thermal ageing are proposed and perspectives are highlighted.

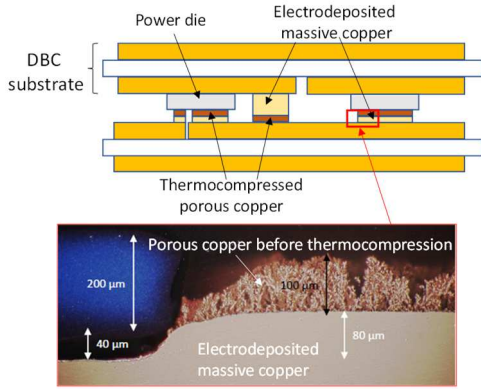


Fig. 1. Electrodeposition of massive and porous copper on a substrate.

2. Test samples and characterization tools

Specific samples are developed for the tests. Porous copper films are deposited on copper-metallized aluminum nitride (AlN) ceramic substrates ("DBC", for Direct Bonding Copper). The thicknesses of the different layers are 300 μm for copper and 1 mm for AlN. On each substrate, four diodes (ref. 5SLY 12E1200 – ABB – 6.3mm×6.3mm) are thermocompressed at the same time.

The electrochemical deposition is achieved using the DHBT technique [9]. Two electrodes are placed in an acid copper bath. By controlling the applied current density, it is possible to achieve a double reduction at the cathode, with both copper ions transforming into metallic copper and H⁺ ions forming into H₂ bubbles. In this way, copper is deposited around the hydrogen bubbles, as presented in Fig. 2, and the film porosity is formed once they have escaped.

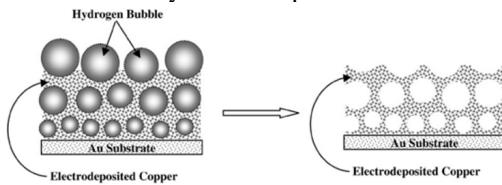
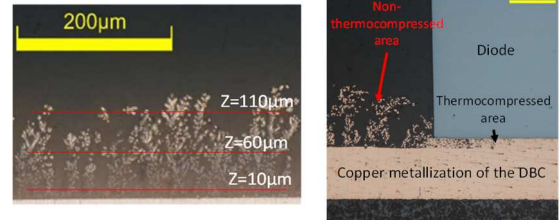


Fig. 2. DHBT principle [9].

For this work, the deposition conditions are: 300 A/dm² DC current, duration 30s. The microstructure of the film is inhomogeneous along its thickness as presented in Fig. 3. It can be seen in Fig. 3.a and Fig. 3.c that the pore size is the smallest close to the interface with the copper metallization of the DBC substrate. After the deposition, an oxidation layer is present on the films and removed in a reducing atmosphere (95% He, 5% H₂) at 500°C prior to the thermocompression step.

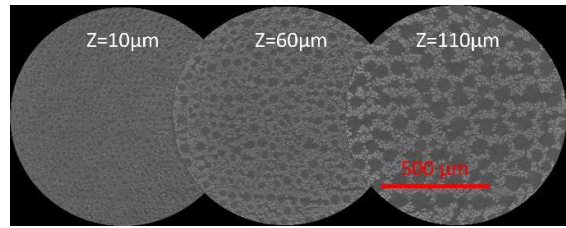
The thermocompression parameters are presented in Tab. 1. The process is described hereafter. A low load is first applied (10% of full pressure, provided in

Tab. 1) on the dies. The whole assembly is then heated in a dynamic vacuum to prevent oxidation, after purging with hydrogenated argon. Throughout the test, the pressure in the thermocompression machine is less than 10⁻¹ mbar. Then, when the required temperature has been reached and stabilized, full pressure is applied for the required time. Fig. 3.b shows a cross section of the assembly after thermocompression.



a. Porous copper film before thermocompression (cross section perpendicular to the substrate)

b. Diode assembled after thermocompression (cross section perpendicular to the substrate)



c. Tomography cross-sections of a film at different heights before thermocompression (cross sections parallel to the substrate)

Fig. 3. Electrodeposition of massive and porous copper on a substrate.

Table 1
Thermocompression parameters

Sample	Temperature (°C)	Duration (min)	Pressure (MPa)
A (ref.)	300	30	20
B	250	30	20
C	350	30	20
D	300	15	20
E	300	60	20
F	300	30	10
G	300	30	30

In order to analyze the quality of the physical contact between the substrates and the dies, Scanning Acoustic Microscopy (SAM) images of the four diodes are obtained. Then, to compare the different process parameters, the thermal characterization of the attachment between diodes and substrates is done by injecting a high current (80 A) into the diodes for a short time (15 ms) and measuring the resulting

junction temperature rise. This junction temperature is obtained by measuring the thermo-sensitive electrical parameter V_f (threshold voltage of the diode under low bias current). The test is carried out using the Phase 12B thermal analyser (Analysis Tech). The duration of the pulse was determined by the help of thermal simulations, which are not presented in this abstract. One sample prepared for thermal characterization is presented in Fig. 4.

Shear strength tests were carried out on three of the four diodes for each sample with a Royce 600 machine. The head tool was positioned 20 μm above the substrate surface and the displacement rate was fixed at 1mm/min.

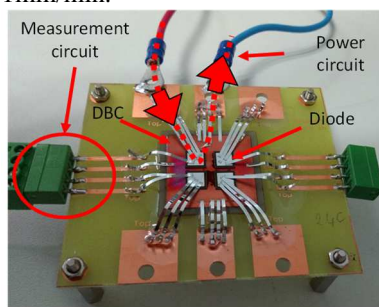


Fig. 4. Sample with 4 diodes before thermal characterization

3. Characterization results after fabrication

To analyze the effectiveness of the thermocompression step, Fig. 5 compares the SAM images of one assembly made with a porous film (sample A) and another made without film. A dark SAM image corresponds to a densified zone and a delamination is characterized by a clearer area. Concerning the sample without film (blank sample), the image analysis shows that at least 60% of the contact is delaminated. This demonstrates the interest of the porous copper film on the surfaces to create an acceptable physical contact.

The homogeneity of the thermocompression on each substrate is confirmed by the thermal test results shown in Fig. 6. Some disparities can be observed between diodes of the same sample, but the differences remain relatively low. The maximum shear strength is also given for each diode in this figure. Values higher than 25 MPa are obtained with the best thermocompression conditions (300 °C, 30 minutes, 30 MPa) which corresponds to the lowest thermal impedance value.

Fig. 6 is also useful to evaluate the main processing parameters. The influence of temperature can be observed with the results of samples A (300°C), B (250°C) and C (350°C). Logically, the thermal tests show a decrease of the average thermal

impedance, with a difference of less than 0.02 K/W. In opposite, the temperature has a great influence on the shear strength. However, at 350°C, the dies could be damaged during the process. Samples A (30 minutes), D (15 minutes) and E (60 minutes) are used to evaluate the impact of the thermocompression duration. The thermal tests do not give decisive results but the shear tests show a clear improvement even if the shear strength remains lower than 10 MPa with the chosen parameters. Finally, the influence of pressure is assessed with samples A (20 MPa), F (10 MPa) and G (30 MPa). As expected, the thermal and shear tests results are better when increasing this parameter. Differences higher than 0.02 K/W are observed in the thermal tests. The shear strength is highly dependent on this parameter with a best result close to 25 MPa in acceptable conditions for the dies.

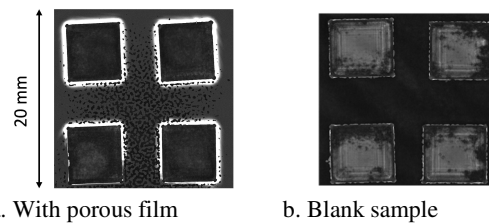


Fig. 5. SAM observations after thermocompression

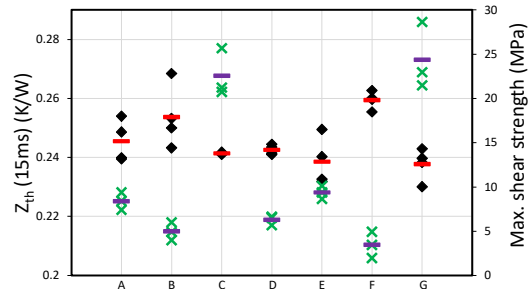


Fig. 6. Thermal and shear tests results – the thermal impedance for each diode is marked by a black square, the average value for each sample is given by a red line – the maximum shear strength is given by a green cross, the average value by a purple line

4. Characterization results after thermal ageing

Because the joint is made with copper, aging tests are necessary to evaluate the impact of oxidation during high temperature storage. Thus, new reference samples (sample A in Tab 1) were fabricated to carry out ageing tests.

In this abstract, the evolution of the thermal impedance of samples after thermal ageing tests at 200°C under air is presented in Fig. 7. In the complete paper, to give results closer to the application and analyze the effect of the atmosphere; thermal impedance measurements after thermal ageing tests

under dielectric gel will also be evaluated. Shear tests will also be proposed for the same conditions.

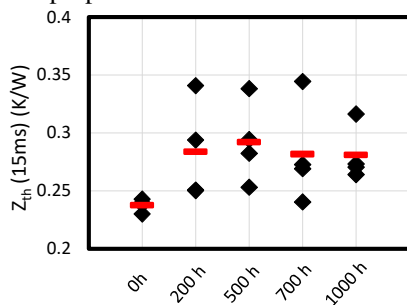


Fig. 7. Thermal tests results after thermal ageing at 200°C under air – the thermal impedance for each diode is marked by a black square, the average value for each sample is given by a red line

To obtain Fig. 7, five samples with 4 diodes were fabricated. The first sample was characterized after fabrication (0h in the figure), the second was characterized after 200h at 200°C, the third after 500h... For each sample, after thermal tests, one diode was used to make microstructural observations and the others were used for shear tests that will be presented in the complete paper.

Fig. 7 shows that a slight degradation is observed during the 200 first hours probably due to an oxidation, then the thermal behavior remains stable.

5. Conclusion

This paper shows that the combination of DHBT and thermocompression methods allows creating effective die attaches. On a thermal point of view, it is difficult to compare the results with literature because the thermal impedance depends a lot on substrate properties. However, the thermal impedance of the same assembly with an Au-Sn solder was evaluated (not presented in this letter) and a higher average thermal impedance (≈ 0.27 K/W) was obtained which demonstrates the good thermal behavior of this novel attachment technique. On a shear strength point of view, it seems to give acceptable results for power electronics but the attachment is less strong than the case of silver or copper paste sintering even with much higher processing temperatures, pressures and durations. It is probably due to larger “grain” sizes in the porous film compared to the ones in copper pastes.

The behavior of this attachment method after thermal ageing at 200°C under air was also evaluated. A slight thermal impedance increase is observed during the 200 first hours then it remains constant. Other results will be given in the complete paper: - thermal ageing tests under silicon gel to analyze the impact of the atmosphere, shear tests in every

condition.

In the future, many parameters must be tested to further improve the quality of the joint: process parameters during porous film deposition (current shape, chemical additives ...). In fact, these parameters have a non-negligible influence on the microstructure and therefore on film densification during thermocompression. Other thermocompression parameters (atmosphere, surface nature...) must also be studied.

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