Advanced wire bonding for high reliability and high temperature applications

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Abstract

The next generation of switches for power electronic will be based on white band gap (WBG) semiconductor GaN or SiC. This materials supports higher switching current and high frequency. White band gap semiconductors enables higher application temperature.

Certainly, high temperature capability is also to discuss in combination with high number of thermal cycles. For a frame module concept shows these paper a comparison of different joining techniques with the focus on the reliability issue on wire and ribbon bonding.

Beside to the 1000 passive thermal cycles from -40°C to +125°C there are active thermals cycles for technology qualification required [3]. Depending on the application and mission profile a high thermal cycling capability is necessary. For this reason, new high temperature joining techniques for die attach, e.g. Silver sintering or diffusion soldering, were developed in the recent past [4]. All of this new joining techniques focusing on higher electrical, thermal and thermo-mechanical performance of power modules.

By using an optimized metallization system for the WBG the numbers of thermal cycles can be increased and the maximum operating temperature advanced up to 300°C. In these new temperature regions silicon semiconductors will be substituted by WBG semiconductors.

The present work shows an active power cycling capability of different wire and ribbon bonds and the failure mechanism will be discussed. A calculation model explained the reliability for the different wire diameter and the impact of bonding materials. This reliability calculation explain the thermo-mechanical effects and based on materials and geometry data and is not optimized for evidence. Through these physical background understanding more than 1.000.000 thermal cycles with a 150 K temperature swing from +30°C to +180°C are now possible. These is a the basic knowledge for a design for reliability based on current, mission profile and reliability optimization for future high end applications with wire or ribbon bonding technique.

Key words

Active power cycling, high temperature joining, reliability, ribbon bonding, WBG, wire bonding

I. Introduction

An issue for power electronics is the thermal cycling reliability in general. For a better thermal cycling capability different joining techniques were developed in the last years. Driven by the EU legislation, the RoHS [1], it is also necessary to substitute lead in electronic products. This paper shows for frame based power module concepts a comparisons of different joining techniques and the corresponding thermal cycling performance (figure 1).

Assembling and interconnection techniques (AIT) with higher robustness are useable for silicon semiconductors and with band gap semiconductors (WBG). The biggest differences between Si, SiC and GaN are the lateral/vertical device structures and maximal operating temperature $T_{junction}$.

WBG semiconductor shows a possibility for higher application temperature. This supports higher switching current and reduces the cost for cooling. Certainly, high temperature capability is to discuss in combination with high number of thermal cycles. Therefore for automotive applications thermal cycling is specified in LV124 [2] (classical Electronics Control Units) and LV324 [3] (Power Electronics Modules). Beside to the 1000 passive thermal cycles from -40°C to +125°C there are active thermals cycles required. Depending on the application and mission profile a higher thermal cycling capability is necessary. For this reason, new high temperature joining techniques for the die attach, e.g. Silver sintering or diffusion soldering and for the top contact were developed in the recent past [4]. All of this new joining techniques focus on higher electrical, thermal and thermo-mechanical performance of power modules.

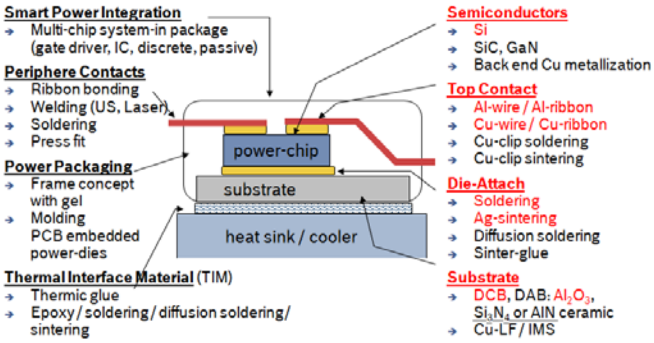

Fig. 1. Design elements for power modules, test read version

II. Experimental Setup and Test Results

The evaluated technology kit based on frame modules concept. As a rough guess the thermo-mechanical performance rises with a higher remelting temperature of the joining techniques. For fitting our simulation tools a technology comparison with different test modules was build up. Si bare die was mounted on DBC (direct bonded copper on ceramics) and with ultrasonic ribbon and wire bonded. For better failure analysing has been omitted a casting or potting. The modules were tested by active thermal cycling afterwards. The selected test procedure by these power cycling focused on a homogeneous through heating during the test. The temperature swung between +30°C and +180°C with a dwell time of 2 seconds (2 seconds on / 2 seconds off) with our 100 Amp and 1000 Amp power cycling tester (Fig. 2).

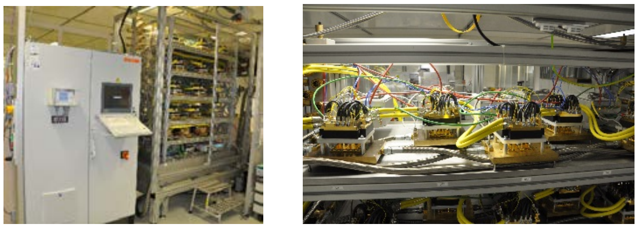

Fig. 1. 1000 Amps power cycling test equipment (left) an device under tests DUT (right)

Samples:

A standard electronic joining technique is soldering with tin based lead free alloys, e.g. SAC (eutectic Tin- Silver-Copper alloy). An overview is shown in figure 1. The weakest point at thermal cycling is the die attach with SAC. Therefore the solder material PbSn5 got till now an exception rule by the RoHS for power electronic applications. All solder materials shows disruptive fault in itself and consecutive fault by the Al-wire- or Al-ribbon-bond lift-off. Replacing the solder material by a high temperature joining technique the failure shifts from the die attach to the Al-based top contact. Therefore a lot of research activities focus on a high temperature capability in combination with a high robustness of the die attach during the thermal cycle. Typical joining materials for high temperature die attaches are silver ore diffusion solder materials based on intermetallic compounds, e.g. Cu_6Sn_5. This high temperature materials stabilized the die attach and the location of the failure shift to top contact (Fig. 3). For these reason it is necessary to strengthen the top contact for further robustness improvement.

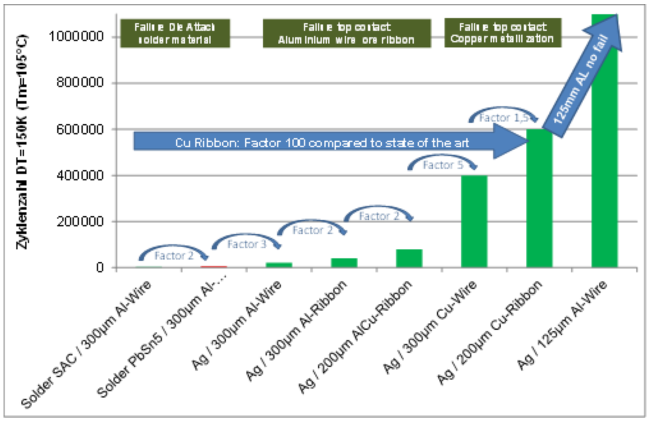

Fig. 3. Power cycling results of different die attach and wire bonding joining techniques (no gel)

One possibility for higher reliability of the top contact is the geometrical optimization or the change to a new material classes with higher melting temperature or/and higher

Young`s modules. Figure 3 shows the performance improvement by the change from 300µm Al wire bond to Al ribbon bond. The next step is the use of Al-Cu sandwich materials with positive impact of the cycling capability. Till this point, standard aluminium backend metallization on dies can be used. The next step to increase the cycling performance is the substitution of the aluminium bonding material by a material with higher Young´s modulus, e.g. copper. In the case of using copper wire or copper ribbon bonds an extreme increased reliability can be shown up (Fig 3.) A high performed Silver sintered die-attach and copper ribbon bonded test samples is shown in Fig. 4. The disadvantage for Copper bonding on active structure is the need of thick Copper backend metallization on the bare die.

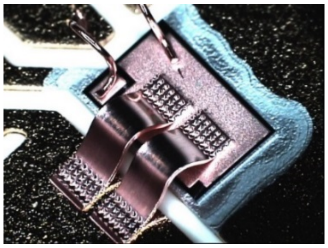

Fig. 4. Silver sintered die attach with Copper ribbon bond [6]

The process technique of Copper backend metallization on SiC, GaN ore Si is a huge challenge and till now it is not automotive specificity. Therefore we used for our tests non-optimized semiconductors with a post Copper metallization on standard Aluminium backend. By this new setting we are able to design a new weak point under extremely increased thermal cycle reliability, namely the interface between the Al-metallization and the post Cu-metallization. Therefor the copper bonded samples failed between aluminium backend and copper metallization.

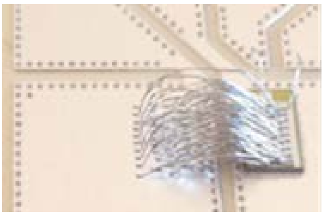

Fig. 5. Silver sintered die attach with 125µm aluminium multi wire bonds [6]

The shift to 125µm Al wire bonds shows increasing of endurance of thermal cycling capability. There was no more lift of to detect. The disadvantage of 125µm Al wire are the low ampacity of a single wire. Driven by the low ampacity the multi wire bond samples was developed and used for first reliability and electrical test. Figure 5 shows the test sample with a silver sintered die in combination with multi wire bonds.

III. Discussion and Modeling of Reliability

For green electronic (power electronic) applications the main task of a bond is to conduct current. For this reason, low-resistance materials and large size geometries are used. Figure 6 gives an overview of tolerable currents in single 6mm bond length.

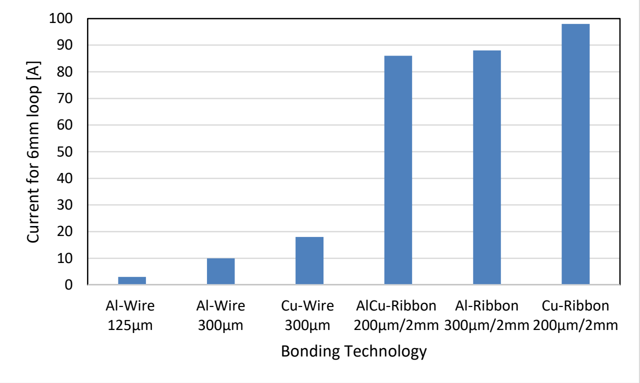

Fig. 6. Current comparison of typical wire and ribbon bonds for 6 mm loop length

Unfortunately, caused by bigger wire diameters a higher stress impact comes into the joined system. These reduced the lifetime of the bond. The comparison between current and thermal cycling capability is shown in figure 7. The main optimization is current versus thermal cycling capability (TC). The multi wire concept with 50 x 125µm aluminium wire is a perfect combination between reliability and available current built on available aluminium backend.

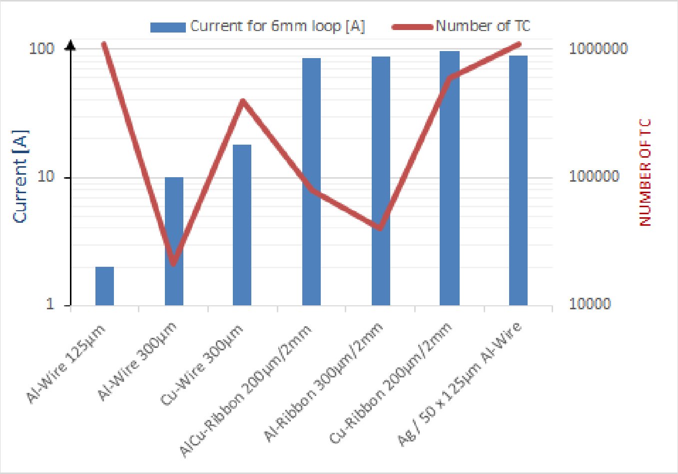

Fig. 7. Comparison of current and thermal cycling capability for different bond technologies

The industrialisation for mass production of the multi wire concept will be the next challenge on the equipment manufactures. Till now the optimization between current and reliability are not finished.

For a better understanding of the test results analytical and numerical calculation started. To model the lifetime prediction pre calculation started with analytic models based on elastic properties.

Especially the differences in the Young´s Modules, aspect ratio and geometry shows a strong influence in the shift between first principal and von Mises stresses. These FEM is the basis for calculation reliability for fitting the lifetime prediction of bonds.

Based on our first simulation results we focused on reducing the complexity and tried to use only mechanical explanations. Therefore we decided to use only elastically stress propagations for the calculation. All plastically effect, e.g. creep, was faded out for these analytical calculation.

A. Calculation

The typical creak propagation is in the bond foot near o the heat effected zone between 2 and 20µm into the bond material. For theses typically creak propagations the main stress impact are shear (1) and peeling (2) stress [8]. According to the work of Wang et al. [8] the bending and shear stresses are functions of the resulting bending moment due to heating, CTE mismatch and the geometry of the electronic assembly (Fig 8). The maximum shear stress results at the free edge of the bond layer an can be written as,

$$\tau_{\max} = \frac{E_a}{2(1+\nu_a)h_a\lambda} \cdot \left[(1+\nu_1)\alpha_1 - (1+\nu_2)\alpha_2\right] \cdot \Delta T \qquad (1)$$

where λ is defined as follows,

$$\lambda = 2\sqrt{\frac{E_a}{2(1+\nu_a)h_a}\left(\frac{1}{E_1h_1} + \frac{1}{E_2h_2}\right)} \qquad (2)$$

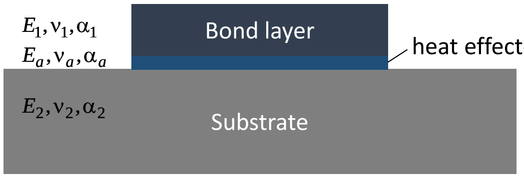

Fig. 8. Schematic representation of a bonded electronic assembly as a multi-layer for calculation

The maximum peeling stresses results also at the free edge of the bond layer and can be obtained from,

$$\sigma_{\max} = \left(1 - \frac{\lambda^2}{2\chi^2} - \frac{2\chi}{\lambda}\right)\beta \frac{E_a}{2(1+\nu_a)h_a\lambda} \cdot \left[(1+\nu_1)\alpha_1 - (1+\nu_2)\alpha_2\right] \cdot \Delta T \qquad (3)$$

where χ and β are given by,

$$\chi = \left[3\frac{E_a}{h_a}\left(\frac{1}{E_1{h_1}^3} + \frac{1}{E_2{h_2}^3}\right)\right]^{1/4} \qquad (4)$$

$$\beta = \frac{2(1+\nu_a)h_a}{E_a}\lambda \cdot \left(\frac{1}{E_1{h_1}^2} - \frac{1}{E_2{h_2}^2}\right) \cdot \left[4(1-\nu_a) \cdot \left(\frac{1}{E_1h_1} + \frac{1}{E_2h_2}\right)^2 + 12\left(\frac{1}{E_1{h_1}^3} + \frac{1}{E_2{h_2}^3}\right)\frac{(1+\nu_a)h_a}{E_a}\right]^{-1} \qquad (5)$$

Once the maximum shear and the peeling stresses are obtained, the maximum equivalent von Mises stress can be written as

$$\sigma_{eq,\max} = \sqrt{{\sigma_{\max}}^2 + 3{\tau_{\max}}^2} \qquad (6)$$

With the given shear and peeling stresses in (1) and (3) the equivalent maximum stress can be obtained as

$$\sigma_{eq,\max} = \frac{E_a}{2(1+\nu_a)h_a\lambda} \cdot \left[(1+\nu_1)\alpha_1 - (1+\nu_2)\alpha_2\right] \cdot \Delta T \cdot \sqrt{\left(\left(1 - \frac{\lambda^2}{2\chi^2} - \frac{2\chi}{\lambda}\right)\beta\right)^2 + 3} \qquad (7)$$

where λ, χ and β are respectively given in (2), (4) and (5). With formula (7) and the material properties for the different layers in table 1, we can now predict the resulting stresses due to the power cycling of some of die attach and wire bonding joining techniques that are shown in Fig. 3.

Table 1: Material parameters and thicknesses of different bonded electronic assemblies

Layer	Al/Cu bond	interface	Si substrate
Young’s modulus (GPa)	71/110	70/100	165
Poisson’s ratio	0.34/0.31	0.33	0.3
CTE (10^{-6}/k)	24/17	-	6.5
Thickness (mm)	acc. to Fig. 8	0.02	2

In high-cycle fatigue needs more than 10.000 cycles. In these situations the performance of materials is commonly characterized by an S-N curve. This is material depending the magnitude of a cyclic stress (*S*) against the logarithmic scale of cycles to failure (N). Therefore, the calculated equivalent stresses before (formula 7) can be related to the lifetime or number of temperature cycles (*TC*) to failure by using a power low assumption as following equation

$$TC = c \cdot \sigma_{eq}^{-n} \tag{14}$$

where c and n are Woehler like material dependent fit parameter and are obtained using a given set of time to failure data. For aluminum and cooper bonds the resulting c and n are shown in table 2.

Table 2: Parameter of the time to failure power law for different bond materials

Bond material	c	n
Al	10^{27}	9.8
Cu	$2.3\cdot10^{22}$	7.2

Figure 3 shows the calculated number of temperature cycles for aluminum and copper wires and ribbons. The tendencies of the predicted and experimental numbers of temperature cycles to failure (*TC*) are qualitatively in good agreement. For the both investigated materials, a decreasing of the thickness of bond material or the amount of temperature change leads to an increase of the predicted lifetime similar to the experimental results.

In comparison with copper, the usage of aluminum bonds in electronic assemblies is clearly disadvantageous regarding the lifetime performance. However in series production, the aluminum bond process has cost advantage because of the higher deformability of aluminum and therefore the lower needed ultrasonic bond energies. Less ultrasonic energies reduced chip cracks and prevent cratering.

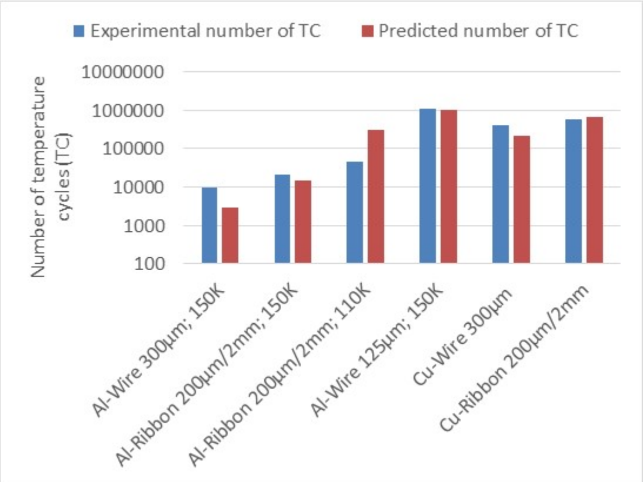

Fig 9. Experimental and predicted numbers of temperature cycles to failure of different bonded electronic assemblies

III. Conclusion

These paper shows are comparison of different joining techniques for frame module concepts with the focus on the reliability issue. New assembling and joining techniques could depict a high reliable module. The present work shows an active power cycling capability of more than 600.000 thermal cycles with a temperature swing from +30°C to +180°C. By using an optimized backend the numbers of thermal cycles can be increased and/or the maximum operating temperature can be advanced up to 300°C. For these new temperature regions it will be necessary to use WBG semiconductors with high reliable backend. The new calculation model can explain the geometry and the material impact and it is helpful for geometry and material optimization.

Acknowledgment

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