New assembly and interconnects beyond sintering methods

Karsten Guth[1], Dirk Siepe[1], Jens Görlich[1], Holger Torwesten[2], Roman Roth[2],
Frank Hille[3], Frank Umbach[3]

[1] Infineon Technologies AG, Max-Planck-Straße 5, 59581 Warstein, Germany
[2] Infineon Technologies Austria AG, Siemensstraße 2, 9500 Villach, Austria
[3] Infineon Technologies AG, Am Campeon 1-12, 85579 Neubiberg, Germany

Abstract

Today, with IGBT power modules a point has been reached where the operation area and life-time is limited by the standard packaging technologies, such as wire bonding and soft soldering. As a result, a further optimisation of the used technologies will not be sufficient to meet the future requirements of automotive industry and high reliability applications, such as wind energy or commercial vehicles. To surpass these limits an integrated technology package has been developed, that improves all life-time limiting areas (chip front side, chip back side, DCB-baseplate interconnect) within the IGBT module. In this paper power cycling results for this new technology package are presented. They clearly outperform today's limits by more than a factor of ten.

1. Introduction

After many years of pushing the limits of IGBT modules by optimising chip- and packaging technologies, we have now come to a limit, where a further improvement of the module's reliability is blocked by several reasons:

a) Chip front side connection

The lifetime of today's aluminium (Al) bond wire interconnects is not limited by the bond interface anymore but by the wire material itself.

In the event of failure, a crack, which is formed near the chip-to-wire interface, is propagating solely through the bond wire material. Thus, the key influencing parameter of this interconnect is not the set of bond parameters, but the choice of material. As a result, the power cycling reliability of Al bond wires for power module applications is basically limited to the well known reliability diagram. Here, expanding the operation area towards an increased temperature swing leads to a significant drop of lifetime.

b) Chip-to-substrate joint

Since the application demands for an increase in power density, a clear trend for higher junction temperatures towards 175°C or even 200°C can be seen. This increase in the junction temperature apparently contradicts the use of standard Sn based soft solders with melting points near 220°C. Operating such a soft solder joint at a homologous temperature $T_{hom}>0.9$ (where T_{op}/T_{melt} is defined as the homologous temperature T_{hom}) will lead to an immediate failure of the joint under thermo-mechanical loading.

c) Substrate-to-baseplate joint

While for short power cycle times (t<3sec) and temperature swings $dT_j<100K$ the module's lifetime is limited by the bond wire interconnect and the chip solder joint, for $dT_j>100K$ and long cycles (t>10sec) the substrate joint becomes the limiting factor for the power cycling reliability.
However, in some applications the use of baseplate modules is still of significant advantage for the thermal management of IGBT modules.
As a result, in order to improve the overall lifetime of the module, for this application area it is essential to provide an improved joining technology for the substrate-to-baseplate interconnect.

All these considerations clearly show, that to open the door for next generation IGBT modules with real operation temperature $T_{j,op}\geq175°C$, today we have the urgent need for an integrated technology package, that solves the problems at all three interconnection layers. And thus, extending today's power cycling reliability to an increased temperature swing of 130K and a maximum operation temperature $T_{j,op}\geq175°C$ [1-3].

2. The new technology package

2.1. Copper wire bonding

After several cycles of optimizing the Al bond interconnect, today it is generally accepted, that the failure of the joint does not happen at the chip-to-wire interface, but within the wire itself. Besides, it is common knowledge that the bond degradation is significantly accelerated by fatigue of the subjacent solder layers (e.g. chip-to-substrate). As a result, two main factors for the improvement of the power cycling reliability of bond wire interconnects have been identified.

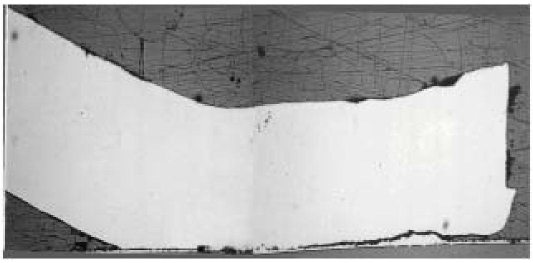

Fig. 1: Cross section through an Al bond wire after power cycling. Here, a crack propagates near the interface through the Al wire matrix.

First, an improvement of the quality of the chip-to-substrate joint will have direct impact on the lifetime of the above lying wire bond. Increasing the lifetime of the chip-to-substrate joint will reduce the increase in junction temperature that triggers the bond wire degradation. As a second, the bond wire material itself offers a high potential for reliability improvement.

Analyzing the failure mode for Al bond wire interconnects in detail, the initial crack always forms near the semiconductor interface. During power cycling this crack propagates within the Al matrix along the Al-Al grain boundaries (Fig. 1). It is common knowledge that the combination of a large mismatch in CTE (coefficient of thermal expansion) between Si and Al as well as low yield strength of the latter is the driving force for this crack propagation. With these considerations in mind, copper (Cu) seems to be a very good candidate as a replacement material for Al for wedge bonding (compare Tab. 1) [4].

In addition to its superior mechanical properties, Cu also offers a much higher electrical and thermal conductivity compared to Al (Tab. 1). This higher conductivity can directly be converted into higher current densities for IGBT modules.

Until now, the main obstacle for ultrasonic Cu bonding of heavy wires has been the mismatch between the mechanical properties of Cu and the semiconductor's topside metallisation. For an Al topside metallisation the Cu wire simply sinks into the soft Al metal, leading to chip damage and weak bond interfaces. Consequently a new metallisation stack with Cu as the final front side metal has been developed.

	Copper	Aluminium
electrical resistivity	1.7µOhm.cm	2.7µOhm.cm
thermal conductivity	400W/m.K	220W/m.K
CTE	16.5ppm	25ppm
yield strength	140MPa	29MPa
elastic modulus	110-140GPa	50GPa
melting point	1083°C	660°C

Tab. 1: Comparison of material properties

In a productive environment, with this new metallisation stack a high level shearing strength can be obtained for 400µm Cu wedge bonds. Here, all production performance indicators are comparable to Al wire bonding, offering a new bonding process for mass production that meets the requirements of a 200°C application (Fig. 2).

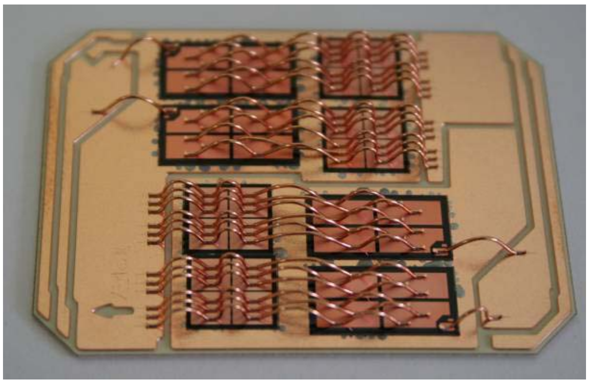

Fig. 2: Ceramic substrate with 400µm Cu wire bonds on Cu metallised IGBTs.

2.2. Diffusion soldering

As has been pointed out before, the improvement of the chip-to-substrate joint, will not only push the limits for solder fatigue but also has direct impact on the lifetime of the wire bond interconnects.

In order to overcome the limits given by the low melting point of standard tin based soft solders, new materials or alloys have to be considered. Obviously one popular alternative to soldering is the low temperature silver sintering being a benchmark concerning power cycling reliability. Nevertheless high material costs, non-compatibility with today’s soldering technologies and extreme process parameters (high pressures and long times) impede the rollout of this technology [5-6].

The compatibility of a new joining technology with today's soft soldering methods for semiconductors will be a major advantage for the technology rollout into existing power module families.

Based on these considerations a diffusion soldering process for power semiconductors to form a high melting bond between chip and substrate [7-8] has been developed.

Depending on the choice of chip metallisation and the soft solder material in standard soldering usually Cu-Sn or Ni-Sn intermetallics are formed as thin interfacial layers. All these intermetallic compounds have a much higher melting point than the Sn-based soft solders. For example, depending on the process parameters in the Cu-Sn system either Cu_3Sn with T_m=676°C or Cu_6Sn_5 with T_m=415°C is formed during the soldering process.

In diffusion soldering this solidification process is exploited to create pure intermetallic joints with a remelting temperature T_m>400°C from Sn-Ag solder.

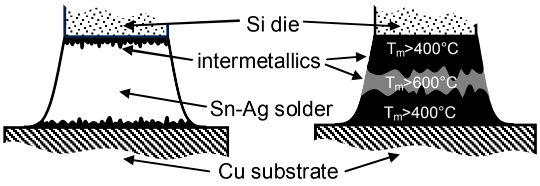

Fig. 3: Schematic comparison of a standard solder joint (left) and a diffusion soldered joint (right). The diffusion soldered joint consists of two different intermetallic phases. Figure is not to scale.

Fig. 3 shows a schematic comparison between a standard and a diffusion soldered joint. While both joints are formed from a Sn-rich solder, in the standard joint only a fraction of the Sn is transferred into a high melting intermetallic. By contrast, in the diffusion soldered joint, the whole volume of low melting solder is consumed by the solidification process. The result is a high melting bond between chip and substrate. Depending on the ratio between the two different intermetallic phases, that are formed in the Cu-Sn system, the homologous temperature for these joints ranges from T_{hom}=0,52-0,65.

Up to now, the phase formation rate has been the main obstacle to develop a productive diffusion soldering process for power semiconductors. Optimised process parameters yield a controlled solidification of the joint within seconds. The complete conversion of the solder into high melting intermetallics can be ensured by the parallelisation of process steps.

By these means a high melting chip-to-substrate bond (T_m>400°C) with joint thickness d≤10µm has been realised (Fig. 4).

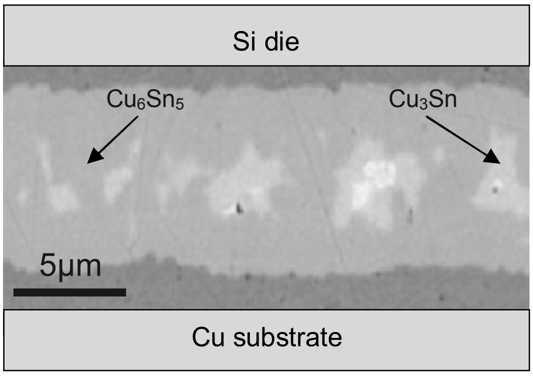

Fig. 4: Cross section of a diffusion soldered sample.

During technology development, this new diffusions soldering technique has been transferred to a fast pick and place process, realising high throughput and a high degree of automation.

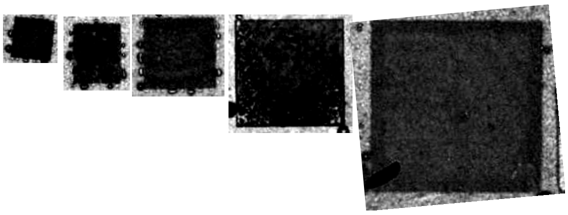

Fig. 5: Acoustic imaging of diffusion soldered joints using a 50MHz sonotrode. Chip areas range from 16 – 185mm².

With this equipment semiconductor dies with thickness ranging from 70µm to 600µm and chip areas between $16mm^2$ and $185mm^2$ have been bonded void-free on Cu metallised ceramics realising a new standard in power cycling reliability (Fig. 5).

2.3. High reliability system soldering

For baseplate free modules Cu wire bonding in combination with diffusion soldering is the technology package to set a new benchmark in power cycling reliability. Nevertheless, today the thermal management of some applications still benefits from the use of baseplates. This is why an integrated technology package also has to include the substrate-to-baseplate joint.

Analysing the crack propagation in different substrate-to-baseplate solder joints, it has been found, that the introduction of macroscopic precipitations into the solder matrix has a positive effect on the crack propagation rate.

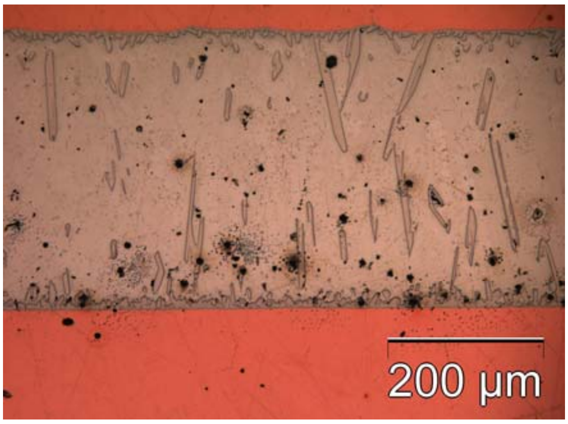

Fig. 6: Cross section of a solder joint with intermetallic crystallites as precipitations.

By an optimisation of the soldering process it is possible to control the formation of Cu-Sn precipitations within a standard SnAg solder matrix (Fig. 6).

	Elastic modulus [GPa]
$SnAg_{3.5}$ solder	51
Cu_3Sn	135
Cu_6Sn_5	117

Tab. 2: Mean values of elastic modulus of different materials.

As can be seen in Tab. 2 the elastic modulus for Cu-Sn intermetallics is much higher than for $SnAg_{3.5}$ solder. Thus, a crack that is formed during solder fatigue either has to break or to circumvent the precipitations. As a result, a much higher activation energy for crack propagation in solder joints with a high degree of precipitations compared to precipitation free joints is needed.

Also for other solder alloys our study revealed a high tendency for precipitation formation.

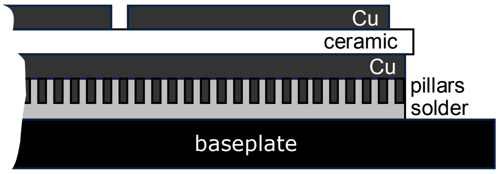

Fig. 7: Artificial pillars in a solder joint acting as pinning sites for propagating cracks.

Furthermore Cu particles, grid structures or pillars that are artificially introduced into the solder joint also act as pinning sited for the crack propagation (Fig. 7).

3. Results

3.1. Active power cycling

To simulate the real application, active power cycling tests are most commonly used in the qualification procedure for power modules. In this test, the semiconductor is periodically heated by current creating a thermal load on the chip and all interconnects.

Depending on the choice of test parameters, for short power cycles with t_{on}<3sec the thermo-mechanical load is located at the top of the test structure, stressing the bond interconnects and the chip-to-substrate joint. By contrast, for long power cycles (t_{on}>10sec) the dissipated heat spreads over the entire system. This leads to a massive increase in thermo-mechanical load at the substrate-to-baseplate joint compared to short cycle times.

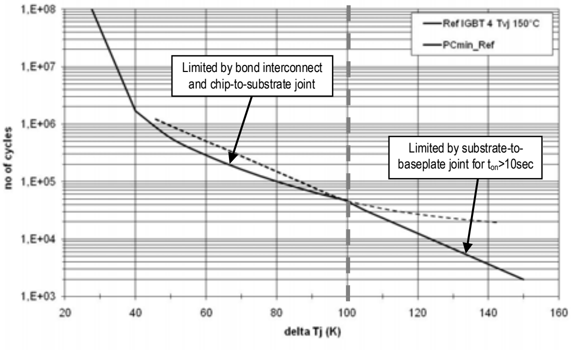

Fig. 8: Power cycling diagram with two different regimes of failure. At dT<100K wire bond and chip joint are limiting, while for dT>100K and t_{on}>10sec the substrate joint limits the lifetime. The dashed lines indicate the lifetime of the non limiting technologies.

Combining these observations into one reliability diagram, the module's lifetime is usually limited by bond wire and chip joint failure at temperature swings dT_j<100K. Above dT_j=100K and t_{on}>10sec modules with baseplate typically fail due to solder fatigue at the substrate-to-baseplate solder joint (Fig. 8).

a) Short cycle times (PC_{sec})

In order to test the lifetime of Cu wire bonding and diffusion soldering, test samples with a single 1200V, 150A IGBT have been assembled into modules without baseplate. To get a more nuanced view on the power cycling reliability of these new technologies different test conditions have been realised.

For the test with a maximum temperature swing of dT_j=132-144K the maximum chip temperature $T_{j,max}$ ranged from 165°C to 171°C. Cycle times were T_{on}=2s and T_{off}=2.2s.

In this setup the test stopped after about 1Mio cycles due to an increase in V_{CE} (Fig. 9). Compared with today's power cycling diagram, this is an improvement of the power cycling reliability of almost two orders of magnitude at a temperature swing of 130K. To put it in other words, we were able to transfer today's lifetime from a temperature swing of dT_j=50K to an elevated swing of dT_j=130K.

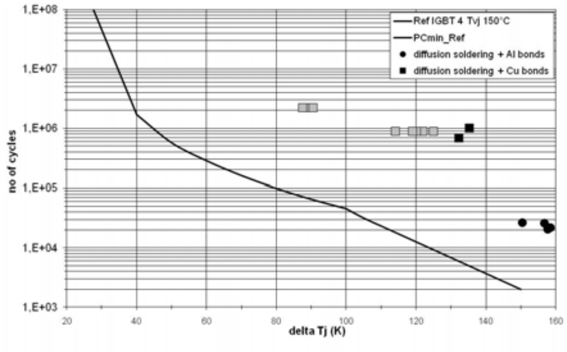

Fig. 9: Power cycling reliability diagram characterising the new packaging technologies for short active cycles (PC_{sec}). Black symbols are end-of-life samples, grey symbols are actual readout.

The following failure analysis neither showed any degradation of the bond interconnects nor of the diffusion soldered joint. In fact, the shear force of all tested Cu bonds remained at a very high level. Instead, the failure of the tested samples could be traced back to a delimitation of the substrate metallisation (Fig. 10).

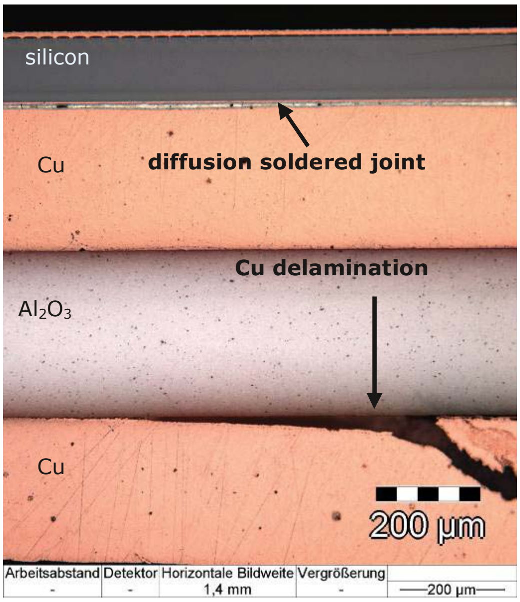

Fig. 10: Cross section of a power cycling test structure after failure. The delamination of the Cu from the Al2O3 ceramic has been identified as the root cause for failure.

The test with a moderate temperature swing of dT_j=87-90K yield a maximum chip temperature of $T_{j,max}$=168-177°C at T_{on}=2s and T_{off}=2.2s. The actual readout is 2.2Mio cycles (Fig. 9).
To prove the benefit from the combination of Cu bonding with diffusion soldering, in Fig. 9 there is also reliability data shown for diffusion soldered samples with standard Al bonds. These specimens failed after about 25k cycles due to bond wire lift-off. This test shows the actual limits for Al wedge bonding and is similar to other publications covering silver sintering.

Herewith it is proven, that with this new technology package the interconnection methods are not necessarily the lifetime limiting factors of today’s power modules any more.

b) Long cycle times (PC_{min})

As has been pointed out before, for a high temperature swing of dT_j>100K typically the substrate joint fails already after some thousand cycles (with typical cycle times t_{on}>10sec).
To analyse the power cycling reliability of the precipitation hardened substrate-to-baseplate solder joints, systems with two 1200V, 150A IGBTs have been assembled onto a Cu baseplate.

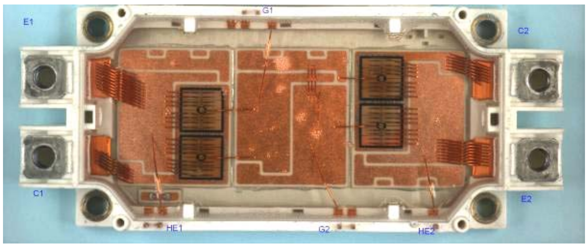

Fig. 11: Test specimen with Cu bonding, diffusion soldering and high reliability system soldering.

In order to ensure a high reliability for all other interconnects, Cu bonding and diffusion soldering was used for the module assembly (Fig. 11).
Three different groups (varying solder parameters and materials) were tested with the following setup: dT_j=100-130K, $T_{j,max}$=160-180°C, T_{on}=15-30sec and T_{off}=30-60sec.
Here, the subsequent analysis revealed a failure of the substrate solder joint due to solder fatigue. But depending on the detailed soldering parameters significantly increased lifetimes could be realised. As can be seen in Fig. 12, for an optimised set of parameters and materials, more than 100.000 cycles can be achieved at a temperature swing of dT_j=130K. This is still an increase of more than a factor of ten compared to today’s power cycling reliability for baseplate modules.

In addition to the improved power cycling results the thermal shock test (TST) and thermal cycling

(TC) performance has been significantly improved by the use of the high reliability system soldering process.

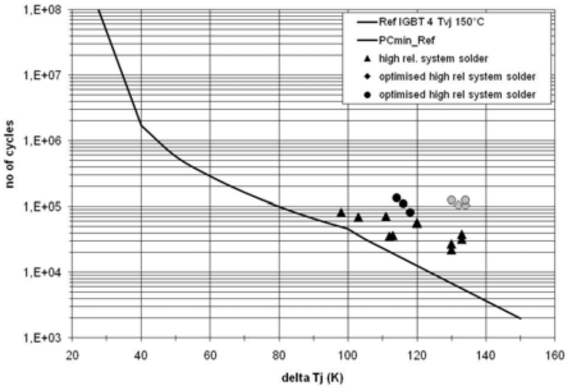

Fig. 12: Power cycling reliability diagram characterising the new packaging technologies for long active cycles (PC_{min}). Black symbols are end-of-life samples, grey symbols are actual readout of ongoing test.

4. Conclusion

It has been outlined, that in order to lay ground for an application with a real operation temperature of $T_{op} \geq 175°C$ it is necessary to introduce a new integrated set of technologies, which overcomes today's limitations for wire bonding as well as chip and substrate soldering.

In accordance to mass production aspects a complete set of interconnection methods for the assembly of a new generation of IGBT modules has been introduced. It offers best in class power cycling reliabilities.

By these measures the active power cycling lifetime of IGBT modules without baseplate has been increased by almost two orders of magnitude without reaching the end of life limit for any of the new technologies.

By the application of the improved system soldering for baseplate modules the lifetime could still be extended by more than a factor of ten.

With this new technology package we lay ground for IGBT modules with high operation temperatures realising best in class power cycling reliabilities.

This new technology package will be introduced to the market under the brand name *.XT* [9].

5. Acknowledgment

This work was partly funded by the Federal Ministry of Economics and Technology (BMWi) of Germany under grant no. 19U6006 and 19U6007.

6. Literature

[1] R. Bayerer, Higher Junction Temperature in Power Modules – a demand from hybrid cars, a potential for the next step increase in power density for various Variable Speed Drives, PCIM, Nuremberg, Germany (2008).

[2] M. Thoben, R. Bayerer, I. Graf, M. Münzer, Potentiale und Grenzen der Leistungshalbleiter-Technologien für Antriebselektronik in Hybridfahrzeugen, Hybridsymposium, Braunschweig, Germany (2006).

[3] M. Thoben, D. Siepe, K. Kriegel, Use of Power electronics for HEV at elevated temperature, Hybridsymposium, Braunschweig, Germany (2008).

[4] D. Siepe, R. Roth, The future of wire bonding is wire bonding, CIPS Conference, Nuremberg, Germany (2010).

[5] R. Amro et al, Double-Sided Low Temperature Joining Technique for Power Cycling Capability at High Temperature, EPE Conference, Dresden, Germany (2005).

[6] Th. Licht, R. Speckels, M. Thoben, Sintering technology used for interconnection of large areas: potential and limitation for power modules, CIPS Conference, Nuremberg, Germany (2010).

[7] S. Bader, W. Gust, H. Hieber, Rapid formation of intermetallic compounds by interdiffusion in the Cu-Sn and Ni-Sn Systems, Acta. metall. mater. 43 (1), 329 (1995)

[8] D. M. Jacobson, G. Humpston, Diffusion soldering, Soldering & Surface Mount Technol. 10, 27 (1992).

[9] A. Ciliox et al, New module generation for higher life-time, paper submitted to PCIM Conference, Nuremberg, Germany (2010).