

Inorganic Substrates for Power Electronics Applications

Anton Miric, M. Sc., Peter Dietrich, M Sc., M.A.
Heraeus Deutschland GmbH and Co. KG
63450 Hanau Germany

anton.miric@heraeus.com ; peter.dietrich@heraeus.com

ABSTRACT

The power electronic modules use ceramic insulation substrates mainly. This is caused by extreme requirements regarding power (voltage, current) and the very high-required heat dissipation capability. This requirement is increasing to make use of higher junction temperature up to 175°C, 200°C and beyond possible.

The right choice of ceramic material highly depends on the applications and certain insulation, reliability and thermal specifications. Of course, cost efficiency plays an important role beside the quality, therefore a perfect fit to each application is desirable.

The most widely used traditional ceramic insulation material is aluminum oxide ceramics (Al_2O_3).

For improved mechanical robustness, to achieve higher reliability, ZTA (Zirconia Toughened Alumina) is often used. ZTA is based of aluminum oxide material in which up to 30 % of ZrO_2 are deposited in the ceramic matrix. It's bending strength is higher than 500 MPa while aluminum oxide ceramics has about 400 MPa.

For applications which are focused on thermal performance and which requires highest insulation capability thicker ceramic aluminum nitride (AlN) is mainly used. AlN offers superior thermal conductivity performance of about 180 W/mK (at r.t.), which is 7 to 8 times higher than that of aluminum oxide that has about 24 W/mK (at r.t.).

However, aluminum nitride has relatively low bending strength of 300-400 MPa. Therefore, the reliability performance is limited and requires use of special base plate material, e.g. AlSiC to compensate this weakness.

A further ceramic material is Silicon nitride (Si_3N_4). It provides the best mechanical robustness, e.g. the bending strength of silicon nitride is higher than 600 MPa. In addition, its thermal conductivity of approximately 90 W/mK (at r.t.) is by far superior to Al_2O_3 and ZTA ceramics. Due to favorable combination of mechanical and thermal properties, this type of ceramics is reasonable choice for applications that require high reliability and high power density.

Several different bonding technologies for connecting of the metal and ceramic material to form the substrates will be discussed. The widely used technology is Direct Bonded Copper (DBC) – at high temperature a thin copper-oxide on the copper foil is used to create a eutectic bond between the copper and ceramic. Another process is Active Metal Brazing (AMB) in which the copper and ceramic foils are joined by using a brazing process. For the sake of completeness, Direct Bonded Aluminum (DBA) has

to be mentioned. It uses AlSi-brazing to bond the aluminum and the ceramic.

Another method to form metal bonded ceramic substrates is Thick Printed Copper (TPC). Thick layers of copper paste are applied by screen printing process and are fired at 850 – 950 °C to sinter the metal powders and create a high adhesion bond between the metallic film and the ceramic substrate. This technology provides excellent temperature cycling reliability and opens possibility to combine power and logic components by parallel realization of thin and thick Cu pattern tracks.

The increase of power density and junction temperatures drive the need for new packaging materials, e.g. sintering technology. These new materials put special requests on the functional surfaces of the substrates - for best reliability the interconnect material and the interface layers must be perfectly matched together.

INTRODUCTION

Power electronic systems are centerpiece components to convert electrical energy. It takes the energy from grid or storage system or from the captured energy in generators and convert it into the desired waveforms regarding frequency, voltage and current.

It is used in a wide range of power applications starting from household appliances (with several Watts) to average power applications like welding equipment or on board auxiliary systems up to high power application like automotive power train, industrial drives, railway traction, renewable energies and energy distribution with some hundred Megawatts or even Gigawatts. Consequently also the voltage classes range is very wide starting with 12 V e.g. in automotive applications up to several thousand Volts in e.g. wind turbines and locomotives. The same is valid for current level which starts with several Ampere and goes to several thousand Ampere.

Even nowadays power electronic efficiency is close to 100% the remaining power losses must be considered in the design and selection of materials because of the high output power and consequently relatively high remaining heat losses that are generated by the small semiconductor dies.

The combination of high power, high voltage, high current and high operating temperatures in the semiconductor devices constitutes a great challenge to the selection of material combinations to achieve desired quality over whole product lifetime. On the other hand, especially for high volume applications, e.g. automotive or industrial, the

cost efficiency is one of the major selection criteria. **Figure 1** presents the contrast of the state of the art requirements to the automotive power train requirements in near future (represented by the goal of the cooperative research project ProPower).

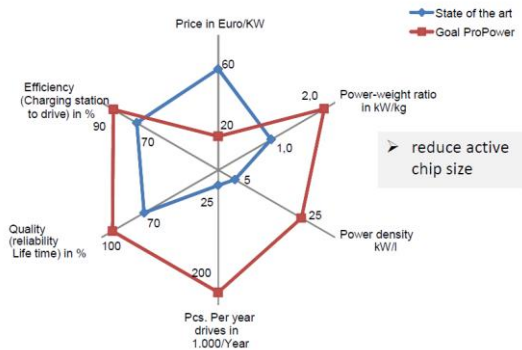


Figure 1 Increased requirements on automotive power electronic modules regarding power density, reliability etc. [3]

In the power electronic modules, the substrate represents the “backbone part”. It is the carrier of the semiconductor die. In addition it is insulator to the heat sink and inverter housing, therefore it has also to fulfil personal safety function even after failure when voltage devices above 100V are used. Furthermore, the substrate provides the topological interconnections (like a printed circuit board), it also dissipates the heat generated in semiconductors.

Therefore, to fit to the previously explained variation of requirements, different types of ceramics are used in power electronic modules.

Compared with organic insulation materials, which are widely used for logic and microelectronic circuits the ceramics provides excellent thermal conductivity, it has very good electrical insulation properties and is extremely heat resistant. Furthermore the thermal coefficient of expansion of ceramics is closer to semiconductor materials e.g. silicon (compared to copper or aluminum or organic materials).

The mechanical joint of the e.g. copper foil to ceramic is strong enough to prevent the thermal expansion of the metal in lateral direction. Therefore, the shear forces at the die joining layer to the substrate caused by load cycles is lower than of organic insulated substrates. Furthermore, under high voltage conditions the insulation capability of ceramic remains constant over whole lifetime while the one of organic insulator becomes deteriorates over time.

The influence and significance of the material combinations in the power electronic module increase analogue to the progressive rise in the power density, the switching frequency and the enhanced reliability requirements.

INORGANIC SUBSTRATE TYPES FOR DIFFERENT REQUIREMENTS

The requirements on power electronics modules vary depending on the application, voltage and current level, module design etc.

The most common inorganic substrates widely used are Direct Bonded Copper (DBC) substrates based on aluminum oxide ceramics (Al_2O_3). At a temperature of approximately $1070^\circ C$ a thin copper-oxide on the copper foil is used to create an eutectic bond between the copper and ceramic without a necessity to use any additional interlayer material. The temperature control is very important as copper itself melts at $\approx 1085^\circ C$. **Figure 2** shows the narrow process window for the eutectic melt bond effect. The thermal capacity of copper and the ceramic is desired by the power electronic application. For the bonding process it is a huge challenge especially for high volume and bigger card size production.

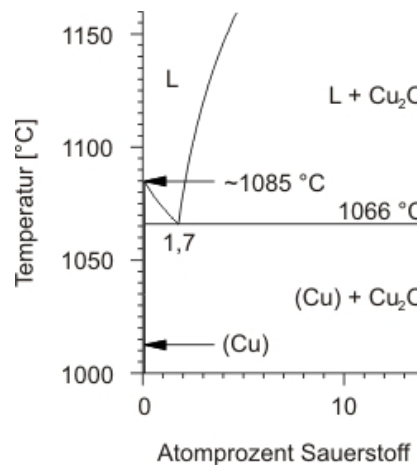


Figure 2 Cu-oxygen Phase diagram [5]

The copper foil of approximately $300 \mu m$ is bonded to both sides of ceramic. The top side layer is structured by chemical etching to form an electrical circuit or the topological interconnection. The bottom copper layer is usually unstructured and features interface to base plate or heat sink.

The DBC alumina oxide ceramic substrate has outstanding ratio of performance vs. cost efficiency. The thick Cu-foil provides high electrical and thermal conductivity properties and has excellent compatibility with soldering and thick wire bonding processes.

For improved mechanical robustness, to achieve higher load cycle capability, the aluminum oxide is toughened by adding zirconium oxide in the ceramic matrix structure. This named ZTA (Zirconia Toughened Alumina) has a weight percent ratio of zirconium oxide (ZrO_2) up to 30%. It's bending strength is higher than 500 MPa while aluminum oxide ceramics has about 400 MPa.

Depending of the production sintering process of the ceramic and as function of zirconium oxide added ratio the reliability in the application has potential to increase from

twice to several times. On the other hand the increased ratio of ZrO_2 has a negative impact on thermal performance and cost efficiency of the substrate. The negative impact on the thermal performance can be compensated by some admixtures which causes additional costs. The DBC process is also typically used for ZTA substrates.

The DBC process technology is described schematically in **Figure 3**

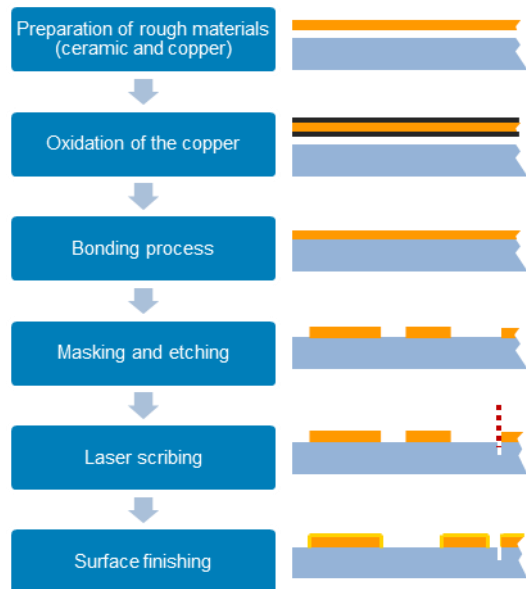


Figure 3 Direct Bonded Copper (DBC) substrate process technology

In conventional building structures the Al_2O_3 based DCB accounts for approximately 50% of the impact ratio of the entire thermal chain network, from junction to case. [7]

circuit substrate	thermal conductivity [W/m·K] (at r.t.)	dielectric strength [kV/mm]	coefficient thermal expansion (CTE) [ppm/K] (at r.t.)	CTE mismatch ratio to Si-Chip (2,6 ppm/K)	CTE mismatch ratio to SiC-Chip (4-5 ppm/K)
FR4-Leiterplatte	0,25	40	20	770%	440%
Al_2O_3 -DCB Substrate (300µm Cu)	19-26 (24 typ)	~15	7,5	290%	170%
Si_3N_4 AMB Substrate (300µm Cu)	90	~18	>3,4	>130%	>120%
AlN-DCB Substrate (300µm Cu)	180	15-20	>4,6	>175%	>90%

Table 1 Comparison of selected substrate properties for high voltage applications [6]

To reduce the thermal resistance ceramic materials with better thermal conductivity are used, e.g. Aluminum nitride ceramics (AlN). This inorganic material has superior thermal conductivity combined with low coefficient of thermal expansion (close to chip). The typical thermal conductivity of the aluminum nitride ceramics (AlN) is approx. 180 W/mK, which is 7 to 8 times higher than that of aluminum oxide that has about 24 W/mK.

On the other side aluminum nitride ceramic has weak mechanical properties, e.g. its bending strength of 300-400 MPa is inferior to the Al_2O_3 or ZTA ceramics. To get mechanical stability the thickness of AlN substrate is $> 600 \mu m$. Therefore, the choice of this material is of particular advantage when higher voltage is used like it is done at grid and traction application (3,3kV to 6,5kV). In this case the insulation ceramic has to be thicker because of the requested higher insulation capability. In general a thicker ceramic layer would cost resulting thermal performance. But the thermal features of AlN substrate overcompensate the negative thermal impact caused by the requested ceramic thickness. This is proven in the **Figure 4** which shows the relative thermal resistance as function of active die size according to the equation: $\frac{R_{th1}}{R_{th2}} = \left(\frac{A_{chip2}}{A_{chip1}}\right)^K$

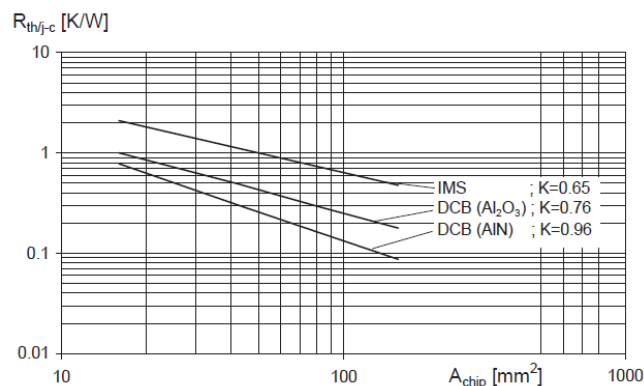


Figure 4 Dependency of the thermal resistance as function of semiconductor die area for IMS, Al_2O_3 and AlN DCB [2]

Due to AlN's low coefficient of thermal expansion which is closer to the one of the semiconductor (AlN has around 4 ppm/K in comparison to 2,6 ppm/K of Silicon while the mismatch to 7,5 ppm/K of Al_2O_3 is higher) the AlN ceramic is especially suitable for bigger dies sizes used e.g. in traction and wind energy applications. The low coefficient of thermal expansion of AlN requires base plate materials like AISiC with adapted CTE values.

AlN is significantly more expensive than Al_2O_3 ceramics. In addition special base plates/heat sinks like AISiC are also more expensive than e.g. Cu base plate.

AlN substrates are available with Copper (Cu) or aluminum (Al) metallization.

The AlN-Cu substrates are manufactured either by Active Metal Brazing (AMB) or by the DBC process. The AMB process is presented in **Figure 5** schematically.

In the case of DBC process the AlN surface need to be treated, e.g. by lapping and controlled oxidation to achieve proper bonding of Copper on the AlN ceramic.

The most common active brazing materials are based on Silver and Copper with additions of 1 to 10% of Titanium and sometimes also Indium to lower the melting temperature. Depending on the composition of the solder the typical brazing temperature is between 800 – 1000 °C (50-100°C above the liquidus of the braze alloy). Due to the high reactivity of the alloy, the brazing process is running under vacuum or under inert atmosphere.

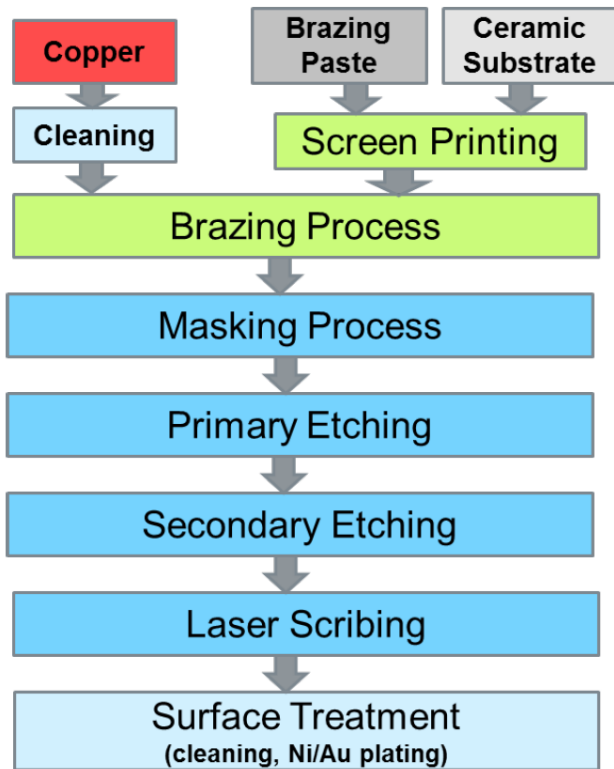


Figure 5 Active Metal Brazing Process [8]

In a case of AlN ceramic with aluminum metallization the Direct Bonded Aluminum (DBA) process is used. In this process aluminum-silicon (AlSi) composite is used to bond aluminum foil with the ceramic. Compared to copper the aluminum has lower density and lower E-modulus. Furthermore, it has significantly lower thermal and electrical conductivity. Therefore thicker aluminum layers are needed to reach the equal heat dissipation or current carrying capacity as with copper metallization. On the other side the thermal cycle capability of AlN-DAB substrate is much higher than of Al₂O₃-DBC, ZTA-DBC and AlN-DBC and AlN-AMB. This is because Aluminum is softer than copper which relaxes the shear forces causes by thermal cycling.

	unit	Al	Cu
thermal conductivity	W / (m * K)	237	401
electrical conductivity	A / (V * m)	37.7 * 10 ⁶	59.1 * 10 ⁶
tensile strength	MPa	40-50	200-230
E-Modulus	GPa	70	100...130
vickers hardness	MPa	167	369
CTE	ppm / K	23	17
melting point	°C	660.3	1084.6
density	g / cm ³	2.70	8.96

Table 2 Comparison of selected material properties of bulk aluminum and copper [9]

A further ceramic material, mostly also made by the AMB process, is Silicon-Nitride (Si₃N₄). It is significantly mechanically more robust than Al₂O₃, ZTA or AlN. The bending strength of silicon nitride is >600 MPa.

Therefore, it can be provided with a thickness of only 320µm or less. Silicon-Nitride's conductivity performance is 90 W/m K which is about half of AlN. But because it can be made thinner than AlN the resulting thermal resistance (R_{Th} junction to case) is approximately the same of AlN.

Due to favorable combination of mechanical and thermal properties this type of ceramics is reasonable choice for applications which require high reliability and high power density.

For the sake of completeness it should be mentioned, that the good mechanical properties of ZTA and Si₃N₄ enables to use thicker copper layer at the bonding process. In the applications this effects a heat spreading close to the semiconductor that reduces significantly the thermal resistance respectively allows to shrink the die size. In addition the current carrying capacity increases.

THICK PRINT COPPER (TPC) [8, 11]

An alternative to the former mentioned DBC, AMB and DAB technologies is using thick film paste technology to build the substrates. Thick film paste technology has been used for decades to build highly reliable electronic circuits on ceramic substrates and is well established in automotive, military, aerospace and other applications which require high reliability.

Advancement of thick film materials have provided systems suitable for building very thick silver (Ag) and copper (Cu) conductors (25-300 µm) on a variety of ceramic substrates, including Al₂O₃ and AlN.

Thick film hybrid circuits are fabricated by screen printing a pattern of thick film paste onto a ceramic substrate and then firing the paste to produce an electrical circuit. For cost and performance considerations, Cu and Ag are the most suitable for power electronics applications as they both offer high electrical and thermal conductivity while Cu also offers lower cost.

Traditionally, thick film materials have been formulated to match the thermal expansion and provide extremely high adhesion to the alumina substrates. The formulas are designed for screen printing 75-125 µm lines and spaces at a fired film thickness of 7-15 µm. For power electronics applications the formulation and the process are developed to enable printing of thin and thick layers, e.g. 25 to 300 µm. Through additive processing (screen printing) it is possible to vary the fired film thickness on the same substrate and to realize fine and large lines and spaces.

Thick power tracks and thinner high density signal circuitry can be printed on the same substrate – this enables combination of power and logic components on one circuit.

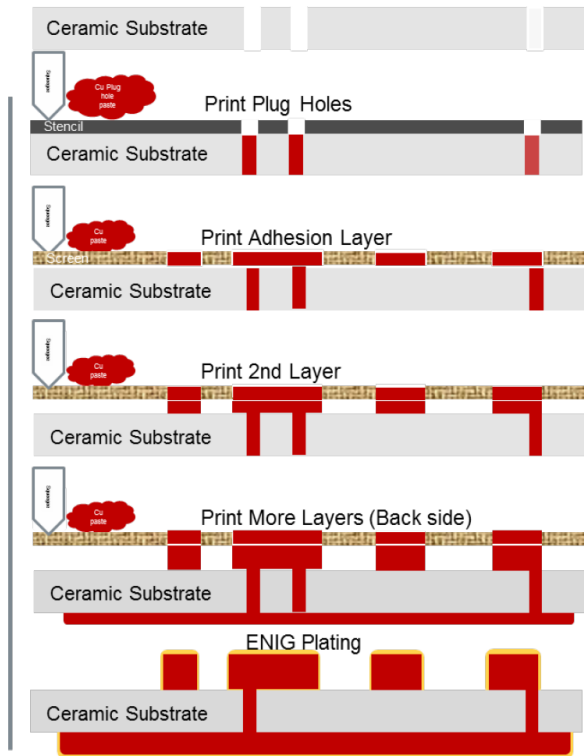


Figure 6 Sequential steps (minus drying and firing steps) from figure top to bottom in making a double sided thick film power circuit [8]

Through-hole interconnects are possible with thick film pastes. This enables double sided circuitry or inclusion of high thermal conductivity vias for heat dissipation.

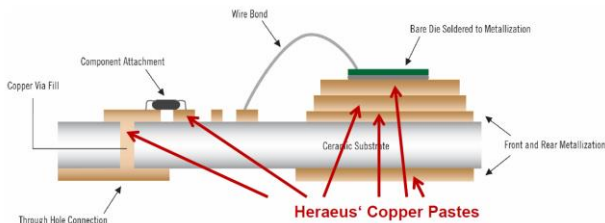


Figure 7 Power and logic components can be integrated on a single substrate [11]

The thick film offers an advantage being a ceramic-metal system such that with a proper selection of adhesion promoting material (glass and oxide materials) the thermal expansion of the thick film can be tailored to match the thermal expansion of the substrate materials. The contents of the copper paste soak into alumina forming a strong and reliable chemical bond – the bonding area with chemical bond extends up to 40 μm into the alumina. This brings benefits for circuits with high thermal cycling requirements.

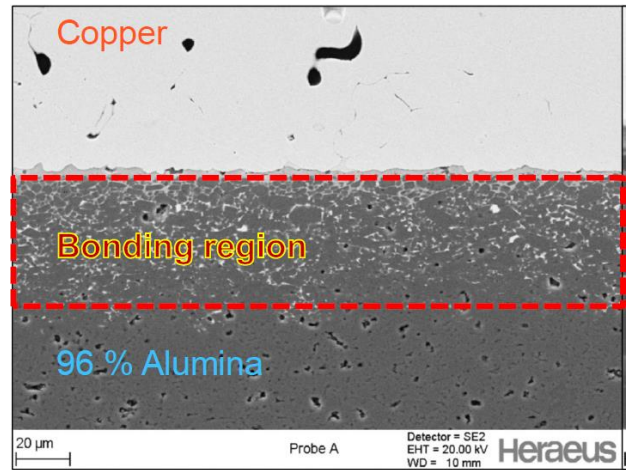


Figure 8 Example of copper film interface with an alumina ceramic substrate [11]

New copper thick film materials perform extremely well in standard assembly processes such as soldering and thick wire bonding. The materials are also compatible with new assembly method - low temperature silver sintering.

Properties	DBC	Thick Film Copper
Typical Cu Thickness	300 μm	300 μm
Min. Cu Thickness(μm)	80 μm	20 μm
Min. Line/Space (μm)	600 at 300 μm thickness	250 at 300 μm thickness
Electrical Resistivity	1.65x10 ⁻⁸ (Ohm m)	2.62x10 ⁻⁸ (Ohm m)
Thermal Conductivity (full system)	242 (W/mK)	174 (W/mK) (290 W/mK for AlN)
Warpage Variation	Strong	Very low
Design freedom (line resolution...)	Limited	Excellent
Reliability	dimplers for acceptable reliability	Excellent
Process Difficulty	Easy	Easy
Cost	Low	Medium, depends on number of layers

Table 3 Comparison of selected properties, DBC versus TPC [11]

SAFTY FUNCTION OF INSULATOR SUBSTRATE

It is indispensable that in power electronic devices which handles with higher voltages the insulation capability has to be assured even after a failure. For the mentioned ceramic insulation solutions this condition is proven and satisfied. The ceramics keeps insulation capability even after the impact of an explosion force from an electric arc caused by short circuit or surge current.

Many of the new joining and package technologies which are still in development try to get a ceramic free solution to improve cost efficiency. But this technologies must prove isolation capability after failure under each conditions, first.

This issue becomes more serious when planar interconnection instead of bond wire is used. This new wiring technology leads to lower stray inductance. In normal operation this is very advantageous. But after a short circuit the lower stray inductance of the system increasing the surge current drastically because of the reduced discharge time of the DC-Link capacitors.

Furthermore, in failure mode the inverter is changing energy transmission direction. If the inverter is used in

power train or traction, the inertia of the vehicle keeps the vehicle moving and this keeps and increases the load on the diodes until a circuit breaker can react. This is an additional stress factor which requires high robustness.

Most of the simple organic insulation substrates uses foil, which cannot withstand the electric arc, or the temperature that occurs when the failure happens, especially when the insulation layer is close to the semiconductor die. The surge current typically causes temperature above 400 to 600°C [13]. This issue is often not taken in account during development time and also often not enough coverage at product qualification because of the expensive and destructive testing and the high variation of failure types. Of course this issue is manageable by the right selection of materials and layer thickness when enough thickness is spend to materials with high thermal capacity like copper arranged between semiconductor die and the insulator.

FUNCTIONAL SURFACES FOR NEW PACKAGING TECHNOLOGIES

The continuous rise in the power density, coupled with the higher operating temperatures (150, 175 °C, 200°C and even further) plus the demands for improved power cycling reliability and long term reliability (>15 years for automotive applications) bring the standard packaging materials, SnAg solder and Al bonding wire, to the edge of their limits. In addition, enormous temperature differences, as for example in cold-starting a car engine in winter create a very particular challenges with regard to thermal cycling reliability.

The demands placed on packaging materials will rise even further in the future due to the use of new semiconductor materials such as SiC or GaN. These semiconductors enable significantly quicker switching frequencies and fewer switching losses with increased power densities, and thus even at heightened juncture temperatures they continue to function reliably. Thanks to its excellent thermal conductivity SiC is also well suited for use in higher voltage classes and/or power densities.

For these reasons there is a call for optimized materials with not only improved mechanical properties, but incorporating thermal and electrical improvements as well. The new advanced materials must work reliably at higher operating temperatures.

Material	Unit	SnAg	SnCu intermetallic phases	Ag	
melting temperature	°C	221	415	961	
homologous temperature at operating temperature	125 C	%	81%	58%	32%
	150 C	%	86%	61%	34%
	200 C	%	96%	69%	38%
	250 C	%	106%	76%	42%

Table 4 Homologous temperature of different interconnect materials [9]

Silver low temperature sintering is very promising technology which brings significant improvement to the high temperature properties and more especially, to the power cycling reliability.

Silver sintering offers significantly better thermal and electrical conductivity as well as higher temperature stability. Melting point of Ag is 961 °C vs. SnAg-solder with the melting point of 221 °C. Furthermore, using sintering pastes enables very high thermal conductivity, e.g. more than 200 W (m-K).

Material properties	SnAg3.5 Solder	Sinter Paste ASP016/043	Sinter Paste LTS295-01P2
Electrical resistivity [mΩ·cm]	0.01 - 0.03	≤ 0.008	≤ 0.008
Thermal conductivity [W/m·K]	20 - 50	> 200	>100
CTE [ppm/K] (below/above T _g)	25 - 30	19	19
E-Modulus @ 25°C [GPa]	~ 30	~ 50	~ 25
Shear strength [N/mm ²]	~ 40	≥ 10	≥ 10
Process temperature [°C]	230-260	≥ 230	≥ 230
Residue free	No	Yes	Yes

Table 5 Comparison of physical properties: solder vs. 2 different sinter pastes (one for pressure and other for pressure-less sintering) [9]

Both the soldering and the sintering process need heat but there is a major difference between these 2 assembly technologies: during soldering the solder particles melt, they wet the surfaces to be contacted, intermetallic phases are formed and in the cooling phase the solder alloy is solidified. During the sintering process the silver particles do not melt: typically, sintering is done at 230-260°C and the melting temperature of silver is 961 °C. The sintering process is based on atomic diffusion which is reinforced by higher temperatures. The atoms in the silver powder particles diffuse across the boundaries of the particles – the single particles fuse together, begin to density and create a solid interconnect.

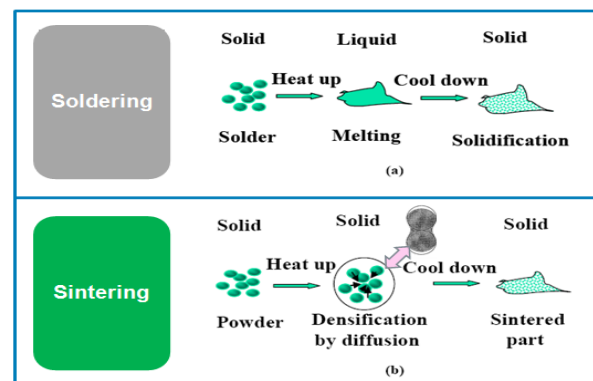


Figure 9 Soldering vs. sintering technology [9]

The diffusion does not occur only between the silver particles of the paste but also with the surface of the partners to be connected (e.g. interface to the substrate & chip). Therefore, it is very important that the surface finish of the substrates is adapted to match the sintering process. The sintering pastes are currently being used preferably for silver and nickel-gold surfaces. New copper-based functional surfaces are also being developed as well as the corresponding pastes. [3]

At elevated temperatures, oxygen diffuses relatively quickly through the silver sintering layers. This can cause

the oxidation of the base material on the substrate and can lead to the delamination of the sinter layer.

Measurements with Auger electron spectroscopy show, that at 200°C the oxidation of the base material starts after approx. 30 minutes in a case of 0,1 µm Ag-protection layer (remark: it should be considered that one 0,1 µm Ag layer is not „dense“). In a case of one 3 µm thick Ag protection layer the base material is oxidized after 144 h (6 days) – the silver sinter layer can be removed from the base material with a simple adhesive tape. By using special barrier layers between the Cu/Ni and the Ag layer it is possible to prevent / slow down the oxidation of the base material. [10]

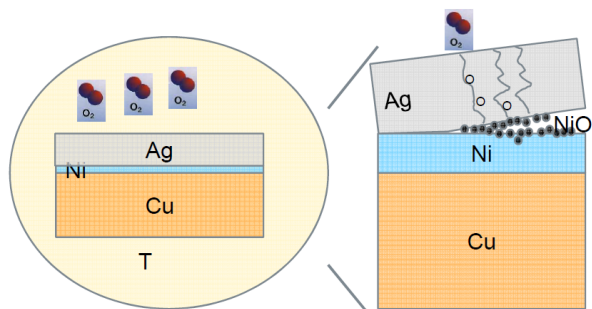


Figure 10 Scheme of the failure mechanism [10]

CONCLUSION

There are four different kinds of ceramic materials that can be bonded with copper foils by either DBC or AMB process. Each combination of these insulating materials and joining technologies meet specific demands and, hence, are suitable for different applications. Furthermore, thick printed copper may be an alternative solution for special applications. According to their physical properties, the costs of metallized substrates vary in a big range.

Because of the outstanding ratio of performance vs. cost efficiency DBC aluminum oxide ceramic is the most common used substrate. For many industrial applications the performance is sufficient to meet life time and the thermal dissipation requirements. If higher mechanical performance is required ZTA DCB offers an even higher bending strength whereas thermal conductivity is comparable to Al₂O₃ DCB. Due to the direct bonding process costs for production are in an acceptable range.

Joining copper foils on highly thermal conductive aluminum nitride can be done utilizing AMB and DCB. However, DCB is a more cost effective method whereas AlN AMB shows enhanced thermal cycling performance. Because of the inherent low mechanical strength of AlN the insulating layer needs to be thick compared to Al₂O₃, ZTA and Si₃N₄. Furthermore, aluminum nitride DCB and especially AMB is quite expensive and is used mainly for very high voltage applications. Silicon nitride combines both, good mechanical properties and enhanced thermal conductivity. However, prices for raw ceramic substrates are still high and, until now, AMB is the only joining technology applicable for metallization.

A further unstoppable trend is set by the die improvement. The power losses is reduced by each new IGBT and die

generation. Therefore, power density increases and die size shrinks over the development time. Recently the maximum junction temperature increases from 125°C from the past to 200°C. In future dies will require new material combinations and joining technologies, especially when a wide band gap (WBG) material like silicon carbide (SiC) or gallium nitride (GaN) is used.

This article shows that in power semiconductor package technology there is still room of improvement. The mostly used stack layer combination from the die to case bottom is used for several decades. The highest potential of improvement comes from material science. It has high impact in cost performance, thermal dissipation and system reliability.

For best reliability the substrate, it's functional surfaces, the die attach and other packaging materials must be perfectly matched together. Therefore the fine tuning of the material set is mandatory that includes a wide range of qualification and intensive FMEAs.

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