Survey of High-Temperature Reliability of Power Electronics Packaging Components

R. Khazaka, L. Mendizabal, D. Henry, and R. Hanna

***Abstract*—In order to take the full advantage of the high-temperature SiC and GaN operating devices, package materials able to withstand high-temperature storage and large thermal cycles have been investigated. The temperature under consideration here are higher than 200 °C. Such temperatures are required for several potential applications such as down-hole oil and gas industry for well logging, aircrafts, automotive, and space exploration. This review focuses on the reliability of a selection of potential components or materials used in the package assembly as the substrates, the die attaches, the interconnections, and the encapsulation materials. It reveals that, substrates with low coefficient of thermal expansion (CTE) conductors or with higher fracture resistant ceramics are potential candidates for high temperatures. Die attaches and interconnections reliable solutions are also available with the use of compatible metallization schemes. At this level, the reliability can also be improved by reducing the CTE mismatch between assembled materials. The encapsulation remains the most limiting packaging component since hard materials present thermomechanical reliability issues, while soft materials have low degradation temperatures. The review allows identifying reliable components and materials for high-temperature wide bandgap semiconductors and is expected to be very useful for researchers working for the development on high-temperature electronics.**

***Index Terms*—Die attach, encapsulation, harsh environments, packaging, power semiconductor devices, reliability, substrate.**

I. INTRODUCTION

SILICON carbide (SiC) and Gallium Nitride (GaN) are wide bandgap semiconductor materials able to operate theoretically at high temperatures up to 600 °C. Compared to silicon (Si) devices, wide bandgap semiconductors can operate at higher temperatures, possess a higher breakdown voltage, present lower switching losses, and withstand higher current densities [1], [2]. In order to assure the high performance and reliability of systems employing such new high-operating-temperature semiconductor dies, all their packaging materials have to be suited to more severe thermal and electrical constraints.

Numerous electronic applications (down-hole oil and gas industry for well logging, aircrafts, automotive, and space exploration) require operation at high temperatures that differ greatly form common standard operating temperature. The temperature and operating life requirement for those applications have been developed in Chin *et al*. and Buttay *et al.* [3], [4]. Increasing the junction temperature of electronic converters by using them at higher ambient temperature (above 200 °C) and under higher power density (several hundred of Watts/cm^2) commit power electronics manufacturers to develop innovative packaging solutions for power semiconductor devices and modules. This is mainly due to the increase in the induced thermal and thermomechanical stresses that reduces significantly the classical components lifetime. The extreme cycling conditions will cause additional thermomechanical stress in the module and, hence, the effective thermal management, the compatibility of the coefficient of thermal expansion (CTE) between different materials, as well as their mechanical properties become more crucial. On the other hand, the high temperature will cause the degradation of polymeric materials used in the module packaging as well as the creation of intermetallic compounds, which may weaken the joints. For Si power converters, the maximal junction temperature is lower than 175 °C and the temperature variations are about 200 °C max. For wide bandgap semiconductors, since packaging components can undergo temperatures higher than 200 °C and deep thermal cycles with temperature variation (ΔT) >250 °C, reliability problems are encountered rapidly in different packaging components. The classically used direct-bonded copper substrates (DBC) with AlN or Al_2O_3 ceramics fails after 20 to 30 cycles with ΔT of about 300 °C [5], [6] and are not suitable for high-temperature power electronic applications. Commonly used solders are not compatible with the high-temperature applications or are not conform to the regulations of the restriction of hazardous substances (RoHS) [7], [8]. For electrical interconnections, Aluminum (Al) wires bonding suffer from thermomechanical reliability even with the classical Si based module ($\Delta T < 200$ °C and $T < 150$ °C) and problems are estimated to be aggravated with the temperature increase [9], [10]. Finally, silicone gels used as encapsulation materials have limited operating temperature that does not exceed the 200 °C in most cases [6], [11]. In order to improve the reliability of different components, alternative solutions have been investigated to replace the classical metallized substrate, the solder, the Al wires as well as the classical silicone gel. Even if some survey papers have addressed the high-temperature packaging materials [12], [13], reliability survey on the latest results of those components has not been addressed yet. In this paper, results on the reliability of commonly used components as well as alternative solutions published in the literature are reported. The survey focuses on thermal and thermomechanical reliability investigations for the following key packaging

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components; the substrate, the die attaches, the interconnection, and the encapsulation materials. This review is expected to be useful for researchers working on the development of power modules for high-temperature applications, since it allows identifying suitable and reliable packaging components for SiC and GaN high-temperature converters.

II. COMPONENTS AND RELIABILITY

A. *Metallized Substrate*

The substrate (insulating ceramic sandwiched between two conductors) provides the electrical insulation and ensures the circuitry in the module through the upper metallic layout. In the next, we will divide the substrates according to the used conductor on the ceramic insulator and we will present a synthesis of their reliability, their failure mechanisms, and solutions allowing the improvement of their lifetime under thermomechanical cycles. Three kinds of substrates have been mainly investigated in the literature; the copper (Cu) metallized substrate, the aluminum (Al) metallized substrate, and the substrate with low CTE conductor.

1) Copper-Metallized Substrate: During large-amplitude thermal cycling, the CTE mismatch between the Cu and the ceramic results in fracture of the ceramic and peel off of the Cu foil [14], [15]. It has been found that 20 to 30 cycles are typically needed to crack or spall the DBC Al_2O_3 or AlN ceramics with a temperature variation of about 300 °C [5]. The fracture starts at the edge of the Cu bonded to the ceramic where the highest stresses are located [14]–[16]. The copper hardening due to the plastic stress is a key parameter in the failure of the DBC and it has been found that the maximal stress is increased by 10 MPa every three cycles between −50 and 180 °C [17], [18]. The decrease in Cu metallization thickness and the creation of dimples in the metallization around edges lead to an increase in the number of cycles to failure by decreasing the stress intensity at the singularities [19], [20]. We note that the decrease of current capability by reducing the metal thickness should be considered. An improvement has been also reported by the use of step-edge metallization (thickness decrease at the edges of the metallic layer) and sealed step edges coated with polymeric materials [5]. Another low-cost-efficient thermomechanical approach allowing the increase of the thermomechanical reliability of DBC consists to apply a few number of overload cycles before applying the thermal fatigue cycles [21]. This leads to diminish the stress intensity of the singularities and tends to increase the fatigue life of the DBC substrate. An additional opportunity allowing the improvement of the thermomechanical performance is the use of ceramics with higher fracture resistance like the Zirconia Toughened Alumina (ZTA) and the Si_3N_4 ceramics using DBC or active metal braze (AMB) technologies [22], [23].

The results obtained by different researchers using different ceramics combinations with different copper thicknesses and different thermal cycle profiles are presented in Table I. Results obtained under the same thermal cycles can be easily compared. In Table I, since the temperatures variation, the ramping rate as well as the holding time at the higher and the lower temperature are not identical and may affect the substrate reliability, precautions should be taken when comparing the reliability of different substrates from different studies.

2) Aluminum Metallized Substrate: Direct-bond aluminum (DBA) on AlN ceramic has also been evaluated for high-temperature power modules [19], [24], [25]. During thermal shock tests (from −196 to 85 °C), DBA were shown a level of reliability (more 100 cycles), which could not be achieved with conventional DBC technology (20 to 40 cycles) [25]. Substrates thermally cycled 1500 times from −55 to +250 °C did not exhibit delamination [24]. This improvement is due to the difference in the plastic hardening behavior between the Al and the Cu. However, since Al is not compatible with most solders and should be protected from oxidation, a nickel (Ni) layer is always plated. The Al has a large CTE (24 ppm/°C) compared to Cu (16 ppm/°C) leading to large plastic deformation occurrence. As consequences, surface roughening of the Al has been observed as well as cracks presence in the Ni layer [24]. This may possibly lead to die attach material and metallic corrosion problems.

3) Substrate With a Low CTE Conductor: Palmer *et al.* have adopted another approach to solve the thermomechanical problems of the metallized substrate. Their approach was to match the CTE between the ceramic and the conductor. A 500 μm of Mo(85%)Cu(15%) with a CTE of about 7 ppm/°C has been attached to a 635-μm Al_2O_3 ceramic by the use of an AMB alloy at 875 °C (TiCuAg) [26]. Results seem promising since no delamination has been observed in the assembled module after 1000 cycles between 35 and 350 °C [26]. A new original all-ceramic substrate technology, based on two cosintered ceramics (AlN-TiN) with potential advantages regarding thermal cycling behavior has been recently developed by Valdez-Nava *et al.* [27]. However, even if the approach seems interesting, reliability tests for this solution have not been reported yet.

B. *Die Attach*

Pb-rich solders such as Pb-5Sn and Pb-10Sn (mass%) alloys with melting points (m.p.) of 310 and 305 °C, respectively, have been widely used because of their desirable properties such as good wettability, high ductility, low shear modulus, high thermomechanical reliability, etc. Recently, recognition of the negative effect of Pb on the environment and human health due to its toxicity has encouraged great effort to develop Pb-free solders based on regulations such as the RoHS and waste electrical and electronic equipment. High-temperature die attach alternatives have been the subject of different studies. Organic die attach, high-temperature lead-free solders, transient liquid-phase bonding technique and micro- and nanosilver paste are potential candidates and their thermal and thermomechanical reliability is discussed in this section. Even if the amount of literature concerning the initial properties and reliability of the formed joints is not negligible, it remains difficult to compare precisely their reliability. This is mainly due to the use of different materials with different metal finishing and different aging conditions. As results, different mechanical stresses are applied to the joints and different intermetallic can be formed, affecting closely the joint lifetime. Coffin–Manson relation has been widely used to

TABLE I
RELIABILITY OF DIFFERENT SUBSTRATES DURING THERMAL CYCLES

Ceramic/bonding technique	Al_2O_3/DBC [6]	ZTA/DBC [6]	Al_2O_3/ DBC [22]	Si_3N_4/AMB [22]	AlN/ DBC [5]	AlN/ DBC [5]	AlN/ DBC [6]	Al_2O_3/ DBC [5]	AlN/ DBA [24]	Si_3N_4/ AMB [23]
Metal	Cu	Cu	Cu	Cu	Cu	Cu stepped edge	Cu+ dimples	Cu sealed stepped edge	Al	Cu
Metal thickness (μm)	300	300	190	154	300	300	200	300	300	170
Ceramic thickness (μm)	630	630	630	642	630	630		630	650	340
Thermal cycle ($T_{\min}$,$T_{\max}$) in °C	−40 250	−40 250	35 350	35 350	−55,250	−55,250	−40,250	−55,250	−55,250	−55,250
Lifetime (cycles)	26	100	< 250	$250 < X < 500$	20	45	40	850	>1500	>600

predict the lifetime of the die attach material [28]

$$N_f = \theta(\Delta v_p)^{\Phi} \tag{1}$$

where N_f is the cycle number until the failure, $\Delta\nu$ is the plastic deformation, and p and Φ are material constants. In simplified form, the strain between two different attached materials can be estimated according to the following equation:

$$\Delta v_p = \Delta\alpha \cdot \Delta T \cdot a/h \tag{2}$$

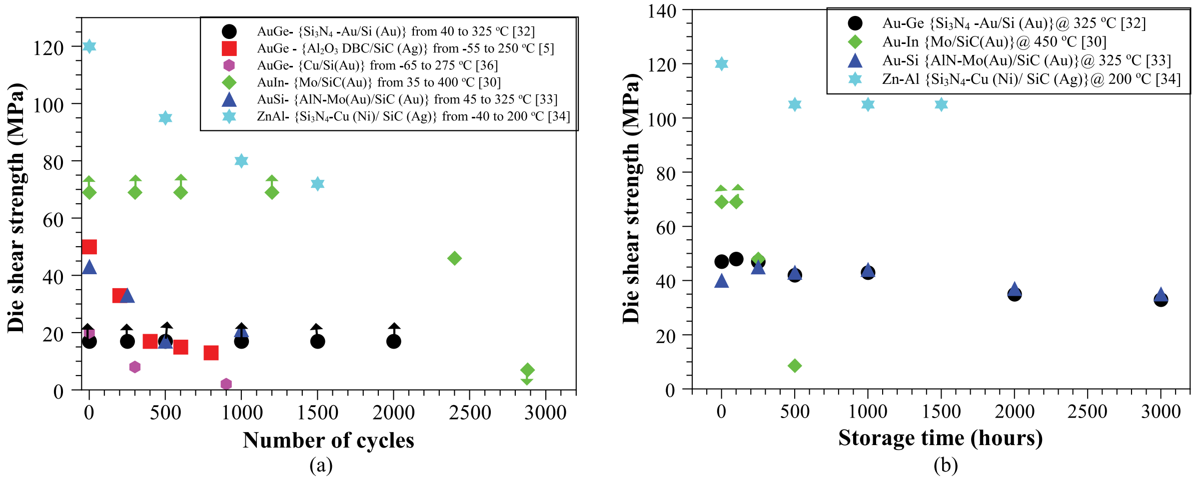
where $\Delta\alpha$ is CTE difference between the two attached materials, ΔT is the temperature variation, a is related to the joint length, and h is the joint thickness.

We note that, as aforementioned for the substrates thermomechanical reliability results, the temperatures variation, the ramping rate as well as the holding time at the higher and the lower temperatures are not identical, making the comparison between different results less straightforward.

1) Organic Die Attach: Generally, Ag-filled organic die attach materials can be used for applications ranging from −60 °C to potentially 225 °C. However, according to the datasheets, some of organic adhesive materials owning high glass transition temperature are announced for temperature as high as 300 °C [29]. To the best of authors' knowledge, those adhesives have not been investigated for working temperature above 250 °C. Apart of the thermal degradation of the organic die attach, one of the main disadvantages of those materials is their low thermal conductivity (about ten folds lower than classical solders).

2) Solder Die Attach: Most of research works dealing with high-temperature solders are based on alloys with a high gold (Au) concentration even if they are very expensive compared to lead-based solders. It is believed that in order to have reliable solder joint, solders can be used up to 80% (temperature in K unit) of their melting temperature before creep effects lead to a fast degradation [7], [8]. AuGe and AuSi have eutectic melting point of 356 and 363 °C, respectively, making them very suitable for high-temperature applications. AuIn with a melting temperature of 521 °C has been also investigated [30]. Results of shear strength variation during thermal storage and thermal cycling tests obtained from different research works are presented in Fig. 1(a) and (b) [5], [31]–[36]. Using AuSi alloy, the shear strength decreased during the first 500 thermal cycles (from 45 to 325 °C), then remained relatively constant after 1000 cycles. This has been explained by Si crystal growth at high temperature due to the Au and Si very limited solid-state solubility [31], [35]. Unlike other AuGe reliability tests, the results of [36] in Fig. 1(a), where the Ni is present in the die metallization scheme, show a strong decrease during thermal cycles. This can be due to the noncompatibility between the AuGe and the Ni for high-temperature applications because of the brittle Ni–Ge intermetallic formation [37]. For the same reason, it has been found that the In is not compatible with copper. In the case of Au–In, the classically used Ni barrier layer is not effective [22], [38] and a diffusion barrier layer able to withstand temperatures of about 520 °C should be used. In addition, Au–In brazed joints stored at 450 °C also showed segregation of In to the surface of internal voids formed during the initial die attach brazing process. This In segregation is thought to be the cause of the degradation in shear strength during the aging at 450 °C [30]. On the other hand, AuGe and AuSi show a good stability during thermal storage at 325 °C. ZnAl solder own a high melting point (382 °C) and a low cost, but its use at high temperature was limited by two major problems: the low substrate wettability and self-fracturing of the solder layer after soldering [39]. Significant improvements of the wettability and of the solder state after soldering have been obtained [34], [40]. ZnAl shows good stability during storage at 200 °C. However, bulk plane fractures are observed after 1500 thermal cycles between −40 and 200 °C leading to a decrease of the shear strength of about 35% as illustrated in Fig. 1(a) [34]. Apart the AuIn final data, all values remain in agreement with the MIL-STD-883H standard [41] concerning die shear tests where shear forces must exceed 5 kgf for dies with areas ≥4 mm^2. Those results show that, except AuIn, the other presented high-temperature solders can be used reliably by using appropriate metallization schemes.

3) Transient Liquid-Phase Bonding: In TLPB, the first metal owning a low melting temperature (In, Sn) is sandwiched between two layers of a base metal with high melting temperature (Cu, Au, Ag, Ni). During the bonding process at temperature above the liquids of the first metal, sandwiched structure is held under low static pressure (several kPa) to ensure intimate contact. The first melted element reacts with the base metals and creates intermetallic compounds until its complete consumption. The remelting temperature of the joint rises from



(a) (b)

Fig. 1. Variations of die shear strength during thermal cycles (a) and thermal storage (b) for different solders. Arrows presented on symbols indicate that the die shear strength is higher than the indicated values (limited by the test equipment). In the graphs' legend, materials used are noted between brackets and a—symbol separates the two assembled materials. The finish layer is represented between parentheses.

the melting point of the interlayer to the melting point of the intermetallic compound.

Using this technique with well-defined metallic layers and bonding conditions, shear strength values higher than 60 MPa can be obtained [33], [42]. The Au–Sn has been tested during thermal storage at high temperatures of 400 and 500 °C. The shear strength values remain higher than 60 MPa after 2000 h of storage at 400 °C [22]. At 500 °C, the shear strength shows a decrease of about 50% during the first 500 h and remains stable until 2000 h with values higher than 30 MPa [33]. Modules fabricated by the use of TLP Au–Sn technique have been thermally cycled from −55 up to 200 °C without any cracks or delamination [26]. Yet, an improvement of the die shear strength has been reported by Mustain *et al.* after an annealing of 100 h at 400 °C using Au–In TLP as die attach [43]. The Ag–In has been tested after ten thermal cycles between −55 and 400 °C and the shear strength level remains higher than the aforementioned military standard requirement [41], [43]. Yoon *et al.* have investigated Ni–Sn TLP for Si die assembled to a DBC substrate, and the joint has passed 1000 thermal cycles between −40 and 200 °C without any delamination [44]. Accordingly, this technique seems to be very promising for high-temperature reliable die attach. However, cost and oxidation issues are the main deficiencies when using Au and In materials respectively.

4) Micro- and Nanosilver Paste: The paste contains dispersant, binder, and thinner that are added to Ag particles, respectively, to produce a paste with good particle dispersion, flowability, and adequate viscosity for screen printing [45]. Heat and pressure are applied to the paste. After the dispersant depletion, the sintering can proceed due to the driving forces provided by surface energy of the Ag particles and the applied external pressure [46]. By reducing the Ag particles size to the nanometer scale, sufficient driving forces for the sintering process are achieved and lower pressures can be allowed [47]. The properties of the sintered silver joint have been extensively investigated. The electrical resistivity of the silver joint is lower than conventional solders and values between 2.5 and 10 $\mu\Omega \cdot \text{cm}$ have been reported (silver bulk 1.6 $\mu\Omega \cdot \text{cm}$) [48]–[51]. The typical thermal conductivity values of the sintered joint are about fivefolds higher than conventional solders [52] and vary in the range of 200 to 300 W(mK)^{-1} [49], [53]–[55]. The main drawback of this technology was the need of pressure that makes the process somehow complicated. Recently, newly developed pastes able to be fired without pressure were commercialized, which make nanosilver paste a very promising technology.

The effect of storage at 250 and 300 °C in air on the die shear strength has been investigated, and no significant variation in the die shear strength has been observed after 500 and 400 h, respectively [55], [56]. This allows us to consider that the storage at temperatures at least until 300 °C did not lead to reliability problems. The ability of nano-Ag joint to operate in thermal cycling application has been the subject of different investigations. In [57], nano-Ag joints have passed 800 thermal cycles between −40 and 125 °C without any significant changes in the microstructure and without cracks apparition. For larger thermal cycles between −5 and 175 °C, the silver joint sintered in good conditions can survive about 1000 cycles, while 70 and 150 cycles have been passed by $Sn_{96.5}Ag_3Cu_{0.5}$ and $Pb_{95}Sn_5$, respectively [8]. For larger temperature variation (from −55 to 175 °C), the silver joint can pass 600 cycles without failure compared to 40 and 80 cycles for $Sn_{96.5}Ag_3Cu_{0.5}$ and $Pb_{95}Sn_5$, respectively [8]. Compared to AuGe solder, a decrease of the die shear strength from 50 to 15 MPa after 400 thermal cycles between −55 and 250 °C is obtained, while the die shear strength of silver sintered joint varies from 25 to 15 MPa [56]. It is believed that the good thermomechanical reliability of the sintered silver is mainly due to its low elastic modulus. In fact, the nanosilver joint shows modulus values between 6 and 9 GPa that are lower than those of commonly used solder alloys and represents about 12% of the elastic modulus of the silver bulk [58], [59]. This reduced elastic modulus (explained by the presence of pores in the sintered structure) leads to a better mechanical buffer layer since it transfers less of the thermally induced stresses from the

CTE mismatch between the semiconductor and the substrate. However, a gain in lifetime by decreasing the density of the sintered joint, consequently its Young's modulus, is not mandatory [8]. This can be related to the strength of the interface between chip and sintered silver than can also have an impact on the joint reliability.

The electromigration of Ag ions is the main disadvantage of the nanosilver die-attached technology. This mechanism has been observed for nanosilver joint and had shown a temperature and field dependence [60]. During the migration, the propagation of silver dendrites continues until they bridge the gap between adjacent electrodes leading to a sudden decrease in resistance. Oxygen plays an initial role in the migration mechanism, and it was found that the lifetime of the sample could increase about 25-fold if the oxygen partial pressure is reduced from 0.4 to 0.03 atm [61]. Accordingly, the electromigration reliability of silver ions at high temperatures can be significantly improved by the use of a protective coating allowing the reduction of oxygen concentration at the nanosilver joint. Due to its thermomechanical reliability as well as the pressure-free developed paste, this technique is also a very promising die attach alternative.

C. Interconnections

In power modules, the most common die interconnection technology is wire bonding. In the last decade, and in order to overcome the shortcoming of wire bonds, 3-D packaging technologies for high density and high-temperature applications have been developed using different processes. Most of those technologies remain laboratory scale experience and reliability results above 200 °C are still very limited. In the next, we will focus the review on the reliability of two interconnection technologies: wires bonding and gold stud bumps.

1) Wire Bonding: In power electronic packages, wire bonding is used for the electrical connection between the chips and with the output pins. Much studies deal with the Al wire bonding failure on the Al pad of the IGBT transistor for power transmission and traction applications. In order to produce consistently high-quality bonds, bonding parameters, such as bonding time, power, and force, need to be adjusted according to the wire size. Prior to any thermomechanical stresses, it has been shown that bonded wires contain a certain amount of damage, brought about by deformation-induced work hardening, a result of the ultrasonic energy and force used during the formation of the bond [62]. In addition to the damage induced during bond formation, bond wires flex during loop formation, and typically, this can result in heel cracks or precracks, which unzip at the interface between the wire and metallization [63], [64]. Mainly two kinds of failures of wire bonds have been reported: the heel crack failure which originates from bending caused by thermal expansion or by mechanical deformation of the wire, and wire lift off as a result of material fatigue at the chip metallization caused by shear forces (CTE mismatch between the chip and the wire). In fact, the highest thermomechanical stress occurs at the wires termination where the locally caused strain initiates a crack. Fatigue failure is accelerated if a microcrack is present at the heel of the wedge bond due to excessive neck down at the heel during bonding, or poor bond shear strength resulting from surface roughness. It has been reported that the number of cycles to heel crack failure has been shown to strongly depend on the loop geometry [65].

Even if cracks at the interfaces appear after several thousands of cycles from −40 to 150 °C, It has been shown that Al wires bonded on Al pad exhibit some capabilities to operate at temperatures in excess of 200 °C [66]. During cycling from −40 to 150 °C and −40 to 250 °C, no variation in the crack propagation has been observed even if the temperature variation ΔT is higher in the second profile [66]. In addition, another study showed that slower wear out rates have been obtained when the maximal temperature is higher even if ΔT is also higher [67]. Those results have been explained by the thermally activated phenomena that take place at sufficiently high-peak cycling temperatures and remove some of the accumulated damage. Accordingly, from a thermomechanical point of view, aluminum wire bonds may be suitable for high operation temperatures on Al pad, due to the benefit released at high temperatures. However, Al–Au interface on the DBC metallization (Cu with NiP–Au or Ni–Pd–Au finishing) causes intermetallic formation and Kirkendall voiding. The Kirkendall effect is the motion of the boundary layer between two metals that occurs as a consequence of the difference in diffusion rates of the metal atoms. Both of these problems can lead to increasing contact resistance over time at the bond interface until the complete failure of the interconnection. The two mentioned problems could be avoided by the use of same nature of wire and metal pad. Au wires can be used but move the problem to die Al pads. A Ni/Au plating approach was investigated to cap the Al pad layer. Ni provides a diffusion barrier between Al and Au. The zincate, electroless Ni, and immersion Au-plating steps are maskless process, which is compatible with postwafer processing. The Ni barrier layer (nominally 3 μm thick) was effective in preventing Au–Al diffusion through 10 000 h at 300 °C [32]. Johnson *et al.* have investigated large diameter Au wire of 250 μm on Cu/Ni/Au alumina substrate and on SiC die (SiC/SiO$_2$/Ti/TiW/Au) during thermal storage at 300 °C [68]. It has been reported that the average pull and shear strength of the gold wire bonds decreased during the first 500 h of aging, which was caused by annealing of the Au wire. After this, the pull and shear strength both remained relatively constant throughout the remainder of the test. Large Pt wires of 250 μm on Cu/Ni/Au alumina substrate have shown good reliability during storage at 300 °C for 2000 h (see Fig. 2). On the other hand, for the Pt wire bonds on SiC die (SiC/SiON/Ti/Pt/Au), 5 of 14 wire pulls resulted in lifts after only 250 h of aging at 300 °C and all failed by lifts after 500 h of aging [68]. The failure mode was the fracture of the SiON layer, which lifted from the SiC surface (cratering) due to the excessive bonding parameters needed to bond the hard Pt wires. The use of Ni wires on Ni pads deposited on 3C-SiC by the use of thermosonic, and ultrasonic bonding techniques have been also investigated by Burla *et al.* [69]. In the two cases, research works show that the wire bonds pass the pull tests military standards up to 400 °C with a better bonding

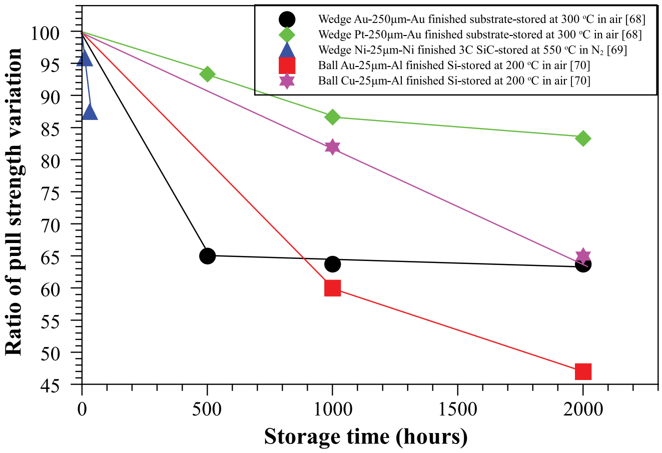


Fig. 2. Variations of the ratio of pull strength to the initial one during the storage at different temperatures. The bonding technique, wire metal, wire thickness, the finish layer, and the storage temperature are indicated in the graph legend.

strength for thermosonic bonded wires. Samples were annealed at 550 in nitrogen for 30 h. Some samples were also subjected to 30 cycles from room temperature up to 500 °C with a ramp of 2.5 °C/min. After annealing and temperature cycling, each sample has been subjected to destructive pull tests performed at room temperature. The average pull strengths greatly exceeded the military specifications. We note that the Ni wire bonding requires very smooth surface and the roughness of the deposited Ni has been reduced from 40 to 2 nm in [69]. However, the use of Ni wires for power electronics remains limited since the required roughness values are very difficult to achieve on DBC substrate. Cu wires bonding are rapidly developed for power electronics.They can have some advantages for high temperature electronics like their lower diffusion coefficient (slower intermetallic compounds) and more compatible CTE (17 ppm/C) compared to Al wires. On the other hand, the copper hardening and the higher Young modulus are the drawbacks of Cu wire bonding during thermal cycles. Fig. 2 summarizes results of the ratio of pull strength during the storage at different temperature to the initial one for different wires metal, bonding technique, diameters, and pad finish [68]–[70]. It is clear that, when the Al pad is used with Au and Cu wires, the formation of the brittle intermetallic compounds leads to the decrease of the pull strength during the storage at temperature as low as 200 °C.

2) Gold Stud Bump: In this technique, the Au bump pattern is thermosonically bonded to the base of the package using a conventional thermosonic wire bonder. The die is then positioned over the bump pattern and bonded using time, temperature, and pressure as parameters. Alternately, the bump pattern could be plated onto the back of the SiC wafer prior to sawing. The bumps assembling the SiC devices on Ni/Au plated DBC substrates (Al_2O_3) have been aged at 500 °C and about 30% decrease of the shear strength is observed after 500 h [31]. However, a decrease of about 75% of the shear strength has been reported after 1000 thermal cycles from 45 to 325 °C [31]. This solution could be promising for high-temperature applications if the CTE mismatch between the chip and the substrate is minimized.

D. Encapsulation

Polymeric soft encapsulation materials have been widely used in electronic packaging industry to protect the power module components from external environmental damages, such as moisture, solvents, gases, and radiations. In addition, encapsulation materials are also expected to improve the voltage ratings of the packages in high-voltage modules (>1000 V) and to prevent arcing at high voltages. The need of high-temperature applications poses challenges to conventional encapsulation materials mainly designed for Si conventional module and limited at temperatures lower than 200 °C. Therefore, identifying new materials for higher temperature application is mandatory. Without considering hermetic packaging where gases, vacuum, and liquids can be used as dielectrics, three types of materials might be suitable for high-voltage high-temperature power electronic packaging: glasses, hydroset ceramics, and polymers. The materials should be processable and compatible with the module structure. In the next, a short description of the characteristics of each of the three materials type including their advantages and drawbacks is presented. Finally, in Section II-D4, results on the reliability issues of different materials tested by different research works are presented and discussed.

1) Glasses: Glasses can work at high temperatures and own good chemical stability and good dielectric properties. The powder of glasses is mixed with liquids in order to form a paste that can be deposited by different techniques like screen printing, spin coating, dispensing, etc. The main disadvantages of these type of materials are their high firing temperature that exceeds the 500 °C and their high Young modulus causing high thermomechanical stresses. Borosilicate glasses seems to be the most suitable for power electronics application with high glass transition temperature, low CTE, and relatively low firing temperature of about 600 °C. Such temperatures remains sufficiently high and can affect the semiconductors metallization properties as well as the component reliability [71], [72]. This can explain why glasses are not investigated as dielectric encapsulation for power modules.

2) Hydroset Ceramics: The second type of materials refers to hydroset ceramics. They can be used at temperatures higher than 1000 °C and own good chemical stability and good dielectric properties. The powder is mixed with an activator (generally water) and stirred until having a paste that can be easily deposited. Compared to glasses, the main advantage of the hydroset ceramics is their low curing temperature that can be done at room temperature. However, those ceramics own a high Young modulus (>100 GPa) and a CTE between 3 and 6 ppm/°C that can engender high stresses in the structure and cause severe reliability problems if the CTE between different used materials are not matching.

3) Polymers: Polymeric encapsulation is the third type of materials and can be divided into two categories: soft and hard encapsulation. Soft encapsulation materials have a glass transition temperature *Tg* lower than the lowest operating temperature.

TABLE II
EFFECT OF THERMAL STORAGE AND THERMAL CYCLE ON SOME TESTED ENCAPSULATION

Materials (type)	Initial problems	Thermal storage tests	Thermal cycles tests
Resbond 919 (hydro-set ceramic)		OK for 260 h at 250 °C [77]	Small cracks at the surface after 250 cycles (−55–200 °C) [77]
Resbond 920 (hydro-set ceramic)		OK for 260 h at 250 °C [77]	No cracks after 100 cycles (−55 −200 °C) [77]
Epo-tek 600–2 (screen printable polyimide)	Adhesion problems and shrinkage after curing at 250 °C [6]		
Durapot 862 (epoxy)		OK for 430 h at 250 °C [77]	Deep cracks after 50 cycles (−55 −200 °C) [77]
Durapot 863 (epoxy)		OK for 430 h at 250 °C [77]	Deep cracks after 50 cycles (−55 −200 °C) [77]
Duraseal 1533 (silicone elastomer)	Adhesion problems after curing at 250 °C [6].	OK for 430h at 250 °C [67].	No cracks after 250 cycles (−55− 200 °C) [77].
Nusil EPM 2421 (silicone gel)		Complete degradation after 140 h at 220 °C [6].	
Nusil R-2188 (silicone gel)		OK for 400 h at 220 °C [6]	
Nusil 8250 (silicone gel)		Cracks after 100 h at 250 °C [11]	
Qsil 556 (silicone elastomer)		OK for 500 h at 250 °C [11]	

Therefore, the material operates in its rubbery state and is soft, exhibiting a high CTE with a very low Young modulus in order of several millipascal. Silicone gels belong to these kind of polymers and are widely retained for encapsulating high-voltage multichip power assemblies, due to their very high softness and high-insulating electrical properties. However, the literature review shows that high-temperature commercially available silicone gels exhibits at maximum temperature limit for continuous service less than 250 °C. The review also reveals that a tradeoff between high temperature ability and softness of silicones generally exists. In fact, a slight extension of the temperature range (up to 275 °C) might be obtained with the use of silicone elastomers, with slightly higher material hardness measurable on Shore A. The second category has Tg higher than the highest working temperature. Materials work in the glassy state and are thus relatively hard and exhibit a low thermal expansion and a relatively high Young modulus (several GPa) [73]. The reliability of some of the second category polymers (like polyimide BPDA-PDA and PA-HT) tested at temperature exceeding the 300 °C seems satisfactory [74], [75]. However, the deposition technique of the former and the limited thickness (50 μm) of the latter (deposited by polymer vapor deposition) limited their use at the wafer level. In addition, benzocyclobutene BCB polymers are candidates and are stable at temperature above 300 °C, but the major issue encountered for thick films is the void generation during the curing process [76].

4) Reliability of High-Temperature Encapsulation Materials: Different types of potential encapsulation materials have been tested at initial time, during thermal storage and or during thermal cycles. Results on the encountered problems, the lifetime during thermal storage and thermomechanical cycles as well as the failure types are listed in the Table II. It is clear that in most cases, the hard materials such as epoxy or hydroset ceramics present reliability problems under thermal cycles where cracks appear [77]. Silicone gels present problems during the thermal storage due their limited thermal stability [3], [8]. The silicone elastomers seem to present a compromise between the hardness and the thermal stability and are suitable for 250 °C applications [11], [77]. For higher temperatures, encapsulation materials will be a serious problem and materials development seems primordial. The development of module structure can also provide benefits since it allows the use of different techniques to ensure the encapsulation and hence allow the use of new kinds of materials.

III. CONCLUSION

This paper has presented at length, a survey on the reliability of packaging components for high-temperature power module applications. Components include the substrate, the die attach, the interconnection, and the encapsulation. Substrate with low-CTE conductors and Si_3N_4 ceramic with Cu metallization seem to the most potential candidates. For the die attach materials, gold-based solder can be used until 300 °C if finishing metal layers on the die and substrates are well selected (to avoid the formation of weak intermetallic). For higher temperatures, nanosilver paste and the transient liquid-phase bonding are more appropriated since their melting temperature can be higher than 400 °C. The Au and Al wires can ensure reliable interconnection if the pad and the wire are formed from the same metal. Gold stud bumps can also be a potential alternative. Apart those two interconnection techniques, reliability results on the 3-D technologies using different interconnection schemes are still lacking. Finally, the encapsulation is one of the most limiting components for high-temperature application since hard materials present thermomechanical reliability issues and soft materials present low thermal stability. Silicone elastomers are potential candidates up to 250 or 275 °C. However, for higher temperatures, reliable solutions are still missing. In addition, authors are aware that other commonly used components like the thermal interface material and the plastic housing present reliability issues at high temperature but have not been addressed in this paper.

As an output of this paper, a set of materials and combinations allowing the fabrication of prototype with potential good reliability at high temperatures can be selected. Nevertheless, this area of research is attracting researchers of electronic packaging all around the word to solve the remaining issues at different packaging levels.

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