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Toward a Reliability Analysis Method of Wide Band Gap Power Electronic Components and Modules

Guillaume PARENT[1, 2], Gregor MASSIOT[1], Vincent ROUET[1], Catherine MUNIER[1]
Paul-Etienne VIDAL[2], and Francisco CARRILLO[2]

[1] EADS Innovation Works, 12 rue Pasteur, 92150 Suresnes, France
[2] Ecole Nationale d'Ingénieurs de Tarbes (ENIT), 47 avenue d'Azeirex, 65000 Tarbes, France

Corresponding Author: +33146973241, guillaume.parent@eads.net

Abstract

This study is addressing on the reliability of COTS (Commercial Off-The-Shelf) power electronic components and modules which could be used in high reliability systems such as aerospace systems. This paper details the first followed steps to achieve a reliability assessment of some COTS power devices. These first steps are:

- Construction analyses for the determination of the packaging assembly technologies of COTS power devices;
- Discussion on the material used in COTS power devices;
- Synthesis of the potential failure risk analysis under harsh environments;
- Determination of several accelerated ageing tests to check the potential failure modes and mechanisms in power electronic for aerospace systems.

Key words: Reliability, COTS, power electronic components and modules, construction analyses, assembly technology.

1 Introduction

COTS power devices arouse the interest of EADS (European Aeronautic Defense and Space Company) group, because they could provide several developments of assembly technologies in terms of diversification. Some of these technologies could match the requirements of high reliability systems such as airplanes, helicopters and satellites. Therefore, the reliability assessment of COTS power devices is required.

The study presented here is one the first steps to assess the reliability of COTS power devices in harsh environments for long life time applications. This allows selecting promising assembly technologies for the power equipment of aerospace applications. This paper will present:

- Some construction analyses for the determination of the assembly technologies of COTS power devices;
- A discussion about the materials used in COTS power devices;
- A synthesis of the potential failure risk analysis under harsh environments;
- And a determination of several accelerated ageing tests to check the potential failure modes and mechanisms in power electronics for aerospace systems.

2 Construction analyses

Some COTS components integrating a SiC die have been selected for their main electrical and thermal characteristics among main packaging assemblers of power devices. These main characteristics match the requirements of the aerospace systems. The studied COTS devices are presented in the table 1.

These COTS components and modules were subject to construction analyses which allowed determining the used assembly technologies. These construction analyses are divided in two classes: the Non-Destructive Analysis (NDA) and the Destructive Physical Analysis (DPA). The NDA techniques used were X-ray analyses and Scanning Acoustic Microscopy (SAM). As for DPA techniques, the micro-section method is being adapted to the power devices integrating SiC semiconductor due to the hardness mismatch between the different materials in power devices.

In a first step, it was noticed that COTS power electronic components from different packaging assemblers are composed of the same main elements presented in

figure 1: die soldered on a baseplate, wire bonds between die and pins, and a molding compound.

Part number	*Packaging assembler*	*Type of component*	*Die material*	*Number of die*	*Type of package*
1	A	Schottky diode	SiC	1	TO-247
2	A	Schottky diode	SiC	2	TO-247
3	B	MOSFET transistor	SiC	1	TO-247
4	B	MOSFET transistor	SiC	1	TO-247
5	B	Schottky diode	SiC	1	TO-220
6	B	Schottky diode	SiC	2	TO-247
7	C	Schottky diode	SiC	1	TO-247
8	C	Schottky diode	SiC	1	D^{2}PAK

Table 1: Presentation of the studied parts.

Part number	*Interconnection*	*Die metallization*		*Solder type*	*Intermetallic compound*			*Comments & manufacturing defects*
		Top	Bottom		Interface die/solder	Bulk	Interface solder/baseplate	
1	Al wire	Al	Ti-Ni-Cu	Sn-Ag-Sb	Cu_6Sn_5	Cu_6Sn_5, Cu_3Sn, Ag_3Sn	Cu_6Sn_5, Cu_3Sn	Die fragment missing
2	Al wire	Al	Ti-Ni-Cu	Sn-Ag-Sb	Cu_6Sn_5	Cu_6Sn_5, Cu_3Sn, Ag_3Sn	Cu_6Sn_5, Cu_3Sn	-
3	Al wire	Al	Ti-Ni-Cu	Sn-Ag-Sb	Cu_6Sn_5	Cu_6Sn_5, Cu_3Sn, Ag_3Sn	Cu_6Sn_5, Cu_3Sn	Voids in solder
4	Al wire	Al	Ti-Ni-Cu	Sn-Ag-Sb	Cu_6Sn_5	Cu_6Sn_5, Cu_3Sn, Ag_3Sn	Cu_6Sn_5, Cu_3Sn	Voids in solder
5	Al wire	Al	Ti-Ni-Ag	Pb-Sn-Ag	-	-	-	-
6	Al wire	Al	Ti-Ni-Ag	Pb-Sn-Ag	-	-	-	-
7	Al wire	Al	Ti-Ni-Cu	Pb-Sn-Ag	-	-	-	Voids in solder
8	Al wire	Al	-	Pb-Sn-Ag	-	-	-	-

Table 2: Identified materials in the different parts of this study.

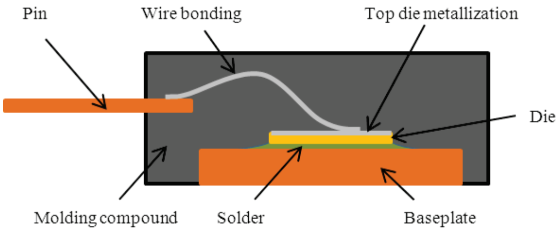

Figure 1: Main elements of a COTS power electronic devices

For DA, the used analysis techniques were optical microscopy and Scanning Electronic Microscopy (SEM) coupled with Energy Dispersive X-Ray (EDX) on micro-sections. Consequently, some materials were identified and they are summarized in the table 2. Several main features of the materials such as intermetallic compounds created during the soldering process are also indicated in the table 2.

2.1 Non-destructive analyses (NDA)

X-ray analyses highlighted the voids in solder as illustrated in figure 2. These kinds of observations have not been achieved for all parts due to the higher absorption of X-ray by the thick Cu baseplate than the other materials and the lowest X-ray absorption of Si and Al materials in presence.

The SAM analyses were performed in reflection mode. This means that the transducer is both source and detector of ultrasound signal.

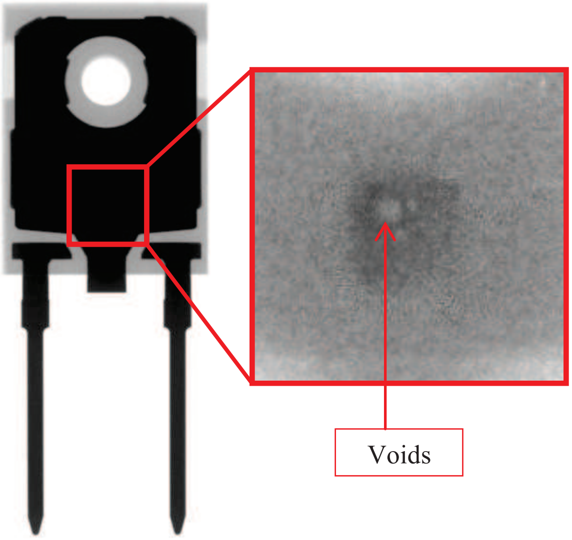

Figure 2: RX images showing voids in the solder die attach of the part 7.

With SAM analyses, the quality of the interfaces such as delamination, roughness and the presence of voids is investigated.

The first SAM analyses have been performed from the surface of the molding compound to the baseplate (top view). The thick molding compound (resin and fillers) requires an ultrasound frequency which allows a high ultrasound penetration with a good spatial resolution. With this method, the analyses of the interfaces molding compound/other element were achieved (figure 3), but no information about the interfaces die/solder, solder/baseplate and voids presences has been extracted. This is due to the ultrasound scattered by the molding compound. The red rectangle of the figure 3 shows a potential defect on a die interface.

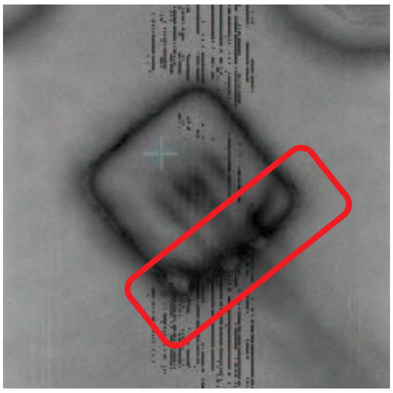

Figure 3: SAM image of the part 1 die – From top

Therefore, several analyses were performed from the baseplate side to the molding compound side (bottom view). The presence of several voids was observed in the solder (figure 4).

To confirm these observations, the micro-sections of the studied parts were performed.

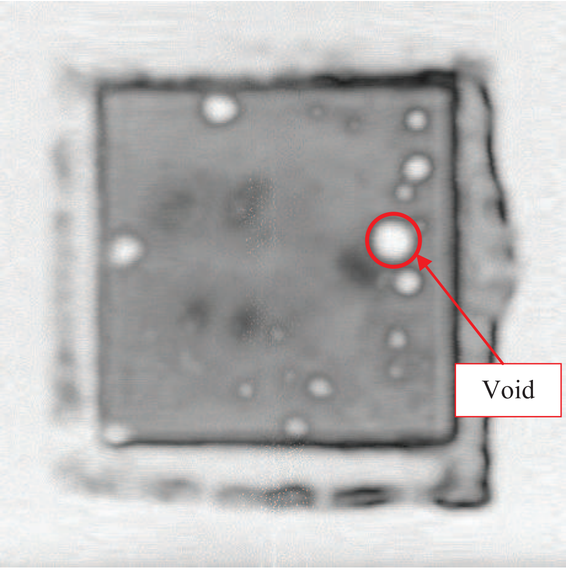

Figure 4: SAM image of the part 4 showing the presence of several voids in the solder (From bottom)

The next investigation could be study of the void impact on the power dissipation.

2.2 Destructives analyses (DA)

The micro-section of the part 1 highlighted a missing fragment of the die bottom side (figure 5). This observation confirms the defect detected by the SAM analyses (cf. figure 3).

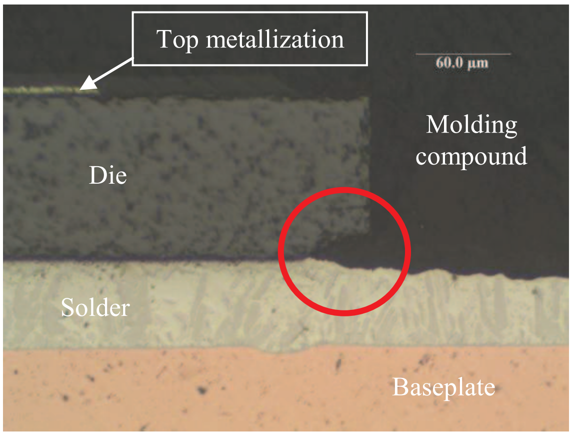

Figure 5: Optical image of the micro-section of the part 1 showing a die fragment missing

The micro-sections of the studied parts have been performed with a classic mechanical polishing process of electronic component: use of polishing papers with SiC grains. It was observed that the die bulk and edges were greatly damaged for all parts (figure 6, (a)). This result was due to the same or very close hardness between the used polishing paper and the die material.

Several tests of polishing using diamond discs have been carried out. Effectively, the hardness of diamond is higher than SiC semiconductor. This polishing method seems to be promising (figure 6 (b)). It allows decreasing the damage of the die bulk and edges. These improvements are very important because the die fragments damage the interfaces and bulk of materials stack and sometimes stay insert in the ductile materials. Moreover, this method allows keeping a better flatness of the micro-section particularly close to the die.

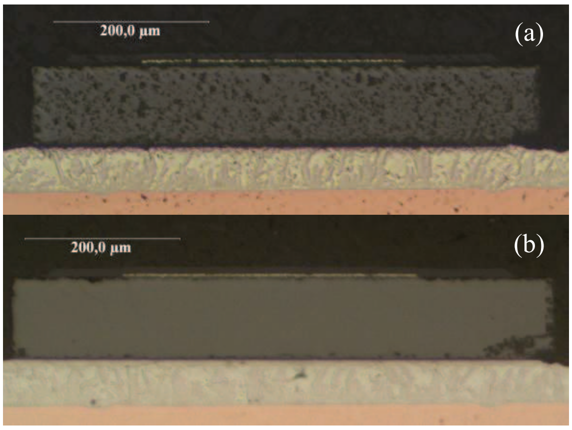

Figure 6: Optical images of the micro-section of the part 1, (a) classical polishing (SiC polishing paper) of devices, (b) polishing with the diamond discs

The composition analyses of the materials have been performed by Energy Dispersive X-ray (EDX) on the micro-sections (cf. Table 2). The figure 7 illustrates the EDX analyses by a mapping of the material stack. The different materials are from the top to the bottom of the figure 7: die (SiC), bottom die metallization (Ti-Ni-Cu), solder (Sn-Ag-Sb) and baseplate (Cu).

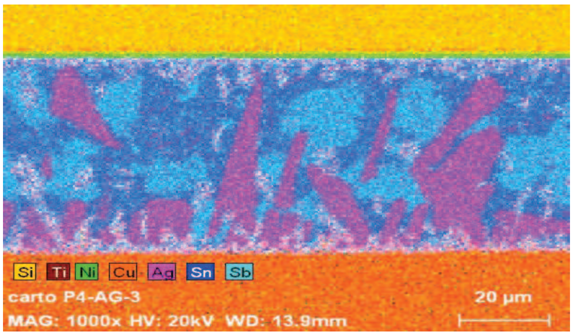

Figure 7: EDX mapping of the material stack of the part 1 at level of the solder

3 Discussion on the materials used

The table 3 presents the CTE (Coefficient of Thermal Expansion) mismatch between the different materials included in the materials of COTS components. All the studied COTS components had an Al top die metallization and Al wire bonding and a copper baseplate whatever the other elements. Therefore, the CTE compatibility of the material only depends on the kind of the die and the solder. In the table 3, the data of the die metallization material is given for a bulk material because the CTE of thin films depends on their thickness [1].

Element	*Material*	*CTE (ppm.K^{-1})*
Interconnection	Al	23.2
Top metallization	Al	23.2
Die	Si SiC	2.6 3.4
Bottom metallization	Ti Ni Cu / Ag	 13.5 16.1 / 19.0
Solder	SnAgSb PbSnAg	27 to 36 27 to 30
Baseplate	Cu	16.1

Table 3: CTE at 300 K [2]

3.1 Die material

The bottom die metallization is a coupled system of three coatings: Ti-Ni-Cu or Ti-Ni-Ag following the studied parts. Each coating has its own function [3]:

- Ti: adhesive coating;
- Ni: under-layer for the formation of a mechanical bond between the solder and the die;
- Cu or Ag: guard of the Ni under-layer against oxidation during the soldering process of the die. It leads to the preservation of the solderability of the Ni under-layer.

3.2 Solder

For solder alloy, the CTE depends on the composition of the solder. Several solder alloys in industry might be used in the studied parts (Table 4). The solder alloys with more than 85%wt. of Pb are not affected by the RoHS directive (Restriction of the use of certain Hazardous Substances).

Another important point to highlight is that SnAgSb alloy is used as alternative to Pb based solder for die attach.

Solder alloy	*Elemental composition (%wt.)*	*Melting point (°C)*	*CTE (ppm.K^{-1})*
SnAgSb	Sn96.2-Ag2.5-Cu0.8-Sb0.5	225	27
	Sn65-Ag25-Sb10	233	36
PbSnAg	Pb97.5-Ag1.5-Sn1	309	30
	Pb95.5-Ag2.5-Sn2	304	-
	Pb92.5-Sn5-Ag2.5	296	29
	Pb90-Sn5-Ag5	292	27
	Pb88-Sn10-Ag2	290	29

Table 4: Different industrial solder alloy for die attach [2], [4], [5]

The addition of Sb in SnAg(Cu) solder has several advantages over SnAg:

- Slow down the growth of the intermetallic compounds (Cu_6Sn5) [6], [7];
- Increase the fatigue resistance of the alloy [8];
- SnSb IMC (InterMetallic Compound) formation increases the creep resistance [9].

The chemical composition of the lead-free solder used as die attach was not exactly determined due to:

- The rapid dissolution and diffusion of the copper in the solder during the soldering process which change the composition of the alloy [10];
- The low thickness of die attach solder.

3.3 Molding compound

The molding compounds are composed of a resin and fillers. The resin could be an epoxy or phenolic resin. These polymers are widely used for semiconductor encapsulation due to their mechanical, electrical, chemical and thermal performances [11].

The molding compound composition translates the resistance against moisture absorption of the power devices. The moisture absorption rate is an important data to evaluate the device susceptibility of failure mechanism in humid environment. The first data allow classifying the molding compound of the studied parts in two categories (Table 5):

- Low absorption molding compound (LA): $0.4 < \%_{Absorption} < 0.6$;
- Very low absorption molding compound (VLA): $\%_{Absorption} < 0.4$.

For the part number 8, there was no noticeable change of weight during the first test.

Category	*LA*	*VLA*
Studied part number	1, 2, 3, 4, 5, 6	7

Table 5: Classification in two categories of the studied parts depending on the moisture absorption

Therefore, there will be a study to investigate the molding compound characteristics in depth: chemical composition, mechanical and thermal properties, moisture absorption rate. These will allow developing a method for the chemical opening of the plastic package and to perform a complete failure risks analysis of the power electronic devices for long term storage applications.

4 Synthesis of failure risk analysis

Thanks to the construction analyses and the available literature data, the potential failure modes and mechanisms in accelerated ageing tests were established. The failure risk analysis has taken into account the following points:

- the material mismatch behavior under high environmental constraints (coefficient of thermal expansion, diffusion phenomenon, corrosion, etc.);
- the assembly technologies used;
- the mastering of assembly processes.

The COTS components and modules could meet different failure modes and mechanisms under specific harsh environments. The harsh environments encountered by aerospace and military systems are a high humidity, a high temperature, thermal cycling and combination of them.

Some failure modes and mechanisms could be created during the mission of aerospace systems. The table 6 presents several failure modes and physicochemical mechanisms linked to the device's elements under the above mentioned environments.

Several accelerated tests have been defined to reproduce these modes and physicochemical mechanisms in COTS power devices.

Environment	***Humidity***	***Thermal cycling***	***High temperature***
Physicochemical mechanisms of ageing (Material identified prone to be affected)	Corrosion (Al wire bonding and top die metallization [12]) Popcorning (molding compound [13]) Ionic contamination Electrochemical migrations	Nucleation and growth of intermetallic compounds & phases, coalescence, recrystallization Chemical evolution of plastic materials Fatigue substrate [14] Fatigue of bond wires & die attach material [15], [16]	Nucleation and growth of intermetallic compounds & phases, coalescence Chemical evolution of plastic materials [17]
Main failure modes	Short-circuit (corrosion, electrochemical migrations) Opened circuit (popcorn, corrosion)	Opened circuit (Fatigue of bond wires & die attach material)	Opened circuit

Table 6: Modes and physicochemical mechanisms linked to the device's elements under the main environments met in aerospace applications.

5 Accelerated ageing tests considered

The accelerated ageing tests have been defined to match several stresses which could be met in the different kinds of aerospace applications. The accelerated ageing tests are:

- High Humidity, High Temperature Reverse Bias (H_3TRB);
- Humidity Popcorn Effect Test (HPET);
- High Temperature Reverse Bias (HTRB);
- Power cycling (PC);
- Rapid Change of Temperature (RCT).

The H_3TRB and HPET tests could match several conditions with a reverse bias overstress of the long term storage applications and maintenance period. The H_3TRB test has for goal to study the electrochemical migrations produced by the moisture absorption of the molding compounds and the reverse bias. The HPET test will investigate the popcorning effect of the molding compound usually met during the soldering process. In long term storage applications, the power devices operation is regularly checked. This produces a high temperature elevation of the die and creates some mechanical stresses due to the harsh evacuation of moisture absorbed during storage.

The HTRB test has been selected to study the influence of the chemical evolution of the dielectric material (molding compound or gel) on the breakdown voltage and to also check the induced leakage current evolution.

The PC and RCT tests will simulate the power variation during operating lifetime and the temperature cycles due to the environmental changes respectively.

For HTRB, PC and RCT tests, the diffusion phenomenon of in the metallic joints will be studied: nucleation, coalescence and growth of IMCs, chemical composition changes of the phases and recrystallization.

6 Conclusion

Initial steps to achieve the reliability assessment of COTS power devices have been made. These steps are:

- Construction analyses to identify the assembly technologies and manufacturing defects;
- Solving of several problems linked to construction analyses with NDA and DA;
- Summarizing of the failure risks in harsh environments;
- Considered accelerated ageing tests to reproduce failure modes and mechanisms of COTS power devices in electrical aerospace equipment.

The considered accelerated ageing tests will allow determining the reliability of COTS power devices in aerospace environment.

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