Design to cost Ag free silicon nitride AMB substrate for automotive power module applications

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Abstract
Silver free AMB technology addresses the cost-performance gap between the active metal brazed (AMB) Si_3N_4 based metal ceramic substrates (MCS) suitable for automotive applications and the cost-efficient direct copper bonded (DCB) Al_2O_3 substrates suitable for applications with lower requirements. The cost-reduction of the condura®.ultra process is achieved by using a silver free brazing technology combined with an efficient brazing process. Within this report we will demonstrate the thermal cycling capability, the peel strength of the condura®.ultra process combined with a design to cost Si_3N_4 ceramic substrate. Additionally showing results regarding isolation partial discharge of performance and robustness in thermal resistance measurements.

Key words
Ag free, Active metal brazing, design to cost, Silicon nitride

I. Introduction
In recent years, high power electronics has become one of the fastest growing market segments of the semiconductor industry. With the development of hybrid/electric vehicles, the market for SiC based power modules is rapidly expanding [1-2]. All power module manufacturer/designers are trying to get high efficiency and high-power density for the main inverter. However, the traditional power module assembly materials have been recognized as a technical barrier in moving to a higher performance system due to inherent limitations. In order to overcome this barrier requires innovative material solutions to improve performance, efficiency and reliability of the power module assembly. To achieve this, packaging design is key, to get high efficiency modules taking advantage of wide band gap materials such as silicon carbide (SiC) and gallium nitride (GaN) devices [3-5]. The features of these devices pose substantial challenges including fast switching speed and heat dissipation. The development of novel packaging techniques is needed to overcome new challenges such as material selection and packaging processes.

In power modules, the metal ceramic substrate (MCS) is an important part that acts as an insulator between the circuit layout with semiconductor devices and the heat sink. Furthermore, the MCS is required to have sufficient thermal conductivity to guide the heat generated from the chip towards the heatsink. In addition, the MCS is subjected to repeated thermal stress in operation. Therefore, MCSs are required to have a high temperature cycling capability to ensure functionally during the lifetime of the power module. Traditionally silicon nitride (Si_3N_4) Active Metal Brazed (AMB) substrates are considered as the best substrate solution to fulfill the high requirements on heat dissipation and high-power density for automotive power modules. The drawback of Si_3N_4 based AMBs are the high costs. OEM manufacturers want to have a “good enough” performing substrate instead of a more expensive, highly reliable and better performing substrate to assemble the power module cost-effectively for standard electric vehicle applications. Heraeus Electronics has developed an alternative unique cost-effective condura®.ultra Si_3N_4 Ag free AMB substrate for this application. Besides, it’s unique feature being Ag free it has similar properties as an AMB substrate. Condura®.ultra Si_3N_4 Ag free AMB silicon nitride substrate

is well positioned, being an acceptable performing substrate, cost-effective, and highly reliable to meet the hybrid/electric vehicles drive train power module requirement.

In this report, the performance of condura®.ultra Si_3N_4 Ag free AMB technology in comparison with the standard AMB substrate which is a well-known benchmark in the industry will be demonstrated. Several industry standard tests have been performed to check the reliability, mechanical integrity and processability of the substrate. Tests such as thermal shock tests (-65 ^{0} C/ + 150 ^{0}C, liquid to liquid), peel strength test, high temperature storage, thermal resistance, and partial discharge tests were conducted. Some of the tests are highlighted here.

2. Experimental Results

2.1 Phase formation

The phase formation and bonding mechanism of the condura®.ultra technology on Si_3N_4 ceramics were characterized by scanning electron microscopy (SEM) which is shown in Figure 1. The actual bonding mechanism is based on the reaction between the active metal (Titanium) and the Si_3N_4 ceramic forming a stable TiN layer. As no silver is present in the condura®.ultra system, there is no formation of the typical Ag-rich and Cu-rich phases which are known from the standard AMB technology using high Ag-containing brazing filler metal pastes. Nevertheless, the bonding mechanism towards the Si_3N_4 ceramic via a TiN reaction layer is similar.

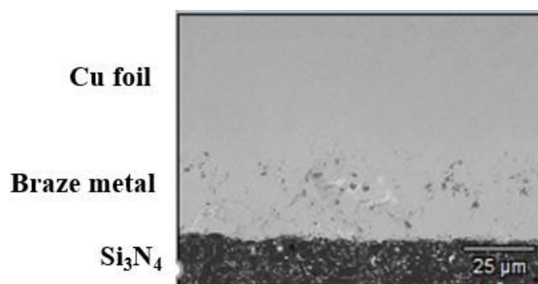

Figure 1: Typical condura®.ultra Ag free AMB microstructure measured by scanning electron microscopy.

The following sections will provide clear evidence that the condura®.ultra Ag free technology validates the manufacturing of highly reliable metal ceramic substrates and that the braze metal layer is stable against temperature influence.

2.2 Thermal Shock

Si_3N_4 based AMB substrates fulfill highest requirements in terms of thermal shock performance. This high reliability performance is enabled by the mechanical properties of the Si_3N_4 ceramic substrate.
Thermal shock tests (TST) were performed using an internal test layout (30 x 29 mm2 with 0.5 mm Cu on 0.32 ceramic). The applied test layout is shown in Figure 2. The substrates were characterized by scanning acoustic microscopy (SAM PVA Tepla SAM300) prior to TST, which is shown in the left picture of Figure 2. The red color indicates an etched isolation groove which is part of the used test layout. If damage to the substrate occurs (delamination between copper and braze metal/ceramic) due to thermal shock, the red colored isolation will be broadened in the SAM image. The substrates were cycled (+150 °C/-55 °C), liquid: Galden D02TS, 3 min dwell time). The integrity of the substrates was re-assessed by SAM after 3000, 5000, and 8000 cycles. The results are presented in the images in Figure 2. No major broadening of the isolation grooves between the initial and the cycled substrate is detectable, which proves that no delamination between the ceramic and braze metal occurred. This shows that condura®.ultra is qualified to fully leverage the mechanical robustness of Si_3N_4 ceramics in a similar manner as the AMB technology.

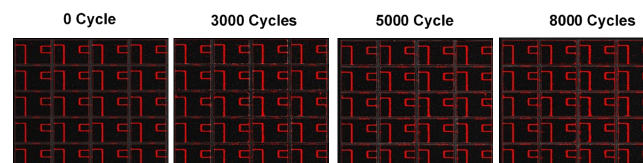

Figure 2: SAM pictures of 20 individual condura®.ultra Ag free Si_3N_4 AMB test layouts before and after thermal shock tests (-55 °C/ + 150 ° C, liquid to liquid)

2.3 Partial discharge

Buried partial discharge (PD) events, i.e. partial discharge processes happening underneath the Cu layer and not at the edge of the Cu pattern, can be linked to either voids within the ceramic itself or within the braze metal layer [6]. PD can be critical for the power module to pass the final electrical test at the module manufacturer and may lead to premature failure in field applications. Therefore, the PD performance of the condura®.ultra Ag free brazing technology was tested. The measurement system used for this test is described in more detail in reference [6]. For all samples, the same test layout was used. The samples, including the sample holder, were immersed into isolating fluid (FC770, 3M) during the measurement. For the characterization, the voltage profile which is shown in **Figure 3** was used. The voltage profile was chosen according to the IEC61287 standard. Two different characteristics were extracted from the measuement:

- The partial discharge inception voltage U_{te} indicating a partial discharge event of more than 10 pC during ramping the voltage to U_1.
- Partial discharge events PD happening during the voltage plateau at U_2.

The partial discharge characteristics of four types of Si_3N_4 based condura®.ultra Ag free AMB and standard AMB substrates were assessed with the material combinations as shown in **Table 1**. No signs of partial discharges could be detected.

Table 1: PD meaurement results of tested substrates. Ute and PD were measured 5 times persubstrate.

Technology	Cu Thickness, mm	Ceramic Thickness mm	Ute V	PD (pC)
AMB	0.3	0.32	-	<1
Condura®.ultra	0.3	0.32	-	<1
Condura®.ultra	0.5	0.32	-	<1
Condura®.ultra	0.8	0.32	-	<1

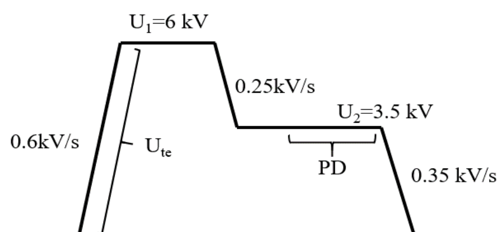

Figure 3: Voltage profile used for the partial discharge measurement.

The typical requirements for the partial discharge are below 4 pC. The above measurements of Ag fee AMB substrate meets the typical requirements.

2.4 Thermal Resistance

The thermal resistance R_{th} of the metal ceramic substrate is an important factor for the design of the power module. A lower thermal resistance enables a higher power density and thereby allows reducing chip size. Major contributors to the R_{th} of the MCS itself are the Cu thickness, type of ceramic and thickness of ceramic.

Condura®.ultra Si_3N_4 Ag free AMB substrates were aged in a high temperature storage (HTS) test for 1000 hours at 175°C to stress the braze metal and prove that the brazing filler metal system is stable. The thermal resistance after HTS was measured again by the transient dual interface method. No difference between the initial status and the aged substrate after HTS is observed, providing evidence that the new Ag-free alloy system displays no degradation and consistent values after 1000 hours of aging at 175°C. Figure 4 shows the R_{th} before temperature storage.

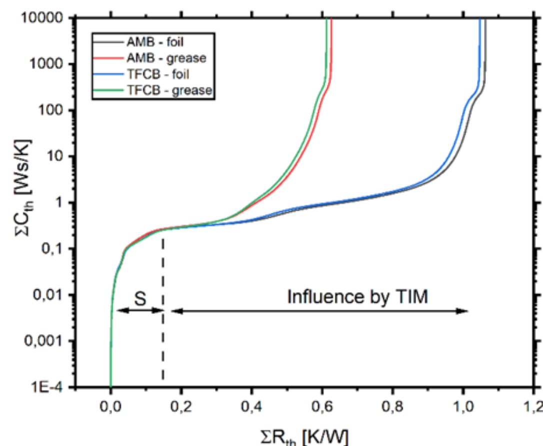

Figure 4: Cumulative structure function of a condura®.ultra Si_3N_4 Ag free AMB substrate and Standard AMB before high temperature storage.

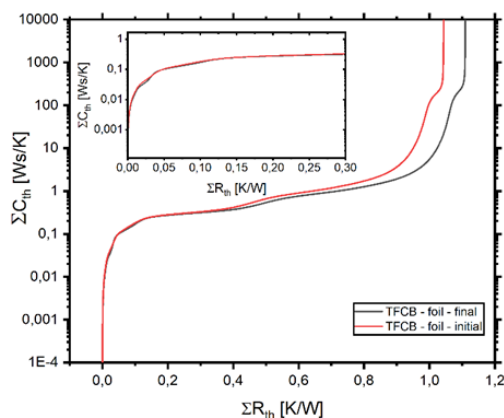

Figure 5: Cumulative structure function of a Condura®.ultra Si_3N_4 Ag free AMB substrate No significant difference in R_{th} of the substrate compared to the initial status before HTS.

2.5 Peel strength Test

Peel strength measurements were conducted to characterize the adhesion strength from copper to ceramic. For this purpose, 0.5 mm thick Cu sheets (OFE grade, purity 99.99%) were brazed onto 0.32 mm thick Si_3N_4 ceramics in mastercard format. Both Si_3N_4 ceramic types were investigated and compared against each other. To ensure repeatable results a dedicated peel strength test layout was manufactured. Each condura®.ultra mastercard was laser-cut into induvial test pieces as can be seen in figure 6. The upper part of the test sample is clamped into a Zwick/Roell 500N Zwick device and the force during peeling off the Cu strip is measured. Afterwards the average of the measured force is divided by the width of the Cu peel strip.

25 strips were peeled. The average peel strength measured on the Si_3N_4 ceramic (condura®.ultra) was 132 N/cm. The peel strength strongly depends on the substrate type and technology under testing.

Fig. 6: Peel test layout used for peel strength characterization.

III. Conclusion

Within this report the new design to cost condura®.ultra Ag free AMB technology was introduced. The performance was demonstrated by thermal shock, peel strength, partial discharge, and thermal measurements. The investigations clearly demonstrate that the condura®.ultra Ag free AMB technology enables cost-efficient but highly reliable metal ceramic substrate using Ag-free condura®.ultra paste and a non-vacuum based brazing process.

Acknowledgment

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