



Title	High temperature reliability of die-attach structure and thermal property characterization for SiC/GaN power device
Author(s)	金, 東辰
Citation	大阪大学, 2020, 博士論文
Version Type	VoR
URL	https://doi.org/10.18910/76534
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Note	

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The University of Osaka

Doctoral Dissertation

**High temperature reliability of die-attach structure
and thermal property characterization for SiC/GaN
power device**

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January 2020

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High temperature reliability of die-attach structure and thermal property characterization for SiC/GaN power device

Abstract

Wide band-gap (WBG) semiconductors such as a silicon carbide (SiC) and a gallium nitride (GaN), provide an important opportunity to implement next-generation power conversion systems that possess a significantly improved energy efficiency. Nevertheless, this superior characteristic indicate that the operating temperature of WBG devices in excess of 250°C suggests that materials and designs established for existing silicon (Si)-based power devices are difficult to apply for WBG power devices. Thus, main issues of the WBG power electronics are development of die-attach material/structure to withstand harsh temperature conditions and establishment of a thermal characterization standardization method for thermal management. This dissertation describes materials design and its thermal characterization standardization for stable implementation of WBG power conversion systems.

At first, to implement a die-attach material and an insulating substrate that can withstand high temperatures above 250°C, a GaN/DBA die attached structure was introduced, structurally sound bonded by micron/submicron Ag sinter pastes. As a results of the thermal aging test, the specimens are subjected to high temperature aging tests at 250°C and compare with conventional a Pb-5Sn solder joint. Initial shear strength of a pressure-less hybrid Ag sinter joint exceeded 42 MPa, and increased stably up to aging of 1000 hours without any defects such as interface oxidation, diffusion, or mechanical deformation. The increase in shear strength of the Ag sinter joints was the result of neck thickness growth of the sintered Ag during thermal aging. On the other hand, the bonding strength of traditional Pb-5Sn solder significantly reduced (by 60%) after 250 hours aging due to its serious degraded interface layer with massive IMC growth.

High-strength and superior thermal shock-resistant GaN/DBA die attach structures with Ag sinter joining by thick Ni metallization (7 μm) were developed. Consequently, the shear strength of the Ag sinter joining structure was sustained above the initial strength after 500 cycles, which showed durable sinter necks and non-deformed interfaces due to the thick Ni

metallization. Thus, Ag sinter joining with metallization design can be expected as an environment-friendly replacement die material for the long-term reliability of WBG semiconductor module packaging.

Finally, for a thermal characteristic standardization of SiC power devices, a SiC thermal engineering group (TEG) chip was developed, direct thermal characterization method of junction temperature in an actual chip packaged using active 4H-SiC TEG chip applied power cycling systems. This demonstration offers the possibility of precise measurement of junction temperature and thermal resistance at high power density, which is no longer limited by the actual SiC direct bonded power module structure. This technology can be extended to perform reliability test standardization for all wide band-gap semiconductors by providing a method of evaluation which will determine which parts of a power module structure are deteriorating at any point in time. We envision that this technology to find wide application in all fields that can benefit from controlled and site-specific power conversion industries, for example, the 5 generation (5G) telecommunication and eco-friendly vehicles, such as WBG semiconductors that require practical applications. The unprecedented active SiC applied direct thermal characterization developed in our model semiconductor system will lead to new avenues for power electronics design with the capability to perform at increased junction temperature.

In this study, the results confirmed that the suggested materials/structure and thermal characterization method could become alternative joining and evaluation technologies for WBG power conversion systems.

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Chapter 1

Introduction

1.1 Next-generation power semiconductors and its applications

The continuously increasing energy consumption has been one of the most critical issues in our society. In particular, the global energy consumption was estimated to increase about 40% before 2040[1]. In order to protect the environment, initiatives to reduce carbon dioxide (CO₂) emissions have been implemented in countries throughout the world. For this reason, the shift to clean energy, such as to wind power, solar power, and eco-friendly transportation system which does not rely on conventional fossil fuels, are becoming prominent[2]. One of the technologies needed to make the transition to eco-friendliness in the electric energy system is the improvement of electric power conversion. In this thesis, the next-generation power semiconductors, wide band-gap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN), are to be discussed. WBG technology has been emerging in various industry sectors requiring high power and high temperature operation.

WBG semiconductors can provide a great opportunity to improve performances of the power electronic conversion system with an increased power density, operation frequency, and breakdown voltage[3,4,5]. As compared with the intrinsic physical properties of traditional silicon (Si) semiconductor, those of WBG semiconductors are significantly superior, which are shown in Table 1.1.

Table 1.1 Comparison of physical properties of Si and various wide band gap semiconductors (SiC, GaN and diamond) [6].

	Si	3C-SiC	4H-SiC	GaN	Diamond
Band-gap (eV)	1.12	2.2	3.2	3.4	5.45
Breakdown field, E_B (MV/cm)	0.25	1.2	3	4	5.6
Electron mobility, μ (cm^2/Vs)	1350	900	800	1300	1900
Saturation velocity, v_s (cm/s)	1×10^7	2×10^7	2×10^7	3×10^7	2.7×10^7
Thermal conductivity, k (W/mK)	150	490	490	130	200
Dielectric constant, ε	11.8	9.6	9.7	9.5	5.5

These differences in physical properties greatly distinguish the areas of their applications as shown in Fig. 1.1. WBG power devices can stably implement much higher power density, low energy loss conversion, and faster operation frequency even at much higher temperature ($<250^\circ\text{C}$) than operating temperature of Si-based power devices ($>150^\circ\text{C}$)[7,8]. Therefore, WBG semiconductors is attracting attention in many applications such as power plants, renewable energy systems such as photovoltaics/wind power, ICT devices, industrial motors, railways, automobiles, 5G telecommunication systems, and etc.

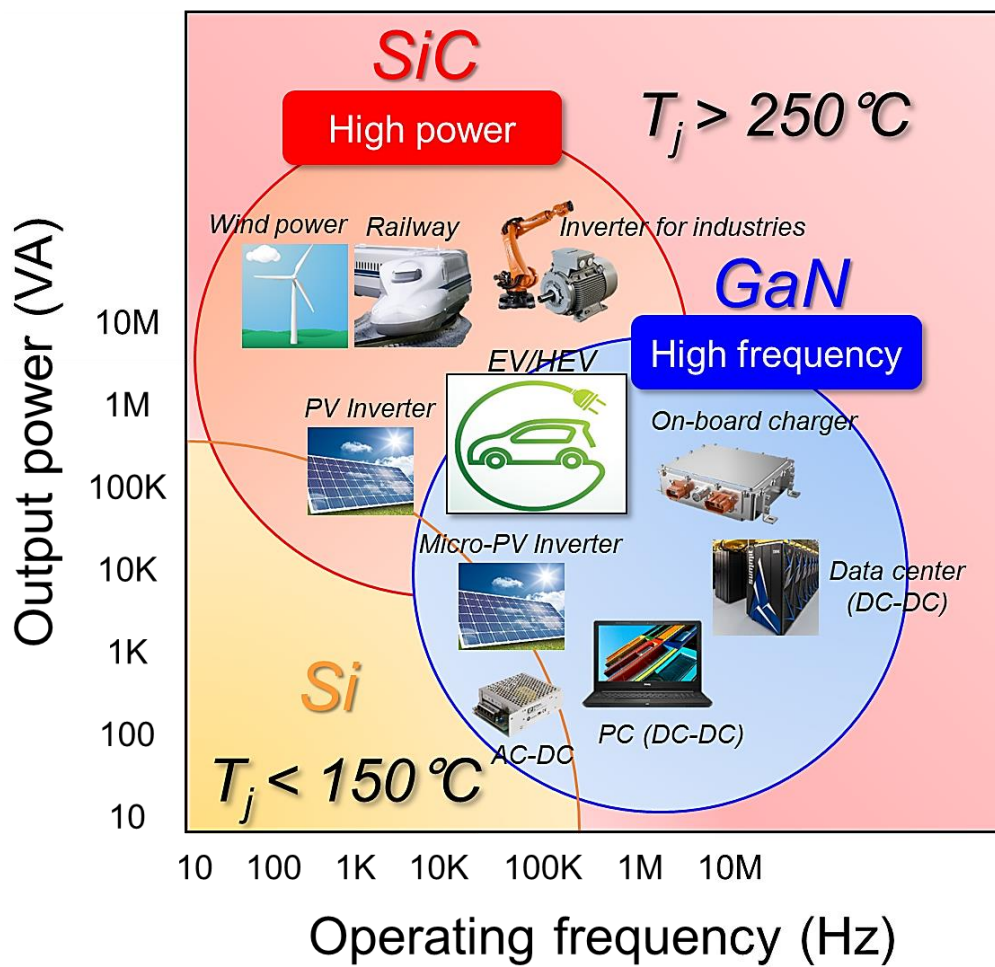


Fig. 1.1 Potential applications of GaN and SiC power devices and its operating power, frequency and temperature ranges.

In particular, the capability of high temperature operation of WBG power devices provide many benefits in transportation applications. They are electrification of mobile systems such as eco-friendly vehicles like electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs) and hybrid electric vehicles (HEVs).

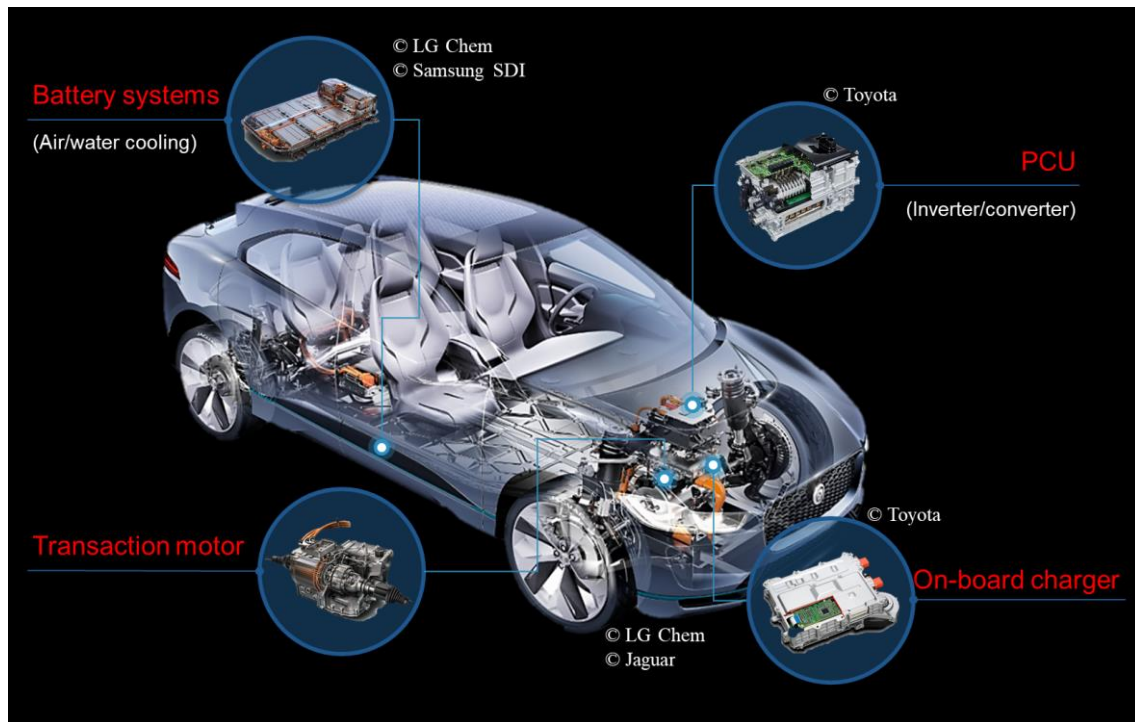


Fig. 1.2 Applications of WBG power devices in eco-friendly vehicle systems. (courtesy of Toyota, Jaguar, LG Chem and Samsung SDI)

Fig.1.2 shows the typical components of WBG power devices can be applied in an EV systems. It is widely applied to key parts of electric driving parts such as battery systems, power control unit (PCU), motor and on-board charger (OBC). In the case of a power module, by adjusting a suitable heat dissipation design, it has been reported that a significant miniaturization of the PCU is possible by reducing a volume of the total system as well as achieving significant improvement of energy loss as compared to the conventional Si power module as displayed in Fig. 1.3. When a conventional Si power device is replaced with a SiC device, the PCU volume can be reduced to 1/5 in volume as seen Fig.1.4.

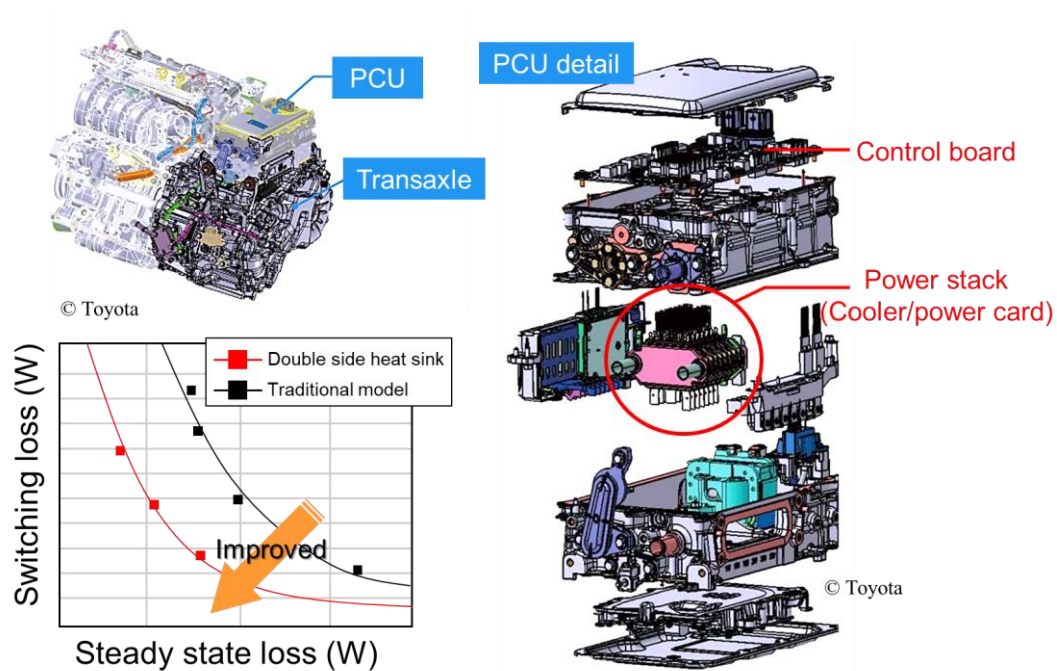


Fig. 1.3 High efficiency by thermal design of power conversion systems. (courtesy of Toyota Motor Corporation)

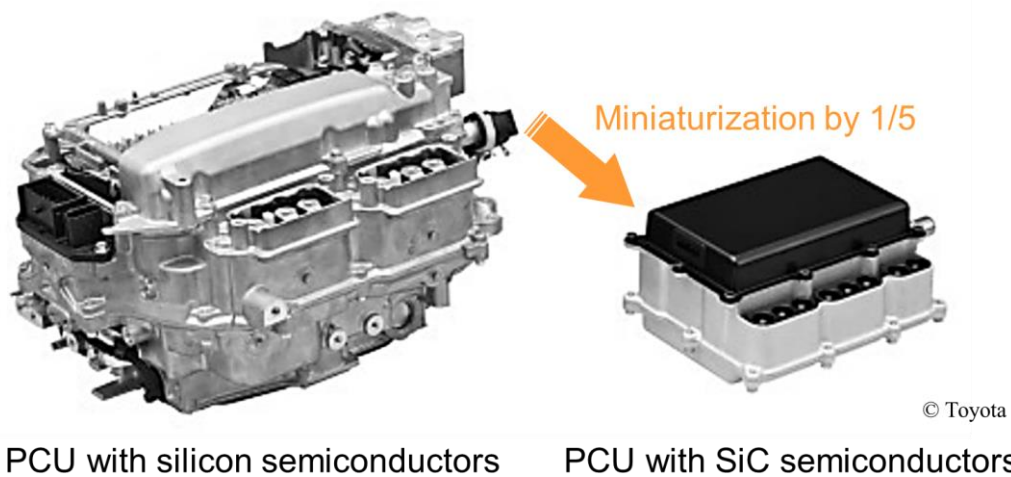


Fig. 1.4 Miniaturization of power conversion system expected when existing Si power semiconductor is replaced by WBG power semiconductor. (courtesy of Toyota Motor Corporation)

In addition, the releasing from the limitations of improved power density and of operation temperature will may be cooled by air cooling. This means that it is possible to secure a cabin and realize extreme energy efficiency by brings an air cooling system required for an internal combustion engine cooling system for the conventional hybrid system as seen Fig.1.5. Thus, the adoption of WBG devices in electric vehicles will provide many attractive features in the next generation of automotive industries. In order to implement WBG power devices, there are several technology issues to be solved. Packaging technology is one of the top priorities, which are interconnection materials/processes, a heat dissipation/insulation substrate, and etc. The conventional materials based on the operating limit temperature criteria ($< 150\text{ }^{\circ}\text{C}$) for the traditional Si power devices must be replaced with new interconnection materials/processes and heat-dissipation/insulation substrates, which can withstand high temperature operation beyond $250\text{ }^{\circ}\text{C}$.

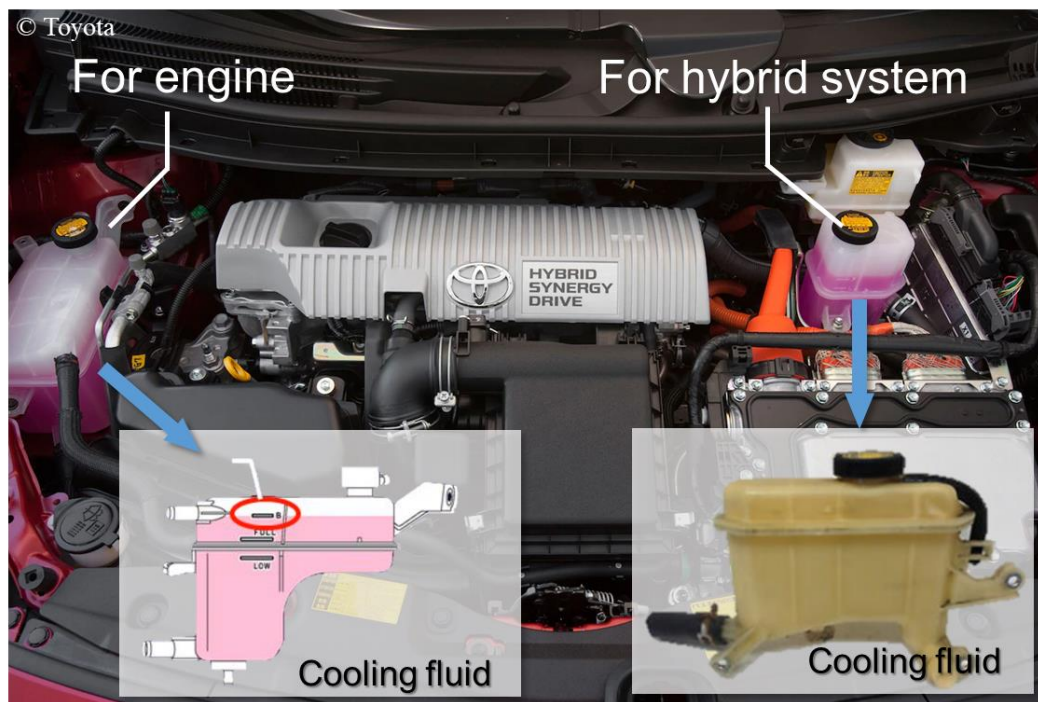


Fig. 1.5 Cooling systems description of current HEV (Toyota Prius).

1.2 Current issues and challenges of high power/temperature packaging

The example of structure a conventional power module is shown in Fig.1.6. It was assembled with the Si power device and Al wiring on the DBC substrate.

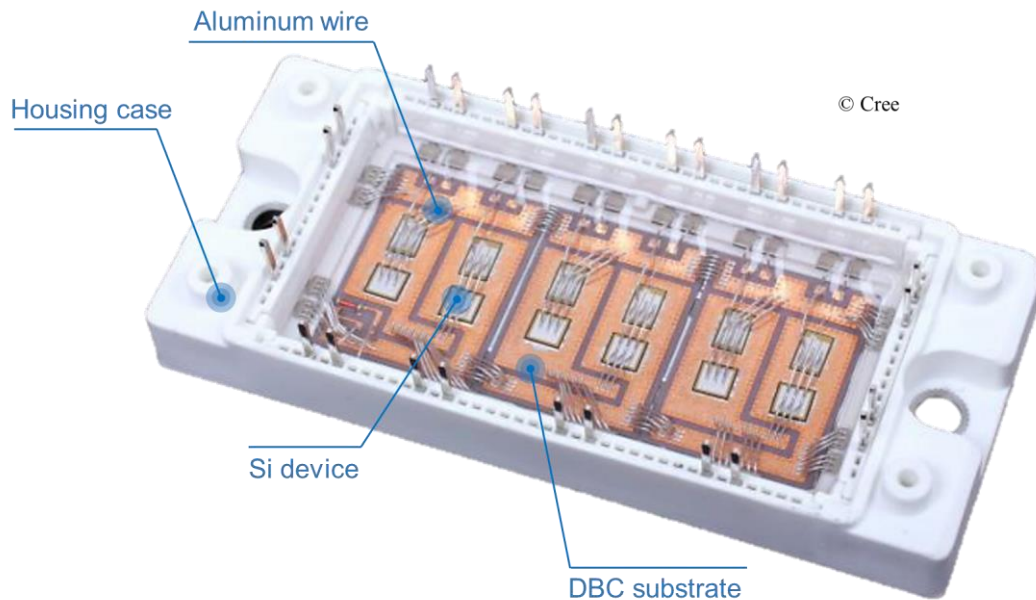


Fig. 1.6 Conventional power module structure.

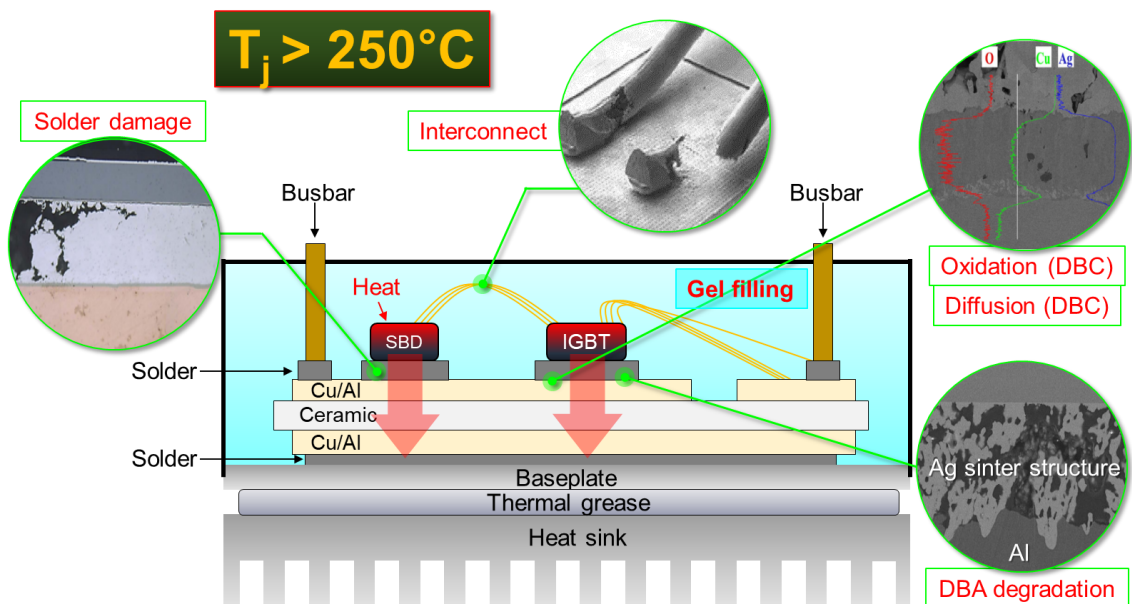


Fig. 1.7 Typical failure mode in typical power module packaging.

The conventional interconnections and module design cannot survive when WBGs are adopted.

Fig. 1.7 exhibits typical failure of a power module that occurs when operating at harsh thermal

environments. When a power module is operated, much heat is generated at a surface of a power semiconductor die, which is dissipated to a heat sink through a die-bonding material and an insulating substrate. In vehicle driving, since severe repetitive thermal stress occurs, an interconnecting material experience severe fatigue damage such as solder layer cracking, wire degradation, and interfacial damage of an insulating substrate[9,10]. The current major problems and challenges of the above mentioned materials and components are discussed in detail in the following sub-sections.

1.2.1 Die attach materials

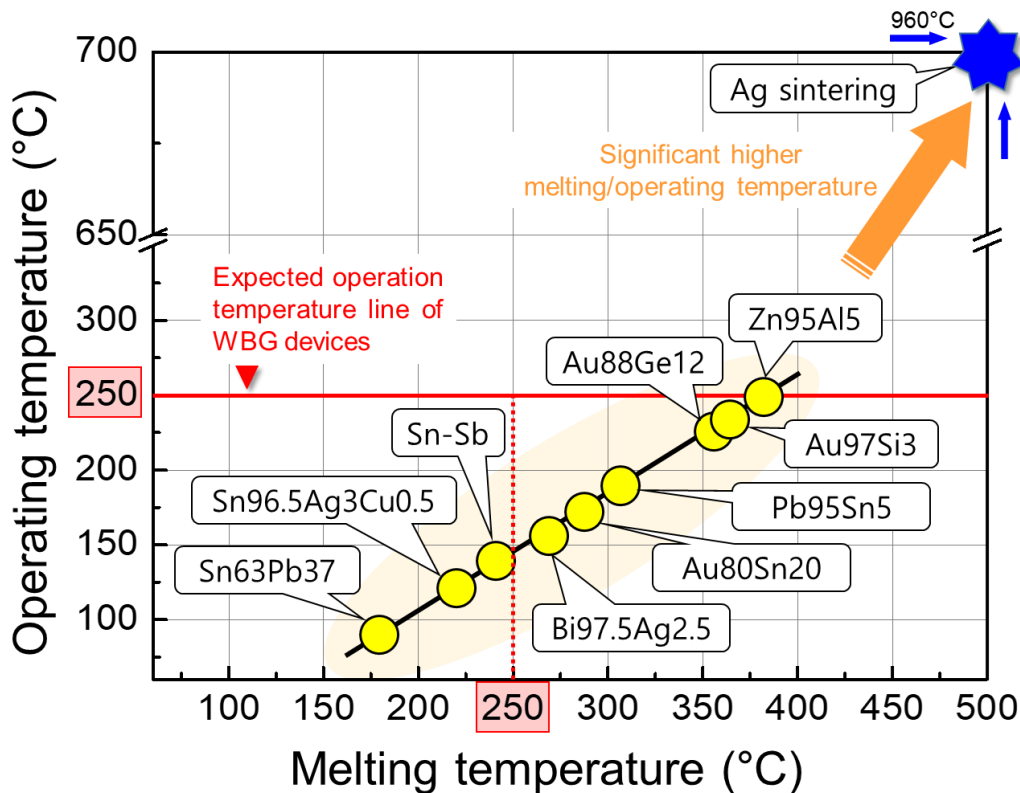


Fig. 1.8 Operating temperature versus melting temperatures of die attach materials.

Fig. 1.8 displays the comparison of various die-attach materials on operating temperature versus melting temperatures.

Ag-Bi, Au-Ge, Zn-Al, transient liquid-phase (TLP) bonding, which is widely used for

high-temperature packaging materials, has a melting point above 250 °C [11], which temperature is not high enough for WBG applications. Au-based solders are priced higher and Bi-Ag and Zn-Al have poor processing abilities [11]. Moreover, these solder alloys can induce massive intermetallic compounds (IMC) which is not suitable for severe thermal stress environment as well as the brittle Bi. These drawbacks prevent the adoption of Au-based and Bi-based solder materials [13,14]. Since Sn system lead-free solders have a low melting point below 250 °C, they are unacceptable for use in WBG power devices [13]. In the case of the high content Pb solder, The Restriction of Hazardous Substances Directive (RoHS) will directly prohibit the use of certain hazardous substances, including Pb, in electrical equipment in future[16, 17]. In addition, thermal damage of typical high melting point solder is another fatal drawback as shown in Fig.1.9.

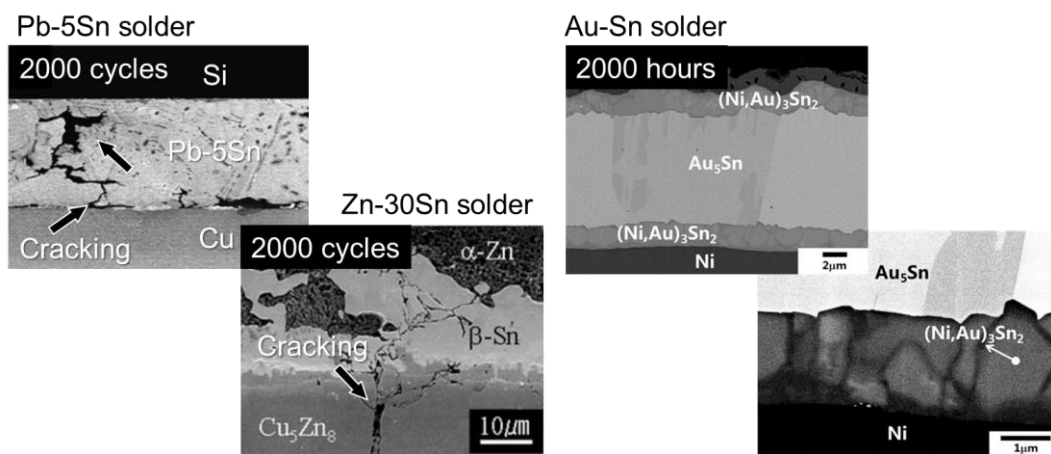


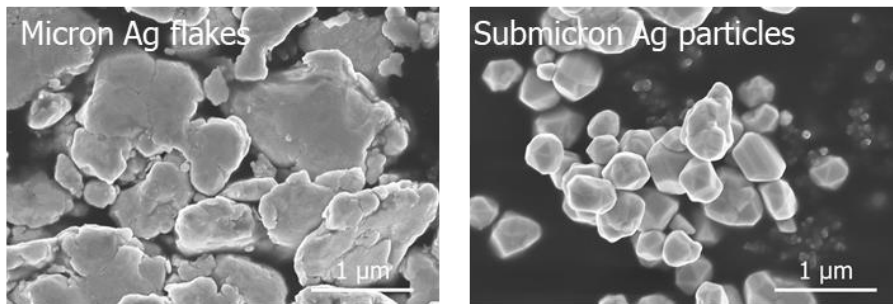
Fig.1.9 Degradation of traditional high temperature solder joints: Pb-Sn, Zn-30Sn (40°C to 125°C for 2000 cycles) and Au-Sn solder IMC images after thermal aging and cycling tests [11][16].

To ensure the high reliability and implement commercialization of WBG power devices at high temperatures and high power density, the die-attach must possess the following characteristics:

1. It should be bonded at relatively low temperatures ($< 300\text{ }^{\circ}\text{C}$) and simple process conditions (without any pressure) and should be easy from storage to use.
2. Die attach materials must withstand high operation temperatures ($> 250\text{ }^{\circ}\text{C}$) and provide high reliability in a package structure (high melting point) [17].
3. To be used in automobiles, it must process reliably in a wide range of temperature. ΔT must be about $300\text{ }^{\circ}\text{C}$ ($-50\text{ }^{\circ}\text{C} \sim 250\text{ }^{\circ}\text{C}$). Thermal stress generated by the coefficient of thermal expansion (CTE) mismatch between WBG dies and the other components at harsh condition should be effectively relaxed. (narrow CTE mismatch low elastic modulus, or effective plasticity) [18].

Ag sinter joining technologies with various particle size Ag have been the most attracting alternative in recent years. Nano-size Ag particles sinter paste prepared have drawn considerable attention for use as potential die-attach materials due to their excellent physical/mechanical properties [19,20,21]. Die attach using nano-Ag sinter paste was performed by sintering in air at $200\text{ }^{\circ}\text{C}$ to $300\text{ }^{\circ}\text{C}$ with the aid of relative high applied pressure 40 MPa [22]. Nano-Ag sinter pastes are generally mixed with binders, solvents, and dispersants in order to maintain dispersion of nanoparticles and viscosity [23]. However, because of the large specific surface area of nano-Ag sinter pastes, a substantial amount of dispersant and binder remains in a sintered die-attach layer. This residue sometimes inhibits to achieve high performance and high reliability from its die-attach structure[24]. To overcome above mentioned issues of nano-Ag sinter pastes, much more affordable paste with micrometer size Ag particles with or without submicron-size Ag particles were developed as shown in Fig. 10. This micron size Ag paste sinter at relative low pressure/temperature in air[13][25].

Micron/submicron Ag particles



Ag sintered structure

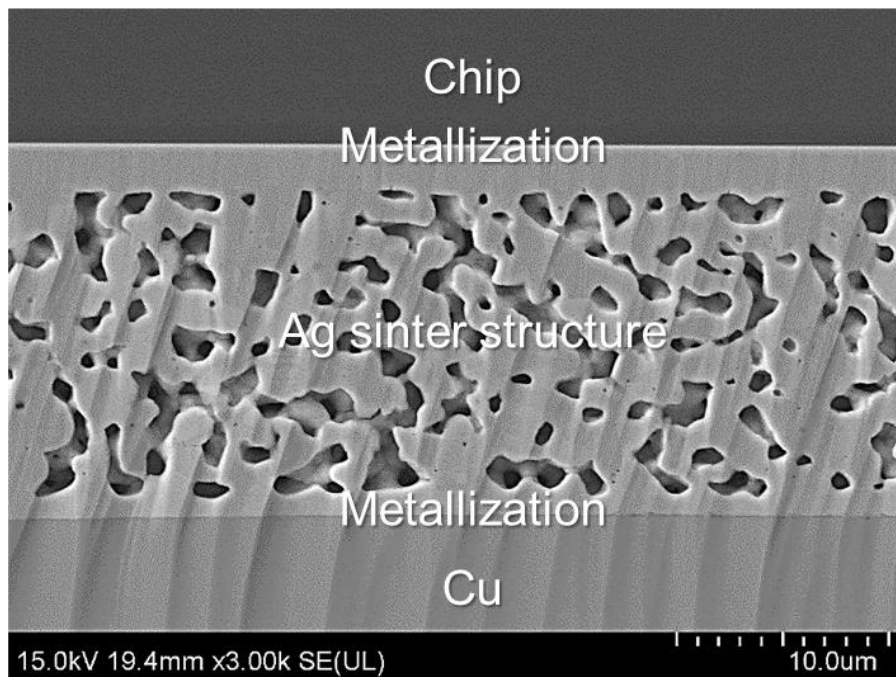


Fig.1.10 Micron/submicron Ag sinter particles and its micro-porous sintered structure.

1.2.2 Insulation substrates

Power electronic substrates play an important role in dissipation of heat from a die as well as maintaining the module structure reliable in harsh environment [26][27][28][25][29][30][31]. Fig.1.11 shows a traditional power electronics ceramic substrate structure. [32]. Heat dissipation/insulation substrate, which is a direct bonded copper (DBC) and a direct bonded aluminum (DBA), are existed between power semiconductor device and heat sink. Heat is transferred from surface of the power semiconductor device to the heat sink. The DBC and DBA were metallized both side of ceramic plate, to improve the thermal conductivity of ceramic substrates and form circuits, and were considered as the most promising substrates for power modules due to their excellent thermal conductivity, low thermal resistance, and high insulation voltage. However, the sandwich structure of the DBC and DBA substrate will cause thermo-mechanical stresses due to the CTE mismatch. It has been reported that heat resistance of the substrate depending on the type of ceramics and metals. In this regard, it has been carried out to evaluate thermo-mechanical stability of various ceramic applied active metal brazed (AMB) DBC substrates with the Ni plating layer during a harsh thermal shock cycling test at the temperature range of from $-50\text{ }^{\circ}\text{C}$ to $250\text{ }^{\circ}\text{C}$. The DBC substrate with silicon nitride (Si_3N_4 -DBC) ceramics middle layer indicate no serious damage within 1,000 cycles of thermal shock cycles, while those of an aluminum nitride (AlN) and alumina (Al_2O_3) caused by Cu layer severe delamination after the same cycles. The results indicated that the failures may impress that the AlN and Al_2O_3 have critical disadvantage of higher CTE value and lower toughness than Si_3N_4 .

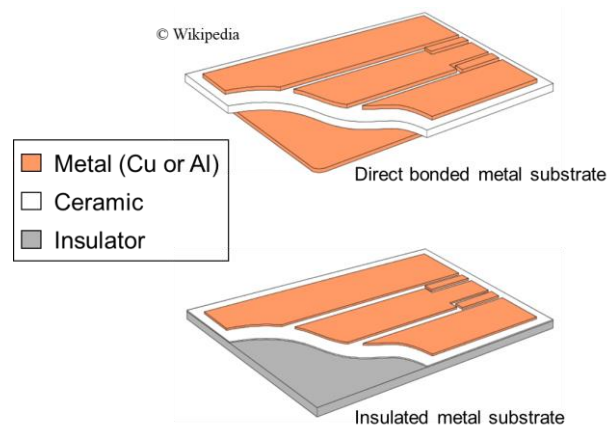


Fig.1.11 Traditional power electronics substrate structure.

On the other hand, some of the previous studies have reported that DBCs showed an unreliable performance due to the oxidation and diffusion of Cu through grain boundary in a high temperature environment ($<250^{\circ}\text{C}$) [33][34][13][35][36][37][38]. In the previous study, while a Ni barrier layer showed poor inhibition of Cu diffusion for high temperature die-attach applications, a Ti barrier layer deposited on a DBC surface helps to prevent Cu diffusion into Ag and consequently preventing Cu oxidation.[38] Traditional $5\text{ }\mu\text{m}$ thick Ni-metallized DBC substrates are no longer stable at high temperatures of 250°C . In the worst case, a DBC substrate caused severe cracking of ceramic due to large CTE mismatches (see Fig. 1.11)[32].

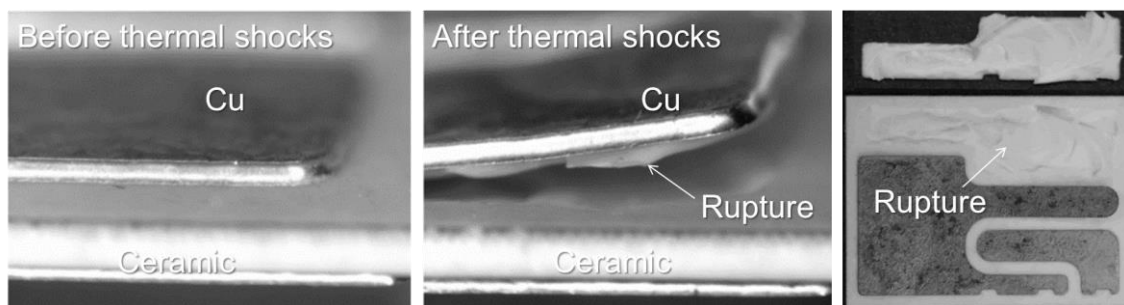


Fig.1.12 DBC substrate failure images (196°C to 85°C).[32].

To ensure the high reliability and implement commercialization of WBG power devices at high temperatures and power density, a metallized ceramic substrate need to possess that should not cause separating at high temperature and should have excellent heat dissipation performance. Table 1.2 exhibits inherent physical properties of various ceramic for power electronics substrate.

Table 1.2 Inherent physical properties of various ceramic for power electronics substrate. (courtesy of Accumet Tech Brief).

	Al ₂ O ₃ (99.5%)	Al ₂ O ₃ (96%)	BeO (99.5%)	AlN	Si ₃ N ₄
Coefficient of thermal expansion, CTE (ppm/K)	7 ~ 8.4	8.2	7.4 ~ 9	4.3 ~ 5.6	3.2
Thermal conductivity, k (W/mK)	25.5 ~ 35	20 ~ 25	209 ~ 330	70 ~ 250	60 ~ 90
Dielectric constant, ϵ	9.8	9	6.1 ~ 7.5	8.3 ~ 9.3	5.5

Typical characteristics of Al₂O₃, AlN and Si₃N₄ for metallized substrates can be summarized as follows:

*Al₂O₃: cheap price, low thermal conductivity poor temperature cycle durability

*AlN: high thermal conductivity, moderate temperature cycle durability

*Si₃N₄: medium thermal conductivity, excellent high temperature durability

In addition, regardless of the type of ceramic, previous study has been reported that an Al metallized ceramic substrate (DBA) can be sustained at harsh thermal shock (-50°C ~ 250 °C) as displayed in Fig.1.13[39]. Therefore, DBA have a better high temperature performance than that DBC, and should be treated as a powerful candidate substrate for next-generation power device.

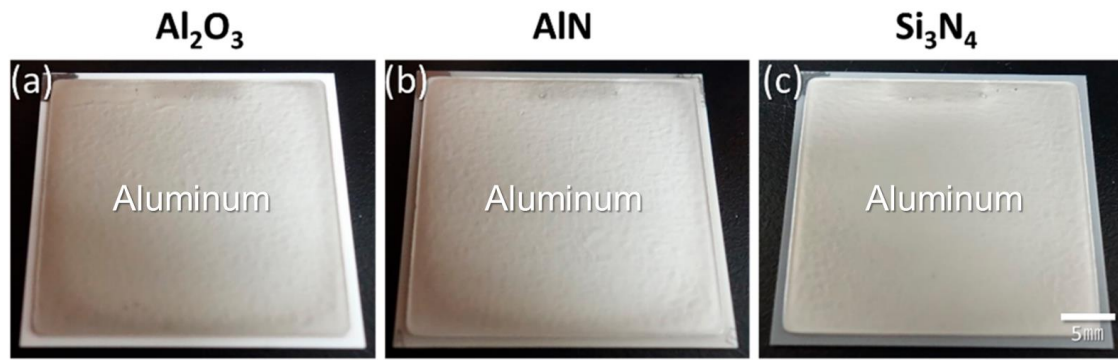


Fig.1.13 DBA substrates with Al_2O_3 (a), AlN (b), and Si_3N_4 (c) after 1000 cycles, plated with Ni ($-50^\circ\text{C} \sim 250^\circ\text{C}$)[39].

1.3 Requirement of thermal management for WBG power devices

Solving the dilemma of the measurement for a junction temperature of WBG semiconductors remain an essential challenge in next generation power electronic devices for future environmentally friendly transportation. For this reason, many research directions are pursued to improve the steady-state junction temperature (T_j) measuring via exploring so far unrevealed or untapped mechanisms and correspondingly controlling the electrical systems or oxide layers of semiconductor devices[40][41][42]. When the p-n junction on the semiconductor devices occurred by ON-switching with the number of kW, a high temperature of the over about 250°C is generated on the surface of the WBG semiconductor device, this heat passes through the interconnection material bonded WBG semiconductor, the substrate, the thermal interface material, and reaches the base-plate and dissipates[8][43]. In this process, the copper, the ceramics, and Si or SiC materials, the phonon scatterings increase with temperature so that the migration of the free electrons is interrupted. It results in the variation of their thermal conductivity. The effect of the temperature dependent thermal properties may be particularly critical for the SiC devices compared to the Si devices, because the SiC device has the operation capability in the wide temperature range. The wider temperature change induces the larger thermal properties variation. Consequently, the variation of the thermal

properties of the package materials results in change of thermal characteristics of the packaged device such as thermal resistance and capacitance. Therefore, thermal characteristics analysis considering temperature effects is required for high temperature operation of the packaged SiC devices.

However, the realistic thermal distribution in a ceramic substrate must have a large temperature gradient to transfer the generated heat from surface of the device chips to the cooling system. The stress induced by the CTE mismatch during the thermal conduction from chips to cooling system was more complexed than single DBC substrate. Therefore, the evaluation of such a practical temperature distribution is urgently needed for designing power module. In this context, power cycling test is the strongly useful evaluation methods to evaluate the reliability of a device packaging used in a condition similar to those in actual operations. In this process, the heat transfer performance of such a substrate mainly depends on the thermal properties of employed ceramic materials, e.g., Al_2O_3 , AlN , and Si_3N_4 . Power modules was required with a comprehensive combination of conductive Cu and insulation ceramics, involving the layer thicknesses and circuit patterns to achieve both thermal management and the least power loss at the same time. Usually, to measure the thermal resistance of devices after a power cycling test, it needs an equipment of power cycling system and also a T3ster system which means the Thermal Transient Tester system. It is a technology to monitor the thermal transport through the devices. However, both of the power cycling system and the T3ster system are very expensive and need to take up a lot of space. A simple, fast and miniaturized thermal measurement system is actually necessary.

1.4 Outline and objective of this study

As mentioned in the preceding sections, WBG power devices have demonstrated excellent potential for enhancing high-temperature performance. To implement stable operating in severe thermal environments, the die attach material components, substrate and its thermal management in the WBG power modules need be studied. There are three purposes in this dissertation, ① to evaluate the thermal aging reliability of sinter Ag joining on DBA substrate and compare with the tradition Pb-5Sn solder material, ② Design a metallization layer on DBA substrate to control its deformation during the thermal shock test, and also compare with the tradition Pb-5Sn solder material in the same thermal shock test, ③ to design a heat chip thermal-resistant measurement system for the die attached structure and thermal characteristics evaluation. The constitute of the dissertation shown in the following:

In **Chapter 1**, the brief descriptions on the background of the challenge and exploration for next-generation power devices and was introduced the immersing issues in the use of WBG semiconductors. It is pointed that the reasons why it need to develop the high temperature materials and structures for the WBG power modules and introduced the thermal characteristics characterization methods.

In **Chapter 2**, a GaN/DBA die attached structure with a hybrid Ag sinter joint was introduced. The specimens are subjected to high temperature aging tests at 250°C up to 1000 hours. A shear strength, microstructure and fracture behavior of the Ag sinter joint is compare with a conventional Pb-5Sn solder joint.

In **Chapter 3**, thermal shock-resistant GaN/DBA die attach structures with Ag sinter joining by thick Ni metallization (7 μm) were suggested. The shear strength of the Ag sinter joining structure was sustained above the initial strength after 500 cycles, which showed durable sinter necks and non-deformed interfaces due to the thick Ni metallization. Thus, Ag sinter joining

with metallization design can be expected as an environment-friendly replacement die material for the long-term reliability of WBG semiconductor module packaging.

In **Chapter 4**, SiC thermal engineering group (TEG) chip was developed, direct thermal characterization method of junction temperature in an actual chip packaged using active 4H-SiC TEG chip applied power cycling systems. This demonstration offers the possibility of precise measurement of junction temperature and thermal resistance at high power density, which is no longer limited by the actual SiC direct bonded power module structure. This technology can be extended to perform reliability test standardization for all wide band-gap semiconductors by providing a method of evaluation which will determine which parts of a power module structure are deteriorating at any point in time.

In **Chapter 5**, the summarizes of this dissertation were presented. These studies can be acknowledged as alternative interconnection technologies and thermal managements for next-generation power conversion systems.

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Chapter 2

High temperature aging of GaN/DBA die-attached module by Ag sinter joint and Pb-5Sn solder joint

2.1 Introduction

In this chapter, to address the many issues mentioned in *chapter 1*, a low-cost micron/submicron hybrid Ag sinter paste was employed for a GaN die-attach power module on a DBA substrate and this was directly compared for high temperature reliability at 250 °C with the traditional Pb-5Sn solder die-attach material. The mechanical characteristics and fracture behaviors of the integrated GaN/DBA die-attached structure for both joint structure during thermal aging were investigated by a shear test, FE-SEM, and EDX analysis, respectively. The fracture behavior and its factors were systematically analyzed for the two kinds of die attach joint structures, to provide a basic understanding from the viewpoint of mechanical and fracture mechanism of GaN power modules during high temperature aging, and particularly with an eye toward improving the long-term reliability of Ag sinter joining for high temperature applications.

2.2 Materials and methods

2.2.1 Preparation of the Ag paste and Pb-5Sn solder

Ag submicron particles (FHD, Mitsui Mining and Smelting Co., Ltd, Japan) and Ag flake (AgC239, Fukuda Metal Foil and Powder, Kyoto, Japan) were mixed as Ag fillers of micron/submicron Ag sinter paste in a weight ratio of 1:1. These micron/submicron particles were then stirred magnetically for 10min and vibrated ultrasonically for 30min in alcohol. Finally, they were mixed with an ether-type solvent (CELTOL-IA, Daicel Corporation) using a mixer (HM-500, Keyence Corporation) to make the Ag paste into a uniform mixture. The amount of solvent was maintained at approximately 10 wt% in the paste to keep a suitable viscosity of 150-250 cPs at room temperature. Also, Pb-5Sn (Senju Metal Co., Ltd, Japan) was employed as a high temperature solder for a reliability comparison.

2.2.2 Die bonding

A GaN die (5 mm × 5mm × 0.5 mm) was introduced for bonding to a DBA substrate (Al/AlN/Al). Prior to Ag sinter joining, 200 nm Ti and 2 μm Ag was sputtered on both the back side of the GaN die and on the top side of the DBA substrate, as shown in Fig. 2. 1(a). For the soldering, 200 nm Ti, 1 μm Ag, and 1 μm Ni was sputtered on both the back side of the GaN die and on the top side of the DBA substrate (see Fig. 2. 1(b)). In order to perform the die bonding process, the GaN die was mounted on the DBA substrate after the die-attach material was mounted, as illustrated in Fig. 2. 1(c). In the case of Ag sintering, the pressure-less sintering was realized by using a temperature profile of 250 °C for 30 min as shown in Fig. 2. 2(a). For the Pb-5Sn soldering, a step- by-step profile, including 200 °C for 5 min at formic acid, and 340 °C for 4 min at nitrogen gas (N₂), was applied to obtain a structurally sound joint without defects, as can be seen in Fig. 2. 2(b).

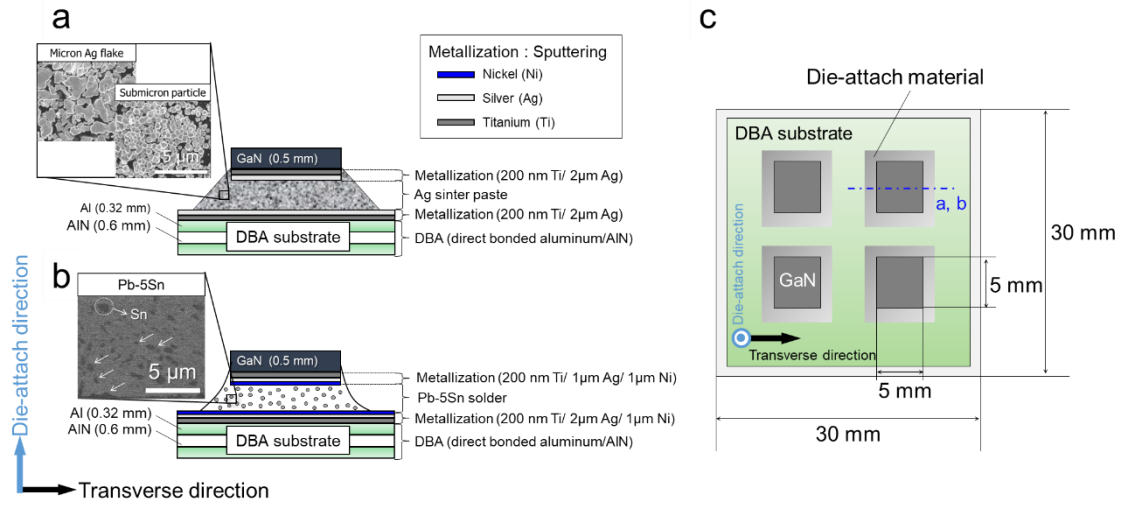


Fig. 2.1 Schematic diagram of specimen structure: (a) cross section of the Ag sinter jointed structure (b) cross section of the Pb-5Sn soldered structure and (c) top-side view of the GaN/DBA assembled structure.

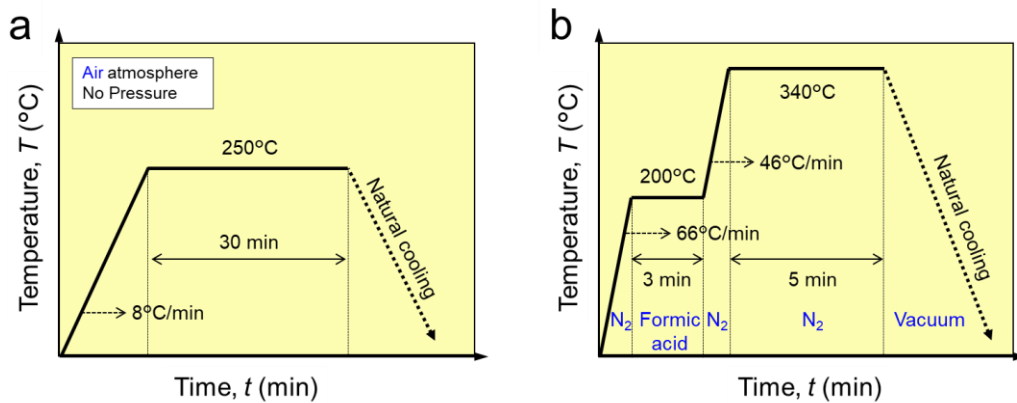


Fig. 2.2 Joining conditions: (a) Ag sintering and (b) Pb-5Sn soldering process.

2.2.3 Thermal aging test and characterization

The evolution of the microstructures was monitored after thermal aging tests at 250 °C for 0 hour (as-bonded state), 250 hours, 500 hours, and 1000 hours. The specimens subjected to thermal aging test were shear tested. The bonding strength of the GaN/DBA joints was evaluated by shear tests (DAGE 4000 bonds tester, UK) at a speed of 50 µm/s. The cross section

of joints was prepared by an ion-milling polishing machine (IM4000, Hitachi, Tokyo, Japan), and the microstructure characteristic was observed by a field-emission scanning electron microscopy (FE-SEM, SU8020, Hitachi, Tokyo, Japan) and energy-dispersive X-ray spectroscopy (EDX).

2.3 Results

2.3.1 Shear strength

Fig. 2.3 displays the change of shear strength during thermal aging tests. The results of the shear test are clearly divided into two trends. In the case of the hybrid Ag sinter joint, as-sintered shear strength achieved above 42.3 MPa without any assist gas or pressures. The shear strength after aging of 250 hours was 52.8 MPa, an increase in strength from the as-bonded state, and even after 1000 hours of aging strength remained above 53.2 MPa. To distinguish the significance of the strength change, the results were analyzed using a one-way analysis of variance (ANOVA) and multiple comparison by using the Tukey–Kramer test with $p < 0.05$ to indicate significance. In ANOVA, turkey-karma test, it was no significant results ($P=0.14$). The P value (0.14) implied that the strength fluctuation was from the normal error of samples rather than the aging effect. Consequently, in the case of Ag sinter joint, the high temperature thermal aging test at 250 °C up to 1000 hours did not significantly affect the shear strength change. By contrast, traditional Pb-5Sn solders tended to be substantially less reliable during thermal aging tests. The initial strength of the Pb-5Sn solder joint was similar to that of the Ag sinter joining, but after 250 hours of thermal aging the shear strength was 14.8 MPa, a significant reduction of 60% from the as-bonded state. Moreover, a decrease in strength was consistently measured up to 1000 hours. These results clearly demonstrate that the traditional high content Pb solder at high temperatures of 250 °C are not suitable in terms of long-term reliability.

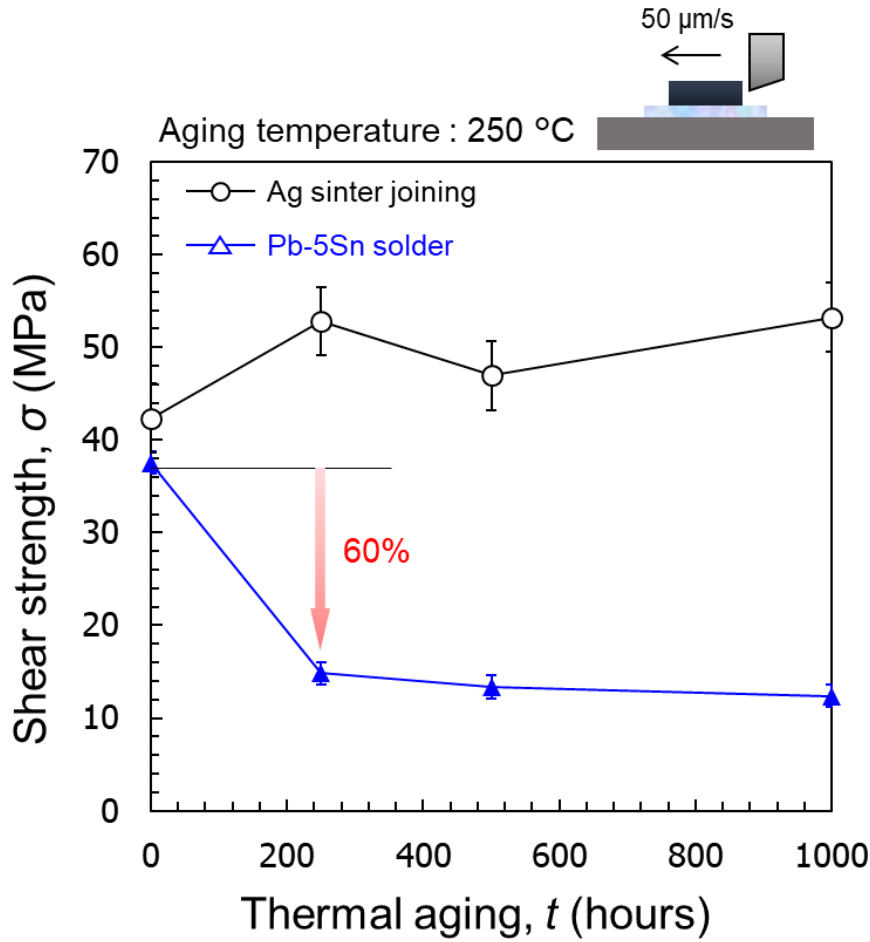


Fig. 2.3 Change of shear strength by thermal aging tests.

2.3.2 Microstructure characteristics of Ag sinter joint

2.3.2.1 Cross section observation

Fig.2.4 shows the microstructural evolution of Ag sinter joint during aging tests at 250 °C. The pattern of aging behavior can be divided into two regions by cross section images. The first region was from as-sintered state. No significant crack growth or plastic deformation occurred and a structurally sound, bonded micro-porous Ag sintered structure can be clearly observed ((see Fig. 2.4(a, b)). The second regions were from 250 hours to 1000 hours of thermal aging. No cracks or interfacial degradation are observed as shown in Fig. 2.4 (c, d, e, f, g and h). In the case of high-temperature aging the condition is unchanged for more than 250 hours, de-

wetting areas were slightly observed but considered not to significantly affect the plastic deformation and strength of the interface in these results ((see Fig. 2.4(b, d, f and h)). In addition, sintered Ag neck thickness was gradually increased after 250 hours in macroscopically.

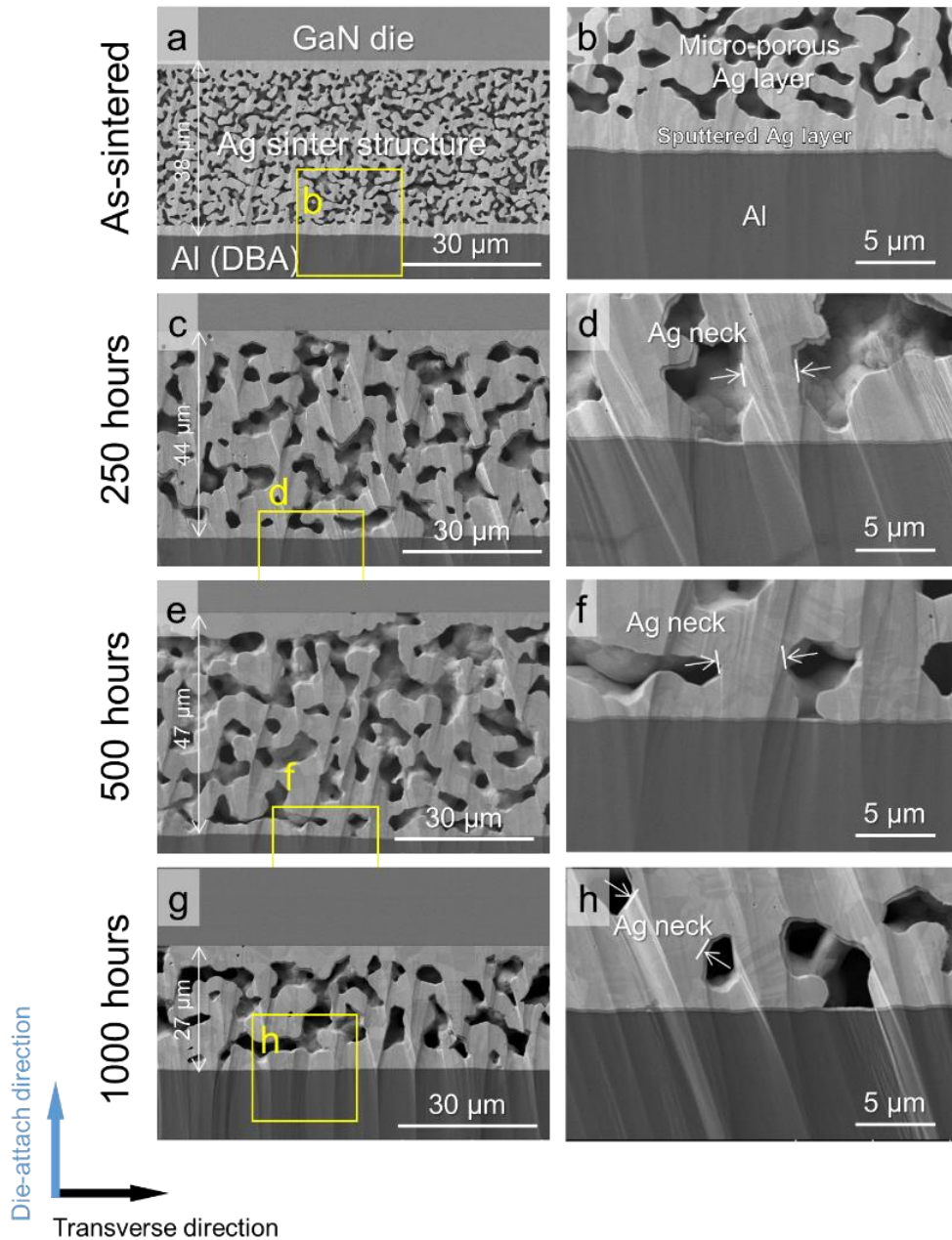


Fig. 2.4 Cross section images of Ag sinter joint by thermal aging tests. (a): as-sintered state and (b): its high magnification image, (c), (d): 250 hours, (e), (f): 500 hours and (g), (h): 1000 hours thermal aged samples.

To quantitatively understand an Ag neck thickness growth behavior during thermal aging tests, the Ag neck thickness was observed by FE-SEM utility. As shown in Fig. 2.5, it was assumed that the thin part was the neck between the sintered Ag particles and the Ag particles, and the thickness of the seven points was measured for each aging time. Fig. 2.5 shows the Ag sintered network growth behavior during thermal aging tests, the Ag necking size of less than the initial $1\ \mu\text{m}$ was significantly increased after the aging tests of 250 hours, and grows to about $4\ \mu\text{m}$. Thereafter, the growth of this Ag necking was stabilized and remains similar until 1000 hours aging tests.

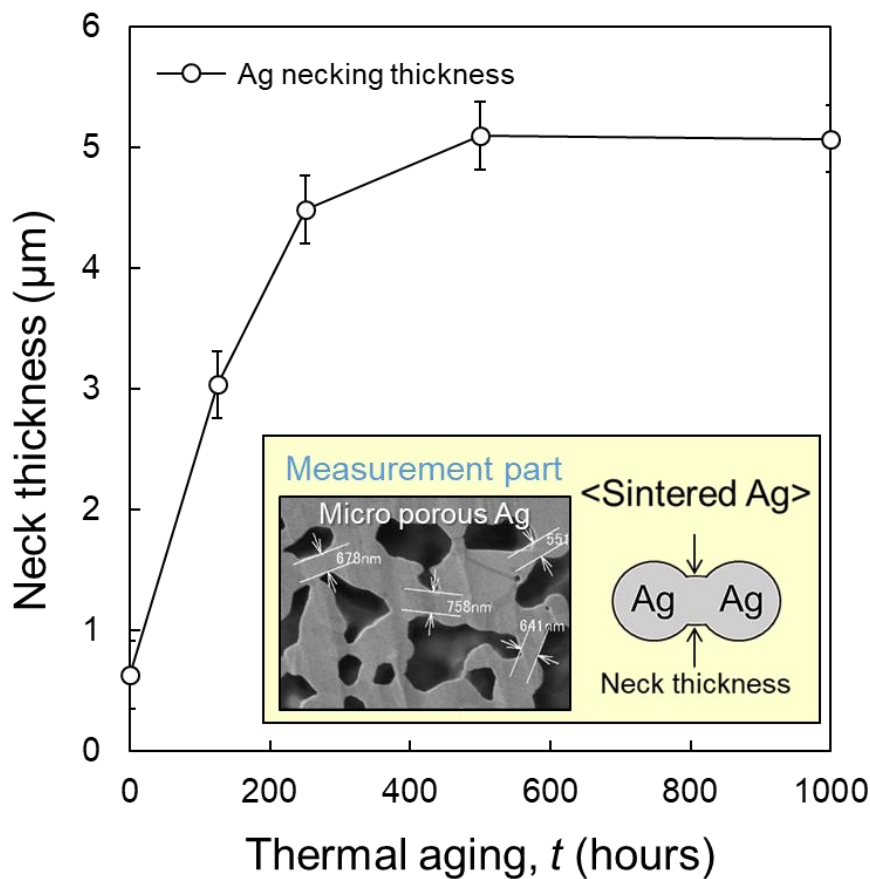


Fig. 2.5 Ag sintered network growth behavior during thermal aging tests.

2.3.2.2 EDX analysis of the Ag sinter joint

EDX analysis was performed to observe the interface oxidation/diffusion and intermetallic compound (IMC) growth behavior. The Ag sinter joint specimen was analyzed after 1000 hours of thermal aging tests, and corresponding element mapping and line analysis can be seen in Fig. 2.6. Both interfaces of the GaN-Ag and Ag-Al show a non-diffusion and non-oxidation interface and this can be confirmed from the elements mapping and its peak intensity ((see Fig. 2.6(a)). Fig. 2.6(b, c) exhibits the line analysis result, which is clearly divided into 3 regions. EDX line analysis on the cross section sample did not find any notable atomic diffusion between the layers, thus confirming that there was no diffusion, oxidation, or IMC (see Fig. 2.6(c)).

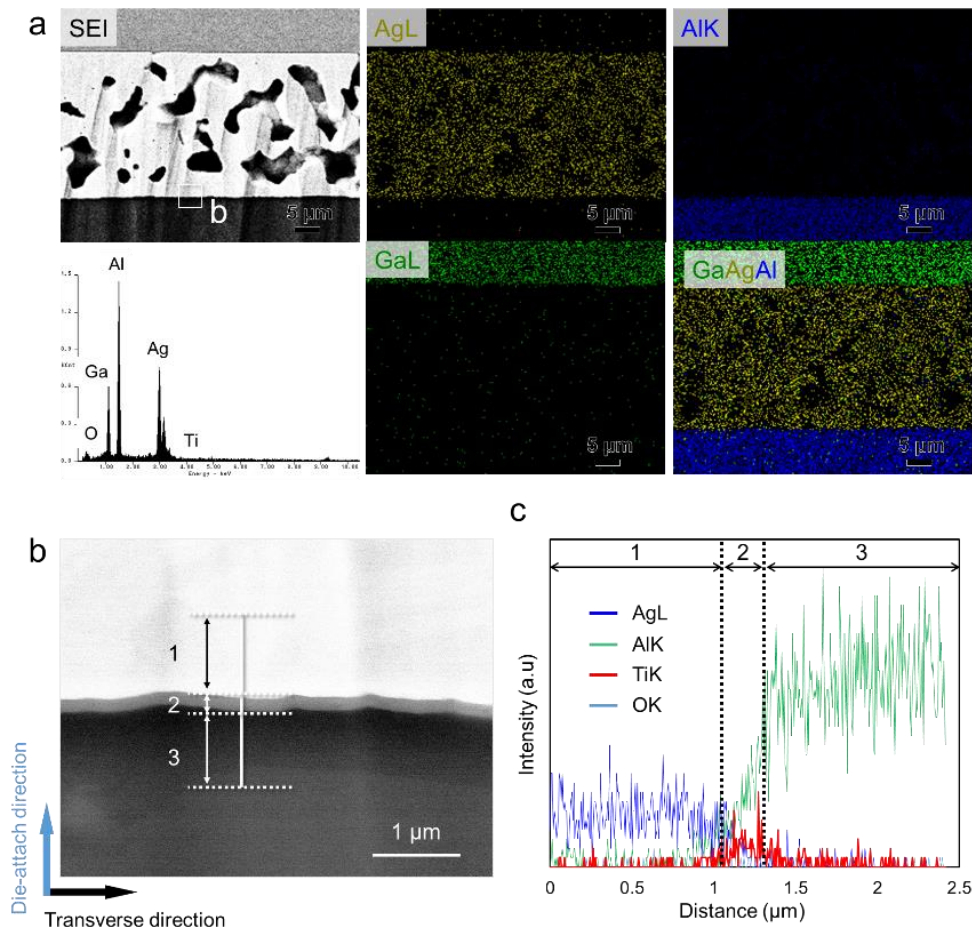


Fig. 2.6 EDX analysis of Ag sinter joint specimen after 1000 hours of thermal aging test: (a) elements mapping results, (b) EDX line analysis area and (c) EDX line result of b area.

2.3.3 Microstructure characteristics of Pb-5Sn solder joint

2.3.3.1 Cross section observation

Fig.2.7 exhibits the cross section back-scatter detector (BSE) images of the Pb-5Sn solder joint during thermal aging tests at 250°C. During high temperature aging, thin IMC appeared and grew into a thick IMC layer with Sn-Ni reaction. The as-bonded state shows the Sn particles are uniformly dispersed and forming relatively stable interfaces between GaN die and Al of DBA without a massive IMC layer as displayed in Fig. 2.7(a, b). On the other hand, after 250 hours aging tests, the IMC layer gradually increases throughout 1000 hours aging (see Fig. 2.7 (c, d, e, f, g and h)). Fig. 2.8 shows the IMC growth behavior during thermal aging. The initial state of the IMC layer was about 500 nm. This IMC layer gradually grew to 1.4 μm throughout 250 hours aging tests. This growth of the IMC layer then stabilized and remained significantly unchanged through 1000 hours aging tests. This IMC behavior shows a tendency to be inversely proportional to the shear strength and has a significant effect on the strength reduction.

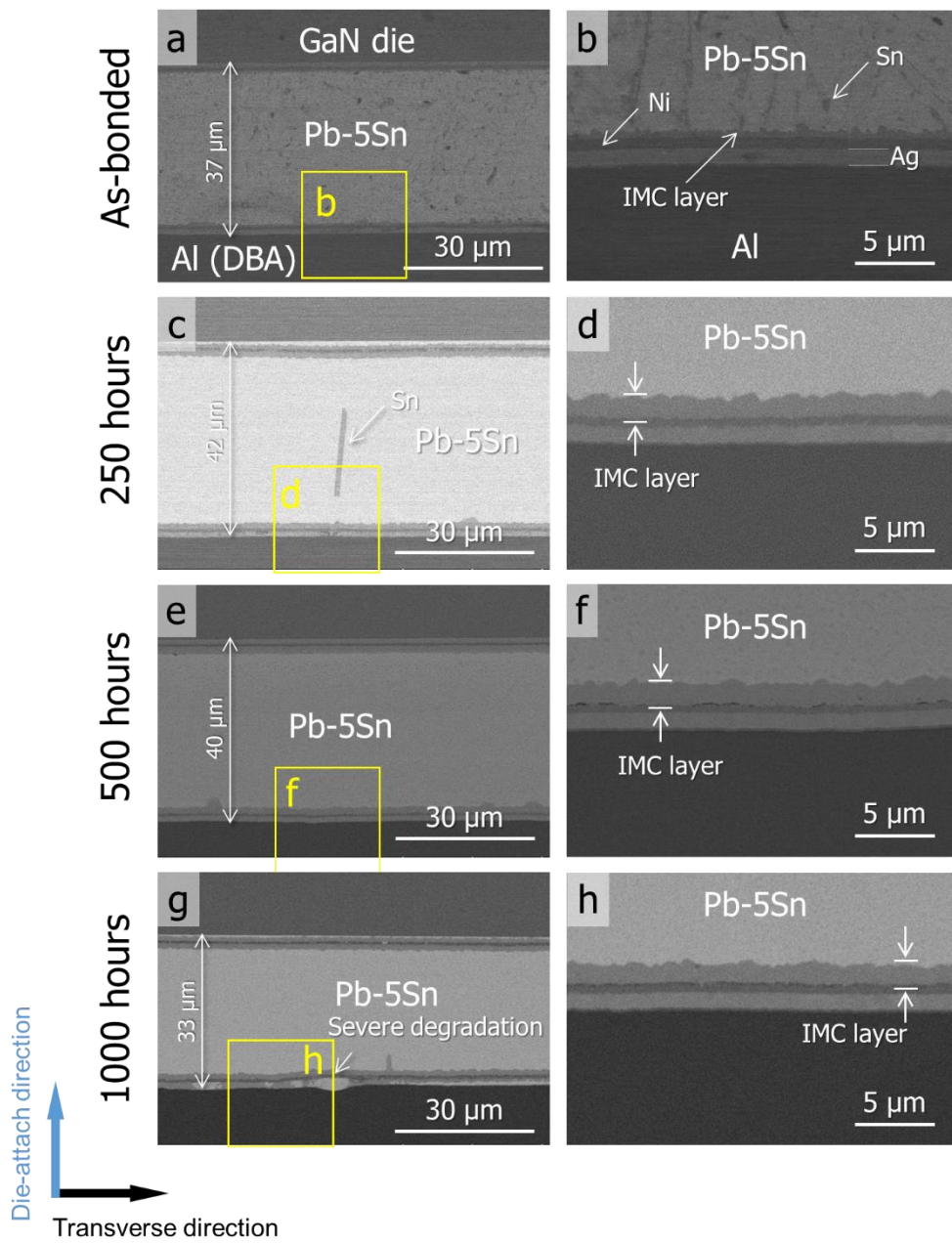


Fig. 2.7 Cross section images of Pb-5Sn solder joint by thermal aging tests: (a) as-sintered state and (b) its high magnification image, (c), (d) 250 hours, (e), (f) 500 hours and (g), (h) 1000 hours thermal aged samples.

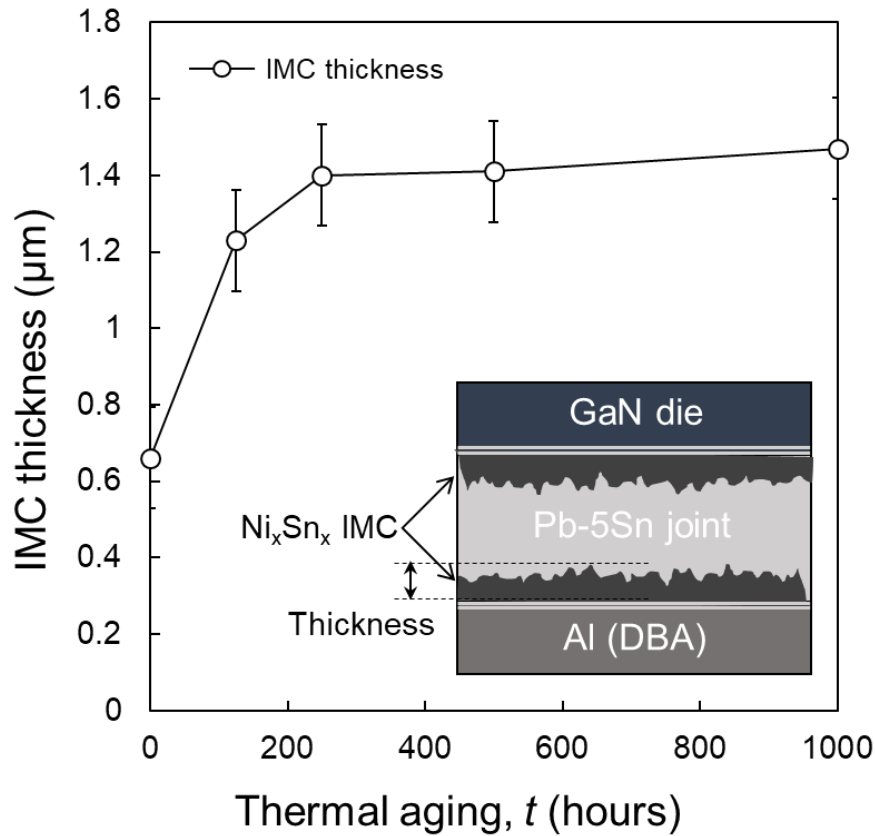


Fig. 2.8 Intermetallic compound (IMC) growth behavior during thermal aging tests.

2.3.3.2 EDX analysis of the Pb-5Sn solder joint

The 1000 hours aged Pb-5Sn solder joint specimen, and corresponding EDS analysis results are presented in Fig. 2.9. The interface of Pb-5Sn solder joint was severely damaged with inter reaction between solder and metallization layers after 1000 hours aging. As shown in Fig. 2.9(a), non-uniform interface between Pb-5Sn and Al of DBA can be seen and a micro delamination layer has formed. Here we can detect the two different interface tendencies as shown in Fig. 9(b-c). In Fig. 9(b), the Ni-Sn IMC and Ni-Ag diffusion layer were detected by line scan. In addition, in Fig. 2.9(c), Ni-Sn IMC can be observed. Additionally, the diffusion of Pb into the Ag metallized layer was detected in line scan. To further understand the element distribution at this time, mapping analysis was performed and the element distribution is shown in Fig. 2.9(d). Diffusion of Pb was observed, and it was also observed that the Ni, Sn, and Ag tended to interact

with one another. In particular, it can be clearly seen that voids formed around the diffused Pb, such as the double arrow in the Fig. 2.9(a). Fig. 2.9(e-g) shows the point analysis for Sn behavior during thermal aging tests. Obviously, in Fig. 2.9(e, f), from the above EDX analysis, it can be seen that this point is a Ni-Sn based intermetallic compound. Surprisingly, the Sn atomic percentage gradually decreased up to 1000 hours aging tests as displayed in Fig. 2.9(g).

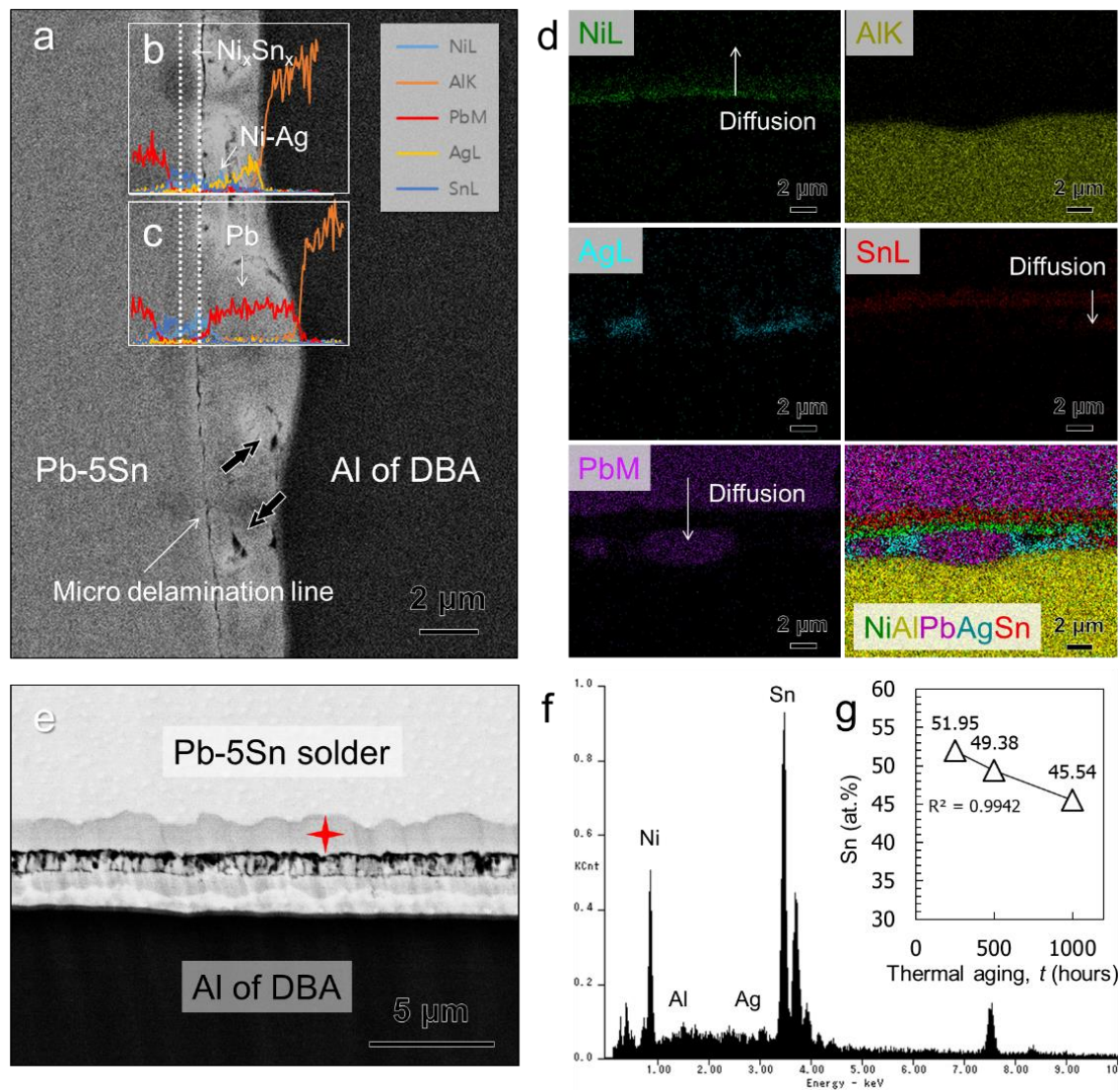


Fig. 2.9 EDX analysis results of Pb-5Sn solder joint after 1000 hours of thermal aging test: (a) cross section image, (b) and (c) line analysis, (d) elements mapping result, (e) SEI for EDX point analysis of IMC layer, (f) its peak intensity and elements table and (g) change of Sn atomic percentage during thermal aging tests.

2.4 Discussion

2.4.1 Fracture characteristics of the Ag sinter joint

The fractured surface of Ag sinter joints after shear test are shown in Fig. 2. 10. Overall, the Ag sinter joint can be seen to have fractured at the Ag sintered layer (observed by optical microscope). As can be seen from the SEM results, the longer the aging time, the coarser the fractured surface became. In Fig. 2.10(a), the as-sintered state fractured area exhibits fine Ag necking dispersed over the whole area. After 250 hours aged, the fracture of the fine Ag necking areas has further expanded (Fig. 2.10 (b, c)), and the fractured area was observed to have relatively stretched in the shear test direction after 1000 hours aged (see Fig. 2. 10(d)).

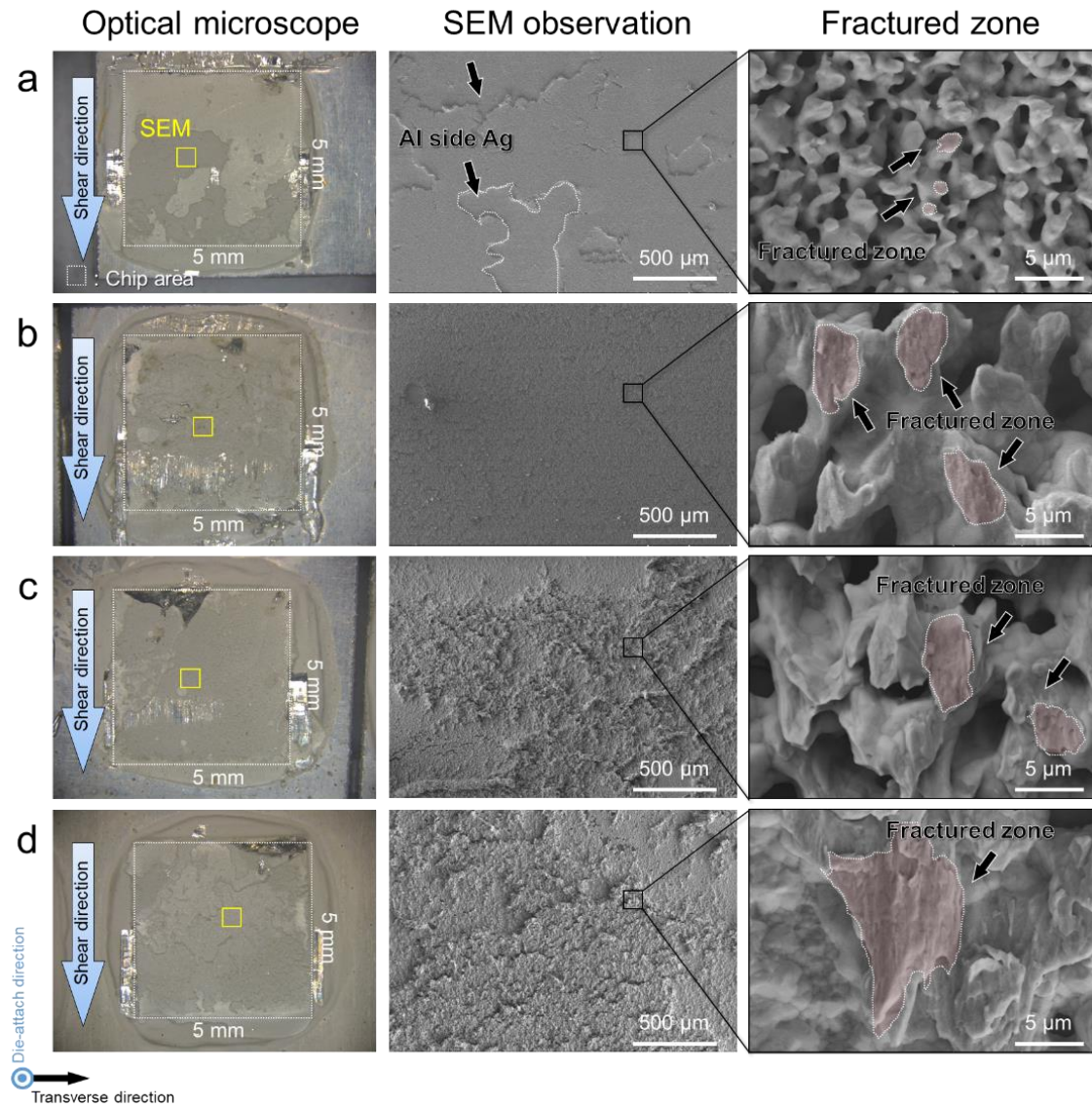


Fig.2.10 Fractured surface analysis of the Ag sinter joints by thermal aging tests: (a) 0h, (b) 125h, (c) 250h, (d) 500h and (e) 1000h.

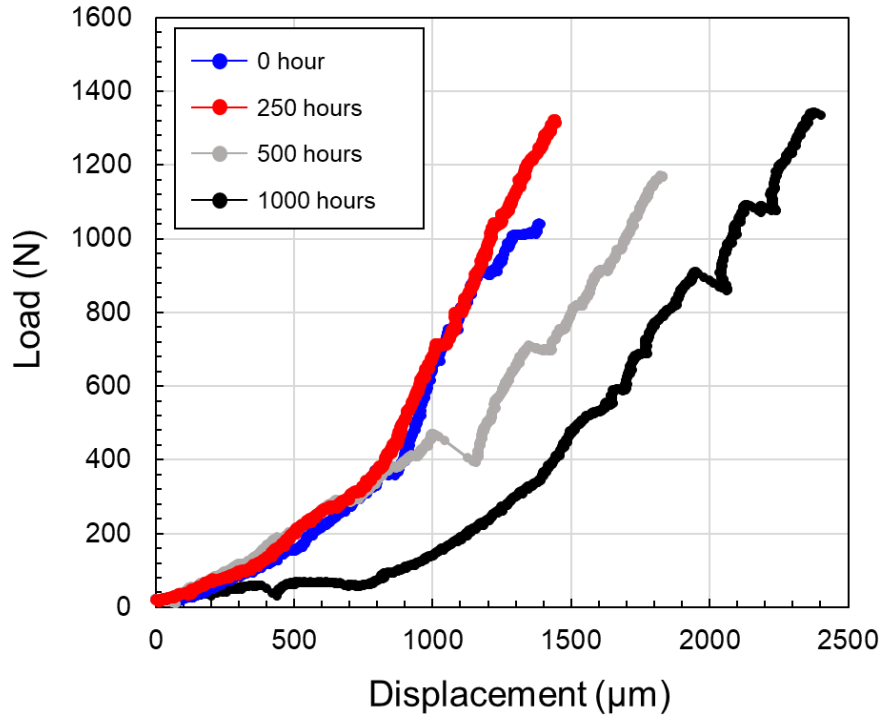


Fig. 2.11 The load-displacement curve of Ag sinter joints.

Fig.2.11 displays a load-displacement curve of pressure-less Ag sinter joints. As the fracture zone expands, the tendency of the elongation to increase was clearly observed. Fig. 2.12 shows the main fracture feature of the Ag sinter joint. As shown in Fig. 2.12(a), the fracture tendency change of the Ag sinter joint is that the stress concentration did not occur at the interfaces because there was no degradation to the interface. For this reason, even after a 1000 hours aging test, fracture still can be induced inside the Ag sinter layer. Moreover, the Ag sinter joints demonstrated that increased shear strength could be sustained even after 1000 hours of aging while remaining resistant to significant external force by widening fracture zone. Consequently, as shown in Fig. 2.12(b), as the aging time became longer, the fracture zone gradually expanded. This tendency is in agreement with the tendencies witnessed in our previous shear test results. In this context, it was clearly found that the Ag sinter joining can realize excellent long-term reliability by using just the simple metallization that is present.

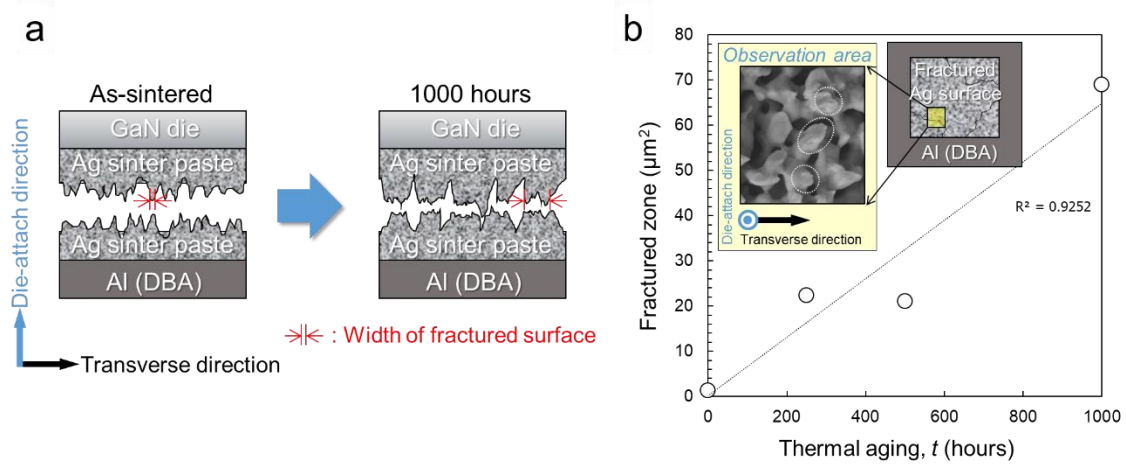


Fig. 2.12 (a) Schematic illustration of the main fracture feature of the Ag sintered specimen before and after thermal aging test, and (b) change of the fractured zone tendency.

2.4.2 Fracture characteristics of the Pb-5Sn solder joint

Lengthening the aging time leads to significantly different fracture characteristics and failure behavior in the Pb-5Sn solder joints as determined from optical microscope observation. The influence of aging time on the fracture behavior of Pb-5Sn solder joints are shown in Fig. 2.13. As-bonded state showed a ductile fracture with the formation of fine dimples at the Pb-5Sn solder layer (see Fig. 2.13(a)). On the other hand, as the Ni-Sn-based IMC gradually grew, the fracture pattern changed in form to a brittle fracture. Subsequently, Al was observed on the fracture surface (Fig. 2.13 (b-d)). In Fig. 2.14, similar to the results of the above fracture surface analysis, it can be seen that the elongation is significantly reduced and the strength is substantially reduced with brittle IMC growth as the aging time of the solder, exhibiting high strength at the initial stage, increases.

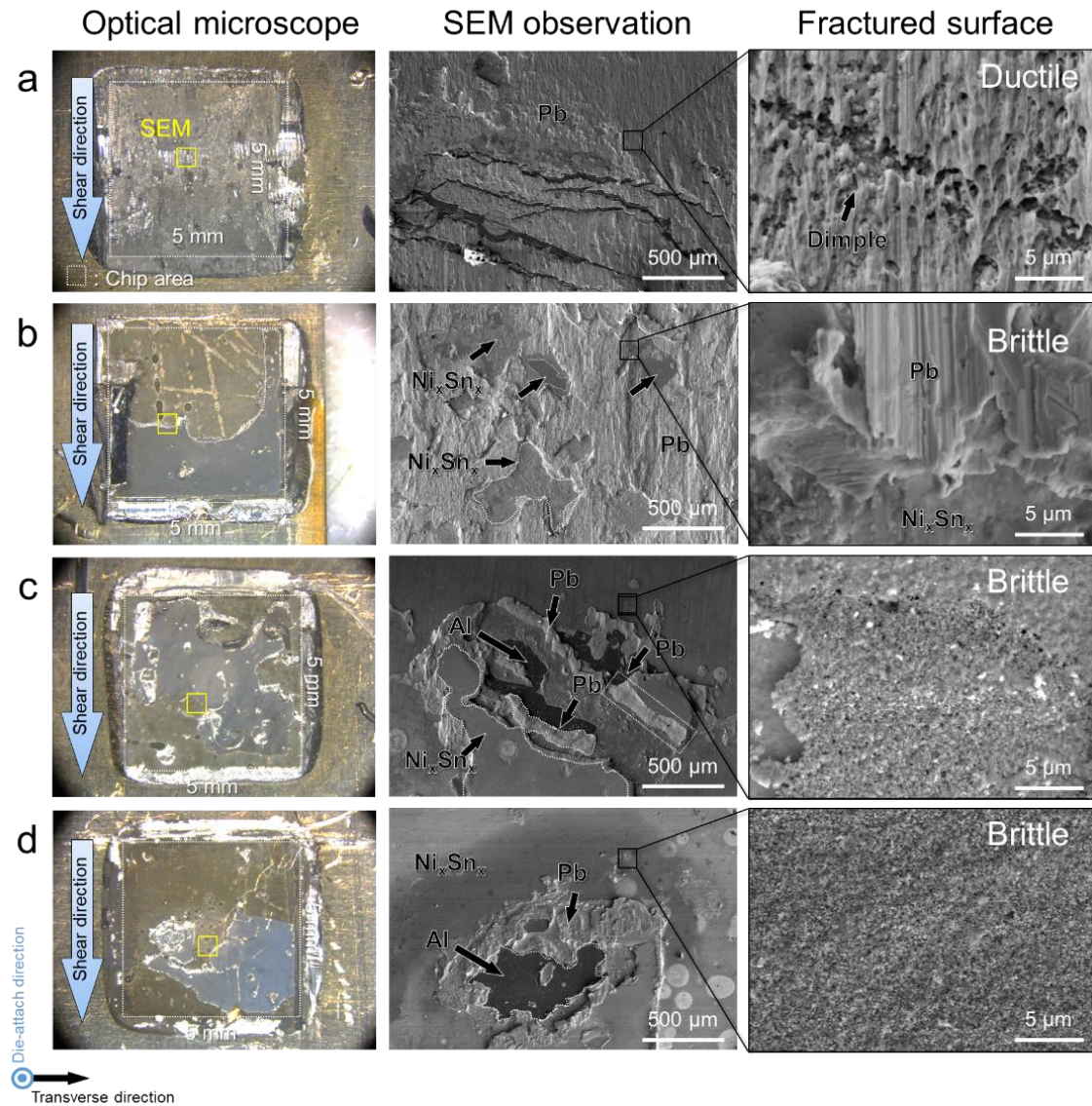


Fig. 2.13 Fractured surface analysis of the Pb-5Sn joints by thermal aging tests: (a) 0h, (b) 125h, (c) 250h, (d) 500h and (e) 1000h.

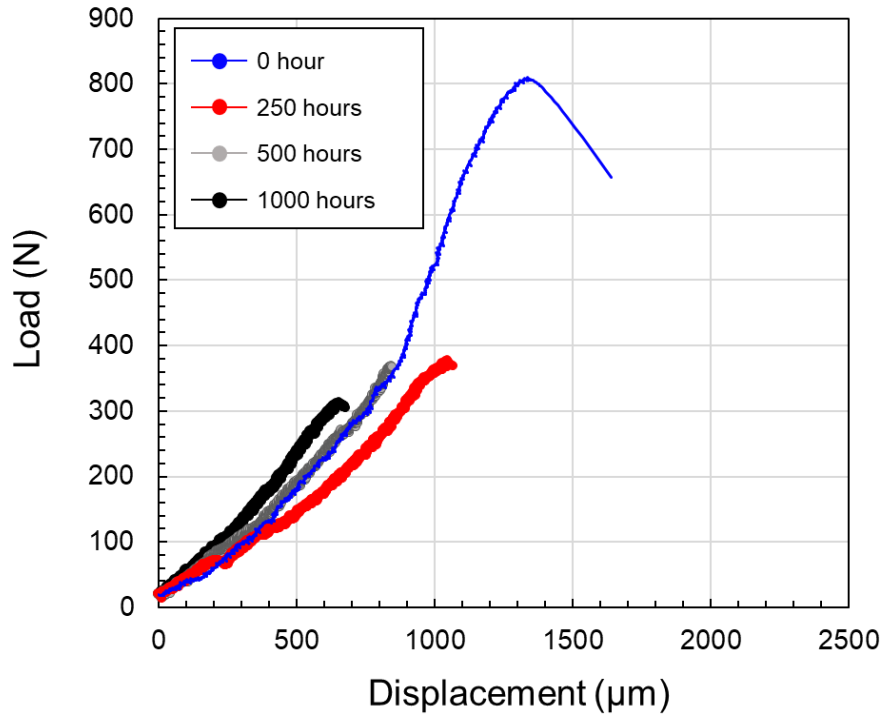


Fig. 2.14 The load-displacement curve of Pb-5Sn solder joints.

To further understand the fracture path after aging tests, EDX mapping analysis was utilized. Fig. 2. 15 (a, b) displays the 1000 hours aged fractured surface and its EDX mapping results. The black zone detected the Al element, other regions were detected to Ni, Sn, Al and Pb complex deposited whole area. Thus, fracture path change of the Pb-5Sn solder joint can be explained by Fig. 2. 15 (c), an initial ductile fracture was changed to brittle fracture by massive IMC, void, diffusion and interface delamination formation after thermal aging tests (see Fig. 2. 15(d)). These brittle Ni-Sn based IMCs have been reported in previous studies and they do play a role in strength reduction [1][2].

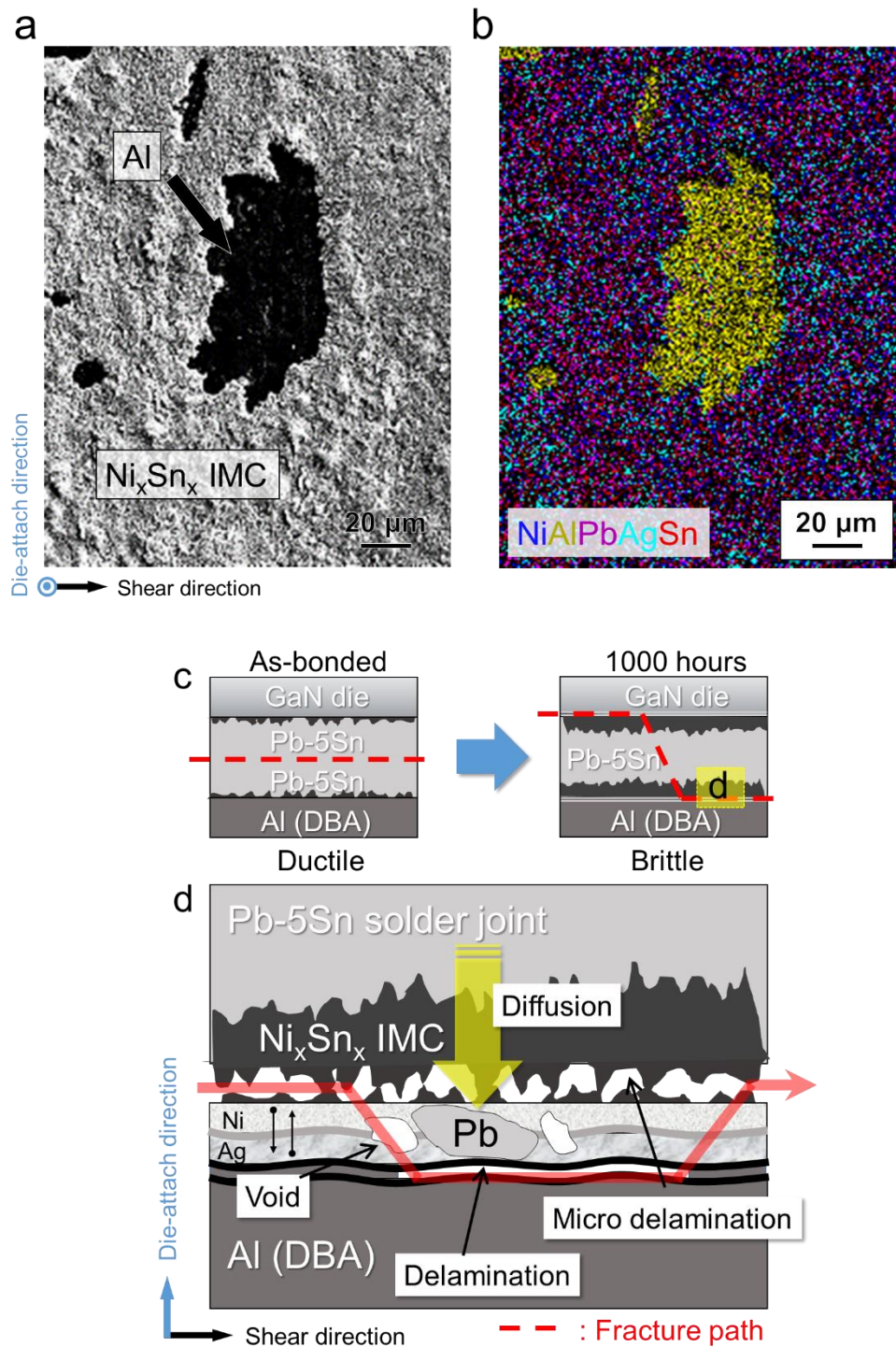


Fig. 2.15 (a) Fractured surface of Pb-5Sn solder joint after 1000 hours of thermal aging test, (b) its EDX mapping result, (c) schematic illustration of Pb-5Sn joint fracture path changing tendency and (d) detail drawing explain of after 1000 hours fractured sample.

2.5 Conclusions

In this chapter, it was systematically investigated the thermal aging reliability of GaN/direct bonded aluminum (DBA) die-attached by pressure-less Ag sintering and by Pb-5Sn soldering. As the results demonstrate, as-sintered shear strength of the Ag sinter joint achieves above 42 MPa when bonded at 250 °C without assisted pressure in air. Moreover, this strength is sustained and improves stably up to 1000 hours at 250 °C of harsh thermal aging tests without any defects such as oxidation, diffusion, or mechanical deformation of the interface. On the other hand, the shear strength of traditional Pb-5Sn solder significantly reduced (by 60%) after 250 hours aging due to its serious degraded interface layer. As determined by fracture surface analysis, the Ag sinter joints fractured at the Ag sinter layer regardless of the aging time, which indicates that a long-term reliable joint can be implemented by simply using a common barrier metal. By contrast, as the aging time was increased, the complex degradation including intermetallic compound growth in the Pb-5Sn solder interface changed the fracture mode from a ductile fracture to a brittle fracture, this interface degradation has been found to have a devastating effect on mechanical strength reduction. Therefore, to realize a reliable bonded interface during long periods at over 250 °C, die-attach must be performed with a material that does not have an interfacial reaction, such as Ag sintering. Our unprecedented research can be an important indicator of material reliability for the GaN power devices, and pressure-less Ag sinter paste is expected to be introduced as an eco-friendly replacement material for high content Pb solder in the future.

Reference

- [1] Y. Jeon and K. Paik, “Studies on Ni-Sn Intermetallic Compound and P-rich Ni Layer at the Electroless Nickel UBM - Solder Interface and Their Effects on Flip Chip Solder Joint Reliability,” in *Components*, 2001, vol. 00, no. C, pp. 1–7.
- [2] A. M. Minor and J. W. Morris, “Growth of a Au-Ni-Sn intermetallic compound on the solder-substrate interface after aging,” *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, vol. 31, no. 3, pp. 798–800, 2000.

Chapter 3

Development of thermal shock-resistant GaN/DBA die-attach structure with Ag sinter joining by added a Ni metallization

3.1 Introduction

As introduced in Chapter 1, for next-generation power modules, die-attach structures must operate reliably in a wide range of temperature, ΔT can be reached about 300 °C (-50 °C ~ 250 °C)[1]. To overcome this harsh environment, thermal stress generated by the coefficient of thermal expansion (CTE) mismatch between WBG dies and the other components at harsh condition should be effectively relaxed. Previous study reported that the DBA substrate have a larger deformation on the soft Al surface, which may lead to a reliability issues during a harsh thermal shock test.

Thus, this chapter firstly focused on that to improve a long-term thermal shock reliability of GaN die-attached on the DBA module joint by hybrid Ag sinter joining through suppression the degradation of the joint interface. A thickness Ni metallization with the thickness of 7 μ m was designed to control the deformation of Al layer, and thus to increase the long-term thermal shock reliability of GaN/DBA joint structure. The Ag sintered GaN/DBA module structures with Ti/Ag metallization were subjected to a thermal shock (-50 °C ~ 250 °C) beyond 500 cycles and compared with a sinter Ag joining on Ni/Ti/Ag metallized DBA substrate in the same thermal shock test. In addition, the thermal shock reliability of sinter Ag joining on Ni/Ti/Ag

metallized DBA substrate also was compared with a traditional Pb-5Sn solder joint in the thermal shock ($-50\text{ }^{\circ}\text{C} \sim 250\text{ }^{\circ}\text{C}$) test. The microstructure and the fracture surface were observed by X-ray, FE-SEM with EDX analysis and EBSD. The relationship between the change of microstructure characteristic and shear strength degradation is discussed in detail by a finite element (FE) simulation. This chapter provides main features of microstructures that are changed by repetitive harsh thermal shock cycles.

3.2 Materials and methods

3.2.1 Die bonding, reliability assessment and microstructural observation

A structure of a GaN/DBA die-attach structure and bonding process with an Ag sinter joint and Pb-5Sn solder joint were introduced same condition as *Chapter 2*. [2] In particular, 7 μm Ni sputtering was applied to strengthen the DBA substrate, and the schematic image is shown in Fig. 3.1.

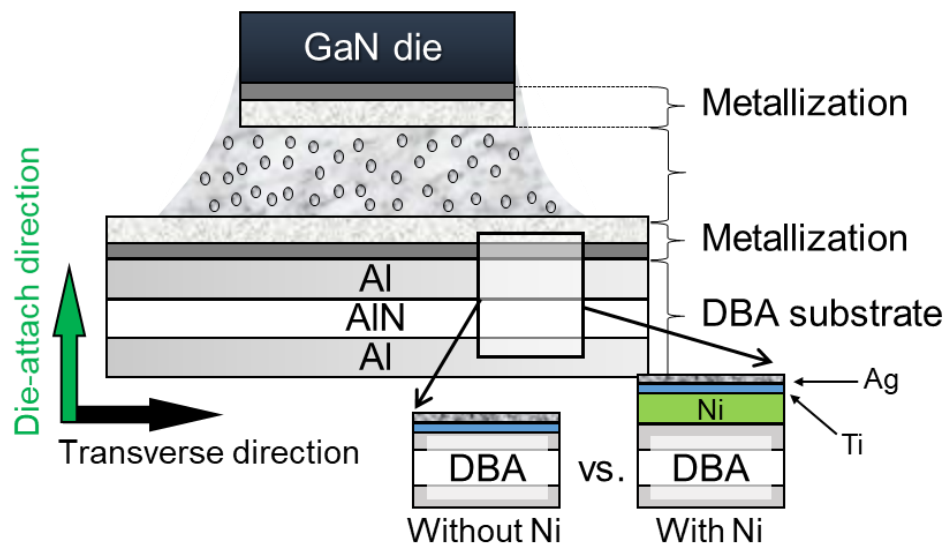


Fig. 3.1 GaN/DBA die-attached module structure and its description of layers

In this chapter, for a thermal shock reliability assessment, a thermal shock chamber (TSE-11-A-S, ESPEC, Osaka, Japan) was introduced. A harsh thermal shock test was conducted at the temperature range of -50 °C to 250 °C per 1 cycle (temperature transition time < 10sec) for a 30 min dwell time at each extreme temperature for 500 cycles as displayed in Fig. 3.2 (a,b,c). The shear strength of the GaN/DBA joints was evaluated by shear tests (DAGE 4000 bonds tester, UK) at a speed of 50 $\mu\text{m/s}$. The die-shear position height from the substrate surface was set as 20 μm .

The cracks and voids growth in the structure were observed by a micro-focus 3D computed tomography (CT) X-ray system (XVA-160N, Uni-Hite System Corporation, Japan) as a non-destructive inspection. For destructive inspection, the cross section of joints were prepared by an ion-milling polishing machine (IM4000, Hitachi, Tokyo, Japan), and the microstructure was observed by a field-emission scanning electron microscopy (FE-SEM, SU8020, Hitachi, Tokyo, Japan) with energy-dispersive X-ray spectroscopy (EDX) and electron backscatter diffractometer (EBSD).

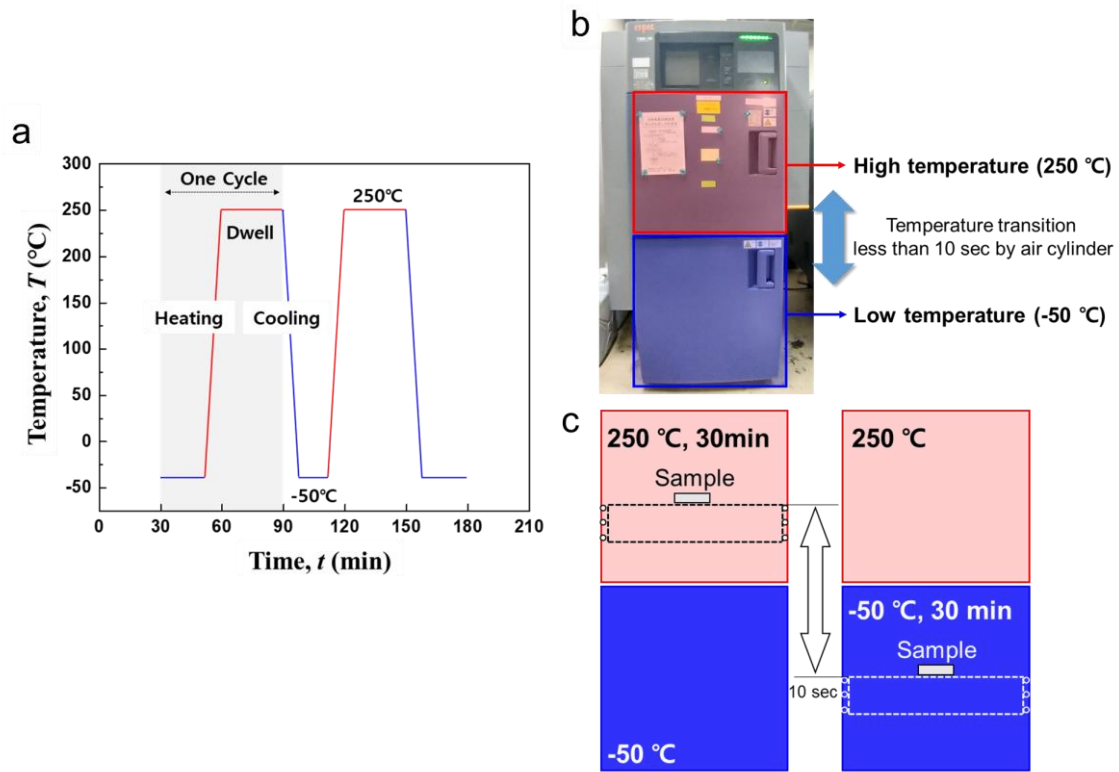


Fig. 3.2 (a)Temperature profiles of harsh environment, (b) thermal shock chamber (TSE-11-A-S, ESPEC, Osaka, Japan) and (c) schematic of driving mechanism of thermal shock chamber: -50°C/250 °C.

3.3 Results and discussion

3.3.1 Thermal shock test of sinter Ag joining on DBA substrate with and without Ni metallization layer

3.3.1.1 Die shear strength and fracture mode

3.3.1.1.1 Die shear strength

The shear strength is one of a key indicator for reliability assessment of the bonding structure. Fig. 3.3 exhibits relationship between shear strength and thermal shock cycle number. When a GaN/DBA die-attached assembly is subjected to harsh thermal shock environments, the strength evolution depends on metallization design. Shear strength of the non Ni metallized specimen gradually reduced at 125 cycles, it was significantly reduced by 33% after 500 cycles of thermal shock (see blue color line). On the other hand, in the case of Ni metallized specimens sustained shear strength above initial strength up to 500 cycles (see red color line). Surprisingly, the shear stress reduction was substantially suppressed by Ni metallization. In addition, these pressure-less hybrid Ag sinter joint results are compared with nano-Ag sinter joint, the thermal shock reliabilities were significantly better than that of the nano-Ag sinter joint (black color line)[6]. The key factor of the strength reduction and strength sustention of the joints will be discussed in the next section.

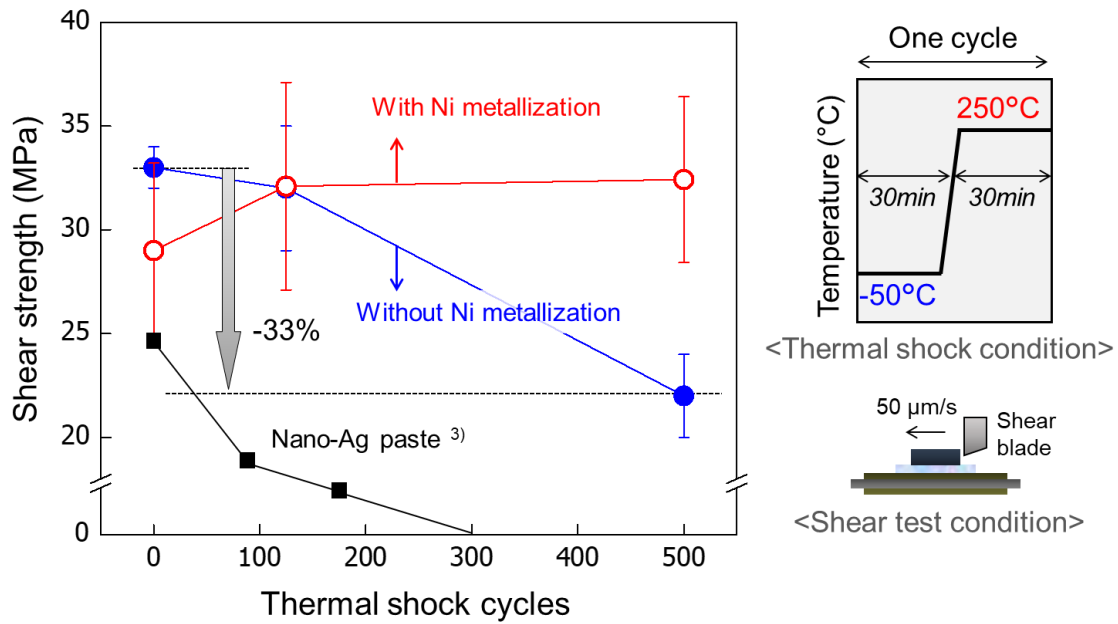


Fig. 3.3 Relationship between die-shear strength and thermal shock cycle number. Blue color line is non Ni metallization specimen and red color line is Ni metallized specimen, they are compared with nano-Ag sinter joint (black line).

3.3.1.1.2 Microstructure characteristics

Fig. 3.4 shows the cross section images of the Ag sinter joint before and after thermal shock cycles. Tendency of the interfaces behavior substantially different with and without the Ni metallization layer. Fig. 3.4 (a) exhibits GaN Ag sinter bonded structure without Ni layer. The initial state formed structurally sound micro-Ag porous joint was shown in Fig. 3.4(a₁). On the other hand, along the yellow line, the interface between the sintered Ag layer and Al of DBA can be clearly seen after 500 cycles (see Fig. 3.4(a₂)). In the case of Ni metallized GaN die attached structure also successfully bonded micro-porous Ag structure by pressure-less Ag sintering process as displayed in Fig. 3.4(b₁). In addition, the Ag-Al interface sustained like initial state after 500 cycles (see Fig. 3.4 (b₂)).

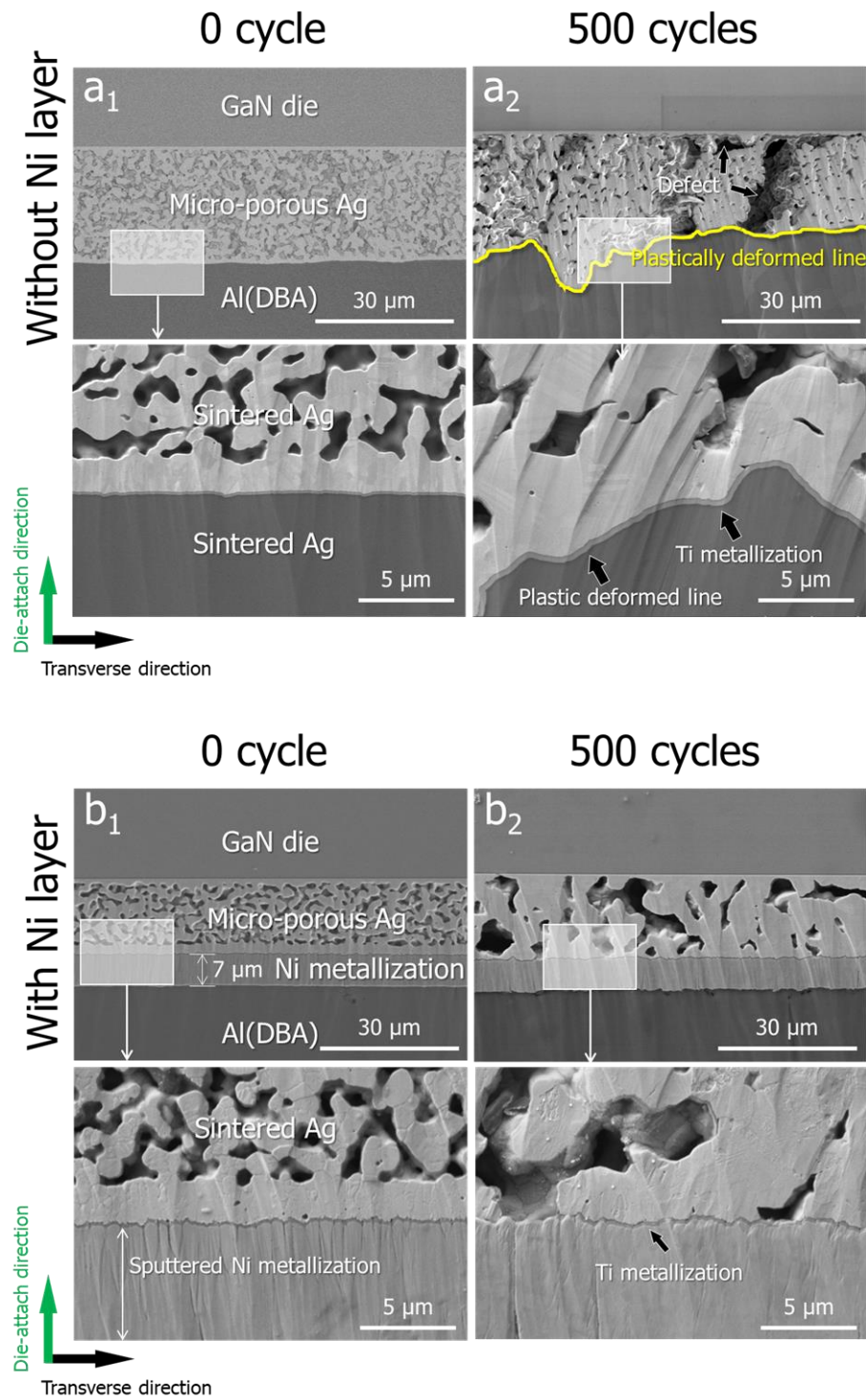


Fig. 3.4 Microstructure evolution images before and after thermal shock cycles. Cross section images of the with Ni metallized GaN/DBA die-attached structure by thermal shocks (a₁): as-bonded without Ni layer, (a₂) 500 cycles without Ni layer and (b₁) as-bonded with Ni layer, (b₂) 500 cycles with Ni layer.

In the process, the Ag neck was a little thicker, but no deformation defects were found, and the Ni metallized specimen suggests a substantially improved interfacial reliability than the non Ni metallized specimen due to the suppressed the plastic deformation of the Al layer by Ni sputtered layer. Thus, through cross-sectional SEM observations, we can clearly be seen that the most predominant factor in strength reduction and sustention attributed an interface deformation between Ag sintered layer and Al layer.

3.3.1.1.3 Fracture surface

To observe that an interfacial deformation affects fracture, a fracture surface analysis of both types of metallized GaN die attached structures were conducted after 500 cycles as shown in Fig. 3.5. With or without the Ni layer, the initial fracture occurred in the Ag sinter joints. The interfacial behavior of the two trends analyzed in the cross-sectional SEM observations had a significant effect on the change of the fracture surface. In the case of without Ni layer, roughened fractured surfaces can be seen as shown in Fig. 3.5(a). Fig. 3.5(b) exhibits high magnification image of the Fig. 3.5(a), it can be clearly seen that the porous structure is on the roughened surface. In addition, roughened surface was Al element and porous structure was Ag element by EDX mapping analysis (see Fig. 3.5(c)). Therefore, in the case of without Ni layer, it is explained that an interfacial failure induced similar to delamination at the Ag-Al interface during shear tests due to the plastic deformed interface. On the other hand, in the case of with Ni layer, an overall flat fracture surface was observed compared to the layer without Ni (see Fig. 3.5(d)). Even in high magnification image, a plate-like fragment, which is regarded as metallization layer off the chip, was observed as shown in Fig. 3.5(e). As the results of EDX element mapping analysis, fragments regarded as a metallization layer was found to be the Ti element, the main element of the fracture surface was found to be Ag element and no Al element was detected at all (see Fig. 3.5(f)). Namely, the entire fracture path is inside the Ag sinter joint,

similar to the initial state. This indicates that that the fracture occurred at the Ag sinter joint as in the initial state due to the without any interface degradation. Therefore, the change of fracture path before and after thermal shocks can be summarized by Fig. 3.6.

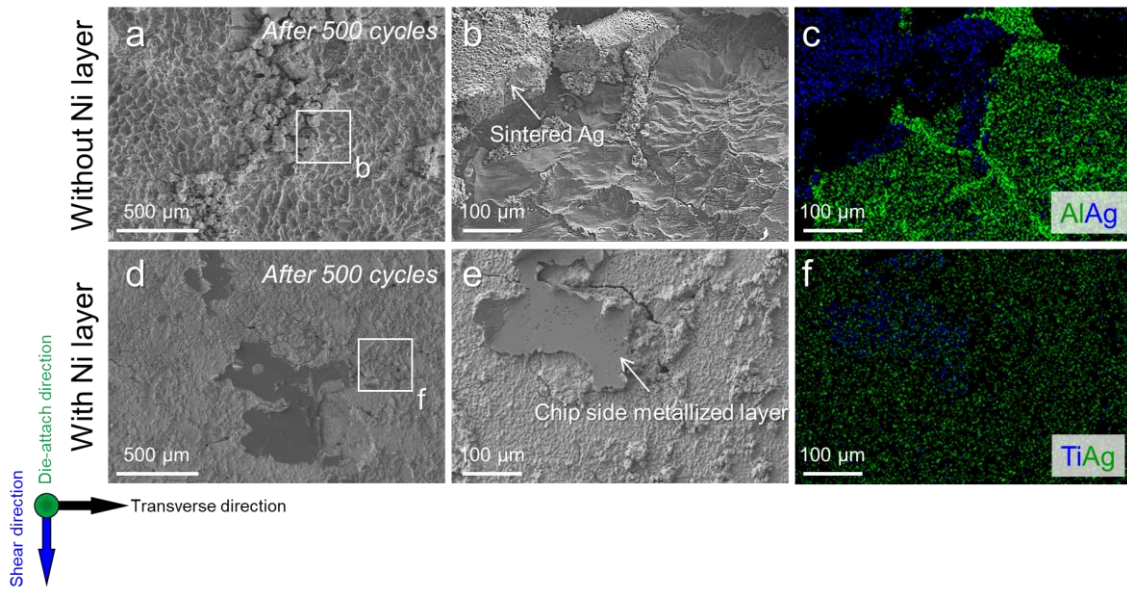


Fig. 3.5 Fracture surface analysis results after 500 cycles. (a) fractured surface image of the non Ni sample of, (b) its high magnification image and (c) EDX elements mapping result, (d) fractured surface of the Ni metallized sample, (e) its high magnification image and (f) EDX elements mapping result.

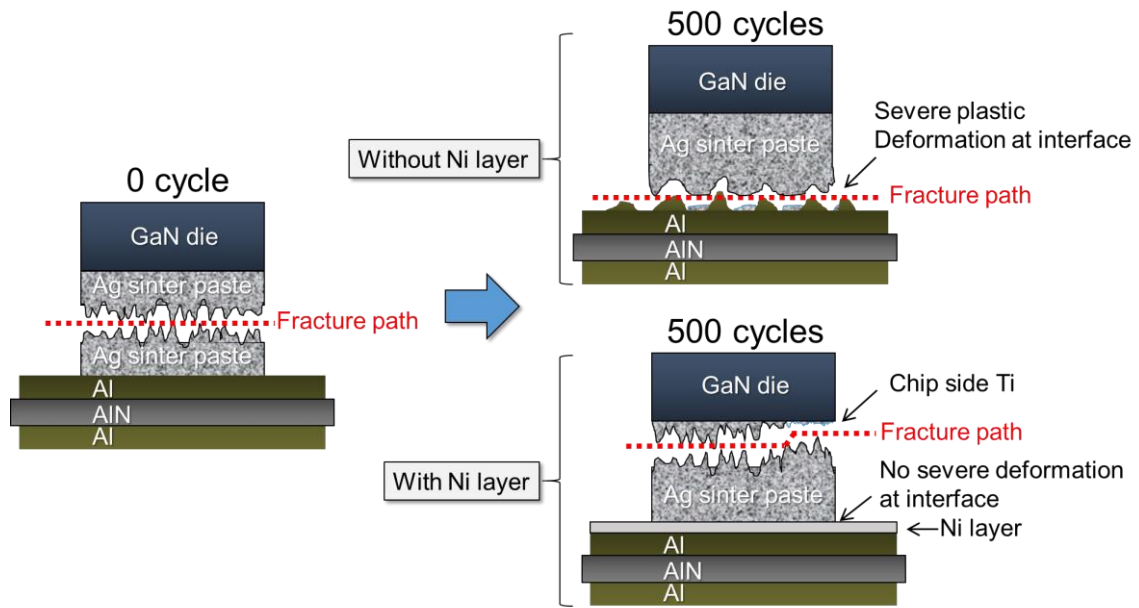


Fig. 3.6 Schematic description of fracture path change.

3.3.1.2 Analysis the Ni effect on Al deformation

3.3.1.2.1 Roughness of Al surface

To investigate an effect of Ni layer on a deformation of an interface of Ag-Al by thermal shocks, a surface roughness measurement of Al was introduced by using a laser microscope. Fig. 3.7 shows the results of the roughness measurement of Al surface of DBA. Initial state of the Al surface was found that no noticeable surface roughness in SEM observation (see Fig. 3.7(a)). In addition, no significant roughening was observed by laser scanning, and a maximum roughness was about $3\mu\text{m}$ as quantified by 3D analysis as shown in Fig. 3.7(b, c). Fig. 3.7(d) exhibits the case of Al surface without Ni layer, severe roughen Al surface with winkle areas and cracks clearly detected. In addition, for the Al surface without Ni layer, the height difference was found to be relatively high more than initial state (see Fig. 3.7(e)). As shown in Fig. 3.7(f), the maximum roughness was about $50\mu\text{m}$ as quantified by 3D analysis. Formation of an Al hillock is attributed this occurrence of surface roughness, and it has been reported that the Al hillock is caused by atomic diffusion due to stress migration (SM) and thermal fatigue (TF)

during repetitive thermal cycling [7]. Finally, in the case of Al surface with Ni layer, the SEM image shows no noticeable surface roughness and cracking. Fig. 3.7(h,i) show similar tendency of the roughness of Al surface as initial state. Thus, it has been found that the Ni layer roles to prevent cracking of the metallized DBA surface by suppressing the deformation behavior of Al during thermal shock cycling, then, the changing grain characteristics are discussed in detail in the next section.

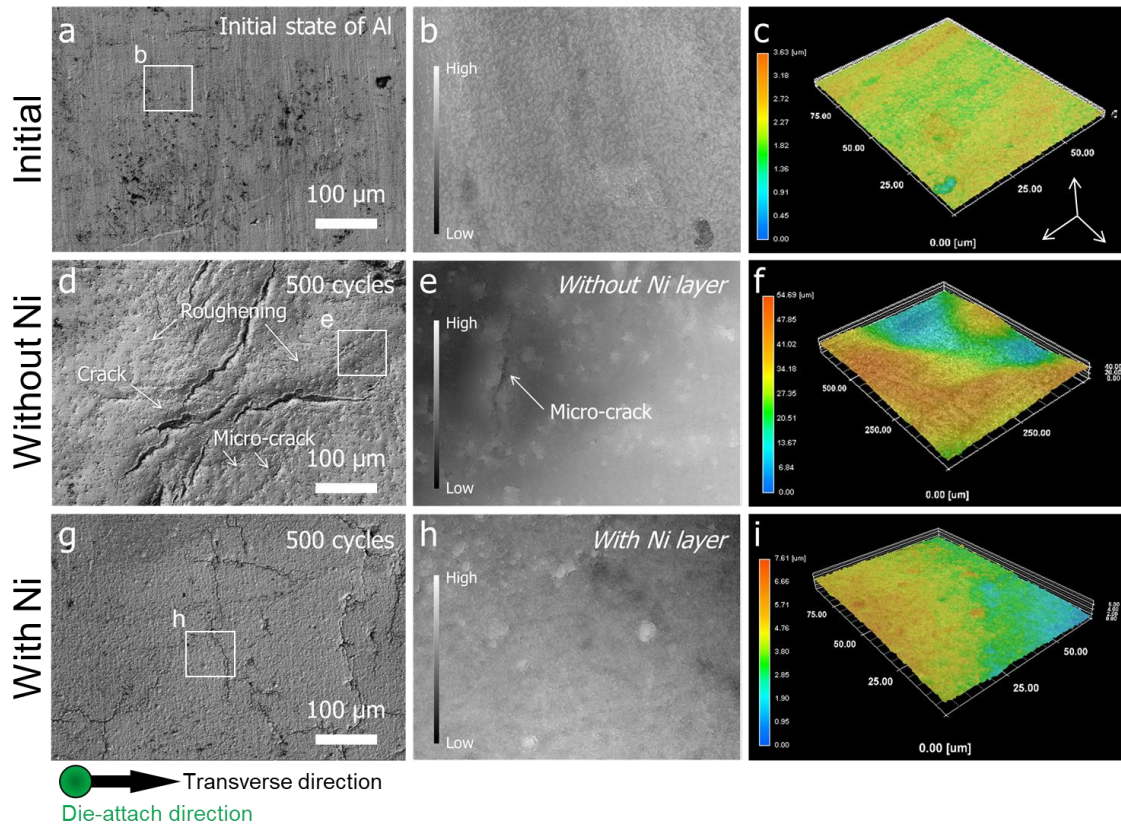


Fig. 3.7 Results of roughness measurement of Al surface of DBA. (a) SEM image of initial state roughness of Al surface, (b) its laser scanning area, (c) 3D roughness measurement result of (b), (d) SEM image of Al surface of without Ni layer after 500 cycles, (e) its laser scanning area, (f) 3D roughness measurement result of (e) and (g) Al surface of with Ni layer after 500 cycles and (h) its laser scanning area, (i) 3D roughness measurement result of (h).

3.3.1.2.2 Grain characteristics of Al and Ni layer

To further understand the relationship between the deformation behavior of the Al layers and the grain characteristics, EBSD analysis was introduced. Fig. 3.8 exhibits EBSD observation results of Al layer, where the observations were performed at the die-attach center and at the corner where the maximum stress occurred. Fig. 3.8 (a) shows the inverse pole figure (IPF) map, the orientation of the initial state of Al layers were (001) both center and corner. After 500 cycles, the Al grain orientation was significantly different depending on the presence of a Ni layer. In the case of Al without the Ni layer, the central orientation distribution is almost (001) direction, and the grain orientation distribution at the corner was changed from initial red color to yellow color unlike center. However, in the case of Al with the Ni layer, grain orientation distributions of the center and corner were similar tendency (similar color distributions). Then, IPF change tendency is displayed in Fig. 3.8(b), after 500 cycles, the grain orientation distributions in the center are green color and the grain orientation distributions in the corners are black color. Here, Al without Ni layer exhibits different grain orientation distribution developed at center and corner. Thus, it was found that the surface was severely deformed when the grain orientation distributions of the center and the corner were not similar. The change of grain boundary distributions is displayed in Fig. 3.8(c). Low angle grain boundaries (LAGBs, $2^\circ < \theta < 15^\circ$) is shown in red line and the high angle grain boundaries (HAGBs, $15^\circ < \theta$) is shown in blue line. Initial state of the grain boundary distribution of Al layer was only LAGBs and large grain at the center and corner. However, after 500 cycles, all the case have occurred a sub-grain rotation recrystallization inside Al layer by repetitive mechanical forces with thermal shock cycles. In particular, Al with Ni layer generated HAGBs more than Al without Ni layer. This sub-grain rotation recrystallization due to the relationship between the energy versus the number of dislocations at the grain boundary, there is a driving force for fewer HAGBs to form and grow instead of a higher number of LAGBs [5,6]. In addition, previous

studies have been reported that recrystallized grains can lead to an improvement in yield strength[10], which makes deformation more difficult. Therefore, Al with Ni layer is expected to be more difficult to plastic deformation as the thermal shock cycle increases, because the grain boundary develops into the HAGBs while the deformation is suppressed. Inconsistencies in the grain orientation of the center and corners have been found to cause severe deformation of the surface. When the deformation of Al was suppressed, the grain characteristics change of Ni were also analyzed by EBSD analysis.

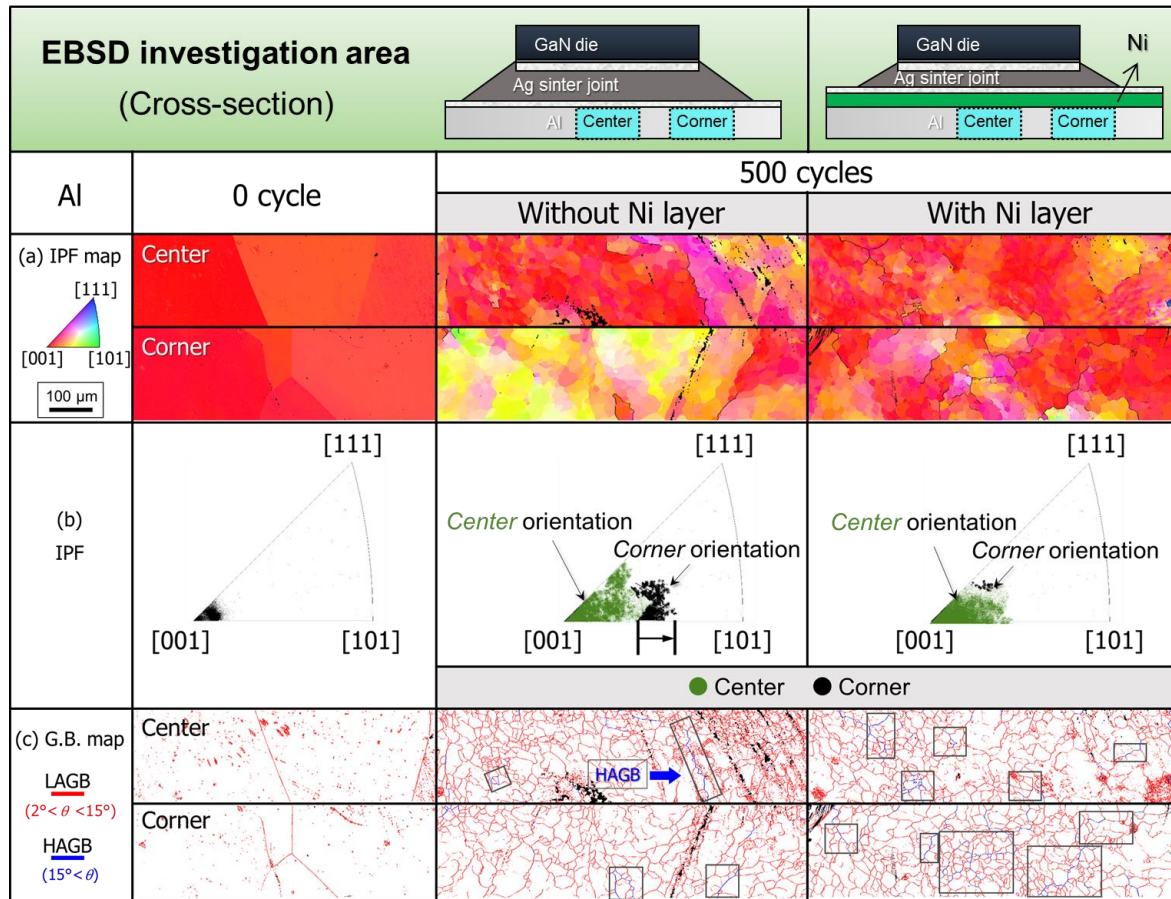


Fig. 3.8 EBSD observation results. Al (DBA): (a) inverse pole figure map, (b) its IPF distribution and (c) its grain boundaries map.

Fig. 3.9 shows grain characteristics analysis results of the sputtered Ni layer before and after thermal shock cycles. As shown in Fig. 3.9(a), no significant physical defects were observed before and after the thermal shock cycle, and grain characteristics were analyzed for the white square box area. Fig. 3.9(b) displays IPF maps, grain orientations were randomly distributed before and after thermal shock cycles, grain size also no significantly changed before and after thermal shock cycles. Fig. 3.9(c) exhibits grain boundary distributions of the Ni layer before and after thermal shock cycles, low angle grain boundaries (LAGBs, $2^\circ < \theta < 15^\circ$) is shown in red line and the high angle grain boundaries (HAGBs, $15^\circ < \theta$) is shown in blue line. HAGBs formed from as-sintered state, no significantly changed after thermal shock cycles, its quantitative misorientation angle distribution plotting are displayed in Fig. 3.9(d). The kernel average misorientation (KAM) maps are drawn using an average misorientation angle around a measurement point with respect to a defined set of the nearest neighbor points with a maximum misorientation angle of 3° . The KAM values were under 1° before and after thermal shock cycles. Since the KAM values of both case are as low as ~ 1.0 , the effect by thermal shock cycles were considered insignificant. Therefore, the Ni layer is considered not to be critically stressed by thermal shock and is considered to play a role in stress relaxation.

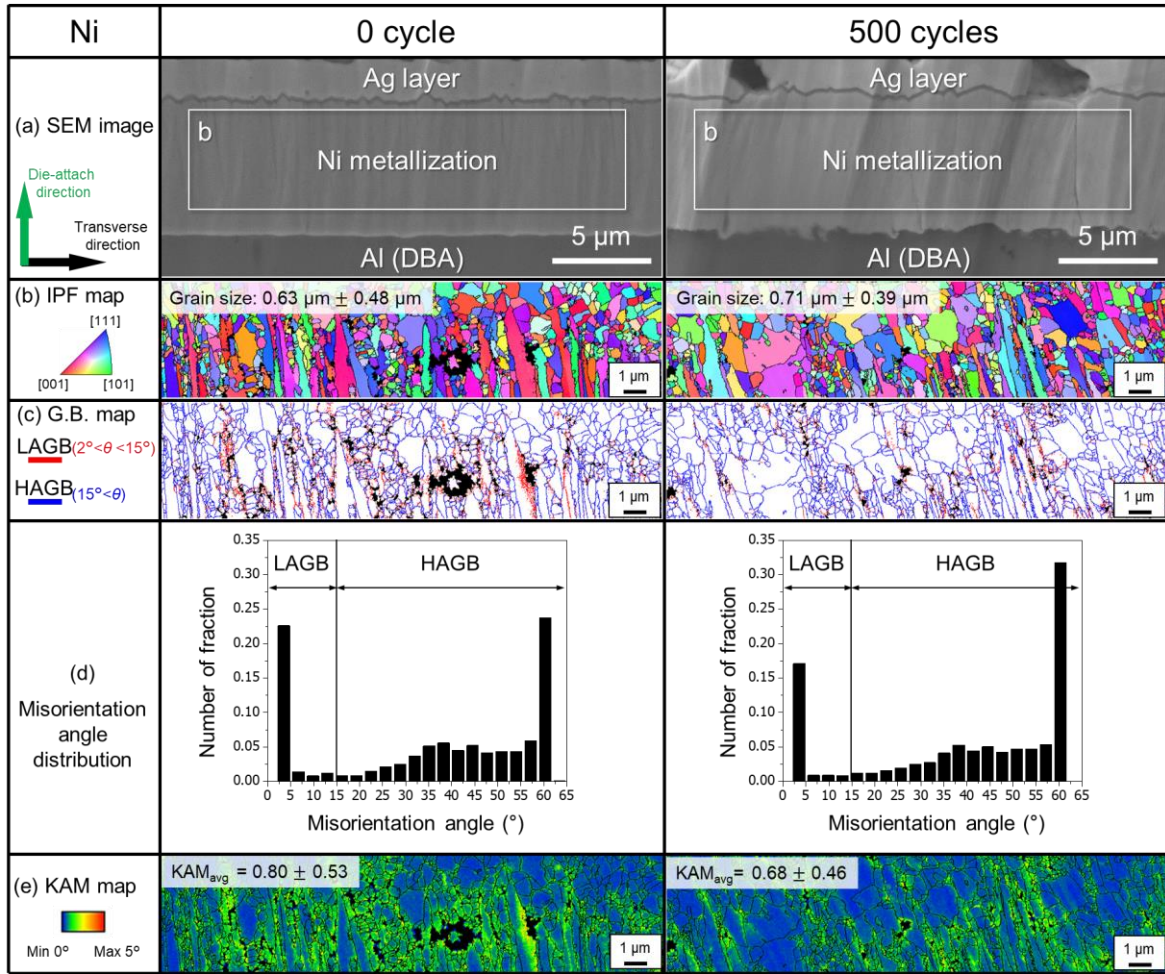


Fig. 3.9 Grain characteristics analysis results of the sputtered Ni layer before and after thermal shocks. (a) SEM images, (b) inverse pole figure (IPF) maps, the red lines denote low-angle boundaries with misorientation angles between 2° and 15° , and the blue lines denote high-angle boundaries with misorientation angles exceeding 15° . (c) grain boundaries maps and (d) misorientation angle distribution, (e) kernel average misorientation (KAM) maps.

3.3.1.3 Interface damage mechanism analysis by FEM simulation

3.3.1.3.1 Ni metallization effect on grain boundaries stress of Al layer

To understand the Ni layer effect of GaN/DBA die-attach module structures, thermo-mechanical finite element method (FEM) simulation was performed by using commercial finite element program ANSYS. Interfaces of Ag-Al with Ni layer and without Ni layer considering grain boundaries for analysis models were conceptual designed as shown in Fig. 3.10(a). Material properties were applied for thermal elastic-plastic analysis as shown in table.3.1. The boundary conditions are applied with the actual thermal shock cycling condition of one cycle as displayed in Fig. 3.10(b).

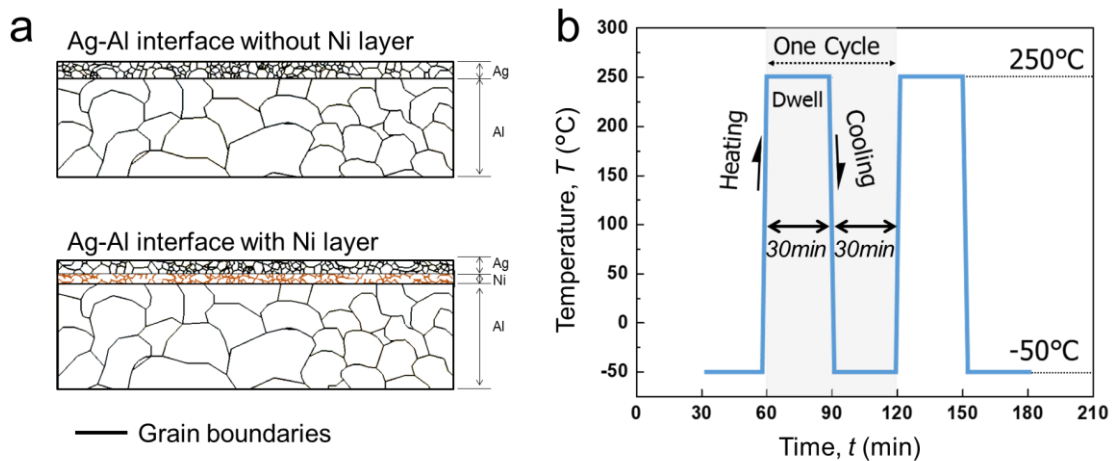


Fig. 3.10 (a) analysis models of Ag-Al interfaces (b) temperature profile for FE-simulation.

Table. 3.1. Material properties of the GaN/DBA module structure. [3][4][5]

Material	Density (kg/m^3)	CTE (/K)	Thermal Conductivity (W/mK)	Young's Modulus (GPa)	Tangent Modulus (MPa)	Poisson's Ratio
Ag Paste	6294	32.5×10^{-6}	430	12.9	6000	0.1
Al	2700	25.7×10^{-6}	137	70	10000	0.33
Ni	8900	13.4×10^{-6}	90.9	200	0.31	-

For the thermal-mechanical simulation, EBSD information based FE-modelling of Ag-Al layers were performed as displayed in Fig. 3.11(a). The Ag sinter paste and Al are assumed to have elastic-plastic properties to reveal deformation behavior. The boundary conditions are applied with the actual thermal shock cycling condition of one cycle. Fig. 3.11(b) shows the stress distribution of non Ni layer model at 250°C, it was confirmed that the stress concentration occurred around the Al grain boundaries by a thermal stress. The thermally induced stress induced a maximum stress at the interface between Ag and Al, and which result shows that similar tendency with actual degradation SEM image (see Fig. 3.11(c)). Therefore, deformation mechanism of the Al without Ni layer can be explained by Fig. 3.11(d). Namely, as the thermal stress acts on Al grain boundaries, the grains deform, and sintered Ag does not resist the Al deformation, and grains are pushed up on the surface such as the initial dotted line, resulting in an uneven Ag-Al interface. On the other hand, compared with the non-Ni model, the Ni model has a lower intensity of the stress concentration in the Al grain boundaries. In particular, the Ni layer produced significantly lower stresses with its rigid property, which show simulation results that correspond to the EBSD-KAM (Fig. 3.9(e)) results as shown in Fig. 3.11(e). Also the stress simulated result exhibits similar tendency with actual SEM observation image as shown in Fig. 3.11(f). Consequently, as shown in Fig. 3.11(d), Al grains tend to rise on the surface by the thermal stress, however the Ni layer has excellent mechanical properties, suppresses the deformation behavior of Al grains and the forces not consumed in the deformation are considered to contribute to the formation of HAGBs as displayed in Fig. 3.11(g).

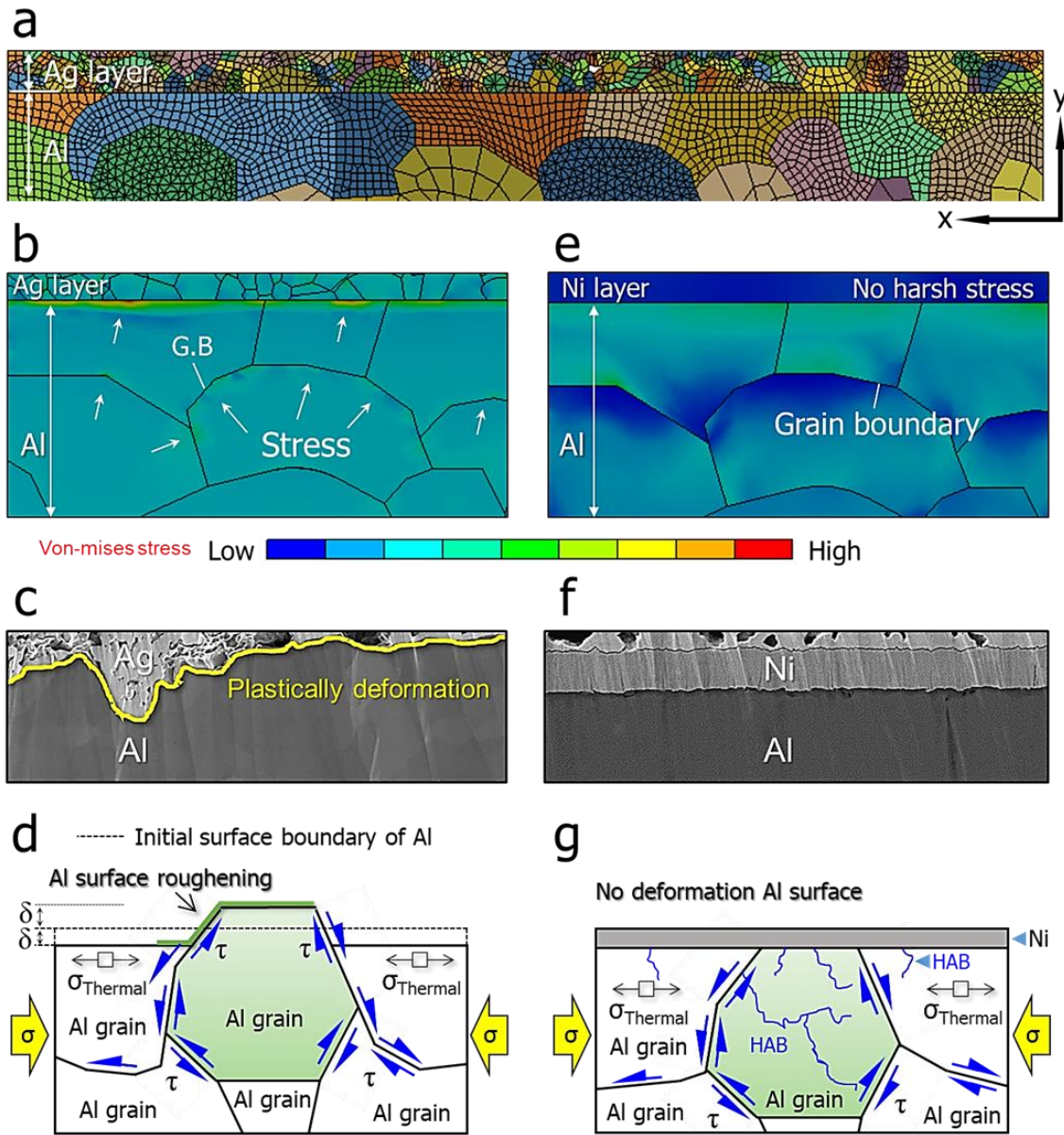


Fig. 3.11 FEM simulation result; description of mechanical behavior of Al-Ag interface without Ni layer and with Ni layer. (a) FE-modelling of Ag-Al interface of analysis models, (b) stress distribution of non Ni model at 250°C, (c) actual degradation SEM image without Ni layer, (d) its schematic description of deformation mechanism, (e) stress distribution of Ni model at 250°C, (f) its actual SEM image with Ni layer, (g) Al surface roughing suppressing mechanism by Ni layer.

3.3.2 Thermal shock reliability of GaN/DBA die attach structure with Ag sinter joint and Pb-5Sn solder joint

3.3.2.1 Bonding strength

The change in the die shear strength due to thermal shock cycles is shown in Fig. 3.12. In the case of the Ag sinter structure, the die shear strength gradually increased by 21% to 33 MPa compared to the initial strength after 125 cycles, this shear strength was sustained 31 MPa after 500 cycles. These results show that the micron/submicron Ag paste shows more superior thermal shock reliability than the nano-Ag paste. In fact, it has been reported that the shear strength of nano-Ag paste significantly reduced as the repetitive thermal shocks increased [3]. Also, the tendency for the shear strength decreased due to thermal shocks was also observed in the Pb-5Sn solder. The initial bonding strength of Pb-5Sn solder was about 28 MPa, and were 27% and 50% lower than the initial strength after the specimens were subjected to 125 and 500 cycles of thermal shocks, respectively.

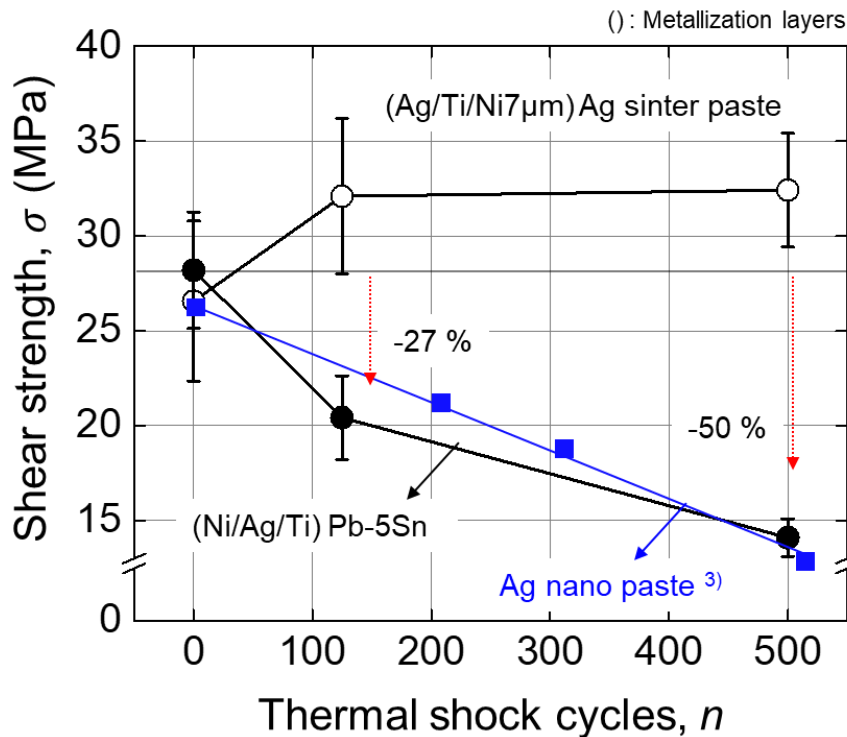


Fig. 3.12 Change of shear strength by thermal shock cycles.

3.3.2.2 Non-destructive test result: X-ray images

Fig. 3.13 shows the X-ray image results for micron/submicron Ag joints and the Pb-5Sn solder joints by harsh thermal shocks. It can be clearly seen that a defect like void is much larger in Pb-5Sn than in Ag sinter paste. In case of Pb-5Sn solder, micro voids were formed after soldering and a similar tendency was observed in the Pb-5Sn solder joints subjected to 125 cycles of thermal shocks.

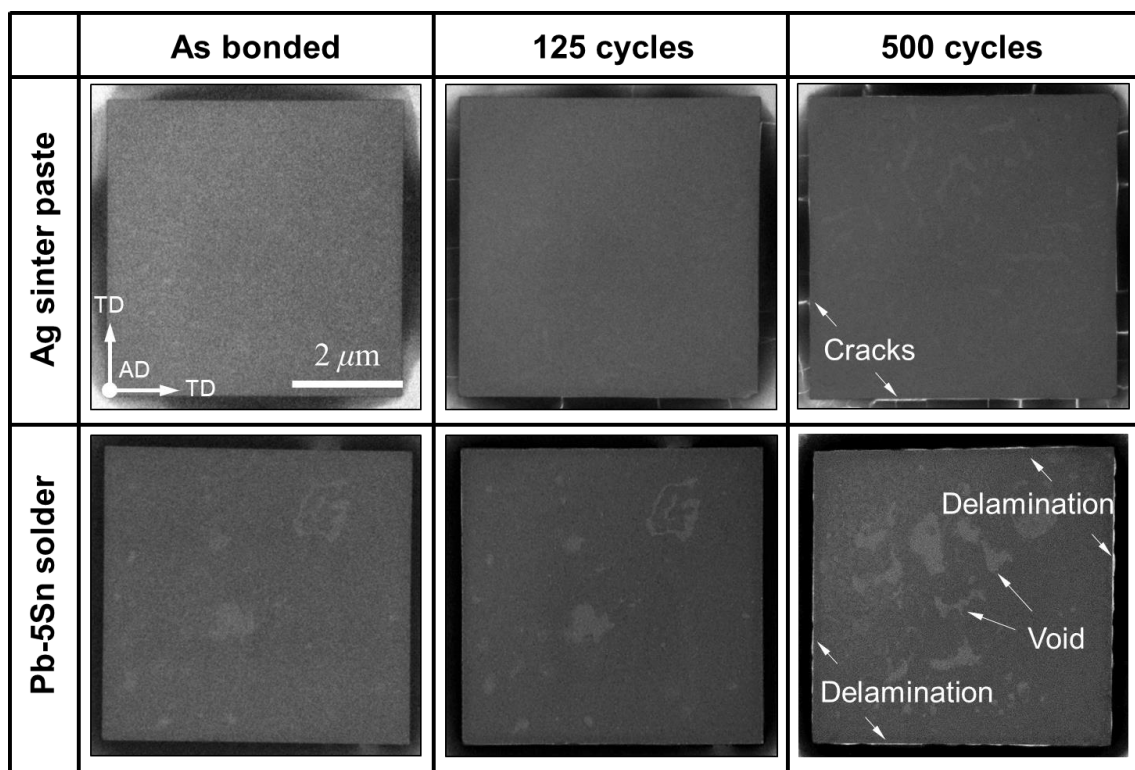


Fig. 3.13 Non-destructive test results: X-ray images of die-attached structures by thermal shock cycles.

3.3.2.3 Microstructure and fracture characteristics

Fig. 3.14 shows cross section images of the joints micron/submicron Ag sinter structure by thermal shock cycles. The initial sintered Ag structure formed a micro-porous structure, these sinter necks further thicken in growth after 125 cycles [see Fig. 3.14(b, e)] and 500 cycles [see Fig. 3.14(c,f)], no serious plastic deformation in the interface of Al/Ni was observed until 500 cycles.

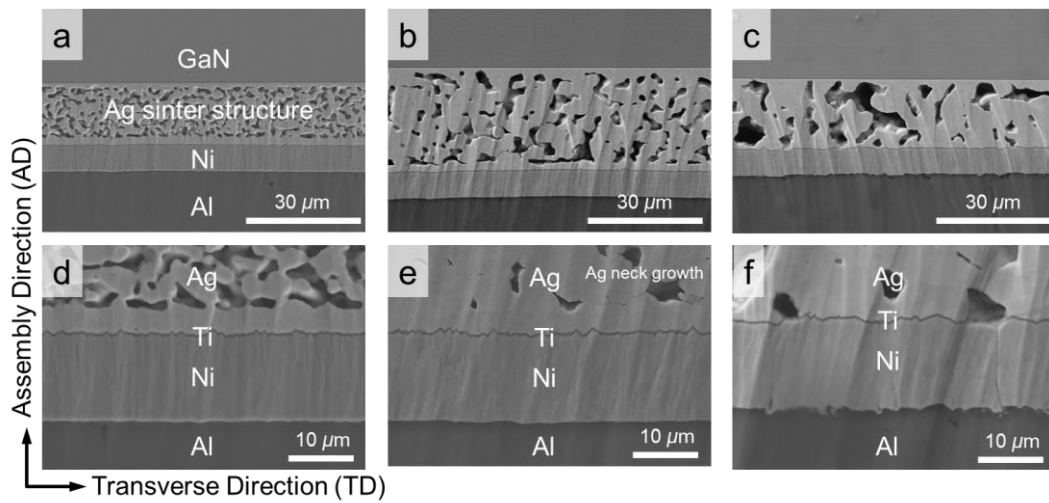


Fig. 3.14 Cross section of the joints micron/submicron Ag sinter structure by thermal shock cycles: (a) as bonded, (b) 125 cycles and (c) 500 cycles, (d) high-resolution image of a, (e) high-resolution image of b and (f) high-resolution image of c.

Fig. 3.15 shows the Ni metallization behavior by thermal shocks, and Fig. 3.15(a) shows SEM images of Ni layer before and after thermal shocks. EBSD observation was performed to compare Ni grain characteristic before and after thermal shocks as shown in Fig. 3.15(b) and (c), respectively. From the inverse pole figure (IPF) maps, the grain crystal orientations of Ni layer before and after thermal shock exhibit a random distribution (see Fig. 3.15(b)), and its grain size also showed no significant change during thermal shock cycles (see Fig. 3.15(c)).

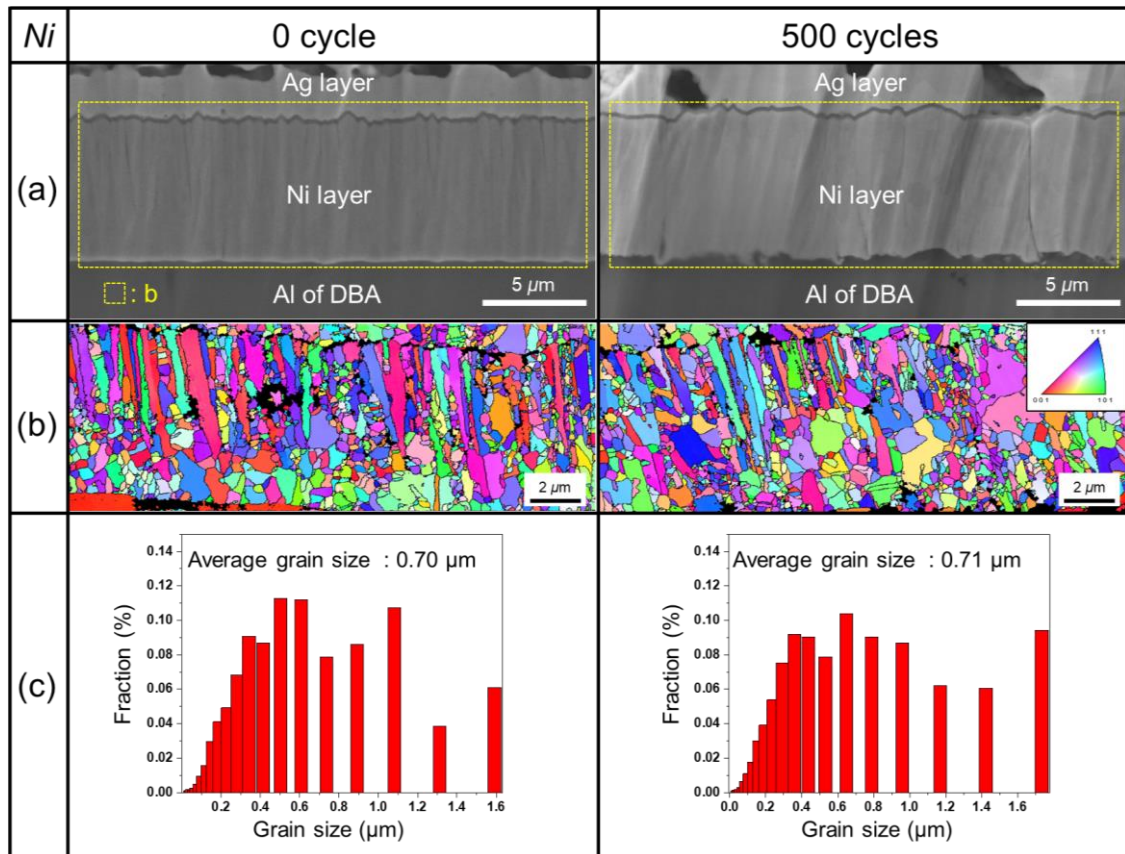


Fig. 3.15 Thermal shock behavior of Ni metallization (a) SEM images (b) IPF maps (c) grain size distribution characteristics.

It can be clearly seen that the sputtered thick Ni layer suppresses the deformation of Al and stress relaxation after repetitive thermal shock cycles. In fact, it has been reported that the GaN/DBA structure without Ni metallization significantly decreased shear strength by 27% against initial state due to the severe plastic deformed interface between the Ag sinter layer and Al of DBA [12]. In contrast with the previous study, in case of the 7 μm Ni metallized design exhibits the significant growth of Ag sinter neck-networks, and the non-deformed interfaces affected that the stable shear strength after harsh thermal shocks displayed. Fig. 3.16 compares the cross-section images of the Pb-5Sn solder with the increasing number of thermal shock cycles. The initial bonded Pb-5Sn specimen formed a relatively thin Ni/Sn IMC, but showed a stable interface without significant deterioration [see Fig. 3.16(a, d)]. After 125 cycles, IMC

had further grown and an unstable interface of solder to Al as shown in Fig. 3.16 (b, e). When the thermal shock reached 500 cycles, the IMC layer showed no growth, but this IMC layer had plastic deformation as displayed in Fig. 3.16(c, f).

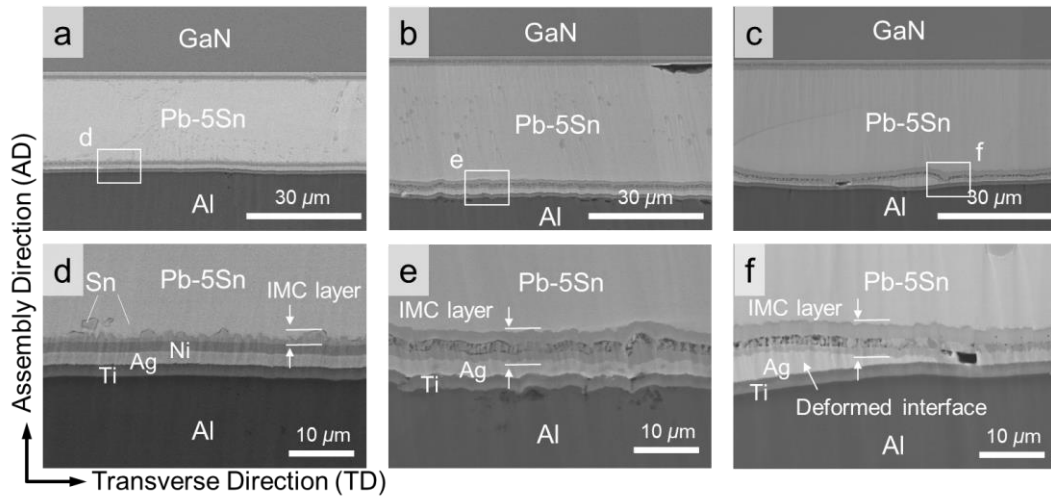


Fig. 3.16 Cross section of the joints with Pb-5Sn solders by thermal shock cycles: (a) as bonded, (b) 125 cycles and (c) 500 cycles, (d) high-resolution image of a, (e) high-resolution image of b and (f) high-resolution image of c.

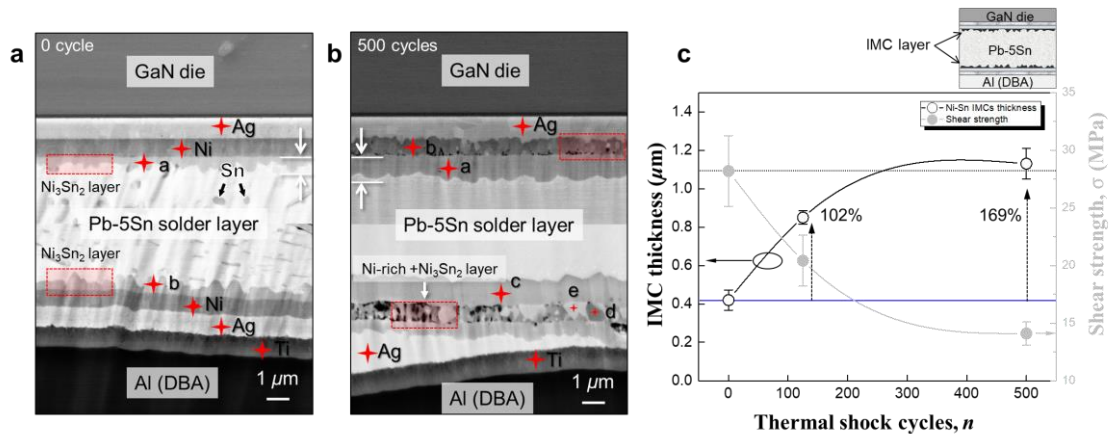


Fig. 3.17 EDX elemental analysis areas of the Pb-5Sn joint interfaces (a) 0 cycle, (b) 500 cycles and (c) change of the IMCs thickness by thermal shock cycles.

Table 3.2 EDX elemental point analysis results of the Pb-5Sn joint interfaces.

Element (At.%)	0 cycle		500 cycles				
	a	b	a	b	c	d	e
Ni	38.88	36.79	34.20	97.05	32.73	94.18	63.31
Sn	41.35	43.24	65.58	1.92	67.27	5.82	36.69

To further quantitatively understand the IMCs element and growth characteristics, the EDX point analysis was carried out. In the case of as-bonded, both interfaces of the Ni layer and Sn of the solder mutually reacted to form a thin Ni_3Sn_2 IMC as shown in Fig. 3.17(a). After 500 cycles of thermal shocks, the IMC layer thickened further than an as-bonded state. They formed complex interfaces including Ni-rich and Sn rich IMC layers as displayed in Fig. 3.17(b), which elemental point analysis results exhibit in Table 3.2 in detail. In Fig. 3.17(c), the thickness of the IMCs layer increased significantly as the number of thermal shocks increased. After 125 cycles and 500 cycles at the initial $0.4\text{ }\mu\text{m}$, they grew to about $0.8\text{ }\mu\text{m}$ and $1.1\text{ }\mu\text{m}$, which increased by about 2 times and 2.5 times, respectively. Here, because between the Ni metallization layer and Ag sintered layer, a barrier layer of Ti exist, which can effective barrier the inter-diffusion for the Ni-Ag. Therefore, in the case of Ag sinter joining, the die-attached structure did not occur the diffusion. In the case of Pb-5Sn solder consist of low melting point materials under about $320\text{ }^\circ\text{C}$. Diffusion occurred with the form of IMC layer. The diffusion coefficient D was estimated as $1.21 \times 10^{-18} \text{ m}^2/\text{s}$ with the Boltzmann-Matano equation, which was calculated based on the EDS mapping of Ag and Pb element during the thermal shock cycling [13]. Fig. 3.18 shows a fracture surface image of Pb-5Sn solder joints. The Pb-5Sn solder showed two different types of fractures before and after thermal shocks. As shown in Fig. 3.18(a, b), as-bonded Pb-5Sn solder showed ductile fracture pattern at the solder joint layer. Inside the layer, the Pb-5Sn joint stretched along the shear direction. In contrast, the Pb-5Sn

solder caused a fracture between Ni_3Sn_2 IMC of solder layer and Ti metallization layer after 125 cycles, and no trace of ductile fracture showed as displayed in Fig. 3.18(b, e). The fracture occurred in the Pb-5Sn/IMC layer after 500 cycles, and the ratio of Ni/Sn IMC in the fracture was higher than the 125 cycles as shown in Fig. 3.18(c, f). As the number of thermal shocks increased, the fracture mode of Pb-5Sn solder changed from a ductile fracture at the initial stage to a brittle fracture after 125 and 500 thermal shock cycles, similar to the previous reports where IMC growth affected the fracture mode [8, 9]. As the results, Pb-5Sn joints caused IMCs growth by repetitive thermal shocks, and in proportion to the thickness of the brittle IMCs their occurred a significant shear strength reduction.

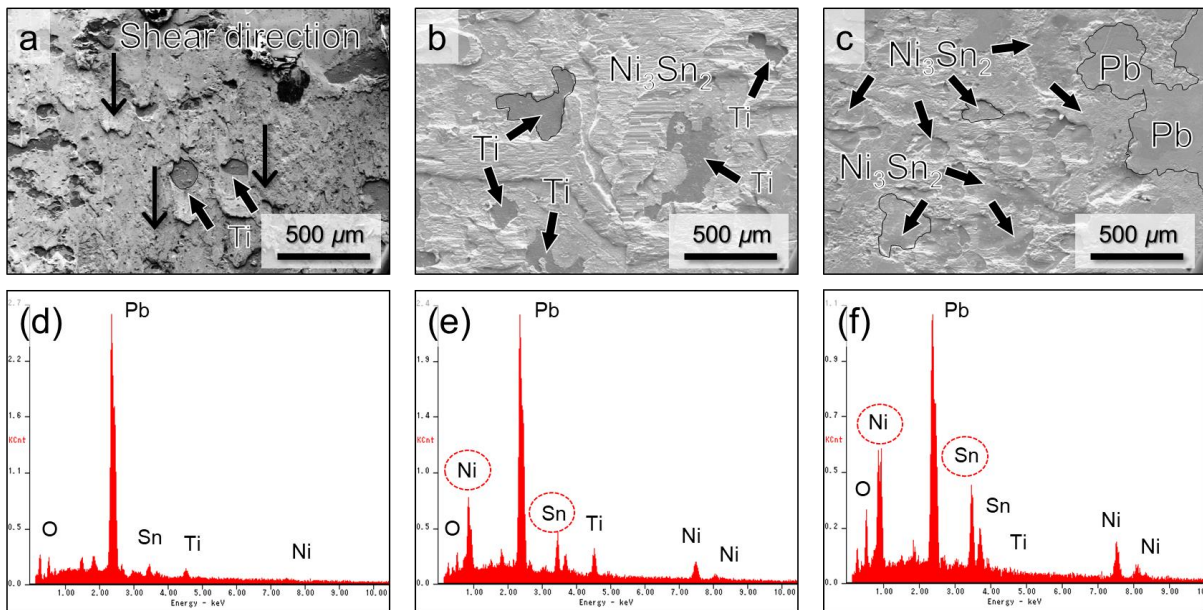


Fig. 3.18 Fracture surface images of Pb-5Sn solder joints: (a) as bonded, (b) 125 cycles and (c) 500 cycles, (d) EDX result of a, (e) EDX result of b and (f) EDX result of c.

3.4 Conclusions

In this chapter, high-strength and superior thermal shock-resistance of a GaN/DBA die attach structure with Ag sinter joining by thick Ni metallization (7 μm) was developed and compared with conventional Pb-5Sn soldering die attach for the high temperature reliability. Also the interfacial degradation suppressing mechanism was clearly revealed. The GaN/DBA die-attached module could be stably sustained without any physical degradation during thermal shock cycles by Ni metallization. In the case of DBA without Ni layer, strength reduced with severe Ag-Al interface deformation by 33% after 500 cycles, and in the case of DBA with Ni layer, the shear strength of joint structure sustained above initial strength after 500 cycles due to the suppression of the Ag-Al interface deformation by Ni metallization layer during repetitive thermal shock cycles. In this process, both cases Al of DBA generated the sub-grain boundary rotation recrystallization, which becomes driving force of the surface roughening during thermal shock cycling. In the case of Al without Ni layer, grain orientation distributions were different between center and corner. On the other hand, in the case of Al with Ni layer, grain orientations similar distributed between center and corner and it is also accompanied by a relative many high angle grain boundaries (HAGBs). In particular, the Ni layer was no significant change before and after harsh thermal shock cycles, it mean that the thermal stresses generated can be relaxed because the Ni layer does not physically react to harsh thermal shock cycles. Consequently, thick Ni metallization suppresses the surface roughness of Al layer caused by the sub-grain rotation recrystallization behavior of Al, thereby preventing the strength reduction because inducing Ag sinter joint fracture even after thermal shock cycles.

In the case of traditional Pb-5Sn solder joint, the shear strength of Pb-5Sn solder significantly reduced by 50% up to 500 cycles due to the grown IMCs layer. Also, as the number of thermal shock cycles increased, the inter-metallic compound growth in the solder interface changed the fracture mode from a ductile fracture to a brittle fracture. Thus, in order to ensure the long-term

reliability in harsh thermal environments, over the 7 μm of Ni metallization can be prevented to serious degradation of Ag sinter joint interfaces without any IMCs and oxidation. The Ag sinter paste is expected as an environmentally friendly replacement material for the high content Pb solder in the future in high power electronic applications.

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Chapter 4

Thermal property characterization for thermal management

4.1 Introduction

Wide band-gap (WBG) power devices provide a significant energy efficiency improvement by the miniaturization of power electronic devices [1][2]. This along with a thermal design that can withstand extreme energy densification caused is the key to the next generation power electronic devices [3][4][5][6][7]. Because WBG devices can operate at temperatures (T_j max) greater than about 100% higher than Si devices, accurately measuring the operating temperature of the power semiconductor device and the thermal resistance of the power modules is a serious issue, which related to the process and materials design and long service life time. Thus, solving the dilemma of the measurement for a junction temperature of WBG semiconductors remain an essential challenge in next generation power electronic devices for future environmentally friendly transportation.

This chapter introduced the SiC micro-heater chip as a novel thermal evaluation device for next-generation power modules. Different die attach materials including Pb-free solder and sinter Ag joining were implanted into the power modules to evaluate the heat resistant performance. In addition, heat resistant of power modules by sinter Ag joining on the direct bonded copper(DBC)substrate with aluminum nitride (AlN-DBC), aluminum oxide (DBC- Al_2O_3) and silicon nitride (Si_3N_4 -DBC) ceramics middle layer were also investigated by using

the SiC micro-heater chip system. The SiC micro-heater chips were structurally sound bonded on the DBC substrates by Ag sinter paste and Au wire was used to interconnect the SiC and DBC substrate. The SiC micro-heater chip power modules were fixed on a water-cooling plate by a thermal interface material (TIM), a steady-state thermal resistance measurement and a power cycling test were successfully conducted. This chapter provides a significant advance in measurement of the junction temperature and power cycling performance during operation for assembled WBG semiconductor power module structure where we have overcome the above challenges by using a thermal test engineering group (TEG) chip.

4.2 Materials and methods

4.2.1 SiC TEG chip and evaluation system

Fig. 4.1 illustrates the power cycling test systems applied to the SiC TEG chip and its integration into a minimized test package. The developed systems consist of three major parts for power supplier, system controller and test plate. These systems are used in controlled by an algorithm built with the python language to implement precise ON/OFF switching in real time. The water-cooling system is maintained at 25 °C and the temperature between a substrate and a heat sink plate is measured by thermocouples during operation. At this time, the temperature gradient, ΔT is occurred between the TEG chip surface of joule heating and the bottom of the metallized substrate. The temperature gradient equation is given by:

$$\Delta T = T_{chip\ surface} - T_{thermocouple} \quad (1)$$

ON-switching this temperature gradient by the input power, thermal resistance can be calculated as followed:

$$R_{th} = \Delta T/Q \quad (2)$$

Where, R_{th} is the thermal resistance of SiC interconnected power module structure [K/W], Q is the power input [W].

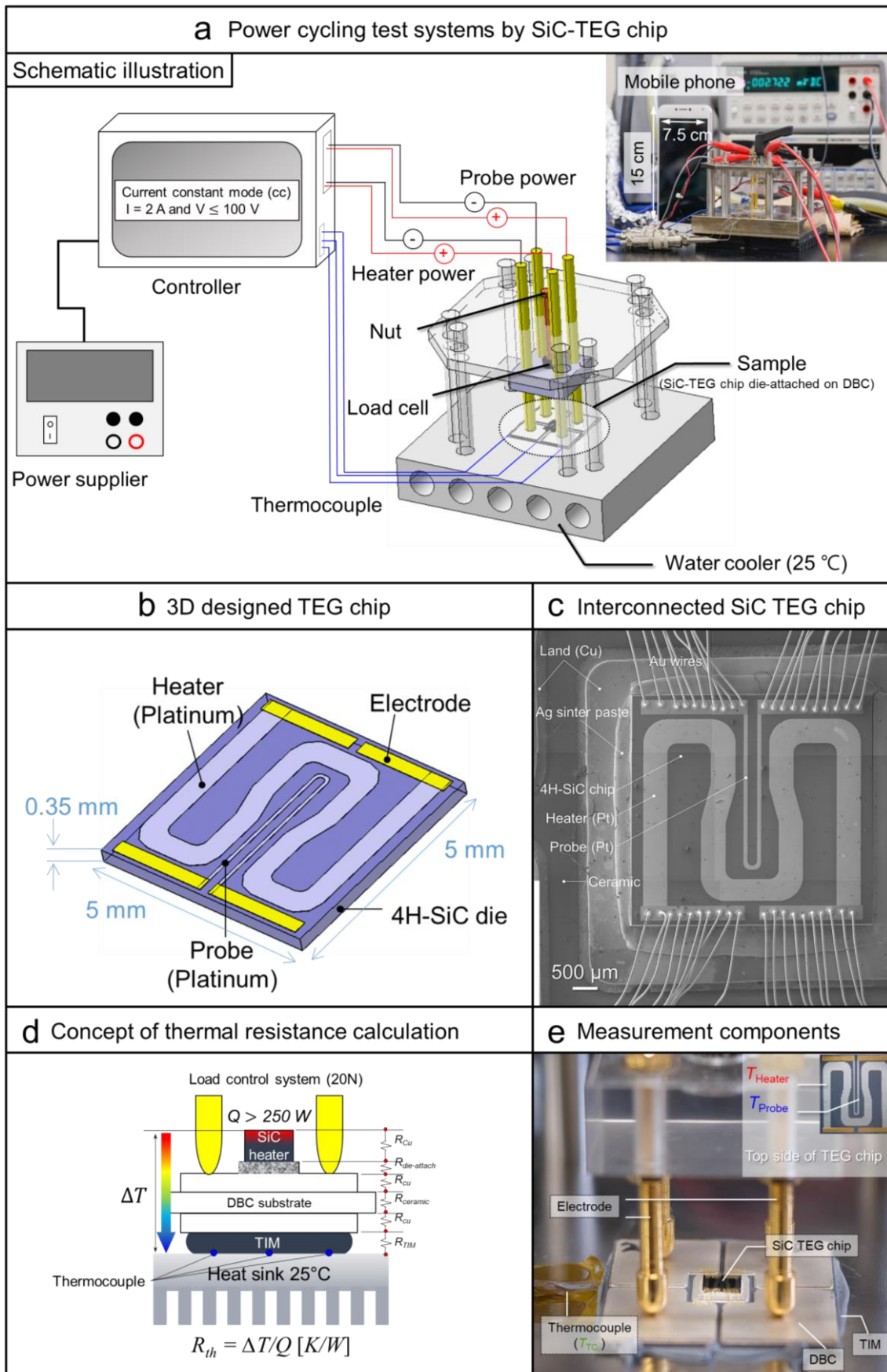


Fig. 4.1 Appearance and schematic descriptions for power cycling test by using TEG chip. (a) Schematic illustration of power cycling test by SiC-TEG chip and its comparison of mobile phone and real scale. And it consisting of the power supply, controller, and water-cooled cooling system, the water cooled system and die module are reliably mounted with diamond thermal grease and 20 N force during power cycling by using by bolt-nut tightening. (b) 3-dimensional designed TEG chip and its component explanation. (c) SiC TEG chip die-attached and wire interconnected on 5 land DBC substrate by using Ag sinter joining and by using 45 μm Au wire bonding process. (d) concept of thermal resistance calculation and its thermal path, and integrated system description. (e) measurement component systems in each parts.

SiC TEG chip was specifically designed to uniformly generate heat stably for the SiC die surface with platinum thermal material, electrode and oxide insulator layers by a lithography fabrication process (see Fig. 4.1(b,c)). This is due to the fact that the cost of actual SiC metal–oxide–semiconductor field-effect transistor (MOSFET), insulated gate bipolar transistor (IGBT) or GaN High-electron-mobility transistor (HEMT) devices are prohibitively high and the thermal measurement difficulties described above. Moreover, when using such devices, there are some risks that are the massive size of the measuring equipment and enormous power exceeding several kW are necessary required. This architecture minimizes the equipment and risk on established standardization of the thermal characteristic evaluation method.

4.2.2 Die bonding processes and various DBC substrate

In order to obtain structurally sound joints and evaluate the reliability of various materials, hybrid Ag sinter paste and high temperature solder materials (Pb-5Sn, Sn-Cu-Ni-P and Sn-Ag-Sb-Cu, Senju Metal Co., Ltd, Japan) were employed for a reliability comparison. The micron size Ag flake and spherical submicron Ag particles (Senju Metal Co., Ltd, Japan) were mixed for use as Ag fillers of paste as a weight ratio of 1:1, these hybrid particles were then stirred magnetically for 10 min and vibrated ultrasonically for 30 min with viscosity of 100 ~ 200 Pa·s solvent (alkylene glycols and polyols) using a mixer (HM-500, Keyence Corporation) to fabricate Ag paste to achieve a uniform mixture. The amount of the solvent was maintained at approximately 10 wt% in the paste to keep a suitable viscosity of 150-250 cPs at room temperature. SiC-TEG chips (5 mm × 5 mm × 0.35 mm) were introduced for bonding to the DBC substrates (Cu/Si₃N₄/Cu). Prior to Ag sintering, 100 nm Ti and 2 μm Ag were sputtered both on the back side of TEG chip and on top side of the DBC substrates. Ag and Ti layers acted as an adhesion layer and diffusion barrier, respectively, as displayed in Fig. 4.2(a). First, the Ag paste was printed on the metallized DBC substrate, then the TEG chips were mounted on the Ag paste to get a joint structure which was then put on a hot plating machine. The sintering temperature was 250 °C and the sintering time was 30 minutes without pressure during the sintering process. The temperature rate and pre-sintering temperature are displayed in Fig. 4.2(b). In the same way, the high temperature Pb and Pb-free soldering process also were applied that the temperature was about 300 °C and formic and Nitrogen gas during pre-heating, cooling and soldering process in order to obtain structurally sound bonding without any critical defect as shown in Fig.4.2(c).

Beside die-attach materials, to evaluate performances of a ceramic substrate, DBC-Al₂O₃, DBC-AlN and DBC-Si₃N₄ were employed as an insulating substrate.

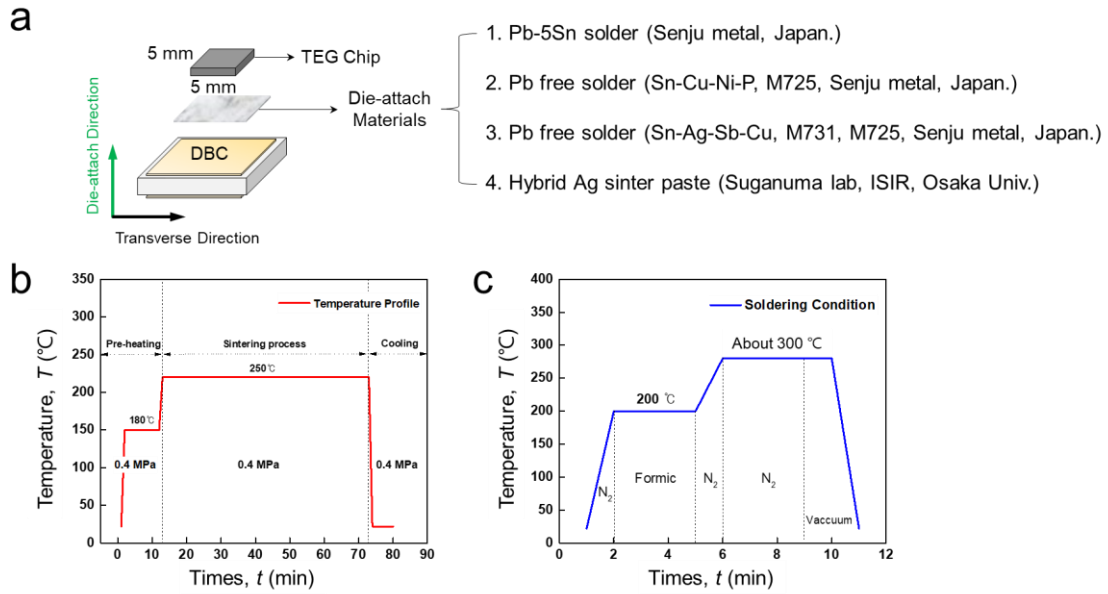


Fig. 4.2 (a) Die-attach structure and applied materials, (b) Ag sinter joining condition (c) Solder joining conditions.

4.3 Results and discussion

4.3.1 Steady-state thermal resistance of die-bonding materials and various ceramic substrates

This heat distribution is directly demonstrated by Infrared temperature measurement as shown in Fig. 4.3(a, b), its heat distribution shows a trend similar to FEM and IR measurements. Here, based on a simulated and experimental heat demonstration, we is confirmed that the heat generation of an active SiC is stable which is similar to results of the simulation. To demonstrate this equipment, the thermal resistance of ceramic wiring substrates and interconnection materials were evaluated statically and dynamically.

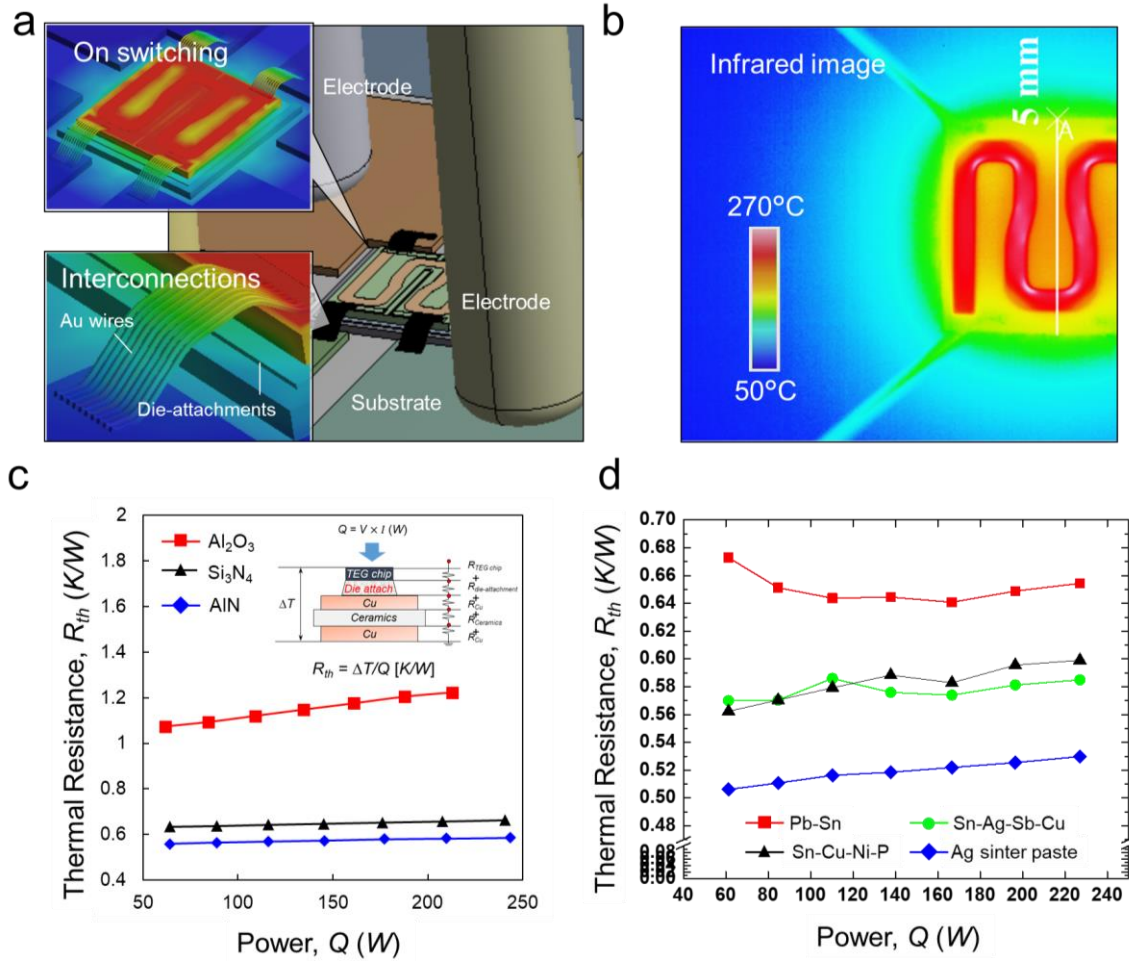


Fig. 4.3 Experimentally and numerically demonstration for uniformly heat generation of TEG chip design and its applied thermal resistance characterization. (a) thermal finite-element (FE) simulated results of the on-switching for TEG chip and its detail components. (b) Image of infrared (IR) temperature measurement during on-operation of active SiC TEG chip, which is that the experimental verification of temperature distribution similar to simulated results. (c) thermal resistance measuring results of various ceramics substrates: unlike the thermal resistance of Si_3N_4 and AlN , the thermal resistance of Al_2O_3 tends to increase in proportion to the increase of power. (d) thermal resistance performance of the die-attach materials: Ag sintered joints show overwhelming thermal performance.

By using this method, the results of power dependence thermal resistance performance evaluation for various metallized ceramics wiring substrates and interconnection materials are shown in Fig. 4.3 (c, d), respectively. Surprisingly, in the case of a traditional Al_2O_3 substrate, the tendency of power dependence thermal resistance was observed, and the other two substrates did not show significant power dependent thermal resistance characteristics. The order of higher thermal resistance was Al_2O_3 , Si_3N_4 , and AlN . The AlN clearly exhibited an excellent thermal resistance performance with its superior thermal conductivity. In the case of die-attach materials, four kind of die-attachment materials were compared. These included lead/lead-free solders and Ag sinter paste for performance evaluation in steady-state. The order of performance for excellent thermal resistance was Ag sinter paste, lead-free solders and lead solder. This is due to the thermal performance of the micro-porous Ag sinter die-attach interconnection material, which possesses a superior heat-sink ability with minimized thermal contact resistance as an interconnection material.

4.3.2 Power cycling test results of various die-bonding materials

Fig. 4.4 shows a long-term reliability of various die-attach materials by power cycling tests with an active SiC TEG chip. As shown in Fig. 4.4(a), the temperature profile was applied in the heater, probe and thermocouple parts during the repetitive power cycling tests. At this time, all temperature fluctuation changed the electrical power information is stored in the controller machine during the power cycling tests in the real time. The first power cycling observation changed of the thermal resistance histories of the various interconnection materials when applied to the same power input. (see Fig. 4.4(b)). The power dependence thermal resistance can be readily expected due to the inherent thermal conductivity differences when in the ON state. On the other hand, in the case of ON/OFF switching, the mechanical properties inherent

to the material, which is changed by repetitive heat generation and heat sink, are also taken into account, and resulted in thermal resistance due to the high thermal density generation on the device surface. As the overall power cycle progressed, the thermal resistance tended to increase, except in the case of the Ag sinter joint. Among all the interconnections, the thermal resistance behavior of Ag sinter paste surprisingly exhibited the lowest value and sustain intact, same as the starting point of the power cycling tests. This is due to its excellent and overwhelming thermal performance, which rapidly dissipates the joule heat generated during repetitive switching, thereby suppressing mechanical damage that can occur. At this time, the interface behavior is as shown in Fig. 4.5, and no deterioration of the interface was observed. On the other hand, in the case of Pb-5Sn die-attached structures, when reaching around 10,000 cycles, the device operation was halted due to the rapidly increased thermal resistance. The reason for stopping the operation was due to the severe damages to the bonding interface between the chip and substrate, such as IMCs and voids due to the repetitive heat generation from switching as shown in Fig. 4.6. Other lead-free solders show a much stable thermal resistance behavior than Pb-5Sn solder joints. Lead free solders start to operate at a significantly higher thermal resistance than Ag sinter paste, and it rises gradually as switching increases up to 20,000 cycles. The cause of such power cycle performance degradation is due to the characteristics of the material having the complex and fatal defects such as an intermetallic compound (IMC) and Kirkendall voids caused by repetitive heat generation (Fig. 3, 4). Fig. 4.4(c) shows IMCs growth behavior of the lead/lead-free solders before and after power cycling tests, and in all cases the thickness of the IMCs solder joints, have grown approximately twice as much against an as-bonded state. It can be clearly seen that the IMC growth is an inevitable result of ON/OFF switching of the power conversion system for all kinds of solder materials. In all cases thickness of the IMCs solder joints grew to, approximately twice its size as in the as-bonded. Fig. 4.4(d)

exhibits the change of warpage after a power cycling test, and indicates the warpage of the substrate also shows a smaller value in the order of superior thermal resistance. Surprisingly, as shown in Fig. 4.9, it can be clearly seen that deformation in the heat sink/insulation substrate is inherently difficult to suppress, even if the interconnection material provides superior performances. These results exhibit the surprising fact that, under the same switching conditions, devices can lose functionality depending on the inherent characteristics of the interconnection material. Therefore, it has been proven that actual WBG semiconductor devices can simulate the junction temperature of a packaged power conversion system and evaluate the reliability of the interconnection material in real time by using TEG chip.

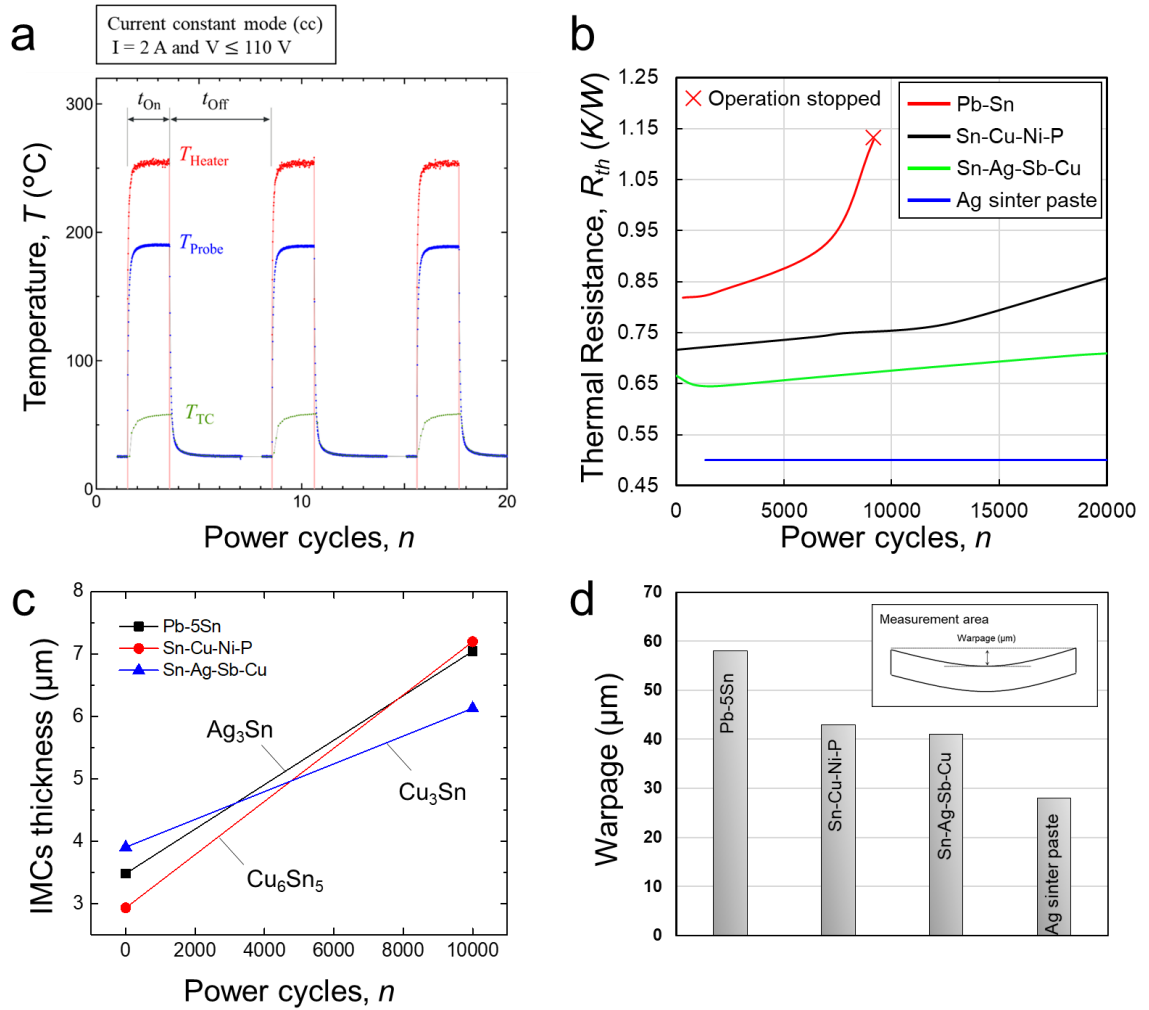


Fig. 4.4 Performances of the long-term reliability of various die-attach materials by power

cycling tests with active SiC TEG chip. (a) temperature frequency for the TEG chip during power cycling tests of 2 second ON and 3 second OFF (b) thermal resistance histories of various die-attachments: as the number of cycles increased, the thermal resistance as a whole increased, but the Ag sinter paste joints exceeds 20000 times as the initial value due to its excellent thermal performance. Whereas, the Pb-5Sn jointed SiC devices stopped operation due to the excessive rise in thermal resistance. (c) IMCs growth behavior of the lead/lead-free solders before and after power cycling tests (d) warpage measurement after power cycling tests.

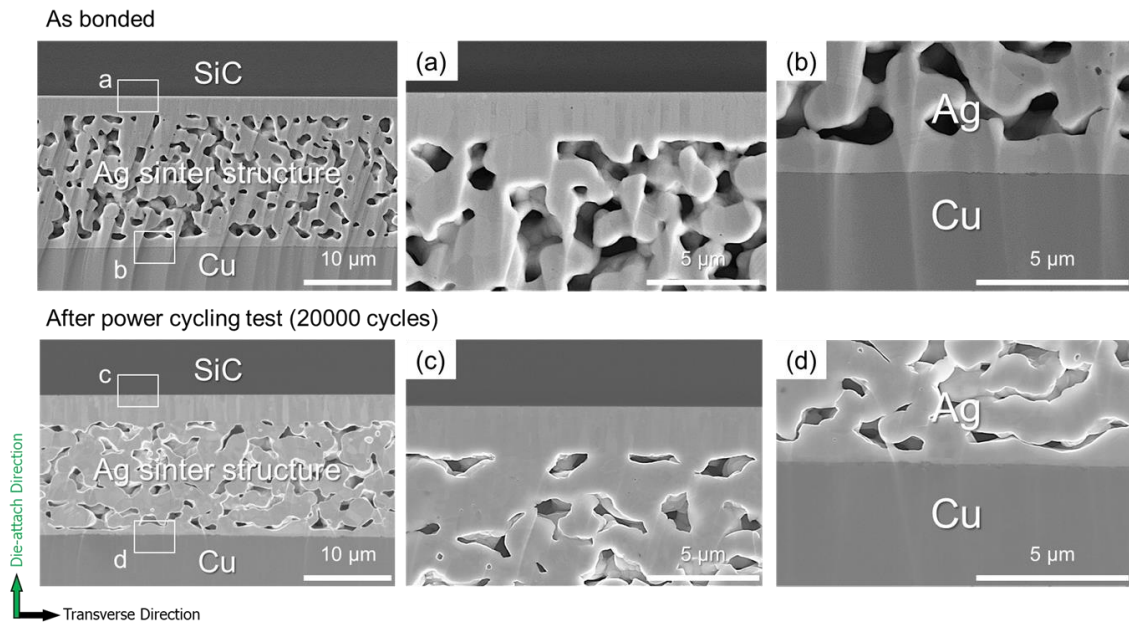


Fig. 4.5 SEM images of specimen of Ag sinter structure by power cycling test: as bonded (upper side) and after power cycling (bottom side)

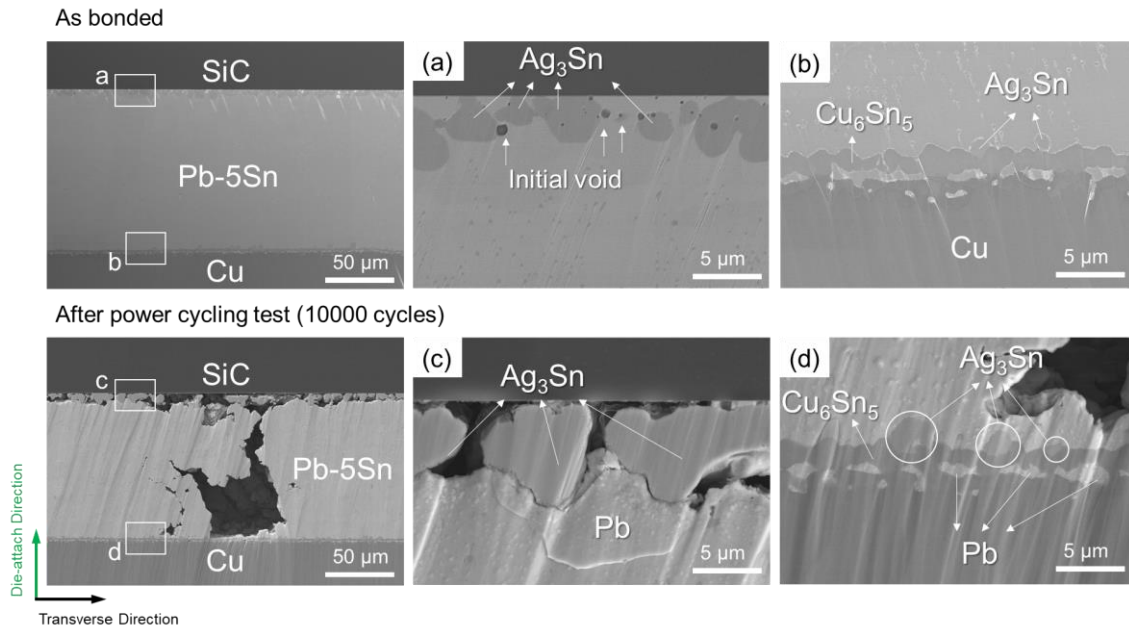


Fig. 4.6 SEM images of specimen of Pb-5Sn by power cycling tests: (a) before power cycling test of interface of SiC/Pb-5Sn solder, (b) Pb-5Sn solder/Cu of DBC, (c) after power cycling test of interface of SiC/Pb-5Sn solder and (d) Pb-Sn solder/Cu of DBC.

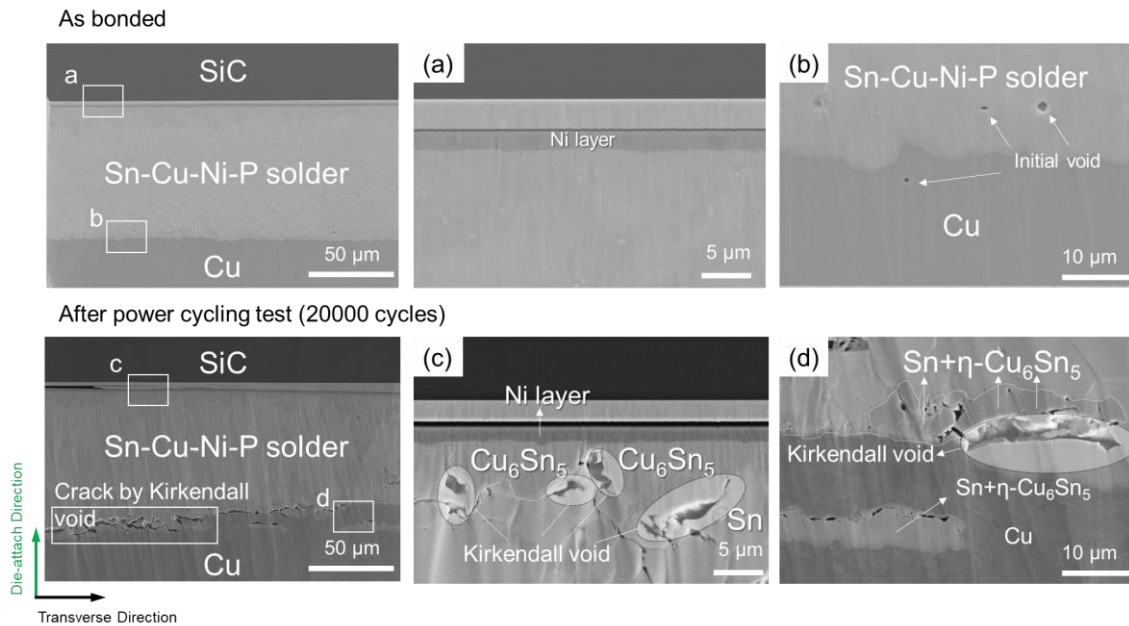


Fig. 4.7 SEM images of specimen of Sn-Cu-Ni-P by power cycling test: as bonded (upper side) and after power cycling (bottom side)

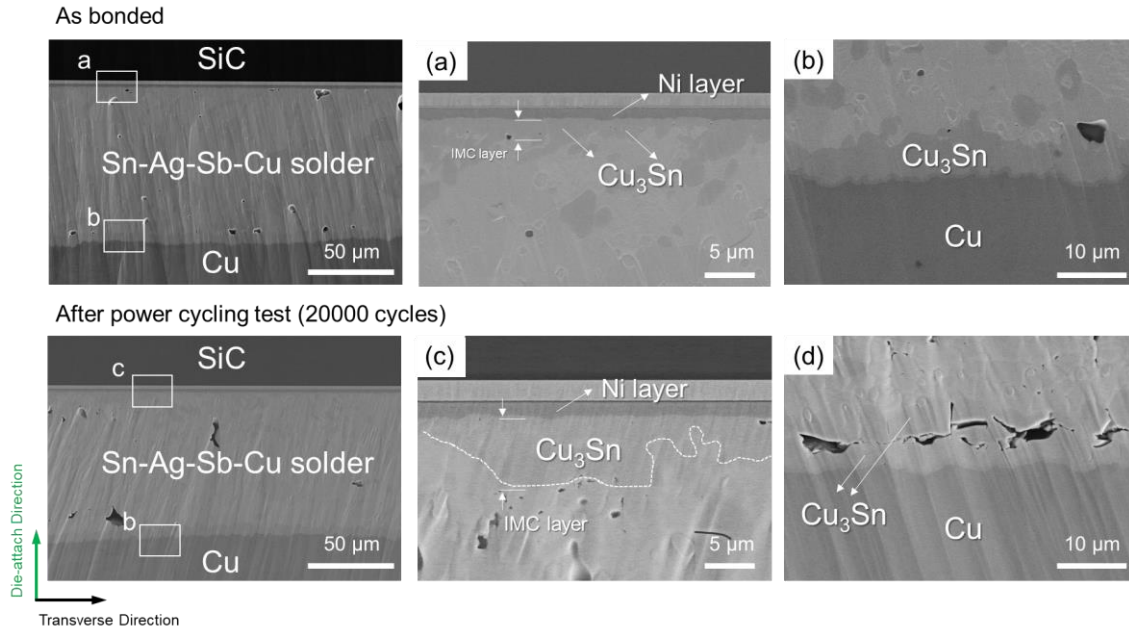


Fig. 4.8 SEM images of specimen of Sn-Ag-Sb-Cu by power cycling test: as bonded (upper side) and after power cycling (bottom side)

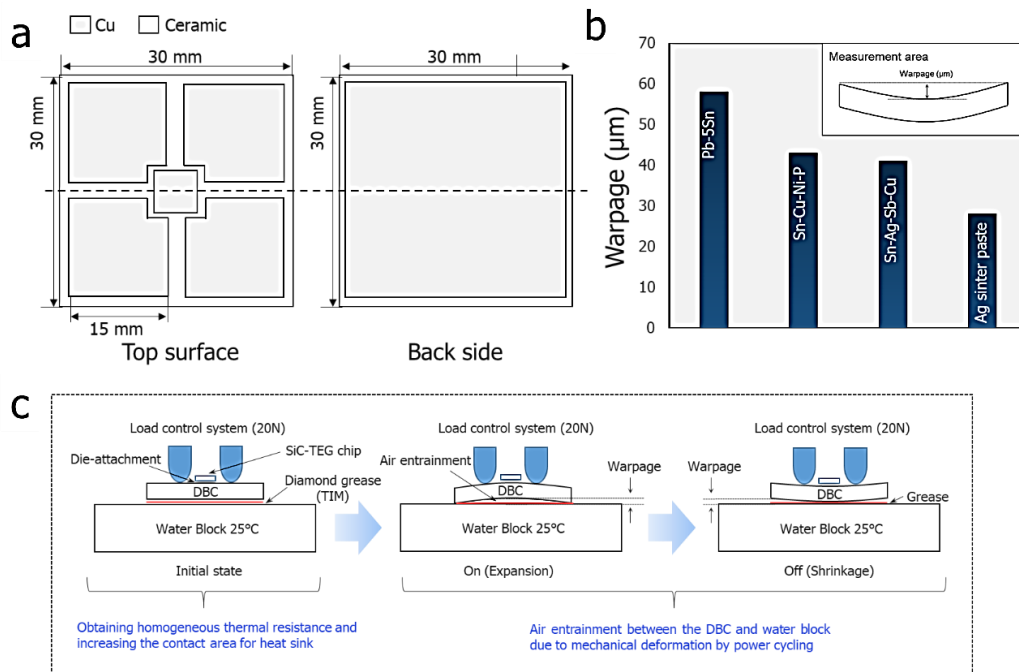


Fig. 4.9 (a) Structure of asymmetry DBC substrate pattern (b) Warpage measurement results of various die-attached samples (c) schematic diagram of warpage mechanism by power cycling.

4.3.2 Power cycling test results of various ceramic substrates

The results indicated that Al_2O_3 was stopped during the power cycle test due to excessive rise in thermal resistance before 1000 cycles, Si_3N_4 and AlN specimens were each subjected to more than 20,000 cycles of power cycle tests. In the case of Al_2O_3 stopping, die-attach and ceramic component were not any degradation but the Pt heater pattern line was partially broken as shown in Fig. 4.10(a) due to the poor heat dissipation performance of Al_2O_3 . The Pt heater pattern line accumulated a lot of heat, leading to the temperature increase significantly, leading to the film of pattern line partially melted as shown in Fig. 4.10(b).

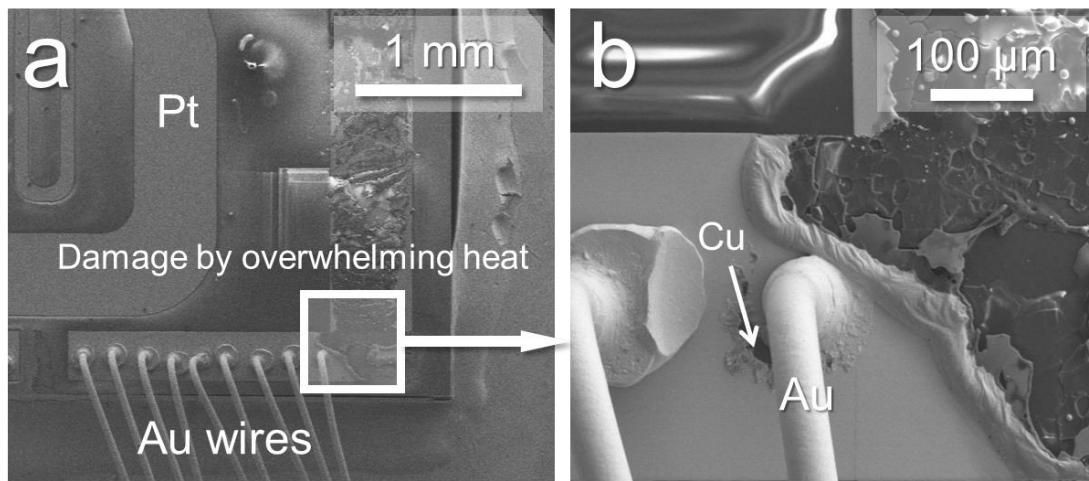


Fig. 4.10. Pt heater pattern line was partly broken (a) and its magnified view (b).

Figure. 4.11(a) shows temperature swing behavior of the Si_3N_4 -DBC substrate, the heater temperature at the beginning was about 240 °C, and when it reached 20,000 cycles, the temperature was about 260 °C. In the case of AlN -DBC substrate, the starting temperature was about 220 °C, and the temperature after 20,000 cycles was about 280 °C (see Fig. 4.11(b)). The temperature ranges of Si_3N_4 and AlN are not significantly different, but the temperature change tendency was remarkable. Unlike Si_3N_4 substrate, which has a small change in temperature, AlN was largely divided into two stages. The stage 1 is from the starting point to 4000 cycles,

it reached up to saturation temperature. The stage 2 is from 4000 cycles to 20,000 cycles, at a relatively stable temperature, the temperature slowly reached its peak point.

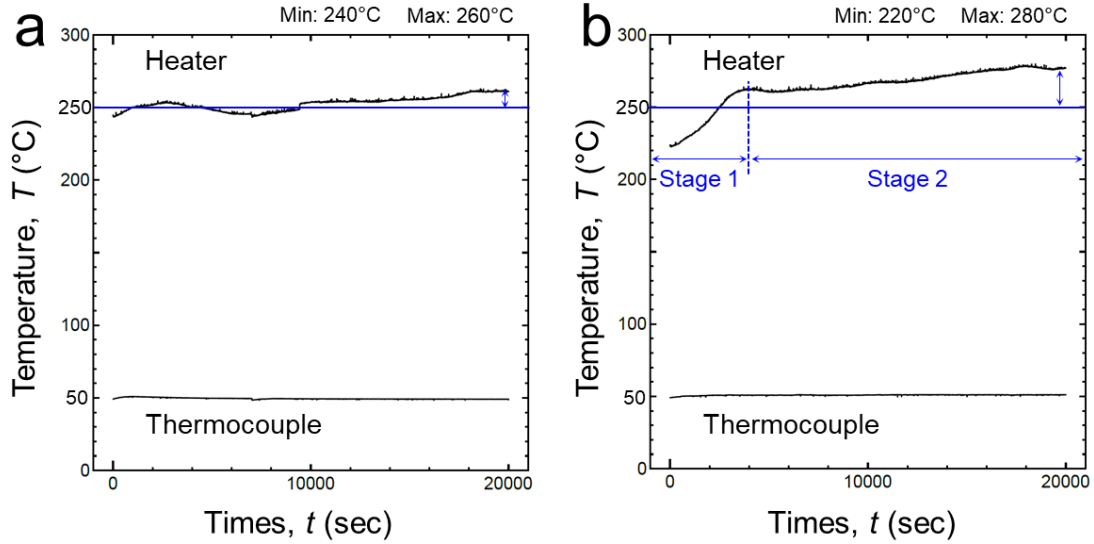


Fig. 4.11. Temperature swing behavior during power cycling tests: (a) Si₃N₄ and (b) AlN.

To investigate a factor of different temperature behavior, a nondestructive test was performed by a micro-focus 3D computed tomography (CT) X-Ray system (XVA-160N, Uni-Hite System Corporation, Yamato City, Japan) on the specimens after power cycling tests. Fig. 4.12 displays nondestructive test results (X-ray) after power cycling tests after power cycling tests (20,000 cycles). Fig. 4.12(a,b) show the SiC micro-heater chip power modules on the DBC-Si₃N₄ substrate and its high magnification image, respectively. Fig. 4.12(b,c) the SiC micro-heater chip power modules on the DBC-Si₃N₄ substrate of AlN and its high magnification image Fig. 4.12(d), respectively. There was no relationship between the different temperature behavior of the two substrates and the substantial damage to the die attach structure. Therefore, no delamination of the ceramic or degradation of the Ag sinter joint occurred during power cycling tests, and it was clearly found that the temperature rise did not cause physical failure. Despite

the excellent thermal conductivity of AlN, the cause of temperature rise shown in Fig. 4.11(b) can be regarded as an issue of the TIM. The mechanism of air entrainment into the TIM are shown in Fig. 13. In the initial state, the DBC substrate and the water cooling plate were closely adhered by TIM (see Fig. 4.13(a)), after experiencing expansion and shrinkage, there should be some gaps generation between the TIM and substrate, the adhesion strength changed to lower with a little gap generation as displayed in Fig. 4.13(b,c). Air entrainment into the TIM also can lead to the temperature swing increase.

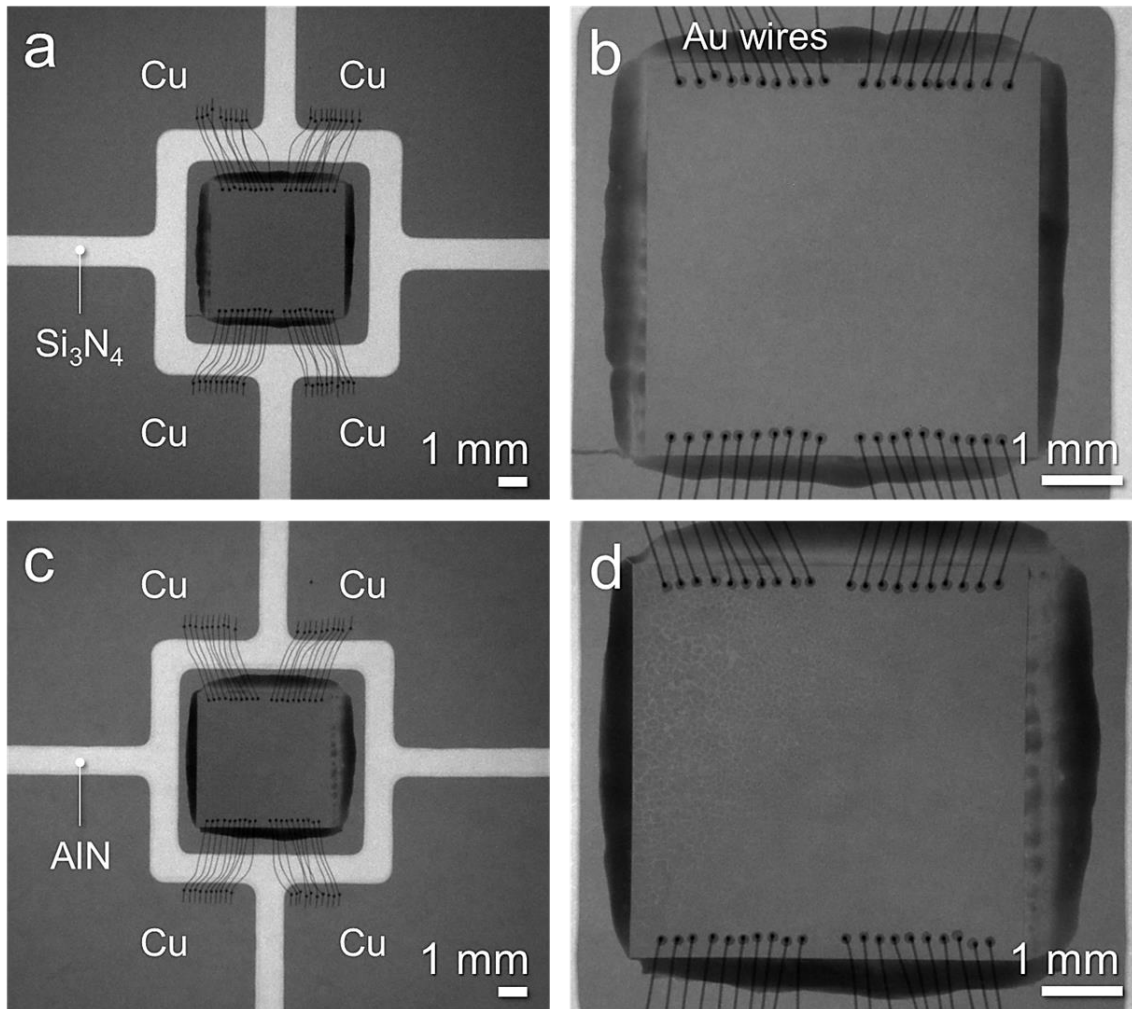


Fig. 4.12. Nondestructive test results (X-ray) after power cycling tests (20,000 cycles): (a) specimen of Si_3N_4 and (b) its high magnification image, (c) specimen of AlN and (d) its high magnification image.

Thus, to avoid this phenomenon, it can be prevented by using a soft TIM or warpage suppression mechanism that does not harden under repeated substrate warpage behavior. The results of the power cycling test using the SiC micro-heater chip show the heat resistance performance of the DBC substrate, are significantly different from the traditional thermal shock test. Consequently, the AlN-DBC substrates may have the best heat dissipation and durability, perhaps by optimizing TIM performance for WBG power conversion systems.

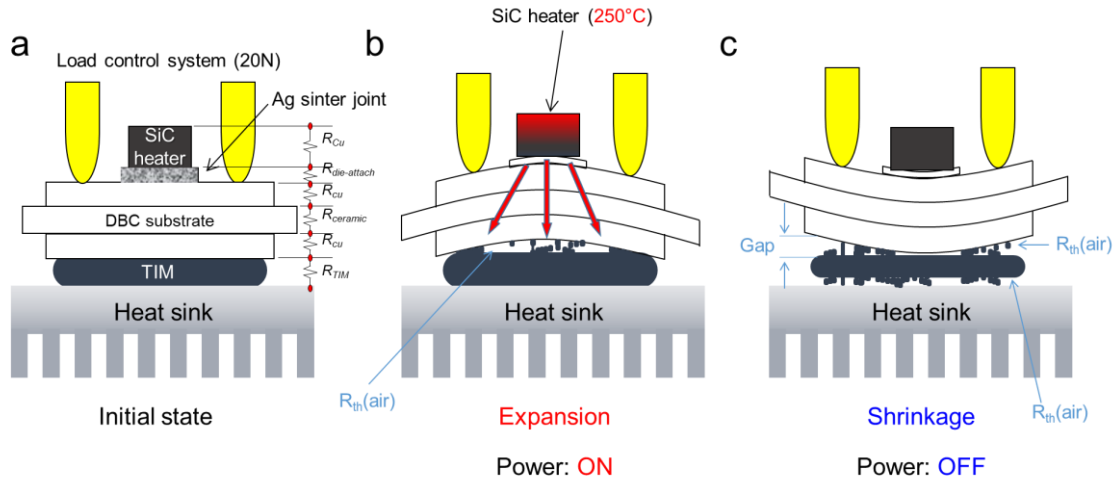


Fig. 4.13. Schematic diagram of AlN temperature rise mechanism by mechanical behavior during power cycling test: (a) initial state (b) expansion (c) shrinkage.

4.4 Conclusion

In this chapter, it was investigated the direct thermal characterization method of junction temperature in an actual SiC chip packaged using 4H-SiC TEG chip applied power cycling systems. This demonstration offers the possibility of precise measurement of junction temperature and thermal resistance at high power density, which is no longer limited by the actual SiC direct bonded power module structure. This technology can be extended to perform reliability test standardization for all wide band-gap semiconductors by providing a method of evaluation which will determine which parts of a power module structure are deteriorating at any point in time. This technology to find wide application in all fields that can benefit from controlled and site-specific power conversion industries, For example, the 5G and eco-friendly cars, such as WBG semiconductors that require practical applications. The unprecedented active SiC applied direct thermal characterization developed in our model semiconductor system will lead to new avenues for power electronics design with the capability to perform at increased junction temperature. Moreover, SiC and GaN are available materials ready and integrated into existing semiconductor production lines.

Reference

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Chapter 5

Summary

In this dissertation, to achieve high reliability for WBG power electronics such, a new die attached module structure has been evaluated for high temperature aging/thermal shock reliability. Based on these evaluation, a thermal shock-resistant die-attached module structure with DBA and micron/submicron Ag sinter paste was developed and its mechanism was experimentally and numerically revealed. Also, a novel SiC micro-heater chip capable of simulating active SiC device was presented to measure steady-state thermal resistance and to evaluate power cycling performances of various die-attach materials and insulating substrates.

In Chapter 1, the brief descriptions on the background of the challenge and exploration for next-generation power devices and was summarized the immersing issues in the use of WBG semiconductors. It is pointed that the reasons why it need to develop the high temperature materials and structures for the WBG power modules and introduced the thermal characteristics characterization methods. The objective of this research were also presented.

In Chapter 2, to implement a die-attach material and an insulating substrate that can withstand high temperatures above 250°C, a GaN/DBA die attached structure were introduced, sound bonded by a micron/submicron Ag sinter pastes. As a results of the thermal aging test, the specimens are subjected to high temperature aging tests at 250°C up to 1000 hours. Initial shear

strength of a pressure-less hybrid Ag sinter joint exceeded 42 MPa, and increased stably up to aging of 1000 hours without any defects such as interface oxidation, diffusion, or mechanical deformation. The increase in shear strength of the Ag sinter joints was the result of neck thickness growth of the sintered Ag during thermal aging. On the other hand, the shear strength of traditional Pb-5Sn solder significantly reduced (by 60%) after 250 hours aging due to its serious degraded interface layer.

In Chapter 3, High-strength and superior thermal shock-resistant GaN/DBA die attach structures with Ag sinter joining by thick Ni metallization (7 μm) were developed. Consequently, the shear strength of the Ag sinter joining structure was sustained above the initial strength after 500 cycles, which showed durable sinter necks and non-deformed interfaces due to the thick Ni metallization. Thus, Ag sinter joining with metallization design can be expected as an environment-friendly replacement die material for the long-term reliability of WBG semiconductor module packaging.

In Chapter 4, for a thermal characteristic standardization of SiC power devices, a SiC thermal engineering group (TEG) chip was developed, direct thermal characterization method of junction temperature in an actual chip packaged using active 4H-SiC TEG chip applied power cycling systems. This demonstration offers the possibility of precise measurement of junction temperature and thermal resistance at high power density, which is no longer limited by the actual SiC direct bonded power module structure. This technology can be extended to perform reliability test standardization for all wide band-gap semiconductors by providing a method of evaluation which will determine which parts of a power module structure are deteriorating at any point in time. We envision that this technology to find wide application in all fields that

can benefit from controlled and site-specific power conversion industries, For example, the 5 generation (5G) telecommunication and eco-friendly vehicles, such as WBG semiconductors that require practical applications. The unprecedented active SiC applied direct thermal characterization developed in our model semiconductor system will lead to new avenues for power electronics design with the capability to perform at increased junction temperature.

Consequently, the demonstrated thermal shock-resistant die-attached module structures presented in this thesis can serve as alternative die-attached module structures for WBG devices that require high thermal performance or can operate at extremely high temperatures. The results confirmed that the suggested materials/structure and thermal characterization method could become alternative joining and evaluation technologies for WBG power conversion systems.

List of publications

A. Papers

1. **Dongjin Kim** et al., Development of thermal shock-resistant of GaN/DBC die-attached module by using Ag sinter paste and thermal stress relaxation structure, *Microelectronics Reliability* **88–90** (2018) 779–787
2. **Dongjin Kim** et al., Thermal shock reliability of a GaN die-attach module on DBA substrate with Ti/Ag metallization by using micron/submicron Ag sinter paste, *Japanese Journal of Applied Physics* **58** SBBD15 (2019)
3. **Dongjin Kim** et al., Development of high-strength and superior thermal shock-resistant GaN/DBA die attach structure with Ag sinter joining by thick Ni metallization, *Microelectronics Reliability* **100–101** (2019) 113380
4. **Dongjin Kim** et al., Measurement of heat dissipation and thermal-stability of power modules on DBC substrates with various ceramics by SiC micro-heater chip system and Ag sinter joining, *Micromachines* **10** (2019) 745
5. **Dongjin Kim** et al., Mechanical characteristic and fracture behavior of GaN/DBA die-attached during thermal aging: pressure-less hybrid Ag sinter joint and Pb-5Sn solder joint, *Journal of Materials Science: Material in Electronics* **31** (2020) 587-598

6. **Dongjin Kim** et al., Strengthening of DBA substrate with Ni/Ti/Ag metallization for thermal fatigue-resistant Ag sinter joining in GaN power modules, Journal of Materials Science: Material in Electronics (2020) (**Published online**)
7. **Dongjin Kim** et al., Direct thermal characterization method of junction temperature of active 4H-SiC device for wide band gap power module, (2020) Advanced Materials Interfaces, (**submitted**)
8. **Dongjin Kim** et al., Interfacial reliability of high-temperature solder by metallization design, 2019 (in preparing)
9. Chuantong Chen, Chanyang Choe, Zheng Zhang, **Dongjin Kim**, Katsuaki Suganuma, Low-stress design of bonding structure and its thermal shock performance (– 50 to 250 °C) in SiC/DBC power die-attached modules, Journal of Materials Science: Materials in Electronics, 29 [16] (2018) 14335–14346
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12. Chuantong Chen, Zheng Zhang, Chanyang Choe, **Dongjin Kim**, Seungjuh Noh, Tohru Sugahara and Katsuaki Suganuma, Improvement of the Bond Strength of Ag Sinter-Joining on Electroless Ni/Au Plated Substrate by a One-Step Preheating Treatment, *Journal of electronic materials*, **48** No. 2, 2019

13. Zheng Zhang, Chuantong Chen, **Dongjin Kim** and Katsuaki Suganuma, Low-temperature and pressureless sinter joining of Cu with micron/submicron Ag particle paste in air, *Journal of alloys and compounds*, **780** (2019) 435-442

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15. Chuantong Chen, Zheng Zhang, **Dongjin Kim**, Bowen Zhang, Masami Tanioku, Takao Ono, Kazuhiko Matsumoto and Katsuaki Suganuma, Interfacial oxidation protection and thermal-stable sinter Ag joining on bare Cu substrate by single-layer graphene coating, *Applied Surface Science*, **497** (15) 2019

B. Proceedings and Presentations

1. **Dongjin Kim** et al., Thermal shock reliability of GaN die-attached on DBA with Ag sinter paste, ICEPT2018 (International Conference on Electronic Packaging Technology 2018), Shanghai, China (2018)
2. **Dongjin Kim** et al., Thermal shock damage mechanism of GaN/DBA die-attach module with Ag sinter paste, SDM2018 (International Conference on Solid State Devices and Materials 2018), Tokyo, Japan (2018)
3. **Dongjin Kim** et al., Development of thermal shock-resistant of GaN/DBC die-attached module by using Ag sinter paste and thermal stress relaxation structure, ESREF 2018 (European Symposium on Reliability of Electron Devices, Failure Physics and Analysis 2018), Aalborg, Denmark (2018)
4. **Dongjin Kim** et al., Power cycle tests of high temperature Ag sinter die-attach on metalized ceramic substrate by using micro-heater SiC chip, IMAPS 2018 (International Symposium on Microelectronics Assembly and Society 2018), Pasadena, U.S.A (2018)
5. **Dongjin Kim** et al., Long-term reliability of GaN/DBA die-attached module with Ag sinter paste and with high temperature solder, EMAP2018 (20st International Conference on Electronic Materials and Packaging), Hong Kong, China (2018)

6. **Dongjin Kim** et al., GaN micro-heater chip for power cycling of die-attach modules with Ag sinter joint and high temperature solder, PCIM2018 Europe, Nuremberg, Germany (2019)
7. **Dongjin Kim** et al., Microstructural and mechanical reliability of a GaN/DBA die-attached module with Ag sinter joining in harsh thermal environments, (The 20th International Conference on Electronic Packaging Technology), Hong Kong (2019)
8. **Dongjin Kim** et al., アルミニウム張りセラミック基板表面の Ni スパッタリングによる GaN チップ銀焼結接合構造の冷熱衝撃耐性の向上, (第 29 回 マイクロエレクトロニクスシンポジウム), 大阪, 日本 (2019)
9. **Dongjin Kim** et al., Development of high-strength and superior thermal shock-resistant GaN/DBA die attach structure with Ag sinter joining by thick Ni metallization, ESREF 2019 (European Symposium on Reliability of Electron Devices, Failure Physics and Analysis 2019), Toulouse, France (2019)

Acknowledgement

I would like to express my sincere gratitude to my supervisor, *Prof. Katsuaki Suganuma*, for his support and academic guidance throughout my doctoral program. It was his steady support and inspiring guidance that brought this dissertation to its fruition. It was a great pleasure to conduct my work under his mentoring. He has also become someone that I aspire to be like in the future.

I would also like to thank the members of doctoral committee. *Prof. Hiroshi Nishikawa*, thank you for insightful comments and helpful discussion for this dissertation. I would so like to thank *Assoc. Prof. Shijo Nagao* and *Assoc. Prof. Tohru Sugahara* for their valuable advices and encouraging comments during the preparation activities for this dissertation. I am also deeply grateful for *Assist. Prof. Chuantong Chen* for his unlimited support throughout my publications.

I would like to express my appreciation to the members and alumni of Suganuma Laboratory, Mrs. Naomi Keenan, Mrs. Seiyo Okuda, Mrs. Sachiko Moribe, Mr. Yukiharu Kimoto, Mr. Aishi Suetake, Mr. Naoki Wakasugi, Mr. Yasuyuki Yamamoto, Mr. Yue Gao, Mr. Tetsu Takemasa, Dr. Wanli Li, Dr. Jeyun Yeom, Dr. Zheng Zhang, Dr. Bowen Zhang, Dr. Leila Alipour, Ms. Linying Li, Dr. Chanyang Choe, Dr. Jinting Jiu, Prof. Zhi-Quan Liu, Dr. Zhenghong Wang, *Prof. Cai-Fu Li*, *Prof. Zhi-Quan Liu*, Dr. Hao Zhang, Mr. Akio Shimoyama, Mrs. Ming-chun Hsieh, Ms. Haoran Ding for their kind support. I would also like to thank my professor during my master's degree, *Prof. Kuk-hyun Song* for his warm encouragement and kind support. His sincere advice raises me up.

I would also like to express my appreciation to my colleagues and alumni of Osaka University, Dr. Semin Park, Dr. Chulmin Oh, Dr. Jungrae Jo, Dr. Seungjun Noh, Mr. Hyunsu Park, Ms. Sujin park, Mr. Sangmin Lee, Mr. Yongwon Park, Dr. Jungmin Kim, Prof. Seung-joon Lee, Dr. Yong-deck Im, Mr. Seung-yeop Baek, Mr. Jongyeong Oh, Mr. Youngseok Im, Ms. Jungin Kim, Ms. Jaebong Yeon, Dr. Hyoseok Si, Ms. Jaebong Yeon, Dr. Sanghun Jin, Mr. Byungho Park, for their warm encouragement and invaluable friendship.

Finally, I would like to express my sincere appreciation and love to my parents, brother and *Ellin Hale* for their advice and moral support. Everyone has made a huge impact on my life and I will forever be grateful.

January, 2020 **Dongjin Kim**

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