COMPARISON OF PRESSURE-ASSIST SILVER SINTERING TO TIN SILVER SOLDER ALLOY AS DIE ATTACH MATERIAL IN HIGH POWER SEMICONDUCTOR

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2020

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RESEARCH PROJECT SUBMITTED TO THE FACULTY OF ENGINEERING UNIVERSITY OF MALAYA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER IN MATERIALS ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2020

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COMPARISON OF PRESSURE-ASSIST SILVER SINTERING TO TIN SILVER SOLDER ALLOY AS DIE ATTACH MATERIAL IN HIGH POWER SEMICONDUCTOR

ABSTRACT

The research is focused on pressure-assisted silver sintering material that is compared to tin silver solder alloy paste as used in power electronics. Material characterization, electrical tests, and reliability tests were conducted in the experiment. After drying process, it was observed that the Ag sintering paste height was reduced to approximately 40 percent. Die attach shear test showed that the average reading is about from 200 to 600 grams which are already enough to hold the dice before proceeding to the pressure sintering process. X-ray revealed that the void percent for SnAg paste sample is about 1.5 percent while pressure-assist Ag sintering paste sample doesn't have any voids after build. Scanning electron microscopy (SEM) microstructure analysis showed that the SnAg solder sample will form Sn-Ag and Sn-Cu intermetallic compounds between the solder alloy after reflow. For Ag sintering sample, it was observed that the die-to-Ag sintering and Ag sintering-to-DBC joint were properly executed. Agglomeration and aggregation take over in Ag-Ni sinter particles. The diffusion of Ag sintering material in die TiNiAg back metal and Cu DBC was also detected. This acquiring a mechanical lock that forms solid-state diffusion in the system. Electrical test reading shows that the VGE and VCES measurement reading for Ag sintering sample is lower compared to SnAg solder alloy sample. The thermal shock and temperature cycle test that were performed in both samples are comparable in performance. The power cycle test runs on the other hand give the opposite output response. SnAg solder sample only reaches the 20000 cycles but failed at 40000cyle. However, Ag sintering sample reaches 60000 cycle without failure.

Keywords: pressure-Assist, Ag sintering, power electronics, diffusion, die attach

PERBANDINGAN ANTARA PENSINTERAN PERAK DIBANTU TEKANAN DENGAN TIMAH PERAK PATERI ALOI DALAM PEMASANGAN BAHAN CIP UNTUK SEMIKONDUKTOR KUASA TINGGI.

ABSTRAK

Penyelidikan ini ditumpukan kepada bahan pensinteran perak dibantu tekanan yang dibandingkan dengan pelekat aloi timah perak pateri yang digunakan untuk kuasa elektronik. Pencirian bahan, ujian elektrik, dan ujian kebolehpercayaan telah dilakukan dalam eksperimen. Pengukuran telah menunjukkan pengurangan sebanyak ~40 peratus bagi pelekat pensinteran perak selepas proses pengeringan. Ujian ricih untuk proses "die attach" telah menunjukkan purata bacaan anatara 200-600 gram untuk menahan dadu sebelum meneruskan proses pensinteran. Ujian sinar-x menunjukkan peratus ruang kekosongan bagi pelekat SnAg adalah 1.5 peratus manakala pelekat Ag pensinteran tidak mempunyai sebarang ruang kekosongan. Mikroskop electron imbasan menunjukkan bahawa sampel pateri SnAg membentuk sebatian intermetalik Sn-Ag dan Sn-Cu antara aloi pateri selepas pengaliran semula. Bagi sampel Ag pensinteran, ia telah menunjukkan bahawa sambungan cip ke pensinteran Ag dan pensinteran Ag ke DBC telah dilakukan dengan cara yang sesuai. Gumpalan dan pengagregatan telah mengambil alih pensinteran zarah Ag-Ni. Penyerapan bahan pensinteran Ag juga telah dikesan di TiNiAg "back metal" dan Cu DBC. Hal ini mewujudkan kunci mekanikal yang membentuk penyerapan keadaan pepejal di dalam sistem. Data ujian elektrik telah menunjukkan bahawa bacaan pengukuran parameter VGE dan VCES bagi pensinteran Ag adalah lebih rendah daripada aloi pateri SnAg. Ujian kejutan termal dan ujian kitaran suhu juga telah menunjukkan prestasi yang setanding bagi kedua-dua bahan. Manakala, data ujian kitaran kuasa memberikan tindak balas pengeluaran yang sebaliknya. Bahan SnAg pateri mencapai 20000 kitaran tetapi gagal pada 40000 kitaran. Namun, bahan pensinteran Ag pensinteran telah mencapai perjalanan 60000 kitaran tanpa gagal.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my research work supervisor Assoc. Prof. Ir. Dr. Tan Chou Yong for the constant support of my M.E. study and research. I would also like to give special thanks to Assoc. Prof. Ir. Dr. Wong Yew Hoong for helping me as well thru out this journey. Their supervision helped me in all the time of research in writing of this thesis.

Besides my advisor, I would like to recognize ON Semiconductor in sponsoring my studies.

I thank my fellow officemates in ON Semiconductor: M.E. Dennis Yborde, Dr. Shutesh Krishnan, Chee Hiong Chew, M.E Pui Leng Low, and Dr. Kathiravan Suppiah for the stimulating discussions and brainstorming of this project.

Finally, to my caring, loving, and supportive family and wife, Eurlynne: my deepest gratitude. Your encouragement when the times got rough is much appreciated and duly noted. My heartfelt thanks.

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LIST OF SYMBOLS AND ABBREVIATIONS

SiC	:	Silicon Carbide
GaN	:	Gallium Nitride
IC	:	Integrated Circuit
PIM	:	Power Integrated Module
DBC	:	Direct Bonded Copper
SEM	:	Scanning Electron Microscopy
EDX	:	Energy-dispersive X-ray spectroscopy
PCT	:	Power Cycle test
TC	:	Temperature Cycle
THS	:	Thermal shock
Ag	:	Silver
SnAg	:	Tin Silver
PbSn	:	Lead Tin
SnBi	:	Tin-Bismuth
Cu	:	Copper
TiNiAg	:	Titanium Nickel Silver
SAC	:	Tin-silver-copper
IMC	:	Intermetallic compound
IGBT	:	Insulated Gate Bipolar Transistor
TLP	:	Transient Liquid Phase
ECA	:	Electrically Conductive Adhesives
BOM	:	Bill of Material
VCES	:	Collector-Emitter Voltage electrical testing
VGE	:	Gate−Emitter Voltage electrical test

CHAPTER 1: INTRODUCTION

1.1 Background

Kyoto's agreement to reduce global greenhouse gas emission provide new opportunities to industry for renewable energy. To name a few, these are Biomass, solar, tidal power, hydroelectric, and wind power (Islam, Nayar, Abu-Siada, & Hasan, 2018). The enabler factor of renewable energy is power electronics in the semiconductor industry. This novel device can accommodate a higher breakdown voltage with low switch loss. This new device can also cater high current density which can operate in elevated temperatures. The new semiconductor breakthroughs are Silicon Carbide (SiC) and Gallium Nitride (GaN) technology. These two technologies have better performance when matched to Silicon die. The junction temperature of silicon devices is limited to 150°C before it starts to de-rate. Whereas the Silicon Carbide and Gallium Nitride device can operate greater than 500°C (Manikam, & Cheong, 2011). Over the past few years, high lead solder alloy has been utilized as a material for die attach to bond an Integrated Circuit (IC) component in a substrate for power electronics. The respectable reliability, decent electrical performance, and high thermal conductivity inherent by the material make it a material of choice. Although its effectiveness, flexibility, and health risks are recognized, the implication was not fully understood until the 1st of July 2003 when the RoHS (Restriction of Hazardous Substance) directive came into effect. This directive restricts the use of poisonous substances in electronic equipment and electrical devices (Gensch, Baron, & Deubzer, 2015). Conventional lead-free solder alloys which contain most of the Tin combined with other non-lead metals such as silver and copper has a good electrical and thermal conductivity that can support the requirement of power electronics in terms of bondability and functionality.

1.2 Problem statement

Power requirements for certain business units require higher levels of thermal capabilities. Lead-free solders alloy is exceeding its limitation since the typical melting temperature is approximately 200 ºC. Today, a group of leading semiconductor companies namely Infineon, NXP, Bosch, ST micro, and Nexperia created a consortium that lists down the minimum reliability requirements for die-attach interconnects for power electronics. To enumerate (1) Typical junction temp requirement at 175 ºC to 200 ºC is required (2) Thermal and electrical properties should exceed high lead solder capability (3) Reflow temperature of 260 ºC with a moisture sensitivity level of MSL 3 or better is needed (4) can withstand the wire bond temperature up to 260 ºC. This opens an opportunity for semiconductor manufacturers to find a solution that can substitute current solders solution with non-lead containing materials (Eilken, 2020). A die attach material is applied to bond silicon die to a DBC substrate. Solder alloys are usually the preferred choice for interconnect. However, the electrical and thermal properties of this material limit the package and reliability performance of the device. This limitation offers new opportunities to use an alternative solution. A pressure-assist silver sintering material can be an option of choice.

1.3 Objective of the study

The main intention of these research work is to compare the pressure-assist silver sintering material to tin silver solder alloy in high power electronic devices. Details of material characterization and reliability assessment were performed, to wit:

- To determine the reduction percentage of Ag sintering paste after drying process and compare the void percentage of Ag sintering paste with SnAg solder.

- To describe the die attach microstructure of Ag sintering paste and SnAg solder.
- To verify the electrical and reliability performance of Ag sintering versus SnAg solder paste by conducting temperature cycle test (TC), thermal shock test (THS) and power cycle test (PCT).

The process flow in applying the pressure-assist Ag sintering material also discussed to show the complexity of the process when compared to traditional solder paste alloy.

1.4 Scope of the study

The research work is focused on pressure-assist Ag sintering die attach material in power electronics. Packaging characterizations were accomplished to evaluate the performance of this hybrid die attach material in package assembly. A depth profiler microscopy was used to measure the height of paste after printing in DBC substrate. This tool was also utilized to measure the height of paste after the drying process. Die attach voids are typically observed when using solder alloys. To verify if voids are present in pressure-assist silver sintering, x-ray equipment was used. The mechanical cross-section was performed to the samples to study the solid-state diffusion of die attach material in silicon back metal and copper substrate. Scanning electron microscopy was utilized to investigate the morphology of die attach interconnects. Energy-dispersive x-ray spectroscopy was performed to verify the elemental composition of the samples. After package assembly, an automated tester machine was utilized to validate the electrical functionality of the device. Electrical test data was also collected to compare if the two samples have a significant difference in terms of electrical readings. To understand the overall package reliability an automated stress test machine was also utilized to perform power cycle, temperature cycle, and thermal shock testing.

1.5 Research outline

The research work was divided into five chapters of structure. Chapter 1 discussing the ever-increasing demand for power energy and what the alternative solution available today. Chapter 2 is the review of literature that discusses the works done in the past and present for power electronics. This chapter also emphasizes the advantage and limitations of the current die attach solder alloy and showing the benefit of pressure-assist Ag sintering material. Chapter 3 is the methodology work project. It showcases the step-by-step procedure on how the experiment was conducted and shows the analytical techniques & method used to compare the Ag sintering and Tin Ag solder alloy die attach. Chapter 4 is the result and discussion. This is where all data are collected from Ag sintering and Tin Ag solder alloy experiments. The collected data are analyzed and discussed by relating the results from previous literature work. Chapter 5 is a summary of the paper that was accomplished in this study. This chapter will position the conclusion of the research work in the problem statement.

CHAPTER 2: LITERATURE REVIEW

The global decrease of greenhouse gas emissions driven by Kyoto's agreement sets new opportunities in the renewable energy industry around the world in recent years. The energy collected from renewable sources such as sunlight, rain, wind, waves and geothermal which are replenished on a human timescale period is termed renewable energy. Most of the renewable technology is now competitive in terms of development, reliability, and cost when compared to conventional fuel generators. The renewable energy cost trend is expected to drop, as supplies and demands increase. The technology for renewable energy such as solar, biomass, wind, hydroelectric, tidal power, and wind energy system are technologies that are considered (Islam, Nayar, Abu-Siada, & Hasan, 2018). To enable renewable energy technology, semiconductor industries in power electronics developed a device that can be used for converting energy to power electricity. The new devices are capable of accommodating high breakdown voltage, low switching losses, acquire high current densities, and can operate in high temperatures. Gallium nitride (GaN) and silicon carbide (SiC) are new semiconductor breakthroughs that can provide wider-band gaps when compared to silicon (Si). It was noted that the SiC and GaN have superior electrical characteristics when compare to silicon (Si). The new device has larger bandgaps, higher die electric constant, and greater electric breakdown field compared to Si (Tolbert, Ozpineci, Islam, & Chinthavali, 2003). This novel SiC and GaN power semiconductors can significantly increase power efficiency and decrease power losses in electricity supply. However, the advantage of new technology needs to be compensated in packaging particularly at the interconnect level between the substrate and die (Tolbert, Ozpineci, Islam, & Chinthavali, 2003). Resourcing new die attach material that can withstand the stringent operating temperature is a crucial component in assembly packaging. The new die attach material must be high performing in terms of electrical and thermal conductivity and the die-to-substrate interconnection should be reliable in which it can withstand the extreme environments and high temperatures. In this literature review, pressure-assisted low-temperature sintered silver is presented as an alternative die-attach solution to traditional tin-silver solder alloy.

2.1 Wide-Bandgap Semiconductor

Silicon carbide (SiC) and gallium nitride (GaN) are wide-bandgap semiconductor technologies. These are candidates to substitute silicon (Si) soon because of their superior electrical properties. The probable benefit of using SiC and GaN devices include thinner drift regions and higher attainable junction temperature. As reported by Manikam and Ozpineci & Tolbert, the major advancement in using wide-bandgap materials in power electronics are as follows. (1) In terms of the wide-bandgap forward and reverse characteristics, these power devices only vary slightly in temperature and time which results in better reliability. (2) Wide-bandgap semiconductor has a higher breakdown field consequential to higher breakdown voltage. (3) Bipolar with wide-bandgap semiconductor devices use less or no snubber circuitry, reduction of turn-on loss, no voltage overshoots, and reduce electromagnetic interference. (4) Wide-bandgap semiconductors can operate at higher frequency (>20 kHz) due to low switching losses. A feature that cannot be done in power level Silicon semiconductor devices that operates in more than a few tens kilowatts. Table 1 is the tabulated characteristics of wide-bandgap and silicon semiconductors. Referring to table 1, diamond is the most preferred large bandgap material to support high power devices because of its superior thermal conductivity. But since it has a high manufacturing cost, SiC and GaN are more favorable. It was also described that there are two characteristics of diamonds that make it less supreme. First, the technology for fabrication is not yet mature compared to SiC and GaN. Second, the diamond's coefficient of thermal expansion (CTE), is very low. It was also described that SiC and GaN when compare to diamond is more suited material in semiconductor packaging because it provides a better thermomechanical match, even better than traditional Si. Besides, the advancement of material fabrication of SiC and GaN power device will be directed onto this development system on later years (Tolbert, Ozpineci, Islam, & Chinthavali, 2003), (Manikam, & Cheong, 2011).

Table 2-1: Material properties of Silicon (Si) and wide bandgap semiconductor

Properties	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Dielectric constant	11.9	13.1	9.66	10.1	9	5.5
Electric Breakdown Field (kV/cm)	300	400	2500	2200	2000	10000
Electron Mobility (cm^2/V.s)	1500	8500	500 80	1000	1250	2200
Hole Mobility (cm2/V.s)	600	400	101	115	850	850
Thermal Conductivity (W/cm.K)	1.5	0.46	4.9	4.9	1.3	22
Saturated Electron Drift Velocity ($x10^7$ cm/s)	1	1	2	2	2.2	2.7

2.2 Traditional die attach material for power electronic devices

Lead-based solder alloy material is generally used in power electronics to attach the chip in the substrate. These provide a mechanical fix and in at the same time carry current and heat during operation. Particularly in semiconductors with large die size, lead-tin (PbSn) is a significant factor for die attach material for high-temperature application. The material advantages of PbSn solders are high ductility, acceptable thermal conductivity, and tolerable melting point for a wide range of applications. The tin melting point is

232°C while lead is 323°C. Lead-tin (PbSn) concerning their alloys, the minimum eutectic point is at 183°C (63Sn-37Pb) (Manikam, & Cheong, 2011).

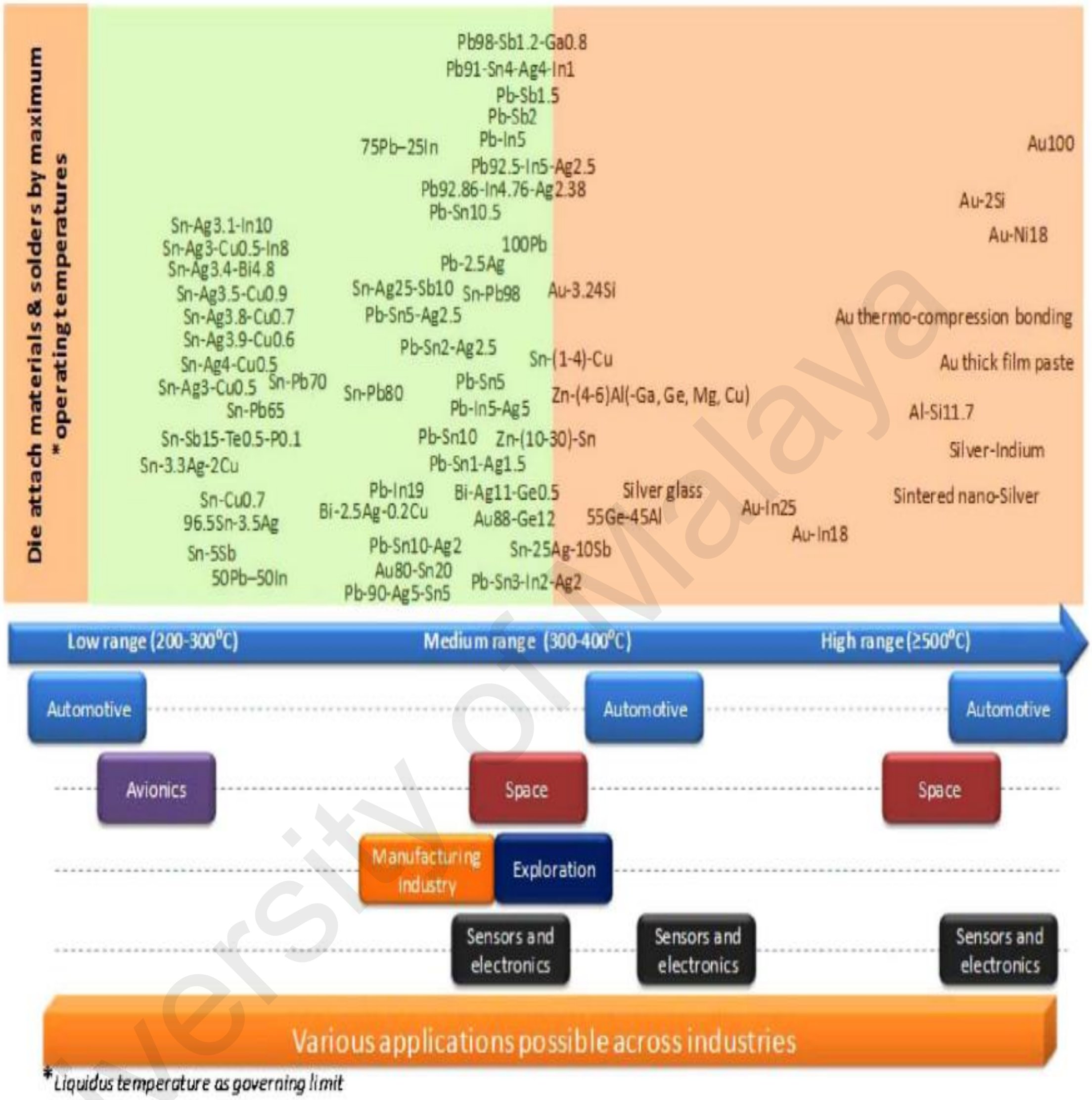

Figure 2-1: Different types of die attach material that operates in range of applications. At least 26 die attach material are qualified for mas manufacturing. Remaining candidate are still under development (Manikam, & Cheong, 2011).

2.3 Solution requirements for high temperature die attach materials

High lead solders have been utilized as a die attach material for power packages for the past few years. This is due to its inherent decent reliability, high thermal conductivity, and good electrical performance (Chiong, Zhang, & Lim, 2016). Though its usefulness, versatility, and health risks are known, the repercussion was not fully realized until the

1st of July 2006 when the RoHS (Restriction of Hazardous Substance) directive came into effect (Gensch, Baron & Deubzer, 2015). This directive restricts the use of poisonous substances in electronic equipment and electrical devices. Conventional lead-free solder alloys which contain most of the tin combined with other non-lead metals such as silver and copper. This combination has a good electrical and thermal conductivity that can support the requirement of power electronics in terms of functionality (Quintero & McCluskey, 2011). However, power requirements for certain business units require higher levels of thermal capabilities. Lead-free solders alloy is exceeding its limitation since the typical melting temperature is approximately 200ºC (Möller, Middelstädt, Grieger, Lindemann & Wilde, 2015). Today DA5 requirement necessitates more than 200ºC working temperature on solders for manufacturing and application purposes. To enumerate (1) Typical junction temp requirement at 175ºC to 200ºC is required (2) Thermal and electrical properties should exceed high Pb solder capability (3) Reflow temperature of 260 ºC with a moisture sensitivity level of MSL 3 or better is needed (4) wire bond temperature up to 260 ºC (Eilken, 2020). This opens an opportunity for microelectronic manufacturers to find a solution that can substitute current solders solution with non-lead containing materials. (Ma, Zeng, Harrington, Ma, Ma, & Guo, 2016) (Clemente, Tolentino, & Azman, 2014).

2.4 Lead free die attach solution

Four type of lead-free die attach material were identified by die attach five (DA5). Electrically conductive adhesives (ECAs), Transient liquid phase (TLP), Tin-based solder alloy and silver (Ag) sintering. This are adhesive material that can replace the high lead solder which are high electrically and thermally conductive.

2.4.1 Electrically Conductive Adhesives (ECAs)

Adhesive epoxy, also known as electrically conductive adhesives (ECAs) shown in Figure 2-2, are typically polymer binder base that to provide desirable mechanical properties filled with metal particles. The metal content is approximately 80% which is used to provide thermal and electrical conductivity. The range of products incorporating various metal such as silver (Ag) and tin-bismuth (SnBi) has been developed. This materials are compatible with glass, ceramics and other material that is hard to solder. However, typically had very low thermal conductivity compared to metals. Thermal conductivity is ranging from 10-25 W/mK (Möller, Middelstädt, Grieger, Lindemann & Wilde, 2015).

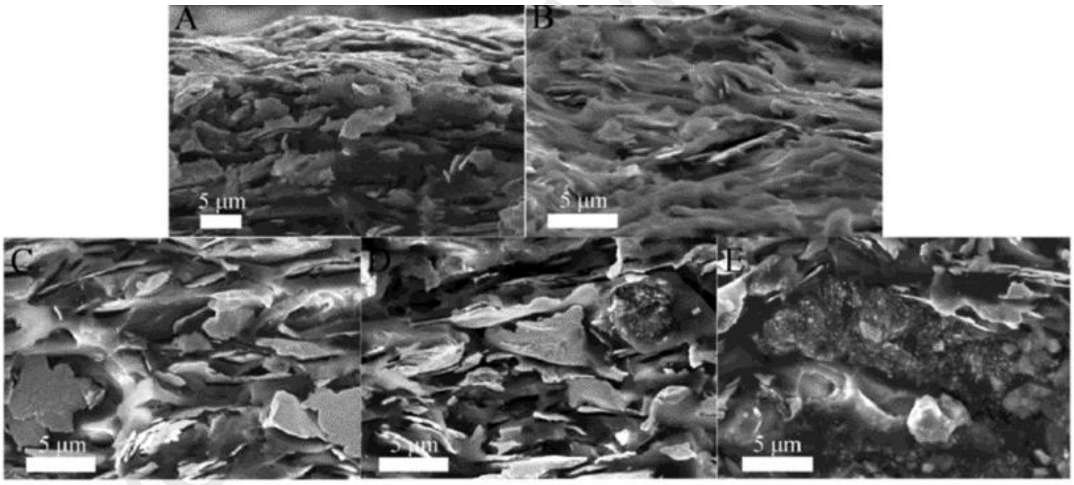

Figure 2-2: SEM images sample of cross-section morphology of electrically conductive adhesives (ECA) (Ma, Zeng, Harrington, Ma, Ma, & Guo, 2016).

2.4.2 Transient liquid phase (TLP)

Transient liquid phase (TLP) bonding is based on the principle that isothermally solidification takes place after diffusion of a high melting material into melted, low melting material and the simultaneous formation of high melting intermetallic phases. Bismuth (Bi) and nickel (Ni) composition are commonly used for the transient liquid phase (TLP).Figure 2-3 showing a strong reaction of molten bismuth (melting point at

271ºC) to nickel (Ni) to form Bi3Ni or BiNi intermetallic layer can withstand over 400 ºC. Figure 2-4 showing the phase diagram of bismuth and nickel. Notice that the liquid and solid state of bismuth and nickel material The main advantage of using transient liquid phase (TLP) is the outcome bonding have a higher melting temperature (Cho, Sheikhi, Mallampati, Yin, & Shaddock, 2017).

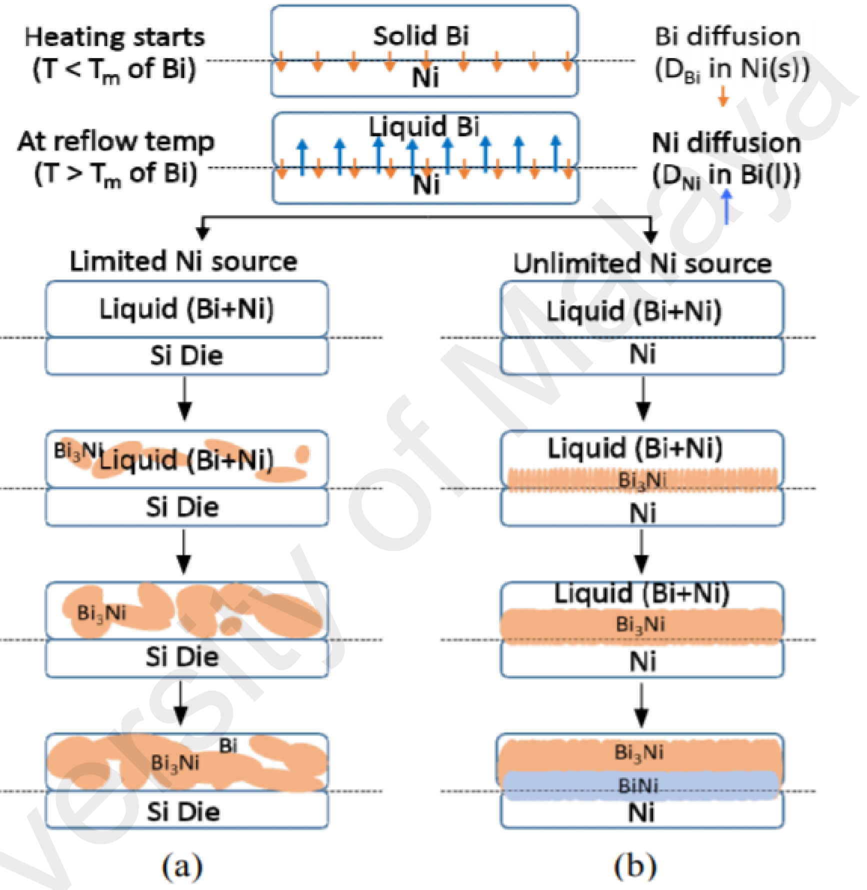

Figure 2-3: Schematics of IMC formation mechanism (a) Bi/(Ni) Si die and (b) Bi/Ni foil (Cho, Sheikhi, Mallampati, Yin & Shaddock, 2017).

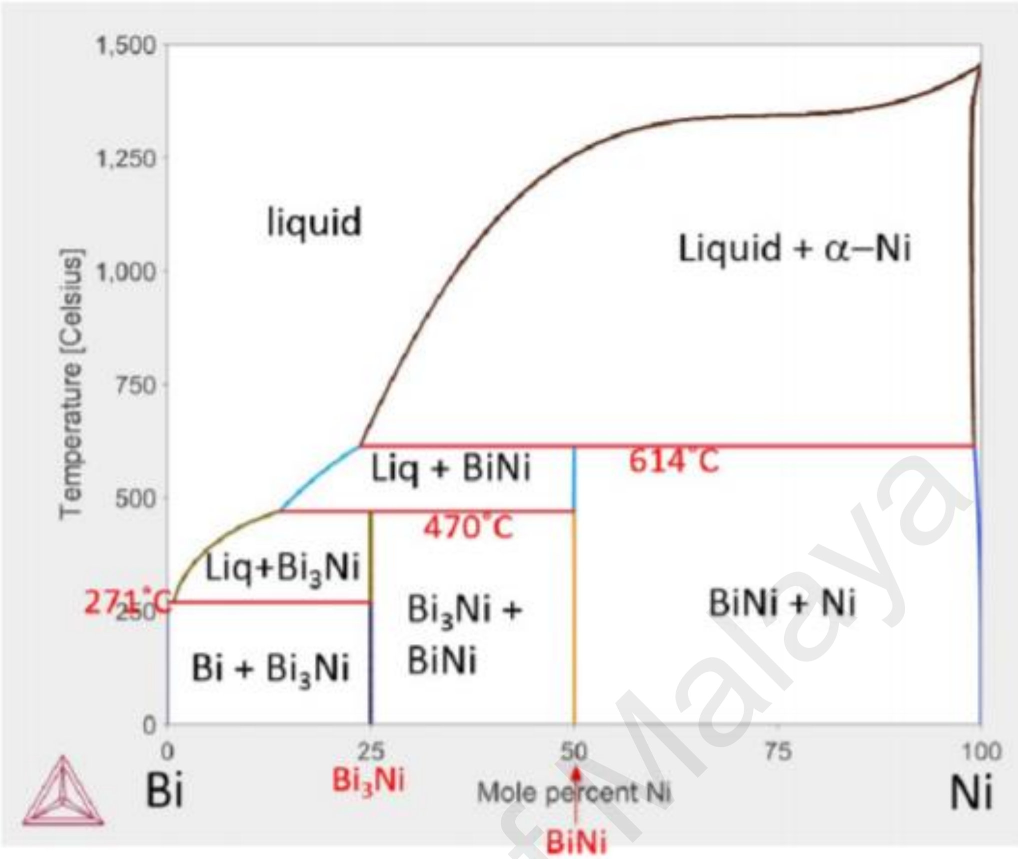

Figure 2-4: Phase diagram of bismuth and nickel. Showing the liquid and solid state of bismuth and nickel material (Cho, Sheikhi, Mallampati, Yin & Shaddock, 2017).

2.4.3 Solder alloy

As a discussion on the traditional die attach material for power electronic devices, it was mention that the tin (Sn) and Pb melt at 232ºC and 328ºC and expected to have a low melting point if combined (alloy). Melting temperature for high lead solder alloys typically at least 250 ºC. However, since this is lead-based material, the restriction of ROHS needs to be considered. This directs to a non-lead solder die attach material. Candidates such as tin-silver (SnAg) and tin-silver-copper (SAC) solder alloy is perhaps the next material that can be deliberate (Titushkin, Surma, Monchy & Lifton, 2016).

2.4.4 Silver sintering technology

The Ag sintering technology is based on a process in which nano-sized particles form joints when subjected to heat. As Shown in Figure 2-5 that these nano-sized particles are coated with a capping agent to prevent oxidation and additives to promote sintering. The capping agent will evaporate at an elevated temperature. The additives then will activate the surface of the particles and facilitate the sintering process. At one time, Ag sintering was attempted with micron-sized particles (Zheng, Berry, Ngo, & Lu, 2014). However, agglomeration of particles at elevated temperature found to affect the sintering efficiency (Becker & Lin, 2003). With nano-sized Ag particles, sintering can be achieved at a lower temperature, but the application of pressure is still required. A delay time at bonding is needed for the pressure to take effect. Hence this was considered as not an ideal solution for mass production (Siow, 2012).

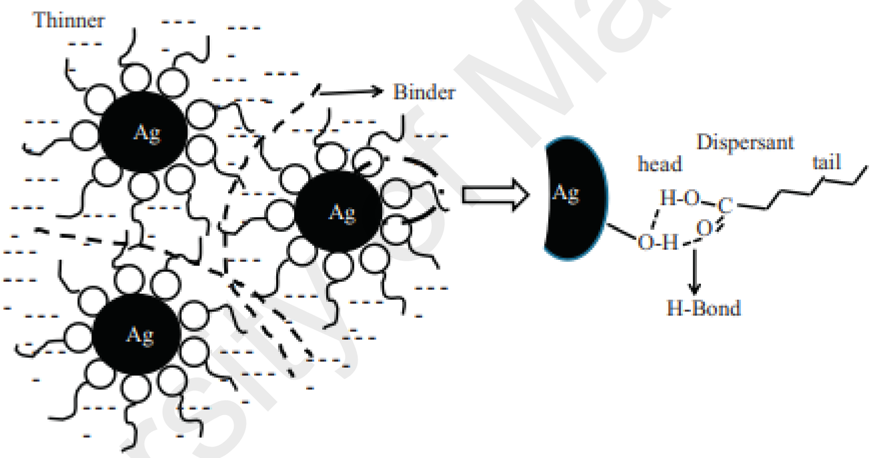

Figure 2-5: Illustration of the Ag sintering particle covered by binder and thinner (Siow, 2012).

2.4.4.1 Silver sintering technique

Low-temperature pressure-less silver sintering is always the preferred method in the assembly package. This approach gives numerous advantages in processability and manufacturability. Application is very similar to the traditional epoxy die attach paste. Writing dispensing, screen printing and dot dispensing is the common method in applying the material in a lead frame or before die attach (Siow, 2012). In terms of curing, pressure-less Ag sintering needs to have two-step curing to perfectly perform particle fusion during sintering. The first step is the binder burnout temperature. This is to ensure that all organic materials will burn out and break the coating of metal particle (Clemente, Tolentino & Azman, 2014) (Knoerr, Kraft & Schletz, 2012). The second step is the sintering temperature, this is where a metal particle will join and perform solid-state fusion (Clemente, Basilia & Tolentino, 2016) (Berry, Townsend, He, Zheng, Ngo & Lu, 2016) (Bai, Calata & Lu, 2007).

To enhance the thermal and electrical conductivity of silver sintering technology. Low-temperature pressure-assist silver sintering is needed for package assembly. However, the process is dissimilar from pressure-less silver sintering. Applying pressure-assist silver sintering paste is commonly done in screen printing, followed by the drying process. The drying process is done to ensure most of the polymers are removed (Chew & Schmitt, 2019). The die attach will then be carried out. This process can either be performed in hot or cold tacking. After securing the die into the substrate, the pressure is applied on top of the die during curing to perform sintering. This technique will make the die attach material further compact, creating the sintered Ag particle to be denser. Depending on the sintering time and pressure applied during sintering, material pore size will significantly reduce. Making the material achieve a very low electrical resistivity (Knoerr, Kraft & Schletz, 2012) (Tolbert, Ozpineci, Islam & Chinthavali, 2003).

CHAPTER 3: METHODOLOGY

3.1 Introduction

Figure 3-1 is a prototype power integrated module (PIM) electronic device that was selected on this experimentation. The assembly build was separated into two batches. The first batch is using standard lead-free solder alloy and the second batch is using pressure-assist silver sintering paste die attach. Figure 3-2 showing the schematic diagram of a power integrated module (PIM). Dice are mounted to a DBC substrate. Aluminum wires and pins are used to connect the dice to input/out source of the package. Silicone gel is used to protect the circuitry of the device. Experimental samples were prepared using a direct bonded copper (DBC) substrate, a diode and a two IGBT silicon dies. The dimension of the IGBT silicon die is 13mm x 13mm x 0.200mm and diode silicon die is 4.9 mm x 9.8mm x 0.200mm. Both dies have a back-metal surface composition of TiNiAg.

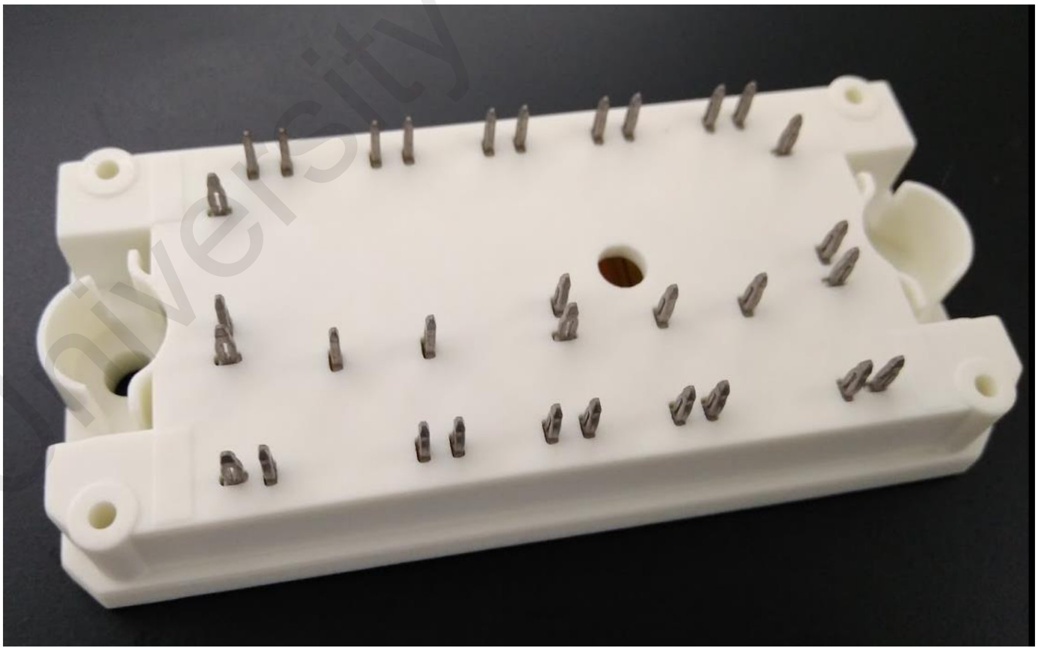

Figure 3-1: Power Integrated Module Actual image.

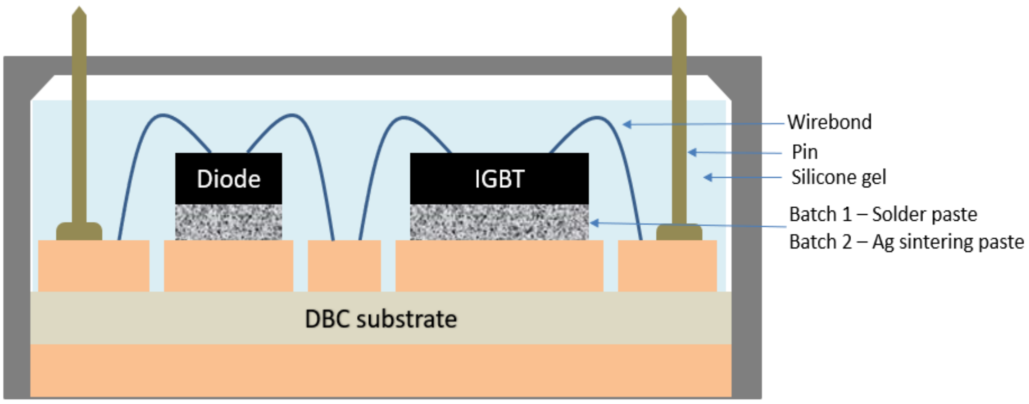

Figure 3-2: Image showing schematic layout of Power Integrated Module.

3.2 Batch-1: Sn96.5Ag3.5 solder alloy paste sample

The first batch lot (Sn96.5Ag3.5 solder alloy paste) was applied to DBC using an equipment printer. After printing, dies were picked and mounted into the DBC substrate using a die attach equipment. Samples were then subjected to a reflow oven for soldering. Reflow peak temperature is 240°C with 40 seconds over 220°C. After reflow, the sample lot was sent to the degreasing process to remove the solder flux residue.

3.3 Batch 2: Pressure-Assist Silver sintering paste sample

The second batch lot is the pressure-assist silver sintering paste sample. This was also printed to a DBC using the same printer equipment. After applying the Ag sintering paste into the DBC. It is required to dry the material before bonding the die to DBC substrate. This ensures that all thinner/solvent will evaporate and avoid channeling voids underneath bonded die when exposing to elevated temperature. A convection oven was used to dry the silver sintering paste in the DBC substrate. The oven profile is from room temperature to 120˚C with a soak time of 30 minutes and then cooled down at room temperature for the next 60 minutes. The Drying process is done in a nitrogen atmosphere which is not greater than 100ppm O2. The low-temperature setting will ensure that the agglomeration and aggregation will not yet happen on this point. Nitrogen is applied to ensure DBC substrate will not oxidize during the curing process. The dice were then picked in a wafer and transfer into a DBC substrate using automated die attach equipment. A heated bond head with a controlled bond force was used to secure the die into the DBC substrate. This will safeguard the dice from moving when pressure is applied during the pressure sintering process. Bond head temperature setting is ranging from 130 to 150˚C and bond force from 5-15 kgf as shown in Figure 3-3.

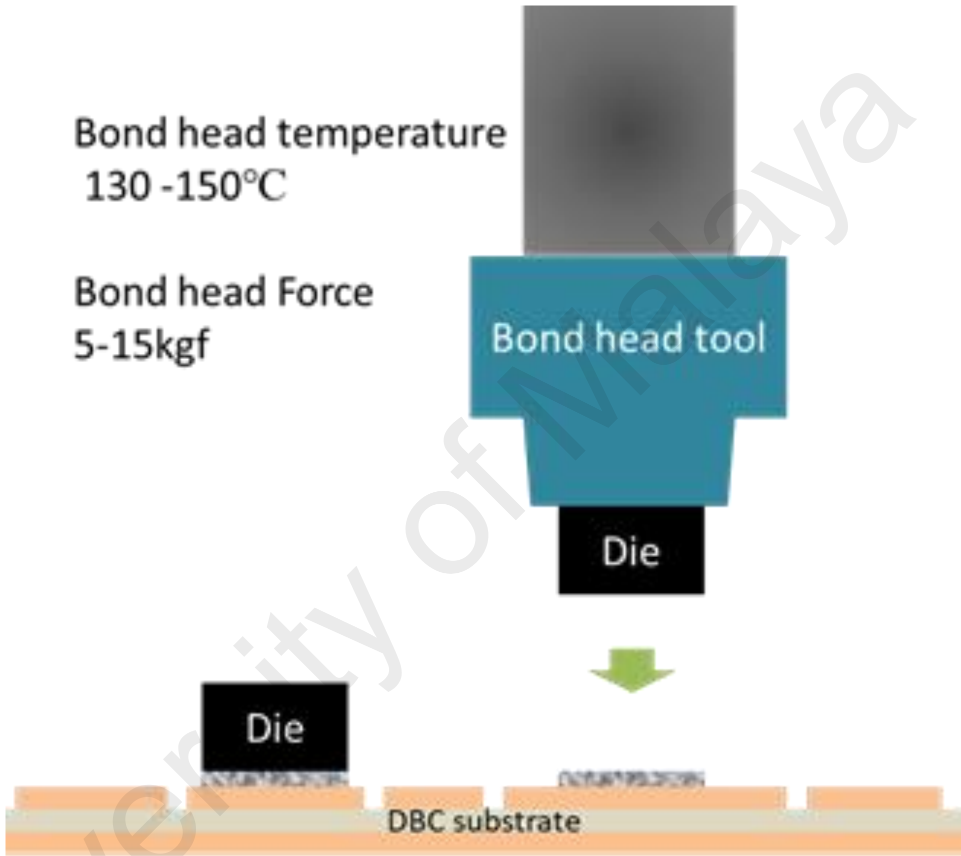

Figure 3-3: Schematics of die attach process. Dice are picked in wafer and placed in DBC substrate with dry Ag sintering material.

After mounting all dice to the DBC substrate, samples were subjected to an automated sintering machine for curing process. The pressure applied during sintering is 10MPa with a temperature of 230˚C for 5 mins as illustrated in figure 3-4. To the event of pressure sintering, a vacuum is applied to ensure that the substrate will not oxidize. At this point in time, materials capping agents and binders are expected to burn-out, followed by the Agglomeration and aggregation of metal particles, and solid-state diffusion is achieved.

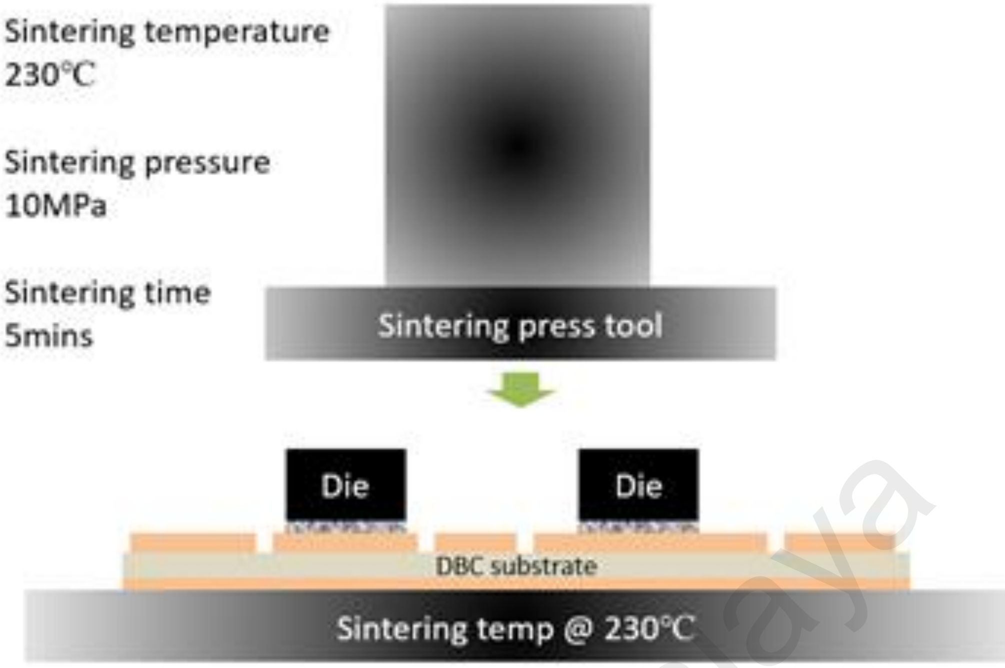

Figure 3-4: Schematics of pressure sintering process. Mechanical pressure is applied to dice to achieve good compaction of Ag sintering material.

3.4 Completing the packaging assembly

To complete the electronic circuit connection, an automated wirebond machine was used to link the die gate and source pad from the DBC substrate. The wires that were used for interconnect is 12 mil aluminum wire for both IGBT and diode dice. A manual singulation tool was used to separate the cluster DBC substrate. After singulation, input/output metal pins were soldered for all the samples for outlet connection. Plastic casing and silicone gel were then introduced to cover and protect the power integrated module device. Besides the die attach material, all bill of material (BOM) used to prepare the sample are maintained. Figure 3-5 showing the process of power integrated module (PIM)

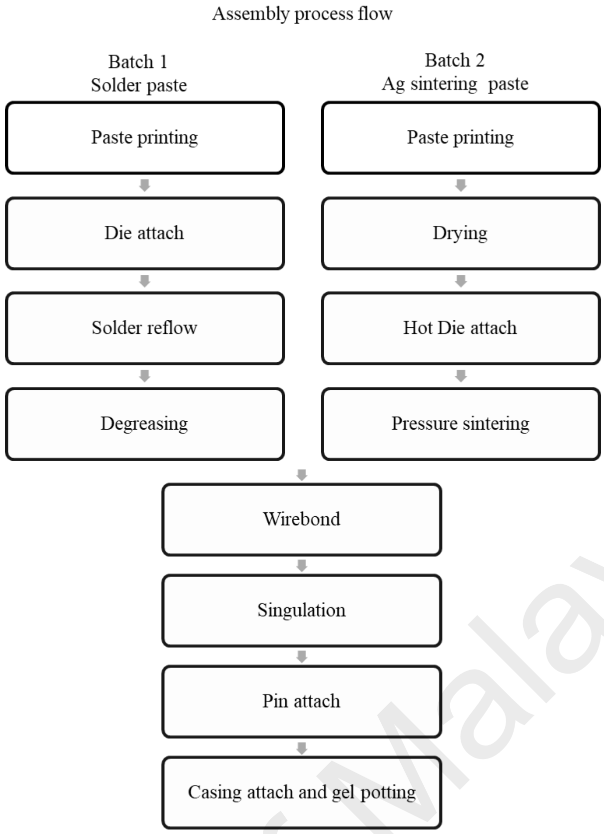

Figure 3-5: Assembly process flow of power integrated module

3.5 Electrical test

An automated tester machine was utilized to validate the electrical functionality of the device. Electrical test data were also collected to compare if batch-1and batch-2 samples have a significant difference in terms of electrical functionality. The gate threshold voltage (VGE-th), and Collector-emitter saturation voltage (VCE sat) are the test output responses.

3.6 Reliability test

To evaluate the package robustness of the device. Samples for batch-1 and batch-2 lot were submitted for reliability testing. The power cycle test, thermal shock, and temperature cycle test are the parameters that were used to characterize the reliability performance of the device. The Setting for power cycle test is 150°C Tj/max and humidity measurement of 150%RH, thermal shock (THS) with a setting of 125 ℃ Tj/max, and temperature minimum of -40℃ Tmin, and temperature cycle (TC) with a setting of Tj 150℃, 125℃ Tj/max and temperature minimum of -40℃ Tmin.

3.7 Analytical tools

A Keyce depth profiler microscopy was used to measure the height of Ag sinter paste after printing and after dry. A Dage 4000 multipurpose bond tester was used to verify the bonding strength between die and DBC substrate. Dage x-ray inspection system was used to check the void percentage of the bonded samples. Scanning electron microscopy (SEM) is an electron microscope use to create image by scanning the surface of a sample with focused beam electrons. Electron coming from a beam interacts with the samples atoms that produce different signals which will carry information regarding the sample's composition and topography of surface. The raster scan pattern will scan the electron beam which is also positioned in a detection signal to produce image. One of the keys take away of SEM is the three-dimensional appearance of an image due to large depth of field that can reach better than 1 nanometer. In a conventional SEM high vacuum setting is required to observe a specimen (Goldstein, Newbury, Michael, Richie, Scott & Joy, 2018). Scanning electron microscopy (SEM) was used to confirm the diffusion of material to die back metal and to copper substrate.

Energy dispersive x-ray spectroscopy (EDS, EDX, EDXS, XEDS), occasionally called energy dispersive x-ray microanalysis (EDXMA) or energy dispersive x-ray analysis (EDXA) is an elemental analysis or chemical characterization technique used in a specimen. This analytical tool depends on x-ray source excitation from sample during interaction. High energy beam of charge particle like protons and electrons is focused into a sample to excite the emission of characteristic x-ray. Atoms in the sample contain unexcited electrons when at rest which is a discrete energy level or electron shell still bound in the nucleus. An incident beam will be introduced to excite the electrons in the inner shell making the electron to be ejected from the shell creating an electron hole. Electrons from the outer shell in high-energy level then fill up the holes. The difference in energy between high and low energy shell may release in a form of x-ray. The energy-dispersive spectrometer can measure the number of energy of the x-ray emitted from the sample. Energy-dispersive X-ray spectroscopy lets the elemental composition of the sample to be measured as the energies of the X-rays are representative of the difference in energy amongst the two shells and of the atomic structure of the emitting element (Goldstein, Newbury, Michael, Richie, Scott & Joy, 2018). Energy-dispersive x-ray spectroscopy (EDS) was performed to validate the element in the bonding interconnect.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

Pressure-assist silver sintering paste is a mixture of micro and nano-sized silver, a few percentages of micro-sized nickle particles with organic components (Schmitt & Chew, 2017). These organic components consist of binders, dispersants/capping agents, and thinner/solvent. Binder is used in acquiring the consistency of the paste. In this manner, the application of paste material is easier. A dispersant/capping agent is necessary to achieve coalescence between metal particles resulting in better diffusion over sinter Ag-Ni. Thinner/solvent is used to get the optimal viscosity level. When applying high temperature in nano-Ag sintering paste. Most of the organic materials will evaporate and burn-out. After this process agglomeration and aggregation will take place in Ag-particles. Ag-Ni particles will acquire mechanical diffusion to form solid-state diffusion (Bai, 2005) (Melchor, n.d.).

4.2 Paste printing height measurement

Paste height measurement was performed after applying the Ag sinter into the DBC substrate. The measuring tool used is a Keyence depth profiler. Results in Figure 4-1 showed that after printing, the Ag sinter paste height is around ~120um. But after the drying process, Ag pastes thickness when down to ~70um. It was noticed that the reduction difference is about ~40 percent. This confirms that the solvents/thinners were already evaporated during the drying process. This result also correlate with Guofeng Bai research work. When Ag sintering paste sample underwent curing process (Bai, 2005).

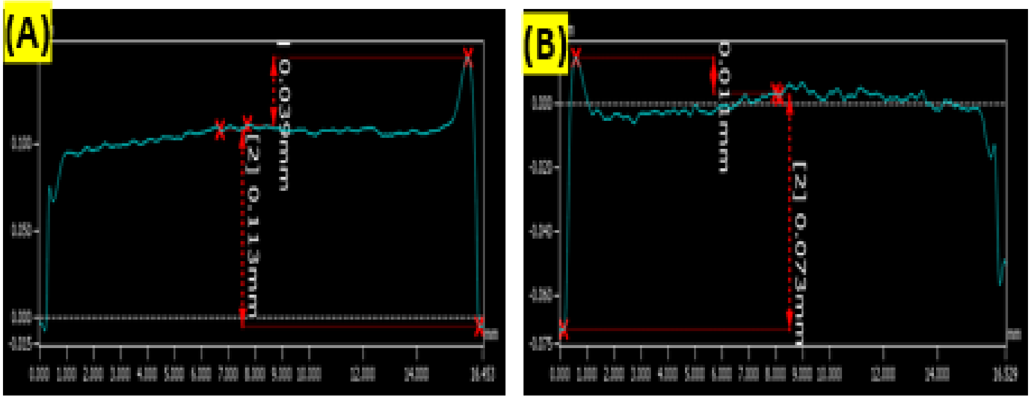

Figure 4-1: Ag sintering paste height measurement. (A) Height thickness ~120um. (B) Height thickness ~70um.

4.3 Batch-2 die shear strength measurement after Die Attach process

Figure 4-2 is Dage 4000 multipurpose bond tester that was used to verify if the dices have good bonding in the DBC substrate after die attach process. The purpose of verification is to guarantee that the dice are properly secure in DBC substrate. This will ensure that movement or dropping of dice will not happen when transferring the samples to the pressure sintering process. Results showed that the average die shear reading is 200 – 600 grams. This can be interpreted that the dice have enough bonding strength to hold itself during minor movements. The failure mode of Ag sintering material is adhesive failure (Campbell, 2004). However, it was noted that the failure mechanism of material at this point in time cannot be used as an indicator of material integrity. This is expected because the sintering process has not yet taken place. Paste height measurement for batch 1 sample was not performed as solder paste does not undergo to dry process. Dices were immediately attached to the DBC substrate after printing. The paste viscosity is already sufficient to hold the dices during reflow curing.

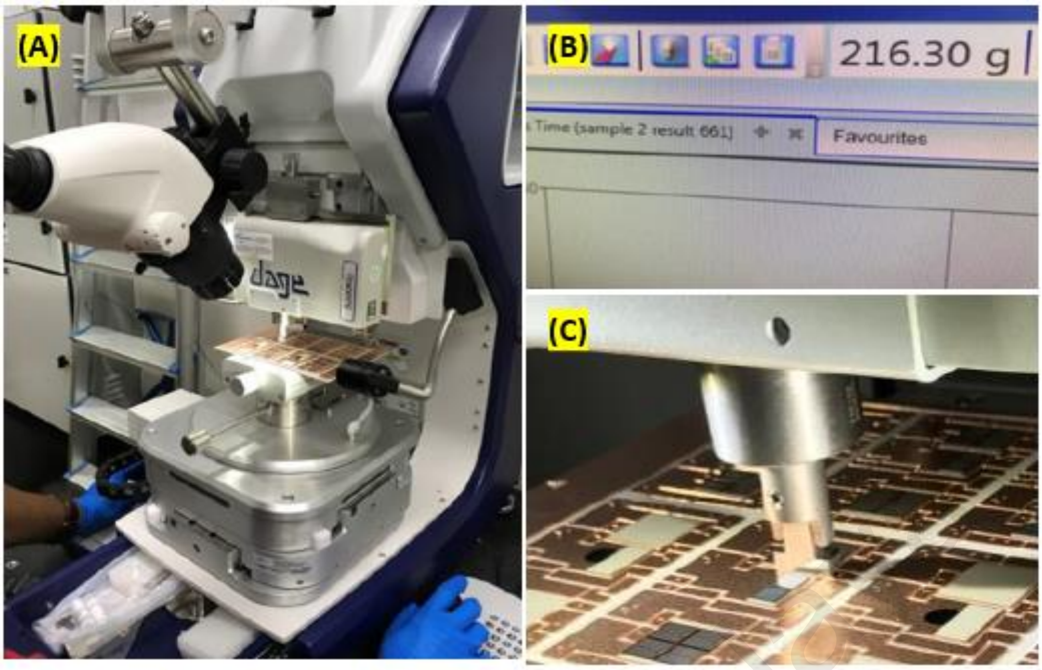

Figure 4-2: (A) Dage 4000 multipurpose bond tester, (B) Die shear reading measurement and (C) Die shear tool in contact with die to perform adhesion reading.

4.4 Die attach void measurement

It was reported that the voids at the solder joint have a great impact on the reliability and mechanical performance of the device. A large number of voids could lead to premature mechanical failure (Otiaba, Okereke & Bhatti, 2014). To investigate if voids are present in batch 1 and batch 2 samples. x-ray tomography image inspection has been carried out. Results from figure 4-3 showed that the Batch-1 sample has voids. The largest accumulated void percentage that was measured is 1.5 percent. On the other hand, the Batch-2 sample in figure 4-4 showed zero voids after curing at the pressure sintering process. The reported outgassing path for pressure-less Ag sinter after curing process by R. Clemente was not observed (Clemente, Tolentino & Azman, 2014). It was assumed for this experiment that the solvent/thinner applied at Ag sintering paste in the DBC substrate was already evaporated throughout the drying process. Both samples demonstrated good control of the void percentage after the curing process.

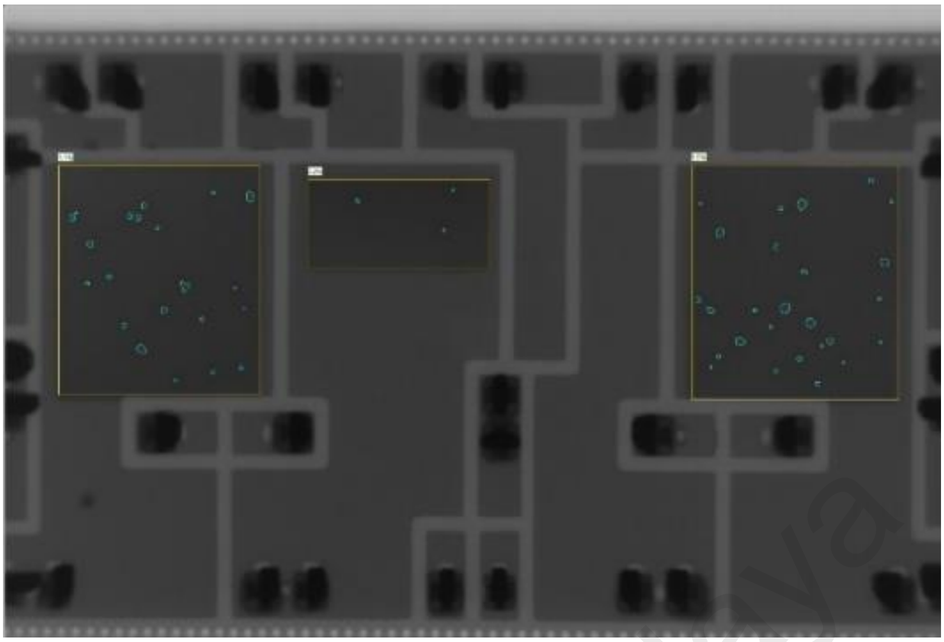

Figure 4-3: Batch 1 x-ray tomography image. Maximum void measurement is 1.5 percent total voids.

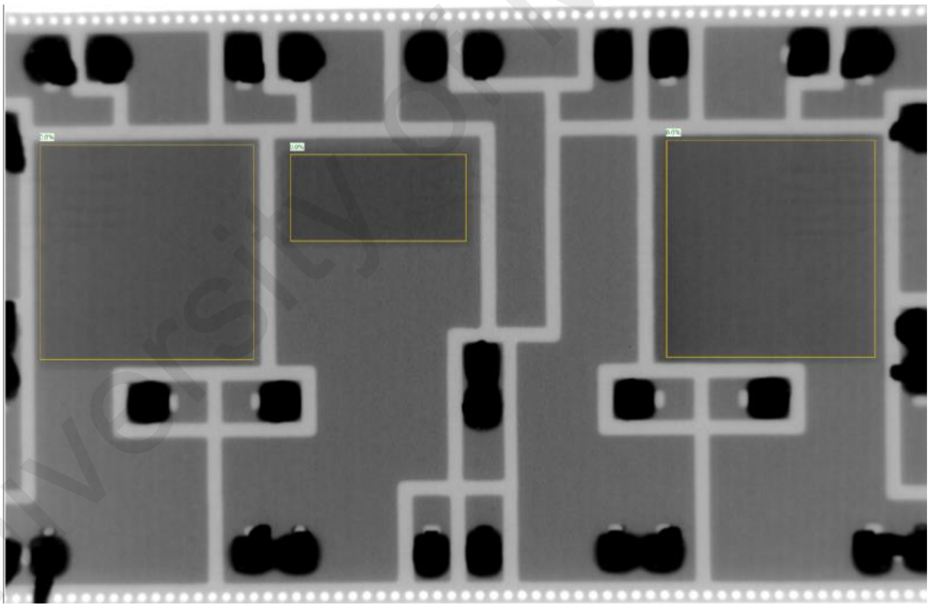

Figure 4-4: Batch 2 x-ray tomography image. Observed zero voids after curing at pressure sintering process.

4.5 Scanning electron microscopy (SEM) and EDX analysis

A mechanical cross-section has been carried out to investigate the die attach microstructure. A scanning electron microscopy (SEM) was used to examine the die-to-DBC substrate joint. Followed by EDX analysis to confirm the elemental composition of the captured morphology. Both batch 1s&2 samples underwent for this analysis.

4.5.1 Batch-1 microstructure analysis of n96.5Ag3.5 solder alloy paste

As seen in figure two layers of Intermetallic compound (IMC) were observed in the Batch-1 sample. The first IMC formation is the Ag-Sn intermetallic compound phase layer. This is found between the Silicon die Ag back metal and SnAg solder alloy. The second IMC formation is the Sn-Cu intermetallic compound phase layer. This is found between SnAg solder alloy and Cu DBC. The thin uniform IMC layers indicate a good bonding condition of the solder joint. Although, solders are known to have inevitable void formation. The SEM analysis did observe voids development though the chances of detecting through SEM is very low since x-ray analysis confirmed the lower percentage of voids at batch 1 sample.

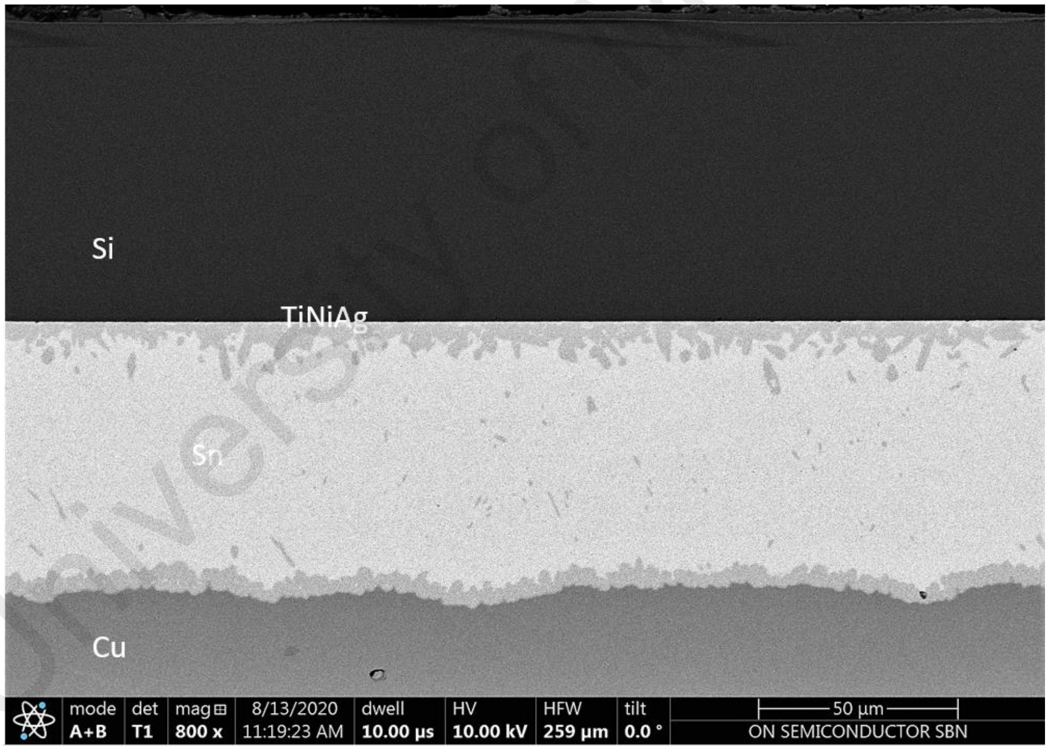

Figure 4-5: Batch-1 cross section microstructure. EDX analysis identifying the elemental composition. Silicon (Si) in Die, Tin (Sn) in solder alloy and Copper (Cu) at DBC substrate. TiNiAg is the thin back metal layer of the die. Image sharing courtesy of ON Semiconductor.

4.5.2 Batch-2 microstructure analysis of pressure-assist silver sintering paste

After the sample underwent to pressure sintering process, it was observed in figure 4-6 image that the die-to-Ag sintering and Ag sintering-to-DBC joint were properly executed. The high temperature applied in Ag sintering paste makes most of the organic materials to evaporates and burn-out. Agglomeration and aggregation take placed in Ag-Ni sinter particles as observed in scanning electron microscopy (SEM) morphology. The diffusion of die attach material in die TiNiAg back metal and Cu DBC was also detected in EDX analysis. Figure 4-7 Shows that the Ag sintering material diffusion in die TiNiAg back metal. 8000x magnification displays that the pore size is reduce since pressure is applied during sintering process. The mechanical diffusion process creates a solid-state diffusion of Ag-Ni particles in the system.

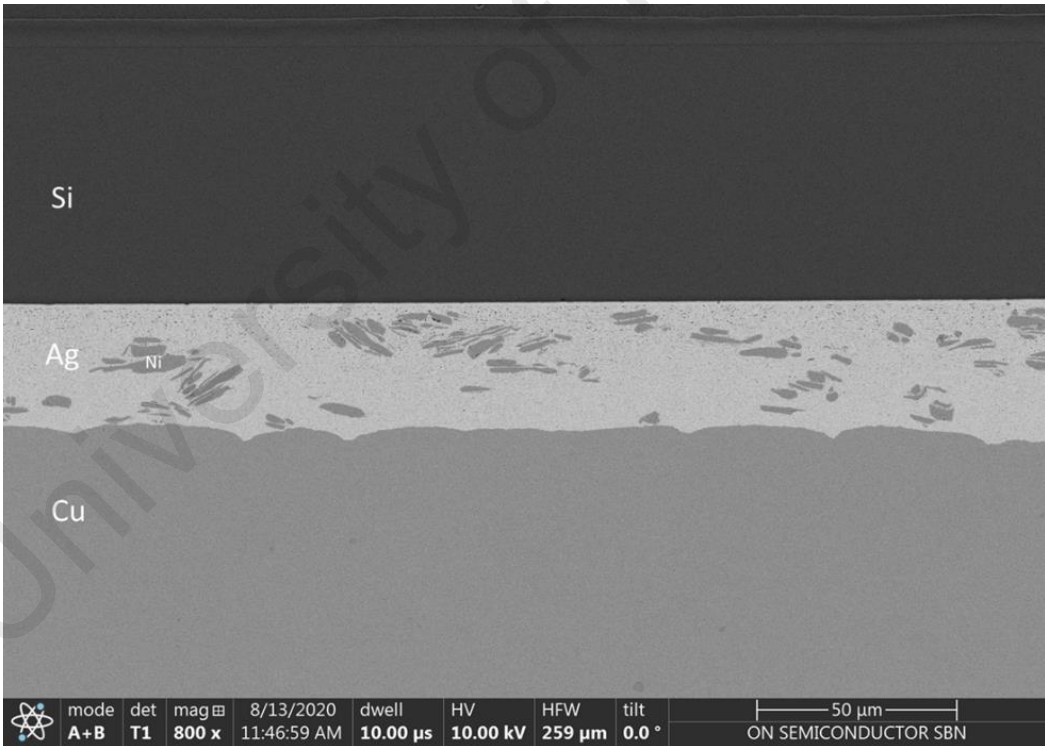

Figure 4-6: Batch-2 SEM cross section microstructure. EDX analysis identifying the elemental composition. Silicon (Si) in Die, Ag-Ni of sintering particle and copper (Cu) at DBC substrate. Image sharing courtesy of ON Semiconductor.

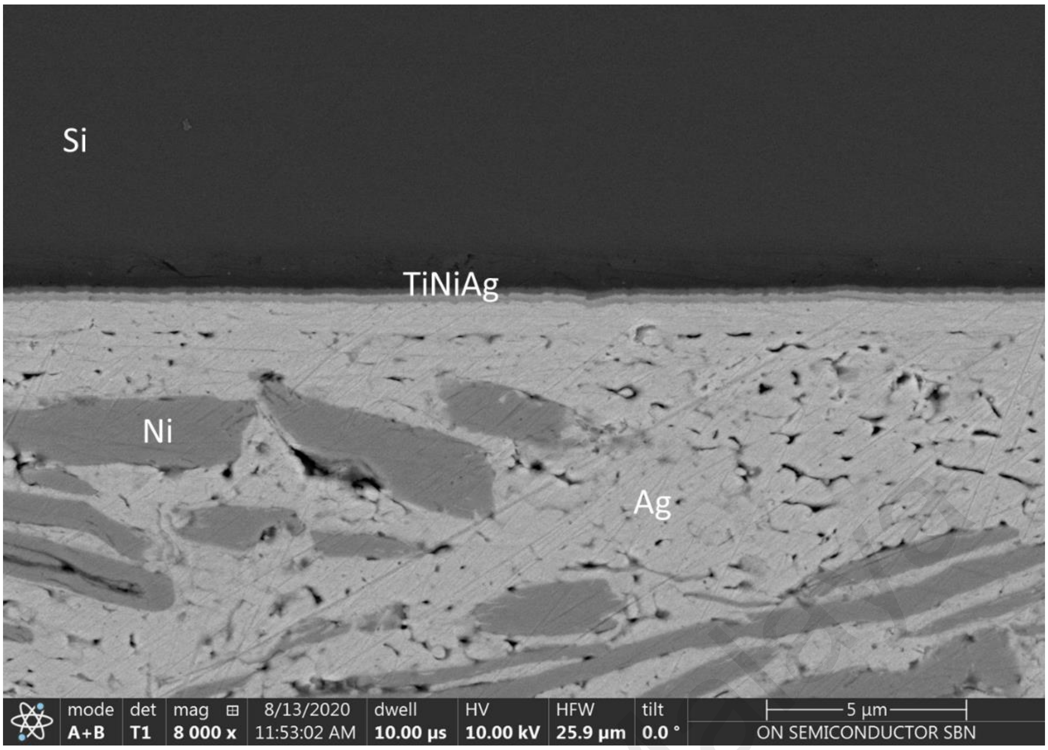

Figure 4-7: Batch-2 SEM cross section microstructure. Showing the Ag sintering material diffusion in die TiNiAg back metal. 8000x magnification showing the pore size of material after sintering. Image sharing courtesy of ON Semiconductor.

4.6 Electrical test results

IGBT or also known as insulated gate bipolar transistor is a high power device that is used as switch. This device is suited for high power application such as solar inverters, motor control, heat induction and UPS. To know the functionality of the device VCES test and VGE test were conducted using automated tester equipment.

4.6.1 VCES test

The VCES test is the collector-emitter voltage electrical testing. The device maximum voltage rating needs to be specified between the collector and emitter terminal. This will present the device to undergo to avalanche breakdown state and dissipating unnecessary energy in the device. The voltage rating requirement specified during the test is ranging from 500mV to 2.5V. Results in figure 4-8 showed that Ag sintering batch-2 samples have an average reading of 1.67 volts compared to SnAg solder alloy Batch-1 sample with an average reading of 1.705 volts. The avalanche breakdown voltage varies with temperature. Low VCES reading interprets better electrical performance (ONSemiconductor, 2012).

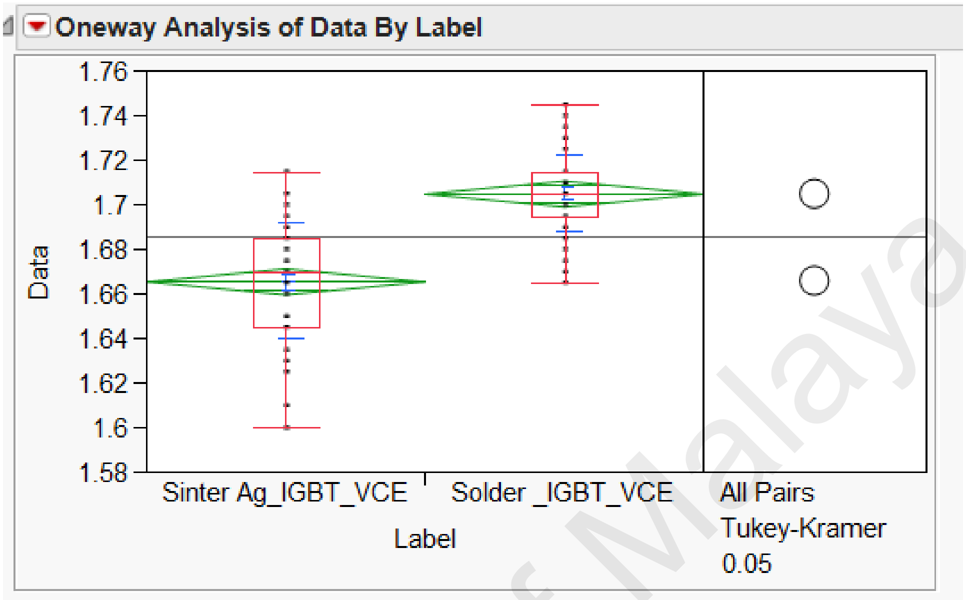

Figure 4-8: Batch-1 and Batch-2 VCES electrical test reading. Sinter Ag Batch-2 sample showed lower measurement with an average voltage reading of 1.67v and SnAg solder Batch-1 sample average voltage reading of 1.705v. All pairs Tukey-Kramer showed significant difference of the two sample readings.

4.6.2 VGE test

The VGE test is the gate–emitter voltage electrical test. This test designates the maximum voltage to be used from the gate to emitter under fault conditions. The VGE voltage is restricted by material properties and thinness of the gate oxide. The gate oxide was normally able to withstand higher voltages. This is typically greater than 80v before it will rapture. For this particular test, the amperage set is from 4.5mA min to 7mA max. Results showed in figure 4-9 that the Ag sintering batch-2 sample has an average reading of 5.715mA compared to the SnAg solder alloy Batch-1 sample with an average reading of 5.865mA. It is described that the reliability of the device and the transient overload condition in the application is restricted to lower gate rupture voltage. This shows that the Ag sintering Batch-1 sample is better in terms of the VGE test (ONSemiconductor, 2012).

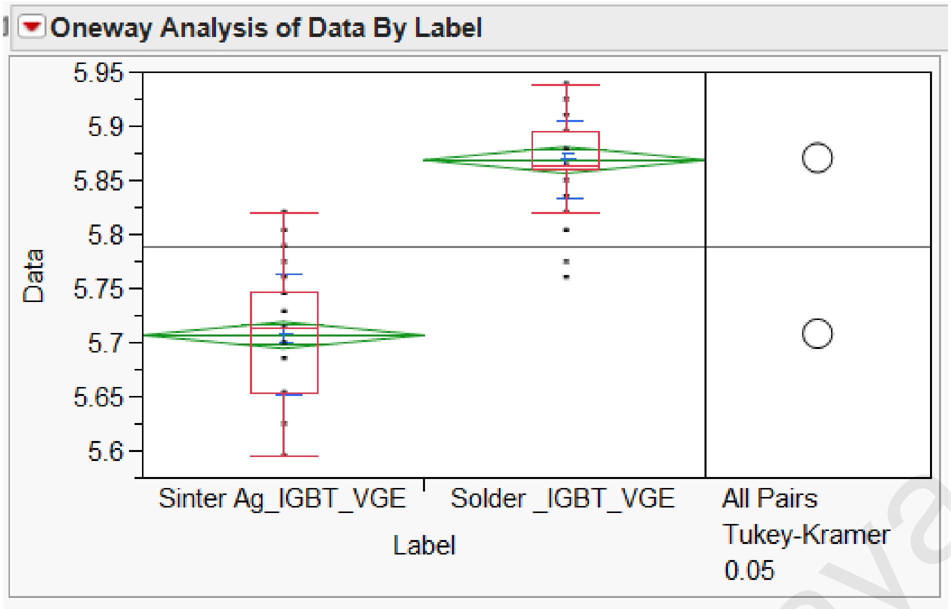

Figure 4-9: Batch-1 and Batch-2 VGE electrical test reading. Sinter Ag Batch-2 sample showed lower measurement with an average voltage reading of 5.715mA and SnAg solder Batch-1 sample average voltage reading of 5.865mA. All pairs Tukey-Kramer showed significant difference of the two sample readings.

4.7 Reliability test

A reliability test is done to measure how robust the device during application. This is normally performed to predict the life of the product. For this test, the temperature cycle, thermal shock, and power cycle test were conducted.

4.7.1 Temperature cycle test

The purpose of this test is to evaluate the ability of the device to withstand both exposures to extreme temperatures and transitions between temperature extremes. This testing will also expose excessive thermal mismatch between materials (JEDEC, 2009). The test condition for all the samples is Ta= -40°C to 150°C air to air with a Tj max of 125°C. The common failure mode for this test is parametric and catastrophic. The common failure mechanism is wire bond lift, die to crack or lifted, and package failure. Batch-1 and Batch-2 sample underwent a Thermal cycle test up to 700cycle run. After the TC test, all samples were summited for electrical testing. Results in the table 4-1 showed that all units for Batch-1 and Batch-2 samples passed the electrical test.

Table 4-1: Reliability test result

Test Condition	1st qual point				2nd qual point				3rd qual point			
	Batch1 Reject	Batch2 Reject	Read point	Status	Batch1 Reject	Batch2 Reject	Read point	Status	Batch1 Reject	Batch2 Reject	Read point	Status
Power cycle test (PCT):	0/5	0/5	20k cycle	Passed	5/5	0/5	40k cycle	Batch1 reject 5/5	0	0/5	60000 cycle	Stop at 6000 cycle
Thermal shock(THS)	0/5	0/5	1000 cycle	Passed	0/5	0/5	1500 cycle	Passed	0/5	0/5	2000 cycle	Passed
Temperature cycle (TC):	0/6	0/6	100 cycle	Passed	0/6	0/6	500 cycle	Passed	0/6	0/6	700 cycle	Passed

4.7.2 Thermal shock test

A thermal shock test is accomplished to know the parts' resistance to sudden experience to extreme temperature changes. This is also to determine the parts' resistance to the influence of alternating extreme environments (JEDEC, 2009). The test condition for all the samples is Tj 125°C. The common failure mode for this test is parametric and catastrophic. The common failure mechanism is wire bond lift, die to crack or lifted, and package failure. Batch-1 and Batch-2 sample underwent Thermal shock test up to 2000cycle run. After the THS test, all samples were summited for electrical testing. Results in the table 4-1 showed that all units for Batch-1 and Batch-2 samples passed the electrical test.

4.7.3 Power cycle test

The test institutes a constant method for carrying out a device package power cycling stress test. The device package will be biased to cover the power induced in the temperature cycle. This simulation of uneven temperature distribution subsequent from an on and off powering device application (JEDEC, 2009). The target maximum Tj is 150°C with a humidity measurement of 150%RH. The common failure mode for this test is parametric and catastrophic. The common failure mechanism is wire bond lift, die crack or lifted, and package failure. Batch-1 and Batch-2 sample experienced Power cycle test up to 60000 cycle run. After 40000 cycle run, 5/5 samples unit from Batch-1 failed electrical testing. All batch-1 sample units exhibit a gradual increase in Rth throughout cycles, leading to an increase in Tjmax. This led to failures of the device during cycles. The batch-2 samples continued the 60000 cycle run. However, the device still did not observe any failure. The power cycle test at this point was discontinued since all batch-1 samples already failed all its units.

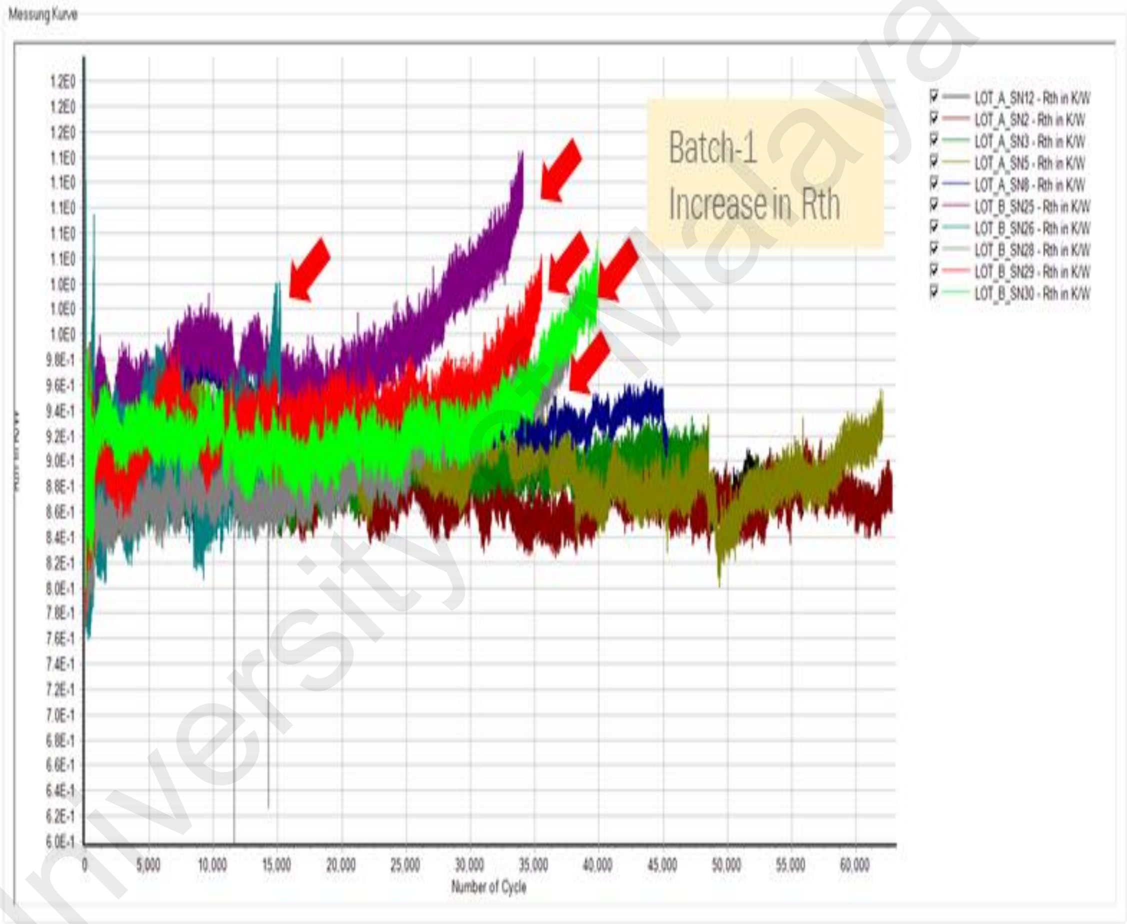

Figure 4-10: Batch-1 sample units exhibit a gradual increase in Rth throughout cycles, leading to increase in Tjmax or ΔT. This led to unit failures during cycles.

CHAPTER 5: CONCLUSION

5.1 Conclusion

Pressure-assist Ag sintering die attach offers a promising solution in replacement of SnAg solder alloy in power electronics. In the course of the research, it was determined that the pressure-assist Ag sintering paste need to undergo drying process before hot chip attach. This is to ensure that most solvent/thinner will evaporate to avoid channeling voids during the sintering process. It was also noted on the Keyence depth profiler that the paste volume reduction can go down up to ~40 percent after the drying process. The 200-600 gram of bonding strength measured in Dage 4000 multipurpose bond tester ratifies that this value is already enough to hold the dice in the DBC substrate before the pressure sintering process. Unlike SnAg solder alloys, the x-ray test confirms that pressure-assist Ag sintering material can achieve zero voids percentage after the pressure sintering process. The pressure-assist Ag sintering paste is better since it was reported earlier that the solder void has a great impact on the reliability and mechanical performance of the device. It was properly demonstrated that the 250°C sintering temperature applied in pressure-assist Ag sintering material, made most of its organic material to evaporate and burn-out. Agglomeration and aggregation take placed in Ag-Ni sinter particles as observed in scanning electron microscopy (SEM) morphology. The diffusion of die attach material in die TiNiAg back metal and Cu DBC was also detected in EDX analysis. The pore size is reduced since the pressure is applied during the sintering process. The mechanical diffusion process creates a solid-state diffusion of Ag-Ni particles in the system. The electrical test comparison of pressure-assist Ag sintering and SnAg solder alloy samples showed that the VGE test reading for the Ag sintering sample is about 5.715mA lower compared to SnAg solder alloy sample with an average reading of 5.865mA. This describes that the reliability of the device and the transient overload condition in the application is restricted to lower gate rupture voltage. This shows that the

Ag sintering sample is better in terms of the VGE test. Another electrical test reading is the VCES test. The VCES test reading for the Ag sintering sample is about 1.67v lower compared to the SnAg solder alloy sample with an average reading of 1.705v. The avalanche breakdown voltage varies with temperature. Low VCES reading interprets lower device temperature, better electrical performance. Reliability test Results showed that thermal shock (THS) and temperature cycle (TC) tests for both samples are comparable to each other. The THS test reaches the 2000 cycle run and the TC test reaches a test run of 700 cycles. The power cycle test (PCT) runs, on the other hand, give an opposite output response. SnAg solder sample only reaches the 20000 cycles run before it fails at 40000 cycles. However, for the Ag sintering sample, the sample reaches 60000 cycles run without failure. This is a clear indication that the pressure-assist Ag sintering paste material is better in terms of robustness testing.

In general, the pressure-assist Ag sintering die attach material can be equal or better when compared to Tin Silver solder alloy in terms of overall package performance.

5.2 Recommendations for future works

The paper is limited to know the failure mechanism of pressure-assist Ag sintering material at reliability test. It is highly recommended to further investigate on this topic. Another recommendation is to investigate the effect of too much compaction of Ag sintering material when applying high pressure. The comparison of pressure-less Ag sintering versus pressure-assist Ag sintering was not discuss on the paper. For this, it is highly recommend to do further study on this field of work.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Reliability Considerations of Sintered Silver Paste on Clip Semiconductor Packages

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Abstract

Sintered Ag has gained attention as a replacement for high lead applications due to its high thermal, electrical and reliability performance. Today, the temperature requirements for certain business units require higher levels of capability. Coupled with the pressures of converting to lead free, a feasible solution needs to be reached soon. This led to the formation of the DA5 (die attach 5) consortium in 2010. This was composed of semiconductor companies NXP, STMicroelectronics, Freescale, Infineon and Bosch. The main purpose was to look for alternative materials that can support application requirements exceeding the capabilities of solders. Although lab scale tests shows that sinter Ag can be an alternative, limited data is available on sintered Ag performance integrated with high power device applications. Samples were assembled using sinter Ag die attach material on using a Zener diode housed on a clip package. The experimental method was divided in two phases: material characterization at varying amounts of N_2 and reliability phase which subjects these units to Temperature Cycle, Highly Accelerated Stress Test (HAST), and Autoclave. All samples underwent normal assembly except for the sintering process which is necessary for silver die attach to achieve solid state diffusion. Microstructure analysis of sinter Ag die attach results into denser formation of sinter Ag paste when subjected to low N_2 concentration. Die shear results were highest at low N_2 concentration due to increased grain boundary formation over the sinter Ag matrix. However, low N_2 concentration leads to copper oxidation which is detrimental on surface adhesion between of the lead frame and mold compound. This was observed during the characterization step wherein oxides were formed on the lead frame surface. Subjecting the copper lead frame with gross oxide formation led to failures at autoclave test. Scanning acoustic tomography reveals gross separation of lead frame to mold compound interface. Also, we have determined that silver migration is a key failure mechanism for sinter Ag die attach when subjected at high N_2 concentration. The reliability results for mid and low N_2 sintering atmosphere show resistive effect on Ag migration. The overall outlook for Sinter Ag based on the current experimentation suggests that sinter Ag could be a viable solution provided that these key failure mechanisms are addressed and fully understood.

Introduction

The need for efficient semiconductor devices coupled with the necessity of moving towards "lead free" has gained attention over the past years. SnPb has been used as a die attach material for power packages due to its inherent reliability, high thermal conductivity and good electrical performance. Though its usefulness, versatility and health risks are known, the repercussion was not fully realized until 1st of July 2006 when the RoHS (Restriction of Hazardous Substance) directive came into effect. This directive prohibits the use of any lead containing alloy in microelectronic devices [1]. In 2010, the DA5 (Die Attach 5) consortium was formed to look into materials that can replace SnPb [2]. Sintered Ag has gained interest due to its compatibility over existing semiconductor process. Also, the low thermal requirement to bond this material is an attractive proposition that brings less thermal stress on other microelectronic components [3]. Based from lab scale results sintered Ag has been proven to perform equal to better in terms of electrical and thermal performance over SnPb [4]. Figure 1 shows the comparison for various die attach materials in terms of thermal conductivity [5].

Figure 1: Thermal conductivities of various solder material interconnect

Sintering on Ag Die attach

Sintering is a heat treatment at elevated temperatures of particles in which the diffusion mechanism is substantial. Sinter Ag methods during the early days are concerned with micron sized Ag particles. It was found out that die attach materials with smaller particles, distribution, temperature are the main factors affects agglomeration on sinter pastes [6]. With the introduction of nano-sized Ag particles, it is possible to achieve sintering with minimal pressure at the same temperature level [7]. This is due to the increased surface energies that provide ease in diffusion between

1

Improving reliability for electronic power modules

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Abstract

The current trend in power electronics, particularly for power module development is focused on improved reliabiliy, quality and energy efficiency. In applications such as in railways or heavy machinery, high power in the ranges of several hundred kilowatts to lower megawatts is required. Innovation in such areas are needed to improve the systems reliability as failures could be extremely costly to replace. In some cases they may involve loss of life. Most systems are expected to function constantly on daily cycles and may be subjected to harsh environments as well. Power module systems today seek to integrate more functions by implementing good electrical design principles. Such ideas can only be realized if the materials and processes used are reliable and robust. The main objective of this literature work is to understand the reliability problems and failures, as well as improvements which are being made on engineering material selection for power modules.

1. Introduction

Today's power electronic module technologies seek to efficiently use, distribute and generate electrical energy. Therefore, power module manufacturers consistently seek to design much more efficient systems. Such systems are typically used in electric cars/trains, aircrafts, wind farms/clean energy systems and consumer electronics [1]. In a nutshell, the general consensus amongst power device experts is that the power module's performance can be improved by increasing the switching frequency of the device, while having parallel reductions in the volume, weight and cost of the module itself [2]. Wideband gap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) with higher operation temperature capabilities as well as faster switching speeds have hastened the need for new high temperature packaging materials [1-2].

A typical power module consists of IGBT's, thyristors, rectifiers and diodes. These devices are used for applications with voltages between 55-6500V and currents of 1-2400A. Such high voltages and currents are bound to generate lots of heat within and around the module itself. For example, the maximum junction temperature for rectifiers and thyristors today is about 130°C, whereas these temperatures go as high as 150-175°C for IGBT's [1-2]. New device technologies are aiming for much higher junction temperatures on IGBT's which reach 200°C. Failures on power module applications are often rather difficult and expensive to replace, and in most cases may even involve loss of human life. This evidently becomes a huge liability for power module manufacturers [3].

In the past, most research efforts have been on improving the stability and reliability of the power devices. This has matured considerably over the years, and presently the main concern surrounds the materials used on these power devices. Researchers have looked at a wide range of materials spanning the casing, use of silicone gel within the module, enhancing the reliability of the interconnects/wire bonds, improving the stability of the die attach materials, providing more robust substrates as well as use of advanced thermal interface materials which are able to dissipate heat quickly from the die to the surroundings. While the module's design can help enhance the efficiency of heat dissipation, this literature work seeks to provide an overview on the most recent use of advanced materials on power modules for thermal and reliability management. A significant amount of effort needs to be put into understanding the fundamentals of high temperature materials behaviour, as well as drive integration of these interesting new materials into existing power module technologies. These new high temperature materials may prove to be more expensive for the short term, but if reliable, market price trends will change for the better when the usage increases.

2. Power module packaging and reliability

Power module packaging is crucial to reliability as it houses the circuitry and functionality of the system, as shown in **Fig.1**. Materials used to connect the high power IGBT dies, thyristors and diodes need to be robust and reliable. In essence, 3 main factors influence reliability; the system design process itself, the selection of engineering materials and the process used to create the power system, i.e. the manufacturing process (**Fig. 2**).

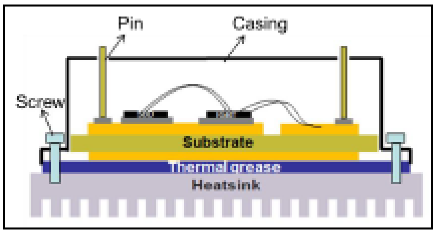

Fig. 1: Typical power module structure.

In the design process, the designer needs to consider the engineering material selection. The operating conditions need to be tied into this preliminary step, i.e. aspects such as mechanical and thermal stresses, vibrations, humidity and heat generated when these power devices are turned on within the module's packaging, so as to avoid localized heating (**Fig. 3**). When such considerations are made, it may be wise to say that in some cases trade-off's between material reliability, design and ease of mass manufacturing applicability may occur, with respect to cost. Therefore the designer needs to be able to combine the influence of

Sintering of Ag paste for power devices die attach on Cu surfaces

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Abstract

The die-attach layer is one of the most critical elements for high-temperature power electronics applications. The increase in operating temperature requires new materials with higher melting points and suitable thermo-mechanical properties. Among the possible solutions, sintering of Ag pastes (nanoparticles, nanoflakes and particles near the nanosize range) is an interesting method, because it requires moderate (<300°C) processing temperatures. These lower processing temperatures are suitable for implementation in mass manufacturing and the equipment for doing so are readily available. The aim of this write-up is to detail the qualification efforts being done on the Ag sinter solutions, in particular on copper (Cu) surfaces. The literature work will cover reliability and manufacturing concerns which are of primary interest to the general engineering community. These concerns must be addressed from several view points; design, processability and equipment. The outlook for implementation of this technology is bright and is in-line with the lead free initiative being addressed by the RoHS and WEEE directives for power devices.

Introduction

There has been a tremendous increase in power device performance over the last decade or so. More semiconductor manufacturers continuously introduce wide-band gap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) which have higher switching speeds and lower losses [1,2]. The junction temperatures of current silicon based power IGBT's are already reaching temperatures of up to 175-200°C [3]. This inevitably requires more reliable packaging materials to cope with much higher heat dissipation from these devices, in particular for integrated power modules having multi-functions. One particular area of interest for power device packaging has been on die attach materials. The die attach layer forms an integral part of the package structure. Besides acting as an interconnect between the die and the substrate, it has to manage thermal and electrical factors too.

Therefore, the basic requirements for such die attach materials include high solidus melting points, good thermal and electrical conductivity, excellent thermo-mechanical reliability as well as compliant CTE mismatch between the die and substrate [1-2, 4]. Over the years, several materials have been introduced to replace high Pb solders which are hazardous in nature, for example gold-tin (Au-Sn), gold-germanium (Au-Ge), gold-silicon (Au-Si), silver glass and silver-indium (Ag-In). Most of these solutions offer high temperature materials which fall into the mid to low operation points [1]. These new material introductions have been developed in parallel with such techniques as transient liquid-phase (TLP) and low-temperature joining (LTJT). LTJT in particular is a process which is used to describe the low processing temperature between 250-300°C of Ag paste via sintering methods [5]. There have been tremendous amounts of research works on Ag particle sintering on various substrate and die back surfaces [6-8]. The initial technique involved used Ag nanoparticles, and has now evolved to include Ag micron-nano hybrid systems, Ag flakes and Ag laminate films as well with and without the use of pressure [6,8]. The challenge lies in developing a suitable material formulation which is compatible on copper (Cu) surfaces [5]. Such an application is suitable for discrete power devices, for example. Ag die attach paste on bare Cu substrates is a low cost solution which enables easy integration into existing power device manufacturing processes. However, there are many challenges, for example the susceptibility of the Cu substrate to oxidation [5]. This is an issue as the sintering of Ag pastes needs oxygen for organic matter burn-off. Such challenges require a good understanding of the die attach material's properties, the fundamentals associated with sintering, as well as the impact on downstream or post die-attach processes. Factors such as these collectively impact the package's reliability. It is the objective of this literature work to analyze and offer a succinct idea about Ag paste sintering on Cu substrates for power devices.

The fundamentals: Sintering and Ag paste for die attach

The term Ag-sintering is quite commonly used. This term is also synonymous with Ag nanopaste-sintering as it entails the fusion of nano-sized particles at lower processing temperatures. However, today the broader use of the term sintering has come to include Ag-nanoflakes as well as particles which are "near the nanosized range" and still cater to low temperature processing. The use of pressure with temperature is important for creating higher density interconnect layers on power modules, for example. It is important to understand why sintering is important for the Ag-nanopaste, and how it helps create a dense and reliable connection. Nanoscale materials can be sintered at lower temperatures due to their larger surface energy which provides the driving force for the diffusion of atoms to neighboring particles during sintering. The scientific term for this fusion is "Solid-state diffusion", which can take place amongst the die attach materials' particles at low temperatures [9].

Based on the excellent thermal and electrical properties of bulk Ag, as well as it being comparatively cheaper than Au, it has been considered as a viable die attach material for high temperature usage. These Ag particles have been incorporated into paste matrixes and have been reported as a high temperature die attach material using sintering to create the die-die attach-substrate joint [6-9]. Ag pastes are usually prepared by mixing Ag particles/flakes in the nanometer range of diameter or thickness, with carefully selected organic components which burn out during the low-temperature sintering. The selected components are typically a binder,

978-1-4799-6994-4/14/$31.00 ©2014 IEEE

International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 11, Issue 12 (December 2015), PP.68-75

Determining the Compatibility of Sintered Silver Die Attach in Terms of Delamination Performance as Compared to Existing High Lead Solder Types in a Semiconductor Power Package

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Abstract:- A quick and simple method for determining thermo-mechanical compatibility of sintered Ag die attach is presented without assembling samples for moisture level sensitivity assessments. Material components of a power semiconductor package such as the die attach material (high lead or SnPb solder and sintered silver die attach) , copper lead frame, silicon die and epoxy mold compounds were isolated. Each components were studied individually by subjecting samples of SnPb, sintered Ag and epoxy mold compound to digital scanning calorimetry (DSC). The purpose is to be able to simulate thermal stimulus during manufacturing process. After the 1st heat treatment, a second heating step was employed on all components which additionally includes a copper lead frame and silicon die. The purpose of this step is to simulate customer reflow conditions during board mount. This step also derives the thermal graphs to determine the thermo-mechanical behavior of each constituent material from low to high temperature stimulus. The results suggests that sintered silver performs better compared to the SnPb die attach thermo-mechcanically. The reason lies in the processing of these materials, SnPb transitions from a solid to liquid state at temperatures above 187°C. Hence during board mount, SnPb die attach has a tendency *not* to maintain structural integrity and thus prone to delamination. Sinter Ag on the other hand does not necessitate melting during its process steps and therefore maintains its structural integrity. Furthermore since sintered silver does not require melting process, the thermo-mechanical profile compared to other component material deviates less as compared to the SnPb solder types.

Keywords:- Sintered Silver, Die Attach, Tin Lead Solders, Thermal Analysis, Digital Scanning Calorimetry

I. INTRODUCTION

A semiconductor package protects the die from external stimulus that can affect the performance of the device thermally, mehcanically or chemically. The silicon die is housed on an outer covering or an encapsulant material called mold compound. A leadframe typically copper is used to connect the final device to the printed wiring board. To connect the silicon die into the leadframe a die attach material is used. There are 3 main functions of a die attach material. First is to attach the die into the lead frame. Second is to dissipate heat across the lead frame and third is to provide reliabile connection and not fluctuate electrical stimulus when the device is in operation [1]. Depending on the complexity, sometimes wirebonds connect the silicon die into the lead frame. Discrete semiconductor devices particularly of high power applications utilizes a clip which eliminates the use of the wire thus increasing the reliability performance by effectively dissipating heat and providing a robust connection on the die [2]. The reliability in terms of connection is compromised if the interface delaminate. This could cause catasthropic effects which may lead to device failures during use[3]. This can also result into thermo mechanical defects such as die or package cracks [4]. Figure 1a and 1b illustrates some failure mechanisms that can be rooted to incompatible thermal expansions.

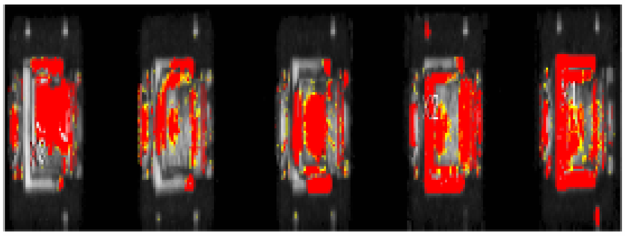

Figure 1a: Delamination occurences on a clip power package

International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 5, Issue 1 (January 2016), PP.01-08

The Significance of Heating Profiles and its effect on Sintered Ag Die Attach Agglomeration, Aggregation and Adhesion On a Copper Lead Frame Surfaces

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Abstract:- Sintered Silver (Ag) die attach is known to be one of the options towards lead free packaging was further characterized in terms of varying heat profiles. To be able to understand the mechanisms at different heating combinations, Thermo-gravimetric (TGA) experimentation coupled with design of experiment (DOE) runs were undertaken to look into main factors (Temperature 1) T_1 and (time/duration 1) t_1 as well as (Temperature 2) T_2 and (time/duration 2) t_2. The DOE result suggests that the critical factors for sintering include the 2nd temperature plateau (T_2) and its duration (t2). T_1 and t_1 values were not significant in the experiments due to the fact that sintered Ag organic components had volatized during temperature ramp up approaching T_1. Also, the DOE suggests higher sintering temperature (T_2) and duration (t_2) results into optimal shear results which correlates to better agglomeration of silver micro and Nano-particles when examined in scanning electron microscope (SEM). Although the values for T_1 were found to be insignificant it is critical that organic burnout is achieved. This was proven in the experiments by re-characterizing a low T_1 (100°C) which results to inferior die shear, agglomeration and aggregation results. Further optimization can be achieved by decreasing the durations of T_1 and augmenting this duration to T_2 wherein actual sintering of silver particles exists.

Keywords: Die Attach, Sintered Silver (Ag), Agglomeration, Aggregation, Design of Experiments

I. INTRODUCTION

Silver Sintering has emerged as an option for lead containing alloys used in attaching the silicon die inside the semiconductor package. DA5 (Die Attach 5) is the research arm for these types of material. The main objective of this group is to look for alternative materials which have equal or better performance in comparison to high lead solder. From current findings [1], they arrived into four types of materials which can replace SnPb in response towards lead free packaging. These are Trans-liquid Phase Sintering (TLPS), conductive die attach, alternative solders and sintered silver. There have been increased research efforts over the years based from Siow [2]. In this work, silver sintering as a die attach material was examined taking into account different heating profiles. Sintering is different from conventional SnPb wherein liquification is necessary to attach the silicon die and the lead frame. Moreover, silver sintering presents a different concept wherein the silver micro and Nano-flakes are suspended in a solution called organic component [3]. The term organic component is to collectively include a dispersant, binder and a solvent [4]. The organic material is responsible for making silver Nano and micro flakes workable in terms of viscosity and rheology when applied in high volume production. During sintering process, it is necessary for the organic material to evaporate (organic burnout). This results to enhanced agglomeration and aggregation of silver micro and Nano flakes. This is the reason why the heat treatment for sintered silver die attach includes 2 heating plateaus. The first plateau is responsible to ensure solvent evaporation and the 2nd plateau is responsible for sintering process. It is necessary that no organic material (full organic burnout) is present in the 2nd plateau otherwise it will hinder effective agglomeration and aggregation.

II. EXPERIMENTAL METHOD

To be able to determine the optimal profiles for sinter Ag die attach, DOE experimentation was carried out to define the critical temperature and required durations for organic burn out and sintering of silver die attach. The heat profiles for this type of paste involve two levels wherein the first temperature plateau is necessary to evaporate the organic material (e.g. composed of a binder, solvent and dispersant). The 2nd temperature plateau activates sintering process of silver micro and Nano flakes in the die attach material. The temperature profile is in the form of figure 1. However, characterization should be carried out to determine the