CURING CHARACTERIZATION OF PRESSURELESS SINTERED DIE ATTACH MATERIAL AS LEADFREE SOLUTION IN MICROELECTRONICS PACKAGING

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CURING CHARACTERIZATION OF PRESSURELESS SINTERED DIE ATTACH MATERIAL AS LEADFREE SOLUTION IN MICROELECTRONICS PACKAGING

ABSTRACT

Tin-silver solder alloy is widely accepted as Pb-free alternative in power electronics. However, this solder alloy cannot meet the requirements of next generation industrial and automotive power drive systems. With the ever-increasing demand for wide bandgap semiconductors with junction temperature exceeding 165°C, the need to develop an alternative solution to traditional Tin-silver solders is unavoidable. Traditional tin-silver solders are unable to withstand the relatively high device operating conditions because of their lower melting temperature ~220°C. Silver sintering is a preferred material for high temperature packaging applications because it is substantially cheaper than gold and palladium but is not susceptible to the oxidation problems like other metals. It has significantly better electrical and thermal conductivity and is more reliable than traditional solder during temperature cycling. Its melting point is more than sufficient to withstand the high operating condition of wide bandgap devices. In this paper, pressureless silver sintering (Ag sintering) is presented as an alternative die-attach solution to traditional SnAg solder alloy. Unlike traditional solder, pressureless Ag sintering needs precise characterization of heat and temperature to achieve efficient solid-state bonding. Challenges in defining the optimum processing parameter such as, temperature, time and curing atmosphere will be enumerated in details. The objective of this work is to enhance the package performance of DRMOS package, housing one IC die and two FET dies. Macdermid Ag sintering paste D800HT2V was used in this study. Techniques such as thermogravimetric analyzer (TGA), differential scanning calorimeter

(DSC), scanning electron microscope (SEM), and X-ray are also used to proliferate sintering efficiency. In parallel, electrical response between assembled devices curing under different environment will be conducted using Eagle Tester System 364.

Keywords: tin-silver, silver sintering, die attach, curing

KARAKTERISI SELURUH UNTUK PRESSURELESS SINTERED DIE ATTACH SEBAGAI PENYELESAIAN UNTUK LEADFREE MIKROELECTRONIK PACKAGING

ABSTRAK

Aloi solder tin-perak diterima secara meluas sebagai alternatif Pb-bebas dalam elektronik kuasa. Walau bagaimanapun, aloi solder ini tidak dapat memenuhi keperluan sistem pemacu kuasa perindustrian dan otomotif generasi yang akan datang. Dengan permintaan yang semakin meningkat untuk semikonduktor bandgap lebar dengan suhu simpang melebihi 165 °C, keperluan untuk membangunkan penyelesaian alternatif kepada tin perak tradisional tidak dapat dielakkan. Tin perak tradisional tidak dapat menahan keadaan operasi peranti yang agak tinggi kerana suhu lebur rendahnya yang berlaku pada 220 ° C. Untuk ini, persinteraan perak adalah bahan pilihan untuk aplikasi pembungkusan suhu tinggi kerana jauh lebih murah daripada emas dan paladium tetapi tidak mudah terdedah kepada masalah pengoksidaan seperti logam lain. Persinderaan perak mempunyai konduksi elektrik dan haba yang jauh lebih baik dan lebih mantap daripada tradisional aloi berbandingkan suhu. Titik leburnya adalah lebih daripada mencukupi untuk menahan keadaan operasi tinggi dalam alat bandgap lebar. Dalam artikel ini, persinteraan perak tanpa tekanan (Ag sintering) dibentangkan sebagai penyelesaian die attach alternatif kepada aloi solder tin-perak tradisional. Tidak seperti solder tradisional, persinteraan Ag tanpa tekanan memerlukan penentuan haba dan suhu yang lebih tepat untuk mencapai ikatan keadaan pepejal yang cekap. Cabaran dalam menentukan parameter yang optimum seperti suhu, masa dan suasana curing akan dinyatakan secara terperinci. Objektif kerja ini adalah untuk meningkatkan prestasi pakej DRMOS, yang mempuyai satu die IC dan dua cip FET. Paste persinteraan perak Macdermid Ag D800HT2V telah digunakan dalam kajian ini. Teknik-teknik seperti termogravimetrik (TGA), kalori pengimbasan berbeza (DSC), mikroskop elektron (SEM) dan X-ray juga digunakan untuk menganalisi kecekapan sintering. Pada masa yang same, tindak balas elektrik antara peranti yang dipasang di bawah persekitaran yang berbeza akan dijalankan menggunakan Sistem Tester Eagle 364.

Keywords: jurang band lebar, persinteraan perak, die attach, curing

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LIST OF SYMBOLS AND ABBREVIATIONS

WBG	:	Wide Band Gap
SiC	:	Silicon Carbide
GaN	:	Gallium Nitride
Si	:	Element: Silicon
Sn	:	Element: Tin
SEM	:	Scanning Electron Microscope
Pb	:	Element: Lead

CHAPTER 1: INTRODUCTION

1.1 Background: High Efficiency Power Electronics

The commercial application of power semiconductor devices is vast and far reaching since this technology is widely used in our daily life. Despite being the most mature technology in power electronics, silicon is known for its limitation of high resistance and conduction loss, low switching frequency, and unable to operate at high temperature. Consequently, this prompted the development of wide-band-gap materials (WBG). Silicon carbide (SiC) and gallium nitride (GaN) materials are gradually gaining much proliferation due to their superior bandgap energy and electrical breakdown strength. With adaptation of WBG with increased thermal performance, a more compact and efficient power electronic system is achievable.

Table 1 Characteristics of Wide Band Gap Semiconductors at 300 K

Semiconductor material	Bandgap (eV)	Electron mobility, (cm2/Vs)	Hole mobility, (cm2/Vs)	Density (g/cm3)	Thermal conductivity (W/cm-K)	CTE (ppm/K)	Electronic maximum operating temp. (C)	Process maturity	Key technical issues and limitations
Si	1.1	1400	450	2.33	1.3	2.6	150	Very high	Not suitable for aggressive environments
GaAs	1.43	8500	400	5.32	0.55	5.73	350	High	Contact stability at high temperatures, Not suitable for aggressive environments
3C-SiC	2.39	300-900	10-30	3.17	7	2.77	600	Low	Not available as bulk material
6H-SiC	3.02	330-400	75	3.21	7	5.12	700	Medium	Bulk material quality, Ohmic contacts to p-type material
4H-SiC	3.26	700	-	-	7	5.12	750	Medium	Bulk material quality, Ohmic contacts to p-type material
GaN	3.44	900	10	6.1	1.1	5.4-7.2	>700	Very low	Material quality and reproducibility, Ohmic contacts
Diamond	5.48	2200	1800	3.52	6-20	0.8	1100	Very low	N-type doping only polycrystalline material available

As shown in Table 1, diamond is identified as the ideal material to support high power devices because it has the largest bandgap and highest thermal conductivity. The astonishing high costs of fabrication diamond, nonetheless have rendered SiC and GaN to be much favorable material. SiC in particular has high thermal conductivity hence they could theoretically operate at high power density. Higher thermal conductivity combined with wide bandgap and high critical field give SiC semiconductors an advantage when high power is a key desirable device. GaN, on the other hand has higher electron mobility, which indicates that it is the best device for very high frequencies application.

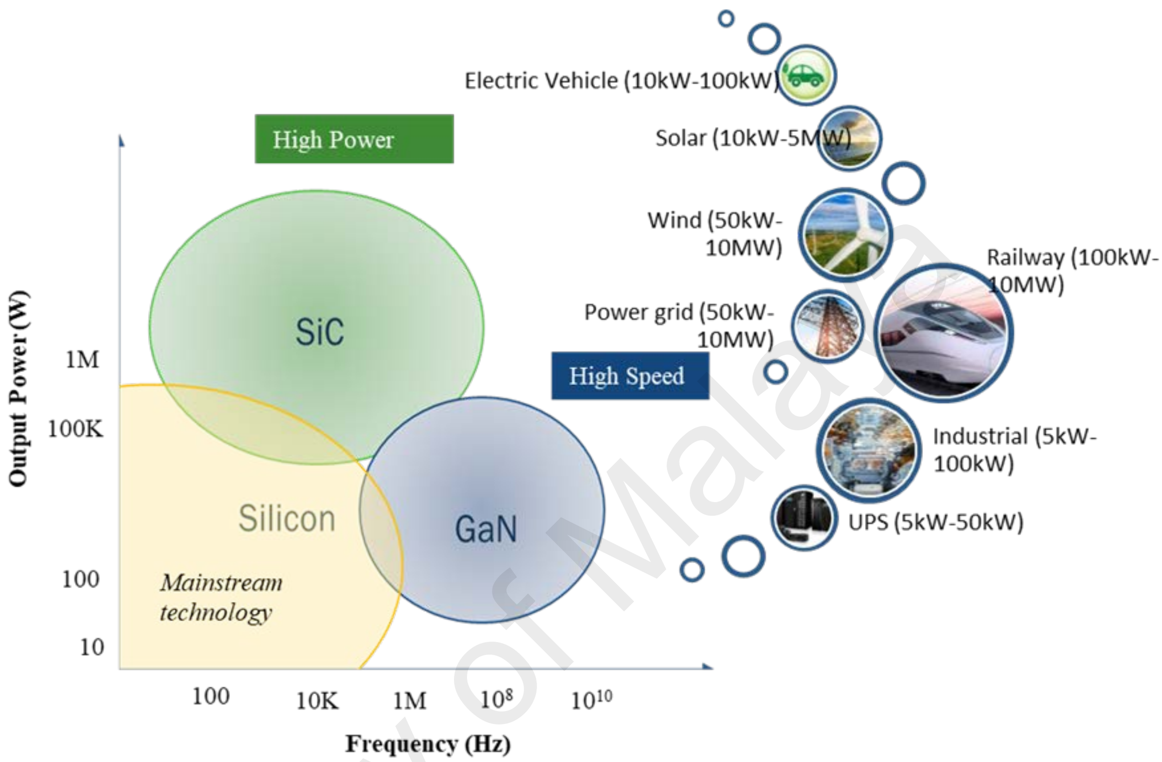


Figure 1 Sample Application of power semiconductor devices.

Figure 1 demonstrates the application of power semiconductor devices across wide range of power and frequency. Si power MOSFET devices are used as switching transistors in industrial supply and home appliances where the power density requirement is low. Si IGBTs and WBG power semiconductor devices are used in a much higher power density. For application with ultra-high power density requirement, SiC IGBTs are the preferred switching devices. Whereas, GaN is widely used in high-speed requirement such as UPS server.

The development of smaller size and higher power demands substantially increase in power density. Substantially, power semiconductor devices are expected to operate in an elevated thermal condition and harsh environment where the operating temperature could go above 200°C. The semiconductor and microelectronics industry have exerted much effort to come up with an effective cooling system to dissipate the heat generated in power electronics, optoelectronics, and telecommunication systems. In some application, the expensive and bulky cooling systems are required to protect electronics components from extreme environments (Li & Wong, 2006). As a result, packaging materials must innovate in order to meet the high thermal operating requirement, to ensure a robust protection, and to support the semiconductor components within the package. Coppola, Huff, Wang, Burgos, and Boroyevich (2007) categorize the critical packaging materials, which require great attention as the die attach material, package substrate or carrier, interconnection, package encapsulation, package casing, and heat sink or spreader. The ultimate goal is to maximize the functionality yet achieve miniaturization of the system, and to achieve robust and reliable product.

1.2 Problem Statement

1.2.1 Adverse Health Impact of Lead (Pb) in Solders

High Pb solder is widely used as semiconductor chip attachment given its low cost advantage, superior mechanical property, and better reliability. Usage of Pb-containing solder, however elevates a serious environmental and public health concern. European Union is introducing restriction of certain Hazardous Substance (ROHS) directive in 2002 requiring the electronic industry to look for substitute on those hazardous substances such as lead (Pb). This consortium involving the academia, the industry and the government vowed to eradicate if not minimize the use of lead (Pb) on electronic products. Hence, this has prompted the industry and the academia alike to look for a lead-free solution in microelectronics packaging. Accumulation of lead over time can cause adverse health effects to human body. Elevated exposure of lead can eventually lead to nervous or reproductive system disorders, anemia, and hypertension, cognitive and behavioral changes.

1.2.2 Demand for High Temperature Die Attach Material

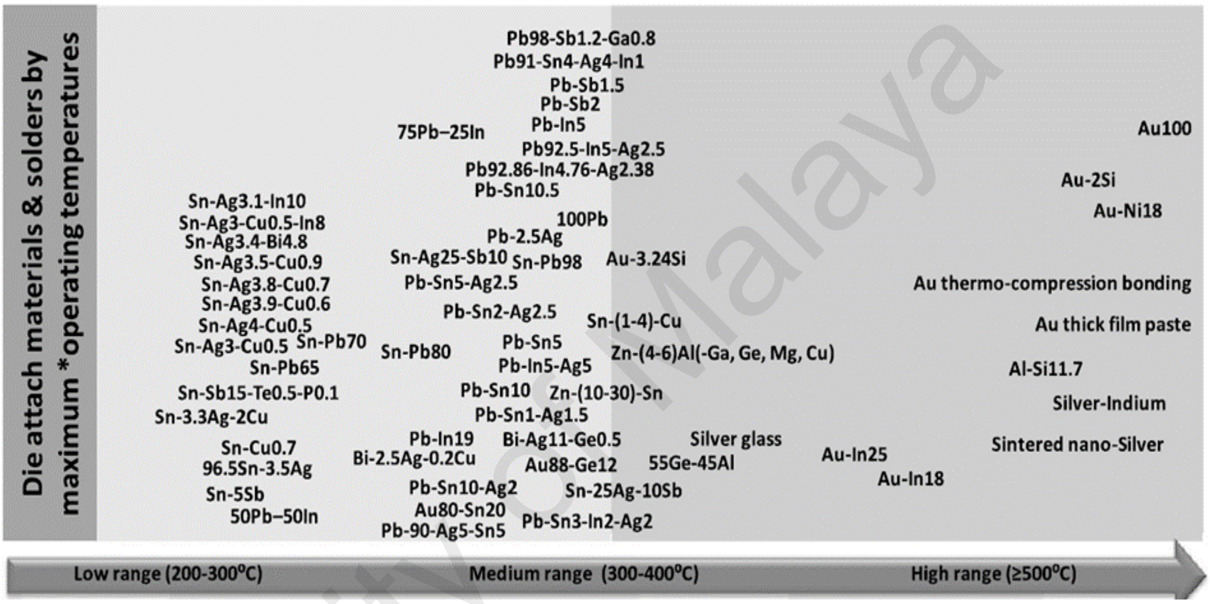


Figure 2 Liquidus temperature of high temperature die attach material. Operating temperature spectrum: (a) 200-300°C, low range (b) 300-400°C, medium range (c) >400°C, high range. (Manikam & Cheong, 2011)

Figure 2 showed all known die attached material for high thermal application being studied thus far (Manikam & Cheong, 2011). Among these materials, tin silver (Sn-Ag) solder is the most popular lead free die attach material in power electronics. Sn Ag is accepted by ROHS as it does not contain hazardous substances. SnAg solders also exhibit superior ductility, cost effective and considerable fatigue resistance (Yamada et al., 2016). Solders application offers a mature manufacturing process, which offer an acceptable cost, ease of use, and high performance (Manikam & Cheong, 2011). The eutectic composition for the Sn-Ag binary system is Sn-3.5Ag in which the eutectic temperature occurs at 221°C.

With the ever-increasing demand for wide bandgap semiconductors with junction temperature exceeding 165°C, SnAg solders are now stretching on their limitation. In addition, as industry consortium (DA5) requires more than 260°C working temperature on solders for manufacturing and application purpose. This solder alloy cannot meet the requirements of next generation industrial and automotive power drive systems because of their low melting point of 221℃. The need to develop an alternative solution to traditional solders is unavoidable. It is imperative that new die attach material should be able to survive and to function in high temperature and extreme condition. The alternative solder also must have a compliant CTE with both the die and substrate, as well as high electrical and thermal conductivity characteristics. SiC in particular needs a high temperature die-attach material with solidus temperature above 260°C and a liquidus temperature above 400°C.

Sintered Ag nano-paste is a viable alternative to high lead solder paste to achieve an environmental friendly packaging solution. Silver is a preferred material for high temperature packaging applications because it is substantially cheaper than gold and palladium but is not susceptible to the oxidation problems like other metals. It has significantly better electrical and thermal conductivity and is more reliable than traditional solder during temperature cycling. Its melting point is more than sufficient to withstand the high operating condition of wide bandgap devices. While the concept of sintering process is more than a century old practice, there is but a quite limited effort that has been done to understand the science involve in the application of sintering process in semiconductor and microelectronics industry (German, 2014). It is accentuated that, since the sintering application has outpaced the science of sintering, understanding the mechanical structure, thermal and electrical attributes of sintered Ag system presents an option for the semiconductor and microelectronics industry to explore other alternatives that they could tailor fit to meet their requirements. Thus, this author seeks to answer the following questions: emphasize

i. Is sintered silver die attach material a feasible lead free die attach alternative that could comply with ROHS legislative?
ii. Is sintered silver an applicable packaging material for wide-band-gap power devices that could withstand high operating temperature?
iii. Is the mechanical and electrical characteristics of sintered silver die attach material able to meet the industry requirement?

1.3 Objective of the Study

This research work was carried out with the primary idea to access the feasibility of an alternative die attach material-Ag sintering. This research work begins with the idea to characterize the curing condition of pressure-less silver sintering paste, thereby easing the implementation of a new technology into a mass manufacturing operations. The objectives are enumerated as below:

i. To enhance the package performance of traditional soldered DrMOS package by using lead free alternative - pressure less-sintered silver technology. Choice of curing parameters such as temperature, time and curing environment will be elaborated in later section.
ii. To characterize the mechanical and electrical properties of the pressure-less sintered Ag joint on selective Ag-plated copper lead frame.

1.4 Scope of the Study

The study is separate into two stages. First stage addresses objective (i), which is to enhance the package performance of DRMOS package that is bonded using sintered silver technology. Thermal analyzer tools are used to characterize each thermal events by carefully analyzing the mass degradation and enthalpy heat change during controlled course of heating. After defining the optimum sintering temperature and time of the Ag sintering paste, choice of curing environment is further accessed to achieve well sintered joint. Reflow oven environment is meticuously accessed by curing the assembled package with reflow oven with full nitrogen, 50% nitrogen and vacuum condition.

The second stage covers another objective (ii). After die attach curing, the integrity of sintered joint is evaluated using Mitotuyo die shear tester. The test offer an indication of the mechanical property of the sintered silver to either die back metallization or copper lead frame. Other characterization tools such as thermogravimetric analyzer (TGA), differential scanning calorimeter (DSC), scanning electron microscope (SEM), and X-ray are used to proliferate the quality of sintering efficiency. After device singulation, each assembled device will subjected for electrical test using Eagle Tester System 364.

CHAPTER 2: LITERATURE REVIEW

2.1 Existing Die Attach Technologies

Among the packaging materials, one of the most studied packaging materials is the die attach. Die attach material function is to adhere semiconductor chip onto the substrate, which is normally copper-based lead frame. The utilization of die attachment material for high thermal application is driven by immediate demand. Therefore, innovation on this material type is necessary to support the practical application of power semiconductor devices. Die Attach-5 is the key industrial consortium for high melting die attach application. The main objective of this group is to look for alternative materials, which have equal or better performance in comparison to high lead solder. Furthermore, it is desirable that die attach material would be non-toxic, cost effective and low processing temperature range. Currently, four die attach materials for lead free solution are proposed. Those die attachment material can be categorized depending upon the application such as adhesives, transient liquid phase system and solder based systems and silver sintering.

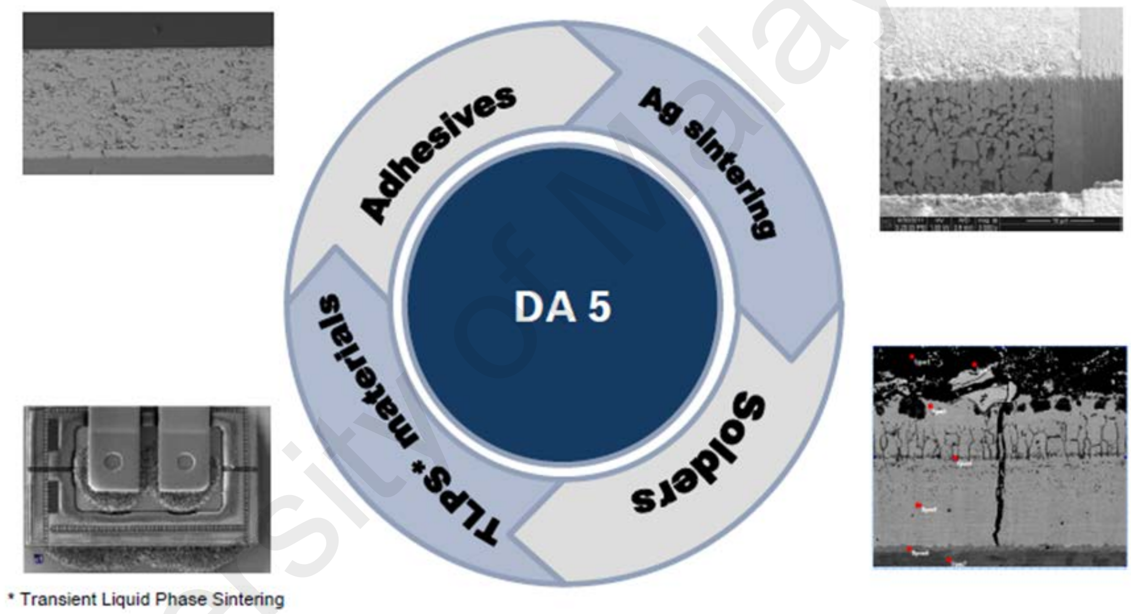


Figure 3 Four Materials in Discussion for Lead free Solution – solder alloy, Transient Liquid Phase Sintering (TLPS) Conductive Adhesive and Ag Sintering.

2.1.1 Solder Alloys

Solders are eutectic or off-eutectic alloys that contain two or more kinds of metals. The melting point of the metal alloy usually is relatively lower than the melting points of each individual metal that form the combination. A die-attach solder can be either a solder paste suitable for the stencil printing, or a solder preform sheet. For reflow processing of die-attachment, solder material is placed in between the die and substrate. It goes through a melting process. The molten solder can dissolve a portion of metal from both the die and substrate bonding surfaces. When the assembly cools down, a solid joint is formed.

Suganuma (2018) summarizes different types of solder alloys as shown in Table 2. Referring to Table 2, solders with high lead content have a maximum liquidus temperature of 322°C while the minimum liquidus temperature is 248°C. This type of material is ideal for high thermal application with operating temperature of 200-300°C. Among these materials, lead-tin (Pb-Sn) solders are the most popular and are considered as a mature die attach material technology for high thermal die attach application In addition, lead based die attach materials are known to have high ductility with good electrical and thermal conductivity (Manikam & Cheong, 2011; Suganuma, 2018). Moreover, high lead solders offer an acceptable cost, ease of use, and performance (Adamson, 2000; Yamada et. al., 2006). As pointed out by (Yamada et al., 2016), lead based alloys exhibits superior ductility, considerable fatigue resistance and cost effectiveness.

Due to government regulation on restriction of hazardous substance (ROHS) enforced in major counties led by the EU, the use of Pb base die attach material in electronic components is strongly discouraged. Hence, lead-free solder alloys present an opportunity for the semiconductor industry to comply on such regulation. The ideal Pb-free solder alloy should have good electrical and mechanical properties, good wetting abilities, no electrolytic corrosion, acceptable cost, and current and future availability for different applications.

Table 2 Types of High Thermal Die Attach Solder Systems (Suganuma, 2018)

Solder Alloys	Composition (wt%)	Solidus Temperature (^{o}C)	Liquidus Temperature (^{o}C)
Pb-Sn	Sn-65wt%Pb	183	248
	Sn-70wt%Pb	183	258
	Sn-80wt%Pb	183	279
	Sn-90wt%Pb	268	301
	Sn-95wt%Pb	300	314
	Sn-98wt%Pb	316	322
Pb-Ag	Pb-2.5wt%Ag	304	304
	Pb-1.5wt%Ag-1wt%Sn	309	309
Sn-Pb	Sn-5wt%Sb	235	240
	Sn-25wt%Ag-10wt%Sb (J-alloy)	228	395
Au-Sn	Au-20wt%Sn	280 (eutectic)	
	Au-3.15wt%Si	363 (eutectic)	
	Au-12wt%Ge	356 (eutectic)	
Bi-Ag	Bi-2.5wt%Ag	263 (eutectic)	
	Bi-11wt%Ag	263	360
Cu-Sn	Sn-(1–4)wt%Cu	227	~400
	Sn-Cu (composites)	~230	
Pure Zn	Zn-0.1wt%Cr	430	
Zn-Al	Zn-(4–6)wt%Al (-Ga, Ge, Mg)	300-340	
Zn-Sn	Zn-(10–30)wt%Sn	199	360

The materials chosen to replace Pb must meet various requirements, such as being available in large quantities, non-toxic, recyclable and comparative low cost. Elements that are available in quantities sufficient to satisfy the high volume of demand include silver and copper. Current industry is utilizing the near-eutectic Sn-Ag-Cu alloys. Some commercially viable examples are 99.3Sn/0.7Cu, 96.5Sn/3.5Ag, and 96.5Sn/3.0Ag/0.5Cu (SAC305). Author's workplace internal effort to qualify one such SnAg solder for SiC power integrated module hit a snag when the Ni on the wafer back metal was completely diminished due to the rapid intermetallic formation. The Ni depletion was found to be more than 95% during the first reflow process and caused early power cycle failure eventually. Many companies had adopted thicker Ni back metal deposition as a solution to compensate the rapid Ni depletion. However, this is definitely a costly fix and it would induce stress onto the wafer and results in warpage if a proper back metal process control were not in place.

Gold alloy solders, have a comparable thermal and electrical conductivity compared with Pb base solders, is also a prominent replacement for lead-free high power semiconductor packaging (Suganuma, 2018). Gold alloy solders are known to have a high melting temperature, a good fit for semiconductor chip with Au backside metallization, a good corrosion resistance, and it exhibits flux-less soldering process (Hartnett & Buerki, 2009; Suganuma, 2018). An obvious drawback of this Au alloy solder is its cost. In addition, in the case of Au-Sn, it is known to be brittle and stiff which is not ideal for large die application (Ivey, 1998). Another alloy worth considering is the Sn-Sb (antimony) based alloys. As shown in Table 2, the maximum liquidus temperature for Sn-Sb alloy is significantly lower as compared to high lead solders. However, liquidus temperature of Sn-Ag-Sb alloy could go as high as 395°C. This ternary alloy, as pointed out by Sagunuma (2018), has a drawback since an increase in Sb and Ag constitute a thick inter-metallic compound formation making the alloy system brittle and stiff.

Alternatively, Bi-AgX is another viable alloy system that can be considered for high temperature package joining process. Bi-2.5wtpercentage Ag alloy exhibits low thermal conductivity and tends to melt at 263°C. The temperature is relatively low as compared to solidus temperature of high lead solder. Literature showed that increasing the Ag content to 12-wt percentage able to achieve a 360°C liquidus temperature. Moreover, Manikam and Cheong (2011) also reported that adding Ag content in Bi alloys significantly improved the electrical and thermal conductivity. In addition, higher Ag content improves ductility of Bi alloys (Suganuma, 2018) as well as better solder wetting behavior on Cu substrate (Tschudin et al., 2002).

On the other hand, as shown in Table 2, Zn based solders such as Zn-0.1wt% Cr, Zn-(4-6)wt% Al with dopants (i.e. Ga, Ge, Mg) and Zn-(10-30)wt% Sn exhibit a melting temperature of 430°C, 300-340°C, and 360°C respectively. Zn based solder system able to cater the mid and high range high temperature requirement yet it is relatively cheap as compared to Au alloy system and to other lead-free alternatives. It is reported that ZnSn alloy offers high melting temperature with good mechanical strength, excellent thermal conductivity and offers superior ductility than most of the lead-free alloys (S. J. Kim, K.S. Kim, S.S. Kim, & Suganuma, 2009). However, referring to Table 2, ZnSn alloy starts to melt at 199°C (solidus temperature) making it rather suitable for lower temperature application. Zn-Al alloy is another lead free material worth considering. Rettenmayr, Lambracht, Kempf, and Tschudin (2002) explored the viability of Zn-Al alloys as a replacement for high-lead solders. The study showed that the binary Zn-Al alloy system was able to achieve a eutectic temperature of 381°C while the ternary Zn-Al-X (-Ga, -Mg) and quaternary Zn-Al-Ga-Mg alloys start to melt at temperatures 341-366°C and 309°C respectively. All Zn alloy solders mentioned so far have high melting temperature that can directly compete with Pb based solders. However, Suganuma (2018) mentioned that Zn alloy solders form a brittle and hard structure. This is a major drawback since a ductile solder joint structure is desirable to absorb thermal stress relaxation.

In brief, most of these Pb-free solders are susceptible to fatigue failure under cyclic temperature loading because of its low yield strength and the accumulation of high inelastic strains during deformation. Thickening of intermetallics after reliability is also a major concern. Literature shown that solder joint failure related to the interface of intermetallic. Introduction and hard and brittle intermetallics leaded to large thermal stress. The effect is getting more severe since the increased operating temperature of power electronics is approaching the limit of solders.

2.1.2 Transient Liquid Phase Bonding (TLPS)

In this this section, this author will take a glance into the concept and briefly discussed the application of transient liquid phase (TLP) bonding. TLP bonding technology is relatively a new idea in semiconductor manufacturing as a method for die attachment. The joining concept of this technology lies between the diffusion bonding and brazing (Cook & Sorensen, 2011) and this concept was first introduced in 1950 (D.H. Jung, Sharma, Mayer, & J.P. Jung, 2018). Advantage of this die attachment method owes to the idea that the resulting joint interface exhibits higher melting temperature as compared to its joining temperature—formed joint has a re-melting temperature almost same with the bulk material's. The mechanism of atomic mass flow in liquid phase bonding can be characterized as diffusion in liquid as oppose to solid state diffusion being discussed in Section 2.3.2. In retrospect, the concept of TLP joining with mixed metallic particles as fillers is based on liquid phase sintering. Table 2.3 depicts the various types of liquid phase sintering.

Table 3 Different types of liquid phase sintering (German, 2014).

Liquid Phase Sintering Variant	Chraracteristics
Persistent	Mixed powders, solid soluble in liquid, liquid low solubility in solid;
	Example: WC-Co to form metal cutting tools
Transient	Mixed powders, liquid soluble in solid, liquid disappears after forming;
	Example: Cu-Sn to form porous bronze bearings
Reactive	Mixed powders, highly exothermic reaction, stoichiometric product;
	Example: MoSi2 for use as furnace heating elements
Supersolidus	Prealloyed powder, solid soluble in liquid, liquid low solubility in solid;
	Example: tool steels for wear applications.

TLP joining can be characterized as a thermal treatment on a mixture of different metallic particles with different melting temperature, with application of brazing temperature the metallic particle with the lowest temperature is then melted, and it undergoes isothermal solidification. Steps involving TLP joining process nominally starts with particle joining, liquid phase initiation and formation, solid-liquid inter-diffusion and isothermal precipitation, and then lastly drying up of liquid phase by way of isothermal solidification and homogenization of joints (German, 2014; Cook and Sorensen, 2011; Tatsumi et al., 2018; Jung et al., 2018). Survey done by Manikam & Cheong (2011), briefly introduced lower temperature TLP joining process. This die attachment technique performed by using a bonding temperature ranging from 60-160°C. It is later reflowed in a much higher temperature. Joining occurs when some of the base metal are dissolves into the solder alloys and hardens by way of isothermal solidification (Roman and Eagar, 1992). The intermetallic joint has a much higher melting point than the initial interlayer. Lately, several techniques are available to materialize TLP joining. These new techniques and approaches in TLP joining as applied in power electronics manufacturing is summarized by Jung et al. (2018) as shown in Table 2.4.

Transient Liquid Phase Bonding (TLPS) is a two-stage diffusion process that joins metallic materials at a sufficiently low bonding temperature. The key advantages of this technology include low bonding temperature as compared to existing soldering/brazing techniques; low residual stresses at the interfaces due to low bonding temperature and pressure application; improved creep & fatigue properties and self-homogenizing; no interface/intermetallic formation for large and complex shapes. However, the implementation of TLPS process remains a challenge for the local industries due to the lack of suitable knowledge and experience. TLPS process requires the understanding on the diffusing fillers as well as post-bond heat treatment for age hardening of different applications. Also, several disadvantages was recorded for Ni-Sn TLP die-attachment method: (1) it has relatively lower thermal and electrical conductivities when compare to Ag sintering die attach in section 2.1.4 (2) long annealing hours are required to achieve uniform distribution of joint metallic materials, which significantly lowers the productivity.

Table 4 Different TLP joining techniques (Jung et al., 2018)

No	Technique	Type	Notes	System
1	Conventional method	Layer	Deposition was used for TLP layer	Cu-Sn Ni-Sn
			Flux-less bonding (Au finish) Ti(adhesion layer), Ni(diffusion barrier)	Au-Sn Ag-Sn
2	Inserted foil TLP	Layer	Sn foil was used for TLP bonding Sn/Cu(thick interlayer)/Cu foil was used Electroplating was used for TLP layer	Ni-Sn Ag-Sn
3	Improved foil TLP	Layer	Foil structure: Cu-Sn-Cu-Sn Foil structure: Ag-Sn-Ag-Sn-Ag, Ag-In-Ag-In-Ag Low vacuum	Cu-Sn Ag-Sn
			Foil structure: Ag-Sn-Ag-Sn-Ag-Sn-Ag-Sn-Ag	Ag-Sn
4	Current assisted bonding	Layer	Flux-less Bonding with electric current (900 A) Sn foil was used for liquid phase Bonded within 250 ms	Cu-Sn
5	Ternary TLP	Layer	Sn foil was inserted between Ag and Cu plate $2 \cdot 10^{-3}$ Pa vacuum was used for bonding	Ag-Sn-Cu
		Powder	Sn-Bi solder paste + Cu powder Sn-Bi solder paste used for liquid phase	Sn-Bi-Cu
		Powder	Powder mixture: Ni, Cu, Sn paste Organic binder was used for paste	Ni-Cu-Sn
6	Ultrasonic assisted TLP	Layer	Sn foil was used for liquid phase. Joint was formed within 8s	Cu-Sn
		Layer	Sn-0.7Cu foil was used for liquid phase Diffusion barrier (Ni) formed on substrate Joint was formed within 10 s	Cu-Sn
		Powder	Powder mixture (Ni, Sn) was used Joint was formed within 10 s	Ni-Sn
		Powder	Ni flake, Sn powder was used	Ni-Sn
7	Sn Coated Cu ball	Powder	Sn was electroplated on Cu ball. Reduce bonding time (within 1 min)	Cu-Sn
			Sn was electroplated on Cu ball Pressure-less bonding	Cu-Sn
8	Thermal Gradient Bonding	Layer	Single side IMC growth Thermal gradient of 100 °C, from 300 to 200 °C IMC growth rate was 3~10 times faster than TLP.	Cu-Sn
9	Solder paste TLP	Powder	Conventional solder paste was printed on the substrate.Liquid solder reacted with substrate to form IMC.	Cu-Sn

2.1.3 Conductive Adhesives

Electrically conductive adhesive is a glue for bonding electronic devices that usually require a relatively low processing temperature and easy processing procedures. Adhesives are ideal to form electrical connection on non-solderable substrates such as polymers and glass substrate. Unlike Pb-based solder alloys, these adhesives are environmental friendly. Meanwhile, when compared with solder joints; adhesive-cured joints also have much lower, lower application temperature, they can be either be cured at room temperature or process quickly with curing temperature between 100 to 150℃. The material is normally comprise solvents to improve rheology for dispensing. Therefore, careful control of process window (bond line thickness, curing conduction) and floor life is expected. Generally, material usage is established for die thickness exceeding 120 µm now.

Electrically conductive adhesives also have their limitations. Their processing is relatively simple, but much more time consuming than solder reflow. Therefore, the use of electrically conductive adhesives is restricted to the low temperature and light duty applications. In fact, conductive adhesives are normally very challenging for high power devices and moisture sensitivity requirement greater than MSL3/260°C.

2.1.4 Silver Sintering

Another emerging die-attach technique is based on Ag sintering. Definition of sintering, as proposed by German (2014), is a "thermal treatment for bonding particles into a coherent, predominantly solid structure via mass transport events that often occur on the atomic scale". The author further conjectured that discoveries and practical application of sintering preceded much earlier than the founding of science in sintering. Evidence of ancient clays and porcelains epitomizes that humankind has indeed discovered sintered materials long before. Indeed, practical application of sintered materials is far reaching and is almost everywhere.

In this work, the discussion on sintering concepts and materials will focus on sintered metallic particles used as joining components applied in microelectronics. Sintering of nanoscale pastes of silver for die attach use at low temperatures is favorable, as they are more of an atomic diffusion process than a change of state from solidus to liquidus. Nanoscale sintering does not need pressure as compared to that of micrometer scale powder, as the nanoscale particles have high surface energies to enable bonding. The bonding is only done once higher temperature is applied to the die-die attach material-substrate structure. The bonding is accomplished via silver atomic diffusion and particles consolidation. This technique of sintering allows dies to be placed onto the die attach material whilst it is in a dense structured condition rather than in a liquidus state.

Sintered Ag is a very promising alternate Pb-free joint candidate owing to its special characteristics:

- Low processing temperature(≤250℃) similar or lower than current high lead solder;
- High melting point of 961℃ which indicates high service temperature abilities;
- High thermal and electrical conductivity as compared to solder because the sintered joint constitutes metal silver with high density
- Superior mechanical properties

Research showed few potential fields that can be benefits from advancement of sintered Ag technologies die attach materials. One of the key group is power module technology that is striving to use wide band-gap semiconductor die at direct bonded copper or direct bonded aluminium substrate. Besides, other potential field include power discrete packaging which is using clip bonding interconnect and consumer integrated circuit that uses PCB or leadframe as their substrate.

2.2 Types of Ag Sintering

In general, Ag die-attach pastes can be classified into three main types, namely micron-Ag, nano-Ag and hybrid Ag. Differentiation criterion is depends on their filler sizes and compositions, even though they share similar constituents. Nano-Ag paste relies on the nano- particle sizes, i.e., less than 100 nm, as the driving force to form the sintered Ag joints, while micron Ag paste relies on the Ag-based endothermically decomposable compounds like Ag carbonate or Ag oxalate to form reactive Ag nanoparticles to bond the adjacent micron -sized Ag fillers.(?) On the other hand, hybrid Ag pastes consisted of mixture of micron and nano-Ag fillers with organic components. It is tailored to achieve high density and good mechanical properties upon sintering.

Two different low-temperature sintering strategies are often discussed: pressure-assisted sintering and pressure less sintering using nanoscale silver particles. Solid-state diffusion can take place amongst the die attach materials nanoparticles even without any outside pressure which is commonly needed for micrometer scale powders instead, in which the process is termed as pressureless sintering. The pressure-less sintering process attracts most of our attention because of its compatibility to present manufacturing process and being a full drop-in solution.

Table 5 Comparison of Die Attach Properties between Soldered and Ag Sintering

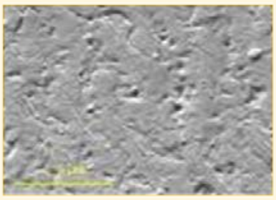
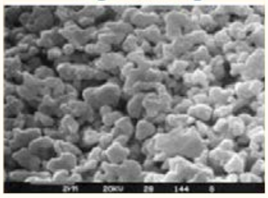
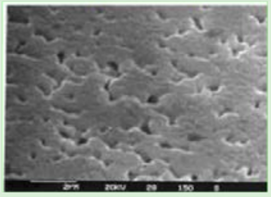
	SnAg Solder	Pressure-less Ag Sintering	Pressure Ag Sintering
			
Material properties			
Melting Point(°C)	221	961	961
Thermal Conductivity (W/mK)	57	60-200	200-400
Electrical Resistivity (mΩ·cm)	0.01	≤0.008	≤0.008
CTE	28	19	19
Advantages/Disadvantages			
Cost	Cost Effective	Good	High Initial Cost
Process Maturity	Mature	Mid	New Technology
Electrical Performance	Mid	Mid	High
Cleaning?	Yes	No	No

Table 5 compares the properties of high lead solders and those of sintered silver. It shows the sintered silver has a higher melting temperature, thermal and electrical conductivity and tensile strength than those of solders. Pressure sintering is gaining insight in microelectronic packaging as it is tailored to achieve high density and good mechanical strength upon sintering. From literature, the pressure helps the densification process by eliminating some fraction of pores through compression/deformation and by increasing the contact area between the silver particles therefore speeding up the free surface area reduction.

The study shows that by using large external pressure, the commercial micro-size silver paste can be sintered to have relative high density at as low as 240°C within a few minutes. The measured properties including electrical conductivity, thermal conductivity, interfacial thermal resistance, and shear strength of sintered silver layer, are also significantly better than those of the reflowed solder layer. Nonetheless, innovations in this area face the challenges of ensuring good bonding without damaging the semiconductor dies while achieving throughput comparable to the conventional soldering or adhesive-based die-attaching process. Application of pressure during sintering however may damage the circuitry on the silicon dies and pose a reliability issue to the devices. Various designs of sinter press and inserts were used to reduce damage to the semiconductor dies during pressure sintering.

Table 6 Organic component of Ag sinter paste

No	Component	Example
1	Dispersant/passivating layer/ organic shell/capping agent	Menhaden fish oils, poly(diallydimethyl ammonium chloride), polyacrylic acid, polystyrene sulfonate, triethylene glycol, methyloctylamine, dodecylamine, hexadecylamine, myristyl alcohol, 1-dodecanol, 1-decanol stearic acid, oleic acid, palmitic acid, dodecanethiol
2	Binder	Ethyl cellulose, polyvinyl alcohol, polyvinyl butyral, wax
3	Solvents/thinner	Isobornyl cyclohexanol, texanol, terpineol, butyl carbitol, toluene, xylene, ethanol, phenol

As shown in Table 6, silver sintering paste contained various kind of organic components such as binders, dispersants/capping agent and thinner/solvent. A dispersant/capping agent is necessary to achieve coalescence between Ag particles resulting in better diffusion over sinter Ag. Binder is used to acquire the consistency of the paste so application of paste material could be performed easier. Thinner/solvent is used to get an optimal viscosity level.

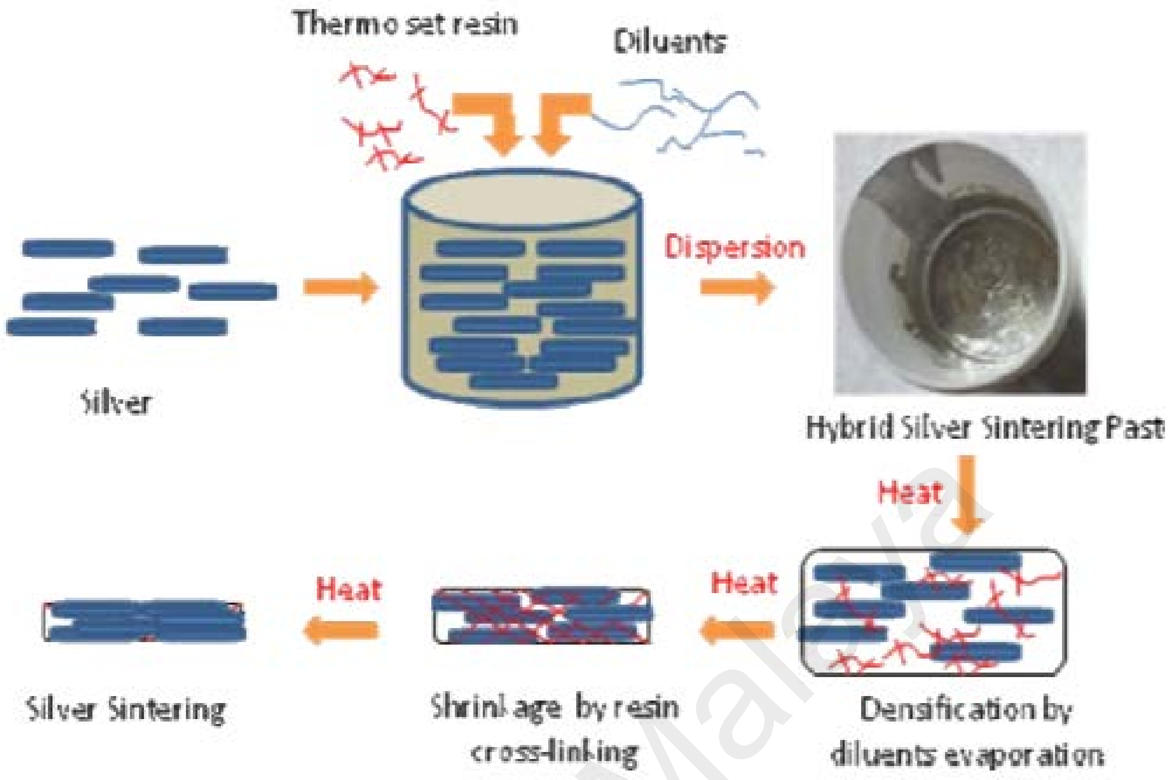


Figure 4 Process diagram for making hybrid silver sintering formulation and silver sintering by resin crosslinking.

Figure 4 illustrates the basic procedure of making hybrid silver paste and processing it. Silver flakes are dispersed in the mixture of thermoset resin and diluents. The mixed paste samples are cured in box oven following the two-step curing profile shown in figure 3. The diluents evaporate in the first step cure temperature (150°C). The thermoset resin starts cross-linkage from 150°C to 250°C. The resin shrinks by the cross-linking reactions and the resin shrinkage forces silver flakes get closer each other. The silver flakes eventually sinter at or below 250°C due to their close proximity.

2.3 Sintering Concept and Principles

Sintering of nanoscale metal powders at low temperature is possible since they have inherently high surface energy; this can be attributed to their large surface area to volume ratio. Hence, application of low temperature even with no outside pressure is enough to achieve a solid-state diffusion between the nano metallic powders (Lalena et al., 2002; Yamada et al., 2006).

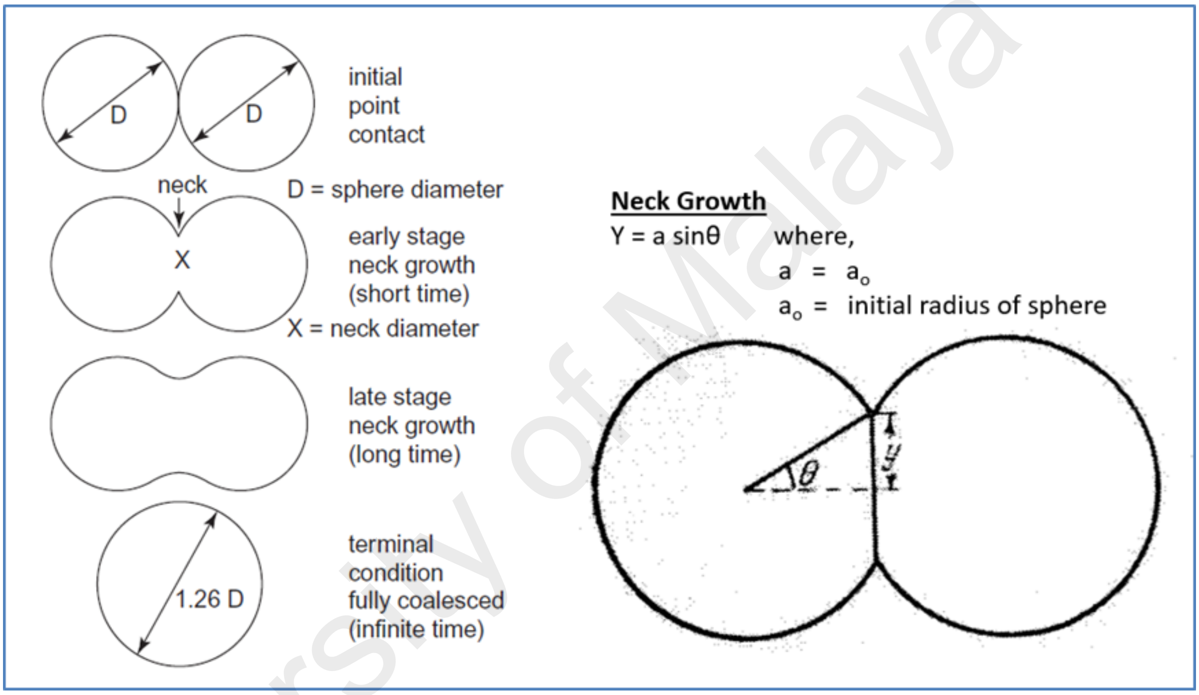


Figure 5 Frenkel's sintering model. Illustrating two spheres coalescing into a larger sphere (German, 2014; Ristic and Milosivec, 2006).

Frenkel proposed this phenomenon in 1945 (German, 2014; Ristić and Milosiveć, 2006). Frenkel sintering model is based on the viscous-diffusion action between particles. As shown in Figure 2.6, sintering process starts with the initiation of neck formation as the two particles are in contact with each other. This is made possible due to Gibb's surface energy action. As the neck grows larger, the smaller particles coalescing into a larger particle and in time it will annihilate the surrounding pores thus completing the sintering process.

German (2014) also describes surface transport mechanism and bulk transport mechanism as types of atomic mass flow in sintering process. Mass flow in sintering is characterized by atoms movement and creation of vacancy. These movement of atoms could be in the form of surface diffusion, diffusion across the pores (i.e. evaporation-condensation mechanism occurring at high temperature), grain boundary diffusion, and viscous flow. During the early stage of sintering process as explained by German (2014), neck formation is initiated. At this stage, curvature gradients is the driving force. In addition, surface transport mechanism is the dominant atomic mass flow. This mechanism involves surface diffusion where the surface area of the particle is still large. Since the activation energy of surface atoms is lower compared to its inner atom, mass transport at the surface of particle is feasible even at lower temperature. Subsequently, as the neck grows, the surface area of the particle reduces—curvature gradients are eliminated as neck grows. Then, the transport mechanism involve is shifted from surface transport to bulk transport. Bulk transport mechanism is dominated by grain boundary diffusion and it happens after the neck formation has completed. This mechanism is responsible for the densification of the sintered material though it also contributes to the atomic mass flow during the neck formation.

Furthermore, German (2014) expounds that as neck formation is less noticeable, pore-grain structure becomes the focus. This stage involves pore formation between the particles and eventually the densification of sintered material. As pore rounding and pore elimination happens, the sintered material undergoes a change on its material property such as an improved in strength. Since there is a reduction in curvature gradients, the driving force at this stage is the surface energy reduction. Diffusion mechanism occurs between grain boundaries through pore mobility and vacancy effect. Furthermore, at this stage, the grain growth is dependent on the temperature. Hence, densification increases as temperature increases. Likewise, grain boundaries are crucial in material densification since smaller grain size increases the curvature and this will retard the grain growth. At this stage, surface transport mechanism is still active and is responsible for facilitating the pore formation and pore rounding as well as enhancing pore migration. However, while surface transport mechanism influences mass flow on the pore surfaces, it never contributes to densification or shrinkage.

Lastly, the final stage of sintering process involves a gradual pore closure. Here, the pore diameter is decreased and the pore length is stretch by the grain growth in order to close the pores. At this stage, both curvature gradient and surface energy are reduced resulting to a slower sintering process. There is a correlation between the pore and grain boundary since pores are attached to the grain boundary. The pore-boundary binding energy increases as the porosity and pore sizes increases. Moreover, pore mobility and pore attachment dictates the grain growth. Grain growth increases rapidly as pores break away from grain boundary. It was noted, then, that a characteristic of a good sintering event is that the pores are attached to the grain boundaries so that it is able to retard grain growth and to enhance pore mobility.

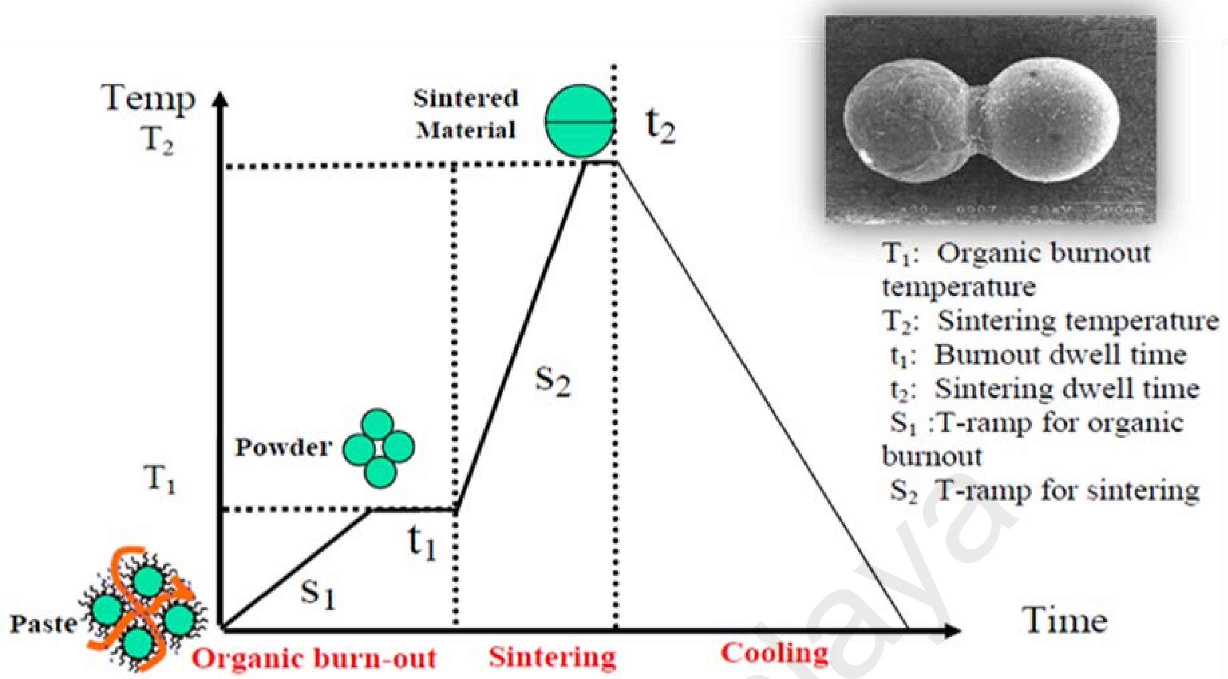


Figure 6 Typical curing profile of pressure-less Ag sintering paste.

In short, Ag particle reaction is separated into 3 phases as shown in a typical curing profile in Figure 6. The heating rate/sintering profile is very critical to drive out the organic solvent and effectively promote sintering simultaneously. With the application of temperature during sintering, these organic materials evaporate and sintering action between Ag particles is initiated. First is the shrinkage of the material that occurs due to the particle rearrangement by sliding across each other. This leads to necking formation between silver particles, which is denoted as t_1. Subsequent temperature ramp leads to densification which results to pore formation due to the interfacial surface energies. Agglomeration and aggregation will take place in Ag particle. The final stage (t_2) includes the collapse of the isolated pores forming grain growth by which the small grains integrates with the larger grains. Ag sintering paste is essentially making use of the process of compacting and forming a solid mass of material by heat or pressure without melting it to the point of liquefaction.

CHAPTER 3: METHODOLOGES

3.1 Package Information

NCP3XXX is a 6mmx6mm 40-pin DrMOS packaging device used in this research study. The device has been qualified at author's work place. This DrMOS device consists of two MOSFET dies (i.e. HSFET and LSFET) and one module IC. This device is used as a high current, high efficiency voltage−mode synchronous buck converter. The application operates from 4.5 V to 21 V input and generates output voltages down to 0.6 V at up to 15 A. It is commonly used in cellular base stations, ASIC, FPGA, DSP, CPU Core, I/O Supplies, telecom network equipment server and storage system. As shown in Figure 6, 1.3mil palladium coated copper (PCC) wires are used to connect the source pad of FET dice to copper pin connection. The source (i.e. internal NMOS switch) pad of the HSFET die is connected to the VSWH pin while the source pad of the LSFET die is connected to the PGND pin (i.e. ground reference and high−current return path for the bottom gate driver and low- side NMOS).

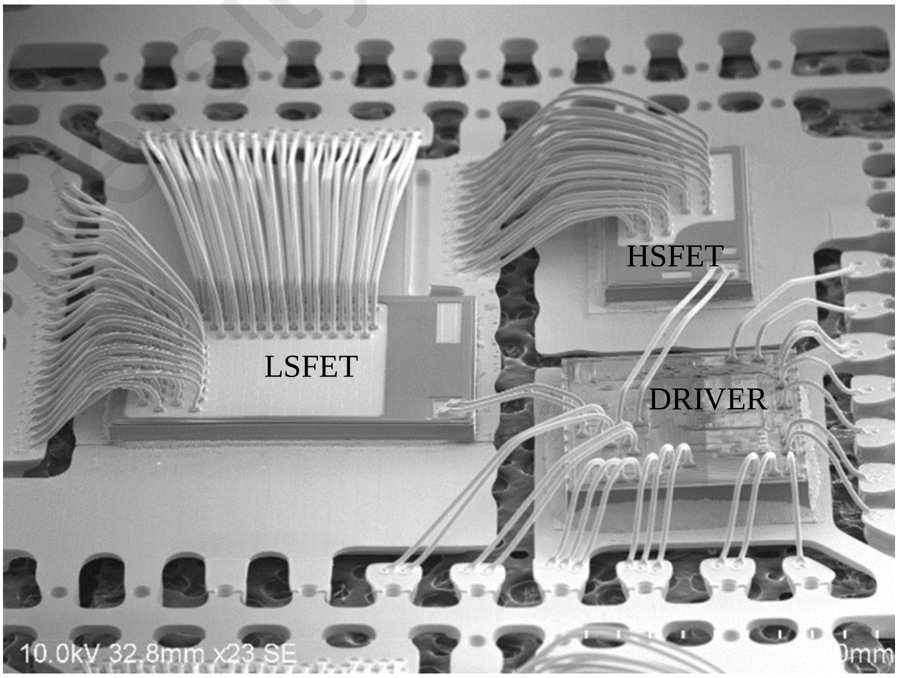
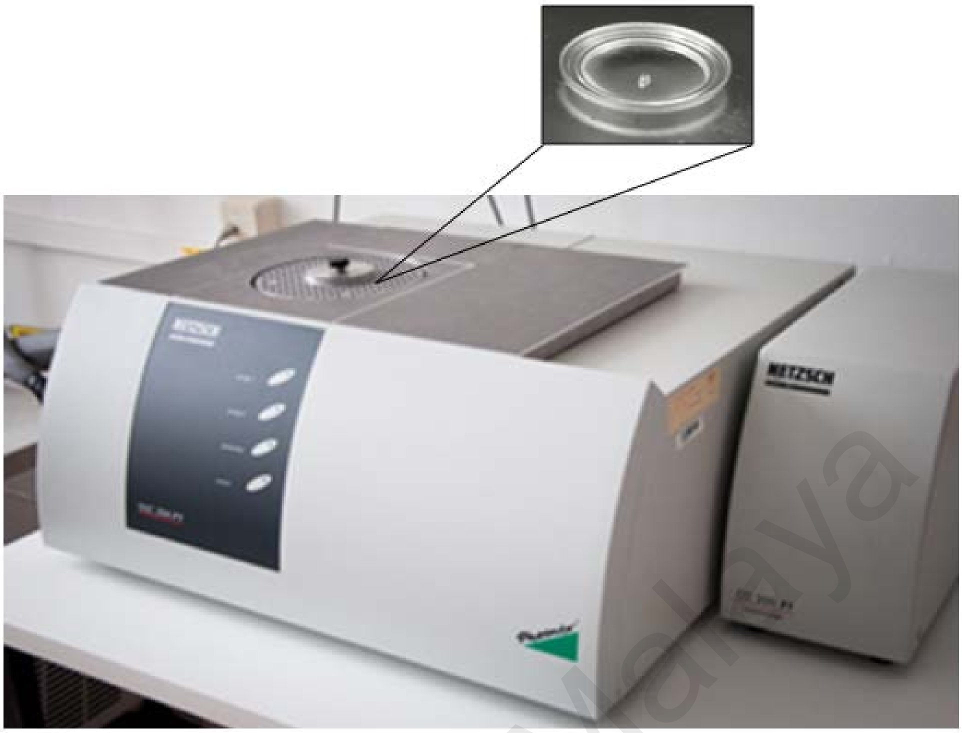


Figure 7 DrMOS NCP3XXX device using 1.3mil PCC wire as interconnect. Die1: Driver die; Die 2: High Side Mosfet Die; Die 3: Low Side Mosfet Die

3.2 Heating Profile Optimization using TGA and DSC

To determine the optimal curing profile for Ag sintering paste, thermal analyses of the pressureless sintering paste were carried out. Netzsch TG 209F1 Libra was used to investigate the burn off temperature of organic additives. Netzsch DSC 204F1 Phoenix was used to analyze endothermic and exothermic heat events throughout the duration of die attach curing. For both experiments, silver sintering paste were heated at a linear rate of 10℃/min, from room temperature to 600℃. The experiment is conducted under inert nitrogen setting.

(a)



(b)

Figure 8 (a) Netzsch TG 209F1 Libra and Al crucible (with lid) used for TGA (b) Netzsch DSC 204F1 Phoenix and Al crucible with lid used for DSC

3.3 Assembly Process Flow

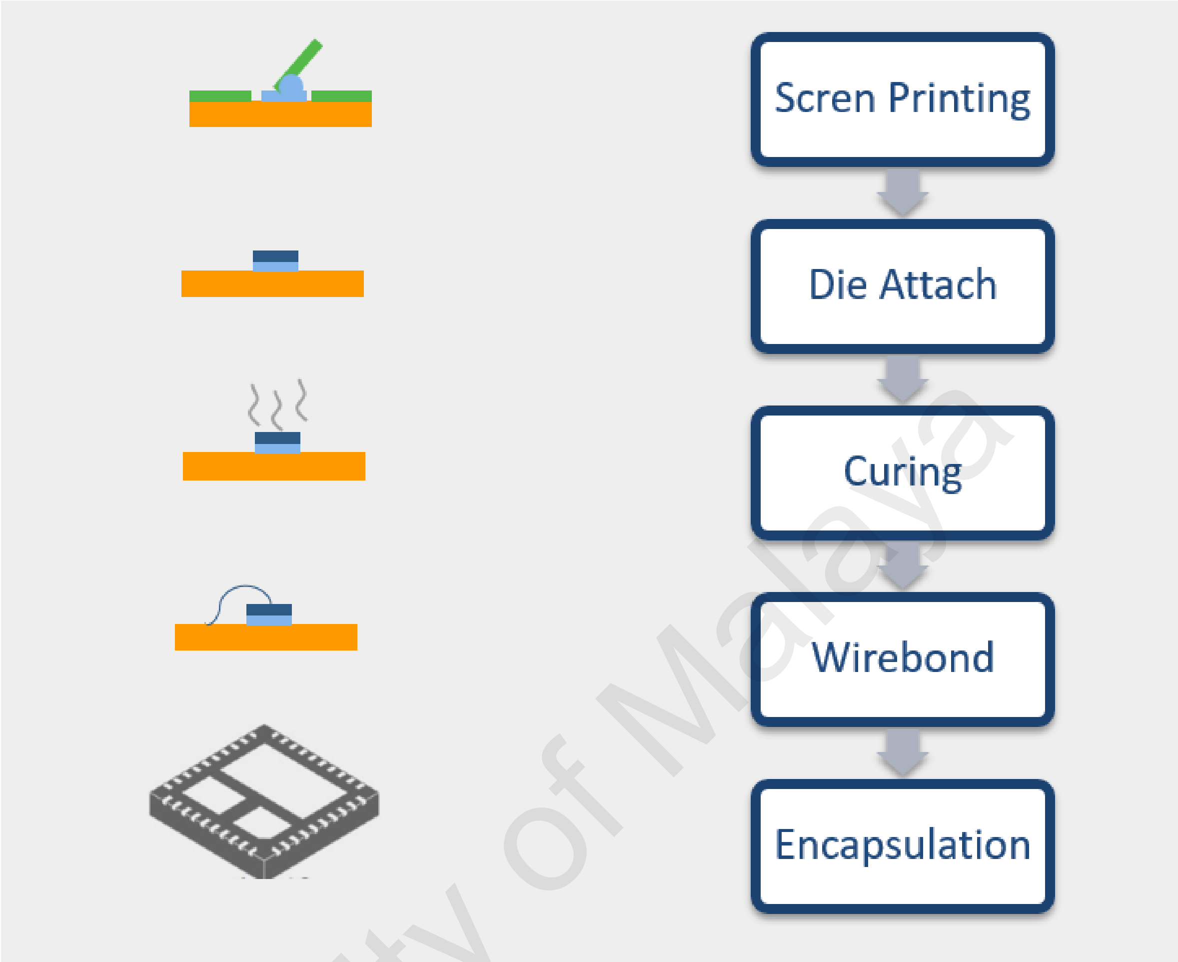


Figure 9 Process flow of the pressureless Ag sintering process: (a) screen printing; (b) die attach; (c) curing of the pressureless paste; (d) wire-bonding and (e) molding.

Figure 9 showed a schematic of the process flow of pressureless Ag sintering application. The Ag sintering paste can be applied by metal stencil printing using conventional DEK printer. The copper lead frame is selectively plate with silver layer to allow efficient sintering diffusion. Next, precise pick and place machine was used to mount the electronic chip on top of the paste. Driver size mounted were measured 1550x1500x200um; HSFET die measures 1750x966x110um, whereas LSFET die measure 2286x1574x110um; surface finish was 750A Ti + 3kA Ni + 750A Ag. The sandwich is then send for programmable heating using a vacuum reflow oven, to promote the sintering and densification of Ag powders and flakes. The sintering profile used in this work is as shown in Figure 13. At the end of the sintering process, the furnace temperature is naturally cool down to room temperature (25℃) and only then, that samples were unloaded from the furnace. Assembled chip will then be wire-bonded to form electric circuit and finally encapsulated for moisture protection. Electrical testing is tested on all singulated packages to compare resistivity between chips sintered under different curing atmosphere.

3.4 Characterization of Ag-sintering die-attachment

3.4.1 Scanning Electron Microscopy (SEM)

Sample will be further cross-sectioned for microstructure analysis via scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Coalescence of the silver particles can be identified using this technique.

3.4.2 X-ray Inspection

X-ray machine is used to examine the die attach voids percentage and the outgassing path of sintered Ag material. X-ray is used to examine samples from each leg to observe outgassing paths of sinter paste curing under different atmosphere. This is to determine if there is a relationship between the outgassing paths, die shear strength, agglomeration and aggregation.

3.4.3 Die Shear Testing

The die shear measurement is performed upon completion of reflow to determine the shear strength of bonding materials in accordance with MIL-STD-883 standard. DAGE 4000 multipurpose bond tester is used to measure the adhesion strength of material. Force in perpendicular direction to semiconductor die is applied to attempt shearing a semiconductor die bonded to copper lead frame. This could serve as an indication of how strong is the interfaces next to sinter paste as a bonding material, especially on the die back metal and copper lead frame.

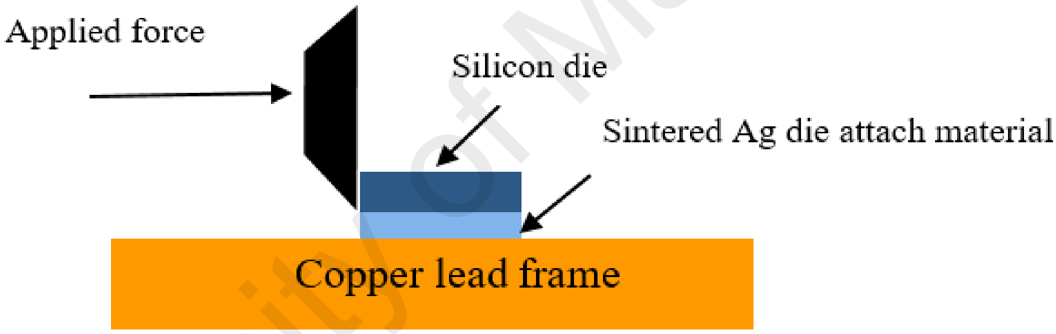


Figure 10 Schematic setup for die shear test

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Thermal Properties of Pressureless Silver Sintering Paste

4.1.1 Thermogravimetric Analyzer (TGA) of Ag Paste

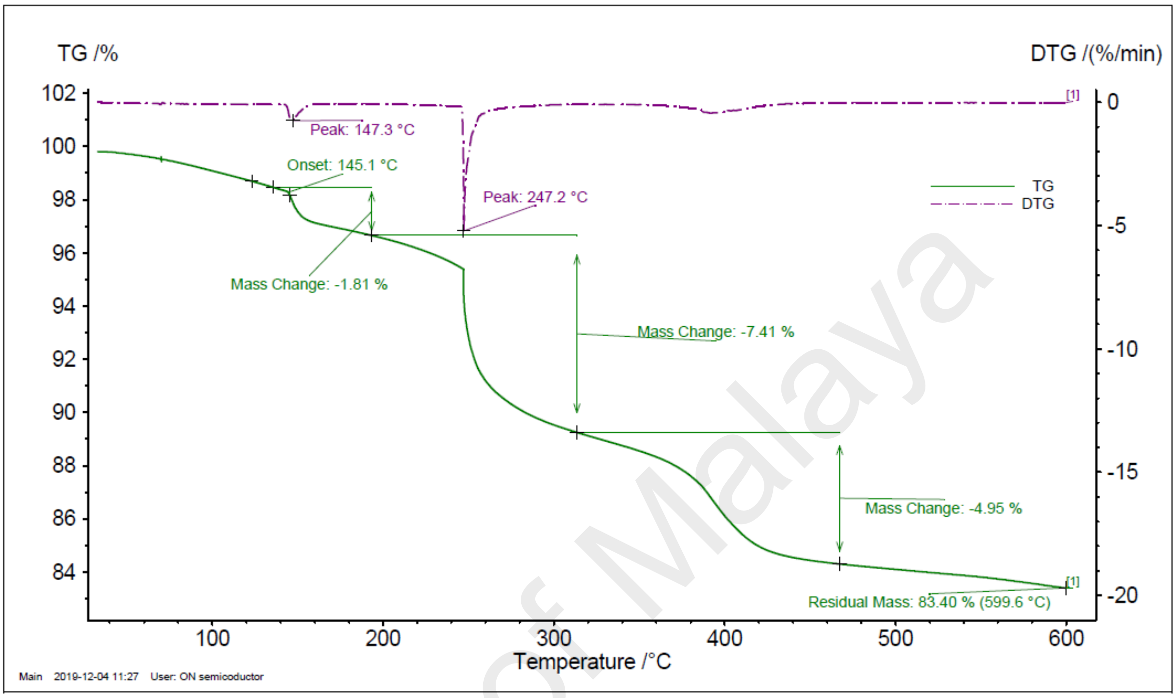


Figure 11 TGA graph of Sinter Ag Paste with linear ramp rate of 10/min

Thermogravimetric Analyzer (TGA) is a suitable technique to determine the weight loss and to identify the sequential disintegration of organic additives in the hybrid sintering paste. The tool quantitatively measures mass change while the temperature of a sample subject to a controlled ramping step. This is a good starting point to define the required sintering profile. Additional sample characteristics such as thermal stability, decomposition behavior, composition (ratio of polymer to filler) could also be determined from the thermogram.

Macdermid hybrid silver sintering paste HTXX was used in this study. 48.45mg of silver sintering paste were weighted in a sealed aluminium. The sample was subjected to a linear ramping rate of 5K/min from room temperature to 600degC. Figure 11 depicts the TG curve for the sintering paste HTXX used in this study. Derivative of the TG curve is plot as time rate of change of mass and represented by purple line DTG.

First weight loss of 1.81% had maxima at 147.3℃, though the onset of its weight loss begins as earlier as 145℃. Second weight loss of 7.41% peaked at 247.2℃. Cross-linking of thermoset resin started from the 150℃. Last weight lost occurred only after 400℃. This reaction is believed to be thermoset resin degradation temperature in the hybrid sintering paste. The residual silver content of pressure-less sintering paste was approximately 83.4 mass percentage, after serial of thermal events. Sintering paste HTXX would have to undergo three stages to burn off, Stage 1: the first stage occurs at temperature below 150℃, reduction of mass is attribute to diluent vaporization. Stage 2: the second stage occurs at temperature 247℃, the shrinkage of resin volume force silver particles to get closer to one another and ultimately promote sintering at 250℃ while Stage 3: the final stage occurs where the components completely disintegrate at 400℃. The curing temperature used in the characterization was build based on this thermogram findings.

4.1.2 Differential scanning calorimetry (DSC) of Sintering Paste

Differential scanning calorimetry, as the name implies, measures the difference in amount of heat (in term of energy) required to increase the temperature of a sample and reference when control heating is applied. Depend on whether the process if exothermic or endothermic, less of more heat will need to flow to the sample as compared to reference to maintain both at the same temperature. This is an effective tool to look for structural changes on silver sintering die attach material and commonly used in tandem with TGA.

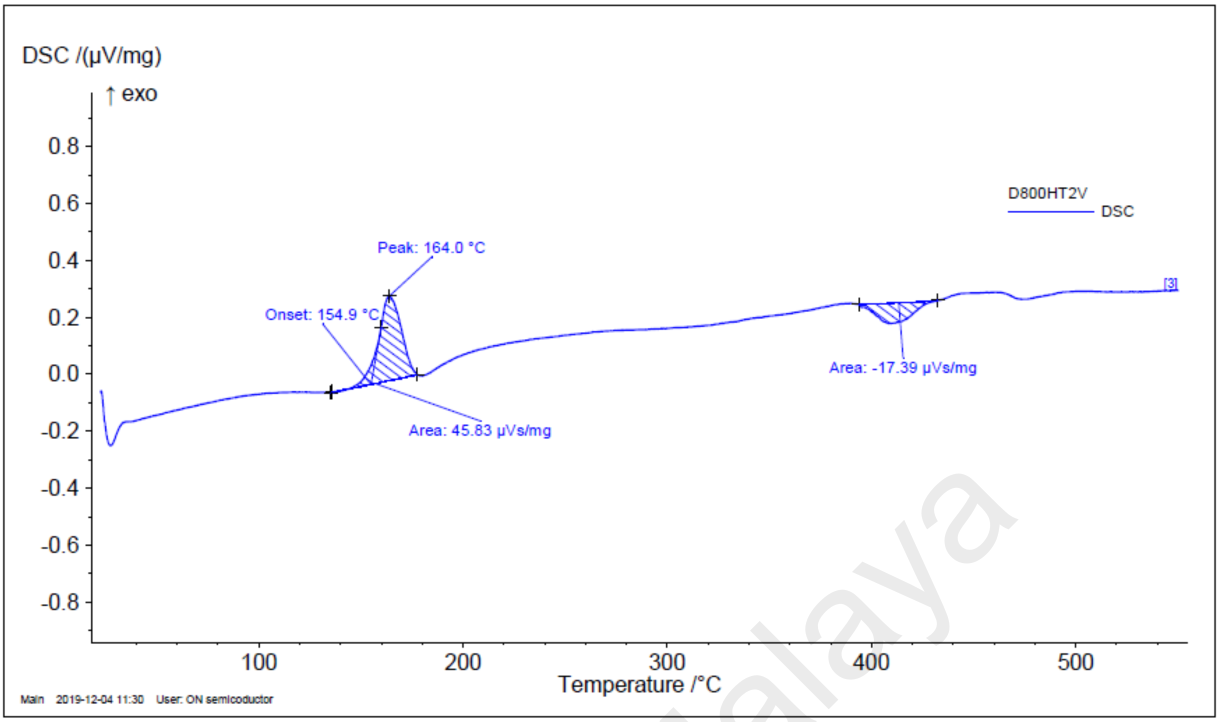


Figure 12 DSC graph of Sinter Ag Paste with linear ramp rate of 10/min

A small quantity of silver sintering paste (~5.9mg) were weight in a sealed Al pan with ventilation hole. The sample subjected to a linear ramping rate of 5K/min from room temperature to 600degC. Figure 12 observed the presence of a discernible exothermic peak at 164°C. This exothermic peak correspondence discovery suggests that evaporation of solvent in the Ag pastes occurred before sintering of Ag particles. Besides that, the onset temperature of the exothermic peak at 154.9°C matches with maxima of DTG curve in Figure 12. Heated under nitrogen, the hybrid-Ag paste also showed an endothermic peak surpassing 400°C. Such endothermic peak attributed to the decomposition of thermoset resin in the paste formulation (decomposition temperatures above 350°C).

Table 7 DOE Plan for Curing Environment

Profile	Soak1(min)	Temp1 (°C)	Soak2(min)	Temp2 (°C)	Nitrogen(mbar)
1	30	150	60	250	0
2	30	150	60	250	500
3	30	150	60	250	1000

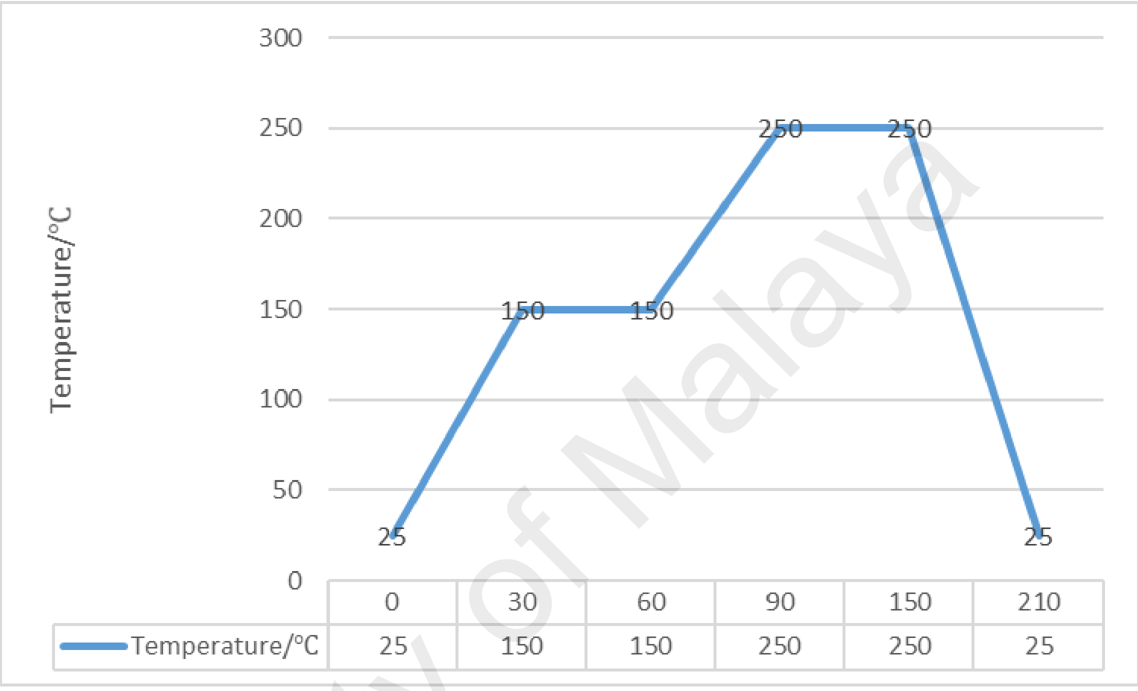


Figure 13 Heating profile for pressure-less silver sintering paste

Based on the TGA and DSC results of the hybrid sintering paste, the heating profile was optimized for curing of hybrid sintering paste use in this study, as shown in Figure 13. The DOE legs are as shown in Table 7. The total processing time is about 2 hours and 30 minutes. Such heating profile aims at smoothly drying off the solvent in sintering paste.

4.2 Effects of different sintering atmospheres

4.2.1 X-ray characterization of sintered silver

(a)

(b)

(c)

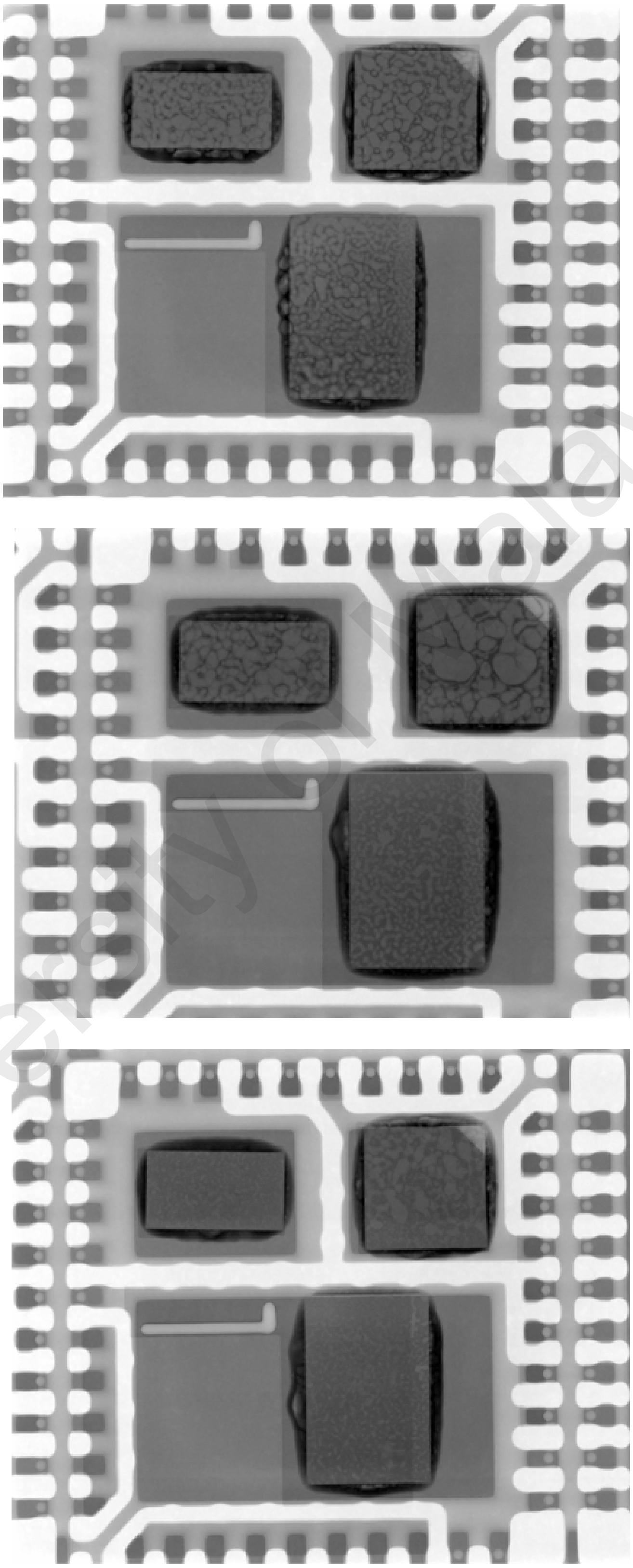
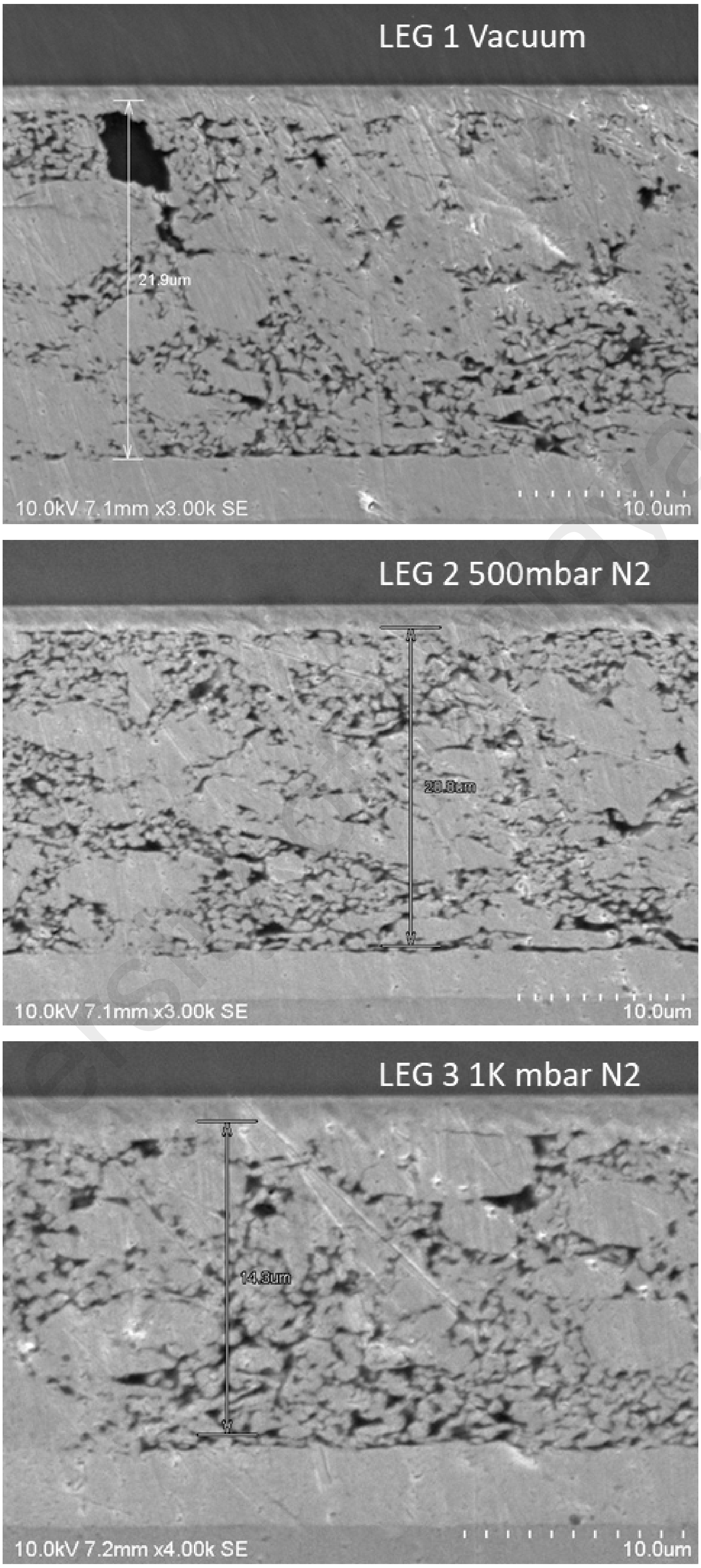


Figure 14 X-ray images of sintering paste cured at 250 °C in (a)0 mbar (b)500mbar and (c)1000mbar N2 reflow oven;

To determine the level of voiding in the bond line, the cured sample of leg 1, leg 2 and leg3 were tested by X-ray imaging. It is observed x-ray images observed severe sporadic void after curing for all legs. Void occurrence is more significant when the die is relatively smaller. In this evaluation, it is observed the driver IC die suffered the most intense outgassing void after the material is cured and cooled to room temperature. Comparatively, as shown in Figure 14© leg 3 had observed controllable amount of outgassing void. Void percentage is hardly observed.

4.2.2 SEM characterization of sintered silver

Assembled devices from each leg were mounted over a resin cup for cross-sectioning purposes in order to expose the surface of interest. These samples were eventually undergo SEM inspection to observe the morphological characteristics as well as the degree of agglomeration and aggregation of the silver paste.



(a)

(b)

(c)

Figure 15 SEM images of the microstructures of sintering paste cured at 250 °C in (a)0 mbar (b)500mbar and (c)1000mbar N2 reflow oven;

Figures 15 give the microstructures SEM images of sintered joint at the nitrogen level of 0mbar (vacuum), 500mbar, and 1000mbar, respectively. Macro void were observed between die back metal and silver particle sintered zone of the joint curedat vaccum environment, as shown by red arrow in Figure 15(a). Pascal’s Law explains this phenomenon. As the chamber pressure decreases, the boiling temperature of the solvent and diluent will be affected. The boiling point of the additives will decrease since it takes less pressure for the molecule to leave the liquid. Voids formed during sudden evaporation of solvent could join and form larger voids.

On the contrary, better metallurgical combination of joining zone was attained as shown in Figure 15(c) when the sintering atmosphere is reaching 1000mbar. Some submicron voids still existed in the sintered layer but the porosity of the joint is decreased compared with that of vacuum and 500mbar. Ag nanoparticles sintered and grew together causing the increase of material density and decrease of the porosity. Apart from that, it is worth mentioning that the bond line thick is decreasing when the nitrogen pressure is increasing. Bond line thickness of Leg 1 measures 20.5um, whereas bond line thickness of Leg 2 and Leg 3are measured as 20.8um and 14.3um respectively. Optimum burn off temperature and time for diluent is the key enabler in Leg 3; thereby allow efficient atomic diffusion to occur.

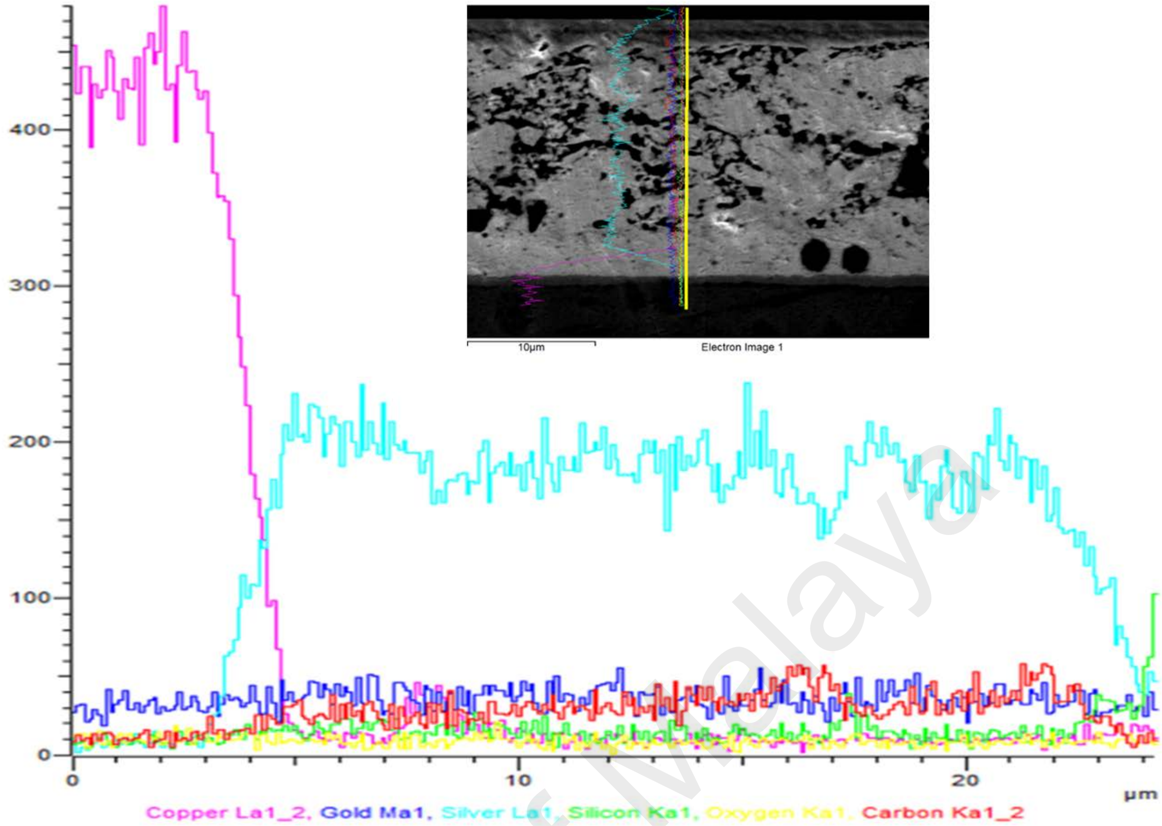


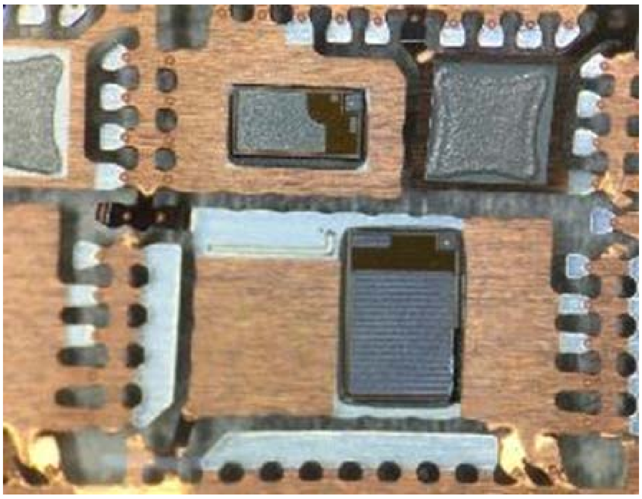
Figure 16 EDX line profile of the microstructures of sintering paste cured at 250 °C in Leg 3 cured in vacuum in N_2 reflow oven

The element distributions across the joining interface are shown in Figure 16. It is observed that Ag content diffuse slowly at the edge of copper surface, which signifies that sintering paste does well in sintering into copper as compared to back metal of Si die. Also, no separation is discovered near the edge of die back metal non copper lead frame.

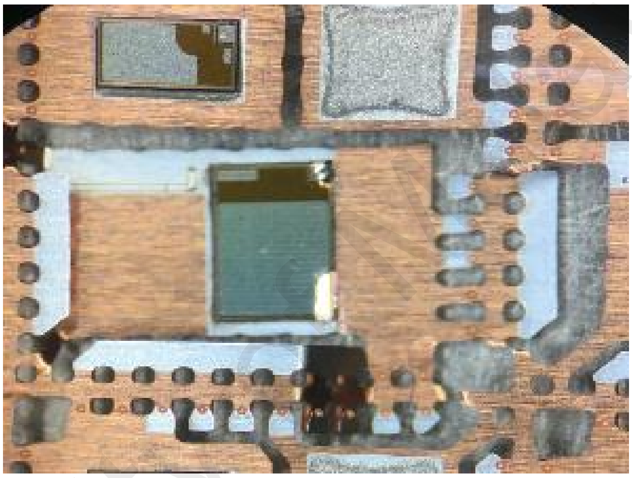
4.2.3 Die Shear Testing of Sintered Joint

When the bonding force between chip and copper were accessed, a meaningful die shear are not pursued because the shear force had already damage the copper lead frame during shearing motion. This reason for this constraint might attributed to the copper lead frame containing hollow structure that is only secure by tie bar.

(a)



(b)



(c)

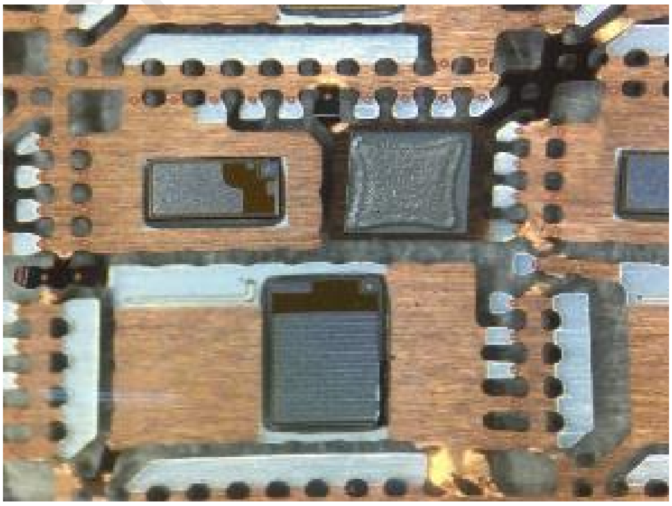


Figure 17 Die shear images showed destroyed leadframe for sintering paste cured at 250 °C in (a)0 mbar (b)500mbar and (c)1000mbar N2 reflow oven;

4.2.4 Electrical Testing of DOE Evaluation

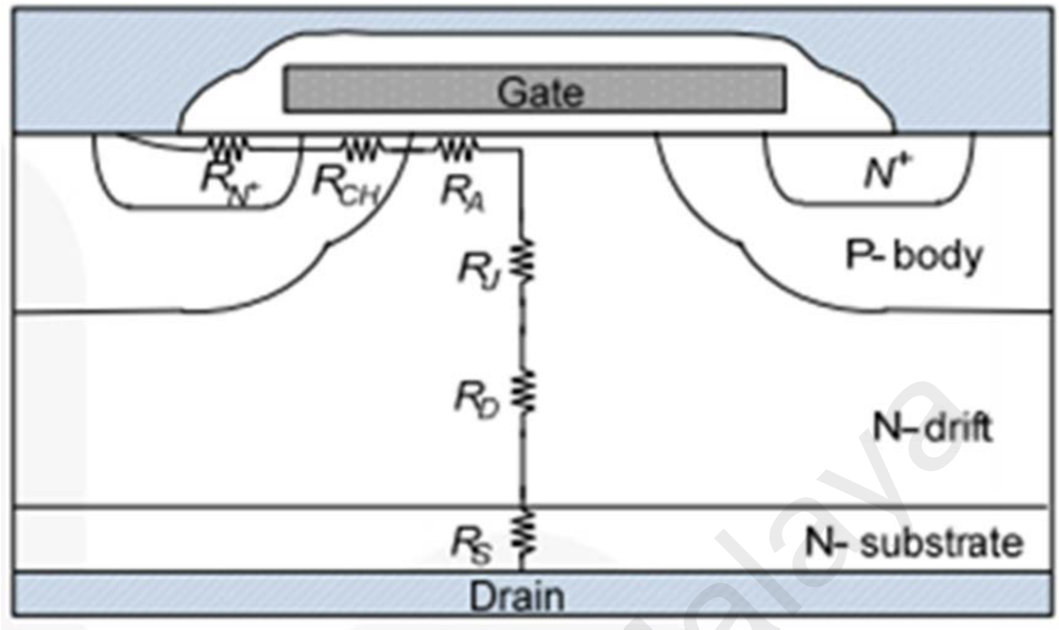


Figure 18 Vertical Structure of a MOSFET transistor showing internal resistance of the device.

In a power MOSFET transistors, drain-source on-state resistance or RDS(on) is dictated by the internal resistance of the die as shown in Figure 20 and also by the resistance of the interconnection used such as the copper clip interconnection, the wire bond wires, the die attach paste and the packaging. Overall RDS (on) is described by the equations below:

Equation 1: RDS (on) = $R_{Internal}$ + $R_{External}$

Equation 2: $R_{Internal}$ = R_N+R_{CH}+R_A+R_J+R_D+R_S

where, R_N is the source diffusion region resistance, R_{CH} is the channel region resistance, R_A is the accumulation region resistance, R_J is the resistance of the JFET component of PN body, R_D is the drift region resistance, and RS is the substrate region resistance. The variables R_N, R_{CH}, R_A, R_J, R_D and R_S are actually the overall internal resistance (i.e. $R_{Internal}$) within the structure of power mosfet die. While, $R_{External}$ is the resistance accumulated external to the structure of the power mosfet die. The $R_{External}$ resistance is the focus of this study albeit controlling this resistance to the minimum as we replace the solder with a silver sintering paste.

Engineering build run is carried out to build the control lot and the experimental lot. Electrical test was performed using the automated tester Eagle Tester System 364 to measure the RDS(on) response between the legs curing at 0mbar, 500mbar and 1000mbar nitrogen remain. Each electrical results are then tabulated as Leg1, 12 and 3 respectively. The test parameters considered in investigation were the RdsonH and RdsonL, which is used to measure the RDS(on) responses of HSFET die and LSFET die. For RdsonH, the lower specification limit is set to 5.0 m-Ω while the upper specification limit was set to 9.5 m-Ω. Besides, for RdsonL, the lower specification limit was 2.0 m-Ω and the upper specification limit was 3.70 m-Ω.

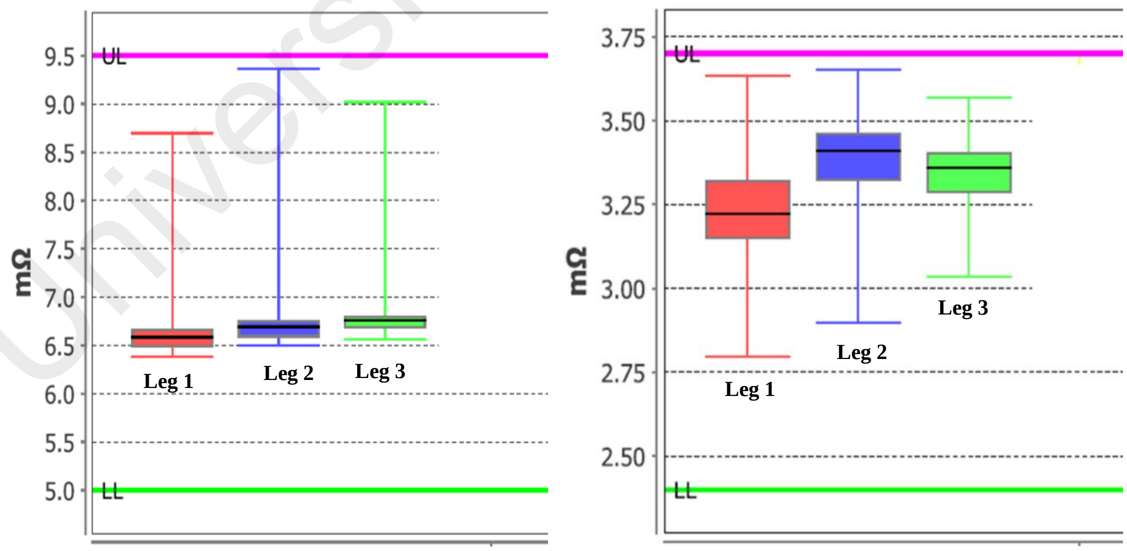


Figure 19 (a) RdsonH Pre-trim Test Response of HSFET die VGS=5V.

(b) RdsonL Pre-trim Test Response of LSFET die VCC=12V

Figure 19 depicts the RDS(on) performance of HS FET die for the two lots. The red curve (Leg 1) represents curing under vacuum condition while the blue(Leg 2) and green curve(Leg 3) represents curing under 500mbar nitrogen and full nitrogen 1000mbar nitrogen, respectively. The measurement for RDS(on) of HSFET all all three legs do not statically significantly difference. In similar manner, Figure 19(b) shows the RDS(on) response of the LSFET die for Leg 1 curing under vacuum is has lower average RDS(on) as compared to other legs. However, it is worthy to mention that RdsonH and RdsonL responses for these three lots were well within the specification limits. Test result also confirmed that the Leg 1 exhibited an increase spread in resistance over Leg 2 and 3 for LSFET dice. However, the increase in resistance is not significant since such level of resistive fluctuation is also observed on wafer-to-wafer variation.

CHAPTER 5: CONCLUSION

5.1 Conclusion

(a) ***Objective 1: To enhance the package performance of traditional soldered DrMOS package by using leadfree alternative- pressure less sintered silver technology.***

In brief, it is the assertion that pressureless sintering die attach system is a viable joining material for semiconductor and microelectronics industry. Pressureless Ag sintering is presented as an alternative die attach solution to traditional SnAg solder. Thermal characteristics of each thermal event occurred can be interpreted and the sintering temperatur with the use of TGA technique. By using DSC tool, it is observed that no re-melting has occurred when the paste is subjected for second heat cycle. Thus, this sintered paste system is ideal for wide-band-gap power devices that demands high operating temperature. It is clearly demonstrated that sintered Ag is a feasible approach for mass production in power modules. We hope the promising outcome of this work would pave way for high temperature lead-free compliant die attach using wide band gap devices in the near future.

(b) ***Objective 2: To characterize the mechanical and electrical properties of the pressure-less sintered Ag joint on selective Ag-plated copper lead frame***

Physical and structural attributes of sintered Ag were examined using SEM. SEM images revealed good Ag particle densification across the cross-sectioned region after sintering. Electron dispersive X-ray spectroscopy (EDX) verified the diffusion of element across the bonding interface between die back metal and direct bonded copper. X-ray analysis showed controllable void passing production specification requirement. A very simple sintering process is performed using existing equipment platform, without any extern al pressure exerted on the devices, and with mechanical strength comparable to that of soldering. Meaningful die shear result was not attained because the shear action had already damage the copper lead frame by using 5kg of shear weight standard

Controlling curing environment such as concentration of nitrogen resulted in a decreasing chamber pressure. Curing the sintering paste under rich nitrogen atmosphere showed efficient diffusion transport of Ag particles and well-sintered joint is attained. When processing under vacuum, weaker sintered bond seems to be established by referencing based on bond line thickness measurement. As the chamber pressure decreases, the boiling temperature of the solvent and diluent will be affected. The boiling point of the additives will decrease since it takes less pressure for the molecule to leave the liquid. Sudden evaporation of solvent caused voids to grow to a larger network, as postulated by Pascal law. For current study, electrical characteristics of hybrid silver sintering presented here were all within the specification limits.

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