Influence of Firing Temperature and Atmospheric Conditions on the Processing of Directly Bonded Copper (DBC)

Abstract

Direct bonded copper (DBC), also called the gas-metal eutectic bonding method, is an important substrate material commonly used for thermal and electrical management in power modules. Developed almost 40 years ago by General Electric, there is wide use of this structure when there is a need of a substrate with high current carrying and high thermal conductive abilities. The components of DBC are a ceramic (usually Aluminum-Oxide (Al_2O_3, also called "alumina") and a bonded piece of copper on one or both sides. This copper is strongly bonded to the alumina, giving strong adhesion and combining benefits from both materials. This paper will give a summary of DBC technology and will discuss the role that furnace temperature and atmosphere perform during processing.

Introduction

The development of DBC has pushed boundaries of power electronic applications. It is used in such products as concentrated photovoltaics and semiconductor modules for automotive applications [1]. The value of DBC comes from its high thermal conductivity due to copper and its low coefficient of thermal expansion as a result of ceramic. The need for low thermal expansion is so that solder on silicon semiconductors won't be damaged with heat cycling. For DBC ceramics, alumina (Al_2O_3) is commonly used, but other ceramics such as aluminum nitride (AlN) or Beryllium Oxide (BeO) are also utilized in bonding. Alumina is preferred because of its low cost and efficiency compared to these other ceramics, and DBC is chosen over other bonding processes because there is no need for intermediary layers in the process. According to Burgess et al. Al., MgO, SiO_2, and CaO are intermediary layers located at the grain boundaries of the ceramic. This layer penetrates into the porous layer of the metal at sintering temperatures and locks the metal into the ceramic. DBC is preferred because intermediary layers often have problems with current flows at the metal ceramic interface and are less corrosion-resistant, leading to early failure.

DBC begins with layering of copper onto alumina as seen in Figure 1. The contact interface between the copper and the alumina is the most important area of processing. Copper exhibits a wetting behavior on alumina that covers the area of contact during firing. With a temperature range between 1065º C and 1083º C, interface adhesion occurs. With research and developments in DBC technology, production is possible on a larger scale using equipment such as the belt furnace. Controlling furnace conditions is important in reaching the high eutectic temperature that is needed to begin the bonding process while staying below the melt temperature of copper. Specific controls of the furnace atmosphere are needed as well during processing.

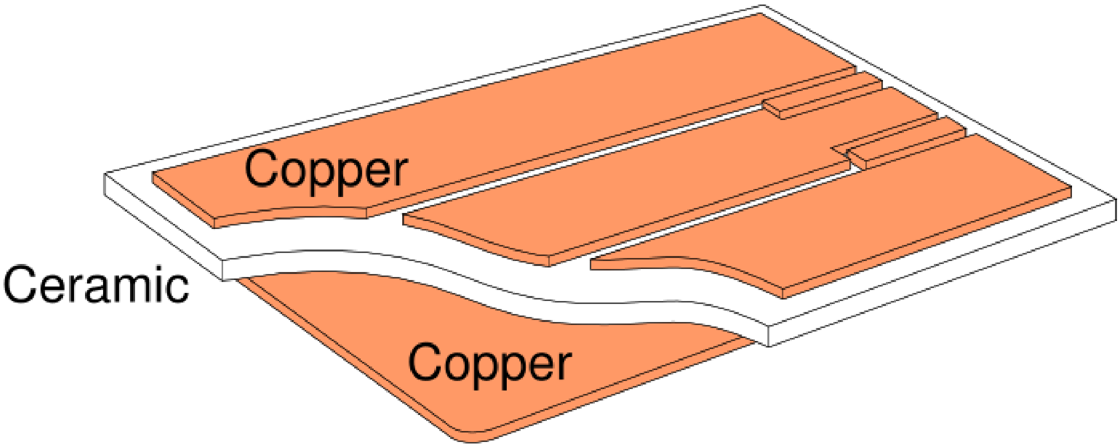

Figure 1. *Ceramic – copper bond representation [2]*

Process of DBC

The process begins with applying copper onto alumina inside an atmosphere-controlled furnace. The ideal settings for the atmosphere are flowing inert gas, such as nitrogen or argon, and a small percentage of oxygen. The eutectic that occurs between copper and oxygen is found to be around 1065ºC as seen in Figure 2.

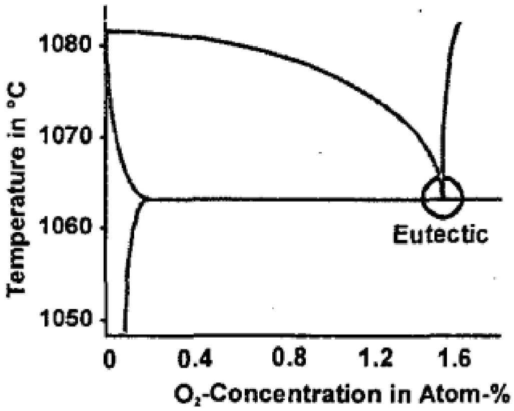

Figure 2. *Eutectic Point and percent concentration of O2 [3]*

According to Faghihi et al. [4], in their process of making DBC, the copper material used was 99.99% pure, and alumina was at least 97% pure. Copper strips of .8 mm in thickness were observed. It will be discussed later on the important effect of copper thickness on peel strength. For cleaning, copper strips are degreased and washed using treatments such as detergent and hot water scrubbing. Alumina is cleaned by polishing, ultrasonic treatment in ethyl alcohol, and annealing in air at 1000˚C to reduce hydroxyl groups [4]. Oxidation takes place after cleaning which involves the heating of copper, creating a thin film layer of cuprous oxide (Cu2O) at the interface between the alumina and copper. This can be done prior to firing with the ceramic or when the copper is already laid onto the ceramic. Either way, the Cu/Cu2O layer serves as a bonding agent with the ceramic.

There are varying rates of heating the substrate as seen by Ning et al. [5], Faghihi et al. [4], or Burgess et al. [**Error! Bookmark not defined.**]. In studies done by Faghihi et al, the first stage of the bonding process occurs with a total inert gas atmosphere, such as argon or nitrogen, with a small percentage of oxygen mixed in as defined by the eutectic. In this atmosphere, the substrate is heated to 1000˚C at 10˚C/min. Then at a slower rate of 2˚C/min, the substrate is heated to 1075˚C. At this point, the hold temperature of 1075˚C is kept constant for an hour. This is the time where the alumina copper bond is formed. The substrate is then cooled down to 400˚C and held at that temperature for an hour to reduce thermal stresses, and it is finally cooled down to room temperature. This process requires proper control of temperature during the entire duration. Likewise, atmospheric conditions need to be observed and controlled. A final stage of vacuum processing increases the pore size and decreases the peel strength, resulting in a substrate that will be more susceptible to failure with high loads [4]. Another aforementioned atmospheric condition that is needed is a 1.4 mole% of oxygen when heating the substrate up to the hold temperature of 1065 -1075˚C. This peak temperature needs to be lower than 1083˚C, the melting temperature of copper [6]. The cooling process is when the diffusion of oxygen out of copper takes place. At this stage, an atmosphere of H2 can be used for cooling. The Hydrogen gas that is injected into the furnace helps remove the Cu2O particles at the interface of the eutectic zone, increasing bond strength due to the Cu/Al2O3 interlock. Another temperature cycling method for DBC is shown below in Figure 3. Note that in this method, there is no hold time at 400˚C during cooling.

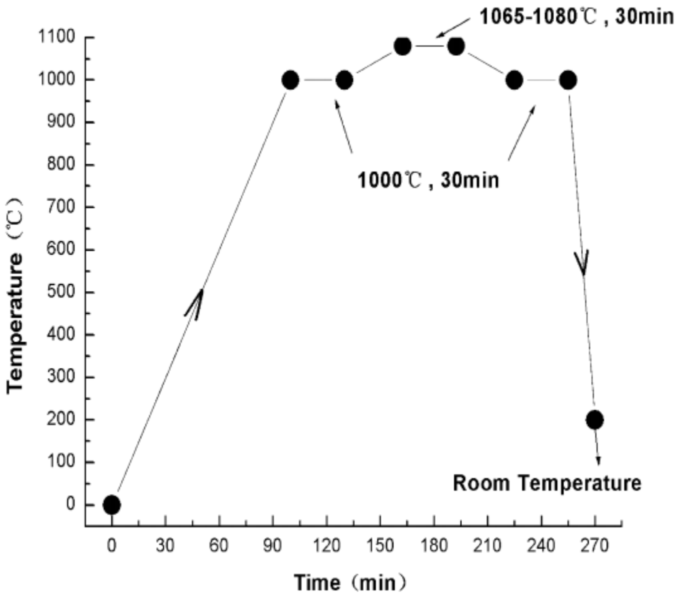

Figure 3. *Time-temperature of DBC substrate bonding [5]*

Characteristic Features of DBC

Copper allows the feature of high thermal conductivity along with good characteristics in electrical conductance. The copper foil used in substrates range from thicknesses of .125 mm to .8 mm. This thickness is important for quality. Research shows thinner .3 mm thick copper sheets were used because of lower occurrences of crack propagation when compared with larger thicknesses [7]. With a .3 mm thick copper foil fused to alumina, the coefficient of thermal expansion is only 7.2 X 10-6, slightly higher than ceramic by itself at 6.8 X 10-6 [3]. Another noted benefit is a better hermetically-sealed

package for power modules. With DBC, a power module package can be as much as 70% less in weight for industry, and new developments such as fluid cooled substrates are able to dissipate heat up to 400 W/cm2. A power module is represented in the following Figure. Ta and Tb denote the temperatures on either side of the module at the copper.

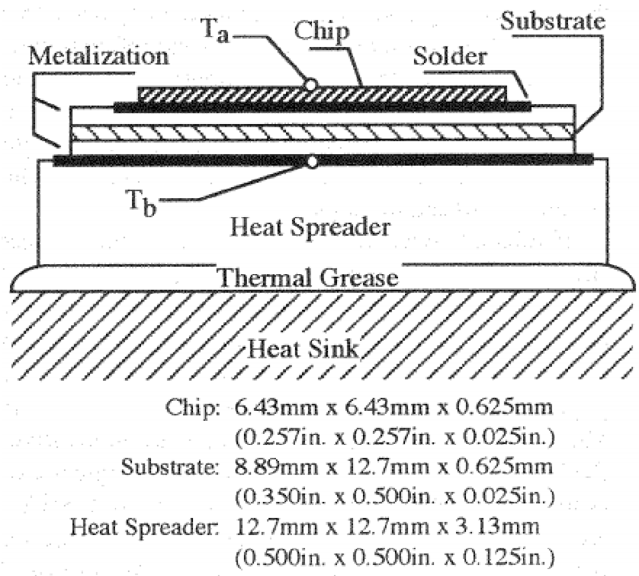

Figure 3. *Generic Structure showing substrate in relation to other components [6]*

Effect of Temperature and Atmosphere in Bonding
Oxidation of the copper is one of the most important factors of bonding the copper to the alumina. The interface needs a thin film layer of Cu-Cu2O, achieved by firing to the eutectic temperature and creating favorable adhesion to alumina. According to studies done by Ning [5], the oxidation temperature that will create a good oxide layer is 300˚C for 60 minutes. Wetting of the Cu-Cu2O onto the alumina is important for adhesion strength. The proper wetting of alumina ensures that the Cu-Al2O3 bond is established. During firing of the alumina and copper substrate, there needs to be an atmosphere with a small amount of oxygen. The oxygen content is .39% by weight (also mentioned before as 1.4 mol % O2) as seen on the Cu-O binary phase diagram of Figure 4. At this percentage of oxygen, the eutectic occurs at 1065˚C.

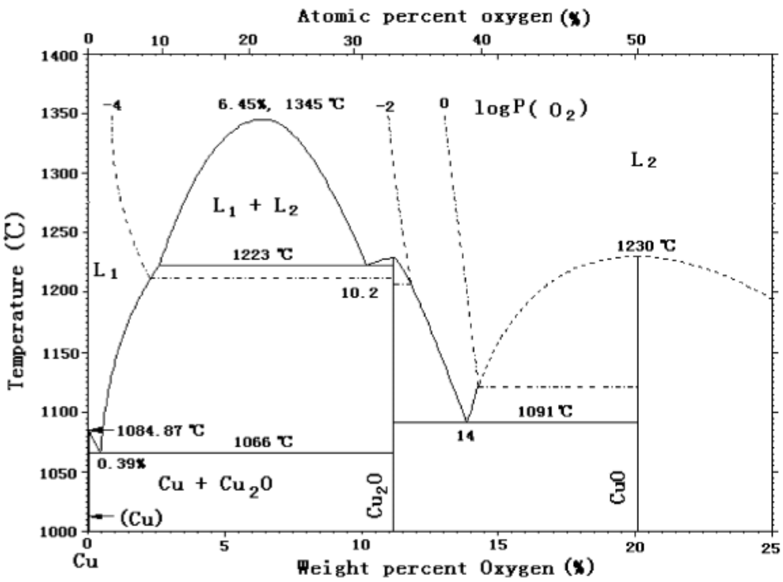

Figure 4. *Cu-O binary phase diagram [5]*

The effect of H2 is important during cooling, but it can also have negative consequences. Hydrogen atmosphere can weaken interface peel strength with temperatures above 400˚C. At lower temperatures, however, H2 atmosphere can help reduce the cuprous oxide (Cu-Cu2O), increasing the strength of the substrate. The peel strength of specimens studied show how peel strength is raised from 13.1 kg/cm to 17.1 kg/cm due this stage.

Firing Operations Using a Belt Furnace

The HSA series furnace is designed to meet the requirements needed to produce DBC. This furnace is able to reach maximum temperatures of 1150˚C. The HSA series furnace comes with a refractory heating chamber equipped with ceramic fiber FEC (fully enclosed coil) heating board. The heating works to give fast thermal response. It is able to work in the temperature range of 1065˚C to 1083˚C. Forced air or water-cooling is used in the cooling section of the furnace. The muffle design located within the furnace helps with control of atmospheric conditions, and it also helps in maintaining a cleaner environment inside the furnace. Belt cleaning is done through use of a steel brush to clean the belt. Ultrasound belt cleaning is also available for cleaning needs as an extra option.

Figure 5. *Hengli HSA Belt Furnace*

A microprocessor-based PID controller provides appropriate system control. Type K thermocouples are used in determining the zone temperatures, and the controls are located on the right hand side of the furnace, which can be viewed from the entrance. The central processing unit (CPU) is located under the exit table and is available with a Windows operating system for ease of use. A program is installed ready to control furnace parameters such as belt speed, zone temperatures, and atmospheric conditions. Additionally, temperature profiles can be stored and retrieved for future purposes. Thermocouple ports are located at the entrance table for connecting the profiling thermocouple directly into the microprocessor. This feature allows for the monitoring and recording of actual temperatures experienced by the part. Included in the software are programs for capturing/storing, displaying, and printing out the furnace profile. Additionally, the furnace is equipped with a redundant overheat safety protection system which incorporates an additional type "K" thermocouple in the center of each controlled zone and the multi-loop alarm. The specifications of a HSA 2006-0812ZNO is given below.

Specification	HSA2006-0812ZNO
Rate Temperature	1180 oC Normal operating temp: RT-1100 oC
Belt Width	200mm / 8"
Above Belt Clearance	60mm / 2.4"
Heating Length	3600mm / 142"
Insulation Cooling Length	400mm / 15.7"
Water Cooling Length	2200mm / 86.6"
Air Cooling Length	200mm / 8"
Control Zones	8
Conveyor Speed	25-150mm(1-6")/min
Heating Elements	Ceramic FEC heating board
Insulation Material	High quality ceramic fiber
Overall System Width	1200mm / 47"
Overall System Length	9350mm / 23 ft
Overall System Height	1350mm / 53"
Typical Temp. Uniformity	+/- 2 deg. C
Controlled Atmosphere	Nitrogen is standard, Oxygen as required.

Specification	HSA2006-0812ZNO
Power	480V, 3 phase, 5 wire, 60 Hz, 48 kW Heat Insulation Power Draw: 18 kW
Spare Parts	1 set of cooling fans, 1 solid state relay, 2 sets of heating elements

Conclusion

Traditional substrates use buffer layers such as molybdenum to lower the thermal expansion coefficient. DBC has taken the place of this, ensuring lower cost and higher production. The proposed HSA furnace has the capabilities to elevate to higher temperatures, maintain cross-belt uniformity, and achieve the required atmospheric conditions. At the same time, the muffle design allows the flowing of specific gasses into the required zones. To conclude, the HSA is an ideal furnace for production of quality DBC products.

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[2]. Buttay, Cyril. *Cross Section of DBC*. [Image].

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