Investigation of the Direct Plating Copper (DPC) on Al2O3, BeO or AlN Ceramic Substrates for High Power Density Applications

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Abstract

In the high power module applications, the power increasing and the size shrinking becomes one of the major topics for the power module design. Due to both the power increasing and the size decreasing, the power density of the device will be much increased. Therefore, not only the thermal conductivity and stability of the substrate material but the long-term material reliability of the substrate have to be seriously considered. For these reasons, the ceramic PCB becomes one of the best solutions. The ceramic substrates now used are normally based on Ag-printed or direct bonding copper (DBC) technology.

In the case of the Ag-printed ceramic substrate, the pattern resolution and metallization thickness are limited by the Ag-printed process. Also the combination strength of the silver and ceramic substrate by glass (which is normally mixed in the silver paste) is normally not good enough. A thermal dissipation barrier will then be formed between silver and ceramic substrate due to the poor thermal conductivity of the glass material. For the DBC ceramic substrate, DBC substrates are manufactured at 1065^{o}C by the diffusion between ceramic and Cu /CuO layer. A thicker Cu layer thickness of normally more than 300 um is required in the thermal compressing bonding process. The Cu pattern resolution will then be limited by the thickness of the Cu layer. However, the about 5~10% of the voids exist randomly between ceramic and Cu layer is the other major issue.

The resolution issues of the Ag-printed and DBC ceramic substrates make the limitation for the device density design (fine line/width and flip-chip device design become very difficult). The glass material in the Ag printed ceramic substrate and the 5~10% voids existence in DBC ceramic substrate may cause the reliability issue operating at a high power density applications.

For high power density module applications, we introduce the DPC technology on the ceramic substrate. In DPC ceramic substrate system, the sputtered Ti is used as the combination material between Cu and ceramic substrate. And the first copper is then sputtered on the top of Ti layer as seed-layer for the following Cu electrode plating (second cupper layer). By the material and the sputtering process control, several ceramic substrate raw materials can be used, such as Al2O3, AlN, BeO, Si3N4 and so on. The Ti combined/buffer layer provides good adhesion strength and material

stability. The second copper layer is plated by electrode casting plating to 3 to 5 oz. (100~150um) in thickness. The key technology of the metal trace plating is the material control of the sputter layers and the second copper layer stress release during plating.

In the DPC system, the double layers design is available. The laser drilled via holes on the various ceramic substrates is introduced. The conducting of the front and back side is connected by the following plating process. The key technology of this process is the stability of the via-holes. We have to make sure the via-holes cleaning, impurity removing and material stability during high temperature laser drilled is well controlled.

DPC ceramic substrates provide a better metal/ceramic interface uniformity and material reliability due to the stable Ti combination material and much less voids in the metal/ceramic interface. Also, the DPC ceramic substrates provide a gold pattern resolution of 50 um line space with tight tolerance of 20 um min. We believe the material characteristic make DPC a very suitable substrate material for high power module applications.

The Copper Thickness Calculation on Ceramic Substrate

In the high power module applications, lots of heat was generated during device operating. One of the major functions of the substrate material is to pass the generated heat from power device to the heat-sink material. To provide a lower substrate internal thermal resistance in the Z direction is required in these applications. Therefore, both a thinner ceramic substrate with suitable mechanical strength and a thinner copper layer thickness with enough electrical conducting ability design is one of the most important factors in the metalized ceramic substrate.

The ceramic material thickness design is widely investigated, in this paper, we providing the design of the copper layer thickness. In a power module, we assumed that the total electrical resistance is contributed by the contact resistance of the wire, wire resistance itself and trace resistance of the copper layer on the ceramic. In general, the wire bonding contact resistance is higher than that of wire itself. In our recommend design rules, the resistance of the copper trace should be < 1/3 of the equivalent resistance of the total Al wires. The electrical conductivity of the parallel Al wires (totally n Al wires) is: $\mathrm{R}_{\mathrm{Al\ wires\ equ.}} = {}^{\mathrm{R}_{\mathrm{Al\ wire}}}/_{\mathrm{n}}$; and the electrical conductivity of the copper trace is R_{Cu}.

Following picture is shown as example:

$R_{Al\ wires\ equ.} < 3R_{Cu}$ at the narrowest place that we set 3 times of the safety current capability factors for current conducting (shown as the red line in the following picture).

$$R_{Al\ wires\ equ.} = \frac{\rho_{Al}\frac{L_{Al}}{A_{Al}}}{n}\ ,$$

Where the ρ_{Al}, L_{Al} and A_{Al} are the resistivity, length and cross-section of the Al wires, respectively.

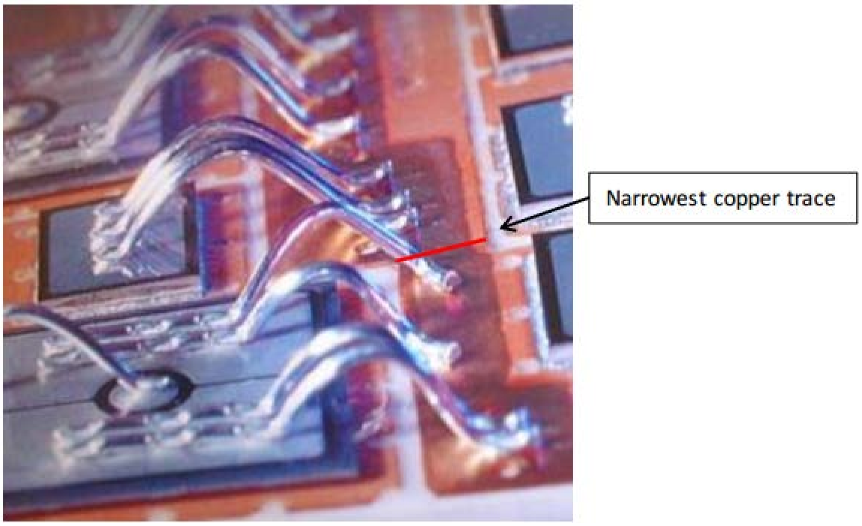


Fig.1 The Al wire bonding on Ceramic substrate

In this study, we introduced DPC with AlN substrate for IGBT application shown as following picture.

In this case, we use 5 Al wires in diameter of 200 um for IGBT device, and the narrowest Cu trace width (W_{Cu})for electrical conducting is 7mm. The request Cu thickness (T_{Cu}) can be calculated as (The Al wire length (L_{Al}) and the length of the narrowest Cu trace (L_{Cu}) are assumed as the same (L)) :

$$R_{Al\ wires\ equ.} = \frac{\rho_{Al}\frac{L_{Al}}{A_{Al}}}{n} = \frac{2.82\times10^{-8}\frac{L}{3.14\times100^2}}{5} < 3\rho_{cu}\frac{L_{Cu}}{A_{cu}} = 3\rho_{cu}\frac{L_{Cu}}{W_{cu\times}T_{Cu}}$$

$$= 3\times1.68\times10^{-8}\frac{L}{7\times1000\times T_{Cu}}$$

$T_{Cu} > 40\ \ um$

According to this calculation, in this design the Cu thickness should be more than 40 um. However, in this case, we used 100um Cu trace in thickness for following study.

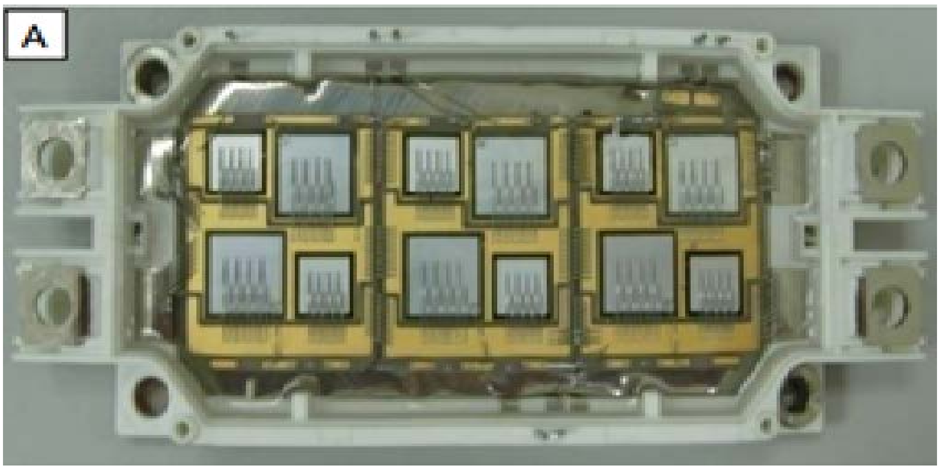


Fig.2 The DPC substrate using in the IGBT applications

Characteristics of the DPC on ceramic substrate

DPC is widely using in high power density LED application with Alumina and AlN ceramic substrate. Following figure shows the standard DPC ceramic substrate manufacturing process.

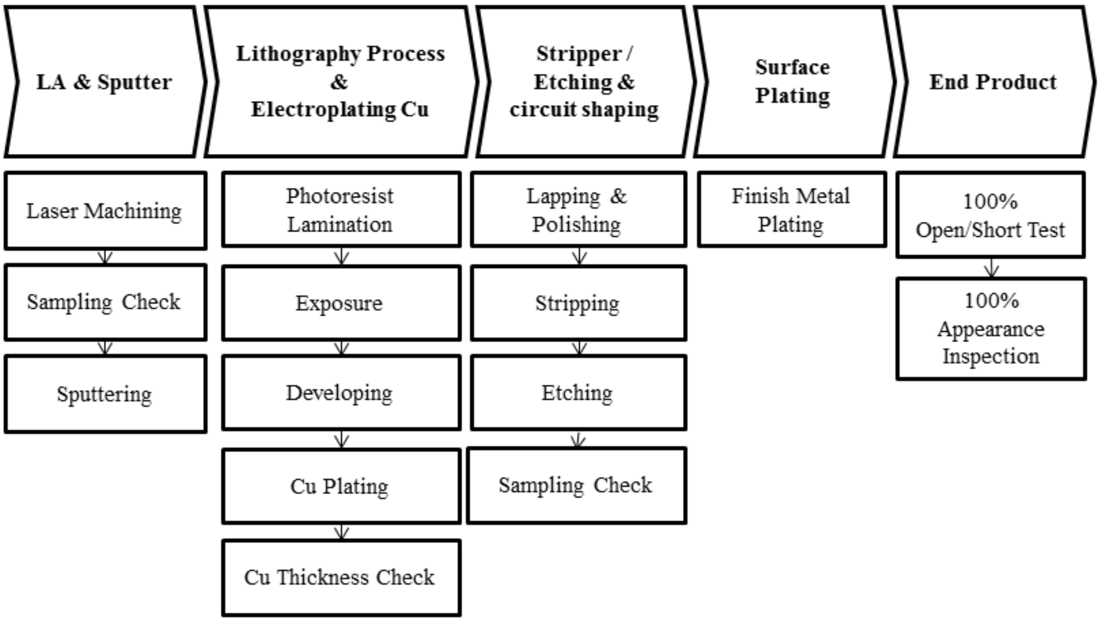


Fig.3 The standard manufacturing process of the DPC process

Comparing to direct bonding copper (DBC) or screen printed thick film (silver printed, LTCC or HTCC) substrates, DPC ceramic substrate provide a better metal/ceramic interface stability. In the high power density applications, the material uniformity and stability of the metal/ceramic interface layers of the metalized ceramic substrate is one of the most important factors for the material reliability. DPC ceramic substrate applied a thin Ti (about 50~100 nm in thickness) layer between metal (Cu) and ceramic as buffer and combination layer. This Ti layer is sputtered on to the ceramic substrate and the first copper layer is also sputtered onto the Ti layer just after Ti deposition in the same chamber. Due to material properties of The Ti material and the material deposition is in a vacuum and high power sputtering environment. This sputtered Ti layer provides a good adhesion between both copper and the Alumina or AlN.

Following Fig.4 shows the metal/ceramic interface SAT analyses of the DPC and DPC ceramic substrate, respectively. Contributing by the sputtered Ti/Cu interlayer, the rough ceramic substrate can be well deposited. Following Cu electrode plating increase the Cu thickness on the sputtered Cu layer. The electrode plated Cu layer is deposited on the sputtered Cu layer contributing a better adhesively duo to the same material connection (Cu-Cu). With the well adhesion of the Ti/ceramic, Ti/Cu and sputtered Cu/electrode plated Cu interface, the interface uniformity of the DPC substrate is better than that of DBC substrate.

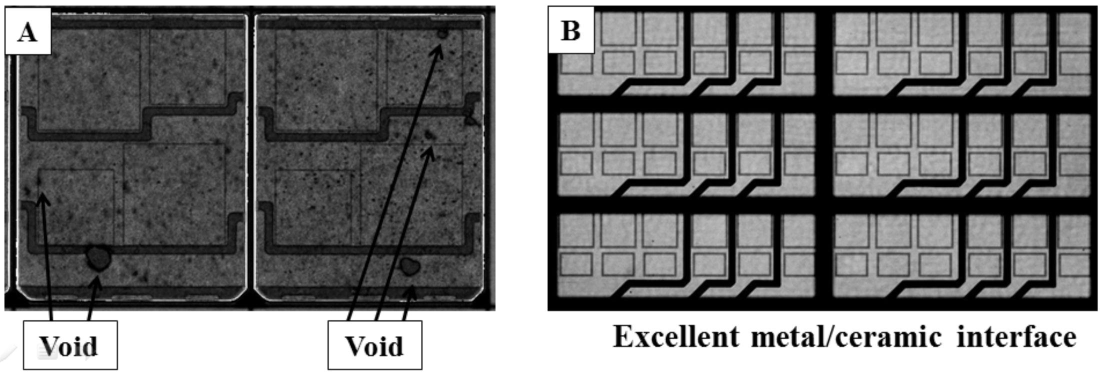
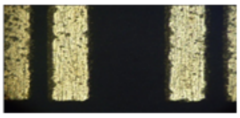


Fig.4 The SAT analyses of the metal/ceramic interface of the (A) DBC and (B) DPC ceramic substrates.

Benchmark of DPC and screen printed thick film ceramic substrate

The major different between DPC and screen printed thick film ceramic substrate is the metal trace accuracy and the bonding material between metal and ceramic. Table 1 shows the metal surface properties and the optical microscope top view of the DPC and silver screen printed thick film ceramic substrate, respectively. The DPC material contributes a better surface uniformity and roughness. Also, due to the difference of the metal/ceramic bonding material, the metal adhesively of DPC is stable than that of silver screen printed ceramic substrate.

Table 1 The metal trace characteristics of the DPC and screen printed thick film ceramic substrate

Item	**Thick film**	**Thin film**
Accuracy	+/- 10%	+/- 1%
Adhesion	Low (especially on AlN substrate)	High
Surface roughness	Low (1~3 μm)	High (<0.3 μm)
Real image		

Following Fig.5 Shows the SEM observation of the Silver screen printed and DPC ceramic substrates. In general, the screen printed metal thickness is normally in the range of 5~20um, and the metal thickness is gradually increased from the edge. On the other hand, the copper thickness of the DPC can be easily controlled from 5 to 150 um. Also, the edge shape of the DPC is related sharp. This shape different make DPC ceramic contributes a much beter chip bonding and wire bonding stability.

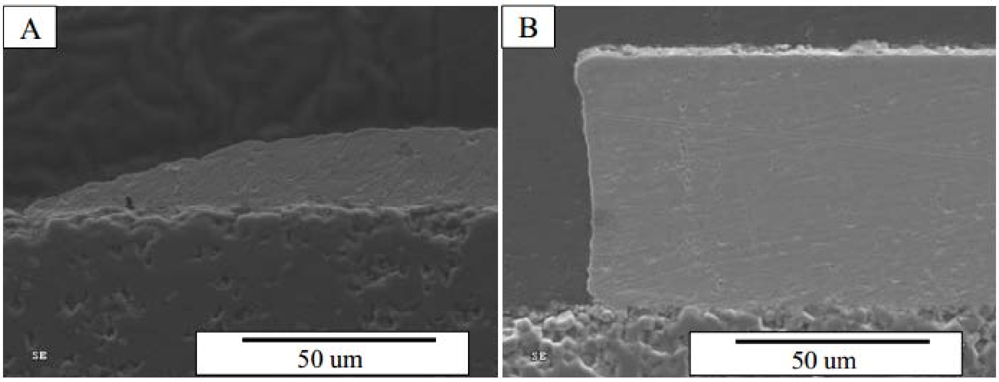


Fig.5 SEM observation of the (a) Silver screen printed and (b) DPC ceramic substrates

In the application of view, the silver screen printed ceramic substrate can be used as SMT substrate in soldering reflow process. And for the first level application with die/wire bonding process, DPC ceramic substrate can be used in soldering, flip-chip or eutectic die bonding and Au, Al or Cu wire bonding process.

Benchmark of the DPC and DBC AlN ceramic substrate in high power module

In this study, both the DPC and DBC AlN ceramic substrate is used in the IGBT module of the automotive application. Table 2 shows the typical material properties of the DPC and DBC substrate. The DBC ceramic substrate typically has a thicker Cu thickness and on the other hand, the DPC ceramic typically has a better Cu/substrate interface uniformity and Cu trace resolution.

Table 2. The benchmark of the DPC and DBC ceramic substrate

	Process Temperature	Cu Thickness	Void Rate of the Cu/Ceramic Interface	Typical Line Width/Space	Typical Dimension Tolerance	Camber
DPC Substrate	< 200ºC	10- 150um	< 1%	0.05/0.05mm	± 0.03mm	< 0.25%
DBC Substrate	~ 850ºC	≥ 200um	≈ 10%	0.2/0.2mm	± 0.15mm	< 0.4%

In this study, the Cu thickness of the DPC substrate is requirement is need to be calculated. Shown as Fig.6, this is a 100 W – 50 kW (600V/450A) automotive IGBT module. The Cu thickness is calculated by the Cu trace resistance should be <1/3 of the parallel resistance of the total aluminum bonding wires. The DPC ceramic substrate shows a good material stability and thermal dissipation behavior.

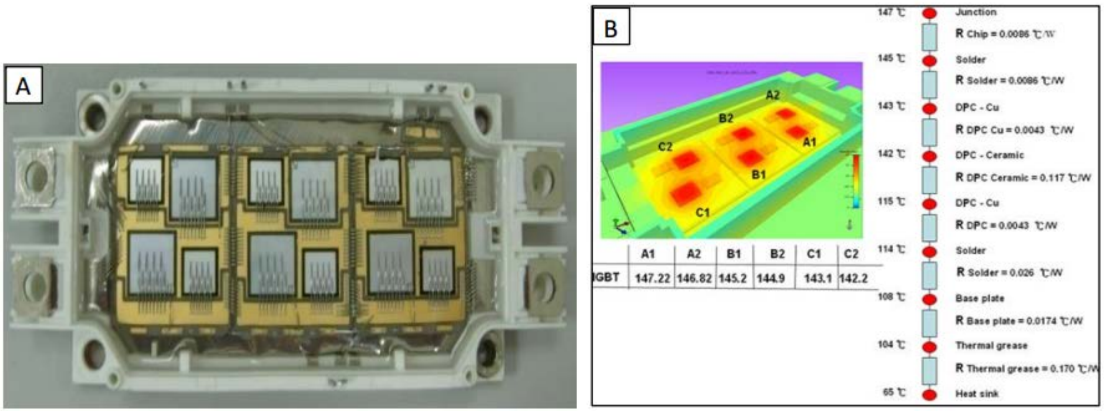


Fig.6 The DPC substrate using in the IGBT applications

Ceramic substrate for DPC

In the DPC process, the metalized process temperature is normally controlled under 200 ºC, therefore the deposited substrate could be sintered ceramic (Al2O3, AlN, SiC, HTCC or LTCC…), glass, silicon or high temperature plastic material. Due to this low temperature metallization process, the material stability of nitride-based ceramic substrate can be protected. Therefore, DPC process can be safely applied on the AlN or Si_3N_4 substrates. Also, by the sputtering deposition of Ti/Cu layer, the HTCC or LTCC can also be used as based substrate material for DPC product. The DPC surface patterning could be a good process to increase the surface pattern accuracy for both HTCC and LTCC applications. In some applications, the more than two layers ceramic substrate design is requested. In this study, the DPC on the LTCC is studied.

Conclusions

In the DPC system, the Cu and ceramic substrate is adhesive by sputtered Ti in vacuum atmosphere that the DPC contribute a good adhesion behavior between Cu and ceramic substrate. The manufacture process of the DPC is controlled under 300^{o}C that using AlN and Si_3N_4 as based material is also provide good material stability.

DPC can be deposited on many kind of the ceramic materials including of Al_2O_3, AlN, BeO, Si_3N_4, HTCC, LTCC, etc. Also, the copper layer is manufactured by photolithography process that the pattern accuracy and metal surface condition of the DPC is much better than that of DBC and screen printed ceramic substrates. The DPC process provides good options for several types ceramic substrate materials and stable material properties between metal and ceramic material. We believe that with a suitable ceramic and copper thickness design, DPC ceramic substrate is one of the most suitable substrate materials for high power applications.