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Research paper

Properties of power electronic substrates based on thick printed copper technology

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ABSTRACT

The aim of this work is to develop new metallisation procedures of 96% alumina substrates with copper using thick film technology and firing in a special batch furnace, designed for the process. Standard firing process of copper pastes is done in conveyor furnaces and it has been described in literature. The firing process in batch furnaces is characterised by different problems and it has not yet been published. The developed batch furnace can combine firing in a protective atmosphere e.g. that of high nitrogen purity gas, automated mixing of different gases, and evacuation of the furnace chamber using rotary pump. The work is concentrated on Heraeus pastes that make it possible to reach up to about 300 μm film thickness and, if needed, high resolution pattern of lower film thickness on the same substrate, metallised through holes and application of ENIG metallisation. Principles and characteristics of particular firing phases in the batch furnace as well as morphology and film properties of the fired copper films are described in the paper. The whole metallisation process proved to be effective offering high quality substrates for power electronics at reasonable investment and production costs.

1. Introduction

Superior thermal conductivity, high ampacity, and excellent dielectric strength are the key parameters for power electronic substrates. These parameters can be achieved using Direct Bonded Copper (DBC) technology that has been commonly used for many decades. The DBC technology exhibits several disadvantages that can be overcome by new prospective Thick Printed Copper (TPC) technology [1]. The conductive pattern is produced by selective printing of copper paste onto ceramic in contrast with the DBC which is based on non-selective copper lamination and its subtractive patterning by etching. The TPC technology can minimalize the amount of wasted copper and eliminates wet etching processes. Up to 300 μm thick copper film can be created in particular parts of the conductive pattern where high current should flow or high thermal dissipation is needed. However, only 20 μm thick copper film with the fine line resolution can be realized on the same substrate as well. Moreover, high reliable copper plated vias can be created by this technology [2,3].

The material savings as well as elimination of waste management makes the TPC technology cost competitive with the standard DBC technology [4]. The TPC technology is still under ongoing development and its intensive optimisation, overall testing of copper film properties, and deep understanding of copper-ceramic joint mechanisms are therefore required.

2. Materials for TPC and sample description

The TPC technology is based on special copper pastes, which can be sintered during firing process. Thick film copper paste can be applied by screen printing technique both on alumina (Al_2O_3) or lapped and oxidized AlN base [3]. Subsequently, the first print samples have to be dried at 125 °C in air and then fired in nitrogen atmosphere at temperatures above 850 °C. Next copper layers can be printed and subsequently dried on the previous layer. Our investigation showed that first copper layer should be printed, dried and fired as a monolayer, while next layers can be fired as double layers until the desired thickness is reached.

Main producers of special thick film copper pastes designed for TPC technology are Heraeus and ElectroScience Laboratories. Both producers have continuously improved parameters of their copper pastes and also relatively often they develop brand new pastes with different compositions [1,5,6].

In 2014 Heraeus introduced two new copper paste systems [7]. Firstly, the copper paste C7403, used as an adhesion layer, is printed on ceramic substrate. Further copper layers, called build-up layers, can be printed using pastes C7720 or C7404 [3]. Heraeus C7403 and Heraeus C7720 pastes have been used for the most of experiments and for the optimisation of the TPC technology in this paper. This research has

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been focused mainly on the optimisation of firing conditions in inert gas/vacuum batch furnace.

A special test pattern was designed to verify all key properties of fired copper films and to optimize the firing profile. The test pattern can be used for evaluation of the print resolution, adhesion measurement by peel and pull tests, resistivity measurement, investigation of copper metallised vias, metallographic cross sections, bonding capability etc. Test pattern can also be used for key physical parameters evaluation. Results of all the important tests are mentioned in the Section 4.

3. TPC manufacturing technology

Belt furnaces, which are usually used for firing TPC pastes, are large expensive firing systems [6,8]–[13] generally used for large-scale production. High nitrogen consumption and power consumption, problems concerning continuous and uniform filling of the furnace with substrates and high investment costs, are the main disadvantages [10].

The firing of copper films in a nitrogen belt furnace is described in literature [11,12] but the copper firing in vacuum batch furnaces or inert gas batch furnaces is not sufficiently described. Any suitable firing systems for small volume production based on a batch furnace are not available nowadays. Processing mechanisms of firing in batch furnaces are significantly different from that of belt furnaces and different phenomena during the firing can arise.

First experiments of this kind were carried out using a special gas tight retort inserted into a standard batch furnace [6]. Samples fired in the retort were generally covered with a thin oxide layer (Cu_2O), which was formed during the firing due to a high level of oxygen partial pressure in accordance with the Cu—O stability diagram (see Fig. 1). The reduction of copper oxides to pure copper can occur only when the oxygen partial pressure during the firing is decreased as shown in Fig. 1.

It can be seen that around the maximum firing temperature of copper film, there should be a partial oxygen pressure lower than 5.10^{-8} bar. Such a low level of oxygen pressure in the furnace can be achieved only by using high vacuum, by using inert gas of a high purity such as nitrogen, or by the combination of both. When the copper film is already oxidized prior the firing or when the Cu_2O film is formed during the temperature rise, it can still be reduced when the oxygen pressure is held below the mentioned limit at the firing temperature.

Based on the previous knowledge of copper pastes firings in the retort, a new batch inert gas/vacuum furnace was developed and optimised. Maximum firing temperature of the furnace is about 1000 °C. The vacuum levels in the furnace pumped with rotary pump do not allow reaching levels shown in the phase stability diagram (Fig.1). Nevertheless, it can be used to pump off the gases in the furnace during the firing process if necessary. Substrates in the furnace can be fired in inert nitrogen or argon atmospheres at atmospheric pressure or even in inert atmosphere at a reduced pressure (down to about 5.10^{-5} bar). It has been proven that firing in inert atmosphere leads to a low level of copper film oxidation. To ensure both non-oxidized copper film and high adhesion of copper to alumina substrates, the firing profile and other key parameters have to be thoroughly optimised. Key parameters include e.g. water vapour content, content of gases produced during the paste organics removal in the "burn out" firing phase, and similar.

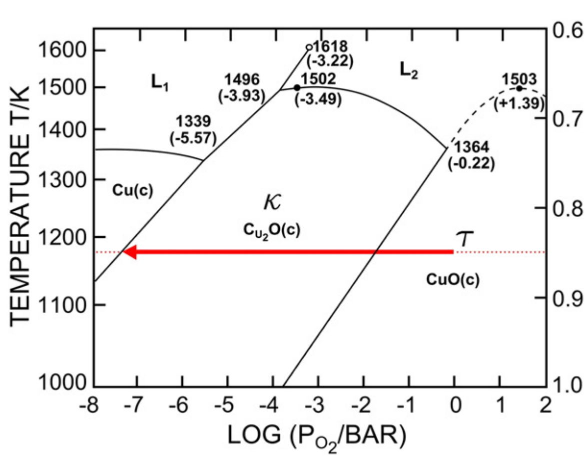

Fig. 1. Cu—O stability diagram [14].

4. Results and discussion

The copper film firing process in inert gas/vacuum furnace is significantly different from that in a belt furnace. We have designed and verified the completely new firing procedure. The typical firing process in the batch furnace is shown in the Table 1.

All commercially available copper pastes for TPC technology are generally designed to be fired in nitrogen belt furnaces. Their firing in a batch furnace requires deep knowledge of the paste behaviour during firing. The example of the thermogravimetric analysis (TGA) of the Heraeus C7403 and Heraeus C7720 pastes is shown in the Fig. 2. The analysed copper paste C7403 contains at least two different types of organic components (see changes in the slope of the curves in Fig. 2). The main organic component of the paste is a thinner (~6.1 wt.%) which adjusts the viscosity of the paste to be easily printable by screen printing technique. It can be removed at the temperature below 200 °C. The second organic component of paste (~3.6 wt.%) protects copper particles against oxidation. This component decomposes at the temperatures up to 400 °C. Copper paste C7420 has more complex composition, but almost all organic components can also be removed until the temperature reaches about 400 °C.

Based on the Heraeus data sheets and on the course of the curves in the Fig. 2 it is possible to set the right temperature level of the organics burn out period and the start of the atmosphere contaminants removal (Table 1).

For proper copper film adhesion, the glass phase presence in the particular paste is very important. In the Fig. 3, there are pictures taken with a scanning electron microscope showing the surface of the printed copper pastes after printing before drying and firing. We can see copper spheres and different glass components. Energy-dispersive X-ray spectroscopy (EDX) was used for the identification of glass phase composition. The paste C7403 contains two different types of glass phases. The first representative of glass particles marked with the dagger no. 2 showed the following elements: silicon 16.4 at.%, bismuth 7.5 at.%, oxygen 62.9 at.%, aluminium 2.7 at.%, carbon 4.1 at.%, copper 2.8 at.%, sodium 2.9 at.%, and titanium 0.6 at.%. The second representative of glass particles marked with the dagger no. 3 showed the following elements composition: bismuth 28.7 at.%, oxygen 55.7 at.%, carbon 7.1 at.% and

Table 1
Typical phases of the firing process in the batch furnace for firing copper films.

	Firing phase	Characteristics
1	Flushing of the furnace and removal of air contamination of the furnace	Nitrogen flushing and pumping off the furnace contamination by air down about 5.10^{-5} bar
2	Paste organics burn out phase	Heating printed substrates in nitrogen with an optimised content of oxidising gases, e.g. oxygen, water vapour, carbon dioxide and similar
3	Removal of contaminants of the furnace atmosphere	Pumping off the furnace atmosphere at flushing by high purity nitrogen
4	Heating the furnace up to the temperature desired	Conditions according to the paste data sheet, usually from 850 °C to 950 °C
5	Dwell time	According to the paste data sheet, usually 10 min
6	Furnace cooling	According to the furnace construction down to about 70 °C