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Spark Plasma Sintering constrained process parameters of sintered silver paste for connection in power electronic modules: Microstructure, mechanical and thermal properties

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HIGHLIGHTS

- The sintered silver joints have nanometric structure.
- The grain growth was controlled by the SPS sintering parameters.
- New connection material improve thermal and electrical properties of current solders.
- Interconnection's plastic strain can absorb thermo-mechanical residual stresses.
- A power semi-conductor chip was successfully connected to a substrate by SPS.

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ABSTRACT

Processing parameters of Spark Plasma Sintering (SPS) technique were constrained to process nano sized silver particles bound in a paste for interconnection in power electronic devices. A novel strategy combining debinding step and consolidation processes (SPS) in order to elaborate nano-structured silver bulk material is investigated. Optimum parameters were sought for industrial power electronics packaging from the microstructural and morphological properties of the sintered material. The latter was studied by Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) to determine the density and the grain size of crystallites. Two types of samples, termed S1 (bulk) and S2 (multilayer) were elaborated and characterized. They are homogeneous with a low degree of porosity and a good adhesion to the substrate and the process parameters are compatible with industrial constraints. As the experimental results show, the mean crystallite size is between 60 nm and 790 nm with a density between 50% and 92% resulting in mechanical and thermal properties that are better than that of lead free solder. The best SPS sintering parameters, the applied pressure, the temperature and the processing time were determined as being 3 MPa, 300 °C and 1 min respectively when the desizing time of the preprocessing step was kept below 5 min at 150 °C. Using these processing parameters, acceptable for automotive packaging industry, a semi-conductor power chip was successfully connected to a metalized substrate by sintered silver with thermal and electrical properties better than those of current solders and with thermomechanical properties allowing absorption of thermoplastic stresses.

1. Introduction

Automotive industry is involved in the production of eco-friendly electric power steering hybrid electric vehicles (HEV) and electric vehicles (EV). As a result, considerable efforts are spent on

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the development of power electronics modules switching at high frequencies and operating at temperatures, between 170 °C and 200 °C [1]. In such a device, an assembly of different components in a housing potted with a polymer-based material as shown in Fig. 1, the electrical current is the source of a very large amount of heat when the die (IGBT) operates as a switch. Hence the interconnection solder supporting this heat flux must have not only good transport properties, but also good mechanical strength to support strong thermo-mechanical stresses as shown by Tummala et al. [1].

Moreover as discussed by Knoerr and Schlettz [2], traditional solders cannot withstand the above temperature range (170 °C–200 °C) because it is 60% above their melting points. Note that materials having a soldering temperature higher than 320 °C cannot be used either because of the presence of plastic components.

New technology choices and lead free materials to comply with ROHS [3] (Restriction of the use of certain Hazardous Substances in electrical and electronic equipment), compared to conventional packaging process, must therefore be investigated to meet the needs of current density, voltage, and thermal management in these power electronic modules. At the same time, the packaging process must be compatible in size, weight and cost reduction and lead to a more compact robust device with increased 3D capabilities.

The present work is motivated by this context and concerns the sintering of silver particles for interconnections in power electronics of packaging automotive industry. Silver paste with micrometric aggregates is commonly used in microelectronics for its excellent electrical conductivity (6.30 Sm^{-1}), thermal conductivity (429 $W\,m^{-1}\,K^{-1}$) [4,5] and high melting temperature (961 °C) [6]. Sintering temperature being too high (>600 °C) for packaging technology as shown by Zhang and Lu [7], and pressure-less conditions unsuitable for robust interconnections as shown by Dahoo et al. [8], an external pressure is applied to lower the sintering temperature, as previously demonstrated [7,9–11]. An innovative low cost industrial packaging process from Low Temperature Joining Technology (LTJT) [12] applied to silver paste with nano or micro inclusions is investigated in order to develop a new strategy combining debinding step and consolidation processes (SPS), and elaborate nanostructured silver bulk material.

SPS technique, which is attributed to Inoue from his patent published in 1966, has been fully described in a review article [13] on the fundamental concepts and physical principles of a broad class of methods and apparatuses based on electric current activated/assisted sintering (ECAS). Development in this field is ever growing and in this respect, new methods using electrical sintering of nanoparticles are being explored [14–17]. Fu et al., [14], for

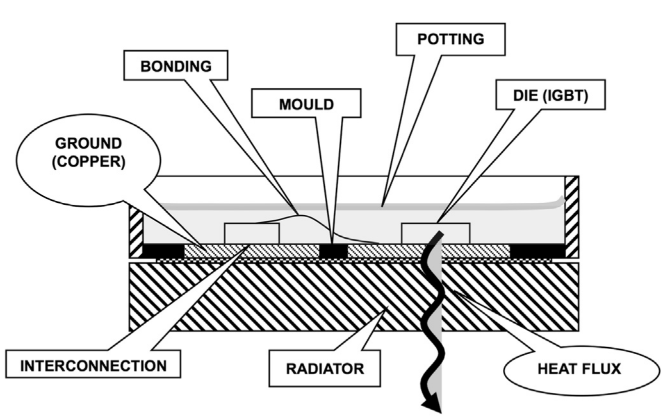

Fig. 1. Schematic of a power electronics module with the connection material between an IGBT chip and a copper substrate and the heat flux direction.

example, using Ag nanopowders prepared directly by the electro-explosion of wire (EEW) process showed that SPS can indeed be used to sinter Ag nanopowders even at low pressure within only 5 min. The density and porosity are then found to depend on the sintering temperature. Mei et al. who investigated current-assisted sintering technology (CAST) [15,16] as an innovative method for sintering nanosilver in power electronic applications, report bonding of bare copper to a copper substrate in less than 1 s.

In this work, Spark Plasma Sintering (SPS) is used for the sintering, under applied pressure, of a silver paste. The main purpose is to determine the optimum constrained process parameters which are the applied pressure, the sintering temperature and dwell time (P, T, and t). To meet industrial constraints, it is required to operate at a low pressure (below 5 MPa to prevent chip fracture), a low temperature (below 320 °C) and within a short processing time (less than 5 min). The criterion for optimization is based on the correlation between these sintering parameters (P, T, and t) and the microstructural and morphological properties of the sintered material which directly impact on its electrical and thermal conductivities as well as on its mechanical strength.

Micro-sized aggregates of silver paste sintered to interconnect die to copper plated base (DCB) coated with Ni/Ag to optimize adhesion with silver paste were prepared. Specific assemblies were studied for their physical transport properties and mechanical strength. Connections and interfaces with other layers were characterized at a microscopic scale. We used scanning electron microscopy (SEM) and X-ray diffraction (XRD) to determine the density and the size of crystallites.

In Section 1, in a first time, a brief description of the two types of samples and the SPS technique are given. In a second time, the different characterization methods used to study the sintered samples in terms of density and crystallite size with the corresponding range of the processing parameters (P, T, t) are described. In Section 2, the different results obtained are discussed with respect to the effect of processing parameters on density, on crystallite size and on the microstructure of SPS samples. Then, mechanical, thermal and electrical properties of the samples are dealt with.

2. Experimental

2.1. Samples preparation

Silver paste from Ferro Company was used to prepare the samples to be sintered. It consists of nano particles of silver having an average size between 15 nm and 20 nm as given by Ferro Company. Upon observation by SEM, it is found that the silver particles form aggregates with a mean diameter of 0.3 μm dispersed in the binder.

A processing step prior to sintering is necessary to avoid formation of cavities with graphite inclusions, which results in poor conductive and mechanical properties of sintered silver. It consists in heating the paste at a temperature of 150 °C to remove the binder within a given period of time (desizing time). Two types of samples termed S1 and S2 were prepared from silver paste, in bulk form (S1) as a solid sample and as a multilayer (S2) sandwiched between two substrates. The former was used to study the microstructure of the sintered material and the latter to study surface effects and the interface between the silver deposit and the substrate.

For S1 samples, the paste was deposited on a plate while controlling the thickness of the deposit. The plate was then heated in an air oven during different desizing times, 25 min, 5 h or 10 h. After the organic matrix was removed, the paste was crushed into a powder consisting of aggregates with the initial average diameter of 0.3 μm before being sintered.