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Abstract: Pressureless silver sintering is an interesting die-attach technique that could overcome the reliability limitations of the power electronic devices caused by their packaging. In this paper, we study the manufacturing parameters that affect the die attach: atmosphere, drying time, heating ramp rate, sintering temperature and duration. It is found that sintering under air gives better results, but causes the substrates to oxidize. Sintering under nitrogen keeps the surfaces oxide-free, at the cost of a weaker attach.

Introduction

Silicon carbide devices are extremely attractive for high power applications. In particular, they can operate at high power density (more than 100 W/cm²), and the high thermal conductivity (3.7 W/cm²/K) of SiC facilitates their cooling. However, the power devices themselves are no longer the only limiting factor for the increase in operating temperature. Their packaging has become the main stumbling block for reliable operation. Different degradation phenomenon can be observed: fracture of the package during large thermal cycling (due to mismatch in the Coefficient of Thermal Expansion of the various materials), diffusion of chemical species, phase change...

The die attach is one of the packaging function that must be improved. Alternative techniques to the classical solder alloys have been proposed, including solders with higher melting temperatures, adhesives, silver glass, diffusion bonding, and silver sintering [1].

This latter solution is very promising: silver has the higher thermal conductivity of all metals (429 W/m.K, on par with that of SiC). Its electrical conductivity is also excellent. It is non-toxic, and has a melting point much higher than that of the soldering alloys (961°C). Silver sintering has been demonstrated with process temperatures ranging from room temperature [2] to 300°C [3]. Currently, most of the sintering processes require some pressure (from a few MPa to 40 MPa) to be applied on the devices during the process. This is unpractical, as it requires dedicated apparatus and may damage the devices. In this article, we present an assessment of a pressureless process for die attach on copper substrates under different atmosphere using silver paste. A design of experiment (DOE) has been used to evaluate the main effects of the different factors corresponding to the process such as the drying time and sintering temperature. In order to determine relevant levels for those factors, preliminary trials have been performed.

Experimental procedure

The test vehicle used for this study is a 25x30 mm DBC substrates. Substrates are cleaned using ethanol/acetone/diluted hydrochloric acid/deionized water/ethanol and then dried using a nitrogen blow nozzle. Silver paste (Heraeus 117-02P2) is then printed on the substrates using a 50 µm-thick stencil. 3x3 mm Si dummy chips are then placed on top of the fresh silver deposit using a die bonder to control the force applied during die placement (JFP PPOne).

A drying step is then applied to the assembly to allow the solvent to be removed from the paste before reaching the sintering temperature. The sintering temperature is maintained for a given time

to allow the silver to diffuse into the copper and into the backside finish of the die. During the sintering, silver also diffuse into itself and then densifies by creation of bridges between the grains and so reduction of the porosity.
The thermal treatment is performed on a hot plate for air atmosphere configuration and in a lamp furnace for the nitrogen atmosphere configuration.

Preliminary trials

Regarding the drying step, TGA (thermogravimetric analyses) were performed (under air only) to evaluate the weight loss of the silver paste (solvent loss) at 80°C. During this trial, a Si die was placed on the silver paste in order to be representative of the real process. The curve shows that nearly 5 min after reaching 80°C, half of the solvent is gone and after 35min, almost all of it is gone (see Figure 1). Consequently, for the drying time factor, levels have been chosen to be 5 and 35min. A fast heating rate is considered beneficial regarding the density of the final silver sintered joint but could generate voids if too much solvent is still present in the paste. Relevant sintering temperatures were deduced from the DSC (Differential Scanning Calorimetry) measurements under air and nitrogen (see Figure 2). It appears that the exothermic peaks are less important for sintering under nitrogen than under air (scales on vertical axis are different). Therefore we can suppose that silver is less reactive under nitrogen.

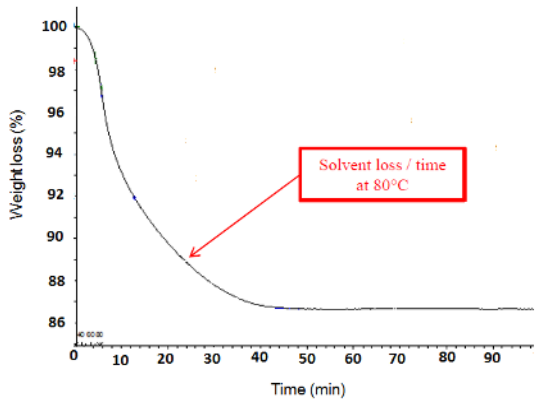

Figure 1 : TGA analysis of an assembly under air

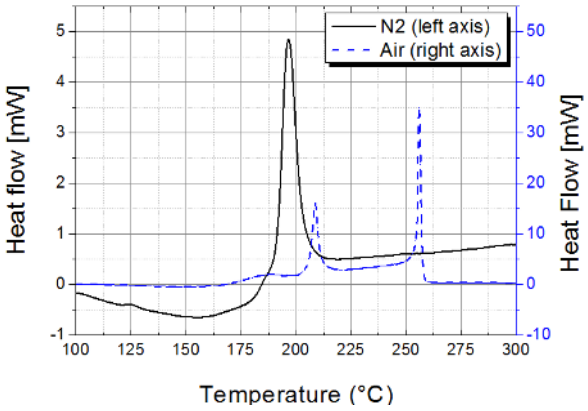

Figure 2: DSC measurement on silver paste under air and nitrogen (scale is different for the curves)

DSC's results are in good accordance with the scanning electron microscope pictures taken from silver sintered under air and nitrogen (see Figure 3: all pictures are at a magnification of 20 000X except Figure 3 c) which is at 5000X). Grain growth and morphological changes under nitrogen are less important than under air. However, bridge formation between silver grains that lead to mechanical strength still occurs under nitrogen (see Figure 3 b). Considering that all the reactions are taking place between 200°C and 300°C but that the densification is expected to be very slow at 200°C, chosen levels were 250°C and 300°C. The sintering duration levels were chosen according to the literature.

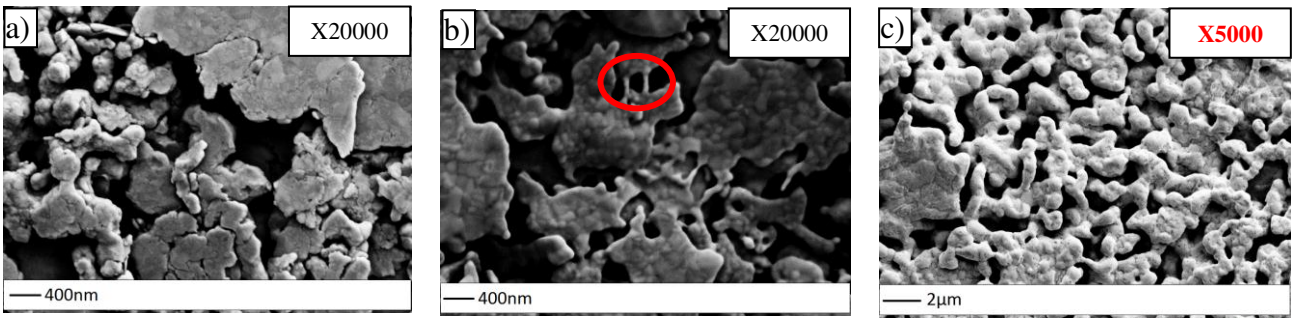

Figure 3: SEM pictures of silver sintered joint (300°C) a) Non sintered b) sintered under nitrogen c) sintered under air

Design of experiment (DOE) parameters

The effect of the process parameters (see Figure 4) on the die shear strength was evaluated using a fractional design, called John's ¾ [4]. The particularity of this type of DOE is that it is possible to evaluate the main effect of the different parameters and the effects induced by coupling between parameters doing only ¾ of the trials. The disadvantage of this DOE is that it is less easy to analyze because it requires the use of least square method (the DOE's matrix is not orthogonal) instead of mean comparison. The experimental matrix is presented in the Table 1.

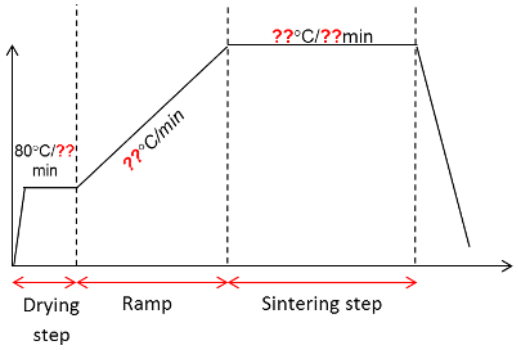

Figure 4 : Process parameters (factors of the DOE)

	Drying duration (min)	Ramp (°C/min)	Sintering temperature (°C)	Sintering duration (min)
1	5	10	250	15
2	35	70	250	15
3	5	10	300	15
4	35	10	300	15
5	5	70	300	15
6	35	70	300	15
7	5	10	250	60
8	35	10	250	60
9	5	70	250	60
10	35	70	250	60
11	35	10	300	60
12	5	70	300	60

Table 1: Experimental matrix

Results

For each of the 12 configurations of the DOE performed under air and nitrogen, at least 8 dies were shear-tested. The results given in Figure 5 show that most configurations satisfy the MIL-STD 883 standard [5] (2.72 MPa on a 9 mm^2 die) either under air or nitrogen. Under air, configurations 2 (35 min drying, 70°C/min ramp, 250°C and 15 min sintering) and 6 (identical, with 300°C sintering) give the best results. Under nitrogen, configuration 3 (5 min drying, 10°C/min ramp, 300°C and 15 min sintering) and 10 (35 min drying, 70°C/min ramp, 250°C and 60 min sintering) give the best results. Surprisingly, sintering under oxidizing atmosphere gives better results than under nitrogen. Regarding the main effects and interactions for the samples sintered under air (see Figure 6, Figure 7), it is possible to say that the die shear strength is related to the oxidization degree of the substrate. After die shear test, it is possible to see copper oxide under a thin silver layer on substrate side (see Figure 7a). This is observed for the configuration sintered at 250°C for 15min, so for a thin copper oxide layer. For the sample sintered at 300°C for 60 min with a slow ramp, un-oxidized copper is observed on the substrate after die shear test and copper oxide is present on the die side (see Figure 7b), which means that for thick copper oxide layer, the weak point is no longer the silver/copper oxide interface but the copper oxide/copper one.

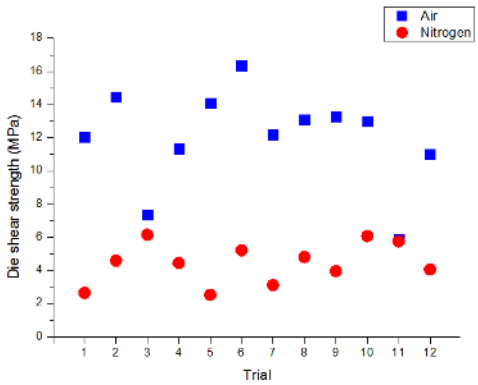

Figure 5 : Die shear strength results (error bars were removed for legibility)

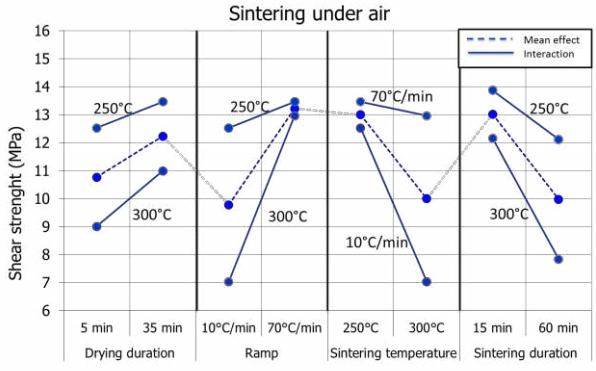

Figure 6: Main effects and interactions for samples sintered under air

For the assemblies under nitrogen, it appears that the bond between the copper and the silver is not strong even for sintering with the highest temperature and time of the DOE (a small amount of silver remains on the copper after die shear test, see Figure 7c). Main influence for sintering under nitrogen could be the drying of the paste. According to Figure 8, increasing the drying duration is beneficial for the process and there is a huge interaction between the drying duration and the ramp rate. A fast ramp with a short drying could lead to solvent elimination issue. Consequently drying of the paste is expected to be different under air or nitrogen and to have a big influence of the strength of the bond. Increase of the die shear strength when increasing the sintering temperature and sintering duration is expected to be due to a more significant densification because more energy is applied for the system.

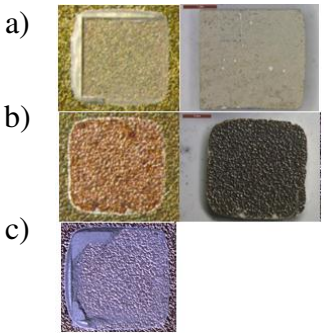

Figure 7 : Substrate (left)/die backside (right) side after die shear test.
a) low temperature and short sintering under air
b) high temperature and long sintering under air
c) sintering under nitrogen

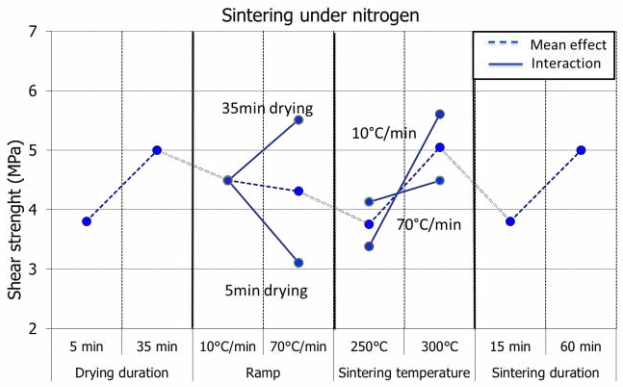

Figure 8: Main effects and interactions for samples sintered under nitrogen

Conclusion

A very simple sintering process has been presented (performed in air or nitrogen, without any pressure applied on the devices, and with process times comparable to that of soldering). When processing under air, a strong bond seems to be established between copper oxide and the sintered silver. Growth of the copper oxide layer could lead to failure of the bond by delamination of the copper oxide layer from the copper during ageing or thermal cycling if not encapsulated. Surprisingly, processing under nitrogen lead to a weaker bond than under air, but the bond is made directly on the copper and keeps the copper surface oxide free for further operation (wire bonding etc).

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