Research on Reliability of Nano Silver Tin Pulp in Flip Chip Solder Joint

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Research article

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Abstract

In order to improve the interconnect properties of nano-silver solders, we have developed a new tin-doped nano-silver paste (referred to as silver tin paste). The hard brittle phase Ag_3Sn formed by the soldering of the silver tin paste acts as a second phase strengthening effect, which significantly improves the shear strength of the solder joint and has the potential to be widely used in the power electronics packaging industry. In this paper, the viscoplastic and elastic composite model is used to simulate the inelastic deformation behavior of flip chip nano silver tin solder joint under uniaxial shear load. The simulated stress-strain response curve agrees well with the experimentally measured data. The finite element method is used to simulate the interconnection state of flip chip solder joints under thermal cycling conditions. It can be seen that the inelastic strain of the silver tin solder joint has increased, and it can be inferred that as this strain increases further, the chip connection will be broken. The fatigue life of silver tin paste is predicted by the creep fatigue life model. Compared with the pure nano silver paste, the equivalent plastic strain of the silver tin paste is reduced and the fatigue life is significantly improved. It is indicated that the solder joint reliability of nano silver paste can be improved by tin doping. The analysis results provide reference data for the development of new nano solder.

1. Introduction

At present, high-temperature power device chip bonding often uses nano silver paste sintering method, and the joint formed by sintering of nano silver paste has good electrical and thermal conductivity ^[1], but there are also the following problems:

- (1) The sintering temperature of the nano silver paste is in the range of 300 ° C to 400 ° C. This high heating temperature is not compatible with other packaging materials ^[2].
- (2) The intermetallic compound is not formed after the nano silver paste is sintered, and the joint shear strength is low.

Therefore, it is imperative to improve the sintering performance of nano silver paste. There are two general methods. One method is to use a short-chain organic surfactant as a dispersing agent in the preparation of the nano-silver. Generally, such organic matter has a relatively low thermal decomposition temperature and can lower the sintering temperature. However, this makes the dispersibility of the nano-silver worse, increasing the risk of agglomeration of the nanoparticles; the other method is to reduce the particle size of the nano-silver particles, and the melting point of the nanoparticles decreases with the decrease of the particle size, thereby lowering the sintering temperature. However, this makes the production process complicated and costly ^[3], which is not conducive to large-scale industrial applications. Adding low-melting alloy elements is a good way to improve the sintering performance of nano-silver solder paste. Among the doped metals, the melting points of tin, indium and gallium are relatively low, but the cost of indium and gallium is relatively high, so we choose nano tin as the Dopant. The sintering process of tin-doped nano-silver is divided into four stages of dissolution, diffusion,

solidification and reaction. As the sintering temperature increases, nano-tin diffuses into the nano-silver. When the Sn melts, the diffusion speed will increase. The liquid phase Sn will contact the solid phase Ag, and the liquid will rise or penetrate along the gap, thereby rapidly diffusing uniformly in the matrix, resulting in matrix lattice changes; after the solidification process, the reaction forms an intermetallic compound IMC phase. Finally, an Ag-based replacement solid solution and a uniformly distributed Ag_3Sn are obtained. The Ag-based replacement solid solution acts as a solid solution strengthening, and Ag_3Sn acts as a second phase strengthening, thereby increasing the shear strength of the joint [4, 5].

Through my previous experiments, it was determined that the sintering performance of the slurry was the best when the tin content was 5%. According to this ratio, the volume of the Ag_3Sn particles was about 20% of the volume of the Ag matrix. In this silver tin solder paste, the reinforcing phase Ag_3Sn particles are very hard, and the plastic deformation of the solder joint is mainly caused by the Ag matrix. Therefore, this paper will regard Ag_3Sn particles as elastic materials and matrix Ag as viscoplastic materials, which are described by Anand unified viscoplastic constitutive model [6]. The uniaxial shear and thermal cycle loading processes were simulated by the finite element method, and the fatigue life of the flip chip solder joints was predicted.

In this study, a series of uniaxial shear tests were performed on flip chip solder joints of silver tin paste. The reason why shear is introduced into the solder instead of the stretching mode is that the plastic instability caused by necking during stretching can be avoided, and a large strain can be obtained when shearing [7].

2. Shear Experiment

2.1 Experimental process

The flip chip used in this article is customized by Wuxi Huajin Semiconductor Co., Ltd., which is a silicon chip containing 54 diameters of 100um solder joints, as shown in Fig. 1.

a) Flip chip (Upper chip) (b) Substrate (Lower chip)

The bottom plate is a silicon substrate, and the sample in which the chip and the substrate are welded together by silver tin paste is used for stress strain measurement. The experiment was carried out on a shear tester Dage 4000, the new material was tested for uniaxial shear at three different shear strain rates, high, medium and low, and at various temperatures ranging from room temperature to high temperature.

2.2 Experimental results

The shear stress-strain curve of the sample is given in Fig. 2. From Fig. 2, the relationship between the temperature and the stress of the silver tin solder joint can be obtained. In the case of the same strain, the

certain extent, the shear strength is significantly reduced. The relationship between the strain rate and the stress of the silver tin solder joint can also be seen by comparing the three graphs a, b, and c. At the same temperature, the shear strength is proportional to the strain rate, that is, the shear strength increases as the strain rate increases. At the same time, from Figure. 2, it can be seen that the simulation curves of the finite element agree well with the experimental data.

3. Finite Element Simulation

3.1 Anand constitutive equation and parameter fitting

The Anand model is a viscoplastic model of metal thermal work proposed by Anand and Brown [8]. Suitable for describing large viscoplastic and small elastic deformations. The characteristics of the unified viscoplastic Anand constitutive model are as follows:

- (1) There is no clear yielding phenomenon during the stress loading process, so the load formula is not required as the standard in the plastic flow process, and the inelastic strain is generated under any size of loading.
- (2) The unique internal variable is used to express the macroscopic impedance of the internal state of the object to the inelastic flow. Internal variable (deformation impedances) are marked with s [9].

The relationship between the saturation stress and the strain rate of the viscoplastic Anand model is as follows:

$$\sigma^* = \frac{s'}{\xi} \left[\frac{\varepsilon_p}{A} \exp \left(\frac{Q}{RT} \right) \right]^n \sinh^{-1} \left\{ \left[\frac{\varepsilon_p}{A} \exp \left(\frac{Q}{RT} \right) \right]^m \right\} \quad (1)$$

The relationship between stress and strain at different temperature and strain rates:

$$\sigma = \sigma^* - \left\{ (\sigma^* - cs_0)^{(1-\alpha)} + (\alpha - 1) [(ch_0)(\sigma^*)^{-\alpha}] \varepsilon_p \right\}^{\frac{1}{(1-\alpha)}}, \alpha \neq 1 \quad (2)$$

The above equation contains the nine parameters of the Anand constitutive equation:

$A, \frac{Q}{R}, \xi, s', n, m, \alpha, h_0, s_0$, They are constant, activation energy/ gas constant, stress multiplier, deformation impedance saturation coefficient, strain rate sensitivity, strain rate sensitivity index, strain hardening parameter, strengthening coefficient, and initial value of deformation resistance.

Their values can be determined by:

- 1) Obtaining a saturation stress value according to a uniaxial shear test;
- 2) Fitting by equation (1) by least squares method $A, \frac{Q}{R}, n, m$ and s'/ξ ;
- 3) cs_0 , ch_0 and α of equation (2) the normal strain rate data is obtained by least squares method [11].

According to the formula derivation and calculation, the parameters of the constitutive equation model of the nano-silver matrix are shown in Table 1 [10].

Table 1
Anand model parameters of nanosilver matrix

$A(s^{-1})$	$Q/R(1/K)$	m	n	ξ	$s' (MPa)$	$h_0 (MPa)$	$s_0s_0(MPa)$	α
9.81	5709	0.6572	0.00326	11	67.389	15800	2.768	1

3.2 ANSYS finite element model

The simplified model consists of two parts. The upper and lower symmetrical part is a silicon chip, and the middle is a copper pillar and a silver tin paste sintered layer solder joint. The dimensions of each component are shown in Table 2. According to the previous experiment, the Ag_3Sn particle diameter was $0.4 \mu m$. According to the volume content of 20%, there were about 32 Ag_3Sn spherical particles in one solder joint, which were evenly distributed in the silver matrix. In the finite element analysis software ANSYS, since the chip has a completely symmetrical structure, a 1/4 model is selected for research, and a simplified 2D FEM model is used for modeling and meshing, as shown in Fig. 3 and Fig. 4. The material of each component is shown in Table 3 and Table 4 [11]. Since the Anand model is used for the research of

nano-Ag matrix in solder joints, the choice of unit type is viscoplastic unit VISCO107, Ag₃Sn particles and other components in solder joints are regarded as elastomers, so entity unit SOLID45 is selected. ^[12].

Table 2
Component size

Material name	Silicon chip	Silver tin slurry layer	Upper copper column	Lower copper column	Ag ₃ Sn
Size(m)	a = b = 6E-3 H = 1.1E-3	D = 1.0E-4 H = 0.2E-4	D = 1.0E-4 H = 0.45E-4	D = 1.0E-4 H = 0.15E-4	D = 0.4E-6

Table 3
Material properties of each component

Ingredient	Young's Modulus(GPa)	Poisson's ratio	Thermal expansion coefficient (10 ⁻⁶ /°C)
Silicon	131	0.3	2.8
Copper column	110	0.34	16.4
Ag ₃ Sn	80	0.35	18
Nano Ag matrix	as follows	0.38	19.9

Table 4
Young's Modulus of Nano Silver Matrix at Different Temperatures

temperature (°C)	-50	0	25	60	120	150
Young's Modulus(GPa)	9.00	8.00	6.25	4.50	2.65	1.60

3.3 Loading loads and boundary conditions

The thermal cycle loading is determined according to various conditions that may be encountered during the service process. The temperature range is – 50 °C~150 °C, the lifting temperature rate is 25 °C/min, the temperature is raised to the highest temperature for 10 min, and the lowest temperature is kept for 10 min, and the cycle time is 36 min. It has been studied that the stress and strain of the solder joints show periodic changes during the thermal cycle. Generally, after loading several cycles, and the results will tend to be stable. This model calculates 5 cycles ^[13], as shown in Fig. 5.

The substrate is mounted on the fixture, and the bottom surface of the lower chip can be applied with zero displacement constraints in each direction, and the two symmetrical planes of the flip chip are

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 t constraints.

4. Calculation Results And Discussion

Alternating changes in displacement and strain occur within the flip chip interconnect material after several thermal cycling conditions have been applied. Figure 6 shows the displacement and strain cloud diagram of the flip chip and solder joint after several thermal cycling conditions. In Fig. 6a, it can be seen that the maximum displacement of the solder joint appears at the center solder joint of the chip. The reason for the analysis may be that the heat dissipation effect at the center is poor and it is a dangerous area. As shown in Fig. 6b, after the end of the thermal cycle loading, there is a large displacement at both ends of the dangerous solder joint, and the displacement at the center of the solder joint is not large. Figure 6c shows that the strain at the contact between the solder and the copper column is large. The main reason is that the thermal expansion coefficients of nano-silver and copper are different, misalignment occurs, and no intermetallic compound is formed between silver and copper, and the interface bonding force is not strong.

Due to the different thermal expansion coefficients of different joint materials, the thermal cycle load is further affected, resulting in different degrees of expansion and deformation at the interface of different materials, resulting in displacement deformation. It can be seen from Fig. 7 that the interface between the copper pillar and the silicon chips and the interface between the solder and the copper pillar have large stresses, and the equivalent stress distribution inside the solder joint is relatively uniform. It can be seen from Fig. 8 that as the number of thermal cycles increases, the equivalent stress is relatively stable and does not change much. However, it can be seen from Fig. 9 that after multiple thermal cycles, the plastic strain of the solder joints has accumulated. It can be inferred that as the thermal cycle is continuously loaded, a large deformation displacement will occur from the middle portion to the periphery, resulting in chip failure.

In order to deeply study the inelastic deformation of flip-chip solder joints under thermal cycling conditions, dangerous solder joints were selected for inelastic strain load history analysis. Figure 10 shows the relationship between inelastic strain and time of hazardous solder joints^[14]. As shown in the figure, the inelastic strain keeps rising during the loading process, However, compared with the pure silver paste, the plastic strain of the silver tin paste is significantly smaller.

In order to study the fatigue life of solder joints in depth, the finite element prediction model was used to predict the fatigue life of the chip. Coffin-Manson is a fatigue life prediction model based on equivalent strain. Engelmaier modified the model to add temperature and frequency data to the fatigue ductility index expression. The stress-strain curve obtained by reaching the saturated state under thermal cycling conditions is calculated by modeling and simulation. The inelastic strain increment $\Delta\epsilon$ of the solder joint is found, and the shear strain increment $\Delta\gamma$ is further obtained, and then substituted into the following equation, ie

$$N_f = \frac{1}{2} \left(\frac{\Delta\gamma}{2\varepsilon_f} \right)^{\frac{1}{c}}$$

Where: ε_f' is the fatigue ductility coefficient; N_f is the average number of failure cycles; $\Delta\gamma$ is the shear strain range; c_1 is the fatigue ductility index [14].

After calculation and analysis, the fatigue life of pure nano-silver solder joints and silver tin paste solder joints is shown in Table 5. It can be found that the fatigue life of the silver tin paste is significantly higher than that of the nano silver paste, mainly due to the addition of the alloying element Sn. After the silver tin paste is welded, Ag_3Sn particles are produced. This hard and brittle phase IMC will produce a second phase strengthening effect. During the working process, the small IMC will pin the dislocation, thereby increasing the shear strength of the solder joint and prolonging its fatigue life. Therefore, for the nano silver paste solder joints, the doping of low melting point elements can prolong the fatigue life of the solder joints.

Table 5
Comparison of solder joint fatigue life

Solder Joint	Plastic Strain Range $\Delta\varepsilon$	Shear Strain Range $\Delta\gamma$	older Joint Fatigue Life N_f (cycle)
Nanosilver	0.0082	0.0142024	2166
Nanosilver + Ag_3Sn	0.0042	0.0072744	9374

5. Conclusion

1. The silver tin paste was modeled by Anand unified viscoplastic constitutive model and elastic model. The simulation results were in good agreement with the experimental values. Provide some reference for the finite element analysis of particle-enhanced nano-solder.
2. Through experiments and finite element simulations, it is determined that the maximum displacement of the flip chip is concentrated at the center solder joint of the chip. After thermal cycling, the plastic strain increases cumulatively, while the equivalent stress remains substantially constant.
3. Through finite element prediction, it is found that the fatigue life of silver tin paste is significantly higher than that of nano silver paste, indicating that adding a certain amount of Sn in the nano silver paste can reduce the plastic strain and improve the service life of the solder joint.

Declarations

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Authors' contributions

Hui Yang conceived and designed the study, Hui Yang and Jihui Wu wrote the paper. All authors read and approved the manuscript.

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Figures

Figure 3

Finite element model. (a) Holistic model (b) Local model

Figure 4

Finite element meshing. (a) Monolithic mesh (b) Local mesh

Figure 5

Temperature cycle load

(a) Overall displacement cloud map

(b) Displacement cloud map of solder joints

(c) Plastic strain cloud map of solder joints

Figure 6

Flip chip solder joint displacement and strain cloud diagram

Figure 7

Stress cloud diagram of solder joints

Curve of stress of solder joints with time

Figure 9

Solder joint stress-strain curve

Figure 10

Solder joint equivalent plastic strain curve