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Influence of temperature and microstructure on the mechanical properties of sintered nanosilver joints

Gang Chen [a], Yi-Zhe Wang [a], Yunhui Mei [b,c,*], Lin Yu [a], Xin Li [b,c], Xu Chen [a]

[a] School of Chemical Engineering and Technology, Tianjin University, Tianjin, PR China
[b] Tianjin Key Laboratory of Advanced Joining Technology, Tianjin University, Tianjin, PR China
[c] School of Material Science and Engineering, Tianjin University, Tianjin, PR China

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ABSTRACT

In order to study the effect of temperature on the mechanical behavior of sintered nanosilver joint for die attachment in power electronics, we developed a non-contact displacement detecting system (NDDS) for measuring the evolution of displacement of joints. Based on a digital image correlation method, the NDDS is capable of detecting a minimum displacement of 3 μm. With the aid of this NDDS, stress-controlled monotonic and cyclic shear tests were conducted on sintered nanosilver joints at various temperatures using an electronic fatigue testing machine. Scanning electron microscopy (SEM) was used to investigate the correlation between loading conditions of the joints and particle size of the sintered nanosilver. The particle size was found susceptible to deformation mode, temperature and holding time. While the particle size is always larger in the cyclic tests than in the shear tests, temperature and holding time play a more important role in the process of particle growth. The shear strength and fatigue life of the sintered nanosilver joints were found to decrease with increasing particle size. This is attributed to the dissolving of the grain boundaries along with the particle growth, which impairs the ability of the sintered nanosilver in inhibiting deformation and retarding crack propagation.

1. Introduction

There is a growing desire to install electronic power and control systems in high temperature environments in order to improve the accuracy of critical measurements, and to reduce the cost of cabling from remote and hostile locations. Air and ground vehicles are also potential candidates for use of high temperature electronics (HTEs) as they have both regions of high temperature (due to combustion) where sense/control is required and there are engineering limitations on their ability to provide active cooling to electronic circuitry in these areas. HTEs additionally offer the potential to operate under harsh but valuable environments such as down-well (including geothermal applications), inside turbomachinery, combustion zones, etc. Such requirement has posed a challenge to the traditional limit of 125 °C for high temperature exposure of electronic systems [1,2].

A typical die attachment of electronic package includes wire-bonds, the die-attach materials, lead-frame materials, and others. Materials used in the package assembly are intended to survive exposure to high temperature. Electrical performance, thermal management and reliability of an electronic system strongly depend on the kind of die attach material used [3,4]. The present work is focused on the critical die attach materials that mechanically attach the die to a substrate.

The progress of high-power semiconductor device [5–7] exposes the fact that traditional die-attach materials, such as solder alloys and conductive adhesions, cannot meet the requirements for higher operating temperature and larger heat dissipation [8,9]. The European power electronics industry is leading the way of introducing a superior lead-free die-attach technology to the market place [10]. Unlike the widely used soldering or adhesive bonding technologies, this new technology, often referred to as the low-temperature joining technology (LTJT) [11], is based on the sintering of micrometer-size silver powder at temperatures below 300 °C. To get such low sintering temperatures, a pressure of about 40 MPa on a 100 mm^2 chip is required. However, when the pressure is applied, even the slightest irregularities can lead to cracking the brittle silicon chips and ceramic substrates. Recently, Lu et al. [12–14] demonstrated a strategy of replacing the high pressure with a chemical driving force by using nanosilver powder to lower the sintering temperature. The introduction of the nanosilver paste significantly simplifies the low-temperature joining or sintering technology (LTJT or LTST) and has paved a way of the nanosilver paste for widespread adaptation by power electronics manufacturers.

* Corresponding author at: School of Materials Science and Engineering, TIanjin University, Tianjin, PR China. Tel.: +86 22 27408399;
fax: +86 22 27405889.
E-mail address: yunhui@tju.edu.cn (Y. Mei).

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Many reliability issues in electronics are related to mechanical strengths, fatigue resistance, coefficient of thermal expansion (CTE), microstructural changes, and intermetallic compound formation. Specifically, the area of mechanical reliability is an issue in which more research is needed so that industry may apply sintered nanosilver to electronic devices. As a result, many studies have been devoted to describing thermo and mechanical behavior of die-attach materials [8,15–17]. Nanosilver paste as an alternative lead-free die-attach material is also important to study the thermo and mechanical behaviors especially for high temperature applications. For example, Knoerr et al. [18] conducted a series of thermal cycling and power cycling on nanosilver sintered components. Ogura et al. [19] founded that diode packages made with sintered silver interconnects had electrical and thermal properties equal to those with lead-soldered interconnects, even after 3000 thermal cycles between −55 °C and 150 °C. Li et al. [20] investigated the creep properties of sintered nanosilver lap-shear joints over a wide range of temperatures. Wang et al. [21] experimentally studied uniaxial ratcheting and fatigue behaviors of sintered nanosilver at room and high temperatures and found that the fatigue failure of sintered nanosilver is dominated by ratcheting response especially for high temperatures and long holding time at peak stress. Chen et al. [22] reported ratcheting behavior of nanosilver joint at room temperature and proposed a modified Goodman model for predicting the fatigue life of joint. However, the basic microstructure mechanism of failure of sintered joints is still unclear. Though Sakamoto et al. [23] investigated the microstructural stability of low-temperature-sintered silver joints by thermal cycling, the evolution of microstructures, e.g., particle size and shape, was not understood well.

Since low-temperature-sintered nanosilver is preferable for high temperature applications, it is important to study the fatigue behavior and microstructure characterization of sintered nanosilver joint at high temperatures. A key issue of high temperature tests lies in measuring the deformation evolution. The digital-image-correlation method (DICM) has been widely used because of its high precision and reliability. Kanchanomai et al. [24] used a DICM system to study the low-cycle fatigue behavior of three types of alloys at different strain-range regimes. Tao et al. [25–28] established a similar system to record the evolution of strain during the entire fatigue life of polymers. However, these tests were only conducted at room temperature.

The objective of this study was to explore microstructural changes in large-area sintered nanosilver joints caused by mechanical cycling at high temperature and correlate these changes to reliability issues in large-area sintered nanosilver constructed semiconductor power devices. In this work, an improved non-contact displacement detecting system combined with infrared heating was developed to measure the deformation of sintered nanosilver joint at high temperatures. The system is introduced in Sections 2.2 and 3.1 in details. The uniaxial monotonic shearing response and uniaxial cyclic shearing response are presented in Section 3.2. In Section 3.3, the fracture surface of sintered nanosilver joint is analyzed by scanning electron microscopy (SEM) and the effect of particle size on mechanical properties is discussed.

2. Experimental procedures

2.1. Sample preparation

Copper electroplated with silver was used as both the substrate and the dummy die to easily perform the mechanical cycling. The specimen was pre-dried at 70 °C for 10 min, and then heated at 225 °C and pressed at 5 MPa for 10 min. At last, the specimen was sintered at 275 °C for 10 min in air. The temperature profile of the process is shown in Fig. 1. Fig. 2 shows the picture and sketch of a typical sintered specimen for the tests. Two silver-plated bulk copper dies are attached to the substrate. The upper one is the dummy die for shearing. The lower one was attached on the substrate by the high temperature adhesive as a reference that is necessary to accurately measure the displacement of the dummy die. The spacing between the two black symbols is 5 mm.

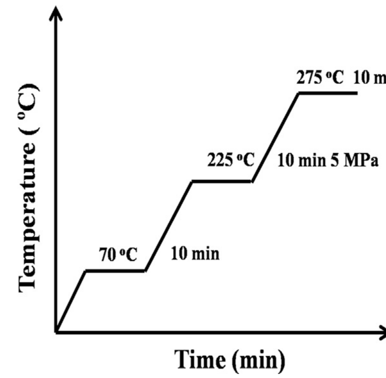

Fig. 1. Temperature profile for sintered nanosilver joint.

2.2. Theory of digital image correlation method

DICM uses the cross-correlation function or its alternatives to compare images captured before and after a small deformation, and to obtain the whole field in-plane displacement quantitatively [34]. Fig. 1 shows schematically the deformation process of a planar object. Quadrangle S (dash-line) is an undeformed subimage and quadrangle S′ (solid-line) is the corresponding deformed subimage. Points M and N on the undeformed subimage move to Points M′ and N′ on the deformed subimage, respectively. To obtain the in-plane displacements u_x and u_y of the point M, subimage S surrounding this point is selected to match the similar subimage S′ using a correlation operation. If subimage S is sufficiently small, the coordinated of the points in S′ can be approximated by first-order Taylor expansion. Therefore, the distance from points M to M′ interpreted as the displacement and the position of point N′ is expressed as follows:

$$x'_n = x_m + u_x + \left(1 + \frac{\partial u_x}{\partial x}\bigg|_M\right)\Delta x + \frac{\partial u_x}{\partial y}\bigg|_M \Delta y = x_n + u_x + \frac{\partial u_x}{\partial x}\bigg|_M \Delta x + \frac{\partial u_x}{\partial y}\bigg|_M \Delta y \tag{1}$$

$$y'_n = y_m + u_y + \left(1 + \frac{\partial u_y}{\partial x}\bigg|_M\right)\Delta x + \frac{\partial u_y}{\partial y}\bigg|_M \Delta y = y_n + u_y + \frac{\partial u_y}{\partial x}\bigg|_M \Delta x + \frac{\partial u_y}{\partial y}\bigg|_M \Delta y \tag{2}$$

where the coordinates are as shown in Fig. 3.

For the best estimate of the displacement, a normalized cross-correlation coefficient, C, defined as the following equation is used [35].

$$C = \frac{\sum_{N \in S}\left[f(x_n, y_n) - f_d(x'_n, y'_n)\right]^2}{\sum_{N \in S}\left[f(x_n, y_n)\right]^2} \tag{3}$$

where $f(x_n, y_n)$ and $f_d(x'_n, y'_n)$ are gray values of each pixel in the deformed subimage and the undeformed subimage, respectively. It is clear that if parameters u_x and u_y are the real displacements and are the displacement derivatives of point M, the correlation coefficient C would be zero. Hence, minimization of coefficient C would provide the best estimates of the parameters.