Proceedings Paper:

Campos-Zatarain, A, Flynn, D, Aasmundtveit, KE et al. (6 more authors) (2014) Characterization of Cu-Sn SLID interconnects for harsh environment applications. In: DTIP 2014 - Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS. DTIP 2014, 02-04 Apr 2014, Côte d'Azur, France. IEEE . ISBN 9782355000287

https://doi.org/10.1109/DTIP.2014.7056665

Characterization of Cu-Sn SLID Interconnects for Harsh Environment Applications

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***Abstract*— this paper reports on the results obtained from performing "shake and bake" testing on demonstrator vehicles bonded using Cu-Sn SLID technique. The demonstrator vehicles were exposed concurrently to vibration and thermal loadings similar to those seen in aerospace and downhole applications. This work demonstrates that Cu-Sn SLID bonding process is ideal for packaging sensors and electronics to be used within harsh environments, especially those encountered in the aerospace and oil & gas industries.**

Keywords- SLID, high-temperature, Cu-Sn, harsh environment, bonding, "shake and bake".

I. INTRODUCTION

Across a myriad of industrial sectors, ranging from aviation, space, subsea and energy, high value assets are deployed in harsh environments. These environments are typically defined by challenging high values of temperature, pressure, radiation, vibration and chemically corrosive conditions.

Assets in such conditions present significant challenges in terms of design, operation and maintenance due to limitations in the visibility of the asset within the harsh environment. The ability to monitor these assets is impeded by several issues related to the thermal limits of materials as aggressive ambient conditions may produce sensor drift and failure, power management and communication problems. In such applications, electronics are often exposed to temperatures above 200° C, which exceeds the 150°C limit of traditional Si devices if used without extra cooling mechanisms. However, the trends across these sectors indicate a rapidly growing demand for more sensing and electronics within harsh environments [1-3].

As the demand for electronics capable of withstanding extreme temperature raises, the number of commercially available high temperature wide band gap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), is increasing. Currently, SiC is the most mature technology as the fabrication of 300°C integrated circuits and 400°C transistors have been reported already [4, 5]. Such devices have been developed, primarily, to target the needs of the gas & oil sector. However, despite the exceptional advantages of the SiC technology, the lack of reliable packaging materials for high temperatures is a barrier to full exploitation. Poor packaging compromises vital aspects such as heat dissipation, mechanical support and electrical connectivity, consequently reducing performance and lifetime.

As interconnects must tolerate high temperatures and provide high fatigue resistance, soft solders, thermoplastics and epoxies cannot be considered for die mount due to their low melting temperatures. There are a number of alternative options for interconnects for high temperature applications, including Au thermo-compression bonding, silver nanoparticle pastes, Au thick film pastes, and Solid Liquid Interdiffusion (SLID) bonding.

SLID is an interconnection and bonding technique which is based in the rapid formation of an intermetallic compound (IMC) between a high melting point metal and a low melting point metal at a temperature above the melting point of the later. The advantage of the resulting intermetallic compound is that it will have a much higher melting temperature than the processing temperature, therefore allowing subsequent manufacturing steps without the need of decreasing processing temperatures [6]. SLID offers several advantages over the other interconnection systems, e.g. it is faster than thermo-compression bonding [7], joints show higher shear strength than those created using silver nanoparticles paste [8] and it is less complex with a lower processing temperature than Au thick film materials [9, 10]. Examples of SLID bonding are Ag-In, Ag-Sn, Au-In, Au-Sn and Cu-Sn systems.

In this work we report test vehicles bonded using Cu-Sn system. Cu-Sn system has a processing temperature between 250 °C and 300 °C which forms an intermetallic compound with melting point of 676 °C. Previous results have shown a shear strength of 45 MPa as bonded and resistance around 100 mΩ [11]. It is well known that the dominant failure mechanism for interconnects is low cycle fatigue caused by a combination of temperature and strain cycling [12]. Previous results by Hoivik *et al.* have shown just slight reduction in the shear strength of Cu-Sn bond pads after being thermally cycled from -40 °C to 150 °C for 1000 cycles over 125 hours [13].

During their lifetime, interconnects used in the aerospace and oil &gas industries are typically exposed concurrently to different loadings such as vibration and thermal shock. However, the contribution of vibration damage to the overall fatigue life of interconnect has not been investigated in any detail previously.Vibration is normally taken as a loading case that only causes elastic material response[14].

In this work we investigate how the bond strength and mechanical integrity of Cu-Sn SLID interconnects are affected after being exposed concurrently to vibration and thermal loading ("shake and bake test"). Test vehicles were exposed simultaneously to thermal loading up to 300 °C and mechanical loading in terms of high random frequency vibration between 1 Hz and 2000 Hz, which is closely associated with the aerospace and oil & gas industries maximum operating conditions.

The following section outlines the fabrication process of the demonstrator devices, test procedure and profile, and summary of the characterisation method. Section III presents the results and discussion, and finally Section IV presents the primary conclusions of this research.

II. Methodology

A. Demonstrator vehicles preparation

Cu-Sn SLID test vehicles for die shear test were fabricated at the Department of Micro and Nano Systems Technology, at Buskerud and Vestfold University College in Norway.

The vehicles were fabricated by electroplating Cu and Sn on oxidized Si wafers with an Au seed layer. The seed multilayer was formed by a 60 nm TiW adhesion layer, onto which an 800 nm Au film was sputtered. The bond pattern for Cu and Sn electroplating on the Au surface was defined using AZ4562 photoresist. Ar/O_2 (ratio 3:1) plasma treatment was carried out before each electroplating procedure to ensure a clean seed layer surface. The Cu and Sn layers were electroplated using commercially available sulfate-based electrolytes. 4.33 µm of Cu and 0.86 µm were deposited on each wafer using pulse-reverse plating. The bias/reverse current density was set to 10 mA/cm^2, and the bias/reverse pulse was 400 ms/20 ms for both materials.

For the test, bond pads with dimensions of 1.0 mm x 0.8 mm were patterned on each Si wafer. Wafers were bonded using a two step-step temperature profile, on which wafers were heated rapidly at a rate of 7 °C/min and brought in contact at 150 °C, initiating the diffusion process between Cu and Sn early on. This reduces the amount of Sn left in the bond line when reaching the melting temperature of Sn at 231.9 °C, thus reducing the amount of Sn squeezed out. Subsequently, wafers were heated at a rate of 3 °C/min until reaching 260 °C and soaked at least for 10 min, allowing the bond line to be converted to $Cu/Cu_3Sn/Cu$ IMC. At 150 °C, the wafers were brought into contact using a bonding pressure of 20 MPa, which was kept constant throughout the soak time. For more information about the fabrication process refer to [13, 15].

B. System set-up

The testing system consisted of two main units: 1) i.e. the LDS-V650 electrodynamic shaker and 2) a hot plate. A vibration control and data acquisition system was used in order to design and run the vibration test. The hot plate which is fixed on the shaker head, was used as a heat source and also sample fixture. The hot plate was powered and controlled by a temperature controller. Fig. 1 shows the final "shake and bake" system set up.

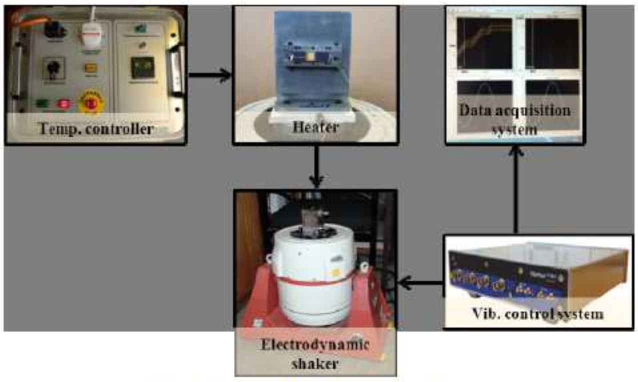

Figure 1 "Shake and bake" testing system set up

C. Testing profile

Sets of six Cu-Sn test vehicles were exposed to the standard random vibration test profile, illustrated in Fig. 2 [16], combined with thermal loading at 25 °C, 100 °C, 200 °C and 300 °C. The "shake and bake" tests were based on the RTCA/DO-160E Environmental Conditions and Test Procedures for Airborne Equipment standard. Tests were performed in each of the equipment's three orthogonal axes for one-hour-per-axis (total of 3 hours per test). The frequency was ranging from 10Hz to 2000Hz and the acceleration power spectral density (APSD) from 0.02 G^2/Hz to 0.08 G^2/Hz. The APSD levels that correspond to each test curve frequency break point can be found in Table 1 [16].

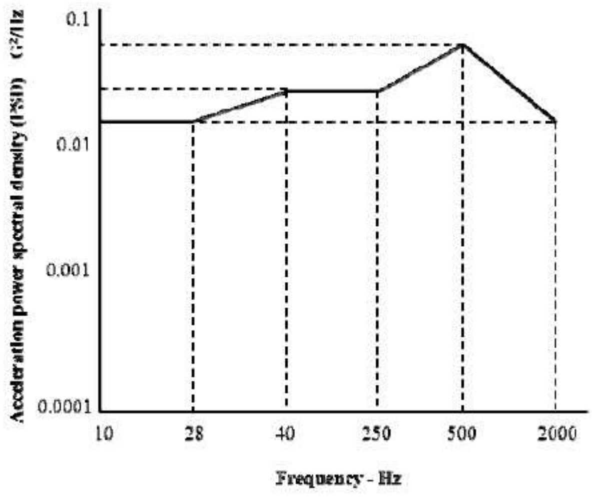

Figure 2 Standard random vibration test curve for equipment installed in fixed-wing aircraft with turbofan engines

Table 1Acceleration power spectral density levels corresponding to each test curve frequency break point

Test levels at test curve frequency break points						
Frequency (Hz)	10	28	40	250	500	2000
APSD (G^2/Hz)	0.02	0.02	0.04	0.04	0.08	0.02

1) Analysis technique: Shear testing was performed to characterize the mechanical strenght of the bond pads after the “shake and bake” test. In order to calculate the efective shear strenght the bonded area must be known. Some of the samples were cross sectioned to be analysed by optical microscopy or scanning electron microscopy (SEM).

D. Shear testing

The die shear tests were performed using a Dage Series 4000 Bondtester with a 100 kg load cartridge. The shear tool height was set at 56.0 µm above the surface of the substrate and shear speed of 70.0 µm/s. Die shear test was performed on four of the six samples from each set with the remaining two samples used for the cross-sectional analysis..

E. Cross sectional analysis

After tests, 2 samples from each set were diced using a 300µm thick fully sintered diamond blade rotating at 13,000 RPM. As a first approach the cross-sectioned samples were inspected, without polishing, using a Leica DM6000 M microscope with an N Plan L 100X/0.75 BD objective.

III. RESULTS AND DISCUSSION

A. Shear testing

Fig. 3 shows the average die shear strength for sets of 4 samples exposed to the vibration/thermal loading described in Sec. II-C and Fig. 4 shows samples exposed only to thermal loading without the vibration shock.

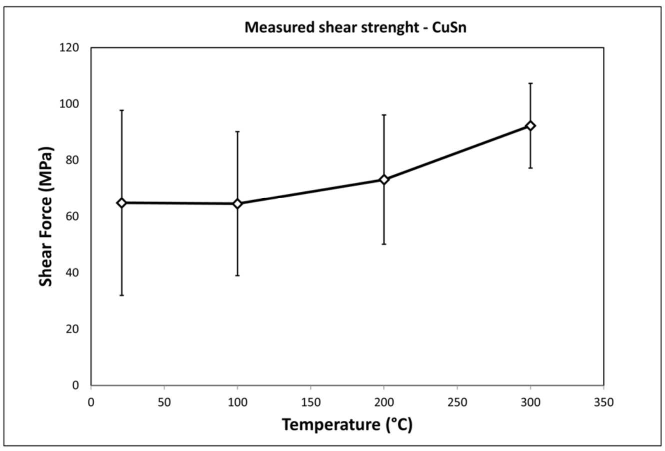

Figure 3 Measured shear strength for sets of samples exposed concurrently to vibration/thermal loading

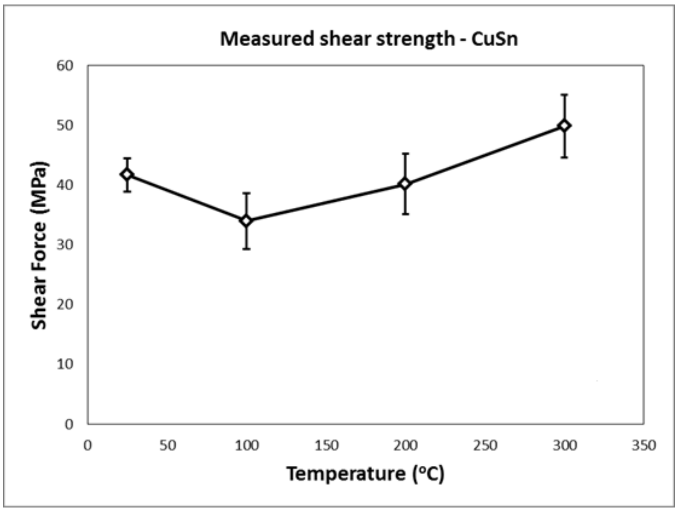

Figure 4 Measured shear strength for sets of samples exposed only to thermal loading

As indicated within Fig 3&4 the samples exposed to thermomechanical affects have an increase in die shear force, with the 300 °C samples exhibiting an increase of 40 MPa. Both sets of samples exhibit an increase in die shear strength beyond 100 °C. At 300 °C there is a compositional change with increasing alloy presence as the Cu layers are incorporated into the CuSn alloy. Finally, there is

B. Microstructural analysis

As mentioned previously, as I first approach, cross-sectioned samples were inspected without being polished. The next group of images show the cross-section of samples exposed to vibration and thermal loading of 21 °C, 100 °C, 200 °C and 300 °C, respectively.

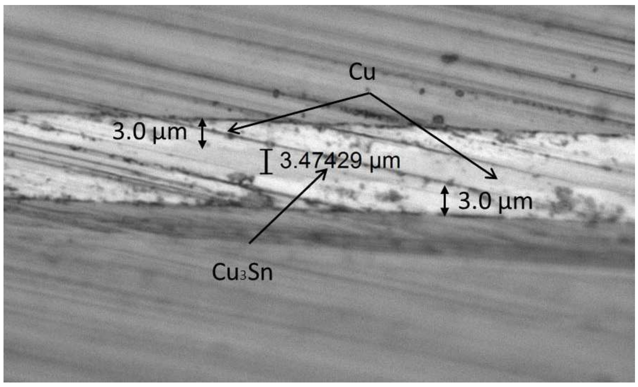

Figure 5 Cross-section of sample exposed to vibration @21°C

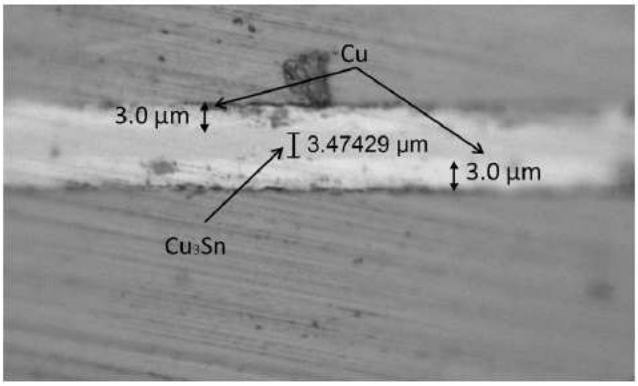

Figure 6 Cross-section of sample exposed to vibration @100 °C

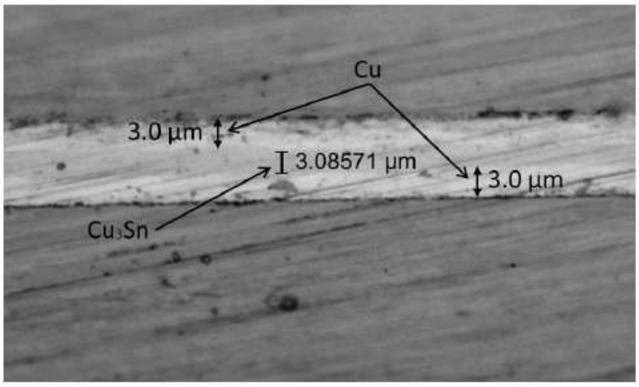

Figure 7 Cross-section of sample exposed to vibration @200°C

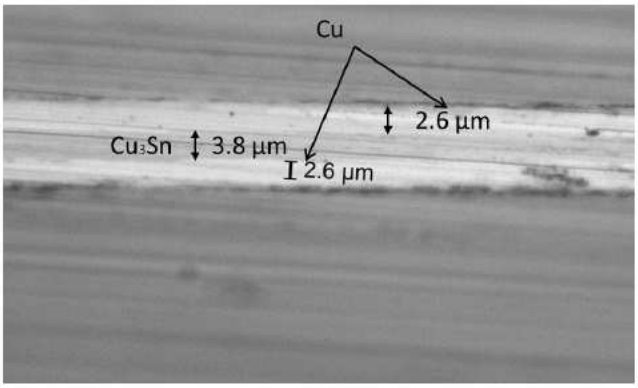

Figure 8 Cross-section of sample exposed to vibration @300 °C

The optical microscopy images indicate that there is a gradual increased in the alloy composition within the interconnect structure. It would appear that increasing alloy composition produces a desirable increase in shear strength.

IV CONCLUSION

Within this research we have fabricated, characterized and analyzed CuSn interconnects for harsh environment applications. The suitability of this interconnect technology has been validated through the seminal testing with a custom shake & bake system. The compositional changes with temperature appear to influence the die shear strength of the samples. Interestingly the influence of the vibrational forces has further enhanced this property. Further testing is required to validate the influence of the compositional change on the electrical properties of the interconnects, as well as a detailed analysis of the resultant grain properties. However, these preliminary results indicate a potential design freedom in the optimization of the interconnects with respect to structural integrity and electrical properties for harsh environments.

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