X-Ray Radiography Study of The Evolution of Defects in Solder Joints*

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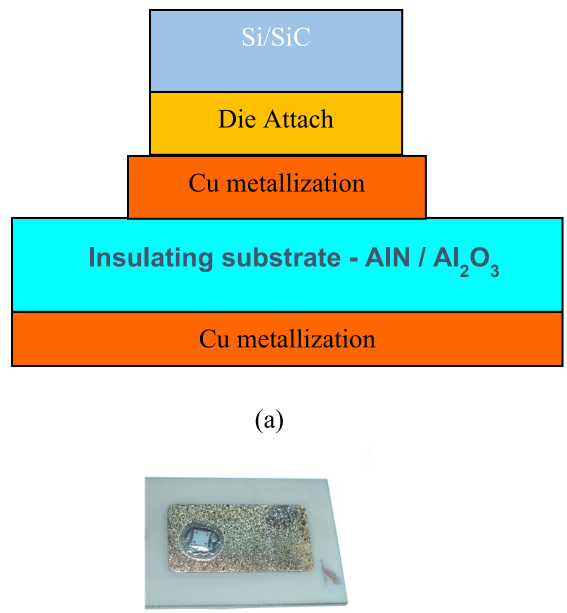
***Abstract*— With the advent of wide band-gap devices which can operate at higher temperatures than Si-based devices, there is interest in the evaluation of Au-based solders or alternate materials for use as die-attach materials. In this study, X-ray radiography and X-ray tomography were used to characterize the evolution of defects due to thermal cycling in Au-based materials used as a die-attach and in brazed joints. Evolution of voids and cracks as a function of thermal cycling was clearly observed using these techniques, highlighting their potential role in understanding joint behavior at high temperatures and after thermal or power cycling.**

Keywords—High temperature packaging, Direct Bonded Copper (DBC), dissimilar metal brazing, Au-Sn, Au-Cu

I. INTRODUCTION

The advent of wide bandgap devices which can operate at higher temperatures (>200°C) compared to Si devices imposes severe demands on materials used in power electronic packages. A typical power package consists of the die mounted onto a Direct Bonded Copper (DBC)-substrate using a die attach material. Direct bonded copper substrates are composed of a ceramic substrate (commonly alumina or aluminum nitride) with a layer of copper bonded to both sides through a high temperature oxidation process as shown in Figure 1 [1-3]. The materials used in these packages must at the minimum be stable for long periods at the higher temperatures. In addition, the higher temperatures of operation result in deeper thermal cycles resulting in larger thermal stresses due to coefficient of thermal expansion mismatch between the materials used in the package. It is important to understand the effect of thermal cycling on die attach materials since these are designed to accommodate the thermal stresses induced by thermal expansion mismatch between the die and the substrate [2-4].

Solders are used for die attach applications because of their desirable combination of properties along with their ease of processing. Solders that can be used for die attach applications can be classified into broad categories: hard solders and soft solders [1,5]. Hard solders such as Au-3%Si, Au-12%Ge and Au-20%Sn. typically have higher melting points (280^{o}C–363^{o}C) [1] and retain their strengths to higher temperatures. However, due to their higher strengths and higher resistance to creep deformation, thermal expansion induced stresses are transmitted to the device to a greater extent resulting in



(a)

(b)

Fig. 1. (a) Schematic of the modules used for the die-attach study. (b) Image of a module showing the insulating substrate, metallization, and the die.

increased tendency for cracking of the relatively brittle silicon die. Au-based alloys are also used as brazes to form dissimilar material joints for high temperature applications. For example, 50Au-50Cu can be used as a braze to join copper to stainless steels [6] and there is interest in evaluating the quality of these joints and to study defect evolution in such joints under simulated operating conditions.

X-ray radiography and tomography are very effective ways to study the evolution of defects in solder, braze and other similar joints [2,3]. These techniques allow for non-destructive evaluation of the joints, thus allowing monitoring the same joint as a function of, for example, thermal cycles. This study will show results from the study of two types of Au-based joints, a Au-Sn solder joint and a Au-Cu braze joint.

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II. Experimental Methods

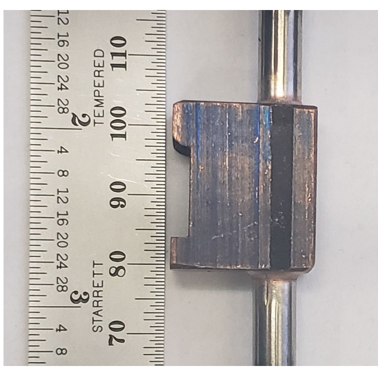
A. Au-Sn die attach

Figure 1 (a) shows a schematic of a module used for the study of modules containing Au-Sn die-attach. The Si or SiC die is attached to a direct bonded copper substrate using eutectic Au-Sn die attach. The DBC substrates were coated with a metallization of medium phosphorus Ni-layer and a flash Au layer. Dies used were 2.5 mm x 2.5 mm in size. Figure 1 (b) shows an example of the module used in the study.

The evolution of damage in solder joints as a function of thermal cycling was evaluated by periodically removing the solder joints. Thermal cycling between 5°C and 200°C was performed in a computer-controlled environmental chamber [2,3]. Chamber was cooled by using high pressure liquid nitrogen which was pumped into the chamber. Each thermal cycle was about 55 minutes with a 30- minute dwell at 200°C, and a 5-minute dwell at 5°C. Modules were placed on an aluminum plate and the temperature of the aluminum plate was monitored and used to control the heating and cooling of the chamber.

B. Au-Cu braze

Fig. 2(a) shows a section of a copper alloy heat-exchanger brazed to a stainless-steel tube using 50Au-50Cu braze. These joints were cycled between room temperature and 290°C and removed after 50 and 100 cycles. Figure 2 (b) shows a volume that consists of the stainless-steel tube, braze, and the adjoining region from the copper alloy heat-exchanger that was removed for X-ray tomography studies.



(a)

(b)

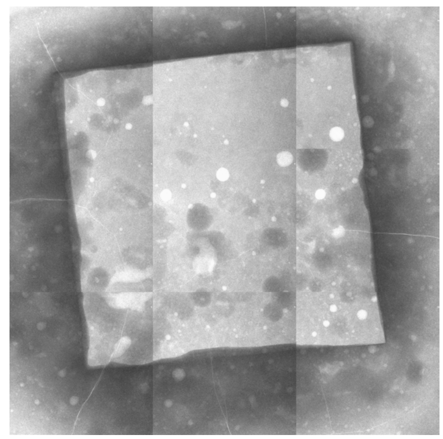
Fig. 2. (a) Section of a copper alloy heat-exchanger brazed to a stainless-steel tube. (b). Volume removed for X-ray tomography studies is shown on the right.

X-ray tomography from the braze joint was obtained using a Zeiss Xradia Versa system operating at 160 kV, 10W, with the imaging conditions resulting in a pixel size of 9.25µm. Dragonfly PRO software v3.5 was used for data visualization and segmentation.

III. Results and discussion

A. Au-Sn die attach

Fig. 3 shows typical X-ray radiographs obtained from the same module (a) in the as-processed condition and (b) after 100 thermal cycles. As observed from Fig. 3 (a) voids are apparent in the solder joint underneath the Si die even in the as-processed condition. In the as-processed condition, some cracks also seem to be present in the solder joint in regions away from the die. Fig. 3 (b) shows significant cracking underneath and/or on in the Si die after the samples were removed after 100 cycles.



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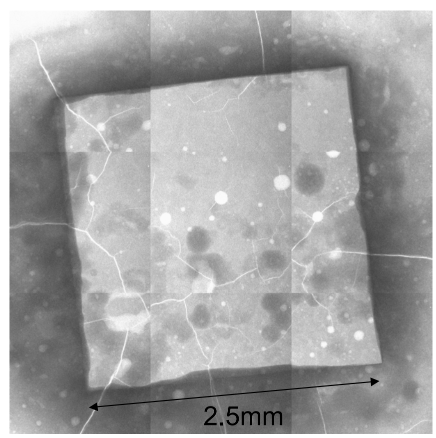

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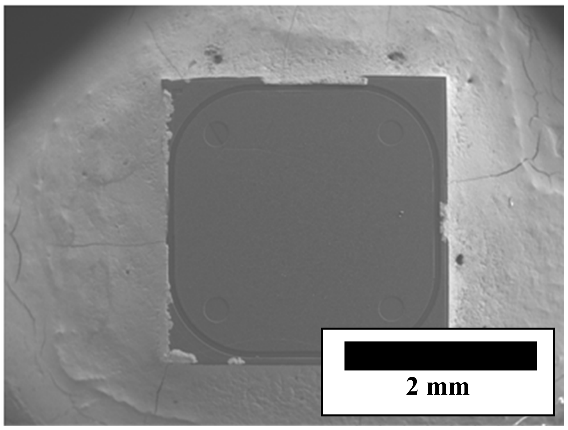
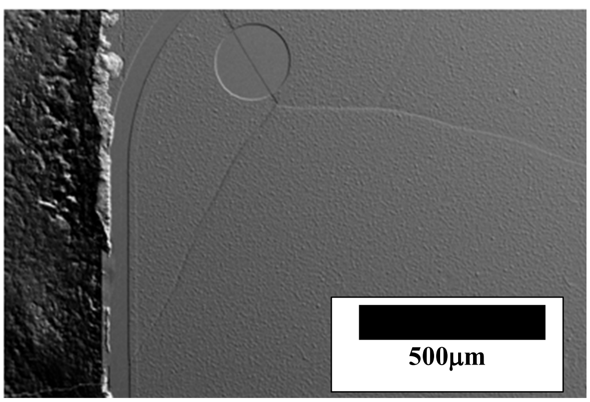
Fig. 3. (a) X-ray image showing Si die bonded to the substrate using eutectic Au-Sn solder before thermal cycling. Voids are clearly observed within the solder joint. (b) X-ray image showing the same Si die shown in Fig. 3(a) after 100 cycles. Note the presence of multiple cracks.

Since the radiograph is a projection and does have depth resolution to help identify the location of the cracks, Scanning Electron Microscopy was performed on the module to obtain complementary information and the results are shown in Fig. 4. Fig. 4 (a) shows the scanning electron microscope (SEM) image in the as-processed condition and Fig. 4 (b) shows the SEM image after 100 thermal cycles. As can be observed from Fig. 4 (a), in the as-processed condition some cracking is observed in the solder joint adjoining the Si die. Fig. 4 (b) shows that the Si die has significant cracking after 100 cycles and consistent with cracking observable in Fig. 3 (b).



(a)



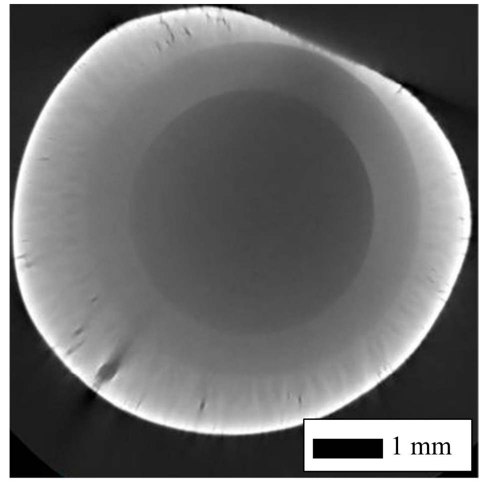
(b)

Fig. 4. (a) Scanning electron microscope image of the joint shown in Fig. 3(a) before thermal cycling. (b) Scanning electron microscope image after 100 cycles showing significant die cracking.

B. 50Au-50Cu braze

Fig 5(a), (b), and (c) show cross-sections obtained from three different locations perpendicular to the longitudinal direction (perpendicular to the length of the tube) from a sample similar to that shown in Fig.2(b) after 50 cycles. These cross-sections were extracted from a tomograph collected from the sample. Note the presence of voids along with numerous, radial, crack-like features.

Fig. 6 (a) shows a cross-section along the longitudinal direction (aligned with the length of the tube) in a sample subject to 100 cycles. Note the presence of a large void in this section.



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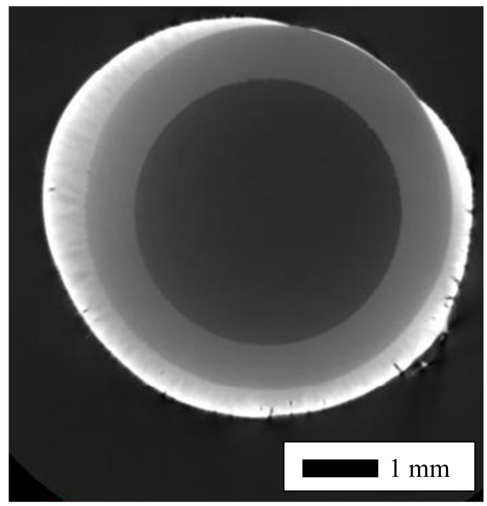

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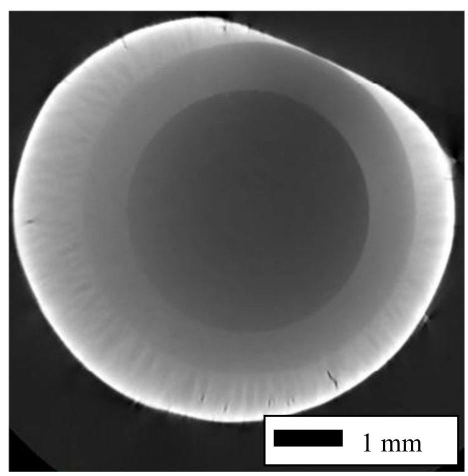
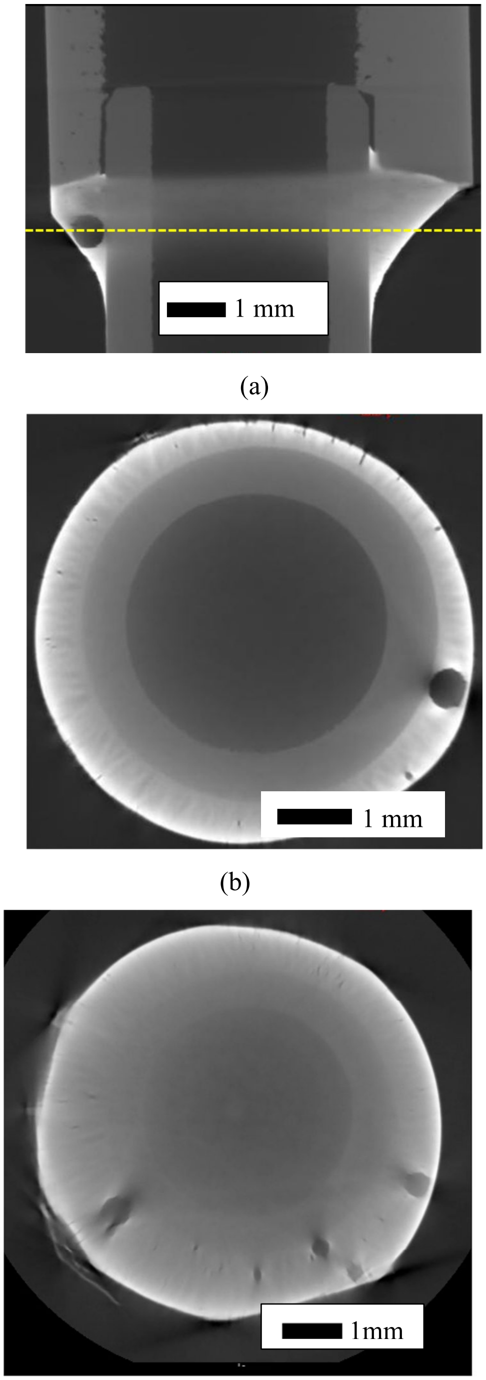


(c)

Fig. 5. (a), (b), (c) X-ray cross-sectional images obtained from three different locations along the longitudinal direction from a tomograph collected from the sample after 50 cycles. Crack-like radial features are observable along with voids.

Fig. 6(b) shows a cross-section in the perpendicular direction at the location shown by the dotted line. This image shows that the



(a)

(b)

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Fig. 6. (a) X-ray cross-sectional image obtained along the longitudinal direction from a tomograph collected from the sample subject to 100 cycles. (b) Cross-section along the dotted line shown in Fig. 6 (a). (c) Cross-section at another location perpendicular to the longitudinal direction showing the presence of multiple voids.

void is in contact with the stainless-steel – copper interface. Smaller voids and crack-like features emanating from the surface are also observed in this condition. The effect of thermal cycling on initiating voiding and crack-like features will be the subject of future studies. The effect of these voids and crack-like features on the mechanical properties are also under evaluation.

IV. Conclusions

With the advent of wide band-gap devices which can operate at higher temperatures than Si-based devices, there is increasing interest on solders that can be used at higher temperatures. X-ray radiography and X-ray tomography were used to characterize the evolution of defects due to thermal cycling in Au-based solder die-attach materials and braze joints. Voids in the initial solder joints, cracking of solder joints, and die cracking were clearing identified in Au-Sn solder joints fabricated on DBC substrates. X-ray tomography was successfully performed on 50Au-50Cu braze joints. It was shown that voiding and cracking could also be identified in these joints. Further work is needed to understand the effects of these defects on the high temperature performance and mechanical properties of these braze joints.

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