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Measurement of Solder/Copper Interfacial Thermal Resistance by the Flash Technique

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A feasibility study was conducted to determine the interfacial thermal resistance (ITR) in both bi- and tri-layered eutectic lead–tin solder/copper specimens by the flash technique. The solder/copper ITR results of the two sets of specimen showed excellent agreement. The values were found to range from 0.011 to $0.033\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$ with an average of about $0.020\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$. The variation was attributed primarily to the imperfection of the solder/copper bonding established by scanning acoustic microscopy.

KEY WORDS: finite element analysis; flash technique; interfacial thermal resistance; scanning acoustic microscopy; transient thermal analysis.

1. INTRODUCTION

Interfacial thermal resistances (ITR) for thermally demanding applications are critical design variables because they can contribute significantly to the total thermal resistance of a heat path [1]. In an electronic package, semiconductor devices—the major heat sources—are usually die-attached to a copper substrate with a several-mil-thick solder layer frequently composed of eutectic lead–tin. The die-attach layer serves as a mechanical support, an electrical interconnection, and a primary heat dissipation path. For a perfectly bonded solder/copper interface, the intrinsic reasons of an ITR

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are usually due to the mismatched crystal structure and the difference of elastic moduli across the interface, which result in electron and phonon scattering at the interface [2]. In practice, further contributions to ITR may come from poor wetting of the substrate by the solder because of surface oxidation and contamination and interfacial voids. The purpose of this study was to explore the feasibility of using the flash technique, initially developed by Parker et al. [3] for measuring the thermal diffusivity of single-phase materials and subsequently extended to multilayer samples [4–6], to determine the ITR of solder/copper interfaces.

2. EXPERIMENTAL PROCEDURE

The materials in this study consisted of pure copper [Alloy 101 oxygen-free (Electronic Grade), McMaster] and a eutectic composition of lead–tin solder (Sn-37Pb, Easy Profile^{TM} 256, Kester). Two sets of specimens were prepared. The bi-layered specimens consisted of one copper layer and one solder layer with only one solder/copper interface in each specimen. The tri-layered specimens consisted of a sandwich of the Cu/solder/Cu with two solder/copper interfaces. The copper layers were in the form of rectangular cylinders with a diameter of 1.27 cm, and their thicknesses were measured by a micrometer. The solder layers were formed by reflowing the eutectic lead–tin solder paste, their thicknesses controlled by varying the amount of solder paste. The specimens were then cleaned and polished to obtain rectangular cylinders, and the thicknesses of the solder layers were measured directly with an optical microscope with micrometer resolution.

The experimental conditions described by Parker et al. [3], the ASTM method E1461-01 [7], and those of Hasselman and Donaldson [8] were followed. The flash source consisted of an Apollo Nd-glass laser with a rod diameter of 1.56 cm, a wavelength of 1.06 μm, and a pulse width of approximate 250 μs. The flash was passed through a beam expander that allowed using the central portion of the beam, which generally is spatially more uniform than at edges of the beam. The uniformity of the radiation which impinged on the sample was checked by using photo-sensitive footprint paper. Following the spatially uniform radiation of the flash on one side of the specimen, the transient temperature of the opposite face of the specimen was monitored by a liquid-nitrogen cooled InSb infrared detector (Electro-Optical Systems, Inc., Malvern, Pennsylvania). The time ($t_{1/2}$) to reach one half of the final temperature at which the sample reached thermal equilibrium was recorded. Each specimen was measured five times. The estimated uncertainty of $t_{1/2}$ is about 2%.

To obtain the solder/copper ITR, bulk thermophysical properties of both solder and copper—density ρ, specific heat c, and thermal diffusivity

α—must be known accurately. The density values were obtained by the Archimedes' method. The specific heat values were measured using differential scanning calorimetry. The thermal diffusivities of the solder and copper were determined from disc-shaped pure solder and pure copper specimens, respectively, by the flash technique using Parker's equation [3],

$$\alpha = 0.1388 l^2 / t_{1/2} \quad (1)$$

where α is the thermal diffusivity, l is the thickness of the disc-shaped specimen, and $t_{1/2}$ is the half temperature rise time at the specimen's rear surface. In the case of single-phase specimens, Eq. (1) can be used directly to obtain the thermal diffusivity of the material once the half temperature rise time is known.

The solder/copper ITR in the bi-layered specimens was then determined with the appropriate computational technique developed by Lee [4]. In the method, the density, specific heat, and thermal diffusivity of solder and copper and the half temperature rise time at the rear solder surface were used as inputs to derive the solder/copper ITR using commercially available software. The half temperature rise times of bi-layered specimens were measured again by the flash technique.

Two methods were used to derive the ITR in the tri-layered specimens. The first method was used by Hasselman et al. [5] to study the ITRs of thermal adhesives for an electronic packaging application. In the method, the bulk thermal resistance of the solder layer R_{solder} plus the two solder/copper ITRs, R_i, which constitute the total middle layer thermal resistance R_{total}, are given by

$$R_{\text{total}} = R_{\text{solder}} + 2R_i = \frac{d}{k} + 2R_i \quad (2)$$

where d and k are the thickness and thermal conductivity of the solder layer, respectively. Since R_{total} includes all the thermal resistance in the tri-layered specimens other than the two copper layers, it can be determined using the same method for the bi-layered specimens [4]. Then R_i was obtained by the least squares-linear fit and extrapolating the thickness d to zero in the R_{total} versus d plot.

The second method obtained R_i directly in the tri-layered specimens using finite-element analysis (FEA). In the method, finite-element models were created in I-DEAS™ following the geometries of the tri-layered specimens. In I-DEAS™, it is convenient to characterize an ITR by defining a "thermal coupling coefficient" (which is the reciprocal of the ITR) at the interfaces of the composite specimens. By simulating the laser flash

and boundary conditions of the experiment, a typical temperature variation curve at the rear surface of a specimen is plotted in Fig. 1. The half temperature rise time $t_{1/2}$ was obtained from the intersection of the rear surface temperature transient curve and the $T = T_f/2$ line as shown, where T_f is the final temperature rise in the specimen after thermal equilibrium. The rear surface temperature transient curve was re-plotted more accurately in Fig. 2. By comparing the FEA simulated $t_{1/2}$ with the measured

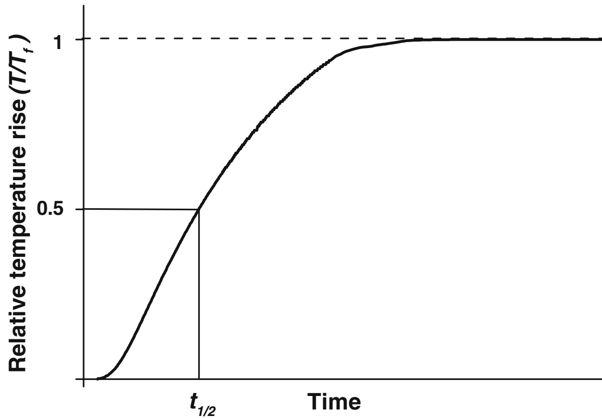

Fig. 1. Typical temperature transient curve at the rear surface of a specimen after the laser flash.

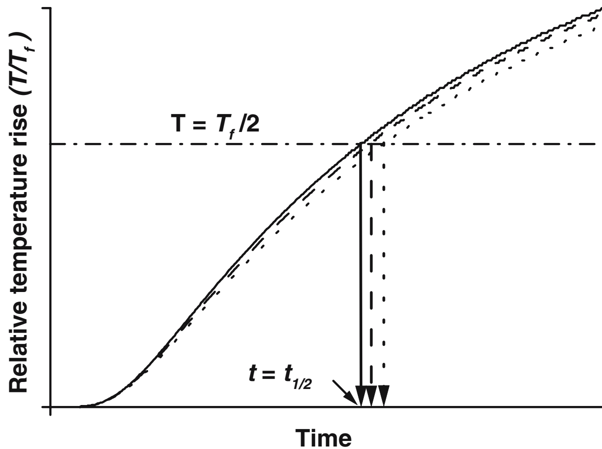

Fig. 2. Changes of the temperature transient curve at the rear surface of a specimen when changing the values of the solder/copper ITR.

$t_{1/2}$ from the flash experiment, a new value of ITR R_i was chosen for the second try, and so on, until the two $t_{1/2}$ match. By this reversed method, R_i could be determined.

3. RESULTS AND DISCUSSION

The thickness values of the solder and copper layers in the bi- and tri-layered specimens are presented in Tables I and II, respectively. The experimental data of the half temperature rise time are listed in the last columns.

The values of the density, specific heat, and diffusivity for the solder and copper are listed in Table III. The corresponding thermal conductivity values were obtained by multiplying the thermal diffusivity, density, and specific heat. Data from the website [9] are also listed for reference.

Table I. Experimental Data of the Bi-layered Specimens

	Thicknesses of bi-layered specimens		
2-layered	Flashed copper (cm)	Rear solder (cm)	Half temp. rise time $t_{1/2}$ (ms)
#1	0.2373	0.1768	48.6
#2	0.3145	0.1247	40.8
#3	0.4549	0.1281	60.0
#4	0.4172	0.0991	43.6
#5	0.3650	0.1108	43.0
#6	0.4014	0.1264	52.2

Table II. Experimental Data of the Tri-layered Specimens

	Thicknesses of tri-layered specimens			
3-layered	Flashed copper (cm)	Middle solder (cm)	Rear copper (cm)	Half temp. rise time $t_{1/2}$ (ms)
#1	0.3780	0.0041	0.2751	66.8
#2	0.2791	0.0050	0.3141	55.2
#3	0.1261	0.0214	0.3207	47.6
#4	0.2658	0.0248	0.2750	66.0
#5	0.2120	0.0279	0.2169	52.4
#6	0.2287	0.0340	0.2801	67.8
#7	0.2608	0.0450	0.3202	99.2
#8	0.1910	0.0534	0.1896	55.8

Table III. Bulk Properties of Solder and Copper for the Calculation of the Solder/Copper ITR

		Density ρ ($g \cdot cm^{-3}$)	Specific heat c ($J \cdot g^{-1} \cdot K^{-1}$)	Thermal Diffusivity α ($cm^2 \cdot s^{-1}$)	Thermal Conductivity k ($W \cdot cm^{-1} \cdot K^{-1}$)
Sn-37Pb	Reference	8.47	0.195	0.309	0.51
	Measured	8.22 $(5\times2)^a$	0.185 $(2\times4)^a$	0.310 $(6\times5)^a$	0.47
Cu	Reference	8.94	0.385	1.150	3.96
	Measured	8.91 $(5\times2)^a$	0.372 $(2\times4)^a$	1.026 $(8\times5)^a$	3.41

[a] (#×#): number of specimen prepared × times of each specimen measured.

The values of R_{total} obtained from the tri-layered specimens using the first method are plotted versus the thickness of the solder layer in Fig. 3. A linear curve fit (see Eq. (2)) of the data results in values of $0.0109\,K \cdot cm^2 \cdot W^{-1}$ for the solder/copper ITR R_i and $0.355\,W \cdot cm^{-1} \cdot K^{-1}$ for the thermal conductivity of the solder, respectively. The 95% confidence limit gives the uncertainty range of R_i of about 0.005 to $0.020\,K \cdot cm^2 \cdot W^{-1}$ as shown in Fig. 3. In view of the uncertainties, the thermal conductivity value for the solder agrees fairly well with the corresponding value of $0.47\,W \cdot cm^{-1} \cdot K^{-1}$ obtained with the bulk sample. Exact agreement is

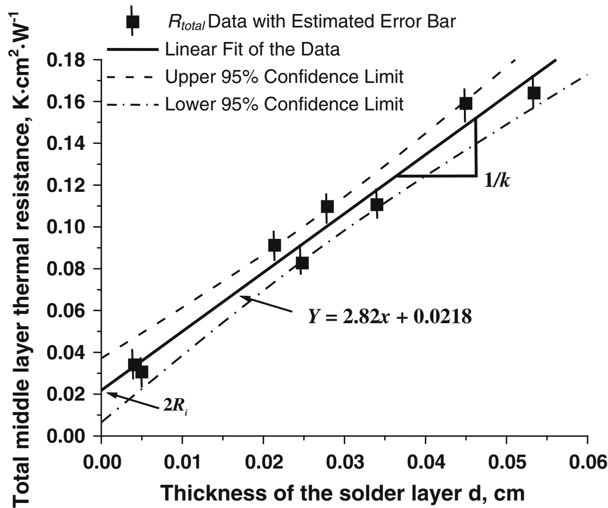

Fig. 3. Total thermal resistance R_{total} of solder in the tri-layered specimens as a function of the solder layer thickness.

not expected, as in the tri-layered samples, the grain growth is constrained by the pressure of the neighboring copper that could result in a textured structure with electrical and thermal properties different from those of the bulk sample.

All the solder/copper ITR R_i results obtained from the bi-layered specimens using Lee's method [4] and those from the tri-layered specimens using the FEA method are summarized in Table IV. The solder/copper ITR values were found to be in a range of $0.011–0.033\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$ and with an average of $0.020 \pm 0.005\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$. Again, the agreement between both sets of results from the bi- and tri-layered specimens is considered excellent.

To investigate the reasons for the range in the solder/copper ITR results, a pulse-echo mode of scanning acoustic microscopy (SAM) was used to check the solder/copper interfaces. In the SAM mode, the transducer produces a high-frequency sound wave that interacts with the sample. The reflected sound was used to produce images. Whenever a sudden change in acoustic impedance is encountered, like at a material boundary, a portion of sound is reflected and the remainder propagates through the boundary. The uniformity of an interface of interest can be related to the image brightness. Figure 4 shows two of the SAM images obtained from the bi-layered specimens #4 and #5 by a 15 MHz sonic transducer. From Fig. 4, one can see that the solder/copper interface in specimen #4 is more uniform than that in #5; this is believed to be the reason why the ITR in specimen #4 is much smaller than that in #5. The latter shows at least three round-shaped low-density areas at the solder/copper interface with

Table IV. Summary of the Solder/Copper ITR Data Obtained from the Bi-layered Specimens Using Lee's Method and Those from the Tri-layered Specimens Using the FEA Method

	Solder/copper ITR R_i $(\mathrm{K \cdot cm^2 \cdot W^{-1}})$	
Specimen #	2-layered	3-layered
#1	0.022	0.017
#2	0.029	0.014
#3	0.020	0.018
#4	0.011	0.012
#5	0.033	0.022
#6	0.025	0.018
#7	–	0.028
#8	–	0.019
Average	0.023	0.018

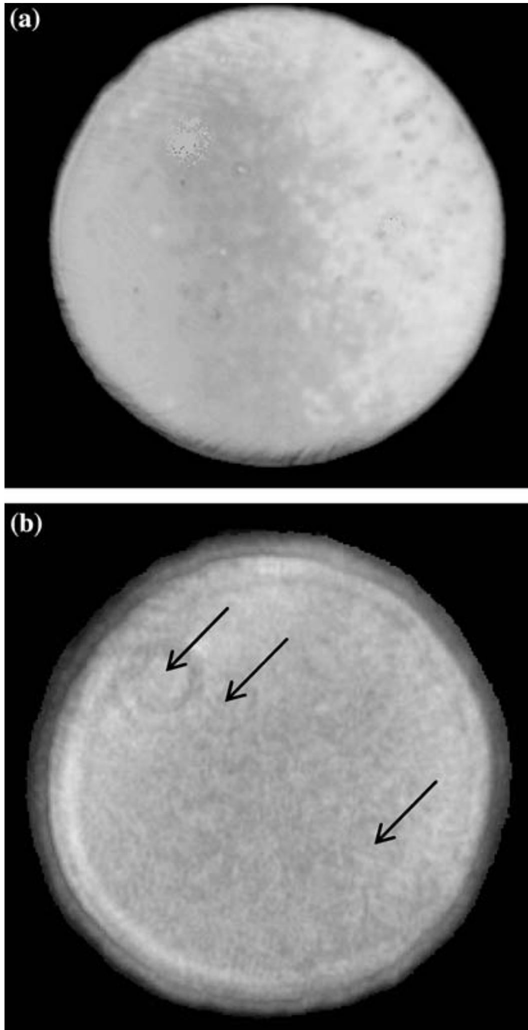

Fig. 4. SAM images of the solder/copper interface in the bi-layered specimens (a) #4 and (b) #5.

diameters of 1–2 mm, which could be poor wetting areas/voids induced at the interface during the solder reflow. As discussed before, the imperfection could add a large extrinsic ITR onto the intrinsic ITR. In an electronic package, the non-uniform structures are very harmful to the thermal performance and reliability of the interconnection layers and they should be avoided as much as possible.

Finally, it is pointed out that the $\sim 0.02\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$ solder-related ITR is equivalent to the thermal resistance of an $\sim 100\,\mu\mathrm{m}$ thick eutectic lead-tin solder layer, which means that for a solder layer less than $100\,\mu\mathrm{m}$ thick, the interfacial contact resistance will contribute more than half of the total thermal resistance. Therefore, it is clear that a designer of electronic packages must address both the bulk and interfacial resistance.

4. CONCLUSION

We demonstrated the feasibility of using the flash technique for measuring the eutectic lead–tin solder/copper ITR from both the bi- and tri-layered specimens. The solder/copper ITR was found to be about $0.020\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$ and within a range of $0.011–0.033\,\mathrm{K \cdot cm^2 \cdot W^{-1}}$. After consideration of the measurement uncertainties and the extrinsic reasons for the existence of ITR, the results from both the bi- and tri-layered specimens show excellent agreement.

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