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(Sn-Ag)$_{eut}$ + Cu Soldering Materials, Part II: Electrical and Mechanical Studies

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Electrical (solder resistivity and solder joint resistance) and mechanical (tensile strength and shear strength of solder joints) parameters of the binary eutectic Sn-Ag and two alloys close to the ternary eutectic Sn-Ag-Cu composition were investigated. The four-probe technique was used for the measurement of electrical parameters. Special equipment was constructed for the tensile strength measurements and also for determination of the shear strengths of solder joints between a typical circuit component and a Cu contact on a printed circuit board (PCB). It was found that electrical and mechanical properties of the three alloys studied are comparable to data in the literature for traditional Pb-Sn solders. A joint resistance below 0.3 mΩ (Ω =ohm) and shear strength of above 20 MPa were found for an individual solder joint between a circuit component (in the current study a "jumper" resistor) and a copper surface on a PCB.

1. Introduction

The majority of electronic assemblies in use today use Pb-Sn solders for interconnection. Emerging environmental regulations worldwide have targeted the elimination of Pb usage in electronic assemblies due to the inherent toxicity of Pb. The most promising alternatives for replacement of Pb-Sn solders are a family of near eutectic Sn-Ag-Cu solders.[1] For practical application of soldering materials, electrical and mechanical properties play an important role above and beyond the wetting characteristics reported in Part I of this work.[2] Measurements of these electrical and mechanical properties of the same alloys as in Part I, but in 1 mm diameter wire form, are reported here for the binary Ag-Sn eutectic alloy and two Ag-Cu-Sn alloys with compositions (Cu/at.% = 0.46 and 0.74) near the ternary eutectic. The electrical resistivity of any such replacement solder must be sufficiently low to permit current flow without heating a solder joint. On the other hand, the mechanical strength of the solder has to be sufficiently high to attach a component to a printed circuit board (PCB). As an example, data[3,4] for resistivities and shear strengths of common solders used for microelectronic applications are listed together with resistivities of pure metals in Table 1.

The resistivities of all three Pb-free solders in the current study were lower than the resistivity of eutectic Pb-Sn. The differences are neither too high nor too low to meaningfully affect the overall functionality of any electronic circuit in current use.

2. Electrical and Mechanical Measurements of Solders in Wire Form

For resistivity measurements, the four-probe method was used. A Keithley 2001 (WUT, Warsaw, Poland) multimeter was used as the detecting instrument. Appropriate equipment for applying tensile forces with accuracies of 0.1 N was constructed. Then the electrical and mechanical measurements were made on solder joints between a jumper resistor and a copper pad on a PCB. The Pb-free solders were of the same compositions as those of the wettability studies (surface tension and interfacial tension) of Part I of this coordinated investigation. Before mechanical and electrical testing, all wire samples were annealed at 100 °C for 1 h for structure stabilization. The room-temperature resistivity measurements of the solders in wire form are presented in Table 2 with each value representing the average of 50 measurements. The resistivity of the eutectic Sn3.8Ag wire was measured as 11.81 μ Ωcm in good agreement with the value of 12.30 μ Ωcm published by Cook.[4] The electrical resistivities of the two near-eutectic Sn-Ag-Cu solders are very close to the resistivity of the Sn-Ag eutectic alloy. Some of these small differences may also result from the

Table 1 Room-Temperature Resistivity and Tensile Strength for Some Pb-Free Solders[3,4]

Materials, at.%	Resistivity, μΩcm	Tensile Strength, MPa	Shear Strength, MPa	Pure Metals	Resistivity, μΩcm
Sn 40Pb	14.4;[a] 15.0[b]	30.6;[a] 46.2[a]	28.4;[a] 41.8[a]	Ag[a]	1.59;[a] 1.62[a]
Sn 3.8Ag	10.0;[a] 12.30[b]	24.0;[a] 55.0[a]	31.7;[a] 39.0[a]	Sn[a]	10.1;[a] 11.5[a]
Sn 1.3Cu	13[a]	22.0[a]	28.5[a]	Pb[a]	21.1;[a] 20.9[b]
Sn3.8Ag1.3Cu	13[b]	48.0[a]	27.0[a]	Cu[a]	1.68[a]

(a) Values from Ref 3
(b) Values from Ref 4

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Table 2 Electrical Resistivity at Room Temperature of Investigated Solder Alloys

Investigated Alloy	Resistivity, μΩcm	Standard Deviation, μΩcm
Sn 3.8Ag	11.81	0.27
(Sn-Au) eut + 0.46Cu	11.77	0.16
(Sn-Ag) eut + 0.74Cu	12.2	0.53

Table 3 Results of Solder Tensile Strength Measurements

Investigated Alloy	Tensile Strength, MPa	Standard Deviation, MPa
Sn 3.8Ag	41.6	5.5
(Sn-Au) eut + 0.46Cu	40.2	4.0
(Sn-Ag) eut + 0.74Cu	68.5	4.9

influence on resistivity of microstructure, grain size, dislocation density, etc. Nevertheless, the resistivity of all three solders that were tested are comparable to resistivities of Pb-Sn solders[4] (Table 1). This is adequate for satisfactory replacement Pb-Sn solders by Ag-Cu-Sn solders in currently functioning electronic circuitry.

The results of tensile strength measurements of the three alloys in wire form are shown in Table 3. Each point represents an average value from five or six samples. The measured values of tensile strength are, on average, higher than values in the range of 24-55 MPa for eutectic Sn-Ag alloys that are reported in a current data base.[3] Such differences may be connected with the cooling rate after melting and/or the plastic deformation during wire formation.

3. Electrical and Mechanical Measurements of Pb-Free Solders After Wave Soldering

Special samples were prepared for measuring the electrical and mechanical properties of solder joints made of our three solders after wave soldering. Solder joints were formed between the contacts of surface mount jumper resistors and copper contacts (Topline, Garden Grove, CA) on PCBs. The configuration of the elements that form a joint are shown in Fig. 1 in their configurations before and after soldering. The jumper contacts have Sn finishing and the PCB contacts have immersion Sn finishing. Rosin low activity (ROLI) (3% solid) flux was applied just before and during soldering. The wave soldering peak temperature was 250 °C, and soldering time was 2 s. The soldering processes were performed on a laboratory scale using a bath of 2 kg of each solder. During soldering, the 2 μm Sn layer dissolved completely in the solder. Special attention was given to be sure that the same soldering conditions existed for all joint preparations with any of the three Pb-free alloys or the Pb-Sn eutectic alloy. Figure 1(a) is a representation of a typical joint before soldering. During soldering, molten solder reacts with contacts on the substrate and circuit component. The interfacial reactions that occur in solder joints can influence the microstructure as well as mechanical and electrical properties of the interconnect.

The idea behind an individual joint resistance measurement is based on the capability of the of the four four-probe method, a method already described in detail by Kisiel.[5] A current passes from a PCB Cu pad through one solder joint to a jumper resistor and from the jumper resistor through a second solder joint to another Cu pad on the PCB (Fig. 1b). By measuring the voltage drop across a single solder joint it is possible to calculate the individual joint resistance. A Keithley 2001 multimeter, option four wire Ohms, was used for such measurements. Automated data acquisition was possible through use of a locally developed software program.

The results of individual solder joint resistance measurements are shown in Table 4. Each value represents an average value of 100 measurements. The value of the joint resistance of the eutectic Pb-Sn solder was included for comparison. The Pb-Sn joints were prepared under the same conditions as those used for the Pb-free alloys. The main factors that can influence joint resistance are solder composition, PCB or component surface finish, joint geometry, and intermetallic compound formation on the boundary between substrate and solder as well as between solder and component Sn finishing. In our experiments, all joints had similar geometry and consistent conditions of preparation were maintained. The joint resistance of our Pb-free solders is comparable to that of the Pb-Sn reference alloy.

Among the mechanical properties that are highly relevant for a Pb-free solder to replace Pb-Sn solders is the shear force that produces failure of a single solder junction. Direct measurement of such a force poses some experimental problems. However, the application and recording of a shear force across a mounted jumper resistor and PCB interface is relatively straightforward, and the stress at failure is readily defined. Thus this approach was used. A shear force was applied directly to the middle of the longer side of the jumper with the PCB fixed in place. The force was gradually increased and recorded, and the point at which failure occurred was the shear strength of interest. This latter force represents the shear force necessary to exceed the combined strength of two solder joints plus the strength of the adhesive bond between the jumper and PCB. The value of the shear force for failure of a single soldered joint was evaluated in the following way. First the shear force necessary for failure of an unsoldered adhesive bond between PCB and jumper was evaluated from the average of thirty direct measurements. This value was subtracted from the shear force causing failure of a mounted jumper and the result was divided by two to compensate for the requirement that mounting requires two solder joints. The results from experimental determination of individual joint strengths of the three Pb-free solders and for a Pb-Sn eutectic alloy are shown in Table 5 with each value representing the average value from twenty samples. The value for the Pb-Sn eutectic in Table 5 was treated in the same way and measured on the same equipment as the Pb-free alloys. Thus, while the shear strengths of Pb-free solders are indicated as slightly lower than that of the Pb-Sn eutectic solder, the

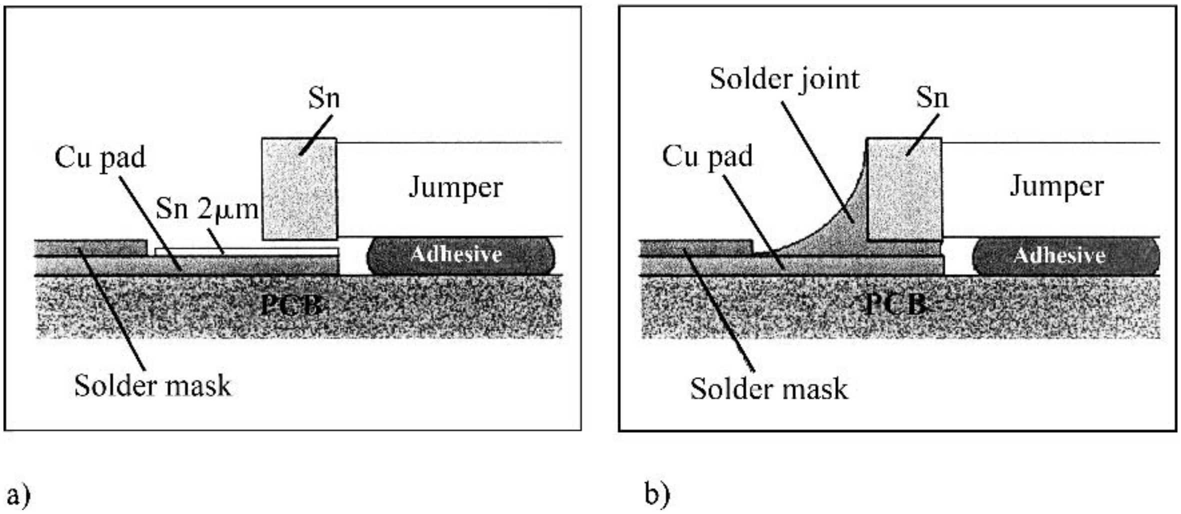

Fig. 1 Cross section of a solder joint: **(a)** before soldering and **(b)** after soldering

Table 4 Results of Solder Joint Resistance Measurements

Investigated Alloy	Joint Resistance, mΩ	Standard Deviation, mΩ
Reference Sn60Pb40	0.261	0.030
Sn 3.8Ag	0.246	0.034
(Sn-Au) eut + 0.46Cu	0.244	0.024
(Sn-Ag) eut + 0.74Cu	0.249	0.039

Table 5 Results of Solder Joint Shear Strength Measurements

Investigated Alloy	Joint Shear Strength N/mm^2	Standard Deviation N/mm^2
Reference Sn60Pb40	28.8	4.9
Sn 3.8Ag	24.1	5.0
(Sn-Au) eut + 0.46Cu	20.6	4.8
(Sn-Ag) eut + 0.74Cu	22.0	6.3

values are comparable. Indeed the values in Table 1 of the shear strengths of the Pb-Sn eutectic alloy and the Ag-Sn eutectic alloy are almost the same with one set of measurements weakly favoring the Ag-Sn eutectic and the other weakly favoring the Pb-Sn eutectic. Thus the small differences in the shear strengths of the solder joints in Table 5 are unlikely to adversely affect the utility of the Ag-Sn alloys in electronic circuitry.

4. Conclusions

This study of the electrical and mechanical properties of three Pb-free solder alloys has shown results that are comparable to data from the literature for Pb-Sn solders. This is sufficiently encouraging to continue measurements with additions of Sb and Bi to Ag-Sn-Cu eutectic alloys to produce quaternary and quinary alloys to get materials closer to traditional Pb-Sn solders. Future measurements on the new alloys will include both surface tension and wetting properties. The electrical and mechanical data that were obtained in the present investigation show that solders based on the Ag-Sn-Cu eutectic composition show promise for providing a replacement for Pb-Sn alloys in electronic assemblies.

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