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A novel low-temperature solder based on intermetallic-compound phases with superior high-homologous temperature properties

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Abstract

A novel low-temperature solder which consists entirely of two phases of intermetallic compounds is reported. The new solder can be reflowed below 125 °C and yet maintains high-temperature mechanical properties at homologous temperatures exceeding 0.9. Specifically, the new solder exhibits creep resistance and high-temperature retention capability exceeding those of conventional low-temperature solders, and its strength even exceeds that of Sn–4%Ag–0.5%Cu (SAC405) at the same homologous temperatures. This intermetallic solder also exhibits room-temperature ductility comparable to conventional solders. Drastic enhancement of wettability is achieved with addition of active metals.

Keywords: Low temperature solder; Intermetallic compound; Creep; Strength; Ductility

1. Introduction

Lowering reflow temperatures reduces thermal stresses on adjacent components. In addition, heat-sensitive materials such as ferroelectric polymers or liquid crystals are increasingly introduced to integrated chips [see e.g., [1]]. These heat-sensitive materials, in general, have limited thermal stabilities and some of them require low-temperature assembly below 125 °C [2]. Several low-temperature solders are known in the commercial market or literature. Most of these low-temperature solders, however, exhibit poor mechanical properties during operation or reliability testing due to high homologous temperatures (T_{hom}). The T_{hom} of near-eutectic Sn–Ag–Cu (T_m = 217 °C) solders is 0.76 at 100 °C (typical microprocessor operation temperature) and those of commercially-available eutectic Sn–Bi (T_m = 139 °C) and Sn–In (T_m = 120 °C) solders are even higher (0.91 and 0.95, respectively). At these high T_{hom}'s, metallic materials are, in general, subject to strength loss, creep deformation and microstructural coarsening which, in turn, limit their long-term reliability [3]. For example, the binary eutectic Sn–In (T_m = 120 °C) alloy, a common solder for low-temperature soldering below 150 °C, is found to exhibit exceedingly poor reliability under a typical temperature cycling condition for microelectronic applications (85 °C to −40 °C) [4].

Ni-based superalloys have been extensively used in jet-propulsion applications at similarly high T_{hom} (>0.7). From the T_{hom} perspective, the superalloy can be viewed as a high-temperature counterpart of the low-temperature solder. It is known that the strength retention ability and creep resistance of Ni-based superalloys partly originate from a high volume fraction (~70%) of the Ni_3Al-type ordered intermetallic compound in their microstructure [5]. Given the parallels between superalloys and low-temperature solders in terms of their use conditions, it would be interesting to examine whether reliable low-temperature solders can be designed based on intermetallic compounds to deliver "superalloy-like" performance. While intermetallic compounds are extremely brittle at low T_{hom}, many of them are ductile at high T_{hom} [6]. Low-temperature soldering application, therefore, may circumvent brittleness issues of intermetallic compounds because solders are used at high T_{hom} typically exceeding 0.7.

In an attempt to develop reliable low-temperature solders for reflow below 125 °C, the authors explored the possibility of

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using an intermetallic compound as a baseline phase. In this letter, we report a newly-developed low-temperature solder which consists entirely of two phases of intermetallic compounds between In and Bi. It can be reflowed below 125 °C and yet exhibits strength retention ability and creep resistance at T_{hom} exceeding 0.9. This intermetallic solder also exhibits ductility comparable to conventional solders at room-temperature. A solder based entirely on intermetallic compounds, to the best of authors' knowledge, has never been reported and the authors believe that this work provides a new paradigm for solder alloy design.

2. Experimental

Samples were prepared by alloying Bi and In (99.99% purity) in an electric heating melter. Thermal analysis was conducted in a differential scanning calorimeter (DSC) with a heating rate of 5 °C/min, and constituent phases were examined with X-ray diffraction (XRD) with Cu radiation. Tensile testing was performed on cylindrical specimen with a gage length of 50 mm in accordance with JIS Z-2201. The creep behavior was examined using miniaturized impression creep testing [7] with a cylindrical punch (100 μm in diameter). Ball pull testing was conducted in order to examine joint strength after reflow. Approximately 50 spheres reflowed on Au-coated Ni (electrolytic NiAu) surfaces were tested in a Dage 4000 bond tester with pull speed of 5 mm/sec. Interfaces at base metals were examined with an electron probe X-ray microanalysis (EPMA) equipped with a wavelength dispersive spectrometer (WDS).

3. Results and discussion

Fig. 1 shows binary In-Bi phase diagram where three line-compounds (BiIn, Bi_3In_5 and $BiIn_2$) are indicated. After several iterations of alloy design and characterization, Bi–51%In (compositions are given in weight %) was identified as a baseline composition for 125 °C reflow applications. Bi–51%In is a near-eutectic alloy with the eutectic temperature of 88.9 °C and exhibits a narrow melting range of 88–91 °C in a DSC. Its constituent phases are all intermetallic compounds (Bi_3In_5 and $BiIn_2$) confirmed by X-ray diffraction.

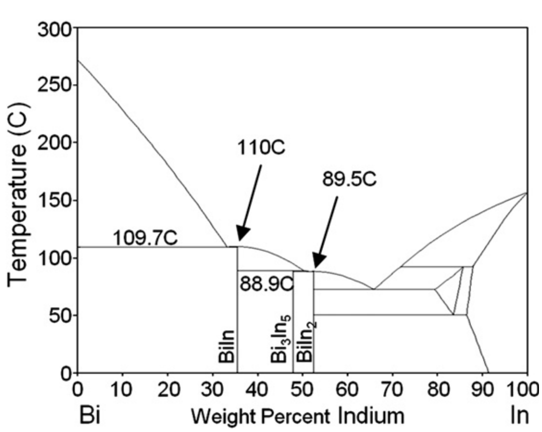

Fig. 1. Equilibrium phase diagram of the binary In–Bi system calculated in the PANDAT software with ADAMIS database by CompuTherm LLC.

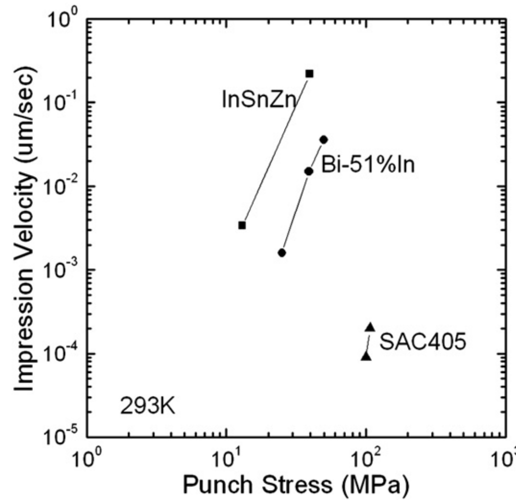

Fig. 2. Impression velocities for Bi–51%In, InSnZn and SAC405 alloys as a function of punch stress measured in impression creep testing at room temperature.

Fig. 2 shows the room-temperature impression velocity as a function of punch stress obtained from impression creep testing conducted on solder spheres (350 μm in diameter). As shown in the figure, Bi–51%In ($T_{\mathrm{m}} \sim 89$ °C) exhibits impression velocity an order of magnitude lower than the ternary eutectic In–46%Sn–1.5%Zn alloy (InSnZn, $T_{\mathrm{m}} \sim 108$ °C), which is based on random-solid solution phases and also can be reflowed below 125 °C. The T_{m} of Bi–51%In is about 20 °C lower than that of InSnZn and therefore the T_{hom} of Bi–51%In is higher than that of InSnZn at the testing temperature (0.82 vs 0.78). In other words, the Bi–51%In alloy exhibits 10 times greater creep resistance than the conventional low-temperature solder despite the fact that Bi–51%In has lower T_{m} or higher T_{hom} during testing.

In Fig. 3, ultimate tensile strengths measured at various temperatures are plotted as a function of T_{hom}. Consistent with creep behavior, Bi–51%In is found to exhibit greater strengths than the random solid solution based InSnZn at all temperatures (absolute or homologous) despite its lower T_{m}. Furthermore, Bi-51%In maintains a considerable strength of ~10 MPa (which is acceptable for soldering applications)

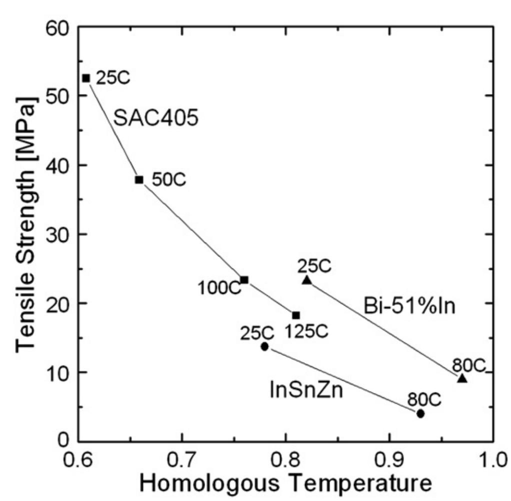

Fig. 3. Ultimate tensile strengths for Bi–51%In, InSnZn and SAC405 as a function of homologous temperatures.