Electrical and Thermal Characteristics of Pb-Free Sn-Zn Alloys for an AC-Low Voltage Fuse Element

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The temperature dependence of specific resistivity and thermal conductivity for some Sn-Zn alloys was measured to use their values in electrical and thermal calculations on the basis of Ohm's and Fourier's laws, in order to obtain the temperature-distribution in lead-free fuse elements of electric power line. The interaction between microstructures and their properties was also investigated in Sn-Zn alloys. Specific resistivity and thermal conductivity could be estimated as a function of temperature and alloy composition in the compositional ranges classified from the standpoint of continuity or non-continuity of constituent phases such as primary Zn, Sn-solid solution and eutectic in microstructures of Sn-1 to 100Zn alloys. In the proposed estimations, not only volume fraction of Zn and Sn-solid solution phases but morphologies of both phases were considered in Sn-Zn alloys. [doi:10.2320/matertrans.48.1105]

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1. Introduction

Lead and its alloys or compounds are considered environmental hazards because of lead's toxicity therefore many countries are going to ban their use.^{1,2)} The practical Pb-Sn alloys used as solders in electrical and electronic industries are classified into two groups (Pb-5 mass%Sn and Pb-60 mass%Sn) by their melting temperatures. The Pb-60Sn alloy has been also used as AC-low voltage fuse elements in electric power line.^{3,4)} Due to the world-wide legislative requirements,^{5,6)} it is important to develop viable alternative Pb-free alloys for AC-fuse elements used in electric power line. The main requirements for alternative fusible alloys are:

- (1) Low melting point: The melting points should be comparable to practical Sn-Pb system alloys.
- (2) Availability: There should be adequate supplies or reserves available of candidate metals.
- (3) Ability of manufacture: The production of raw materials should not be difficult.

The Sn-9Zn alloy has been investigated in our previous study as a Pb-free alloy for low-voltage fuse elements, except for the points of its performance in a break at high value (3000A) in electric current, weather proof and wettability on copper.^{3,4,7)} In contrast, since an eutectic point (471 K) of Sn-Zn system alloys is similar to that (456 K) of the practically used Pb-60Sn, it has been also considered by other investigators as a candidate alloy system for a lead-free solder material.^{8,9)} The Sn-Zn eutectic system which is basically classified as an anomalous eutectic alloy, has a broken-lamellar type eutectic structure.¹⁰⁾ The faceting lamellas are Zn and the nonfaceting face is the Sn matrix. Under rapid cooling conditions, the lamellar Zn becomes fibrous,^{10,11)} which means the sensitivity to solidifying conditions. It is considered that electrical and thermal conductivity of Sn-Zn eutectic system alloys are difficult to be estimated using Maxwell¹²⁾ and Landauer¹³⁾ models, because those properties are directly influenced by morphology of each phase in them.

It is important in the shape-design of fuse elements that temperature distributions in the fuse element-connector-electric wire system, are exactly known in some conditions evaluating the main requirements⁷⁾ (period showing melt or un-melt down and temperature increment at fixed current flow conditions) for AC-low voltage fuse elements. The heterogeneity in potential and temperature was predicted by simulations for fuse elements at higher temperatures.⁷⁾ The temperature dependence of specific resistivity, thermal conductivity and specific heat or the temperature conductivity in Sn-Zn system alloys, must measured exactly for optimization of shape and alloy-composition in fuse elements, because computer simulation consists of electrical and thermal calculations on the basis of Ohm's and Fourier's laws, respectively. Furthermore, the interaction between microstructures and thermal or electrical properties is not clear for variously compositional alloys of the Sn-Zn system as the two phase materials consisting of pure Zn and Sn-solid solution containing Zn of less than 1 mass%.

The present study aimed to measure the temperature dependence of the specific resistivity and thermal conductivity used in electrical and thermal calculations, and to investigate the interaction between microstructures and thermal or electrical properties, for Sn-Zn system alloys with several different compositions as a candidate alloy system for lead-free fuse elements used in electric power line.

2. Experimental Procedures

Pure Sn with the purity of 99.9% and pure Zn with the purity of 99.9% were weighed according to the nominal compositions of some Sn-Zn alloys (Sn-0, 1, 9, 20, 50, 80, 100 mass% Zn). They were melted in a graphite crucible in air. Molten metals were held for 1.2 ks at temperatures which were 50 K higher than their liquidus temperatures. Their melts were poured into the cold split-die made of carbon steel in air. Figure 1 shows the cylindrical die which has the inner diameter of 15 mm and height of 116 mm.

Fig. 1 Schematic drawing of the split-die made of carbon steel, used in this study. Units are given in mm.

The microstructural observation was carried out using an optical microscope. The specific resistivity (ρ_e) was simultaneously measured from room temperature to about 470 K by the standard four probe d.c. method in air using a computer-controlled equipment. The size of samples was $1 \times 1 \times 17$ mm. The temperature gradient along the length (17 mm) of samples for the measurement of ρ_e was about 5 K. The thermal conductivity (λ) was measured from 293 K to 460 K using samples with the diameter of 11 mm and length of 50 mm, under the steady-state condition in air. Figure 2 shows the construction of a Sn-Zn sample, copper heating rod with a cartridge heater and cooling plate for measurement of the heat conduction. The value of λ was obtained using the relation represented in eq. (1),

$$\lambda \frac{\Delta T_i}{L_i} \frac{\pi D^2}{4} = EI \quad (1)$$

where, the product of E and I represented the amount of Joule's heat discharged to a cartridge heater with a capability of 200 V and 200 W, D and ΔT_i represented the diameter of samples and the temperature difference caused between the points keeping a fixed length (L_i) of 5 mm, respectively. The temperature was measured by the K type thermocouples of the diameter of 0.1 mm.

Density measurement using a high density liquid was performed by Archimedes' method. Differential thermal analysis (DTA) was carried out on some alloys. DTA measurement was conducted at a constant heating and cooling rates of 5 K/min in a low purity argon stream.

Fig. 2 The construction of a Sn-Zn sample, copper heating rod with a cartridge heater and cooling plate for measurement of the heat conduction under steady-state condition. Units are given in millimeters.

3. Results and Discussion

3.1 Microstructures

The microstructures of as-cast alloys (Sn-0, 1, 9, 20, 50, 80, 100Zn) are shown in Fig. 3. Pure Sn, Sn-1Zn and pure Zn samples showed pure Sn-, Sn solid solution- and pure Zn-monophases with the particle size of 72, 127 or 40 μm , respectively, depending on their cooling rates. The microstructure of the Sn-9Zn alloy showed a typical Sn-Zn eutectic structure with the light contrast Sn-solid solution and the dark contrast Zn phases which were formed alternately. Sn-9Zn is considered to be a two phase material consisting of pure Zn and Sn-solid solution with Zn of less than 1 mass%, and Sn-solid solution phase was continuous one in this alloy. Sn-20Zn showed a microstructure consisting of a plate-like primary Zn and eutectic consisting of Sn-solid solution and pure Zn. The amount of the primary Zn phase increased and the amount of eutectic decreased as Zn contents increased in Sn-20, 50, 80Zn alloys, as shown in Fig. 2(d)–(f). The Sn-20, 50, 80Zn alloys showed two grains consisting of the primary Zn and eutectic. The eutectic and primary Zn were continuously present throughout the microstructures of Sn-20Zn and Sn-80Zn alloys, respectively. In other words, the primary Zn and eutectic were considered to be second phases in eutectic and Zn matrixes for Sn-20Zn and Sn-80Zn alloys, respectively. In contrast, both the eutectic and primary Zn were continuously present in Sn-50Zn alloy.

3.2 Specific resistivity

The ρ_e of some Sn-Zn alloys (Sn-0, 1, 9, 20, 50, 80, 100Zn)

Fig. 3 The optical micrographs of as-cast materials for (a) pure Sn, (b) Sn-1Zn, (c) Sn-9Zn, (d) Sn-20Zn, (e) Sn-50Zn and (f) Sn-80Zn and (g) pure Zn.

was measured at various temperatures in the range of 293–470 K. Figure 4 shows the temperature and compositional dependence of the ρ_e . In this figure, 7 straight lines approximated by a least squares method using experimental values of ρ_e for each composition mean only the qualitative tendency of its change. As can be seen in the figure, the ρ_e increased monotonously with increasing temperature, regardless of Zn contents in alloys. The ρ_e also increased even at same temperatures as the Sn content increased in alloys.

The temperature dependence of the ρ_e increased as the Sn content increased in alloys. Below the eutectic point (471 K) for Sn-0 to 100Zn alloys of the widely compositional range, the ρ_e is roughly represented as the functions of the composition and temperature using eq. (2),

$$\rho_e = (-0.0313Zn + 0.0549)Temp + 2.2011Zn - 3.3643 \quad (2)$$

where, Zn and $Temp$ represent the mass fraction of Zn in alloys and temperature, respectively.

Fig. 4 Specific resistivity measured in this study for some Sn-Zn alloys.

Fig. 5 Relation between specific resistivity and volume fraction of Sn-solid solution at some temperatures for several Sn-Zn alloys.

The ρ_e in microstructures consisting of two phases depends on microstructural characteristics such as volume fraction and morphology of each phase. It is considered from Fig. 3 and the constitutional diagram¹⁴⁾ that Sn-Zn system alloys are two phase materials consisting of the Sn-solid solution with Zn of less than 1 mass% and pure Zn, in widely compositional range of Sn-Zn system. There are different morphologies in Zn and Sn-solid solution grains between the primary phase and eutectic depending on alloy compositions. Figure 5 shows relation between the experimental value of ρ_e obtained from its straight line for each composition in Fig. 4 and volume fraction of Sn-solid solution at some temperatures. The values in volume fraction of Sn-solid solution

were obtained from the density (Sn-solid solution: 7.30 Mg/m³, Zn: 7.13 Mg/m³, described in detail in section 3.4) and amount ratio in the equilibrium diagram¹⁴⁾ for Sn-solid solution and Zn. In this figure, the value of 1 in volume fraction of the Sn-solid solution corresponds to the composition of Sn-1Zn showing the solubility limit of Zn in the Sn-solid solution.¹⁴⁾ The lines showing compositional dependence of ρ_e can be classified into three regions (1, 2 and 3). The composition showing the change in slopes of the lines corresponded to that showing the change in microstructural characteristics which meant the difference in the kinds and continuity for matrix and second phases consisting of primary Zn, Sn-solid solution or eutectic, as shown in Fig. 3. The ρ_e depends on the microstructural characteristics mentioned above. The lines were approximated by eq. (3),

$$\rho_e = aSn + b \quad (3)$$

where, Sn and a or b represent the volume fraction of Sn-solid solution and constants, respectively. The values of a and b are listed in Table 1. Furthermore, ρ_e in the narrowly compositional range of the region 1, 2 and 3 can be exactly represented as the function of the composition and temperature using eqs. (4), (5) and (6), respectively, compared with eq. (2) which was roughly proposed in widely compositional range,

$$\rho_e = (0.0304Sn + 0.0236)Temp - 0.8564Sn - 1.4518 \quad (4)$$

$$\rho_e = (0.0177Sn + 0.0292)Temp - 0.0295Sn - 1.5555 \quad (5)$$

$$\rho_e = (0.1611Sn - 0.1024)Temp - 37.2265Sn + 32.5440 \quad (6)$$

Higher and lower values in a and b , respectively at higher temperatures were shown in the region 3 showing compositions of higher Sn contents, because of strongly dependence in temperatures for ρ_e of pure Sn as shown in Fig. 4. The values of a and b are mainly decided depending on values in ρ_e of pure Zn and Sn.

Figure 6 shows the relation between the experimental values of ρ_e at 293 and 460 K which were obtained from the straight lines in Fig. 4 and the approximation using eqs. (4)–(6) in the compositional range of Sn-1 to 100Zn. The primary Zn and eutectic are continuous grains in region 1 and 2 shown in Fig. 5, respectively. Fan,¹⁵⁾ Maxwell¹²⁾ and Landauer¹³⁾ models can be represented using eqs. (7), (8) and (9), respectively. Their estimations were also shown in this figure, and their models were proposed for ρ_e of composites with widely range in the volume fraction of second phases,

Table 1 The values of a and b in eq. (3) for approximation of slopes in three regions shown in Fig. 5.

Temperatures	Region 1 (Sn-50 to 100Zn)		Region 2 (Sn-9 to 50Zn)		Region 3 (Sn-1 to 9Zn)	
	a	b	a	b	a	b
293 K	8.053	5.4718	5.1491	6.9915	9.9703	2.5403
340 K	9.4822	6.5824	5.9862	8.3609	17.542	-2.2727
380 K	10.698	7.5276	6.6885	9.529	23.986	-6.3689
420 K	11.915	8.4728	7.3963	10.696	30.431	-10.465
460 K	13.131	9.418	8.104	11.862	36.875	-14.561

Fig. 6 Relation between the experimental values of specific resistivity at (a) 293 and (b) 460 K shown in Fig. 4 and the approximation using eqs. (4)–(6) in the compositional range of Sn-1 to 100Zn, and comparison of fitting data by eqs. (4)–(6) proposed in this study with those by Fan's, Maxwell's and Landauer's models.

$$\frac{1}{\rho_e} = \frac{f_m^r}{\rho_m} + \frac{f_2^s}{\rho_2} + \frac{(1 - f_m^r - f_2^s)^2}{\rho_m(f_m - f_m^r) + \rho_2(f_2 - f_2^s)} \quad (7)$$

$$\rho_e = \rho_m \left[\frac{2\rho_2 + \rho_m + f_2(\rho_2 - \rho_m)}{2\rho_2 + \rho_m - 2f_2(\rho_2 - \rho_m)} \right] \quad (8)$$

$$\frac{1}{\rho_e} = \frac{1}{4} \left\{ \frac{1}{\rho_m} (3f_m - 1) + \frac{1}{\rho_2} (3f_2 - 1) + \sqrt{D} \right\} \quad (9)$$

where, ρ_m and ρ_2 were the ρ_e of a matrix (Sn-solid solution) and second phase (pure Zn), respectively, f_m and f_2 were volume fraction of matrix and second phases, respectively, r and s were constants meaning characteristics of the phase arrangement in the microstructure, D was defined by eq. (10),

$$D = \left\{ \frac{1}{\rho_m} (3f_m - 1) + \frac{1}{\rho_2} (3f_2 - 1) \right\}^2 + 8 \frac{1}{\rho_m} \frac{1}{\rho_2} \quad (10)$$

The estimation results by Fan, Maxwell and Landauer models showed appreciable deviations from experimental results, because the difference in the morphologies could not be considered between the Zn or Sn-solid solution phase as a primary crystal and these phases crystallized by the eutectic reaction. In contrast, the approximation of ρ_e using eqs. (4)–(6) in the compositional classification (region 1–3) from the point of microstructural characteristics, is in good agreement with the experimental results, because not only volume fraction of Zn and Sn-solid solution phases but morphologies of these phases were considered by both use of these equations and application of three compositional ranges for

Fig. 7 Thermal conductivity measured in this study for some Sn-Zn alloys.

Fig. 8 Relation between thermal conductivity and volume fraction of Sn-solid solution at some temperatures for several Sn-Zn alloys.

the microstructural characteristics shown in Fig. 3. The ρ_e of Sn-Zn alloys can be exactly estimated by the procedure mentioned above, which leads to an exact estimation of temperature-distribution in lead-free fuse elements of electric power line, by electrical and thermal calculations on the basis of Ohm's and Fourier's laws.

3.3 Thermal conductivity

The λ of some Sn-Zn alloys (Sn-0, 1, 9, 20, 50, 80, 100Zn) were measured at some temperatures of the range of 293–460 K. Figure 7 shows the temperature and compositional dependence of the λ , and the behavior of its change using 7 lines in the same manner with Fig. 4. As can be seen in this figure, the λ decreased monotonously with increasing temperature, regardless of Zn contents in alloys. The λ also decreased even at same temperatures as the Sn content increased in alloys. Below the eutectic point (471 K) for Sn-0 to 100Zn alloys of the widely compositional range, the λ is roughly represented as the functions of the composition and temperature using eq. (11),

$$\lambda = (0.0273Zn - 0.0982)Temp + 38.183Zn + 98.24 \quad (11)$$

Figure 8 shows relation between the experimental values of λ and volume fraction of Sn-solid solution at some temperatures in the same manner with Fig. 5. In this figure, the value of 1 in volume fraction for the Sn-solid solution

Table 2 The values of a and b in eq. (12) for approximation of slopes in three regions shown in Fig. 8.

Temperatures	Region 1 (Sn-50 to 100Zn)		Region 2 (Sn-9 to 50Zn)		Region 3 (Sn-1 to 9Zn)	
	a	b	a	b	a	b
293 K	-35.344	113.25	-50.799	121.61	-75.101	143.5
340 K	-37.606	110.04	-51.66	117.98	-72.679	136.48
380 K	-40.631	107.78	-52.401	114.86	-69.045	129.04
420 K	-41.551	104.66	-53.21	111.86	-67.833	123.93
460 K	-44.549	102.36	-53.882	108.73	-65.411	117.61

corresponds to the composition of Sn-1Zn showing the solubility limit of Zn in the Sn-solid solution.¹⁴⁾ The lines showing compositional dependence of λ , as well as ρ shown in Fig. 5, can be also classified into three regions (1, 2 and 3). The composition showing the change in slopes of the lines corresponded to that showing the change in microstructural characteristics which meant the difference in the kinds and continuity for matrix and second phases consisting of primary Zn, Sn-solid solution or eutectic, as shown in Fig. 3. The λ depends on the microstructural characteristics mentioned above. The lines were approximated by eq. (12),

$$\lambda = aSn + b \quad (12)$$

The values of a and b are listed in Table 2. Furthermore, λ in the narrowly compositional range of the region 1, 2 and 3 can be exactly represented as the function of the composition and temperature using eqs. (13), (14) and (15), respectively, compared with eq. (11) which was roughly proposed in widely compositional range,

$$\lambda = (-0.0540Sn - 0.0656)Temp - 19.497Sn + 132.46 \quad (13)$$

$$\lambda = (-0.0186Sn - 0.0770)Temp - 45.335Sn + 144.16 \quad (14)$$

$$\lambda = (0.0585Sn - 0.1554)Temp - 92.180Sn + 188.95 \quad (15)$$

Lower and higher values in a and b , respectively were shown in the region 3 showing compositions of higher Sn contents regardless of temperatures, because of lower values of λ in pure Sn.

Figure 9 shows the relation between the experimental values of λ at 293 and 460 K which were obtained from its straight line for each composition in Fig. 7 and the approximation using eqs. (13)–(15) in the compositional range of Sn-1 to 100Zn. The primary Zn and eutectic are continuous grains in region 1 and 2 shown in Fig. 8, respectively. Estimations by Maxwell¹²⁾ and Landauer¹³⁾ models represented using eqs. (8) and (9), respectively, were also shown in this figure. Eqs. (8) and (9) were also used in the estimation of λ , by substituting λ into $1/\rho_e$. In eqs. (8) and (9), λ_m and λ_2 were thermal conductivity of a matrix (Sn-solid solution) and second phase (pure Zn), respectively.

The estimation results by Maxwell and Landauer models showed appreciable deviations from experimental result. In contrast, the approximation of λ using Eqs. (13)–(15) in the compositional classification (region 1–3) from the point of microstructural characteristics, is in good agreement with the experimental results, because not only volume fraction of Zn

Fig. 9 Relation between the experimental values of thermal conductivity at (a) 293 and (b) 460 K shown in Fig. 7 and the approximation using eqs. (13)–(15) in the compositional range of Sn-1 to 100Zn, and comparison of fitting data by eqs. (13)–(15) proposed in this study with those by Maxwell's and Landauer's models.

and Sn-solid solution phases but morphologies of these phases were considered by both use of these equations and application of three compositional ranges for microstructural characteristics shown in Fig. 3. The λ of Sn-Zn alloys can be exactly estimated by the procedure mentioned above, which leads to an exact estimation of temperature-distribution in lead-free fuse elements of electric power line, by electrical and thermal calculations on the basis of Ohm's and Fourier's laws.

It is found that ρ_e and λ can be estimated with good accuracy by use of eqs. (4)–(6) and (13)–(15), respectively, in application of the compositional ranges classified from the standpoint of continuity or non-continuity of constituent phases such as the primary Zn, Sn-solid solution and eutectic in microstructures of Sn-1 to 100Zn alloys.

Table 3 Density measured according to Archimedes' principle.

Alloys	Density, Mg/m ³
Pure Sn	7.31
Sn-1Zn	7.30
Sn-9Zn	7.29
Sn-20Zn	7.27
Sn-50Zn	7.23
Sn-80Zn	7.17
Pure Zn	7.13

Fig. 10 DTA curves obtained from the practically used Sn-39Pb-1.6Ti-0.1Cu alloy.

3.4 Other properties and comparisons with the practical alloy

The densities of Sn-0, 9, 20, 50, 80, 100Zn alloys were measured at 293 K according to Archimedes' principle. Their values are listed in Table 3. The values of their densities were changed depending on the contents of the primary Sn-solid solution and Zn phases.

The Sn-39Pb-1.6Ti-0.1Cu alloy has been used as an AC-low voltage fuse element in electric power line.⁴⁾ The melting point of Pb-free alloys should be comparable to that of practical used alloys. The determination of the melting point was carried out on the practical alloy, as seen in Fig. 10. In the DTA heating curves of the practical alloy, one endothermic peak (P_0) appeared at 454 K. Meanwhile, one peak (P_2) appeared at 451 K in its cooling curve. P_0 or P_2 corresponded to the eutectic reaction.

DTA was also carried out using Sn-Zn alloys in order to compare with the result obtained from Sn-39Pb-1.6Ti-0.1Cu. Figure 11 shows DTA curves obtained from the Sn-9Zn and Sn-80Zn alloys, as typical examples. In the DTA heating curves of Sn-9Zn and Sn-80Zn, one endothermic peak (P_0) appeared at 474 and 471 K, respectively. Meanwhile, in the cooling curve of Sn-80Zn, two exothermic peaks (P_1 and P_2) appeared at 649 and 470 K, respectively, and in that of Sn-9Zn, one peak (P_2) appeared at 471 K. P_0 or P_2 and P_1 corresponded to the eutectic reaction and the crystallization of primary Zn phase, respectively. The amount of primary Zn phase increased as the temperature decreased in the range of temperature of 649 to 470 K in the cooling process for the Sn-80Zn alloy. In other words, both liquid caused by the eutectic

Fig. 11 DTA curves obtained from (a) Sn-80Zn and (d) Sn-9Zn alloys.

reaction and Zn-solid were present in this temperature range of heating process. In the range between the liquidus and eutectic temperatures, the presence of the solid and liquid lead to satisfy the property of un-melt down under the higher fixed value (210A) of electric current as one of main requirements for fuse elements,^{3,4)} compared with the Sn-9Zn and Sn-39Pb-1.6Ti-0.1Cu alloys of eutectic compositions. Furthermore, the value in volume fraction of Zn-solid in this temperature range has to be optimized experimentally for satisfying both melt and un-melt down under the fixed values of 99A and 210A, respectively.^{3,4)} The reaction temperatures are listed in Table 4 for several Sn-Zn alloys.

The same behavior of DTA was observed for the Sn-39Pb-1.6Ti-0.1Cu and Sn-9Zn alloys, as shown in Figs. 10 and 11(b). Temperature in the eutectic reaction of Sn-Zn system alloys was approximately 20 K higher than that of the Sn-39Pb-1.6Ti-0.1Cu alloy, as listed in Table 4. Therefore, it is roughly considered that the Sn-Zn system alloys satisfy the requirement of melting point for an alternative fusible alloy, except for wettability on copper.

The ρ_e , λ and specific heat (c_p) measured at room temperature are listed in Table 5, for the Sn-9Zn, Sn-39Pb-1.6Ti-0.1Cu⁴⁾ alloys and pure copper⁴⁾ for electric power line. Their values of Sn-9Zn in Sn-Zn system alloys are listed as a typical example. The c_p was measured on a sample with the diameter of 9 mm and thickness of 1.7 mm, by the laser flash method.⁷⁾ Temperature conductivity was obtained using values of the λ , c_p and density. The value of the temperature conductivity for Sn-9Zn is 1.41 times larger than that of the Sn-39Pb-1.6Ti-0.1Cu alloys, which approaches to that of pure copper and leads to the larger amount of the heat transfer by heat conduction. In contrast, the value of ρ_e of Sn-9Zn alloy is 0.78 times, compared with that of the practical alloy, which means lower amount of the heat generation in the proposed alloy.

Table 4 Reaction temperatures obtained from DTA curves of the several Sn-Zn alloys and the practical alloy as a reference.

Alloys	Heating process	Cooling process	
	P ₀ (Eutectic Temp.), K	P ₁ (Liquidus Temp.), K	P ₂ (Eutectic Temp.), K
Sn-9Zn	474	—	471
Sn-20Zn	474	556	471
Sn-50Zn	472	626	471
Sn-80Zn	471	649	470
Sn-39Pb-1.6Ti-0.1Cu	454	—	451

Table 5 The specific resistivity, thermal conductivity, specific heat and temperature conductivity at room temperature of Sn-9Zn, Sn-39Pb-1.6Ti-0.1Cu alloys and pure copper.

Alloys	Specific Resistivity, $\mu\Omega\text{ cm}$	Thermal conductivity, W/m/K	Specific heat, kJ/kg/K	Temperature conductivity, m^2/s
Sn-9Zn	12.1	75.3	0.226	4.57×10^{-5}
Sn-39Pb-1.6Ti-0.1Cu	15.6	52.0	0.196	3.24×10^{-5}
Pure Cu	1.6	394.0	0.385	1.15×10^{-4}

Fuse elements are optimized by design of shape and alloy-composition. Size and composition of fuse elements can be proposed using eqs. (4)–(6) and (13)–(15) of ρ_e and λ represented as a function of composition and temperature in the compositional classification (region 1–3) from the point of microstructural characteristics, by computer simulation consists of electrical and thermal calculations on the basis of Ohm's and Fourier's laws.

4. Conclusinos

- (1) Sn-Zn alloys showed two phase microstructures consisting of Sn-solid solution and pure Zn phases. The eutectic, primary Zn or Sn-solid solution was present as a continuous grain depending on compositions of Sn-Zn alloys. Sn-Zn alloys could be classified into three microstructural groups (Sn-50 to 100Zn, Sn-9 to 50Zn and Sn-1 to 9Zn) depending on the difference in the kinds and continuity for matrix and second phases consisting of the primary Zn, Sn-solid solution or eutectic.
- (2) Specific resistivity increased as temperatures and Sn contents increased in Sn-Zn alloys. In contrast, thermal conductivity decreased as temperature and Sn contents increased in Sn-Zn alloys. Specific resistivity and thermal conductivity were estimated using equations representing by a function of the alloy composition and temperature.
- (3) Specific resistivity and thermal conductivity could be estimated with good accuracy by use of proposed equations as a function of temperature and composition in the compositional ranges classified from the stand-point of continuity or non-continuity of constituent phases such as primary Zn, Sn-solid solution and eutectic phases in microstructures of Sn-1 to 100Zn alloys. In the proposed estimations, not only volume fraction of Zn and Sn-solid solution phases but

morphologies of these phases were considered in Sn-Zn alloys.

- (4) Temperature in the eutectic reaction of Sn-Zn alloys was approximately 20 K higher than that of the practically used Sn-39Pb-1.6Ti-0.1Cu alloy. The presence of the solid of Zn or Sn solid solution and liquid above the eutectic temperature, leads to satisfy the property of unmelt down under the higher fixed value (210A) of electric current as one of main requirements for fuse elements, compared with the Sn-9Zn alloy showing the eutectic composition.

REFERENCES

- 1) S. Jin, D. R. Frear and J. W. Morris, Jr.: J. Electron Mater. **23** (1994) 709–713.
- 2) K. Suganuma: Solid State Mater. Sci. **5** (2001) 55–64.
- 3) T. Narahashi: Thesis for Master Degree, Hiroshima University, Higashi-Hiroshima, Japan, (2006) pp. 2–5.
- 4) O. Yanagisawa, K. Matsugi, Y. Kikuchi, M. Sako, T. Narahashi, K. Fujii, Y. Kumagai and K. Fujita: Sn alloys for electric fuse elements and electric fuses using their elements, Japan Patent, (2006) opening 2006–161130.
- 5) *Electronic Material Handbook*: ed. by ASM International, vol. 1, (ASM International, Materials Park, Ohio, 1989) pp. 965–966.
- 6) P. Biocca: Surf. Mount Technol. **13** (1999) 64–67.
- 7) K. Matsugi, G. Sasaki, O. Yanagisawa, Y. Kumagai and K. Fujii: Mater. Trans. **47** (2006) 2413–2420.
- 8) W. Yang and R. W. Messler Jr.: J. Electron Mater. **23** (1994) 765–772.
- 9) H. Mavoori, J. Chin, S. Vaynman, B. Moran, L. Keer and ME. Fine: J. Electron Mater. **26** (1997) 783–790.
- 10) F. Vnuk, M. Sahoo, D. Baragar and R. W. Smith: J. Mater. Sci. **15** (1980) 2573–2583.
- 11) R. Elliott and A. Moore: Scripta Metall. **3** (1969) 249–251.
- 12) J. C. Maxwell: *A Treatise on Electricity and Magnetism*, vol. 1, (Oxford Univ. Press, Oxford, 1873) p 365.
- 13) R. Landauer: J. Appl. Phys. **23** (1952) 779–784.
- 14) M. Hansen: *Constitution of Binary Alloys* (McGraw-Hill Book Company, Inc., New York, 1958) pp. 1217–1219.
- 15) Z. Fan: Acta Metall. Mater. **43** (1995) 43–49.