Research Article

Toru Akasofu*, Masanobu Kusakabe, and Shigeru Tamaki

An interpretation on the thermodynamic properties of liquid Pb–Te alloys

https://doi.org/10.1515/htmp-2020-0068
received April 21, 2020; accepted June 15, 2020

Abstract: The bonding character of liquid lead telluride PbTe is thermodynamically investigated in detail. Its possibility as an ionic melt composed of cation Pb\(^{2+}\) and anion Te\(^{2-}\) is not acceptable, by comparing the ionization energy of Pb atom, electron affinity of Te atom and the ion bonding energy due to the cation Pb\(^{2+}\) and anion Te\(^{2-}\) with the help of structural information. Solid lead telluride PbTe as a narrow band gap semiconductor might yield easily the overlapping of the tail of valence band and that of conduction one. And on melting, it becomes to an ill-conditioned metallic state, which concept is supported by the electrical behaviors of liquid Pb–Te alloys observed by the present authors. As structural information tells us about the partial remain of some sorts of covalent-type mono-dipole and poly-dipole of the molecule PbTe, all systems are thermodynamically explained in terms of a mixture of these molecules and cations Pb\(^{4+}\) and Te\(^{2+}\) and a small amount of the conduction electrons are set free from these elements based on the ternary solution model.

Keywords: liquid Pb–Te, complex formation, thermodynamics, phase diagram

1 Introduction

In the glory days of liquid metals and alloys, the compound-forming liquid alloys have also been investigated as one of the complicated systems in view of physics. Although the solid compound telluride PbTe is known as a narrow band gap semiconductor, it turns to be an ill-conditioned metallic alloy in the liquid state, because, for example, its electrical resistivity is in the range of 6–8 \(\mu\Omega\) m. In due course, liquid Pb–Te binary alloys are classified as typical compound-forming liquid alloys [1,2]. However, it was not known what sort of compound in liquid Pb–Te binary alloys is formed, until the recent time. Several years ago, we have clarified that this compound-forming complex is a covalent-type molecule of PbTe, which is incorporated with the remaining metallic part composed of cation Pb\(^{4+}\), cation Te\(^{2+}\) and conduction electrons set free from them [2].

On the other hand, Gierlotka et al. have tried to interpret the thermodynamic properties of liquid Pb–Te binary alloys based on an ionic model, considering a mixture of the cation Pb\(^{2+}\), the anion Te\(^{2-}\) and the remaining lead atoms and tellurium ones [3]. By using various parameters based on this model, they insisted to reproduce the experimental phase diagram and thermodynamic properties.

Question is whether the ionic model survives in the case of liquid Pb–Te binary alloys or not. To answer this question, we investigate the energy diagram of liquid lead telluride PbTe in Section 2.

2 Failure of ionic model in liquid lead telluride PbTe

Problem to be clarified is the stability of virtual ionic compound Pb\(^{2+}\)Te\(^{2-}\) in its liquid state. First of all, let us consider the ionization of gas-like lead atom, Pb(g) atom, as follows:

\[
Pb(g) + I_M \rightarrow Pb^{2+}(g) + 2e, \tag{1}
\]

where \(I_M\) is the energy required to remove two electrons from a gas-like lead atom Pb(g) atom and is equal to 2160.6 \(kJ/mol\) [4]. In the case that a gas-like tellurium atom Te(g) combines with two electrons set free from a gas-like lead atom Pb(g), that is, the electron's affinity, \(E_x\), of Te(g) is expressed as follows:

\[
Te(g) + 2e \rightarrow Te^{2-}(g) + E_x, \tag{2}
\]

or, described as follows:

\[
Te(g) + 2e \rightarrow E_x \rightarrow Te^{2-}(g). \tag{3}
\]
Usually, typical anions have negative values of \((-E_a\)). However, the value of \((-E_a\)) accompanying with \(\text{Te}^2- (g)\) is positive and is equal to \(\sim 405 \text{ kJ/mol}\), although the value might include some ambiguity [5].

On the other hand, the structural data tell us that the nearest neighboring distance between Pb and Te atoms in liquid lead telluride \(\text{PbTe}\) is not unique, that is, from about 0.24 to 0.30 nm with smaller coordination than six in the short range region [6]. If we assume that liquid lead telluride \(\text{PbTe}\) is locally approximated to as the quasi-ionic-crystalline cubic structure of \(\text{Pb}^{2+}\text{Te}^2-\), then its lattice energy, \(U_l\) (the ionic liquid forming \(\text{Pb}^{2+}\text{Te}^2-\)), is shown in the following form:

\[
U_l \sim N_A A_M \frac{\sqrt{e_2}}{r_0} \left[ 1 - \frac{\rho}{r_0} \right],
\]

where \(N_A\) is the Avogadro number, \(A_M\) is the Madelung constant, \(r_0\) is the nearest neighbor distance between the cation \(\text{Pb}^{2+}\) and the anion \(\text{Te}^2-\) ions and \(\rho\) is the parameter in relation to the core–core repulsive force between \(\text{Pb}^{2+}\) and \(\text{Te}^2-\) ions, respectively. Taking \(r_0 = 0.30 \text{ nm}\) and assuming \(\rho = 0.035 \text{ nm}\) which is adopted from a standard textbook [5], \(U_l\) is estimated to be approximately \(U_l \sim 1849.2 \text{ kJ/mol}\). Thus, the heat of formation, \(\Delta H(\text{calc})\), from the mixture \([\text{Pb}(g) + \text{Te}(g)]\) to the virtual ionic liquid \(\text{Pb}^{2+}\text{Te}^2-\) is equal to,

\[
\text{Pb}(g) + \text{Te}(g) + \Delta H(\text{calc}) \rightarrow \text{Pb}^{2+}\text{Te}^2-(\text{liquid}),
\]

\[
\Delta H(\text{calc}) = I_m - E_X - U_l = 2160.6 + 405 - 1849.2
\]

\[
= 716.4 \text{ kJ/mol}.
\]

Therefore, it is concluded that the liquid lead telluride \(\text{PbTe}\) is definitely not formed as an ionic liquid of \(\text{Pb}^{2+}\text{Te}^2-\).

### 3 Energy state of liquid lead telluride \(\text{PbTe}\)

In this section, we derive the real heat of formation, \(\Delta H\), from a gas-like mixture of \([\text{Pb}(g) + \text{Te}(g)]\) to liquid lead telluride \(\text{PbTe}\), in what follows. The cohesive energy of each element is defined as the energy, \(E_{\text{coh}}\), required to the energy from its solid state at 0 K to its gaseous state. As the notation in the present case,

\[
\text{Pb}(s, 0 \text{ K}) + \text{Te}(s, 0 \text{ K}) \rightarrow \text{Pb}(g) - E_{\text{coh}}(\text{Pb}) + \text{Te}(g)
\]

\[
\rightarrow \text{Pb}(g) + \text{Te}(g).
\]

The cohesive energies of the metallic \(\text{Pb}\) and \(\text{Te}\) are equal to 195.2 and 209.8 kJ/mol, respectively [7]. With increasing temperature of solid \(\text{Pb}(s, 0 \text{ K})\) and \(\text{Te}(s, 0 \text{ K})\) up to the room temperature, 298 K, the following vibrational energies are added,

\[
E_{\text{vib}}(\text{Pb}) + E_{\text{vib}}(\text{Te}) = \int_{298}^{298} [C_p(\text{Pb}) + C_p(\text{Te})] dT. \quad (9)
\]

Here, we tentatively assume that the value of \([E_{\text{vib}}(\text{Pb}) + E_{\text{vib}}(\text{Te})]\) is equal to 14.6 kJ/mol.

At the temperature of 298 K, it is known that the heat of formation from solid \(\text{Pb}\) metal and \(\text{Te}\) metal to solid lead telluride \(\text{PbTe}\) is equal to \(-70.3 \text{ kJ/mol}\) [4]. Thus, the energy state of solid \(\text{PbTe}\) at 298 K, \(E_{\text{298}}(\text{PbTe})\), resulting from the gaseous state of \(\text{Pb}\) and \(\text{Te}\) atoms, is given by the following expression:

\[
E_{\text{298}}(\text{PbTe}) = -405.0 + 14.6 - 70.3
\]

\[
= -460.7(\text{kJ/mol}).
\]

Furthermore, in order to heat up this solid lead telluride \(\text{PbTe}\) until its melting point \((\sim 1,200 \text{ K})\), we need additional thermal vibration energy as follows:

\[
E_{\text{vib}}(\text{PbTe}) = \int_{298}^{1,200} C_t(\text{PbTe}) dT. \quad (11)
\]

This quantity can be obtained from the measurement of specific heat of the solid lead telluride \(\text{PbTe}\). Although we are not sure of its experimental result, we tentatively presume its value as \(28.0(\text{J}) \times 2 \times (1,200 - 298) - 50.5 \text{ kJ/mol}\). On melting of solid lead telluride \(\text{PbTe}\), the latent heat of fusion, \(L_m\), is known as to be equal to 39.3 kJ/mol [8]. The heat of formation, \(\Delta H\), from a mixture of \([\text{Pb}(g) + \text{Te}(g)]\) to liquid lead telluride \(\text{PbTe}\) at about 1,200 K is then given by,

\[
\Delta H = E_{\text{298}}(\text{PbTe}) + E_{\text{vib}}(\text{PbTe}) + L_m
\]

\[
= -460.7 + 50.5 + 39.3
\]

\[
= -370.9 \text{ kJ/mol}.
\]

In Figure 1, we show the energy diagram in relation to the above procedure. In equation (12), we have used all experimental data and then naturally the difference between equations (6) and (12) is ascribed to that liquid \(\text{Pb–Te}\) alloys might include some of the covalent bonding molecules of \(\text{PbTe}\) pairs, of dissociated cations \(\text{Pb}^{4+}\) and \(\text{Te}^{4+}\), and conduction electrons in regard to these dissociations. In Section 4, we clarify what happens in the structure of liquid lead telluride \(\text{PbTe}\), which tells us a short range correlation among the constituents.
4 Brief review of structure in liquid lead telluride PbTe

Recently, we have analyzed our formerly observed data on the neutron diffraction measurement for liquid Pb–Te alloys in detail [6, 9]. As a result, we have found in liquid lead telluride PbTe that there are two types in the nearest neighboring distance between Pb and Te atoms, that is, one is 0.24 nm and the other is 0.30 nm. The former might have resulted from a covalent bond and the latter seems to be a usual alloy configuration. Also, some metallic configurations between Pb$^{4+}$–Pb$^{5+}$ and Te$^{2+}$–Te$^{2+}$ are located approximately at 0.40 nm. Furthermore, the nearest neighboring at 0.35 nm is assigned for the distance between the covalent molecule and Pb$^{4+}$ or Te$^{2+}$ ion forming a metallic state. And all these configurations are combined as the sixfold co-ordination, which indicates a cubic configuration with some fluctuation in the nearest neighboring distance. It is emphasized that we can fully express for the molar volume of liquid lead telluride PbTe, by using the above model [9]. Upon analysis of the structures in liquid Pb–Te alloys, we are sure that this is a kind of mixture composed of the covalent molecule of Pb–Te pairs, Pb$^{4+}$ and Te$^{2+}$ ions and conduction electrons.

5 Electrical properties of liquid Pb–Te alloys

As a narrow band gap semiconductor, the electronic study on the solid lead telluride PbTe has long been carried out. Its band gap is experimentally known as 0.18 eV. The nearest neighboring distances between Pb–Pb, Pb–Te and Te–Te in liquid PbTe are shorter than those in its solid lead telluride, which might easily lead to the overlapping of the tail of valence band and that of conduction one, that is, a disappearance of the band gap occurs and it reaches an ill-conditioned metallic state. In all other concentration ranges, the metallic remains produced from either Pb or Te atoms are naturally mixed together with the compound molecules of PbTe.

Corresponding to this inference, the electrical resistivity of liquid Pb–Te binary alloys shows a metallic behavior with a compound formation, as shown in a previous study [2]. The compounds in these alloys are certainly composed of the covalent molecule of PbTe pairs as derived from the structural information [9]. Also, referring to the experimental data on the Hall coefficients of liquid Pb and Te metals, we can consider that the effective numbers of conduction electrons supplied from Pb atom and Te one are equal to four and two, respectively [10]. In other words, Pb–Te binary alloys are composed of the covalent molecule of PbTe pairs, Pb$^{4+}$ cations, Te$^{2+}$ cations and conduction electrons.

In these situations, the liquid Pb–Te binary alloy is, as a chemical equation of the ternary system, written as follows:

\[
cPb + (1 - c)Te \rightarrow (c - c')Pb + (1 - c - c')Te
\]

\[
+ c'PbTe,
\]

where \(c = c_{Pb}\) is the fraction of Pb and \(c'\) is the fraction of covalent molecules of PbTe pair, whose existence is also inferred from the structural data [9].

6 Thermodynamic model of liquid binary Pb–Te alloys

As described above, liquid Pb–Te binary alloys can be treated as a ternary component system, composed of some metallic parts of Pb and Te and covalent molecules of PbTe pair. Hereafter, we apply the standard three-component regular solution model to the present system. Although a detailed description for the Gibbs free energy of the liquid ternary system was reported before, we hereby describe it again [11]. Corresponding to equation (13), a simple expression for the Gibbs free energy of liquid binary alloy of Pb$_{1-x}$Te$_x$, under the scheme of a regular solution model, is written as follows:
\[ G = (c - c') G_1^{(0)} + (1 - c - c') G_2^{(0)} + c' G_3^{(0)} \\
+ RT[(c - c') \ln(c - c') + (1 - c - c') \ln(1 - c - c')] (14) \\
+ c' \ln c' - (1 - c') \ln(1 - c') + \Phi, \]

where the suffixes are 1 = Pb atom, 2 = Te atom and 3 = PbTe molecule, respectively. \( G_i^{(0)} (i = 1–3) \) is the molar Gibbs free energy of \( i \)th species in its pure state. The last term in the mixing entropy terms of equation (14) is obtained by accounting that the fraction of Pb is equal to \( c'/(1 - c - c') + (c - c') + c' \) and that of molecule PbTe is equal to \( (1 - c - c')/(1 - c') \). The term \( \Phi \) is the summation of all pair-wise interactions and is written as follows:

\[ \Phi = \frac{1}{(1 - c')^2}[(c - c')(1 - c - c') \phi_{12} + (c - c')c' \phi_{13} \\
+ (1 - c - c')c' \phi_{23}], \]

where \( \phi_{ij} \) is the molar interchange energy between species \( i \) and \( j \), and it is expressed in the following form:

\[ \phi_{ij} = 2 \chi_{ij} - \chi_i - \chi_j, \]

where \( \chi_{ij} \) is defined as follows:

\[ \chi_{ij} = \frac{N^2}{V_m} \int 4\pi r^2 \psi_{ij}(r) \, dr, \]

where \( \psi_{ij}(r) \) is the effective pair interacting potential between the particles \( i \) and \( j \). The coefficient \((1/2)\) on the right hand side of equation (17) is ascribed to avoid double counting.

At a given temperature in thermal equilibrium, we have,

\[ (\partial G/\partial c')_{p,T,c} = 0. \]

Putting equation (14) into this equation, we have,

\[ \frac{c'(1 - c'}{c'(1 - c - c')} = \exp \left( -\frac{\Delta g + A}{RT} \right), \]

where

\[ \Delta g = G_1^{(0)} - G_2^{(0)} - G_3^{(0)}, \]

and

\[ A = \frac{2}{(1 - c')^2}[(c - c')(1 - c - c') \phi_{12} \\
+ (c - c')c' \phi_{13} + (1 - c - c')c' \phi_{23}] + \frac{1}{(1 - c')^2} (21) \]

\[ [-1 - 2c'] \phi_{12} + (c - 2c') \phi_{13} + (1 - c - c') \phi_{23}]. \]

The observed Gibbs free energy of mixing \( \Delta G_{\text{obs}} \) is then given by:

\[ \Delta G_{\text{obs}} = c' \Delta g + RT((1 - c - c') \ln(1 - c - c') \\
+ (c - c') \ln(c - c') + c' \ln c' - (1 - c') \ln(1 - c') + \Phi. \]

Equations (19)–(22) are fundamental for the determination of parameters \( c', \Delta g \) and \( \phi_{ij} \). In Section 7, we describe how these parameters can be derived from the observed \( \Delta G \) and \( \Delta S \).

### 7 Derivations of thermodynamic parameters by comparison with the experimental data

Kameda et al. have measured electro-motive force (EMF) in liquid Pb–Te binary alloys [12]. Their obtained results for the thermodynamic quantities on mixing seem to be fine. In what follows, however, we will briefly show how the mixing thermodynamic quantities, \( \Delta G \) and \( \Delta S \), can be obtained from EMF data. The observed EMF is given by:

\[ -zFE(c_{\text{Pb}}, T) = kT \ln \alpha_{\text{Pb}} = \Delta \mu_{\text{Pb}} = \mu_{\text{Pb}}(c_{\text{Pb}}, T) - \mu_{\text{Pb}}^0(T), \]

where \( z \) is the charge of carrier ions which is equal to 2, because Kameda et al. have used PbCl\(_2\) as the electric cell. \( F \) is the Faraday constant, \( \alpha_{\text{Pb}} \) is the activity of Pb in the alloys and \( \Delta \mu_{\text{Pb}} \) is the change of chemical potential of Pb. From the Gibbs-Duhem equation, we have

\[ d \mu_{\text{Te}} = -(c_{\text{Te}}/c_{\text{Pb}}) d \mu_{\text{Pb}}, \]

Therefore, we have,

\[ \mu_{\text{Te}}(c_{\text{Pb}}) - \mu_{\text{Te}}^0 = - \int_{c_{\text{Pb}}}^{c_{\text{Pb}}^0} \frac{c_{\text{Pb}}}{1 - c_{\text{Pb}}} \frac{d \mu_{\text{Pb}}}{d c_{\text{Pb}}}, \]

After a mathematical treatment, we have,

\[ \Delta G = -(1 - c_{\text{Pb}})RT \int_{c_{\text{Pb}}}^{c_{\text{Pb}}^0} \ln \alpha_{\text{Pb}} \frac{d \mu_{\text{Pb}}}{d c_{\text{Pb}}}, \]

or

\[ \Delta G = (1 - c_{\text{Pb}})RT \int_{c_{\text{Pb}}}^{c_{\text{Pb}}^0} \frac{zFE(c_{\text{Pb}}, T)}{(1 - c_{\text{Pb}})^2} \frac{d c_{\text{Pb}}}{d c_{\text{Pb}}}, \]

In a similar way, we have,

\[ \Delta S = (1 - c_{\text{Pb}})RT \int_{c_{\text{Pb}}}^{c_{\text{Pb}}^0} zF \frac{d \mu_{\text{Pb}}}{d T} \frac{d c_{\text{Pb}}}{d c_{\text{Pb}}}. \]
And the enthalpy of mixing is immediately obtained by 
\[ \Delta H = \Delta G + T \Delta S. \]
As seen in equation (28), the temperature dependence is necessary to deduce the mixing entropy, \( \Delta S \). Therefore, it is natural that the obtained raw data for \( \Delta S \) seem to be slightly less reliable, in comparison with the mixing \( \Delta G \).

In these situations, Kameda et al. have obtained the thermodynamic quantities of mixing, \( \Delta G \), \( T \Delta S \) and \( \Delta H \) at 1,210 K [12], which are shown in Figure 2. We are, now, in a position to derive the thermodynamic parameters so as to fit the experimental data of \( \Delta G \), \( T \Delta S \) and \( \Delta H \) as much as possible. The obtained thermodynamic parameters, \( \Delta g \) and \( \varphi_{ij} \), are listed in Table 1, and the values of \( c' \) as a function of \( c_{Pb} \) are listed in Table 2 and shown in Figure 3. Using these obtained parameters based on the ternary regular solution model, we have tried to reproduce the mixing quantities \( \Delta G \), \( T \Delta S \) and \( \Delta H \) and compared with the experimental ones as shown in Figure 4. The estimated values of \( \Delta G \) and \( \Delta H \) based on the model, agree with their experimental data. But the agreement for \( T \Delta S \) is slightly less than good but acceptable. The obtained values of \( c' \) in Table 2 and Figure 3, so as to fit the experimental data of \( \Delta G \), \( T \Delta S \) and \( \Delta H \) at 1,210 K are numerically close to those obtained from data of electrical resistivity at 1,198 K measured by the present author group [2]. Therefore, it is emphasized that liquid Pb–Te binary alloys can be, without any question, analyzed in terms of a ternary mixture of metallic Pb and Te and the molecule PbTe.

### 8 Phase diagram of Pb–Te binary alloys

As described above, the application of the ternary regular solution model is fair to good for liquid Pb–Te alloys. The phase diagram of this system is characteristic as it is composed of two eutectic phase diagrams of the pseudo-binary mixture of Pb–PbTe and that of PbTe–Te. For this characteristic phase diagram, we will try to investigate how the melting curves of these pseudo binary mixtures between lead telluride PbTe and Te metal and also between lead telluride PbTe and Pb metal are reproduced.

The expression for the melting point curve in a binary regular solution composed of the constituents A and B was fully discussed and known as the Schröder-Van Laar equation as follows [13]:

![Diagram](image-url)

**Figure 3:** Fraction of the molecule PbTe, \( c' \) as a function of \( c_{Pb} \).

### Table 1: Numerical results of physical parameters \( \Delta g \) and \( \varphi_{ij} \)

| Parameter | Value (kJ/mol) |
|-----------|---------------|
| \( \Delta g \) | \(-71.46\) |
| \( \varphi_{12} \) | \(-37.31\) |
| \( \varphi_{13} \) | \(8.61\) |
| \( \varphi_{23} \) | \(-9.02\) |

### Table 2: Fraction of \( c' \) as a function of \( c_{Pb} \)

| \( c_{Pb} \) | \( c' \) |
|-------------|---------|
| 0.0         | 0.000   |
| 0.1         | 0.083   |
| 0.2         | 0.157   |
| 0.3         | 0.227   |
| 0.4         | 0.291   |
| 0.5         | 0.332   |
| 0.6         | 0.240   |
| 0.7         | 0.158   |
| 0.8         | 0.096   |
| 0.9         | 0.043   |
| 1.0         | 0.000   |
\[ R \ln \alpha_A = R \ln \gamma_A c_A = R \ln \gamma_A (1 - c_B) = \int_{T_A}^T \frac{L_A^\Delta}{T^2} dT' + \int_{T_A}^T \int_{T_A}^T \frac{\Delta C_P^A}{T'^2} dT'', \]

where \( \gamma_A \) is the activity coefficient of constituent \( A \), \( T_A \) is its melting point, \( L_A^\Delta \) is its latent heat of fusion and \( \Delta C_P^A \) is the difference of its specific heat on melting, that is, \( \Delta C_P^A = C_P^A - C_P^B \), respectively. Usually, the last term of equation (29) can be negligibly small compared to the first term on the right hand side of equation (29) and then hereafter we will use the following expression as an approximate Schröder-Van Laar equation:

\[ RT \ln \gamma_A (1 - c_B) = -L_m (1 - T/T_A). \]  

Combining equations (30) and (31), we have the following liquidus temperature \( T \) at a given fraction of \( c_B \):

\[ T = \frac{\varphi_{AB} c_B^2 + L_m^{\Delta}}{L_m/T_A - R \ln(1 - c_B)}. \]  

Taking \( c_A \) and \( c_B \) as the fraction of molecule PbTe and that of Te, respectively, in the partial system of PbTe–Te, we have the relations of \( c_{pb} = (1 - c_B)/2 \) and \( c_{Te} = (c_B + 1)/2 \). In the partial system of Pb–PbTe, we have used the similar relations. The obtained liquidus curves in both partial systems are shown in Figures 5 and 6. Agreement between the calculated liquidus curve and the observed liquidus one for Pb–Te alloys is satisfactorily fine.

**9 Conclusions**

In this article, we have shown that the liquid Pb–Te binary alloy is approximated to a ternary regular solution of Pb metal, Te metal and the molecules of PbTe. Thermodynamic parameters to reproduce the experimental data of mixing quantities \( \Delta G, \Delta H, \Delta S \) can be determined. Using these determined parameters, we have also tried to calculate the liquidus curve of the Pb–Te binary system. The obtained results agree excellently with the observed phase diagram.

**Acknowledgments:** The authors are grateful to Emeritus Professor Y. Waseda of Tohoku University and Professor T. Ishiguro of Tokyo University of Science for their valuable comments and discussion.
References

[1] Enderby, J. E. Structure and electronic properties of liquid semiconductors. In Amorphous and liquid semiconductors, Tauc, J., Ed, Springer US, New York, 1974, pp. 361–433.

[2] Akasofu, T., S. Takeda, and S. Tamaki. Compound-forming effect in the electrical resistivity of liquid Pb–Te alloys. Journal of the Physical Society of Japan, Vol. 52, 1983, pp. 2485–2491.

[3] Gierlotka, W., J. Łapsa, and D. Jendrzejczyk-Handzlik. Thermodynamic description of the Pb–Te system using ionic liquid model. Journal of Alloys and Compounds, Vol. 479, 2009, pp. 152–156.

[4] Haynes, W. M. CRC handbook of chemistry and physics. 95th edn. CRC Press, Oakville, 2014.

[5] Greenwood, N. N. Ionic crystals. Lattice Defects and Nonstoichiometry. Butterworth, London, 1968.

[6] Takeda, S., K. Iida, S. Tamaki, and Y. Waseda. The structure of liquid Pb–Te alloys by neutron diffraction. Bulletin of the College of Biomedical Technology Niigata University, Vol. 1, 1983, pp. 30–37.

[7] Kittel, C. Introduction to solid state physics. 8th edn. John Wiley & Sons, New York, 2005.

[8] Kulwicki, B. M. The phase equilibria of some compounds semiconductors by DTA calorimetry, University of Michigan Progress Report, Ann Arbor, 1963, 04650-16-P.

[9] Akasofu, T., M. Kusakabe, S. Takeda, and S. Tamaki. Structural evidence of complex formation in liquid Pb–Te alloys. High Temperature Materials and Processes (in press), DOI: 10.1515/htmp-2020-0064.

[10] Faber, T. E. Introduction to the theory of liquid metals. Cambridge University Press, London, 1972.

[11] Tamaki, S., T. Ishiguro, and S. Takeda. Thermodynamic properties of liquid Na-Sn alloys. Journal of Physics F: Metal Physics, Vol. 12, 1982, pp. 1613–1624.

[12] Kameda, K., K. Yamaguchi, H. Horie, and T. Kon. Thermodynamic properties of liquid Te–Pb alloys by EMF method. Journal of the Japan Institute of Metals and Materials, Vol. 57, 1993, pp. 774–780.

[13] Prigogine, I., and R. Defay. Chemical thermodynamics. Longmans Green, London, 1950.