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**New comments on the Melting Entropy  
of Binary Eutectic Alloys without solid state solubility**

**Pierre Guiraldenq \***

**Summary**

A new approach is given for the solid - liquid transition at the melting temperature for a family of well known binary eutectic alloys, problem which has been introduced in a preceding paper in 2020.

In a first time, a mechanism is described for the beginning of the melting process, with the role played by the interfaces between the two lattices. A second question concerns the vibration frequencies of atoms at that time for the two components in relation with the self diffusion constants. At the end, it is proposed an order-disorder model by damped oscillations of the entropy before the final stabilized amorphous liquid state.

**KEYWORDS** : eutectic transition, melting entropy, diffusion in the solid state, interfaces, amorphous phases, vibration frequencies.

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## 1 A RECALL ON THE PRECEEDING RESULTS :

In a previous paper (1), we have focused on a singularity about a small group of binary eutectic alloys (without solid state solubility) and for which the solid-liquid transformation at the eutectic temperature is characterized by an excess of entropy, compared to other thermodynamic systems (at the atmospheric pressure).

This group contains eight binary diagrams ;

**Si - Au, Ge-Au, B-Pt, Ge-Al, As-Pb, Ge-Ag, Si-Ag, Si-Be**

which corresponds to a simple binary semi-conductor - metal family.

For this family, it has been noted a linear relation between an entropy excess during the melting process,  $\Delta SE$ , with a specific parameter taking in account the self diffusion properties of each component (m1, m2) by the cumulative ratio of the eutectic temperature TE compared with the two melting temperatures (Tm1, Tm2) according the relation ;

$$\Delta SE \propto ( TE / Tm1 + TE / Tm2 )$$

The Figure 1 shows a linear relationship for the eight binary alloys seen before, with a slope which value is  $3 \text{ kB NA}$ , with kB the Boltzmann Constant and NA the Avogadro Number. Other results at a low level for  $\Delta S E$  are not taken into account here (Ag - Bi, Al - Sn, Be - Al, etc).

We note with surprise the same property defined a very long time ago by Albert Einstein for the solid state heat capacity corresponding to one simple solid, in which all the atoms have a same vibration frequency (2) (3). The problem is presently clearly different because it concerns, at the same time, two solid phases in equilibrium and in contact, with the classical lamellar eutectic structure giving at the end only one liquid phase, at the same temperature TE, like a pure metal. To obtain an analysis of this singular state, we have considered two complementary approaches : the first one by a structural analysis at the interfaces between the two components and, in a second way, by a quantitative description of the vibration frequencies calculated from the self diffusion coefficients in the solid state.

## 2 A STRUCTURAL REGARD TO THE EUTECTIC TRANSITION AT A NANOSCOPIC SCALE :

We have described before in (1) the role played by the interfaces between two lamellar phases as simple diffusion couples : We know that several diffusion processes may be present and in which the interfacial diffusion process is preponderant when the ratio  $T_{\text{Eutectic}} / T_m$  is low ( $T_E / T_{m1}$  and  $T_E / T_{m2}$  under 0,5) and, on the contrary, in relation with a bulk diffusion when the ratio  $T_E / T_m$  is larger than 0,6-0,7.

At the beginning and at a very low temperature, before the heating process to the melting temperature  $T_E$ , and taking into account the crystallographic properties of each element, we can consider possible crystallographic coincidences sites between the two systems, as described a long time ago by Aust and Chalmers (4), Smith (5) in 1951, then later by Spaepen in 1975 to describe the liquid transition with an amorphous phase (6).

In a first time, applied to the eutectic Si-Au system, the figure 2 gives a possible equilibrium coincidence sites, taking for instance the same simple (100) plane and the same axis  $\langle 100 \rangle$ , with the crystallographic parameters for each element.

By a rotation of  $20^\circ$  around one axis  $\langle 001 \rangle$  for the Au lattice, it appears, at the interface, coincidence sites for Au(F.C.C) and Si (D.C.) every eight atomic positions, the other places being with possible local or other disturbing defects (dislocations, etc)

For very high interfacial energies which characterize the diffusion process in relation with the atomic configurations, we can imagine a progressive structural instability like in Figure 3. The new transitory medium, presented here, like a local amorphous structure, should be the progressive evolution toward the liquid state from the initial quasi- ordered structure between the two lamellar phases, giving so an higher transitory entropy compared to the self melting entropy alone.

### 3 ANALYSIS OF THE ATOMIC VIBRATIONS WITH THE DIFFUSION CONSTANTS IN THE SOLID STATE

As said before in (1), the atomic diffusion processes are defined for each element in a binary system by an Arrhenius law giving the diffusion coefficients in the bulk, or in the grain boundaries and interfaces at lower temperatures.

In the present case, we consider only the bulk diffusion coefficients through the Arrhenius law because this mechanism is always present at the same time in the transverse directions of the interfaces at medium temperatures ( $T_E / T_m$  higher than 0.5)

The literature gives a large panel of results obtained with radiotracers or other physical methods, giving the frequency factor  $D_0$  by the well known relation :

$$D_0 = a^2 \nu \exp(-\Delta S/k) \quad \text{equ. 1}$$

with  $k = k$  Boltzmann

$\nu =$  vibration frequency

and "a" the lattice parameter taken at low temperature

(for F.C.C., C.C. and D.C. cubic structures)

In the present case, the entropy which characterizes all the defects present during the transition at  $T_E$ , is the excess of entropy  $\Delta S_E$  which has been calculated in the preceding paper at the melting temperature of the eutectic alloys with this singular property (Figure 1).

So, taking the values of the frequency factor  $D_0$  and the crystal parameters "a" (taken constant at low temperature), we can define an average frequency " $\nu_E$ " for each element corresponding at the end to the solid-liquid transition. We have noted that the two atomic concentrations for CE (with  $CE = C_1 + C_2$ ) at  $T_E$  have no importance at this level because this factor disappears at the atomic scale for the two elements without solubility (each element has the same concentration (100 at. per cent) on each side of the interfaces at low temperature, before heating to  $T_E$ ).

So, we have taken only four typical diagrams covering high and low values for  $\Delta S E$  (with cubic structures and with well defined  $D_0$  values)

**Si - Au      Si - Ag      Ge - Au      Ge - Ag**

For each case, the best  $D_0$  experimental values have been chosen in the literature (7) (8) and the lattice parameters from the classical Charles S. Barrett book (9) :

<b>Au</b>	<b><math>D_0 = 0.09 \cdot 10^{-4} \text{ (m}^2 / \text{sec)}</math></b>	<b><math>a = 0,4078</math></b>	<b>nm</b>
<b>Ag</b>	<b><math>D_0 = 0.44 \cdot 10^{-4}</math></b>	"	<b><math>a = 0,4085</math></b>
<b>Si</b>	<b><math>D_0 = 2 \cdot 10^{-1}</math></b>	"	<b><math>a = 0,5422</math></b>
<b>Ge</b>	<b><math>D_0 = 7.8 \cdot 10^{-4}</math></b>	"	<b><math>a = 0,5658</math></b>

The table gives below the frequencies  $\nu E$  obtained by this way from equ.1

<b>Alloy</b>	<b>T E (K)</b>	<b>TE/Tm1 + TE/Tm2</b>	<b><math>\nu E</math> (Hz)</b>	<b><math>\nu_1/\nu_2 \approx</math></b>
<b>Si</b>	<b>643</b>	<b>0,85</b>	<b><math>2.9 \cdot 10^{+16}</math></b>	<b>10+4</b>
<b>Au</b>	"	"	<b><math>2.3 \cdot 10^{+12}</math></b>	
<b>Si</b>	<b>1103</b>	<b>1,54</b>	<b><math>2.9 \cdot 10^{+16}</math></b>	<b>10+3</b>
<b>Ag</b>	"	"	<b><math>1.1 \cdot 10^{+13}</math></b>	
<b>Ge</b>	<b>629</b>	<b>0,98</b>	<b><math>1 \cdot 10^{+14}</math></b>	<b>10+2</b>
<b>Au</b>	"	"	<b><math>2.3 \cdot 10^{+12}</math></b>	
<b>Ge</b>	<b>924</b>	<b>1,5</b>	<b><math>1 \cdot 10^{+14}</math></b>	<b>10+1</b>
<b>Ag</b>	"	"	<b><math>1.1 \cdot 10^{+13}</math></b>	

Between these different binary alloys, we note a decreasing ratio of the vibration frequencies which values are in coherence with many other physical properties. It is certainly the expression of different atomic interactions during the solid-liquid transition at TE between the structure of a semi-conductor (Si or Ge) with a classical noble metal (Au or Ag). These same components have been a long time ago studied at an atomic level for electronic devices (10) and for the vibration frequencies in the crystalline or amorphous states by P. Dean (11) and A.T. Willis and A.W. Prior (12).

In the present case, the vibration frequencies  $\nu E$  have been obtained only in relation with the diffusion mechanisms and it should be interesting, with new other methods, like Laser Spectroscopy, to obtain in situ confirmation of these results. The other cases, seen in the Figure 1, should be also discussed, but with some difficulties according their different crystalline structures (B, Be, Sn, As, Bi, Th) and the best rigorous values obtained for the self diffusion constants  $D_0$ , as said before.

At the end and for the progressive evolution of the micro structure of such eutectic alloys to the amorphous liquid state at TE, it is possible to imagine a damped oscillations process, starting from the interfaces toward the bulk, like in the figure 3. A such decreasing evolution of the duplex lamellar structure should be so described by a Fourier series model (13) for the entropy  $\Delta S E$  before the final liquid eutectic state (Figure 4).

#### **4 FINAL CONCLUSION :**

Using the simple thermodynamic concepts, a new analysis has been suggested with a singular family of binary alloys, characterized by an insolubility in the solid state.

It has been noted a set of such alloys which match this property with a singular entropy corresponding to the melting temperature in relation with a factor  $3kN$ , which has been formerly taken as a reference to define the upper solid state heat capacity.

This historical review inside the Materials Science chapter, particularly with only the self diffusion constants to define the atomic vibrations, has shed some light at a nano scale level to suggest other works on the order- disorder phenomena in the solid-liquid transitions.

**Conflicts of interest :** the author declare no conflict of interest

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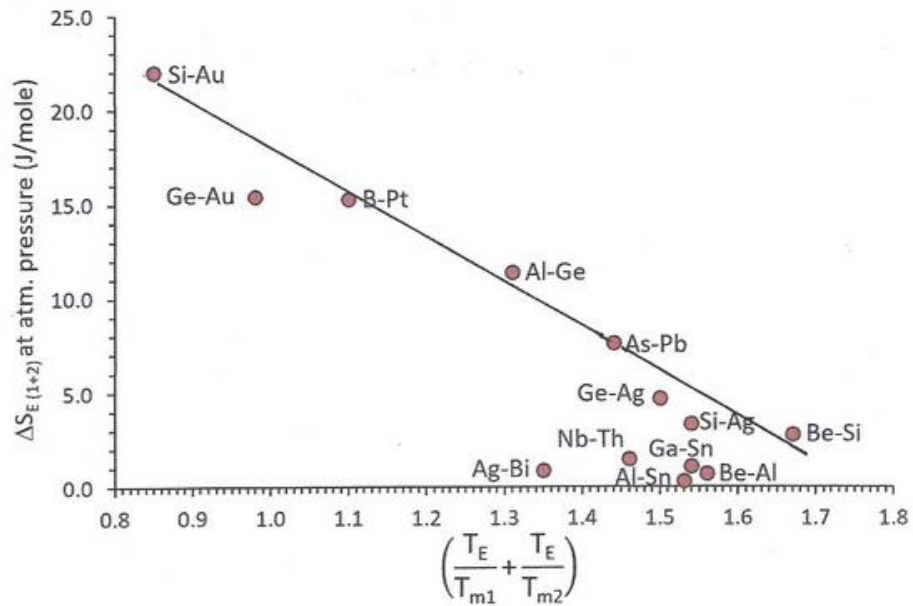
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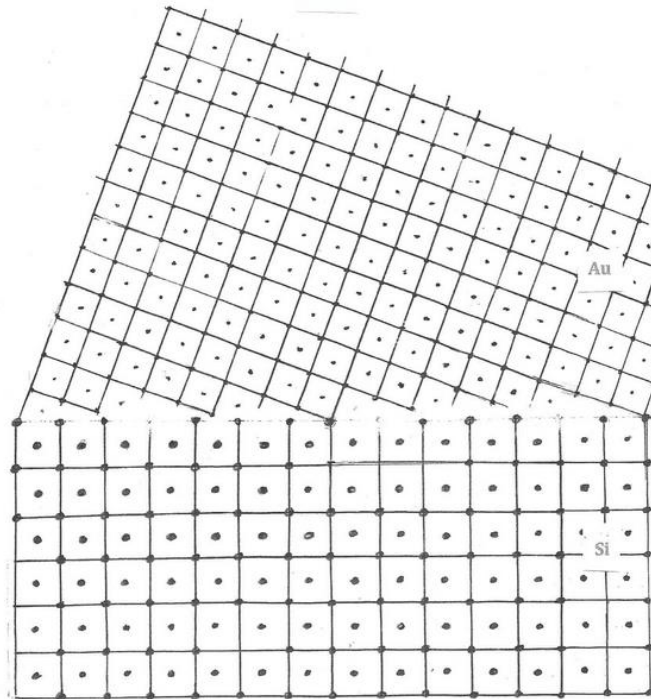


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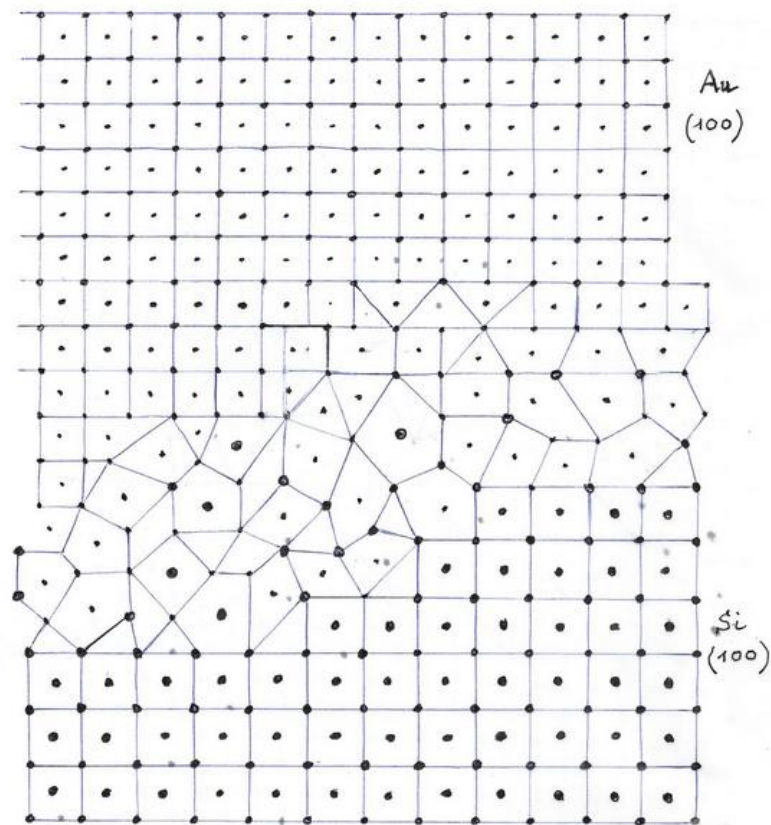
FIGURES 1 to 4 (pages 9 to 10)



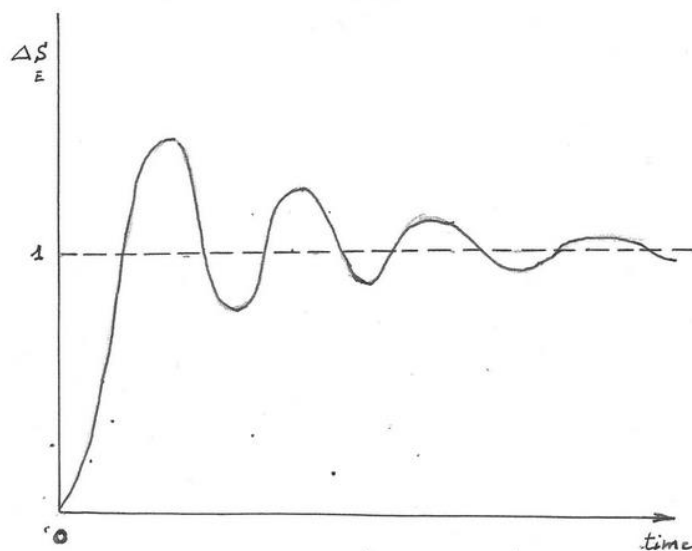
**Figure 1** : Recall for the increasing entropy obtained at TE during the transformation solid-liquid as a function of the parameter  $(T_E/T_{m1} + T_E/T_{m2})$  for binary eutectic alloys without solid state solubility (1)



**Figure 2** : Coincidence sites at the interface between the two elements Si and Au in the same plane (100) and a rotation of 20 degrees for Au lattice around an axis  $\langle 001 \rangle$  (parameters ref. (9))



**Figure 3 :** The possible first evolution of the interface between the two lattices of Au and Si, for the same plane (100) without rotation and with several local distortions of the two lattices under the influence of vibration frequencies and short range diffusion at TE.



**Figure 4 :** Evolution of the entropy excess at TE, growing from the interfacial zones by a damping oscillations process during the progressive transformation of the eutectic structure to the final amorphous liquid state.