

Optimising Solder Paste Volume for Low Temperature Reflow of BGA Packages

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Abstract

The need to minimise thermal damage to components and laminates, to reduce warpage-induced defects to BGA packages, and to save energy, is driving the electronics industry towards lower process temperatures. For soldering processes the only way that temperatures can be substantially reduced is by using solders with lower melting points. Because of constraints of toxicity, cost and performance, the number of alloys that can be used for electronics assembly is limited and the best prospects appear to be those based around the eutectic in the Bi-Sn system, which has a melting point of about 139°C.

Experience so far indicates that such Bi-Sn alloys do not have the mechanical properties and microstructural stability necessary to deliver the reliability required for the mounting of BGA packages. Options for improving mechanical properties with alloying additions that do not also push the process temperature back over 200°C are limited. An alternative approach that maintains a low process temperature is to form a hybrid joint with a conventional solder ball reflowed with a Bi-Sn alloy paste. During reflow there is mixing of the ball and paste alloys but it has been found that to achieve the best reliability a proportion of the ball alloy has to be retained in the joint, particular in the part of the joint that is subjected to maximum shear stress in service, which is usually the area near the component side.

The challenge is then to find a reproducible method for controlling the fraction of the joint thickness that remains as the original solder ball alloy. Empirical evidence indicates that for a particular combination of ball and paste alloys and reflow temperature the extent to which the ball alloy is consumed by mixing with the paste alloy is dependent on the volume of paste deposited on the pad. If this promising method of achieving lower process temperatures is to be implemented in mass production without compromising reliability it would be necessary to have a method of ensuring the optimum proportion of ball alloy left in the joint after reflow can be consistently maintained.

In this paper the author explains how the volume of low melting point alloy paste that delivers the optimum proportion of retained ball alloy for a particular reflow temperature can be determined by reference to the phase diagrams of the ball and paste alloys. The example presented is based on the equilibrium phase diagram of the binary Bi-Sn system but the method could be applied to any combination of ball and paste alloys for which at least a partial phase diagram is available or could be easily determined.

Introduction

The dependence of the electronics industry on solder to provide the reliable connections necessary to turn a collection of individual components into a functional circuit has created an ongoing dilemma that has challenged the industry since its inception. The main consideration in the design of electronic components is functionality, whether it be to provide a specific resistance, capacitance or inductance in passive components, logical processing in integrated circuits, and responsiveness in sensors or just electrical connectivity. A need to survive the thermal profile required to form a joint with a molten metal has been just an annoying complication. The industry got off to a fairly easy start with the Sn-Pb eutectic that has the relatively low melting point of 183°C and mechanical properties and microstructural stability that have been considered to be the benchmark for reliability in service. Because of the need to maximise heat transfer into the joint to get the substrates to wetting temperature, process temperatures (e.g. soldering tool tip temperature, wave solder bath temperature, reflow oven peak temperature) had to be substantially higher than that 183°C melting point. However, with proper process control the temperature/time profile to which the most sensitive parts of the component were exposed could be kept within a safe limit.

The move to Pb-free solder brought a renewed challenge because the alloy endorsed by the IPC and others in the industry as “the Pb-free alloy of choice for the electronics industry”, Sn-3.0Ag-0.5Cu (“SAC305”), does not start to melt until 217°C, 34°C higher than the melting point of the Sn-37Pb it was replacing. However, as long as the higher process temperatures could be accommodated by the use of resins and polymers that could survive the higher thermal profiles the electronics industry was able to adapt to this new alloy.

When the problem with higher process temperatures was not just thermal degradation of materials but gross deformation/warpage of component packages the challenge moved to a new level. Integrated circuit packages have evolved

into complex stacks of a wide range of materials with very different coefficients of thermal expansion so that as the package heats the differential expansion of bonded layers results in warpage of the package. The problem is exacerbated by the temperature gradients that develop within the package as a result of variations in thermal conductivity and thermal mass. The extent of warpage can mean that at its peak the warpage in area array packages is sufficient to cause complete separation of joints at their extreme edges [1].

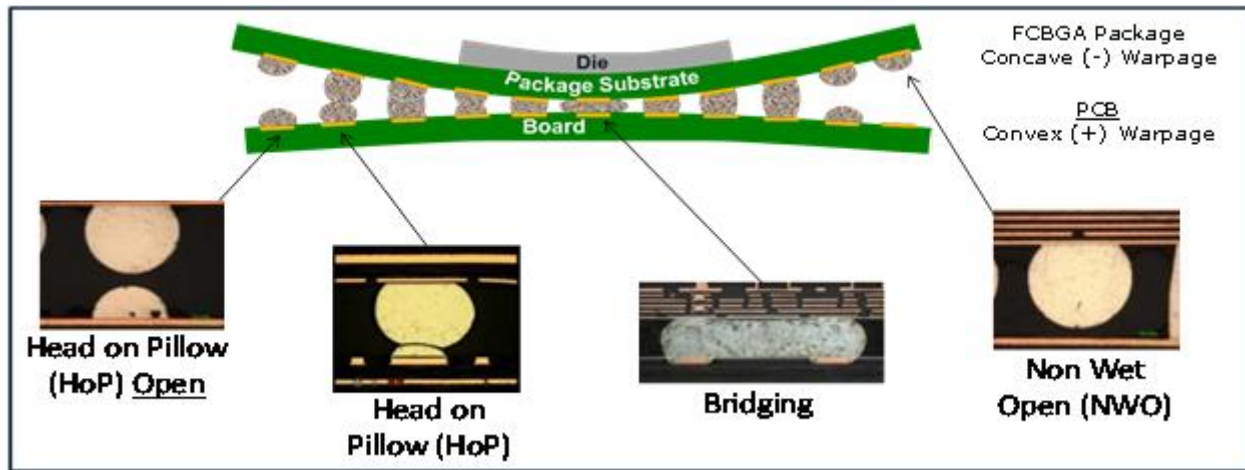


Figure 1. Defects caused by dynamic warpage of FCBA components during reflow soldering [1]

Depending on the temperature at which that peak separation is reached for a particular component, the separation can take different forms:

1. Unreflowed solder paste can be split with some adhering to the solder ball and some to the pad
2. Unreflowed solder paste adheres only to the solder ball and is lifted off the pad
3. Unreflowed solder paste adheres only to the pad with the solder ball detaching from the solder paste

Depending on how the warpage changes as a function of temperature the solder paste might reflow while separation is at its peak. When, later in the reflow profile, the component returns to its original shape there is no certainty that the separate and now molten solder will coalesce as the activity of the flux, which facilitates wetting and coalescence might have been exhausted. In the case of Type 1 separation, the result is a defect known as “head-in-pillow” (HIP). In the case of Type 2 and 3 separation the result is a defect known as a “non-wetted open” (NWO).

Because the design of the layers of the package and the selection of materials is determined by many complex considerations that cannot be compromised by a need to minimize warpage at the peak process temperature, ways of reducing process temperature have had to be sought. For many years the electronics industry has been aware of, and made limited use of solders based around the Sn-57Bi eutectic that has a melting point of 139°C. With that melting point the peak process temperature could be kept below 200°C, at which the component warpage is low enough that the risk of separation defects is significantly reduced. However, this alloy is brittle and cannot deliver the reliability required in joints to area array packages. The reliability of Sn-Bi alloys can be improved by reducing the Bi content and adding small amount of elements such as Ag or Sb but the alloy still cannot match the reliability of the higher melting point alloys. And, as the composition moves further away from the Sn-Bi eutectic the liquidus temperature increases, necessitating higher process temperature.

A solution that the industry is now evaluating is to continue to use a conventional SnAgCu (SAC) alloy for the BGA ball but to reflow solder the package to the substrate with a low melting point alloy based around the Sn-57Bi eutectic. With this technique it is possible to securely attach a BGA package to a substrate with a peak process temperature under 200°C.

The result of this process is a joint such as that in Figure 2 [2].

Reliability testing of these mixed alloy or hybrid joints indicate that as long as a substantial part of the SAC ball alloy remains after the soldering process the joints have adequate reliability. The distribution of strain in a typical assembly means that it tends to be concentrated in the outer areas of solder close to the interface with the component package. If the solder in

that area is an alloy that is known to be able to deliver the required service life under the expected conditions, then the reliability of the mixed alloy joint is comparable with that of a joint that is reflowed with the same alloy as the BGA ball.

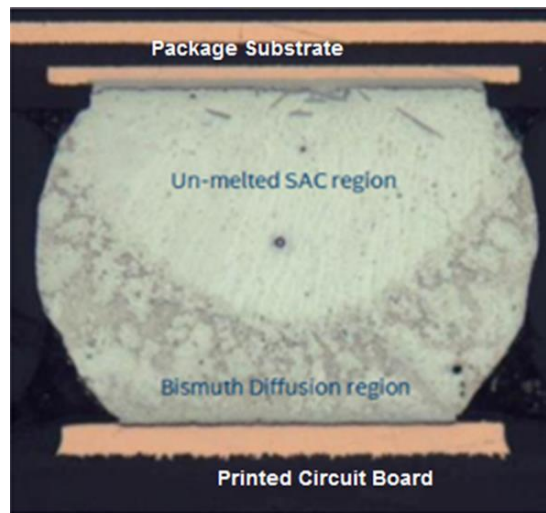


Figure 2. Typical joint formed by reflow of a Sn-Ag-Cu solder ball with a Sn-Bi low melting point solder[2]

The challenge with this technique has been determining how to complete the mixed alloy reflow soldering process with sufficient of the original ball alloy remaining on the component that an adequate level of reliability can be achieved.

While there has been much discussion about “Bi diffusion” from the low melting point solder into the SAC alloy the purpose of this paper is to explain that the extent to which the BGA ball is lost to the mixed alloy is determined by the thermodynamics of the alloy system made up of the solder ball and the solder paste. Those thermodynamics are neatly summarized in one of the basic tools of the material scientist, the equilibrium phase diagram.

Equilibrium Phase Diagram

The equilibrium phase diagram can be considered a map of the location of phases, liquid or solid, in space defined by the dimensions of composition and temperature. Where vapour pressures are significant a third dimension is pressure but in the case being considered here, at the process temperatures being used, the alloy constituents have relatively low vapour pressures so that dimension need not be considered.

For a particular composition at a particular temperature an equilibrium phase diagram will show what phases are present and their composition. With the application of the “lever rule”, the relative proportions of the phases present at any such point can be calculated. For a binary system, i.e. in the case of an alloy, a mixture of two metals, the phase diagram is two dimensional. The phase equilibria for three elements can be presented in a three dimensional diagram or, if the level of one element is fixed, as a two dimensional pseudo-binary plot. For more than three elements the level of one or more of the elements has to be fixed to reduce the number of dimensions to three or two.

Figure 3 is the equilibrium phase diagram for the binary Sn-Bi system on which the low melting point alloys used in mixed alloy reflow are currently based. An alloy with the composition and temperature at point A would be entirely liquid. An alloy with the composition and temperature at point B would be a roughly 50/50 mixture of liquid and solid Sn-Bi alloy with about 10wt% Bi in solid solution. An alloy with the composition and temperature point C would be completely solid with about 5wt % Bi in solid solution. An alloy at the composition and temperature point D would be completely solid with a roughly 50/50 mix of nearly pure Bi and Sn with about 15% Bi in solid solution.

The Model

A solder ball and the solder in the deposit of solder paste on which it is mounted can be considered as an isolated system in that all the materials that will form the final solder joint are already present. In that regard it is different from a joint being wave soldered in which there is a virtually unlimited supply of solder on which the joint substrates can draw to form a fillet.

To the extent that, during the soldering process there can be some reaction between the Cu or Ni substrates, those substrates should also be considered as part of the system. Whether those reactions need to be taken into account depends on the size of the solder ball. In some very small joints the Sn from the solder and the solder ball consumed in the reaction with the

substrates to form the intermetallic compounds Cu_6Sn_5 or Ni_3Sn_4 could be a significant fraction of the total amount of Sn available in the solder ball/solder paste system. However, for the purposes of explaining the method of calculating the extent to which the solder ball is consumed in the process of reflow with a low temperature solder that effect will be neglected. Where reactions with substrates are significant they can be factored into the calculations.

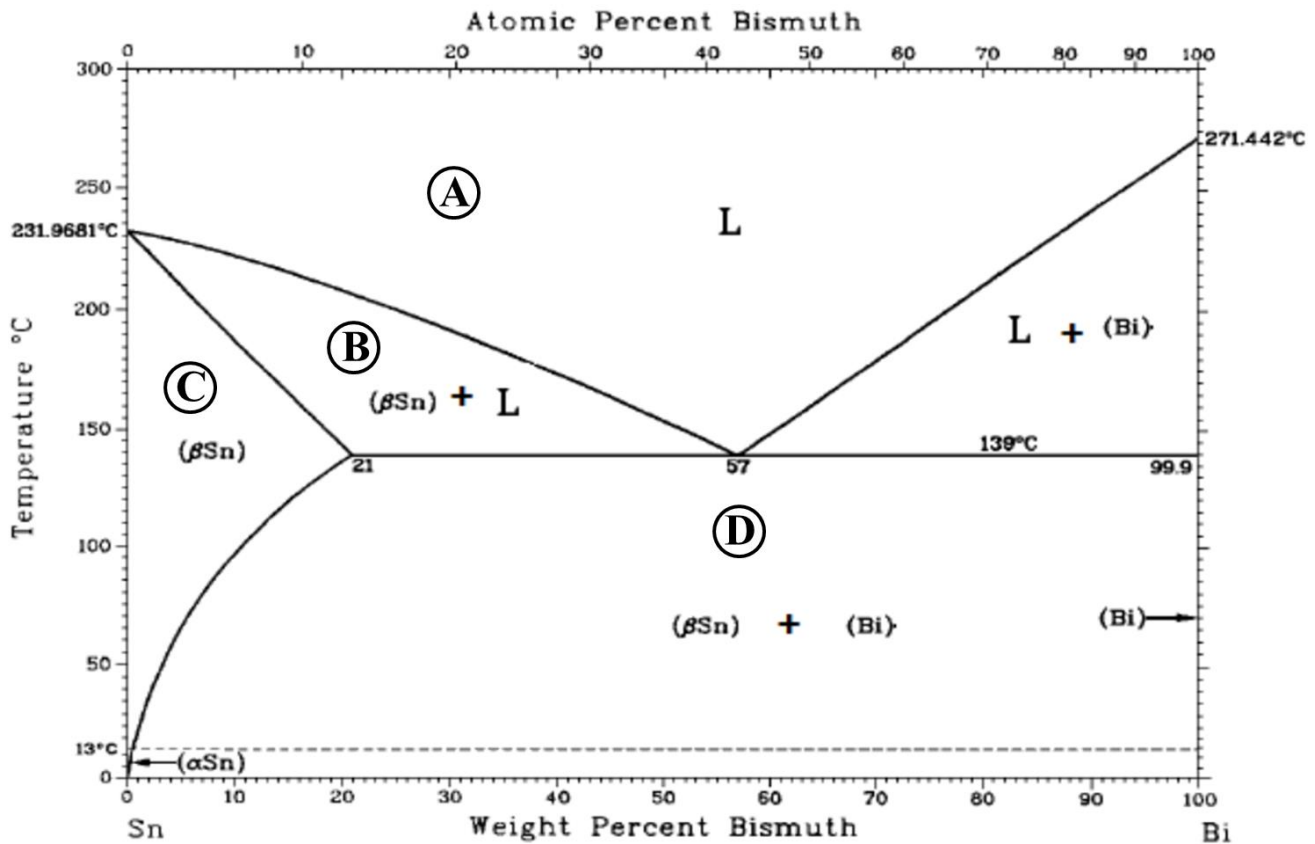


Figure 3. The Sn-Bi equilibrium phase diagram

For the purpose of explaining the method the system will be simplified to a solder ball and the solder in the solder paste. In a solder paste the solder itself accounts for about 50% of the paste volume, with the remainder being the flux medium that determines the printing characteristic and tackiness of the paste and provides the fluxing action required to facilitate coalescence of the powder particles into a single mass of solder, the wetting of the joint substrates and controls the surface tension of the liquid solder that determines the joint profile. However, once the solder ball has been wetted the flux medium plays no role in the process that determines how much of the BGA ball is lost to the mixed alloy.

To further simply the explanation of the method it will be presumed that the solder ball is pure Sn and the low melting point solder a simple binary Sn-Bi alloy. In fact the low-Ag SnAgCu alloys that are often preferred for BGA spheres because their greater compliance reduces the incidence of pad cratering in drop impact, the alloy is already about 98.5wt% Sn (with the remainder typically being 1wt% Ag and 0.5wt% Cu). Even SAC305 is 96.5wt% Sn (with the remainder 3w% Sn and 0.5wt% Cu). In any case the process that determines the extent of penetration of the LMP alloy into the ball involves only the Sn. The Ag is present only as the Ag_3Sn intermetallic compound and the Cu as the intermetallic compound Cu_6Sn_5 both of which remain in fairly stable equilibrium with the Sn phase over the likely temperature range of the mixed alloy reflow process. They would, therefore play no role in the interactions that occur in the reflow process. With the likely tolerances on the quantities of the materials in the system the difference in the outcome with a pure Sn ball should not be very different from that with SAC alloy balls. However, with the basic principle established, allowance can be made for the presence of Ag and Cu in the BGA ball alloy.

Commercial Bi-Sn alloys usually contain a small alloying addition to improve their properties, typically 0.5wt% of Ag or Sb. Over the temperature range of the mixed alloy reflow process the Ag has no solubility in Bi and so would be expected to be present in the low melting point solder as the Ag_3Sn intermetallic compound. Antimony (Sb) is completely soluble in Bi and

soluble in Sn and so could play a role in the determination of the final equilibrium but its effect would be small and will not be taken into account in the proposed model. Again allowance could be made for its effect once the basic model is recognized.

If the interaction between the solder ball and solder from the solder paste is allowed to proceed to equilibrium the factors that ultimately determine the extent to which the solder ball alloy is replaced by mixed alloy are:

- The location of the solidus line on the Sn-rich side of the Sn-Bi phase diagram
- The composition of the low melting point alloy
- The peak reflow temperature

If the time that the system is held at reflow temperature is limited then the system might not reach thermodynamic equilibrium. In that case another factor determining the extent the solder ball is replaced by the mixed alloy will be:

- The time at reflow temperature

Process

The process that occurs during reflow can be described as follows:

1. The solder powder in the paste melts and coalesces into a single mass of molten solder.
2. The molten solder wets the substrate pad and the lower part of the solder ball
3. The flux medium, having done its job of facilitating reflow and wetting is displaced from the solder mass but largely remains as a coating on the molten solder, contributing to heat transfer and protecting the molten solder and the lower part of the solder ball from oxidation.
4. Tin (Sn) from the BGA ball starts to dissolve in the molten low melting point alloy increasing the Sn content of the molten solder.
5. Dissolution of Sn from the solder ball continues until the Sn content of the molten solder moves into the two phase region of the phase diagram when a solid phase, a Sn-Bi solid solution, starts to freeze out of the melt
6. Dissolution of Sn from the BGA ball into the molten solder continues until the composition reaches the solidus composition at the reflow temperature at which point dissolution of Sn stops.
7. With the system then completely solid the only mechanism by which further intermixing of the low melting point alloy and the BGA ball can continue is by solid state diffusion, which, during the time available in a commercial reflow profile would be negligible.

If at this point the temperature is increased some of the mixed alloy will melt and there will be an opportunity for more Sn to dissolve from the BGA ball until the composition reaches the solidus at that higher temperature.

This process is illustrated schematically in Figure 4 for a low melting point alloy that is 50wt% Bi/50wt% Sn and a reflow temperature of 165°C.

At the end of Stage 3 the Sn-Bi alloy is fully molten (Figure 4, Point A).

If the flux has done its job the solder will have fully wetted the solder ball as well as the substrate. Sn from the ball would be starting to dissolve in the molten solder and the Sn content of the molten solder increases.

At Point B, the Sn content of the molten Sn-Bi alloy has reached saturation (approximately 58wt%Sn). As more Sn dissolves in the remaining liquid a solid phase starts to freeze out. That phase is a solid solution of Bi in Sn with a composition of approximately 86% Sn. By the time the system reaches Point C (approximately 70wt% Sn) the wt% solid Sn-Bi in the semi-molten solder mix can be calculated by the lever rule as:

$$\frac{BC}{BD} \times 100\% \Rightarrow \frac{(42-30)}{(42-14)} \times 100\% \Rightarrow \frac{12}{28} \times 100\% \approx 43\%$$

Sn from the solder ball continues to dissolve until it reaches a level of approximately 86wt% (Point D) when the mix of low melting point alloy and Sn is completely solid. While the temperature remains no higher than 165°C the system remains solid with solid state diffusion the only mechanism by which the Bi can migrate further into the solder ball.

The only other change in the system predicted by the phase diagram is that as the system cools the mixed alloy phase will cross the solvus line at about 130°C (Point E), which means that the Bi level has reached its saturation limit at that temperature and Bi will start to precipitate out of the Sn-Bi alloy.

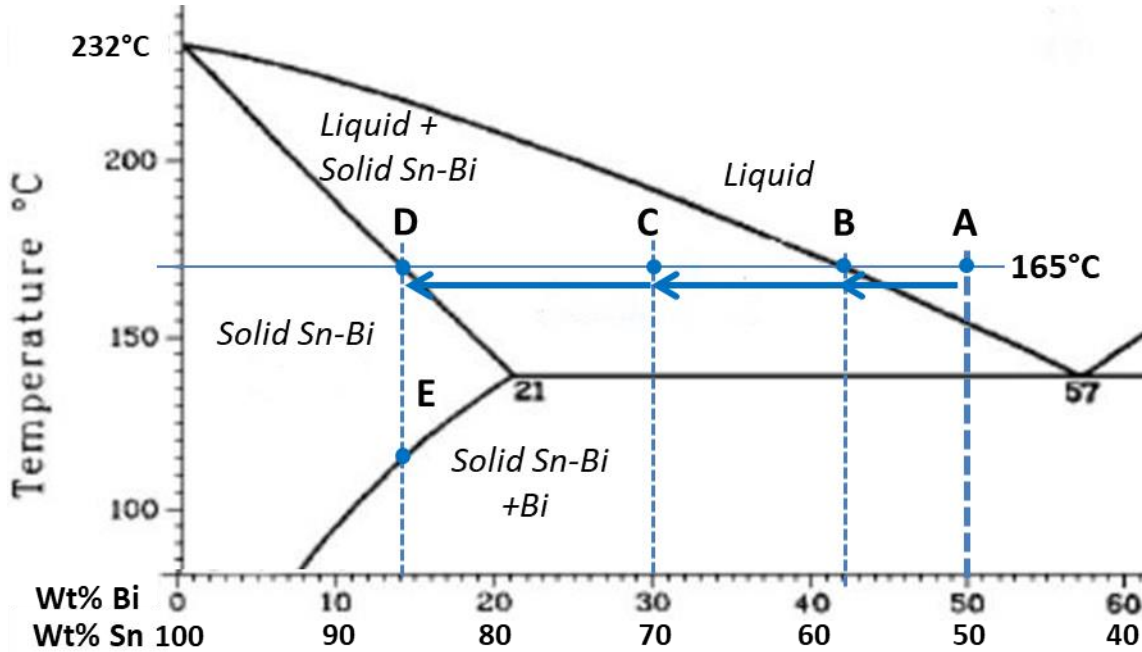


Figure 4. The process of a pure Sn BGA ball dissolving into Sn-50Bi solder at 165°C

Effect of Bi Level in Low Melting Point Alloy

In the example described in the previous section the length of the line AD provides an indication of the amount of Sn that will dissolve from the ball alloy before the melting point of the Sn-Bi alloy reaches the reflow temperature and the mixing process stops. If the starting alloy were 60% Bi rather than 50% then more Sn would have to dissolve from the ball alloy before the Sn content of the alloy mixture reaches the solvus limit at that temperature. In reality for a particular reflow temperature the location of the liquidus line on the Bi-rich side of the eutectic sets an upper limit on the Bi content of the solder that is usable at a particular target reflow temperature.

Effect of Reflow Temperature

As the temperature increases the amount of Bi that can be held in solid solution decreases. Put another way, as the Bi content of the alloy increases the temperature at which the alloy starts to melt decreases. In the phase diagram that trend is reflected in the slope of the solidus line that runs from the melting point of Sn to the limit of Bi solubility in Sn at the eutectic temperature. That means that as the reflow temperature increases the amount of Sn that will dissolve from the solder ball before the solidus line is crossed and the mixed alloy is completely frozen increases.

Calculating Actual Sn Dissolved

For a given volume of low melting point solder, the amount of Sn that will be dissolved from the solder ball at a particular temperature before the composition of the resulting mixed alloy reaches the solvus can be calculated from the slope of the solidus line.

In geometric terms the solidus line on the Sn-rich side of the Sn-Bi equilibrium phase diagram in Figure 5 can be described by the equation:

$$\text{wt\%Sn}_S = 79 + (T_R - 139) \times (100 - 79) \quad \text{Equation 1}$$

where %Sn_S is the minimum Sn content of the Sn-rich Sn-Bi alloy that is solid at the chosen reflow temperature T_R. 79 is the maximum wt%Sn at the eutectic temperature of 139°C (Figure 5). When T_R is set as the melting point of pure Sn, 232°C, the equation calculates the wt%Sn at 100% Sn (allowing for rounding errors).

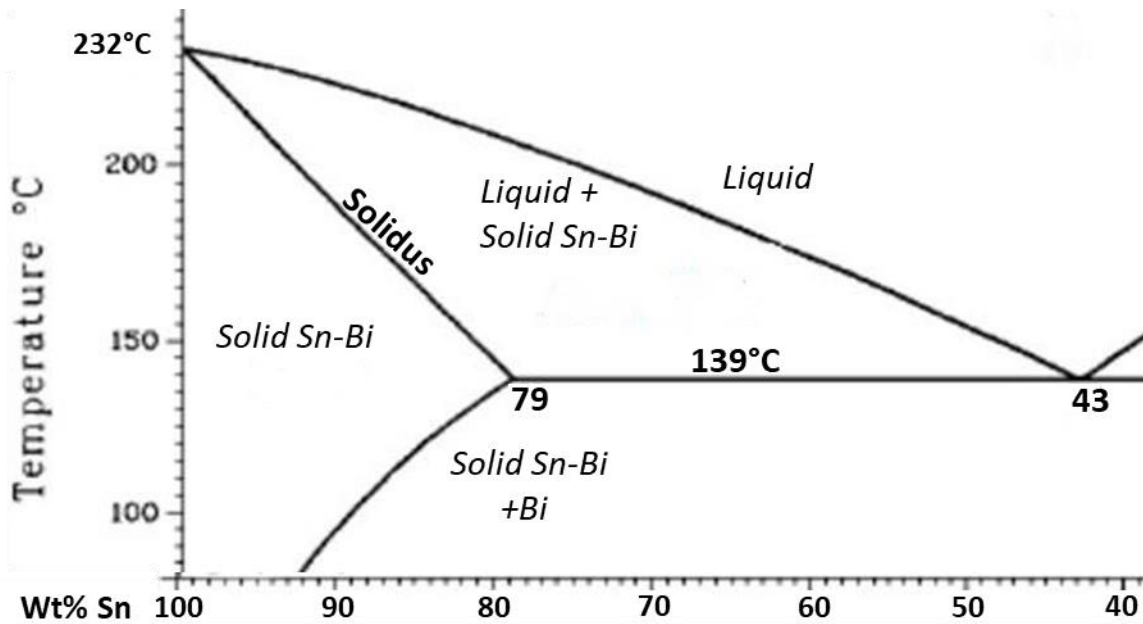


Figure 5. Phase diagram used for expressing the slope of the solidus line as a function of Sn content and temperature.

For a given quantity of a low melting point Sn-Bi alloy, with a chosen Sn content and the chosen reflow temperature, this equation can be used to calculate how much Sn will dissolve from the solder ball before the mixing process is brought to a halt by the composition of the resulting alloy crossing the solidus line. If the objective is that a significant proportion of the original solder ball remains at the completion of the reflow profile then the volume of solder paste and its initial Sn content would have to be carefully calculated, taking into account the size of the solder ball and the Sn content of its alloy.

Calculating Paste Volume for Reliable BGA Joints

For the purpose of demonstrating the application of this approach to the design of reliable mixed alloy reflow the reflow of a 500µm solder ball will be used as an example. A number of other simplifying assumptions are made in constructing this model but in its practical application to the selection of assembly parameters actual data would be used.

As in the earlier example the paste alloy will be a 50wt% Sn Sn-Bi solder. This alloy is slightly hypereutectic with respect to Sn but still has a relatively low liquidus temperature of around 155°C (reference Figure4).

Because of the large difference in density between solder and the flux medium a stencil printable solder paste is typically about 50% solder by volume. The density of a 50wt% Bi Sn-Bi solder can be estimated by calculation at about 8.4g/cm³.

For simplicity the paste deposit will be assumed to be circular so that the volume of paste can be calculated as:

$$\frac{\pi d^2 \times t}{4} \quad \text{Equation 2}$$

where d is the diameter of the paste deposit and t the thickness. With the chosen volume fraction of solder in the paste deposit and the estimated density of the low melting point alloy the weight of solder can be estimated as a function of the thickness and/or diameter of the deposit.

For a reflow temperature of 165°C the wt% Sn at which the mixed alloy will reach its solidus composition can be calculated by Equation 1 as around 84.5wt%. The amount of Sn required to raise the Sn level in the molten solder can be calculated on the basis of the weight of solder in the paste deposit. It is the dissolution of that Sn that will determine how much of the original solder ball will be lost to the mixed alloy phase in the final joint. A complication is that in calculating the amount of Sn that will be dissolved from the solder ball to reach the solidus composition at the reflow temperature allowance has to be made for the diluting effect of the increase in volume of the molten phase. The calculations made on this basis for a range of paste deposit thicknesses are set out in Table 1.

Paste Thickness cm	Paste Volume cm ³	Solder Volume cm ³	Solder Weight (g)	Wt of Sn (g)	Wt of Sn from Ball (g)	Volume of Sn from Ball cm ³
0.0010	1.9635E-06	9.81748E-07	8.2467E-06	4.1233E-06	1.8459E-05	0.000003
0.0020	3.92699E-06	1.9635E-06	1.6493E-05	8.2467E-06	3.6918E-05	0.000005
0.0030	5.89049E-06	2.94524E-06	2.4740E-05	1.2370E-05	5.5377E-05	0.000008
0.0040	7.85398E-06	3.92699E-06	3.2987E-05	1.6493E-05	7.3836E-05	0.000010
0.0050	9.81748E-06	4.90874E-06	4.1233E-05	2.0617E-05	9.2294E-05	0.000013
0.0060	1.1781E-05	5.89049E-06	4.9480E-05	2.4740E-05	1.1075E-04	0.000015
0.0070	1.37445E-05	6.87223E-06	5.7727E-05	2.8863E-05	1.2921E-04	0.000018
0.0080	1.5708E-05	7.85398E-06	6.5973E-05	3.2987E-05	1.4767E-04	0.000020
0.0090	1.76715E-05	8.83573E-06	7.4220E-05	3.7110E-05	1.6613E-04	0.000023
0.0100	1.9635E-05	9.81748E-06	8.2467E-05	4.1233E-05	1.8459E-04	0.000025
0.0110	2.15984E-05	1.07992E-05	9.0713E-05	4.5357E-05	2.0305E-04	0.000028
0.0120	2.35619E-05	1.1781E-05	9.8960E-05	4.9480E-05	2.2151E-04	0.000030
0.0130	2.55254E-05	1.27627E-05	1.0721E-04	5.3603E-05	2.3997E-04	0.000033
0.0140	2.74889E-05	1.37445E-05	1.1545E-04	5.7727E-05	2.5842E-04	0.000035
0.0150	2.94524E-05	1.47262E-05	1.2370E-04	6.1850E-05	2.7688E-04	0.000038
0.0160	3.14159E-05	1.5708E-05	1.3195E-04	6.5973E-05	2.9534E-04	0.000040
0.0170	3.33794E-05	1.66897E-05	1.4019E-04	7.0097E-05	3.1380E-04	0.000043
0.0180	3.53429E-05	1.76715E-05	1.4844E-04	7.4220E-05	3.3226E-04	0.000046
0.0190	3.73064E-05	1.86532E-05	1.5669E-04	7.8343E-05	3.5072E-04	0.000048
0.0200	3.92699E-05	1.9635E-05	1.6493E-04	8.2467E-05	3.6918E-04	0.000051
0.0210	4.12334E-05	2.06167E-05	1.7318E-04	8.6590E-05	3.8764E-04	0.000053
0.0220	4.31969E-05	2.15984E-05	1.8143E-04	9.0713E-05	4.0610E-04	0.000056
0.0230	4.51604E-05	2.25802E-05	1.8967E-04	9.4837E-05	4.2455E-04	0.000058
0.0240	4.71239E-05	2.35619E-05	1.9792E-04	9.8960E-05	4.4301E-04	0.000061
0.0250	4.90874E-05	2.45437E-05	2.0617E-04	1.0308E-04	4.6147E-04	0.000063

Table 1. Calculation of dissolution of Sn from solder ball as function of the thickness of the solder paste deposit.

To interpret the volume of Sn that dissolves in the low melting point paste in terms of the extent to which the mixed alloy penetrates into the ball the volume of a slice of a sphere is used as an approximation (Figure 6)

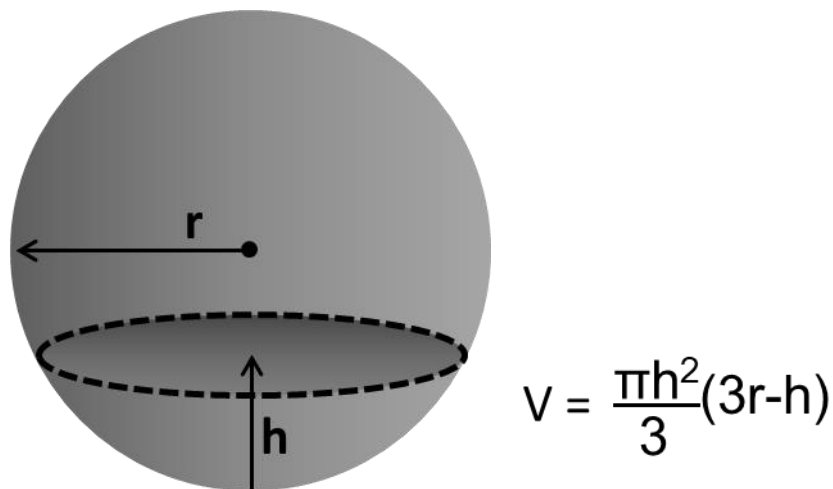


Figure 6. Equation from which the distance h of penetration of the mixed alloy into a solder ball can be estimated.

Because of the difficulty of solving the equation in Figure 6 to calculate h when V is known a graphical solution is used (Figure 7).

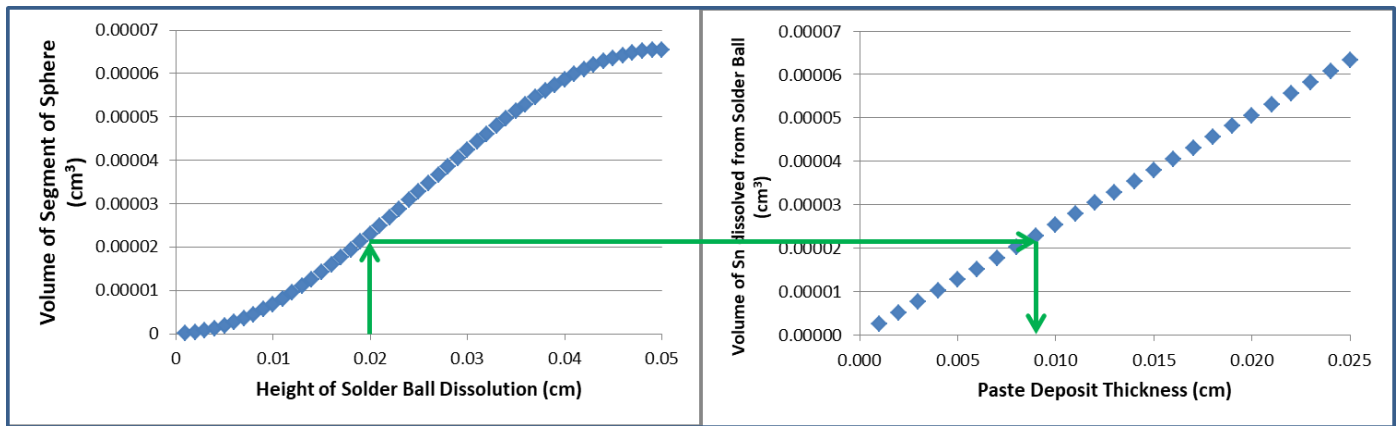


Figure 7. The plot on the right is the volume of Sn dissolved in the low melting point solder as a function of the thickness of a 500 μm diameter paste deposit. The plot on the left is the height of a slice of a 500 μm diameter solder ball as a function of the volume of the slice.

In the example illustrated on Figure 7 a 100 μm thickness 500 μm diameter print of Sn-50wt%Bi solder paste reflowed at 165 $^{\circ}\text{C}$ would result in the formation of a zone of mixed solder that would penetrate about 220 μm into a 500 μm pure Sn solder ball.

Conclusions

As is realised in practice, as indicated in Figure 2, the interface between the mixed alloy and the remaining solder ball is not planar but since it is determined by temperature, it follows the thermal gradients. However, the point of this paper is not to make an accurate prediction but to demonstrate the underlying principle that the extent of penetration of the mixed alloy phase into solder can be calculated on the basis of the following:

- The location of the solvus line in the relevant equilibrium phase diagram
- The composition of the low melting point solder
- The volume of low melting point solder in the solder paste deposit
- The peak reflow temperature

How far the mixed alloy penetrates into the solder ball will depend on the volume of the solder ball.

If a limit is to be set on the amount of original ball alloy that has to be retained to ensure the reliability of the joint then the paste alloy, the paste volume and the reflow temperature have to be set so that the volume of the ball alloy that will have to dissolve to bring the mixed alloy to its solidus composition at that temperature is no greater than the loss of original alloy volume that can be tolerated.

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